C++ Annotations Version 12.1.0

Frank B. Brokken
University of Groningen,
PO Box 407,
9700 AK Groningen
The Netherlands
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Abstract

This document is intended for knowledgeable users of **C** (or any other language using a **C**-like grammar, like **Perl** or **Java**) who would like to know more about, or make the transition to, **C++**. This document is the main textbook for Frank's **C++** programming courses, which are yearly organized at the University of Groningen. The **C++** Annotations do not cover all aspects of **C++**, though. In particular, **C++**'s basic grammar is not covered when equal to **C**'s grammar. Any basic book on **C** may be consulted to refresh that part of **C++**'s grammar.

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Chapter 1

Overview Of The Chapters

The chapters of the **C++** Annotations cover the following topics:

- Chapter 1: This overview of the chapters.
- Chapter 2: A general introduction to **C++**.
- Chapter 3: A first impression: differences between **C** and **C++**.
- Chapter 4: Name Spaces: how to avoid name collisions.
- Chapter 5: The ‘string’ data type.
- Chapter 6: The **C++** I/O library.
- Chapter 7: The ‘class’ concept: structs having functions. The ‘object’ concept: variables of a `class`.
- Chapter 8: Static data and functions: members of a class not bound to objects.
- Chapter 9: Allocation and returning unused memory: `new`, `delete`, and the function `set_new_handler()`.
- Chapter 10: Exceptions: handle errors where appropriate, rather than where they occur.
- Chapter 11: Give your own meaning to operators.
- Chapter 12: Abstract Containers to put stuff into.
- Chapter 13: Building classes upon classes: setting up class hierarchies.
- Chapter 14: Changing the behavior of member functions accessed through base class pointers.
- Chapter 15: Gaining access to private parts: friend functions and classes.
- Chapter 16: Classes having pointers to members: pointing to locations inside objects.
- Chapter 17: Constructing classes and enums within classes.
- Chapter 18: The Standard Template Library.
- Chapter 19: The STL generic algorithms.
- Chapter 20: Multi Threading.
- Chapter 21: Function templates: using *molds* for type independent functions.

- Chapter 22: Class templates: using *molds* for type independent classes.
- Chapter 23: Advanced Template Use: programming the compiler.
- Chapter 24: Coroutines.
- Chapter 25: Several examples of programs written in **C++**.

Chapter 2

Introduction

This document offers an introduction to the **C++** programming language. It is a guide for **C/C++** programming courses, yearly presented by Frank at the University of Groningen. This document is not a complete **C/C++** handbook, as much of the **C**-background of **C++** is not covered. Other sources should be referred to for that (e.g., the `on-line book`[1] suggested to me by George Danchev (danchev at spnet dot net)).

The reader should be forewarned that extensive knowledge of the **C** programming language is actually assumed. The **C++** Annotations continue where topics of the **C** programming language end, such as pointers, basic flow control and the construction of functions.

Some elements of the language, like specific lexical tokens (like *digraphs* (e.g., `<:` for `[`, and `>:` for `]`)) are not covered by the **C++** Annotations, as these tokens occur extremely seldom in **C++** source code. In addition, *trigraphs* (using `??<` for `{`, and `??>` for `}`) have been removed from **C++**.

The working draft of the **C++** standard is freely available, and can be cloned from the git-repository at `https://gitlab.com/cplusplus/draft.git`

The version number of the **C++** Annotations (currently 12.1.0) is updated when the content of the document change. The first number is the major number, and is probably not going to change for some time: it indicates a major rewriting. The middle number is increased when new information is added to the document. The last number only indicates small changes; it is increased when, e.g., series of typos are corrected.

This document is published by the Center of Information Technology, University of Groningen, the Netherlands under the `GNU General Public License`[2].

The **C++ Annotations** were typeset using the `yodl`[3] formatting system.

All correspondence concerning suggestions, additions, improvements or changes to this document should be directed to the author:

Frank B. Brokken
University of Groningen,
PO Box 407,
9700 AK Groningen
The Netherlands

---

[1] http://publications.gbdirect.co.uk/c_book/
[2] http://www.gnu.org/licenses/
[3] https://fbb-git.gitlab.io/yodl/

(email: f.b.brokken@rug.nl)

In this chapter an overview of **C++**'s defining features is presented. A few extensions to **C** are reviewed and the concepts of object based and object oriented programming (OOP) are briefly introduced.

2.1 What's new in the C++ Annotations

This section is modified when the first or second part of the version number changes (and occasionally also for the third field of the version number). At a major version upgrade the entries of the previous major version are kept, and entries referring to older releases are removed.

- Version 12.1.0 adds a description of the `__file_clock::to_sys` static member (section 4.3.1), repaired the descriptions of `pop*()` members of various abstract containers, and reorganized the description of the facilities of the `filesystem::path` class.
- Version 12.0.0 adds a new chapter about coroutines (chapter 24) and a new section (20.1.3) to chapter 20.
- Version 11.6.0 adds section 18.11 to chapter 18 and section 19.1.24 to chapter 19. The `std::optional` class is used to return values from functions that are optionally available, `std::iota` is used to fill a range with a sequence of incremented values.
- Version 11.5.0 adds section 18.10 to chapter 18 showing how local variables can directly be associated with structured data returned by functions.
- Version 11.4.0 contains a complete overhaul of section 23.13, covering the `C++20` *concepts*.
- Version 11.3.0 covers the three-way comparison operator (cf. section 11.6.2) and various comparison classes (cf. section 18.7), added to **C++** at the `C++20` standard.
- Version 11.2.0 moves the (rewritten) coverage of the chrono and filesystem namespaces to the Namespaces chapter, and contains a rewrite of the sections covering `error_codes`, `error_categories`, and `error_conditions` (cf. sections 4.3.2, 10.9, and 23.7).
- Version 11.1.0 contains an almost complete rewrite of the sections covering concepts (section 23.13).
- Version 11.0.0 covers new elements and elements that were re-introduced at the `C++20` standard. Version 11.0.0 is made available at the time the `C++20` standard has not yet formally been released, and compilers do not yet implement all its new elements. Therefore, modifications and updates may be required once the `C++20` standard has officially become the next standard. However, the elements of the new standard that are now covered by the **C++** Annotations are (mostly) supported by compilers.
  - Modules (cf. section 7.11.2) simplify header processing. E.g., when using modules header include guards are not required anymore.
  - The section about unrestricted unions (9.9) received a major upgrade, and was moved to chapter 9.
  - The section about the syntax of lambda expressions (section 11.11) received a major upgrade.
  - Section 4.3 covering the `std::filesystem` namespace received a new subsection showing which facilities of the `std::filesystem` namespace are replacing traditional **C** functions.
  - Transactional memory (covered in section 20.14) simplify access to shared data in multithreaded programs.

- Section 22.5.5 covers *folding expressions* can be used to associate binary operators with a variadic number of arguments.
- Section 22.6 received a sub-section covering specializing `std::tuple` elements in combination with structured binding declarations.
- Section 23.13 covers concepts (re-introduced into the language after having been considered before), allowing template writers to define requirements for their templates that must be satisfied before their templates can be used.

2.2 C++'s history

The first implementation of **C++** was developed in the 1980s at the AT&T Bell Labs, where the Unix operating system was created.

C++ was originally a 'pre-compiler', similar to the preprocessor of **C**, converting special constructions in its source code to plain **C**. Back then this code was compiled by a standard **C** compiler. The 'pre-code', which was read by the **C++** pre-compiler, was usually located in a file with the extension `.cc`, `.C` or `.cpp`. This file would then be converted to a **C** source file with the extension `.c`, which was thereupon compiled and linked.

The nomenclature of **C++** source files remains: the extensions `.cc` and `.cpp` are still used. However, the preliminary work of a **C++** pre-compiler is nowadays usually performed during the actual compilation process. Often compilers determine the language used in a source file from its extension. This holds true for Borland's and Microsoft's **C++** compilers, which assume a **C++** source for an extension `.cpp`. The GNU compiler `g++`, which is available on many Unix platforms, assumes for **C++** the extension `.cc`.

The fact that **C++** used to be compiled into **C** code is also visible from the fact that **C++** is a superset of **C**: **C++** offers the full **C** grammar and supports all **C**-library functions, and adds to this features of its own. This makes the transition from **C** to **C++** quite easy. Programmers familiar with **C** may start 'programming in **C++**' by using source files having extensions `.cc` or `.cpp` instead of `.c`, and may then comfortably slip into all the possibilities offered by **C++**. No abrupt change of habits is required.

2.2.1 History of the C++ Annotations

The original version of the **C++** Annotations was written by Frank Brokken and Karel Kubat in Dutch using `LaTeX`. After some time, Karel rewrote the text and converted the guide to a more suitable format and (of course) to English in September 1994.

The first version of the guide appeared on the net in October 1994. By then it was converted to `SGML`.

Gradually new chapters were added, and the content was modified and further improved (thanks to countless readers who sent us their comments).

In major version four Frank added new chapters and converted the document from SGML to `yodl`[4].

> The **C++** Annotations are freely distributable. Be sure to read the `legal notes`[5].
>
> **Reading the annotations beyond this point implies that you are aware of these notes and that you agree with them.**

---

[4] https://fbb-git.gitlab.io/yodl/

[5] legal.shtml

If you like this document, tell your friends about it. Even better, let us know by sending email to `Frank`[6].

2.2.2 Compiling a C program using a C++ compiler

Prospective **C++** programmers should realize that **C++** is not a perfect superset of **C**. There are some differences you might encounter when you simply rename a file to a file having the extension `.cc` and run it through a **C++** compiler:

- In **C**, `sizeof('c')` equals `sizeof(int)`, `'c'` being any ASCII character. The underlying philosophy is probably that `char`s, when passed as arguments to functions, are passed as integers anyway. Furthermore, the **C** compiler handles a character constant like `'c'` as an integer constant. Hence, in **C**, the function calls

  ```
  putchar(10);
  ```

  and

  ```
  putchar('\n');
  ```

  are synonymous.

  By contrast, in **C++**, `sizeof('c')` is always 1 (but see also section 3.4.2). An `int` is still an `int`, though. As we shall see later (section 2.5.4), the two function calls

  ```
  somefunc(10);
  ```

  and

  ```
  somefunc('\n');
  ```

  may be handled by different functions: **C++** distinguishes functions not only by their names, but also by their argument types, which are different in these two calls. The former using an `int` argument, the latter a `char`.

- **C++** requires very strict prototyping of external functions. E.g., in **C** a prototype like

  ```
  void func();
  ```

  means that a function `func()` exists, returning no value. The declaration doesn't specify which arguments (if any) are accepted by the function.

  However, in **C++** the above declaration means that the function `func()` does *not* accept any arguments at all. Any arguments passed to it result in a compile-time error.

  Note that the keyword `extern` is not required when declaring functions. A function definition becomes a function declaration simply by replacing a function's body by a semicolon. The keyword `extern` *is* required, though, when declaring variables.

---

[6] mailto:f.b.brokken@rug.nl

2.2.3 Compiling a C++ program

To compile a **C++** program, a **C++** compiler is required. Considering the free nature of this document, it won't come as a surprise that a *free compiler* is suggested here. The Free Software Foundation (FSF) provides at `http://www.gnu.org` a free **C++** compiler which is, among other places, also part of the Debian (`http://www.debian.org`) distribution of Linux (`http://www.linux.org`).

Always use the latest **C++** standard supported by your compiler. When the latest standard isn't used by default, but is already partially implemented it can usually be selected by specifying the appropriate flag. E.g., to use the C++20 standard specify the flag `--std=c++20`. In the **C++** Annotations it is assumed that this flag is used when compiling the examples.

2.2.3.1 C++ under MS-Windows

For MS-Windows Cygwin (`http://cygwin.com`) or MinGW (`http://mingw-w64.org/doku.php`) provide the foundation for installing the *Windows port* of the GNU `g++` compiler (see also `https://docs.microsoft.com/en-us/windows/wsl/about`).

The GNU `g++` compiler's official home page is `http://gcc.gnu.org`, also containing information about how to install the compiler in an MS-Windows system.

2.2.3.2 Compiling a C++ source text

Generally the following command can be used to compile a **C++** source file '`source.cc`':

```
g++ source.cc
```

This produces a binary program (`a.out` or `a.exe`). If the default name is inappropriate, the name of the executable can be specified using the `-o` flag (here producing the program `source`):

```
g++ -o source source.cc
```

If a mere compilation is required, the compiled module can be produced using the `-c` flag:

```
g++ -c source.cc
```

This generates the file `source.o`, which can later on be linked to other modules.

C++ programs quickly become too complex to maintain 'by hand'. With all serious programming projects program maintenance tools are used. Usually the standard `make` program is used to maintain **C++** programs, but good alternatives exist, like the `icmake`[7] or `ccbuild`[8] program maintenance utilities.

It is strongly advised to start using maintenance utilities early in the study of **C++**.

2.3 C++: advantages and claims

Often it is said that programming in **C++** leads to 'better' programs. Some of the claimed advantages of **C++** are:

---

[7] https://fbb-git.gitlab.io/icmake/

[8] https://gitlab.com/bneijt/ccbuild/

- New programs would be developed in less time because old code can be reused.
- Creating and using new data types would be easier than in **C**.
- The memory management under **C++** would be easier and more transparent.
- Programs would be less bug-prone, as **C++** uses a stricter syntax and type checking.
- 'Data hiding', the usage of data by one program part while other program parts cannot access the data, would be easier to implement with **C++**.

Which of these allegations are true? Originally, our impression was that the **C++** language was somewhat overrated; the same holding true for the entire object-oriented programming (OOP) approach. The enthusiasm for the **C++** language resembles the once uttered allegations about Artificial-Intelligence (AI) languages like Lisp and Prolog: these languages were supposed to solve the most difficult AI-problems 'almost without effort'. New languages are often oversold: in the end, each problem can be coded in any programming language (say BASIC or assembly language). The advantages and disadvantages of a given programming language aren't in 'what you can do with them', but rather in 'which tools the language offers to implement an efficient and understandable solution to a programming problem'. Often these tools take the form of syntactic *restrictions*, enforcing or promoting certain constructions or simply suggesting intentions by applying or 'embracing' such syntactic forms. Rather than a long list of plain assembly instructions we now use flow control statements, functions, objects or even (with **C++**) so-called *templates* to structure and organize code and to express oneself 'eloquently' in the language of one's choice.

Concerning the above allegations of **C++**, we support the following, however.

- The development of new programs while existing code is reused can also be implemented in **C** by, e.g., using function libraries. Functions can be collected in a library and need not be re-invented with each new program. **C++**, however, offers specific syntax possibilities for code reuse, apart from function libraries (see chapters 13 and 21).
- Creating and using new data types is certainly possible in **C**; e.g., by using `struct`s, `typedef`s etc.. From these types other types can be derived, thus leading to `struct`s containing `struct`s and so on. In **C++** these facilities are augmented by defining data types which are completely 'self supporting', taking care of, e.g., their memory management automatically (without having to resort to an independently operating memory management system as used in, e.g., **Java**).
- In **C++** memory management can in principle be either as easy or as difficult as it is in C. Especially when dedicated **C** functions such as `xmalloc` and `xrealloc` are used (allocating the memory or aborting the program when the memory pool is exhausted). However, with functions like `malloc` it is easy to err. Frequently errors in **C** programs can be traced back to miscalculations when using `malloc`. Instead, **C++** offers facilities to allocate memory in a somewhat safer way, using its `operator new`.
- Concerning 'bug proneness' we can say that **C++** indeed uses stricter type checking than **C**. However, most modern **C** compilers implement 'warning levels'; it is then the programmer's choice to disregard or get rid of the warnings. In **C++** many of such warnings become fatal errors (the compilation stops).
- As far as 'data hiding' is concerned, **C** does offer some tools. E.g., where possible, local or `static` variables can be used and special data types such as `struct`s can be manipulated by dedicated functions. Using such techniques, data hiding can be implemented even in **C**; though it must be admitted that **C++** offers special syntactic constructions, making it far easier to implement 'data hiding' (and more in general: 'encapsulation') in **C++** than in **C**.

C++ in particular (and OOP in general) is of course not *the* solution to all programming problems. However, the language *does* offer various new and elegant facilities which are worth investigating. At the downside, the level of grammatical complexity of **C++** has increased significantly as compared to **C**. This may be considered a serious drawback of the language. Although we got used to this increased level of complexity over time, the transition was neither fast nor painless.

With the **C++** Annotations we hope to help the reader when transiting from **C** to **C++** by focusing on the additions of **C++** as compared to **C** and by leaving out plain **C**. It is our hope that you like this document and may benefit from it.

Enjoy and good luck on your journey into **C++**!

2.4 What is Object-Oriented Programming?

Object-oriented (and object-based) programming propagates a slightly different approach to programming problems than the strategy usually used in **C** programs. In **C** programming problems are usually solved using a 'procedural approach': a problem is decomposed into subproblems and this process is repeated until the subtasks can be coded. Thus a conglomerate of functions is created, communicating through arguments and variables, global or local (or `static`).

In contrast (or maybe better: in addition) to this, an object-based approach identifies the **keywords** used in a problem statement. These keywords are then depicted in a diagram where arrows are drawn between those keywords to depict an internal hierarchy. The keywords become the objects in the implementation and the hierarchy defines the relationship between these objects. The term object is used here to describe a limited, well-defined structure, containing all information about an entity: data types and functions to manipulate the data. As an example of an object oriented approach, an illustration follows:

> The employees and owner of a car dealer and auto garage company are paid as follows. First, mechanics who work in the garage are paid a certain sum each month. Second, the owner of the company receives a fixed amount each month. Third, there are car salesmen who work in the showroom and receive their salary each month plus a bonus per sold car. Finally, the company employs second-hand car purchasers who travel around; these employees receive their monthly salary, a bonus per bought car, and a restitution of their travel expenses.

When representing the above salary administration, the keywords could be mechanics, owner, salesmen and purchasers. The properties of such units are: a monthly salary, sometimes a bonus per purchase or sale, and sometimes restitution of travel expenses. When analyzing the problem in this manner we arrive at the following representation:

- The owner and the mechanics can be represented by identical types, receiving a given salary per month. The relevant information for such a type would be the monthly amount. In addition this object could contain data as the name, address and social security number.
- Car salesmen who work in the showroom can be represented as the same type as above but with some *extra* functionality: the number of transactions (sales) and the bonus per transaction.

  In the hierarchy of objects we would define the dependency between the first two objects by letting the car salesmen be 'derived' from the owner and mechanics.
- Finally, there are the second-hand car purchasers. These share the functionality of the salesmen except for travel expenses. The additional functionality would therefore consist of the expenses made and this type would be derived from the salesmen.

The hierarchy of the identified objects are further illustrated in Figure 2.1.

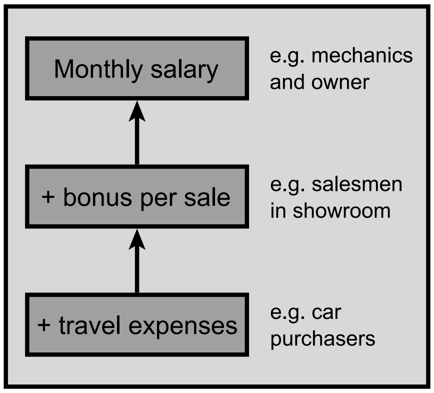

Figure 2.1: Hierarchy of objects in the salary administration.

The overall process in the definition of a hierarchy such as the above starts with the description of the most simple type. Traditionally (and still encountered with some popular object oriented languages) more complex types are thereupon derived from the basic type, with each derived type adding some new functionality. From these derived types, more complex types can again be derived *ad infinitum*, until a representation of the entire problem can be made.

Over the years this approach has become less popular in **C++** as it typically results in very tight *coupling* among those types, which in turns *reduces* rather than enhances the understanding, maintainability and testability of complex programs. The term *coupling* refers to the degree of independence between software components: tight coupling means a strong dependency, which is frowned upon in **C++**. In **C++** object oriented programs more and more favor small, easy to understand hierarchies, limited coupling and a developmental process where *design patterns* (cf. *Gamma et al.* (1995)) play a central role.

In **C++** *classes* are frequently used to define the characteristics of *objects*. Classes contain the necessary functionality to do useful things. Classes generally do not offer all their functionality (and typically *none* of their data) to objects of other classes. As we will see, classes tend to *hide* their properties in such a way that they are not directly modifiable by the outside world. Instead, dedicated functions are used to reach or modify the properties of objects. Thus class-type objects are able to uphold their own integrity. The core concept here is *encapsulation* of which *data hiding* is just an example. These concepts are further elaborated in chapter 7.

2.5 Differences between C and C++

In this section some examples of **C++** code are shown. Some differences between **C** and **C++** are highlighted.

2.5.1 The function 'main'

In **C++** there are only two variants of the function `main`: `int main()` and `int main(int argc, char **argv)`.

Notes:

- The return type of `main` is `int`, and *not* `void`;
- The function `main` cannot be overloaded (for other than the abovementioned signatures);

- It is *not* required to use an explicit `return` statement at the end of `main`. If omitted `main` returns 0;
- The value of `argv[argc]` equals 0;
- The 'third `char **envp` parameter' is not defined by the **C++** standard and should be avoided. Instead, the global variable `extern char **environ` should be declared providing access to the program's environment variables. Its final element has the value 0;
- A **C++** program ends normally when the `main` function returns. Using a *function try block* (cf. section 10.11) for `main` is also considered a normal end of a **C++** program. When a **C++** ends normally, destructors (cf. section 9.2) of globally defined objects are activated. A function like **exit**(3) does not normally end a **C++** program and using such functions is therefore deprecated.

2.5.2 End-of-line comment

According to the ANSI/ISO definition, 'end of line comment' is implemented in the syntax of **C++**. This comment starts with `//` and ends at the end-of-line marker. The standard **C** comment, delimited by `/*` and `*/` can still be used in **C++**:

```
int main()
{
    // this is end-of-line comment
    // one comment per line

    /*
        this is standard-C comment, covering
        multiple lines
    */
}
```

Despite the example, it is advised *not* to use **C** type comment inside the body of **C++** functions. Sometimes existing code must temporarily be suppressed, e.g., for testing purposes. In those cases it's very practical to be able to use standard **C** comment. If such suppressed code itself contains such comment, it would result in nested comment-lines, resulting in compiler errors. Therefore, the rule of thumb is not to use **C** type comment inside the body of **C++** functions (alternatively, `#if 0` until `#endif` pair of preprocessor directives could of course also be used).

2.5.3 Strict type checking

C++ uses very strict type checking. A prototype must be known for each function before it is called, and the call must match the prototype. The program

```
int main()
{
    printf("Hello World\n");
}
```

often compiles under **C**, albeit with a warning that `printf()` is an unknown function. But **C++** compilers (should) fail to produce code in such cases. The error is of course caused by the missing `#include <stdio.h>` (which in **C++** is more commonly included as `#include <cstdio>` directive).

And while we're at it: as we've seen in **C++** `main` *always* uses the `int` return value. Although it is possible to define `int main()` without explicitly defining a return statement, within `main` it is not possible to use a `return` statement without an explicit `int`-expression. For example:

```
int main()
{
    return;     // won't compile: expects int expression, e.g.
                // return 1;
}
```

Implicit conversions from `void *` to non-void pointers are not allowed. E.g., the following isn't accepted in **C++**:

```
void *none()
{
    return 0;
}

int main()
{
    int *empty = none();
}
```

2.5.4 Function Overloading

In **C++** it is possible to define functions having identical names but performing different actions. The functions must differ in their parameter lists (and/or in their `const` attribute). An example is given below:

```
#include <stdio.h>

void show(int val)
{
    printf("Integer: %d\n", val);
}

void show(double val)
{
    printf("Double: %lf\n", val);
}

void show(char const *val)
{
    printf("String: %s\n", val);
}

int main()
{
    show(12);
    show(3.1415);
    show("Hello World!\n");
}
```

In the above program three functions `show` are defined, only differing in their parameter lists, expecting an `int`, `double` and `char *`, respectively. The functions have identical names. Functions having identical names but different parameter lists are called *overloaded*. The act of defining such functions is called ‘function overloading’.

The **C++** compiler implements function overloading in a rather simple way. Although the functions share their names (in this example `show`), the compiler (and hence the linker) use quite different names. The conversion of a name in the source file to an internally used name is called ‘name mangling’. E.g., the **C++** compiler might convert the prototype `void show (int)` to the internal name `VshowI`, while an analogous function having a `char *` argument might be called `VshowCP`. The actual names that are used internally depend on the compiler and are not relevant for the programmer, except where these names show up in e.g., a listing of the content of a library.

Some additional remarks with respect to function overloading:

- Do not use function overloading for functions doing conceptually different tasks. In the example above, the functions `show` are still somewhat related (they print information to the screen).

  However, it is also quite possible to define two functions `lookup`, one of which would find a name in a list while the other would determine the video mode. In this case the behavior of those two functions have nothing in common. It would therefore be more practical to use names which suggest their actions; say, `findname` and `videoMode`.

- **C++** does not allow identically named functions to differ only in their return values, as it is always the programmer’s choice to either use or ignore a function’s return value. E.g., the fragment

  ```
  printf("Hello World!\n");
  ```

  provides no information about the return value of the function `printf`. Two functions `printf` which only differ in their return types would therefore not be distinguishable to the compiler.

- In chapter 7 the notion of `const` member functions is introduced (cf. section 7.7). Here it is merely mentioned that classes normally have so-called member functions associated with them (see, e.g., chapter 5 for an informal introduction to the concept). Apart from overloading member functions using different parameter lists, it is then also possible to overload member functions by their `const` attributes. In those cases, classes may have pairs of identically named member functions, having identical parameter lists. Then, these functions are overloaded by their `const` attribute. In such cases only one of these functions must have the `const` attribute.

2.5.5 Default function arguments

In **C++** it is possible to provide ‘default arguments’ when defining a function. These arguments are supplied by the compiler when they are not specified by the programmer. For example:

```
#include <stdio.h>

void showstring(char *str = "Hello World!\n");

int main()
{
    showstring("Here's an explicit argument.\n");

    showstring();            // in fact this says:
                             // showstring("Hello World!\n");
}
```

The possibility to omit arguments in situations where default arguments are defined is just a nice touch: it is the compiler who supplies the lacking argument unless it is explicitly specified at the call. The code of the program will neither be shorter nor more efficient when default arguments are used.

Functions may be defined with more than one default argument:

```
void two_ints(int a = 1, int b = 4);

int main()
{
    two_ints();             // arguments:  1, 4
    two_ints(20);           // arguments: 20, 4
    two_ints(20, 5);        // arguments: 20, 5
}
```

When the function `two_ints` is called, the compiler supplies one or two arguments whenever necessary. A statement like `two_ints(,6)` is, however, not allowed: when arguments are omitted they must be on the right-hand side.

Default arguments must be known at compile-time since at that moment arguments are supplied to functions. Therefore, the default arguments must be mentioned at the function's *declaration*, rather than at its *implementation*:

```
// sample header file
void two_ints(int a = 1, int b = 4);

// code of function in, say, two.cc
void two_ints(int a, int b)
{
    ...
}
```

It is an error to supply default arguments in both function definitions and function declarations. When applicable default arguments should be provided in function declarations: when the function is used by other sources the compiler commonly reads the header file rather than the function definition itself. Consequently the compiler has no way to determine the values of default arguments if they are provided in the function definition.

2.5.6 NULL-pointers vs. 0-pointers and nullptr

In **C++** all zero values are coded as `0`. In **C** `NULL` is often used in the context of pointers. This difference is purely stylistic, though one that is widely adopted. In **C++** `NULL` should be avoided (as it is a macro, and macros can --and therefore should-- easily be avoided in **C++**, see also section 8.1.4). Instead `0` can almost always be used.

Almost always, but not always. As **C++** allows function overloading (cf. section 2.5.4) the programmer might be confronted with an unexpected function selection in the situation shown in section 2.5.4:

```
#include <stdio.h>

void show(int val)
{
    printf("Integer: %d\n", val);
}

void show(double val)
{
    printf("Double: %lf\n", val);
}

void show(char const *val)
{
    printf("String: %s\n", val);
}

int main()
{
    show(12);
    show(3.1415);
    show("Hello World!\n");
}
```

In this situation a programmer intending to call `show(char const *)` might call `show(0)`. But this doesn't work, as 0 is interpreted as `int` and so `show(int)` is called. But calling `show(NULL)` doesn't work either, as **C++** usually defines `NULL` as 0, rather than `((void *)0)`. So, `show(int)` is called once again. To solve these kinds of problems the new **C++** standard introduces the keyword `nullptr` representing the 0 pointer. In the current example the programmer should call `show(nullptr)` to avoid the selection of the wrong function. The `nullptr` value can also be used to initialize pointer variables. E.g.,

```
int *ip = nullptr;      // OK
int value = nullptr;    // error: value is no pointer
```

2.5.7 The 'void' parameter list

In **C**, a function prototype with an empty parameter list, such as

```
void func();
```

means that the argument list of the declared function is not prototyped: for functions using this prototype the compiler does not warn against calling `func` with any set of arguments. In **C** the keyword `void` is used when it is the explicit intent to declare a function with no arguments at all, as in:

```
void func(void);
```

As **C++** enforces strict type checking, in **C++** an empty parameter list indicates the *total absence* of parameters. The keyword `void` is thus omitted.

2.5.8 The '#define __cplusplus'

Each **C++** compiler which conforms to the ANSI/ISO standard defines the symbol `__cplusplus`: it is as if each source file were prefixed with the preprocessor directive `#define __cplusplus`.

We shall see examples of the usage of this symbol in the following sections.

2.5.9 Using standard C functions

Normal **C** functions, e.g., which are compiled and collected in a run-time library, can also be used in **C++** programs. Such functions, however, must be declared as **C** functions.

As an example, the following code fragment declares a function `xmalloc` as a **C** function:

```
extern "C" void *xmalloc(int size);
```

This declaration is analogous to a declaration in **C**, except that the prototype is prefixed with `extern "C"`.

A slightly different way to declare **C** functions is the following:

```
extern "C"
{
    // C-declarations go in here
}
```

It is also possible to place preprocessor directives at the location of the declarations. E.g., a **C** header file `myheader.h` which declares **C** functions can be included in a **C++** source file as follows:

```
extern "C"
{
    #include <myheader.h>
}
```

Although these two approaches may be used, they are actually seldom encountered in **C++** sources. A more frequently used method to declare external **C** functions is encountered in the next section.

2.5.10 Header files for both C and C++

The combination of the predefined symbol `__cplusplus` and the possibility to define `extern "C"` functions offers the ability to create header files for both **C** and **C++**. Such a header file might, e.g., declare a group of functions which are to be used in both **C** and **C++** programs.

The setup of such a header file is as follows:

```
#ifdef __cplusplus
extern "C"
{
#endif

    /* declaration of C-data and functions are inserted here. E.g., */
    void *xmalloc(int size);

#ifdef __cplusplus
}
#endif
```

Using this setup, a normal **C** header file is enclosed by `extern "C" {` which occurs near the top of the file and by `}`, which occurs near the bottom of the file. The `#ifdef` directives test for the type of the compilation: **C** or **C++**. The 'standard' **C** header files, such as `stdio.h`, are built in this manner and are therefore usable for both **C** and **C++**.

In addition **C++** headers should support *include guards*. In **C++** it is usually undesirable to include the same header file twice in the same source file. Such multiple inclusions can easily be avoided by including an `#ifndef` directive in the header file. For example:

```
#ifndef MYHEADER_H_
#define MYHEADER_H_
    // declarations of the header file is inserted here,
    // using #ifdef __cplusplus etc. directives
#endif
```

When this file is initially scanned by the preprocessor, the symbol `MYHEADER_H_` is not yet defined. The `#ifndef` condition succeeds and all declarations are scanned. In addition, the symbol `MYHEADER_H_` is defined.

When this file is scanned next while compiling the same source file, the symbol `MYHEADER_H_` has been defined and consequently all information between the `#ifndef` and `#endif` directives is skipped by the compiler.

In this context the symbol name `MYHEADER_H_` serves only for recognition purposes. E.g., the name of the header file can be used for this purpose, in capitals, with an underscore character instead of a dot.

Apart from all this, the custom has evolved to give **C** header files the extension `.h`, and to give `C++` header files *no* extension. For example, the standard *iostreams* `cin`, `cout` and `cerr` are available after including the header file `iostream`, rather than `iostream.h`. In the Annotations this convention is used with the standard **C++** header files, but not necessarily everywhere else.

There is more to be said about header files. Section 7.11 provides an in-depth discussion of the preferred organization of **C++** header files. In addition, starting with the `C++20` standard *modules* are available resulting in a somewhat more efficient way of handling declarations than offered by the traditional header files.

Currently, the **C++** Annotations very briefly covers *modules* (cf. section 7.11.2).

2.5.11 Defining local variables

Although already available in the **C** programming language, local variables should only be defined once they're needed. Although doing so requires a little getting used to, eventually it tends to produce more readable, maintainable and often more efficient code than defining variables at the beginning of compound statements. We suggest to apply the following rules of thumb when defining local variables:

- Local variables should be created at 'intuitively right' places, such as in the example below. This does not only entail the `for`-statement, but also all situations where a variable is only needed, say, half-way through the function.
- More in general, variables should be defined in such a way that their scope is as *limited* and *localized* as possible. When avoidable local variables are not defined at the beginning of functions but rather where they're first used.
- It is considered good practice to *avoid global variables*. It is fairly easy to lose track of which global variable is used for what purpose. In **C++** global variables are seldom required, and by localizing variables the risk of using the same variable for multiple purposes (thereby invalidating the separate purposes of the variable), can easily be avoided.

If considered appropriate, *nested blocks* can be used to localize auxiliary variables. However, situations exist where local variables are considered appropriate inside nested statements. The just mentioned `for` statement is of course a case in point, but local variables can also be defined within the condition clauses of `if-else` statements, within selection clauses of `switch` statements and condition clauses of `while` statements. Variables thus defined are available to the full statement, including its nested statements. For example, consider the following `switch` statement:

```
#include <stdio.h>

int main()
{
    switch (int c = getchar())
    {
        case 'a':
        case 'e':
        case 'i':
        case 'o':
        case 'u':
            printf("Saw vowel %c\n", c);
        break;

        case EOF:
            printf("Saw EOF\n");
        break;

        case '0' ... '9':
            printf("Saw number character %c\n", c);
        break;

        default:
            printf("Saw other character, hex value 0x%2x\n", c);
    }
}
```

Note the location of the definition of the character '`c`': it is defined in the expression part of the `switch` statement. This implies that '`c`' is available *only* to the `switch` statement itself, including its nested (sub)statements, but not outside the scope of the `switch`.

The same approach can be used with `if` and `while` statements: a variable that is defined in the condition clause of an `if` and `while` statement is available in their nested statements. There are some caveats, though:

- The variable that is defined in the condition clause must be a variable which is initialized to a numeric or logical value;
- The variable definition cannot be nested (e.g., using parentheses) within a more complex expression.

The former point of attention should come as no big surprise: in order to be able to evaluate the logical condition of an `if` or `while` statement, the value of the variable must be interpretable as either zero (false) or non-zero (true). Usually this is no problem, but in **C++** *objects* (like objects of the type `std::string` (cf. chapter 5)) are often returned by functions. Such objects may or may not be interpretable as numeric values. If not (as is the case with `std::string` objects), then such variables can *not* be defined at the condition or expression clauses of condition- or repetition statements. The following example will therefore *not* compile:

```
if (std::string myString = getString())      // assume getString returns
{                                            // a std::string value
    // process myString
}
```

The above example requires additional clarification. Often a variable can profitably be given local scope, but an extra check is required immediately following its initialization. The initialization *and* the test cannot *both* be combined in one expression. Instead *two* nested statements are required. Consequently, the following example won't compile either:

```
if ((int c = getchar()) && strchr("aeiou", c))
    printf("Saw a vowel\n");
```

If such a situation occurs, either use two nested `if` statements, or localize the definition of `int c` using a nested compound statement:

```
if (int c = getchar())              // nested if-statements
    if (strchr("aeiou", c))
        printf("Saw a vowel\n");

{                                   // nested compound statement
    int c = getchar();
    if (c && strchr("aeiou", c))
       printf("Saw a vowel\n");
}
```

2.5.12 The keyword 'typedef'

The keyword `typedef` is still used in **C++**, but is not required anymore when defining `union`, `struct` or `enum` definitions. This is illustrated in the following example:

```
struct SomeStruct
{
    int     a;
    double  d;
    char    string[80];
};
```

When a `struct, union` or other compound type is defined, the tag of this type can be used as type name (this is `SomeStruct` in the above example):

```
SomeStruct what;

what.d = 3.1415;
```

2.5.13 Functions as part of a struct

In **C++** we may define functions as members of structs. Here we encounter the first concrete example of an object: as previously described (see section 2.4), an object is a structure containing data while specialized functions exist to manipulate those data.

A definition of a `struct Point` is provided by the code fragment below. In this structure, two `int` data fields and one function `draw` are declared.

```
struct Point            // definition of a screen-dot
{
    int x;              // coordinates
    int y;              // x/y
    void draw();        // drawing function
};
```

A similar structure could be part of a painting program and could, e.g., represent a pixel. With respect to this `struct` it should be noted that:

- The function `draw` mentioned in the `struct` definition is a mere *declaration*. The actual code of the function defining the actions performed by the function is found elsewhere (the concept of functions inside `struct`s is further discussed in section 3.2).
- The size of the `struct Point` is equal to the size of its two `int`s. A function declared inside the structure does not affect its size. The compiler implements this behavior by allowing the function `draw` to be available only in the context of a `Point`.

The `Point` structure could be used as follows:

```
Point a;                // two points on
Point b;                // the screen

a.x = 0;                // define first dot
a.y = 10;               // and draw it
a.draw();

b = a;                  // copy a to b
b.y = 20;               // redefine y-coord
b.draw();               // and draw it
```

As shown in the above example a function that is part of the structure may be selected using the dot (.) (the arrow (->) operator is used when pointers to objects are available). This is therefore identical to the way data fields of structures are selected.

The idea behind this syntactic construction is that several types may contain functions having identical names. E.g., a structure representing a circle might contain three `int` values: two values for the coordinates of the center of the circle and one value for the radius. Analogously to the `Point` structure, a `Circle` may now have a function `draw` to draw the circle.

2.5.14 Evaluation order of operands

Traditionally, the evaluation order of expressions of operands of binary operators is, except for the boolean operators `and` and `or`, not defined. C++ changed this for postfix expressions, assignment expressions (including compound assignments), and shift operators:

- Expressions using postfix operators (like index operators and member selectors) are evaluated from left to right (do not confuse this with postfix increment or decrement operators, which cannot be concatenated (e.g., `variable++++` does not compile)).

- Assignment expressions are evaluated from right to left;
- Operands of shift operators are evaluated from left to right.

In the following examples `first` is evaluated before `second`, before `third`, before `fourth`, whether they are single variables, parenthesized expressions, or function calls:

```
first.second
fourth += third = second += first
first << second << third << fourth
first >> second >> third >> fourth
```

In addition, when overloading an operator, the function implementing the overloaded operator is evaluated like the built-in operator it overloads, and not in the way function calls are generally ordered.

Chapter 3

A First Impression Of C++

In this chapter **C++** is further explored. The possibility to declare functions in `struct`s is illustrated in various examples; the concept of a `class` is introduced; casting is covered in detail; many new types are introduced and several important notational extensions to **C** are discussed.

3.1 Notable differences with C

Before we continue with the ‘real’ object-approach to programming, we first introduce some notable differences with the **C** programming language: not mere differences between **C** and **C++**, but important syntactic constructs and keywords not found or differently used in **C**.

3.1.1 Using the keyword ‘const’

Even though the keyword `const` is part of the **C** grammar, its use is more important and much more common and strictly used in **C++** than it is in **C**.

The `const` keyword is a modifier stating that the value of a variable or of an argument may not be modified. In the following example the intent is to change the value of a variable `ival`, which fails:

```
int main()
{
    int const ival = 3;     // a constant int
                            // initialized to 3

    ival = 4;               // assignment produces
                            // an error message
}
```

This example shows how `ival` may be initialized to a given value in its definition; attempts to change the value later (in an assignment) are not permitted.

Variables that are declared `const` can, in contrast to **C**, be used to specify the size of an array, as in the following example:

```
int const size = 20;
char buf[size];             // 20 chars big
```

Another use of the keyword `const` is seen in the declaration of pointers, e.g., in pointer-arguments. In the declaration

```
char const *buf;
```

`buf` is a pointer variable pointing to `char`s. Whatever is pointed to by `buf` may not be changed through `buf`: the `char`s are declared as `const`. The pointer `buf` itself however may be changed. A statement like `*buf = 'a';` is therefore not allowed, while `++buf` is.

In the declaration

```
char *const buf;
```

`buf` itself is a `const` pointer which may not be changed. Whatever `char`s are pointed to by `buf` may be changed at will.

Finally, the declaration

```
char const *const buf;
```

is also possible; here, neither the pointer nor what it points to may be changed.

The rule of thumb for the placement of the keyword `const` is the following: whatever occurs to the *left* to the keyword may not be changed.

Although simple, this rule of thumb is often used. For example, Bjarne Stroustrup states (in `http://www.research.att.com/~bs/bs_faq2.html#constplacement`):

> *Should I put "const" before or after the type?*
>
> *I put it before, but that's a matter of taste. "const T" and "T const" were always (both) allowed and equivalent. For example:*
>
> ```
> const int a = 1;        // OK
> int const b = 2;        // also OK
> ```
>
> *My guess is that using the first version will confuse fewer programmers ("is more idiomatic").*

But we've already seen an example where applying this simple 'before' placement rule for the keyword `const` produces unexpected (i.e., unwanted) results as we will shortly see (below). Furthermore, the 'idiomatic' before-placement also conflicts with the notion of *const functions*, which we will encounter in section 7.7. With const functions the keyword `const` is also placed behind rather than before the name of the function.

The definition or declaration (either or not containing `const`) should always be read from the variable or function identifier back to the type identifier:

> "Buf is a const pointer to const characters"

This rule of thumb is especially useful in cases where confusion may occur. In examples of **C++** code published in other places one often encounters the reverse: `const` *preceding* what should not be altered. That this may result in sloppy code is indicated by our second example above:

```
char const *buf;
```

What must remain constant here? According to the sloppy interpretation, the pointer cannot be altered (as `const` precedes the pointer). In fact, the char values are the constant entities here, as becomes clear when we try to compile the following program:

```
int main()
{
    char const *buf = "hello";

    ++buf;                     // accepted by the compiler
    *buf = 'u';                // rejected by the compiler
}
```

Compilation fails on the statement `*buf = 'u';` and *not* on the statement `++buf`.

Marshall Cline's `C++ FAQ`[1] gives the same rule (paragraph 18.5) , in a similar context:

> *[18.5] What's the difference between "const Fred* p", "Fred* const p" and "const Fred* const p"?*
>
> *You have to read pointer declarations right-to-left.*

Marshall Cline's advice can be improved, though. Here's a recipe that will effortlessly dissect even the most complex declaration:

1. start reading at the variable's name
2. read as far as possible until you reach the end of the declaration or an (as yet unmatched) closing parenthesis.
3. return to the point where you started reading, and read backwards until you reach the beginning of the declaration or a matching opening parenthesis.
4. If you reached an opening parenthesis, continue at step 2 beyond the parenthesis where you previously stopped.

Let's apply this recipe to the following (by itself irrelevant) complex declaration. Little arrows indicate how far we should read at each step and the direction of the arrow indicates the reading direction:

```
char const *(* const (*(*ip)())[])[]

                         ip          Start at the variable's name:
                                         'ip' is

                         ip)         Hitting a closing paren: revert
                         -->

                       (*ip)         Find the matching open paren:
                       <-                'a pointer to'

                       (*ip)())      The next unmatched closing par:
                            -->          'a function (not expecting
                                          arguments)'
```

---

[1] http://www.parashift.com/c++-faq-lite/const-correctness.html

```
                     (*(*ip)())      Find the matching open paren:
                     <-                  'returning a pointer to'

                     (*(*ip)())[])   The next closing par:
                               -->       'an array of'

            (* const (*(*ip)())[])   Find the matching open paren:
            <--------                    'const pointers to'

            (* const (*(*ip)())[])[] Read until the end:
                                  ->     'an array of'

char const *(* const (*(*ip)())[])[] Read backwards what's left:
<-----------                             'pointers to const chars'
```

Collecting all the parts, we get for `char const *(* const (*(*ip)())[])[]`: *ip is a pointer to a function (not expecting arguments), returning a pointer to an array of const pointers to an array of pointers to const chars*. This is what `ip` represents; the recipe can be used to parse any declaration you ever encounter.

3.1.2 Namespaces

C++ introduces the notion of a *namespace*: all symbols are defined in a larger context, called a *namespace*. Namespaces are used to avoid name conflicts that could arise when a programmer would like to define a function like `sin` operating on *degrees*, but does not want to lose the capability of using the standard `sin` function, operating on *radians*.

Namespaces are covered extensively in chapter 4. For now it should be noted that most compilers require the explicit declaration of a *standard namespace*: `std`. So, unless otherwise indicated, it is stressed that all examples in the Annotations now implicitly use the

```
using namespace std;
```

declaration. So, if you actually intend to compile examples given in the **C++** Annotations, make sure that the sources start with the above `using` declaration.

3.1.3 The scope resolution operator ::

C++ introduces several new operators, among which the scope resolution operator (`::`). This operator can be used in situations where a global variable exists having the same name as a local variable:

```
#include <stdio.h>

double counter = 50;                 // global variable

int main()
{
    for (int counter = 1;            // this refers to the
         counter != 10;              // local variable
         ++counter)
    {
        printf("%d\n",
                    ::counter           // global variable
                    /                   // divided by
                    counter);           // local variable
        }
    }
```

In the above program the scope operator is used to address a global variable instead of the local variable having the same name. In **C++** the scope operator is used extensively, but it is seldom used to reach a global variable shadowed by an identically named local variable. Its main purpose is encountered in chapter 7.

3.1.4 'cout', 'cin', and 'cerr'

Analogous to **C**, **C++** defines standard input- and output streams which are available when a program is executed. The streams are:

- `cout`, analogous to `stdout`,
- `cin`, analogous to `stdin`,
- `cerr`, analogous to `stderr`.

Syntactically these streams are not used as functions: instead, data are written to streams or read from them using the operators <<, called the *insertion operator* and >>, called the *extraction operator*. This is illustrated in the next example:

```
#include <iostream>

using namespace std;

int main()
{
    int     ival;
    char    sval[30];

    cout << "Enter a number:\n";
    cin >> ival;
    cout << "And now a string:\n";
    cin >> sval;

    cout << "The number is: " << ival << "\n"
            "And the string is: " << sval << '\n';
}
```

This program reads a number and a string from the `cin` stream (usually the keyboard) and prints these data to `cout`. With respect to streams, please note:

- The standard streams are declared in the header file `iostream`. In the examples in the **C++** Annotations this header file is often not mentioned explicitly. Nonetheless, it *must* be included (either directly or indirectly) when these streams are used. Comparable to the use of the `using namespace std;` clause, the reader is expected to `#include <iostream>` with all the examples in which the standard streams are used.

- The streams `cout`, `cin` and `cerr` are variables of so-called *class*-types. Such variables are commonly called *objects*. Classes are discussed in detail in chapter 7 and are used extensively in **C++**.
- The stream `cin` extracts data from a stream and copies the extracted information to variables (e.g., `ival` in the above example) using the extraction operator (two consecutive > characters: >>). Later in the Annotations we will describe how operators in **C++** can perform quite different actions than what they are defined to do by the language, as is the case here. Function overloading has already been mentioned. In **C++** *operators* can also have multiple definitions, which is called *operator overloading*.
- The operators which manipulate `cin`, `cout` and `cerr` (i.e., >> and <<) also manipulate variables of different types. In the above example `cout << ival` results in the printing of an integer value, whereas `cout << "Enter a number"` results in the printing of a string. The actions of the operators therefore depend on the types of supplied variables.
- The *extraction operator* (>>) performs a so called *type safe* assignment to a variable by 'extracting' its value from a text stream. Normally, the extraction operator skips all *whitespace* characters preceding the values to be extracted.
- Special symbolic constants are used for special situations. Normally a line is terminated by inserting `"\n"` or `'\n'`. But when inserting the `endl` symbol the line is terminated followed by the flushing of the stream's internal buffer. Thus, `endl` can usually be avoided in favor of `'\n'` resulting in somewhat more efficient code.

The stream objects `cin`, `cout` and `cerr` are not part of the **C++** grammar proper. The streams are part of the definitions in the header file `iostream`. This is comparable to functions like `printf` that are not part of the **C** grammar, but were originally written by people who considered such functions important and collected them in a run-time library.

A program may still use the old-style functions like `printf` and `scanf` rather than the new-style streams. The two styles can even be mixed. But streams offer several clear advantages and in many **C++** programs have completely replaced the old-style **C** functions. Some advantages of using streams are:

- Using insertion and extraction operators is *type-safe*. The format strings which are used with `printf` and `scanf` can define wrong format specifiers for their arguments, for which the compiler sometimes can't warn. In contrast, argument checking with `cin`, `cout` and `cerr` is performed by the compiler. Consequently it isn't possible to err by providing an `int` argument in places where, according to the format string, a string argument should appear. With streams there are no format strings.
- The functions `printf` and `scanf` (and other functions using format strings) in fact implement a *mini-language* which is interpreted at run-time. In contrast, with streams the **C++** compiler knows exactly which in- or output action to perform given the arguments used. No mini-language here.
- In addition the possibilities of the insertion and extraction operators may be *extended* allowing objects of classes that didn't exist when the streams were originally designed to be inserted into or extracted from streams. Mini languages as used with `printf` cannot be extended.
- The usage of the left-shift and right-shift operators in the context of the streams illustrates yet another capability of **C++**: operator overloading allowing us to redefine the actions an operator performs in certain contexts. Coming from **C** operator overloading requires some getting used to, but after a short little while these overloaded operators feel rather comfortable.
- Streams are independent of the media they operate upon. This (at this point somewhat abstract) notion means that the same code can be used without *any* modification at all to interface

> your code to *any* kind of device. The code using streams can be used when the device is a file on disk; an Internet connection; a digital camera; a DVD device; a satellite link; and much more: you name it. Streams allow your code to be decoupled (independent) of the devices your code is supposed to operate on, which eases maintenance and allows reuse of the same code in new situations.

The *iostream library* has a lot more to offer than just `cin, cout` and `cerr`. In chapter 6 *iostreams* are covered in greater detail. Even though `printf` and friends can still be used in **C++** programs, streams have practically replaced the old-style **C** `I/O` functions like `printf`. If you *think* you still need to use `printf` and related functions, think again: in that case you've probably not yet completely grasped the possibilities of stream objects.

3.2 Functions as part of structs

Earlier we noted that functions can be part of `struct`s (see section 2.5.13). Such functions are called *member functions*. This section briefly discusses how to define such functions.

The code fragment below shows a `struct` having data fields for a person's name and address. A function `print` is included in the `struct`'s definition:

```
struct Person
{
    char name[80];
    char address[80];

    void print();
};
```

When defining the member function `print` the structure's name (`Person`) and the scope resolution operator (`::`) are used:

```
void Person::print()
{
    cout << "Name:      " << name << "\n"
            "Address:   " << address << '\n';
}
```

The implementation of `Person::print` shows how the fields of the `struct` can be accessed without using the structure's type name. Here the function `Person::print` prints a variable `name`. Since `Person::print` is itself a part of `struct person`, the variable `name` implicitly refers to the same type.

This `struct Person` could be used as follows:

```
Person person;

strcpy(person.name, "Karel");
strcpy(person.address, "Marskramerstraat 33");
person.print();
```

The advantage of member functions is that the called function automatically accesses the data fields of the structure for which it was invoked. In the statement `person.print()` the object `person` is the 'substrate': the variables `name` and `address` that are used in the code of `print` refer to the data stored in the `person` object.

3.2.1 Data hiding: public, private and class

As mentioned before (see section 2.3), **C++** contains specialized syntactic possibilities to implement data hiding. Data hiding is the capability of sections of a program to hide its data from other sections. This results in very clean data definitions. It also allows these sections to enforce the integrity of their data.

C++ has three keywords that are related to data hiding: `private`, `protected` and `public`. These keywords can be used in the definition of `struct`s. The keyword `public` allows all subsequent fields of a structure to be accessed by all code; the keyword `private` only allows code that is part of the `struct` itself to access subsequent fields. The keyword `protected` is discussed in chapter 13, and is somewhat outside of the scope of the current discussion.

In a `struct` all fields are `public`, unless explicitly stated otherwise. Using this knowledge we can expand the `struct Person`:

```
struct Person
{
    private:
        char d_name[80];
        char d_address[80];
    public:
        void setName(char const *n);
        void setAddress(char const *a);
        void print();
        char const *name();
        char const *address();
};
```

As the data fields `d_name` and `d_address` are in a `private` section they are only accessible to the member functions which are defined in the `struct`: these are the functions `setName`, `setAddress` etc.. As an illustration consider the following code:

```
Person fbb;

fbb.setName("Frank");         // OK, setName is public
strcpy(fbb.d_name, "Knarf");  // error, x.d_name is private
```

Data integrity is implemented as follows: the actual data of a `struct Person` are mentioned in the structure definition. The data are accessed by the outside world using special functions that are also part of the definition. These member functions control all traffic between the data fields and other parts of the program and are therefore also called ‘interface’ functions. The thus implemented data hiding is illustrated in Figure 3.1. The members `setName` and `setAddress` are declared with `char const *` parameters. This indicates that the functions will not alter the strings which are supplied as their arguments. Analogously, the members `name` and `address` return `char const *`s: the compiler prevents callers of those members from modifying the information made accessible through the return values of those members.

Two examples of member functions of the `struct Person` are shown below:

```
void Person::setName(char const *n)
{
    strncpy(d_name, n, 79);
    d_name[79] = 0;
}
```

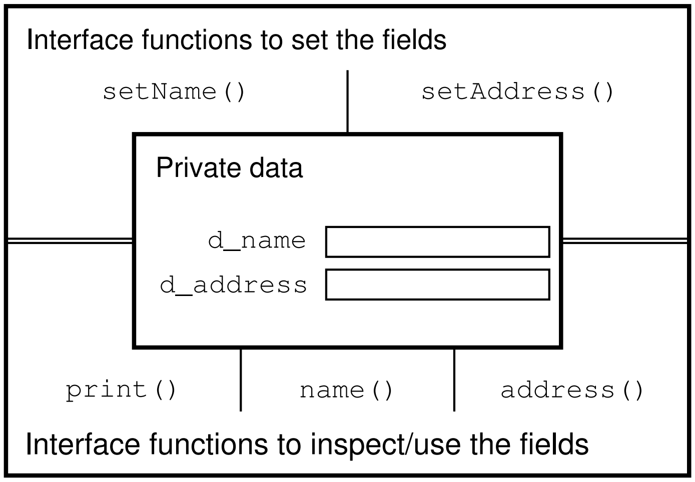
Interface functions to set the fields
setName()
setAddress()
Private data
d_name
d_address
print()
name()
address()
Interface functions to inspect/use the fields

Figure 3.1: Private data and public interface functions of the class Person.

```
char const *Person::name()
{
    return d_name;
}
```

The power of member functions and of the concept of data hiding results from the abilities of member functions to perform special tasks, e.g., checking the validity of the data. In the above example `setName` copies only up to 79 characters from its argument to the data member `name`, thereby avoiding a buffer overflow.

Another illustration of the concept of data hiding is the following. As an alternative to member functions that keep their data in memory a library could be developed featuring member functions storing data on file. To convert a program storing `Person` structures in memory to one that stores the data on disk no special modifications are required. After recompilation and linking the program to a new library it is converted from storage in memory to storage on disk. This example illustrates a broader concept than data hiding; it illustrates *encapsulation*. Data hiding is a kind of encapsulation. Encapsulation in general results in reduced coupling of different sections of a program. This in turn greatly enhances reusability and maintainability of the resulting software. By having the structure encapsulate the actual storage medium the program using the structure becomes independent of the actual storage medium that is used.

Though data hiding can be implemented using `struct`s, more often (almost always) *classes* are used instead. A class is a kind of struct, except that a class uses private access by default, whereas structs use public access by default. The definition of a `class Person` is therefore identical to the one shown above, except that the keyword `class` has replaced `struct` while the initial `private:` clause can be omitted. Our typographic suggestion for class names (and other type names defined by the programmer) is to start with a capital character to be followed by the remainder of the type name using lower case letters (e.g., `Person`).

3.2.2 Structs in C vs. structs in C++

In this section we'll discuss an important difference between **C** and **C++** structs and (member) functions. In **C** it is common to define several functions to process a `struct`, which then require a pointer to the `struct` as one of their arguments. An imaginary **C** header file showing this concept is:

```
/* definition of a struct PERSON    This is C   */
typedef struct
{
    char name[80];
    char address[80];
} PERSON;

/* some functions to manipulate PERSON structs */

/* initialize fields with a name and address    */
void initialize(PERSON *p, char const *nm,
                   char const *adr);

/* print information    */
void print(PERSON const *p);

/* etc..    */
```

In **C++**, the declarations of the involved functions are put inside the definition of the `struct` or `class`. The argument denoting which `struct` is involved is no longer needed.

```
class Person
{
    char d_name[80];
    char d_address[80];

    public:
        void initialize(char const *nm, char const *adr);
        void print();
        // etc..
};
```

In **C++** the `struct` parameter is not used. A **C** function call such as:

```
PERSON x;

initialize(&x, "some name", "some address");
```

becomes in **C++**:

```
Person x;

x.initialize("some name", "some address");
```

3.3 Several additions to C's grammar

3.3.1 References

In addition to the common ways to define variables (plain variables or pointers) **C++** introduces *references* defining synonyms for variables. A reference to a variable is like an *alias*; the variable and the reference can both be used in statements involving the variable:

```
int int_value;
int &ref = int_value;
```

In the above example a variable `int_value` is defined. Subsequently a reference `ref` is defined, which (due to its initialization) refers to the same memory location as `int_value`. In the definition of `ref`, the reference operator `&` indicates that `ref` is not itself an `int` but a reference to one. The two statements

```
++int_value;
++ref;
```

have the same effect: they increment `int_value`'s value. Whether that location is called `int_value` or `ref` does not matter.

References serve an important function in **C++** as a means to pass modifiable arguments to functions. E.g., in standard **C**, a function that increases the value of its argument by five and returning nothing needs a pointer parameter:

```
void increase(int *valp)    // expects a pointer
{                           // to an int
    *valp += 5;
}

int main()
{
    int x;

    increase(&x);           // pass x's address
}
```

This construction can *also* be used in **C++** but the same effect is also achieved using a reference:

```
void increase(int &valr)    // expects a reference
{                           // to an int
    valr += 5;
}

int main()
{
    int x;

    increase(x);            // passed as reference
}
```

It is arguable whether code such as the above should be preferred over **C**'s method, though. The statement `increase (x)` suggests that not `x` itself but a *copy* is passed. Yet the value of `x` changes because of the way `increase()` is defined. However, references can also be used to pass objects that are only inspected (without the need for a copy or a const *) or to pass objects whose modification is an accepted side-effect of their use. In those cases using references are strongly preferred over existing alternatives like copy by value or passing pointers.

Behind the scenes references are implemented using pointers. So, as far as the compiler is concerned references in **C++** are just const pointers. With references, however, the programmer does not need to know or to bother about levels of indirection. An important distinction between plain pointers and references is of course that with references no indirection takes place. For example:

```
extern int *ip;
extern int &ir;

ip = 0;      // reassigns ip, now a 0-pointer
ir = 0;      // ir unchanged, the int variable it refers to
             // is now 0.
```

In order to prevent confusion, we suggest to adhere to the following:

- In those situations where a function does not alter its parameters of a built-in or pointer type, value parameters can be used:

  ```
  void some_func(int val)
  {
      cout << val << '\n';
  }

  int main()
  {
      int x;

      some_func(x);       // a copy is passed
  }
  ```

- When a function explicitly must change the values of its arguments, a pointer parameter is preferred. These pointer parameters should preferably be the function's initial parameters. This is called *return by argument*.

  ```
  void by_pointer(int *valp)
  {
      *valp += 5;
  }
  ```

- When a function doesn't change the value of its class- or struct-type arguments, or if the modification of the argument is a trivial side-effect (e.g., the argument is a stream) references can be used. Const-references should be used if the function does not modify the argument:

  ```
  void by_reference(string const &str)
  {
      cout << str;    // no modification of str
  }

  int main ()
  {
      int x = 7;
      by_pointer(&x);         // a pointer is passed
                              // x might be changed
      string str("hello");
      by_reference(str);      // str is not altered
  }
  ```

  References play an important role in cases where the argument is not changed by the function but where it is undesirable to copy the argument to initialize the parameter. Such a situation occurs when a large object is passed as argument, or is returned by the function. In these cases the copying operation tends to become a significant factor, as the entire object must be copied. In these cases references are preferred.

If the argument isn't modified by the function, or if the caller shouldn't modify the returned information, the `const` keyword should be used. Consider the following example:

```
struct Person                   // some large structure
{
    char    name[80];
    char    address[90];
    double  salary;
};

Person person[50];          // database of persons

                            // printperson expects a
                            // reference to a structure
                            // but won't change it
void printperson (Person const &subject)
{
    cout << "Name: " << subject.name << '\n' <<
            "Address: " << subject.address << '\n';

}
                            // get a person by index value
Person const &personIdx(int index)
{
    return person[index];   // a reference is returned,
}                           // not a copy of person[index]

int main()
{
    Person boss;

    printperson(boss);      // no pointer is passed,
                            // so `boss' won't be
                            // altered by the function
    printperson(personIdx(5));
                            // references, not copies
                            // are passed here
}
```

- Furthermore, note that there is yet another reason for using references when passing objects as function arguments. When passing a reference to an object, the activation of a so called *copy constructor* is avoided. Copy constructors are covered in chapter 9.

References *could* result in extremely 'ugly' code. A function may return a reference to a variable, as in the following example:

```
int &func()
{
    static int value;
    return value;
}
```

This allows the use of the following constructions:

```
func() = 20;
func() += func();
```

It is probably superfluous to note that such constructions should normally not be used. Nonetheless, there are situations where it is useful to return a reference. We have actually already seen an example of this phenomenon in our previous discussion of streams. In a statement like `cout << "Hello" << '\n';` the insertion operator returns a reference to `cout`. So, in this statement first the `"Hello"` is inserted into `cout`, producing a reference to `cout`. Through this reference the `'\n'` is then inserted in the `cout` object, again producing a reference to `cout`, which is then ignored.

Several differences between pointers and references are pointed out in the next list below:

- A reference cannot exist by itself, i.e., without something to refer to. A declaration of a reference like

  ```
  int &ref;
  ```

  is not allowed; what would `ref` refer to?
- References can be declared as `external`. These references were initialized elsewhere.
- References may exist as parameters of functions: they are initialized when the function is called.
- References may be used in the return types of functions. In those cases the function determines what the return value refers to.
- References may be used as data members of classes. We return to this usage later.
- Pointers are variables by themselves. They point at something concrete or just “at nothing”.
- References are aliases for other variables and cannot be re-aliased to another variable. Once a reference is defined, it refers to its particular variable.
- Pointers (except for const pointers) can be reassigned to point to different variables.
- When an address-of operator `&` is used with a reference, the expression yields the address of the variable to which the reference applies. In contrast, ordinary pointers are variables themselves, so the address of a pointer variable has nothing to do with the address of the variable pointed to.

3.3.2 Rvalue References

In **C++**, temporary (rvalue) values are indistinguishable from `const &` types. **C++** introduces a new reference type called an *rvalue reference*, which is defined as `typename &&`.

The name *rvalue* reference is derived from assignment statements, where the variable to the left of the assignment operator is called an *lvalue* and the expression to the right of the assignment operator is called an *rvalue*. Rvalues are often temporary, anonymous values, like values returned by functions.

In this parlance the **C++** reference should be considered an *lvalue reference* (using the notation `typename &`). They can be contrasted to *rvalue references* (using the notation `typename &&`).

The key to understanding rvalue references is the concept of an *anonymous variable*. An anonymous variable has no name and this is the distinguishing feature for the compiler to associate it automatically with an rvalue reference if it has a choice. Before introducing some interesting constructions let's first have a look at some standard situations where *lvalue* references are used. The following function returns a temporary (anonymous) value:

```
int intVal()
{
    return 5;
}
```

Although `intVal`'s return value can be assigned to an `int` variable it requires copying, which might become prohibitive when a function does not return an `int` but instead some large object. A *reference* or *pointer* cannot be used either to collect the anonymous return value as the return value won't survive beyond that. So the following is illegal (as noted by the compiler):

```
int &ir = intVal();          // fails: refers to a temporary
int const &ic = intVal();    // OK: immutable temporary
int *ip = &intVal();         // fails: no lvalue available
```

Apparently it is not possible to modify the temporary returned by `intVal`. But now consider these functions:

```
void receive(int &value)            // note: lvalue reference
{
    cout << "int value parameter\n";
}
void receive(int &&value)           // note: rvalue reference
{
    cout << "int R-value parameter\n";
}
```

and let's call this function from `main`:

```
int main()
{
    receive(18);
    int value = 5;
    receive(value);
    receive(intVal());
}
```

This program produces the following output:

```
int R-value parameter
int value parameter
int R-value parameter
```

The program's output shows the compiler selecting `receive(int &&value)` in all cases where it receives an anonymous `int` as its argument. Note that this includes `receive(18)`: a value 18 has no name and thus `receive(int &&value)` is called. Internally, it actually uses a temporary variable to store the 18, as is shown by the following example which modifies `receive`:

```
void receive(int &&value)
```

```
{
    ++value;
    cout << "int R-value parameter, now: " << value << '\n';
        // displays 19 and 6, respectively.
}
```

Contrasting `receive(int &value)` with `receive(int &&value)` has nothing to do with `int &value` not being a const reference. If `receive(int const &value)` is used the same results are obtained. Bottom line: the compiler selects the overloaded function using the rvalue reference if the function is passed an anonymous value.

The compiler runs into problems if `void receive(int &value)` is replaced by `void receive(int value)`, though. When confronted with the choice between a value parameter and a reference parameter (either lvalue or rvalue) it cannot make a decision and reports an ambiguity. In practical contexts this is not a problem. Rvalue references were added to the language in order to be able to distinguish the two forms of references: named values (for which lvalue references are used) and anonymous values (for which rvalue references are used).

It is this distinction that allows the implementation of *move semantics* and *perfect forwarding*. At this point the concept of *move semantics* cannot yet fully be discussed (but see section 9.7 for a more thorough discussion) but it is very well possible to illustrate the underlying ideas.

Consider the situation where a function returns a `struct Data` containing a pointer to a dynamically allocated NTBS. We agree that `Data` objects are only used after initialization, for which two `init` functions are available. As an aside: when `Data` objects are no longer required the memory pointed at by `text` must again be returned to the operating system; assume that that task is properly performed.

```
struct Data
{
    char *text;

    void init(char const *txt);      // initialize text from txt

    void init(Data const &other)
    {
        text = strdup(other.text);
    }
};
```

There's also this interesting function:

```
Data dataFactory(char const *text);
```

Its implementation is irrelevant, but it returns a (temporary) `Data` object initialized with `text`. Such temporary objects cease to exist once the statement in which they are created end.

Now we'll use `Data`:

```
int main()
{
    Data d1;
    d1.init(dataFactory("object"));
}
```

Here the `init` function duplicates the NTBS stored in the temporary object. Immediately thereafter the temporary object ceases to exist. If you think about it, then you realize that that's a bit over the top:

- the `dataFactory` function uses `init` to initialize the `text` variable of its temporary `Data` object. For that it uses `strdup`;
- the `d1.init` function then *also* uses `strdup` to initialize `d1.text`;
- the statement ends, and the temporary object ceases to exist.

That's two `strdup` calls, but the temporary `Data` object thereafter is never used again.

To handle cases like these *rvalue reference* were introduced. We add the following function to the `struct Data`:

```
void init(Data &&tmp)
{
    text = tmp.text;       // (1)
    tmp.text = 0;          // (2)
}
```

Now, when the compiler translates `d1.init(dataFactory("object"))` it notices that `dataFactory` returns a (temporary) object, and because of that it uses the `init(Data &&tmp)` function. As we know that the `tmp` object ceases to exist after executing the statement in which it is used, the `d1` object (at (1)) *grabs* the temporary object's `text` value, and then (at (2)) assigns 0 to `other.text` so that the temporary object's `free(text)` action does no harm.

Thus, `struct Data` suddenly has become *move-aware* and implements *move semantics*, removing the (extra copy) drawback of the previous approach, and instead of making an extra copy of the temporary object's NTBS the pointer value is simply transferred to its new owner.

3.3.3 Lvalues, rvalues and more

Although this section contains forward references to chapters 5, 7, and 16, its topic best fits the current chapter. This section can be skipped without loss of continuity, and you might consider returning to it once you're familiar with the content of these future chapters.

Historically, the **C** programming language distinguished between *lvalues* and *rvalues*. The terminology was based on assignment expressions, where the expression to the left of the assignment operator receives a value (e.g., it referred to a location in memory where a value could be written into, like a variable), while the expression to the right of the assignment operator only had to represent a value (it could be a temporary variable, a constant value or the value stored in a variable):

```
lvalue = rvalue;
```

C++ adds to this basic distinction several new ways of referring to expressions:

- `lvalue`: an *lvalue* in **C++** has the same meaning as in **C**. It refers to a location where a value can be stored, like a variable, a reference to a variable, or a dereferenced pointer.
- `xvalue`: an *xvalue* indicates an *expiring value*. An expiring value refers to an *object* (cf. chapter 7) just before its lifetime ends. Such objects normally have to make sure that resources they own (like dynamically allocated memory) also cease to exist, but such resources may, just before the object's lifetime ends, be moved to another location, thus preventing their destruction.

- `glvalue`: a *glvalue* is a *generalized lvalue*. A generalized lvalue refers to anything that may receive a value. It is either an lvalue or an xvalue.
- `prvalue`: a *prvalue* is a *pure rvalue*: a literal value (like `1.2e3`) or an immutable object (e.g., the value returned from a function returning a constant `std::string` (cf. chapter 5)).

An expression's value is an xvalue if it is:

- the value returned by a function returning an rvalue reference to an object;
- an object that is cast to an rvalue reference;
- an expression accessing a non-static class data member whose object is
  - an xvalue, or
  - a `.*` (pointer-to-member) expression (cf. chapter 16) in which the left-hand side operand is an xvalue and the right-hand side operand is a pointer to a data member.

  The effect of this rule is that named rvalue references are treated as lvalues and anonymous rvalue references to objects are treated as xvalues.
  Rvalue references to functions are treated as lvalues whether anonymous or not.

Here is a small example. Consider this simple struct:

```
struct Demo
{
    int d_value;
};
```

In addition we have these function declarations and definitions:

```
Demo &&operator+(Demo const &lhs, Demo const &rhs);
Demo &&factory();

Demo demo;
Demo &&rref = static_cast<Demo &&>(demo);
```

Expressions like

```
factory();
factory().d_value;
static_cast<Demo &&>(demo);
demo + demo
```

are xvalues. However, the expression

```
rref;
```

is an lvalue.

In many situations it's not particularly important to know what kind of lvalue or what kind of rvalue is actually used. In the **C++** Annotations the term *lhs* (left hand side) is frequently used to indicate an operand that's written to the left of a binary operator, while the term *rhs* (right hand side) is frequently used to indicate an operand that's written to the right of a binary operator. Lhs and rhs operands could actually be gvalues (e.g., when representing ordinary variables), but they could also be prvalues (e.g., numeric values added together using the addition operator). Whether or not lhs and rhs operands are gvalues or lvalues can always be determined from the context in which they are used.

3.3.4 Strongly typed enumerations

Enumeration values in **C++** are in fact `int` values, thereby bypassing type safety. E.g., values of different enumeration types may be compared for (in)equality, albeit through a (static) type cast.

Another problem with the current `enum` type is that their values are not restricted to the enum type name itself, but to the scope where the enumeration is defined. As a consequence, two enumerations having the same scope cannot have identical names.

Such problems are solved by defining *enum classes*. An *enum class* can be defined as in the following example:

```
enum class SafeEnum
{
    NOT_OK,     // 0, by implication
    OK          = 10,
    MAYBE_OK    // 11, by implication
};
```

Enum classes use `int` values by default, but the used value type can easily be changed using the `: type` notation, as in:

```
enum class CharEnum: unsigned char
{
    NOT_OK,
    OK
};
```

To use a value defined in an enum class its enumeration name must be provided as well. E.g., `OK` is not defined, `CharEnum::OK` is.

Using the data type specification (noting that it defaults to `int`) it is possible to use enum class forward declarations. E.g.,

```
enum Enum1;                 // Illegal: no size available
enum Enum2: unsigned int;   // Legal: explicitly declared type

enum class Enum3;           // Legal: default int type is used
enum class Enum4: char;     // Legal: explicitly declared type
```

A sequence of symbols of a strongly typed enumeration can also be indicated in a `switch` using the ellipsis syntax, as shown in the next example:

```
SafeEnum enumValue();

switch (enumValue())
{
    case SafeEnum::NOT_OK ... SafeEnum::OK:
        cout << "Status is known\n";
    break;

    default:
        cout << "Status unknown\n";
    break;
}
```

3.3.5 Initializer lists

The **C** language defines the initializer list as a list of values enclosed by curly braces, possibly themselves containing initializer lists. In **C** these initializer lists are commonly used to initialize arrays and structs.

C++ extends this concept by introducing the *type* `initializer_list<Type>` where `Type` is replaced by the type name of the values used in the initializer list. Initializer lists in **C++** are, like their counterparts in **C**, recursive, so they can also be used with multi-dimensional arrays, structs and classes.

Before using the `initializer_list` the `<initializer_list>` header file must be included.

Like in **C**, initializer lists consist of a list of values surrounded by curly braces. But unlike **C**, *functions* can define initializer list parameters. E.g.,

```
void values(std::initializer_list<int> iniValues)
{
}
```

A function like `values` could be called as follows:

```
values({2, 3, 5, 7, 11, 13});
```

The initializer list appears as an argument which is a list of values surrounded by curly braces. Due to the recursive nature of initializer lists a two-dimensional series of values can also be passes, as shown in the next example:

```
void values2(std::initializer_list<std::initializer_list<int>> iniValues)
{}

values2({{1, 2}, {2, 3}, {3, 5}, {4, 7}, {5, 11}, {6, 13}});
```

Initializer lists are constant expressions and cannot be modified. However, their *size* and values may be retrieved using their `size,` `begin`, and `end` members as follows:

```
void values(initializer_list<int> iniValues)
{
    cout << "Initializer list having " << iniValues.size() << "values\n";
    for
    (
        initializer_list<int>::const_iterator begin = iniValues.begin();
            begin != iniValues.end();
                ++begin
    )
        cout << "Value: " << *begin << '\n';
}
```

Initializer lists can also be used to initialize objects of classes (cf. section 7.5).

Implicit conversions, also called *narrowing conversions* are not allowed when specifying values of initializer lists. Narrowing conversions are encountered when values are used of a type whose range is larger than the type specified when defining the initializer list. For example

- specifying `float` or `double` values to define initializer lists of `int` values;

- specifying integral values exceeding the range of `float` to define initializer lists of `float` values;
- specifying values of integral types of a wider range than the integral type that is specified for the initializer list, except if the specified values lie within the range of the initializer list's integral type

Some examples:

```
initializer_list<int> ii{ 1.2 };        // 1.2 isn't an int value
initializer_list<unsigned> iu{ ~0ULL }; // unsigned long long doesn't fit
```

3.3.5.1 Designated initialization

C++, like **C**, also supports *designated initialization*. However, as **C++** requires that destruction of data members occurs in the opposite order as their construction it is required that, when using designated initialization, members are initialized in the order in which they are declared in their class or struct. E.g.,

```
struct Data
{
    int d_first;
    double d_second;
    std::string d_third;
};

Data data{ .d_first = 1, .d_third = "hello" };
```

In this example, `d_first` and `d_third` are explicitly initialized, while `d_second` is implicitly initialized to its default value (so: 0.0).

In **C++** it is not allowed to reorder the initialization of members in a desginated initialization list. So, `Data data{ .d_third = "hello", .d_first = 1 }` is an error, but `Data data{ .d_third = "hello" }` is OK, as there is no ordering conflict in the latter example (this also initializes `d_first` and `d_second` to 0).

Likewise, a union can be initialized using designated initialization, as illustrated by the next example:

```
union Data
{
    int d_first;
    double d_second;
    std::string *d_third;
};
                    // initialize the union's d_third field:
Data data{ .d_third = new string{ "hello" } };
```

3.3.6 Initializers for bit-fields

Bit-fields are used to specify series of bits in an integral value type. For example, in networking software processing IP4 packets, the first `uint32_t` value of IP4 packets contain:

- the version (4 bits);

- the header length (4 bits);
- the type of service (8 bits);
- the total length (16 bits)

Rather than using complex bit and bit-shift operations, these fields inside integral values can be specified using bit-fields. E.g.,

```
struct FirstIP4word
{
    uint32_t version:   4;
    uint32_t header:    4;
    uint32_t tos:       8;
    uint32_t length:   16;
};
```

To total size of a `FirstIP4word` object is 32 bits, or four bytes. To show the version of a `FirstIP4word first` object, simply do:

```
cout << first.version << '\n';
```

and to set its header length to 10 simply do

```
first.header = 10;
```

Bit fields are already available in **C**. The `C++20` standard allows them to be initialized by default by using initialization expressions in their definitions. E.g.,

```
struct FirstIP4word
{
    uint32_t version:   4 = 1;  // version now 1, by default
    uint32_t header:    4 = 10; // TCP header length now 10, by default
    uint32_t tos:       8;
    uint32_t length:   16;
};
```

The initialization expressions are evaluated when the object using the bit-fields is defined. Also, when a variable is used to initialize a bit-field the variable must at least have been declared when the struct containing bit-fields is defined. E.g.,

```
extern int value;

struct FirstIP4word
{
    ...
    uint32_t length:   16 = value;  // OK: value has been declared
};
```

3.3.7 Type inference using 'auto'

The keyword `auto` can be used to simplify type definitions of variables and return types of functions if the compiler is able to determine the proper types of such variables or functions.

Using `auto` as a storage class specifier is no longer supported by **C++**: a variable definition like `auto int var` results in a compilation error.

The keyword `auto` is used in situations where it is very hard to determine the variable's type. These situations are encountered, e.g., in the context of *templates* (cf. chapters 18 until 23). It is also used in situations where a known type is a very long one but also automatically available to the compiler. In such cases the programmer uses `auto` to avoid having to type long type definitions.

At this point in the Annotations only simple examples can be given. Refer to section 21.1.2 for additional information about `auto` (and the related `decltype` function).

When defining and initializing a variable `int variable = 5` the type of the initializing expression is well known: it's an `int`, and unless the programmer's intentions are different this could be used to define `variable`'s type (a somewhat contrived example as in this case it reduces rather than improves the clarity of the code):

```
auto variable = 5;
```

However, it is attractive to use `auto`. In chapter 5 the *iterator* concept is introduced (see also chapters 12 and 18). Iterators frequently have long type definitions, like

```
std::vector<std::string>::const_reverse_iterator
```

Functions may return objects having such types. Since the compiler knows about these types we may exploit this knowledge by using `auto`. Assume that a function `begin()` is declared like this:

```
std::vector<std::string>::const_reverse_iterator begin();
```

Rather than writing a long variable definition (at `// 1`, below) a much shorter definition (at `// 2`) can be used:

```
std::vector<std::string>::const_reverse_iterator iter = begin();    // 1
auto iter = begin();                                                // 2
```

It's also easy to define and initialized additional variables of such types. When initializing such variables `iter` can be used to initialize those variables, and `auto` can be used, so the compiler deduces their types:

```
auto start = iter;
```

When defining variables using `auto` the variable's type is deduced from the variable's initializing expression. Plain types and pointer types are used as-is, but when the initializing expression is a reference type, then the reference's basic type (without the reference, omitting `const` or `volatile` specifications) is used.

If a reference type is required then `auto &` or `auto &&` can be used. Likewise, `const` and/or pointer specifications can be used in combination with the `auto` keyword itself. Here are some examples:

```
int value;
auto another = value;   // 'int another' is defined

string const &text();
auto str = text();      // text's plain type is string, so
```

```
                            // string str, NOT string const str
                            // is defined
    str += "...";           // so, this is OK

    int *ip = &value;
    auto ip2 = ip;          // int *ip2 is defined.

    int *const &ptr = ip;
    auto ip3 = ptr;         // int *ip3 is defined, omitting const &
    auto const &ip4 = ptr;  // int *const &ip4 is defined.
```

In the next to last `auto` specification, the tokens (reading right to left) from the reference to the basic type are omitted: here `const &` was appended to `ptr's` basic type (`int *`). Hence, `int *ip2` is defined.

In the last `auto` specification `auto` also produces `int *`, but in the type definition `const &` is added to the type produced by `auto`, so `int *const &ip4` is defined.

The `auto` keyword can also be used to postpone the definition of a function's return type. The declaration of a function `intArrPtr` returning a pointer to arrays of 10 `int`s looks like this:

```
    int (*intArrPtr())[10];
```

Such a declaration is fairly complex. E.g., among other complexities it requires 'protection of the pointer' using parentheses in combination with the function's parameter list. In situations like these the specification of the return type can be postponed using the `auto` return type, followed by the specification of the function's return type after any other specification the function might receive (e.g., as a const member (cf. section 7.7) or following its `noexcept` specification (cf. section 23.8)).

Using `auto` to declare the above function, the declaration becomes:

```
    auto intArrPtr() -> int (*)[10];
```

A return type specification using `auto` is called a *late-specified return type*.

Since the C++14 standard late return type specifications are no longer required for functions returning `auto`. Such functions can now simply be declared like this:

```
    auto autoReturnFunction();
```

In this case some restrictions apply, both to the function definitions and the function declarations:

- If multiple return statements are used in function definitions they all must return values of identical types;
- Functions merely returning `auto` cannot be used before the compiler has seen their definitions. So they cannot be used after mere declarations;
- When functions returning `auto` are implemented as recursive function then at least one return statement must have been seen before the recursive call. E.g.,

```
        auto fibonacci(size_t n)
        {
            if (n <= 1)
                return n;
            return fibonacci(n - 1) + fibonacci(n - 2);
        }
```

3.3.7.1 Structured binding declarations

Usually functions return single-valued results: `doubles, ints, strings`, etc. When functions need to return multiple values a *return by argument* construction is often used, where addresses of variables that live outside of the called function are passed to functions, allowing the functions to assign new values to those variables.

When multiple values should be *returned* from a function a `struct` can be used, but *pairs* (cf. section 12.2) or *tuples* (cf. section 22.6) can also be used. Here's a simple example, where a function `fun` returns a `struct` having two data fields:

```
struct Return
{
    int first;
    double second;
};

Return fun()
{
    return Return{ 1, 12.5 };
}
```

(Briefly forward referencing to sections 12.2 and 22.6: the `struct` definition can completely be omitted if `fun` returns a `pair` or `tuple`. In those cases the following code remains valid.)

A function *calling* `fun` traditionally defines a variable of the same type as `fun's` return type, and then uses that variable's fields to access `first` and `second`. If you don't like the typing, `auto` can also be used:

```
int main()
{
    auto r1 = fun();
    cout << r1.first;
}
```

Instead of referring to the elements of the returned `struct, pair` or `tuple` *structured binding declarations* can also be used. Here, `auto` is followed by a (square brackets surrounded) comma-separated list of variables, where each variable is *defined*, and receives the value of the corresponding field or element of the called function's return value. So, the above `main` function can also be written like this:

```
int main()
{
    auto [one, two] = fun();
    cout << one;                  // one and two: now defined
}
```

Merely specifying `auto` results in `fun's` return value being copied, and the structured bindings variables will refer to the copied value. But structured binding declarations can also be used in combination with (lvalue/rvalue) return values. The following ensures that `rone` and `rtwo` refer to the elements of `fun's` anonymous return value:

```
int main()
{
        auto &&[rone, rtwo] = fun();
    }
```

If the called function returns a value that survives the function call itself, then structured binding declarations can use *lvalue references*. E.g.,

```
    Return &fun2()
    {
        static Return ret{ 4, 5 };
        return ret;
    }

    int main()
    {
        auto &[lone, ltwo] = fun2();    // OK: referring to ret's fields
    }
```

To use structured binding declarations it is not required to use function calls. The object providing the data can also anonymously be defined:

```
    int main()
    {
        auto const &[lone, ltwo] = Return{ 4, 5 };
        // or:
        auto &&[lone, ltwo] = Return{ 4, 5 };
    }
```

The object doesn't even have to make its data members publicly available. In section `TUPLES` using structured bindings not necessarily referring to data members is covered.

Another application is found in situations where nested statements of `for` or selection statements benefit from using locally defined variables of various types. Such variables can easily be defined using structured binding declarations that are initialized from anonymous structs, pairs or tuples. Here is an example illustrating this:

```
    // define a struct:
    struct Three
    {
        size_t year;
        double firstAmount;
        double interest;
    };
    // define an array of Three objects, and process each in turn:
    Three array[10];
    fill(array);             // not implemented here

    for (auto &[year, amount, interest]: array)
        cout << "Year " << year << ": amount = " << amount << '\n';
```

When using structured bindings the structured binding declaration must specify all elements that are available. So if a struct has four data members the structured binding declaration must define four elements. To avoid warnings of unused variables at lease one of the variables of the structured binding declaration must be used.

3.3.8 Defining types and 'using' declarations

In **C++** `typedef` is commonly used to define shorthand notations for complex types. Assume we want to define a shorthand for 'a pointer to a function expecting a double and an int, and returning an unsigned long long int'. Such a function could be:

```
unsigned long long int compute(double, int);
```

A pointer to such a function has the following form:

```
unsigned long long int (*pf)(double, int);
```

If this kind of pointer is frequently used, consider defining it using `typedef`: simply put `typedef` in front of it and the pointer's name is turned into the name of a type. It could be capitalized to let it stand out more clearly as the name of a type:

```
typedef unsigned long long int (*PF)(double, int);
```

After having defined this type, it can be used to declare or define such pointers:

```
PF pf = compute;         // initialize the pointer to a function like
                         // 'compute'
void fun(PF pf);         // fun expects a pointer to a function like
                         // 'compute'
```

However, including the pointer in the typedef might not be a very good idea, as it masks the fact that `pf` is a pointer. After all, `PF pf` looks more like '`int x`' than '`int *x`'. To document that `pf` is in fact a pointer, slightly change the `typedef`:

```
typedef unsigned long long int FUN(double, int);

FUN *pf = compute;       // now pf clearly is a pointer.
```

The scope of typedefs is restricted to compilation units. Therefore, typedefs are usually embedded in header files which are then included by multiple source files in which the typedefs should be used.

In addition to `typedef` **C++** offers the `using` keyword to associate a type and an identifier. In practice `typedef` and `using` can be used interchangeably. The `using` keyword arguably result in more readable type definitions. Consider the following three (equivalent) definitions:

- The traditional, **C** style definition of a type, embedding the type name in the definition (turning a variable name into a type name):

  ```
  typedef unsigned long long int FUN(double, int);
  ```

- Apply `using` to improve the visibility (for humans) of the type name, by moving the type name to the front of the definition:

  ```
  using FUN = unsigned long long int (double, int);
  ```

- An alternative construction, using a late-specified return type (cf. section 3.3.7):

  ```
  using FUN = auto (double, int) -> unsigned long long int;
  ```

3.3.9 Range-based for-loops

The **C++** for-statement is identical to **C**'s for-statement:

```
for (init; cond; inc)
    statement
```

Often the initialization, condition, and increment parts are fairly obvious, as in situations where all elements of an array or vector must be processed. Many languages offer the `foreach` statement for that and **C++** offers the `std::for_each` generic algorithm (cf. section 19.1.18).

In addition to the traditional syntax **C++** adds new syntax for the `for`-statement: the *range-based for-loop*. This new syntax can be used to process all element of a range in turn. Three types of ranges are distinguished:

- Plain arrays (e.g., `int array[10]`);
- Initializer lists;
- Standard containers (or comparable) (cf. chapter 12);
- Any other type offering `begin()` and `end()` functions returning so-called *iterators* (cf. section 18.2).

The following additional for-statement syntax is available:

```
// assume int array[30]
for (auto &element: array)
    statement
```

The part to the left of the colon is called the *for range declaration*. The declared variable (`element`) is a formal name; use any identifier you like. The variable is only available within the nested statement, and it refers to (or is a copy of) each of the elements of the range, from the first element up to the last.

There's no formal requirement to use `auto`, but using `auto` is extremely useful in many situations. Not only in situations where the range refers to elements of some complex type, but also in situations where you know what you can do with the elements in the range, but don't care about their exact type names. In the above example `int` could also have been used.

The reference symbol (`&`) is important in the following cases:

- if you want to modify the elements in the nested statements
- if the elements themselves are `struct`s (or *classes*, cf. chapter 7)

When the reference symbol is omitted the variable will be a copy of each of the subsequent elements of the range. Fine, probably, if you merely need to look at the variables when they are of primitive types, but needlessly inefficient if you have an array of `BigStruct` elements:

```
struct BigStruct
{
    double array[100];
    int    last;
};
```

Inefficient, because you don't need to make copies of the array's elements. Instead, use references to elements:

```
BigStruct data[100];    // assume properly initialized elsewhere

int countUsed()
{
    int sum = 0;
                        // const &: the elements aren't modified
    for (auto const &element: data)
        sum += element.last;
    return sum;
}
```

Range-based for-loops can also benefit from structured bindings. If `struct Element` holds a `int key` and a `double value`, and all the values of positive keys should be added then the following code snippet accomplishes that:

```
Element elems[100];     // somehow initialized
double sum = 0;
for (auto const &[key, value]: elems)
{
    if (key > 0)
        sum += value;
}
```

The `C++20` standard also supports an optional initialization section (like the ones already available for `if` and `switch` statements) for range-based for-loops. Assume the elements of an array must be inserted into `cout`, but before each element we want to display the element's index. The index variable is not used outside the `for`-statement, and the extension offered in the `C++20` standard allows us to localize the index variable. Here is an example:

```
                        // localize idx: only visible in the for-stmnt
for (size_t idx = 0; auto const &element: data)
    cout << idx++ << ": " << element << '\n';
```

3.3.10 Raw String Literals

Standard series of ASCII characters (a.k.a. *C strings*) are delimited by double quotes, supporting escape sequences like `\n`, `\\` and `\"`, and ending in 0-bytes. Such series of ASCII-characters are commonly known as *null-terminated byte strings* (singular: *NTBS*, plural: *NTBSs*). **C**'s NTBS is the foundation upon which an enormous amount of code has been built

In some cases it is attractive to be able to avoid having to use escape sequences (e.g., in the context of XML). **C++** allows this using *raw string literals*.

Raw string literals start with an `R`, followed by a double quote, optionally followed by a label (which is an arbitrary sequence of non-blank characters, followed by `(`). The raw string ends at the closing parenthesis `)`, followed by the label (if specified when starting the raw string literal), which is in turn followed by a double quote. Here are some examples:

```
R"(A Raw \ "String")"
R"delimiter(Another \ Raw "(String))delimiter"
```

In the first case, everything between `"(` and `)"` is part of the string. Escape sequences aren't supported so the text `\ "` within the first raw string literal defines three characters: a backslash, a blank character and a double quote. The second example shows a raw string defined between the markers `"delimiter(` and `)delimiter"`.

Raw string literals come in very handy when long, complex ascii-character sequences (e.g., usage-info or long html-sequences) are used. In the end they are just that: long NTBSs. Those long raw string literals should be separated from the code that uses them, thus maintaining the readability of the using code.

As an illustration: the **bisonc++** parser generator supports an option `+NOTRANS(-{}-{})prompt`. When specified, the code generated by **bisonc++** inserts prompting code when debugging is requested. Directly inserting the raw string literal into the function processing the prompting code results in code that is very hard to read:

```
void prompt(ostream &out)
{
    if (d_genDebug)
        out << (d_options.prompt() ? R"(
        if (d_debug__)
        {
            s_out__ << "\n================\n"
                       "? " << dflush__;
            std::string s;
            getline(std::cin, s);
        }
)"               : R"(
        if (d_debug__)
            s_out__ << '\n';
)"
                ) << '\n';
}
```

Readability is greatly enhanced by defining the raw string literals as named NTBSs, defined in the source file's anonymous namespace (cf. chapter 4):

```
namespace {

char const noPrompt[] =
R"(
        if (d_debug__)
            s_out__ << '\n';
)";

char const doPrompt[] =
R"(
        if (d_debug__)
        {
            s_out__ << "\n================\n"
                       "? " << dflush__;
            std::string s;
            getline(std::cin, s);
        }
)";

} // anonymous namespace
```

```
void prompt(ostream &out)
{
    if (d_genDebug)
        out << (d_options.prompt() ? doPrompt : noPrompt) << '\n';
}
```

3.3.11 Binary constants

In addition to hexadecimal integral constants (starting with 0x), octal integral constants (starting with 0), and decimal integral constants (starting with one of the digits 1..9), *binary* integral constants can be defined using the prefixes `0b` or `0B`. E.g., to represent the (decimal) value 5 the notation `0b101` can also be used.

The binary constants come in handy in the context of, e.g., bit-flags, as it immediately shows which bit-fields are set, while other notations are less informative.

3.3.12 Selection statements with initializers

The standard `for` repetition statements start with an optional initialization clause. The initialization clause allows us to localize variables to the scope of the for statements. Initialization clauses van also be used in selection statements.

Consider the situation where an action should be performed if the next line read from the standard input stream equals `go!`. Traditionally, when used inside a function, intending to localize the string to contain the content of the next line as much as possible, constructions like the following had to be used:

```
void function()
{
    // ... any set of statements
    {
        string line;    // localize line
        if (getline(cin, line))
            action();
    }
    // ... any set of statements
}
```

Since `init ;` clauses can also be used for selection statements (`if` and `switch` statements) (note that with selection statements the semicolon is part of the initialization clause, which is different from the optional `init` (no semicolon) clause in `for` statements), we can rephrase the above example as follows:

```
void function()
{
    // ... any set of statements
    if (string line; getline(cin, line))
        action();
    // ... any set of statements
}
```

Note that a variable may still also be defined in the actual condition clauses. This is true for both the extended `if` and `switch` statement. However, before using the condition clauses an initialization clause may be used to define additional variables (plural, as it may contain a comma-separated list of variables, similar to the syntax that's available for `for`-statements).

3.3.13 Attributes

Attributes are compiler directives that are inserted into source files to inform the compiler of some peculiarity of the code (variable or function) that follows the specified attribute. Attributes are used to inform the compiler about situations that are intentional, and thus prevent the compiler from issuing warnings.

The following attributes are recognized:

- `[[carries_dependency]]`:
  This attribute is currently not yet covered by the **C++** Annotations. At this point in the **C++** Annotations it can safely be ignored.

- `[[deprecated]]`:
  This attribute (and its alternative form `[[deprecated("reason")]]`) is available since the C++14 standard. It indicates that the use of the name or entity declared with this attribute is allowed, but discouraged for some reason. This attribute can be used for classes, typedef-names, variables, non-static data members, functions, enumerations, and template specializations. An existing non-deprecated entity may be redeclared deprecated, but once an entity has been declared deprecated it cannot be redeclared as 'undeprecated'. When encountering the `[[deprecated]]` attribute the compiler generates a warning, e.g.,

  ```
  demo.cc:12:24: warning: 'void deprecatedFunction()' is deprecated
                  [-Wdeprecated-declarations] deprecatedFunction();

  demo.cc:5:21: note: declared here
                   [[deprecated]] void deprecatedFunction()
  ```

  When using the alternative form (e.g., `[[deprecated("do not use")]] void fun()`) the compiler generates a warning showing the text between the double quotes, e.g.,

  ```
  demo.cc:12:24: warning: 'void deprecatedFunction()' is deprecated:
      do not use [-Wdeprecated-declarations]
   deprecatedFunction();

  demo.cc:5:38: note: declared here
       [[deprecated("do not use")]] void deprecatedFunction()
  ```

- `[[fallthrough]]`

  When statements nested under `case` entries in `switch` statements continue into subsequent `case` or `default` entries the compiler issues a 'falling through' warning. If falling through is intentional the attribute `[[fallthrough]]`, which then must be followed by a semicolon, should be used. Here is an annotated example:

  ```
  void function(int selector)
  {
      switch (selector)
      {
  ```

```
        case 1:
        case 2:             // no falling through, but merged entry points
            cout << "cases 1 and 2\n";
        [[fallthrough]];    // no warning: intentionally falling through

        case 3:
            cout << "case 3\n";

        case 4:             // a warning is issued: falling through not
                            // announced.
            cout << "case 4\n";
        [[fallthrough]];    // error: there's nothing beyond
    }
}
```

- `[[maybe_unused]]`

  This attribute can be applied to a class, typedef-name, variable, parameter, non-static data member, a function, an enumeration or an enumerator. When it is applied to an entity no warning is generated when the entity is not used. Example:

  ```
  void fun([[maybe_unused]] size_t argument)
  {
      // argument isn't used, but no warning
      // telling you so is issued
  }
  ```

- `[[nodiscard]]`

  The attribute `[[nodiscard]]` may be specified when declaring a function, class or enumeration. If a function is declared `[[nodiscard]]` or if a function returns an entity previously declared using `[[nodiscard]]` then the return value of such a function may only be ignored when explicitly cast to void. Otherwise, when the return value is not used a warning is issued. Example:

  ```
  int [[nodiscard]] importantInt();
  struct [[nodiscard]] ImportantStruct { ... };

  ImportantStruct factory();

  int main()
  {
      importantInt();         // warning issued
      factory();              // warning issued
  }
  ```

- `[[noreturn]]`:
  `[[noreturn]]` indicates that the function does not return. `[[noreturn]]`'s behavior is undefined if the function declared with this attribute actually returns. The following standard functions have this attribute: `std::_Exit`, `std::abort`, `std::exit`, `std::quick_exit`, `std::unexpected`, `std::terminate`, `std::rethrow_exception`, `std::throw_with_nested`, `std::nested_exception::rethrow_nested`, Here is an example of a function declaration and definition using the `[[noreturn]]` attribute:

  ```
      [[noreturn]] void doesntReturn();
  ```

```
[[noreturn]] void doesntReturn()
{
    exit(0);
}
```

3.3.14 Three-way comparison (<=>)

The `C++20` standard added the *three-way comparison* operator <=>, also known as the *spaceship operator*, to **C++**. In **C++** operators can be defined for class-types, among which equality and comparison operators (the familiar set of `==, !=, <, <=, >` and `>=` operators). To provide classes with all comparison operators merely the the equality and the spaceship operator need to be defined.

Its priority is less than the priorities of the bit-shift operators << and >> and larger than the priorities of the ordering operators `<, <=, >`, and `>=`.

Section 11.6.2 covers the construction of the three-way comparison operator.

3.4 New language-defined data types

In **C** the following built-in data types are available: `void, char, short, int, long, float` and `double`. **C++** extends these built-in types with several additional built-in types: the types `bool`, `wchar_t`, `long long` and `long double` (Cf. ANSI/ISO draft (1995), par. 27.6.2.4.1 for examples of these very long types). The type `long long` is merely a double-long `long` datatype. The type `long double` is merely a double-long `double` datatype. These built-in types as well as pointer variables are called *primitive types* in the **C++** Annotations.

There is a subtle issue to be aware of when converting applications developed for 32-bit architectures to 64-bit architectures. When converting 32-bit programs to 64-bit programs, only `long` types and pointer types change in size from 32 bits to 64 bits; integers of type `int` remain at their size of 32 bits. This may cause data truncation when assigning pointer or `long` types to `int` types. Also, problems with sign extension can occur when assigning expressions using types shorter than the size of an `int` to an `unsigned long` or to a pointer. More information about this issue can be found `here`[2].

Except for these built-in types the class-type `string` is available for handling character strings. The datatypes `bool`, and `wchar_t` are covered in the following sections, the datatype `string` is covered in chapter 5. Note that recent versions of **C** may also have adopted some of these newer data types (notably `bool` and `wchar_t`). Traditionally, however, **C** doesn't support them, hence they are mentioned here.

Now that these new types are introduced, let's refresh your memory about *letters* that can be used in *literal constants* of various types. They are:

- `b` or `B`: in addition to its use as a hexadecimal value, it can also be used to define a *binary constant*. E.g., `0b101` equals the decimal value 5. The `0b` prefix can be used to specify binary constants starting with the C++14 standard.
- `E` or `e`: the *exponentiation* character in floating point literal values. For example: `1.23E+3`. Here, `E` should be pronounced (and interpreted) as: *times 10 to the power*. Therefore, `1.23E+3` represents the value `1230`.
- `F` can be used as *postfix* to a non-integral numeric constant to indicate a value of type `float`, rather than `double`, which is the default. For example: `12.F` (the dot transforms 12 into

---

[2] http://developers.sun.com/solaris/articles/ILP32toLP64Issues.html

a floating point value); `1.23E+3F` (see the previous example. `1.23E+3` is a `double` value, whereas `1.23E+3F` is a `float` value).

- `L` can be used as *prefix* to indicate a character string whose elements are `wchar_t`-type characters. For example: `L"hello world"`.
- `L` can be used as *postfix* to an integral value to indicate a value of type `long`, rather than `int`, which is the default. Note that there is no letter indicating a `short` type. For that a `static_cast<short>()` must be used.
- `p`, to specify the power in hexadecimal floating point numbers. E.g. `0x10p4`. The exponent itself is read as a decimal constant and can therefore not start with 0x. The exponent part is interpreted as a power of 2. So `0x10p2` is (decimal) equal to 64: `16 * 2^2`.
- `U` can be used as *postfix* to an integral value to indicate an `unsigned` value, rather than an `int`. It may also be combined with the postfix `L` to produce an `unsigned long int` value.

And, of course: the `x` and `a` until `f` characters can be used to specify hexadecimal constants (optionally using capital letters).

3.4.1 The data type 'bool'

The type `bool` represents boolean (logical) values, for which the (now reserved) constants `true` and `false` may be used. Except for these reserved values, integral values may also be assigned to variables of type `bool`, which are then implicitly converted to `true` and `false` according to the following conversion rules (assume `intValue` is an `int`-variable, and `boolValue` is a `bool`-variable):

```
    // from int to bool:
boolValue = intValue ? true : false;

    // from bool to int:
intValue = boolValue ? 1 : 0;
```

Furthermore, when `bool` values are inserted into streams then `true` is represented by `1`, and `false` is represented by `0`. Consider the following example:

```
cout << "A true value: "  << true << "\n"
        "A false value: " << false << '\n';
```

The `bool` data type is found in other programming languages as well. **Pascal** has its type `Boolean`; **Java** has a `boolean` type. Different from these languages, **C++**'s type `bool` acts like a kind of `int` type. It is primarily a documentation-improving type, having just two values `true` and `false`. Actually, these values can be interpreted as `enum` values for `1` and `0`. Doing so would ignore the philosophy behind the `bool` data type, but nevertheless: assigning `true` to an `int` variable neither produces warnings nor errors.

Using the `bool`-type is usually clearer than using `int`. Consider the following prototypes:

```
bool exists(char const *fileName);  // (1)
int  exists(char const *fileName);  // (2)
```

With the first prototype, readers expect the function to return `true` if the given filename is the name of an existing file. However, with the second prototype some ambiguity arises: intuitively the return value 1 is appealing, as it allows constructions like

```
    if (exists("myfile"))
        cout << "myfile exists";
```

On the other hand, many system functions (like `access`, `stat`, and many other) return 0 to indicate a successful operation, reserving other values to indicate various types of errors.

As a rule of thumb I suggest the following: if a function should inform its caller about the success or failure of its task, let the function return a `bool` value. If the function should return success or various types of errors, let the function return *enum* values, documenting the situation by its various symbolic constants. Only when the function returns a conceptually meaningful integral value (like the sum of two `int` values), let the function return an `int` value.

3.4.2 The data type 'wchar_t'

The `wchar_t` type is an extension of the `char` built-in type, to accommodate *wide* character values (but see also the next section). The `g++` compiler reports `sizeof(wchar_t)` as 4, which easily accommodates all 65,536 different *Unicode* character values.

Note that **Java**'s `char` data type is somewhat comparable to **C++**'s `wchar_t` type. **Java**'s `char` type is 2 bytes wide, though. On the other hand, **Java**'s `byte` data type is comparable to **C++**'s `char` type: one byte. Confusing?

3.4.3 Unicode encoding

In **C++** string literals can be defined as NTBSs. Prepending an NTBS by `L` (e.g., `L"hello"`) defines a `wchar_t` string literal.

C++ also supports 8, 16 and 32 bit Unicode encoded strings. Furthermore, two new data types are introduced: `char16_t` and `char32_t` storing, respectively, a `UTF-16` and a `UTF-32` unicode value.

A `char` type value fits in a `utf_8` unicode value. For character sets exceeding 256 different values wider types (like `char16_t` or `char32_t`) should be used.

String literals for the various types of unicode encodings (and associated variables) can be defined as follows:

```
    char     utf_8[] = u8"This is UTF-8 encoded.";
    char16_t utf16[] = u"This is UTF-16 encoded.";
    char32_t utf32[] = U"This is UTF-32 encoded.";
```

Alternatively, unicode constants may be defined using the `\u` escape sequence, followed by a hexadecimal value. Depending on the type of the unicode variable (or constant) a `UTF-8, UTF-16` or `UTF-32` value is used. E.g.,

```
    char     utf_8[] = u8"\u2018";
    char16_t utf16[] = u"\u2018";
    char32_t utf32[] = U"\u2018";
```

Unicode strings can be delimited by double quotes but raw string literals can also be used.

3.4.4 The data type 'long long int'

C++ also supports the type `long long int`. On 32 bit systems it has at least 64 usable bits.

3.4.5 The data type 'size_t'

The `size_t` type is not really a built-in primitive data type, but a data type that is promoted by **POSIX** as a typename to be used for non-negative integral values answering questions like 'how much' and 'how many', in which case it should be used instead of `unsigned int`. It is not a specific **C++** type, but also available in, e.g., **C**. Usually it is defined implicitly when a (any) system header file is included. The header file 'officially' defining `size_t` in the context of **C++** is `cstddef`.

Using `size_t` has the advantage of being a *conceptual* type, rather than a standard type that is then modified by a modifier. Thus, it improves the self-documenting value of source code.

Sometimes functions explictly require `unsigned int` to be used. E.g., on `amd`-architectures the X-windows function `XQueryPointer` explicitly requires a pointer to an `unsigned int` variable as one of its arguments. In such situations a pointer to a `size_t` variable can't be used, but the address of an `unsigned int` must be provided. Such situations are exceptional, though.

Other useful bit-represented types also exists. E.g., `uint32_t` is guaranteed to hold 32-bits unsigned values. Analogously, `int32_t` holds 32-bits signed values. Corresponding types exist for 8, 16 and 64 bits values. These types are defined in the header file `cstdint` and can be very useful when you need to specify or use integral value types of fixed sizes.

3.4.6 std::byte

TO DO

3.4.7 Digit separators

To improve the readability of large numbers *digit separators* for integer and floating point literals can be used. The digit separator is a single quote which may be inserted between digits of such literals to enhance human readability. Multiple digit separators may be used, but only one separator can be inserted between successive digits. E.g.,

```
1'000'000
3.141'592'653'589'793'238'5
''123       // won't compile
1''23       // won't compile either
```

3.5 A new syntax for casts

Traditionally, **C** offers the following *cast* syntax:

```
        (typename)expression
```

here `typename` is the name of a valid *type*, and `expression` is an expression.

C style casts are now deprecated. **C++** programs should merely use the new style **C++** casts as they offer the compiler facilities to verify the sensibility of the cast. Facilities which are not offered by the classic **C**-style cast.

A cast should not be confused with the often used *constructor notation*:

```
typename(expression)
```

the constructor notation is not a cast, but a request to the compiler to construct an (anonymous) variable of type `typename` from `expression`.

If casts are really necessary one of several *new-style casts* should be used. These new-style casts are introduced in the upcoming sections.

3.5.1 The 'static_cast'-operator

The `static_cast<type>(expression)` is used to convert 'conceptually comparable or related types' to each other. Here as well as in other **C++** style casts `type` is the type to which the type of `expression` should be cast.

Here are some examples of situations where the `static_cast` can (or should) be used:

- When converting an `int` to a `double`.

  This happens, for example when the quotient of two `int` values must be computed without losing the fraction part of the division. The `sqrt` function called in the following fragment returns 2:

  ```
  int x = 19;
  int y = 4;
  sqrt(x / y);
  ```

  whereas it returns 2.179 when a `static_cast` is used, as in:

  ```
  sqrt(static_cast<double>(x) / y);
  ```

  The important point to notice here is that a `static_cast` is allowed to change the representation of its `expression` into the representation that's used by the destination type.

  Also note that the division is put outside of the cast expression. If the division is performed within the cast's `expression` (as in `static_cast<double>(x / y)`) an *integer division* has already been performed *before* the cast has had a chance to convert the type of an operand to `double`.

- When converting `enum` values to `int` values (in any direction).

  Here the two types use identical representations, but different semantics. Assigning an ordinary `enum` value to an `int` doesn't require a cast, but when the enum is a *strongly typed enum* a cast *is* required. Conversely, a `static_cast` is required when assigning an `int` value to a variable of some enum type. Here is an example:

  ```
  enum class Enum
  {
      VALUE
  };

  cout << static_cast<int>(Enum::VALUE);    // show the numeric value
  ```

- When converting related pointers to each other.

  The `static_cast` is used in the context of class inheritance (cf. chapter 13) to convert a pointer to a so-called 'derived class' to a pointer to its 'base class'. It cannot be used for casting unrelated types to each other (e.g., a `static_cast` can*not* be used to cast a pointer to a `short` to a pointer to an `int`).

A `void *` is a *generic pointer*. It is frequently used by functions in the **C** library (e.g., **memcpy**(3)). Since it is the generic pointer it is related to any other pointer, and a `static_cast` should be used to convert a `void *` to an intended destination pointer. This is a somewhat awkward left-over from **C**, which should probably only be used in that context. Here is an example:

The `qsort` function from the **C** library expects a pointer to a (comparison) function having two `void const *` parameters. In fact, these parameters point to data elements of the array to be sorted, and so the comparison function must cast the `void const *` parameters to pointers to the elements of the array to be sorted. So, if the array is an `int array[]` and the compare function's parameters are `void const *p1` and `void const *p2` then the compare function obtains the address of the `int` pointed to by `p1` by using:

```
static_cast<int const *>(p1);
```

- When undoing or introducing the signed-modifier of an `int`-typed variable (remember that a `static_cast` is allowed to change the expression's representation!).

  Here is an example: the **C** function `tolower` requires an `int` representing the value of an `unsigned char`. But `char` by default is a signed type. To call `tolower` using an available `char ch` we should use:

```
        tolower(static_cast<unsigned char>(ch))
```

3.5.2 The 'const_cast'-operator

The `const` keyword has been given a special place in casting. Normally anything `const` is `const` for a good reason. Nonetheless situations may be encountered where the `const` can be ignored. For these special situations the `const_cast` should be used. Its syntax is:

```
    const_cast<type>(expression)
```

A `const_cast<type>(expression)` expression is used to undo the `const` attribute of a (pointer) type.

The need for a `const_cast` may occur in combination with functions from the standard **C** library which traditionally weren't always as const-aware as they should. A function `strfun(char *s)` might be available, performing some operation on its `char *s` parameter without actually modifying the characters pointed to by `s`. Passing `char const hello[] = "hello";` to `strfun` produces the warning

```
    passing `const char *' as argument 1 of `fun(char *)' discards const
```

A `const_cast` is the appropriate way to prevent the warning:

```
    strfun(const_cast<char *>(hello));
```

3.5.3 The 'reinterpret_cast'-operator

The third new-style cast is used to change the *interpretation* of information: the `reinterpret_cast`. It is somewhat reminiscent of the `static_cast`, but `reinterpret_cast` should only be used when it is *known* that the information as defined in fact is or can be interpreted as something completely different. Its syntax is:

```
        reinterpret_cast<pointer type>(pointer expression)
```

Think of the `reinterpret_cast` as a cast offering a poor-man's union: the same memory location may be interpreted in completely different ways.

The `reinterpret_cast` is used, for example, in combination with the `write` function that is available for *streams*. In **C++** streams are the preferred interface to, e.g., disk-files. The standard streams like `std::cin` and `std::cout` also are stream objects.

Streams intended for writing ('output streams' like `cout`) offer `write` members having the prototype

```
        write(char const *buffer, int length)
```

To write the value stored within a `double` variable to a stream in its un-interpreted binary form the stream's `write` member is used. However, as a `double *` and a `char *` point to variables using different and unrelated representations, a `static_cast` cannot be used. In this case a `reinterpret_cast` is required. To write the raw bytes of a variable `double value` to `cout` we use:

```
    cout.write(reinterpret_cast<char const *>(&value), sizeof(double));
```

All casts are potentially dangerous, but the `reinterpret_cast` is the most dangerous of them all. Effectively we tell the compiler: back off, we know what we're doing, so stop fuzzing. All bets are off, and we'd better *do* know what we're doing in situations like these. As a case in point consider the following code:

```
    int value = 0x12345678;     // assume a 32-bits int

    cout << "Value's first byte has value: " << hex <<
            static_cast<int>(
                *reinterpret_cast<unsigned char *>(&value)
                            );
```

The above code produces different results on little and big endian computers. Little endian computers show the value 78, big endian computers the value 12. Also note that the different representations used by little and big endian computers renders the previous example (`cout.write(...)`) non-portable over computers of different architectures.

As a rule of thumb: if circumstances arise in which casts *have* to be used, clearly document the reasons for their use in your code, making double sure that the cast does not eventually cause a program to misbehave. Also: avoid `reinterpret_casts` unless you *have* to use them.

3.5.4 The 'dynamic_cast'-operator

Finally there is a new style cast that is used in combination with polymorphism (see chapter 14). Its syntax is:

```
        dynamic_cast<type>(expression)
```

Different from the `static_cast`, whose actions are completely determined *compile-time*, the `dynamic_cast`'s actions are determined *run-time* to convert a pointer to an object of some class (e.g., `Base`) to a pointer to an object of another class (e.g., `Derived`) which is found further down its so-called *class hierarchy* (this is also called *downcasting*).

At this point in the *Annotations* a `dynamic_cast` cannot yet be discussed extensively, but we return to this topic in section 14.6.1.

3.5.5 Casting 'shared_ptr' objects

This section can safely be skipped without loss of continuity.

In the context of the class `shared_ptr`, which is covered in section 18.4, several more new-style casts are available. Actual coverage of these specialized casts is postponed until section 18.4.5.

These specialized casts are:

- `static_pointer_cast`, returning a `shared_ptr` to the base-class section of a derived class object;
- `const_pointer_cast`, returning a `shared_ptr` to a non-const object from a `shared_ptr` to a constant object;
- `dynamic_pointer_cast`, returning a `shared_ptr` to a derived class object from a `shared_ptr` to a base class object.

3.6 Keywords and reserved names in C++

C++'s keywords are a superset of **C**'s keywords. Here is a list of all keywords of the language:

```
alignas
alignof
and
and_eq
asm
atomic_cancel
atomic_commit
atomic_noexcept
auto
bitand
bitor
bool
break
case
catch
char
char16_t
char32_t
class
co_await
co_return
co_yield
compl
concept
const
const_cast
constexpr
continue
decltype
default
delete
do
double
dynamic_cast
else
enum
explicit
export
extern
false
float
for
friend
goto
if
import
inline
int
long
module
mutable
namespace
new
noexcept
not
not_eq
nullptr
operator
or
or_eq
private
protected
public
register
reinterpret_cast
requires
return
short
signed
sizeof
static
static_assert
static_cast
struct
switch
synchronized
template
this
thread_local
throw
true
try
typedef
typeid
typename
union
unsigned
using
virtual
void
volatile
wchar_t
while
xor
xor_eq
```

Notes:

- Since the C++17 standard the keyword `register` is no longer used, but it remains a reserved identifier. In other words, definitions like

  ```
  register int index;
  ```

result in compilation errors. Also, `register` is no longer considered a storage class specifier (storage class specifiers are `extern`, `thread_local`, `mutable` and `static`).

- the *operator keywords*: `and`, `and_eq`, `bitand`, `bitor`, `compl`, `not`, `not_eq`, `or`, `or_eq`, `xor` and `xor_eq` are symbolic alternatives for, respectively, `&&`, `&=`, `&`, `|`, `~`, `!`, `!=`, `||`, `|=`, `^` and `^=`.
- **C++** also recognizes the special identifiers `final`, `override`, `transaction_safe`, and `transaction_safe_override`. These identifiers are special in the sense that they acquire special meanings when declaring classes or polymorphic functions. Section 14.4 provides further details.

Keywords can only be used for their intended purpose and cannot be used as names for other entities (e.g., variables, functions, class-names, etc.). In addition to keywords identifiers starting with an underscore and living in the *global namespace* (i.e., not using any explicit namespace or using the mere `::` namespace specification) or living in the *std namespace* are reserved identifiers in the sense that their use is a prerogative of the implementor.

Chapter 4

Namespaces

4.1 Namespaces

Imagine a math teacher who wants to develop an interactive math program. For this program functions like `cos, sin, tan` etc. are to be used accepting arguments in degrees rather than arguments in radians. Unfortunately, the function name `cos` is already in use, and that function accepts radians as its arguments, rather than degrees.

Problems like these are usually solved by defining another name, e.g., the function name `cosDegrees` is defined. **C++** offers an alternative solution through *namespaces*. Namespaces can be considered as areas or regions in the code in which identifiers may be defined. Identifiers defined in a namespace normally won't conflict with names already defined elsewhere (i.e., outside of their namespaces). So, a function `cos` (expecting angles in degrees) could be defined in a namespace `Degrees`. When calling `cos` from within `Degrees` you would call the `cos` function expecting degrees, rather than the standard `cos` function expecting radians.

4.1.1 Defining namespaces

Namespaces are defined according to the following syntax:

```
namespace identifier
{
    // declared or defined entities
    // (declarative region)
}
```

The identifier used when defining a namespace is a standard **C++** identifier.

Within the *declarative region*, introduced in the above code example, functions, variables, structs, classes and even (nested) namespaces can be defined or declared. Namespaces cannot be defined within a function body. However, it is possible to define a namespace using multiple *namespace* declarations. Namespaces are '*open*' meaning that a namespace `CppAnnotations` could be defined in a file `file1.cc` and also in a file `file2.cc`. Entities defined in the `CppAnnotations` namespace of files `file1.cc` and `file2.cc` are then united in one `CppAnnotations` namespace region. For example:

```
// in file1.cc
```

```
namespace CppAnnotations
{
    double cos(double argInDegrees)
    {
        ...
    }
}

// in file2.cc
namespace CppAnnotations
{
    double sin(double argInDegrees)
    {
        ...
    }
}
```

Both `sin` and `cos` are now defined in the same `CppAnnotations` namespace.

Namespace entities can be defined outside of their namespaces. This topic is discussed in section 4.1.4.1.

4.1.1.1 Declaring entities in namespaces

Instead of *defining* entities in a namespace, entities may also be *declared* in a namespace. This allows us to put all the declarations in a header file that can thereupon be included in sources using the entities defined in the namespace. Such a header file could contain, e.g.,

```
namespace CppAnnotations
{
    double cos(double degrees);
    double sin(double degrees);
}
```

4.1.1.2 A closed namespace

Namespaces can be defined without a name. Such an anonymous namespace restricts the visibility of the defined entities to the source file defining the anonymous namespace.

Entities defined in the anonymous namespace are comparable to **C**'s `static` functions and variables. In **C++** the `static` keyword can still be used, but its preferred use is in `class` definitions (see chapter 7). In situations where in **C** static variables or functions would have been used the anonymous namespace should be used in **C++**.

The anonymous namespace is a closed namespace: it is not possible to add entities to the same anonymous namespace using different source files.

4.1.2 Referring to entities

Given a namespace and its entities, the scope resolution operator can be used to refer to its entities. For example, the function `cos()` defined in the `CppAnnotations` namespace may be used as follows:

```
// assume CppAnnotations namespace is declared in the
// following header file:
#include <cppannotations>

int main()
{
    cout << "The cosine of 60 degrees is: " <<
            CppAnnotations::cos(60) << '\n';
}
```

This is a rather cumbersome way to refer to the `cos()` function in the `CppAnnotations` namespace, especially so if the function is frequently used. In cases like these an *abbreviated* form can be used after specifying a *using declaration*. Following

```
using CppAnnotations::cos;  // note: no function prototype,
                            // just the name of the entity
                            // is required.
```

calling `cos` results in a call of the `cos` function defined in the `CppAnnotations` namespace. This implies that the standard `cos` function, accepting radians, is not automatically called anymore. To call that latter `cos` function the plain scope resolution operator should be used:

```
int main()
{
    using CppAnnotations::cos;
    ...
    cout << cos(60)         // calls CppAnnotations::cos()
        << ::cos(1.5)       // call the standard cos() function
        << '\n';
}
```

A `using` declaration can have restricted scope. It can be used inside a block. The `using` declaration prevents the definition of entities having the same name as the one used in the `using` declaration. It is not possible to specify a `using` declaration for a variable `value` in some namespace, and to define (or declare) an identically named object in a block also containing a `using` declaration. Example:

```
int main()
{
    using CppAnnotations::value;
    ...
    cout << value << '\n';  // uses CppAnnotations::value
    int value;              // error: value already declared.
}
```

4.1.2.1 The ‘using’ directive

A generalized alternative to the `using` declaration is the *using directive*:

```
using namespace CppAnnotations;
```

Following this directive, *all* entities defined in the `CppAnnotations` namespace are used as if they were declared by `using` declarations.

While the `using` directive is a quick way to import all the names of a namespace (assuming the namespace has previously been declared or defined), it is at the same time a somewhat dirty way to do so, as it is less clear what entity is actually used in a particular block of code.

If, e.g., `cos` is defined in the `CppAnnotations` namespace, `CppAnnotations::cos` is going to be used when `cos` is called. However, if `cos` is *not* defined in the `CppAnnotations` namespace, the standard `cos` function will be used. The `using` directive does not document as clearly as the `using` declaration what entity will actually be used. Therefore use caution when applying the `using` directive.

Namespace declarations are context sensitive: when a `using namespace` declaration is specified inside a compound statement then the declaration is valid until the compound statement's closing curly bracket has been encountered. In the next example a string `first` is defined without explicit specifying `std::string`, but once the compound statement has ended the scope of the `using namespace std` declaration has also ended, and so `std::` is required once again when defining `second`:

```
#include <string>
int main()
{
    {
        using namespace std;
        string first;
    }
    std::string second;
}
```

A `using namespace` directive cannot be used within the declaration block of a class- or enumeration-type. E.g., the following example won't compile:

```
struct Namespace
{
    using namespace std;      // won't compile
};
```

4.1.2.2 'Koenig lookup'

If *Koenig lookup* were called the 'Koenig principle', it could have been the title of a new Ludlum novel. However, it is not. Instead it refers to a **C++** technicality.

'Koenig lookup' refers to the fact that if a function is called without specifying its namespace, then the namespaces of its argument types are used to determine the function's namespace. If the namespace in which the argument types are defined contains such a function, then that function is used. This procedure is called the 'Koenig lookup'.

As an illustration consider the next example. The function `FBB::fun(FBB::Value v)` is defined in the `FBB` namespace. It can be called without explicitly mentioning its namespace:

```
#include <iostream>

namespace FBB
{
    enum Value        // defines FBB::Value
    {
        FIRST
    };

    void fun(Value x)
    {
        std::cout << "fun called for " << x << '\n';
    }
}

int main()
{
    fun(FBB::FIRST);    // Koenig lookup: no namespace
                        // for fun() specified
}
/*
    generated output:
fun called for 0
*/
```

The compiler is rather smart when handling namespaces. If `Value` in the `namespace FBB` would have been defined as `typedef int Value` then `FBB::Value` would be recognized as `int`, thus causing the Koenig lookup to fail.

As another example, consider the next program. Here two namespaces are involved, each defining their own `fun` function. There is no ambiguity, since the argument defines the namespace and `FBB::fun` is called:

```
#include <iostream>

namespace FBB
{
    enum Value        // defines FBB::Value
    {
        FIRST
    };

    void fun(Value x)
    {
        std::cout << "FBB::fun() called for " << x << '\n';
    }
}

namespace ES
{
    void fun(FBB::Value x)
    {
        std::cout << "ES::fun() called for " << x << '\n';
    }
}

int main()
{
    fun(FBB::FIRST);    // No ambiguity: argument determines
                        // the namespace
}
/*
```

```
        generated output:
    FBB::fun() called for 0
    */
```

Here is an example in which there *is* an ambiguity: `fun` has two arguments, one from each namespace. The ambiguity must be resolved by the programmer:

```
    #include <iostream>

    namespace ES
    {
        enum Value        // defines ES::Value
        {
            FIRST
        };
    }

    namespace FBB
    {
        enum Value        // defines FBB::Value
        {
            FIRST
        };

        void fun(Value x, ES::Value y)
        {
            std::cout << "FBB::fun() called\n";
        }
    }

    namespace ES
    {
        void fun(FBB::Value x, Value y)
        {
            std::cout << "ES::fun() called\n";
        }
    }

    int main()
    {
        //  fun(FBB::FIRST, ES::FIRST); ambiguity: resolved by
        //                              explicitly mentioning
        //                              the namespace
        ES::fun(FBB::FIRST, ES::FIRST);
    }
    /*
        generated output:
    ES::fun() called
    */
```

An interesting subtlety with namespaces is that definitions in one namespace may break the code defined in another namespace. It shows that namespaces may affect each other and that namespaces may backfire if we're not aware of their peculiarities. Consider the following example:

```
    namespace FBB
```

```
{
    struct Value
    {};

    void fun(int x);
    void gun(Value x);
}

namespace ES
{
    void fun(int x)
    {
        fun(x);
    }
    void gun(FBB::Value x)
    {
        gun(x);
    }
}
```

Whatever happens, the programmer'd better not use any of the functions defined in the `ES` namespace, since that would result in infinite recursion. However, that's not the point. The point is that the programmer won't even be given the opportunity to call `ES::fun` since the compilation fails.

Compilation fails for `gun` but not for `fun`. But why is that so? Why is `ES::fun` flawlessly compiling while `ES::gun` isn't? In `ES::fun fun(x)` is called. As `x`'s type is not defined in a namespace the Koenig lookup does not apply and `fun` calls itself with infinite recursion.

With `ES::gun` the argument is defined in the `FBB` namespace. Consequently, the `FBB::gun` function is a possible candidate to be called. But `ES::gun` itself also is possible as `ES::gun`'s prototype perfectly matches the call `gun(x)`.

Now consider the situation where `FBB::gun` has not yet been declared. Then there is of course no ambiguity. The programmer responsible for the `ES` namespace is resting happily. Some time after that the programmer who's maintaining the `FBB` namespace decides it may be nice to add a function `gun(Value x)` to the `FBB` namespace. Now suddenly the code in the namespace `ES` breaks because of an addition in a completely other namespace (`FBB`). Namespaces clearly are not completely independent of each other and we should be aware of subtleties like the above. Later in the **C++** Annotations (chapter 11) we'll return to this issue.

Koenig lookup is only used in the context of namespaces. If a function is defined outside of a namespace, defining a parameter of a type that's defined inside a namespace, and that namespace also defines a function with an identical signature, then the compiler reports an ambiguity when that function is called. Here is an example, assuming the abovementioned namespace `FBB` is also available:

```
void gun(FBB::Value x);

int main(int argc, char **argv)
{
    gun(FBB::Value{});          // ambiguity: FBB::gun and ::gun can both
                                // be called.
}
```

4.1.3 The standard namespace

The `std` namespace is reserved by **C++**. The standard defines many entities that are part of the runtime available software (e.g., `cout, cin, cerr`); the templates defined in the *Standard Template Library* (cf. chapter 18); and the *Generic Algorithms* (cf. chapter 19) are defined in the `std` namespace.

Regarding the discussion in the previous section, `using` declarations may be used when referring to entities in the `std` namespace. For example, to use the `std::cout` stream, the code may declare this object as follows:

```
#include <iostream>
using std::cout;
```

Often, however, the identifiers defined in the `std` namespace can all be accepted without much thought. Because of that, one frequently encounters a `using` directive, allowing the programmer to omit a namespace prefix when referring to any of the entities defined in the namespace specified with the `using` directive. Instead of specifying `using` declarations the following `using` directive is frequently encountered: construction like

```
#include <iostream>
using namespace std;
```

Should a `using` directive, rather than `using` declarations be used? As a rule of thumb one might decide to stick to `using` declarations, up to the point where the list becomes impractically long, at which point a `using` directive could be considered.

Two restrictions apply to `using` directives and declarations:

- Programmers should not declare or define anything inside the `namespace std`. This is *not* compiler enforced but is imposed upon user code by the standard;
- `Using` declarations and directives should not be imposed upon code written by third parties. In practice this means that `using` directives and declarations should be banned from header files and should only be used in source files (cf. section 7.11.1).

4.1.4 Nesting namespaces and namespace aliasing

Namespaces can be nested. Here is an example:

```
namespace CppAnnotations
{
    int value;
    namespace Virtual
    {
        void *pointer;
    }
}
```

The variable `value` is defined in the `CppAnnotations` namespace. Within the `CppAnnotations` namespace another namespace (`Virtual`) is nested. Within that latter namespace the variable `pointer` is defined. To refer to these variable the following options are available:

- The *fully qualified names* can be used. A fully qualified name of an entity is a list of all the namespaces that are encountered until reaching the definition of the entity. The namespaces and entity are glued together by the scope resolution operator:

  ```
  int main()
  {
      CppAnnotations::value = 0;
      CppAnnotations::Virtual::pointer = 0;
  }
  ```

- A `using namespace CppAnnotations` directive can be provided. Now `value` can be used without any prefix, but `pointer` must be used with the `Virtual::` prefix:

  ```
  using namespace CppAnnotations;

  int main()
  {
      value = 0;
      Virtual::pointer = 0;
  }
  ```

- A `using namespace` directive for the full namespace chain can be used. Now `value` needs its `CppAnnotations` prefix again, but `pointer` doesn't require a prefix anymore:

  ```
  using namespace CppAnnotations::Virtual;

  int main()
  {
      CppAnnotations::value = 0;
      pointer = 0;
  }
  ```

- When using two separate `using namespace` directives none of the namespace prefixes are required anymore:

  ```
  using namespace CppAnnotations;
  using namespace Virtual;

  int main()
  {
      value = 0;
      pointer = 0;
  }
  ```

- The same can be accomplished (i.e., no namespace prefixes) for specific variables by providing specific `using` declarations:

  ```
  using CppAnnotations::value;
  using CppAnnotations::Virtual::pointer;

  int main()
  {
      value = 0;
      pointer = 0;
  }
  ```

- A combination of `using namespace` directives and `using` declarations can also be used. E.g., a `using namespace` directive can be used for the `CppAnnotations::Virtual` namespace, and a `using` declaration can be used for the `CppAnnotations::value` variable:

```
using namespace CppAnnotations::Virtual;
using CppAnnotations::value;

int main()
{
    value = 0;
    pointer = 0;
}
```

Following a `using namespace` directive all entities of that namespace can be used without any further prefix. If a single `using namespace` directive is used to refer to a nested namespace, then all entities of that nested namespace can be used without any further prefix. However, the entities defined in the more shallow namespace(s) still need the shallow namespace's name(s). Only after providing specific `using namespace` directives or `using` declarations namespace qualifications can be omitted.

When fully qualified names are preferred but a long name like

```
CppAnnotations::Virtual::pointer
```

is considered too long, a *namespace alias* may be used:

```
namespace CV = CppAnnotations::Virtual;
```

This defines `CV` as an *alias* for the full name. The variable `pointer` may now be accessed using:

```
CV::pointer = 0;
```

A namespace alias can also be used in a `using namespace` directive or `using` declaration:

```
namespace CV = CppAnnotations::Virtual;
using namespace CV;
```

Nested namespace definitions

Starting with the C++17 standard, when nesting namespaces a nested namespace can directly be referred to using scope resolution operators. E.g.,

```
namespace Outer::Middle::Inner
{
    // entities defined/declared here are defined/declared in the Inner
    // namespace, which is defined in the Middle namespace, which is
    // defined in the Outer namespace
}
```

4.1.4.1 Defining entities outside of their namespaces

It is not strictly necessary to define members of namespaces inside a namespace region. But before an entity is defined *outside* of a namespace it must have been declared *inside* its namespace.

To define an entity outside of its namespace its name must be *fully qualified* by prefixing the member by its namespaces. The definition may be provided at the global level or at intermediate levels in the case of nested namespaces. This allows us to define an entity belonging to namespace `A::B` within the region of namespace `A`.

Assume the type `int INT8[8]` is defined in the `CppAnnotations::Virtual` namespace. Furthermore assume that it is our intent to define a function `squares`, inside the namespace `CppAnnotations::Virtual` returning a pointer to `CppAnnotations::Virtual::INT8`.

Having defined the prerequisites within the `CppAnnotations::Virtual` namespace, our function could be defined as follows (cf. chapter 9 for coverage of the memory allocation operator `new[]`):

```
namespace CppAnnotations
{
    namespace Virtual
    {
        void *pointer;

        typedef int INT8[8];

        INT8 *squares()
        {
            INT8 *ip = new INT8[1];

            for (size_t idx = 0; idx != sizeof(INT8) / sizeof(int); ++idx)
                (*ip)[idx] = (idx + 1) * (idx + 1);

            return ip;
        }
    }
}
```

The function `squares` defines an array of one `INT8` vector, and returns its address after initializing the vector by the squares of the first eight natural numbers.

Now the function `squares` can be defined outside of the `CppAnnotations::Virtual` namespace:

```
namespace CppAnnotations
{
    namespace Virtual
    {
        void *pointer;

        typedef int INT8[8];

        INT8 *squares();
    }
}

CppAnnotations::Virtual::INT8 *CppAnnotations::Virtual::squares()
{
    INT8 *ip = new INT8[1];

    for (size_t idx = 0; idx != sizeof(INT8) / sizeof(int); ++idx)
        (*ip)[idx] = (idx + 1) * (idx + 1);
        return ip;
    }
```

In the above code fragment note the following:

- `squares` is declared inside of the `CppAnnotations::Virtual` namespace.
- The definition outside of the namespace region requires us to use the fully qualified name of the function *and* of its return type.
- *Inside* the body of the function `squares` we are within the `CppAnnotations::Virtual` namespace, so inside the function fully qualified names (e.g., for `INT8`) are not required any more.

Finally, note that the function could also have been defined in the `CppAnnotations` region. In that case the `Virtual` namespace would have been required when defining `squares()` and when specifying its return type, while the internals of the function would remain the same:

```
    namespace CppAnnotations
    {
        namespace Virtual
        {
            void *pointer;

            typedef int INT8[8];

            INT8 *squares();
        }

        Virtual::INT8 *Virtual::squares()
        {
            INT8 *ip = new INT8[1];

            for (size_t idx = 0; idx != sizeof(INT8) / sizeof(int); ++idx)
                (*ip)[idx] = (idx + 1) * (idx + 1);

            return ip;
        }
    }
```

4.2 The std::chrono namespace (handling time)

The **C** programming language offers tools like **sleep**(3) and **select**(2) to suspend program execution for a certain amount of time. And of course the family of **time**(3) functions for setting and displaying time

`Sleep` and `select` can be used for waiting, but as they were designed in an era when multi threading was unavailable, their usefulness is limited when used in multi threaded programs. Multi threading has become part of **C++** (covered in detail in chapter 20), and additional time-related functions are available in the `std::filesystem` namespace, covered below in this chapter.

In multi threaded programs threads are frequently suspended, albeit usually for a very short time. E.g., when a thread wants to access a variable, but the variable is currently being updated by another thread, then the former thread should wait until the latter thread has completed the update.

Updating a variable usually doesn't take much time, but if it takes an unexpectedly long time, then the former thread may want to be informed about that, so it can do something else while the latter thread is busy updating the variable. Interactions between threads like these cannot be realized with functions like `sleep` and `select`.

The `std::chrono` namespace bridges the gap between the traditionally available time-related functions and the time-related requirements of multi-threading and of the `std::filesystem` name space. All but the specific `std::filesystem` related time functionality is available after including the `<chrono>` header file. After including the `<filesystem>` header file the facilities of the `std::filesystem` are available.

Time can be measured in various resolutions: in Olympic games time differences of hundreds of seconds may make the distinction between a gold and silver medal, but when planning a vacation we might talk about months before we go on vacation. Time resolutions are specified through objects of the class `std::ratio`, which (apart from including the `<chrono>` header file) is also available after including the `<ratio>` header file.

Different events usually last for different amounts of time (given a specific time resolution). Amounts of time are specified through objects of the class `std::chrono::duration`.

Events can also be characterized by their points in time: midnight, January 1, 1970 GMT is a point in time, as is 19:00, December 5, 2010. Points in time are specified through objects of the class `std::chrono::time_point`.

It's not just that resolutions, durations of events, and points in time of events may differ, but the devices (clocks) we use for specifying time also differ. In the old days *hour glasses* were used (and sometimes they're still used when boiling eggs), but on the other hand we may use atomic clocks when measurements should be very precise. Four different types of clocks are available. The commonly used clock is `std::chrono::system_clock`, but in the context of the file system there's also an (implicitly defined) `filesystem::__file_clock`.

In the upcoming sections the details of the `std::chrono` namespace are covered. First we look at characteristics of time resolutions. How to handle amounts of time given their resolutions is covered next. The next section describes facilities for defining and handling time-points. The relationships between these types and the various clock-types are covered thereafter.

In this chapter the specification `std::chrono::` is often omitted (in practice `using namespace std` followed by `using namespace chrono` is commonly used; `[std::]chrono::` specifications are occasionally used to avoid ambiguities). Also, every now and then you'll encounter *forward references* to later chapters, like the reference to the chapter about multi-threading. These are hard to avoid, but studying those chapters at this point fortunately can be postponed without loss of continuity.

4.2.1 Time resolutions: std::ratio

Time resolutions (or *units of time*) are essential components of time specifications. Time resolutions are defined through objects of the class `std::ratio`.

Before the class `ratio` can be used, the `<ratio>` header file must be included. Instead the `<chrono>` header file can be included.

The class `ratio` requires two *template arguments*. These are positive integral numbers surrounded by pointed brackets defining, respectively, the numerator and denominator of a fraction (by default the denominator equals 1). Examples:

```
ratio<1>        - representing one;
ratio<60>       - representing 60
```

```
ratio<1, 1000>  - representing 1/1000.
```

The class `ratio` defines two directly accessible static data members: `num` represents its numerator, `den` its denominator. A `ratio` definition by itself simply defines a certain amount. E.g., when executing the following program

```
#include <ratio>
#include <iostream>
using namespace std;

int main()
{
    cout << ratio<5, 1000>::num << ',' << ratio<5, 1000>::den << '\n' <<
            milli::num << ',' << milli::den << '\n';
}
```

the text 1,200 is displayed, as that's the 'amount' represented by `ratio<5, 1000>`: `ratio` simplifies the fraction whenever possible.

A fairly large number of predefined `ratio` types exist. They are, like `ratio` itself, defined in the standard namespace and can be used instead of the more cumbersome `ratio<x>` or `ratio<x, y>` specification:

yocto	10^{-24}	zepto	10^{-21}		
atto	10^{-18}	femto	10^{-15}	pico	10^{-12}
nano	10^{-9}	micro	10^{-6}	milli	10^{-3}
centi	10^{-2}	deci	10^{-1}		
deca	10^{1}	hecto	10^{2}	kilo	10^{3}
mega	10^{6}	giga	10^{9}	tera	10^{12}
peta	10^{15}	exa	10^{18}		
zetta	10^{21}	yotta	10^{24}		

(*note:* the definitions of the types `yocto, zepto, zetta` and `yotta` use integral constants exceeding 64 bits. Although these constants are defined in **C++**, they are not available on 64 bit or smaller architectures.)

Time related ratios can very well be interpreted as fractions or multiple of seconds, with `ratio<1, 1>` representing a resolution of one second.

Here is an example showing how these abbreviations can be used:

```
    cout << milli::num << ',' << milli::den << '\n' <<
            kilo::num << ',' << kilo::den << '\n';
```

4.2.2 Amounts of time: std::chrono::duration

Amounts of time are specified through objects of the class `std::chrono::duration`.

Before using the class `duration` the `<chrono>` header file must be included.

Like `ratio` the class `duration` requires two template arguments. A numeric type (`int64_t` is normally used) defining the type holding the duration's amount of time, and a time-resolution (called its *resolution*), usually specified through a `std::ratio`-type (often using one of its `chrono` abbreviations).

Using the predefined `std::deca ratio`, representing units of 10 seconds an interval of 30 minutes is defined as follows:

```
duration<int64_t, std::deca> halfHr(180);
```

Here `halfHr` represents a time interval of 180 deca-seconds, so 1800 seconds. Comparable to the predefined ratios predefined duration types are available:

nanoseconds	`duration<int64_t, nano>`
microseconds	`duration<int64_t, micro>`
milliseconds	`duration<int64_t, milli>`
seconds	`duration<int64_t>`
minutes	`duration<int64_t, ratio<60>>`
hours	`duration<int64_t, ratio<3600>>`

Using these types, a time amount of 30 minutes can now simply be defined as `minutes halfHour(30)`.

The two types that were specified when defining a `duration<Type, Resolution>` can be retrieved as, respectively,

- `rep`, which is equivalent to the numeric type (like `int64_t`). E.g., `seconds::rep` is equivalent to `int64_t`;
- `period`, which is equivalent to the `ratio` type (like `kilo`) and so `duration<int, kilo>::period::num` is equal to 1.

Duration objects can be constructed by specifying an argument of its numeric type:

- `duration(Type const &value)`:
  a specific duration of `value` time units. `Type` refers to the duration's numeric type (e.g., `int64_t`). So, when defining

  ```
  minutes halfHour(30);
  ```

  the argument 30 is stored inside its `int64_t` data member.

Duration supports copy- and move-constructors (cf. chapter 9) and its default constructor initializes its `int64_t` data member to zero.

The amount of time stored in a duration object may be modified by adding or subtracting two duration objects or by multiplying, dividing, or computing a modulo value of its data member. Numeric multiplication operands may be used as left-hand side or right-hand side operands; in combination with the other multiplication operators the numeric operands must be used as right-hand side operands. Compound assignment operators are also available. Some examples:

```
minutes fullHour = minutes{ 30 } + halfHour;
fullHour = 2 * halfHour;
halfHour = fullHour / 2;
```

```
fullHour = halfHour + halfHour;

halfHour /= 2;
halfHour *= 2;
```

In addition, `duration` offers the following members (the first member is an ordinary member function requiring a `duration` object). The other three are static members (cf. chapter 8) which can be used without requiring objects (as shown at the `zero` code snippet):

- `Type count() const` returns the value that is stored inside the `duration` object's data member. For `halfHour` it returns 30, not 1800;
- `duration<Type, Resolution>::zero()`:
  this is an (immutable) duration object whose `count` member returns 0. E.g.:

  ```
  seconds::zero().count();    // equals int64_t 0
  ```

- `duration<Type, Resolution>::min()`:
  an immutable duration object whose `count` member returns the lowest value of its `Type` (i.e., `std::numeric_limits<Type>::min()` (cf. section 21.11));
- `duration<Type, Resolution>::max()`:
  an immutable duration object whose `count` member returns the lowest value of its `Type` (i.e., `std::numeric_limits<Type>::max()`).

Duration objects using different resolutions may be combined as long as no precision is lost. When duration objects using different resolutions are combined the resulting resolution is the finer of the two. When compound binary operators are used the receiving object's resolution must be the finer or the compilation fails.

```
minutes halfHour{ 30 };
hours oneHour{ 1 };

cout << (oneHour + halfHour).count();   // displays: 90

halfHour += oneHour;             // OK
// oneHour += halfHours;         // won't compile
```

The suffixes `h, min, s, ms, us, ns` can be used for integral values, creating the corresponding `duration` time intervals. E.g., `minutes min = 1h` stores 60 in `min`.

4.2.3 Clocks measuring time

Clocks are used for measuring time. **C++** offers several predefined *clock* types, and all but one of them are defined in the `std::chrono` namespace. The exception is the clock `std::filesystem::__file_clock` (see section 4.3.1 for its details).

Before using the `chrono` clocks the `<chrono>` header file must be included.

We need clock types when defining points in time (see the next section). All predefined clock types define the following types:

- the clock's duration type: `Clock::duration` (predefined clock types use `nanoseconds`). E.g., `system_clock::duration oneDay{ 24h };`

- the clock's resolution type: `Clock::period` (predefined clock types use `nano`). E.g., `cout << system_clock::period::den << '\n';`
- the clock's type that is used to store amounts of time: `Clock::rep` (predefined clock types use `int64_t`). E.g., `system_clock::rep amount = 0;`
- the clock's type that is used to store time points (described in the next section): `Clock::time_point` (predefined clock types use `time_point<system_clock, nanoseconds>`) E.g., `system_clock::time_point start`.

All clock types have a member `now` returning the clock type's `time_point` corresponding to the current time (relative to the clock's epoch). It is a static member and can be used this way: `system_clock::time_point tp = system_clock::now()`.

There are three predefined clock types in the chrono namespace:

- `system_clock` is the 'wall clock', using the system's real time clock;
- `steady_clock` is a clock whose time increases in parallel with the increase of real time;
- `high_resolution_clock` is the computer's fastest clock (i.e., the clock having the shortest timer-tick interval). In practice this is the same clock as `system_clock`.

These clock types also In addition, the `__file_clock` clock type is defined in the `std::filesystem` namespace. The epoch time point of `__file_clock` differs from the epoch time used by the other clock types, but `__file_clock` has a static member `to_sys(__file_clock::time_point)` converting `__file_clock::time_points` to `system_clock::time_points` (`__file_clock` is covered in more detail in section 4.3.1).

In addition to `now` the classes `system_clock` and `high_resolution_clock` (referred to as `Clock` below) offer these two static members:

- `std::time_t Clock::to_time_t(Clock::time_point const &tp)`
  a `std::time_t` value (the same type as returned by **C**'s **time**(2) function) representing the same point in time as `timePoint`.
- `Clock::time_point Clock::from_time_t(std::time_t seconds)`
  a `time_point` representing the same point in time as `time_t`.

The example illustrates how these functions can be called:

```
system_clock::from_time_t(
    system_clock::to_time_t(
        system_clock::from_time_t(
            time(0);
        )
    )
);
```

4.2.4 Points in time: std::chrono::time_point

Single moments in time can be specified through objects of the class `std::chrono::time_point`.

Before using the class `time_point` the `<chrono>` header file must be included.

Like `duration` the class `time_point` requires two template arguments: A clock type and a duration type. Usually `system_clock` is used as the clock's type using `nanoseconds` as the default duration type (it may be omitted if `nanoseconds` is the intended duration type). Otherwise specify the duration type as the `time_point's` second template argument. The following two time point definitions therefore use identifcal time point types:

```
time_point<standard_clock, nanoseconds> tp1;
time_point<standard_clock> tp2;
```

The class `time_point` supports three constructors:

- `time_point()`:
  the default constructor is initialized to the beginning of the clock's *epoch*. For `system_clock` it is January, 1, 1970, 00:00h, but notice that `filesystem::__file_clock` uses a different epoch (see section 4.3.1 below);
- `time_point(time_point<Clock, Duration> const &other)`:
  the copy constructor (cf. chapter 9) initializes a `time_point` object using the time point defined by `other`. If `other's` resolution uses a larger period than the period of the constructed object then `other's` point in time is represented in the constructed object's resolution (an illustration is provided below, at the description of the member `time_since_epoch`);
- `time_point(time_point<Clock, Duration> const &&tmp)`:
  the move constructor (cf. chapter 9) acts comparably to the copy constructor, converting `tmp's` resolution to the constructed object while moving `tmp` to the constructed object.

The following operators and members are available:

- `time_point &operator+=(duration const &amount)`:
  The amount of time represented by `amount` is added to the current `time_point` object. This operator is also available as binary arithmetic operator using a `time_point const &` and a `duration const &` operand (in any order). Example:

  ```
  system_clock::now() + seconds{ 5 };
  ```

- `time_point &operator-=(duration const &amount)`:
  The amount of time represented by `amount` is subtracted from the current `time_point` object. This operator is also available as binary arithmetic operator using a `time_point const &` and a `duration const &` operand (in any order). Example:

  ```
  time_point<system_clock> point = system_clock::now();
  point -= seconds{ 5 };
  ```

- `duration time_since_epoch() const`:
  `duration` is the duration type used by the time point object for which this member is called. It returns the amount of time since the epoch that's represented by the object.
- `time_point min() const`:
  a static member returning the time point's `duration::min` value. Example:

  ```
  cout <<
      time_point<system_clock>::min().time_since_epoch().count() << '\n';
      // shows -9223372036854775808
  ```

- `time_point max() const`:
  a static member returning the time point's `duration::max` value.

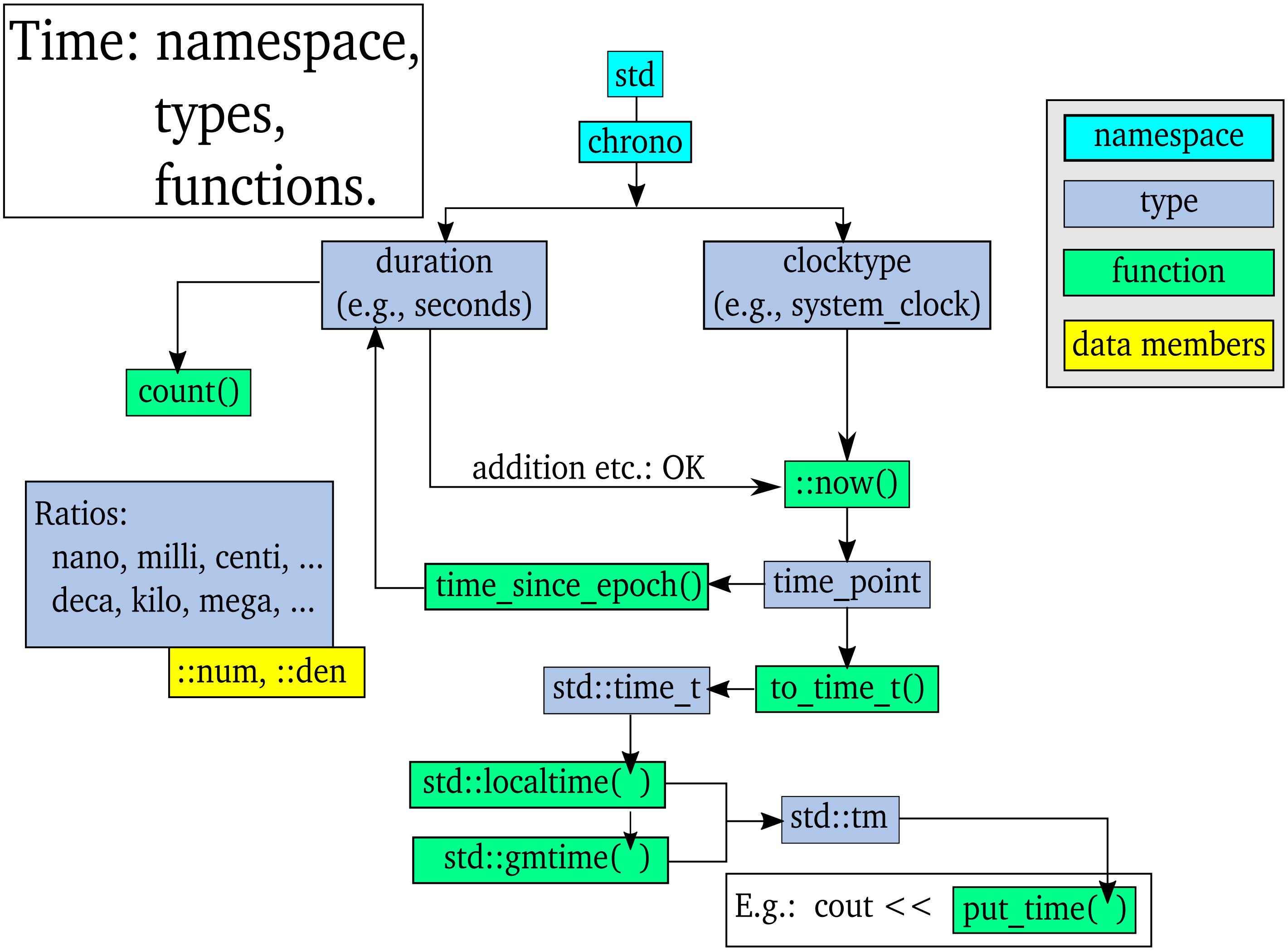
Time: namespace, types, functions.
std
chrono
duration (e.g., seconds)
clocktype (e.g., system_clock)
namespace
type
function
data members
count()
addition etc.: OK
::now()
Ratios: nano, milli, centi, ... deca, kilo, mega, ...
::num, ::den
time_since_epoch()
time_point
std::time_t
to_time_t()
std::localtime( )
std::gmtime( )
std::tm
E.g.: cout <<
put_time( )

Figure 4.1: Time according to **C++**

All predefined clocks use nanoseconds as their time resolution. To express the time in a less precise resolution take one unit of time of the less precise resolution (e.g., `hours(1)`) and convert it to nanoseconds. Then divide the value returned by the time point's `time_since_epoch().count()` member by `count` member of the less precise resolution converted to nanoseconds. Using this procedure the number of hours passed since the beginning of the epoch can be determined:

```
cout << system_clock::now().time_since_epoch().count() /
        nanoseconds(hours(1)).count() <<
        " hours since the epoch\n";
```

Time point objects based on the system clock or on the high resolution clock can be converted to `std::time_t` (or the equivalent type `time_t`) values. Such `time_t` values are used when converting time to text. For such conversions the *manipulator* `put_time` (cf. section 6.3.2) is commonly used, but `put_time` must be provided with the address of a `std::tm` object, which in turn can be obtained from a `std::time_t` value. The whole process is fairly complex, and the core elements are visualized in figure 4.1.

The essential step eventually leading to the insertion of a time point's value into a `std::ostream` consists of using `system_clock::to_time_t(time_point<system_clock>`

`const &tp)` to convert a time point to a `time_t` value (instead of using `system_clock` the `high_resolution_clock` can also be used). How a time point can be inserted into a `std::ostream` is described in section 6.4.4.

4.3 The std::filesystem namespace

Computers commonly store information that must survive reboots in their file systems. Traditionally, to manipulate the file system the **C** programming language offers functions performing the required system calls. Such functions (like **rename**(2), `truncate`(2), **opendir**(2), and **realpath**(3)) are of course also available in **C++**, but their signatures and way of use are often less attractive as they usually expect `char const *` parameters and may use static buffers or memory allocation based on **malloc**(3) and **free**(3).

Since 2003 the `Boost library`[1] offers *wrappers* around these functions, offering interfaces to those system calls that are more **C++**-like.

Currently **C++** directly supports these functions in the `std::filesystem` namespace. These facilities can be used after including the `<filesystem>` header file.

The `filesystem` namespace is extensive: it contains more than 10 different classes, and more than 30 free functions. To refer to the identifiers defined in the `std::filesystem` namespace their fully qualified names (e.g., `std::filesystem::path` can be used). Alternatively, after specifying '`using namespace std::filesystem;`' the identifiers can be used without further qualifications. Namespace specifications like '`namespace fs = std::filesystem;`' are also encountered, allowing specifications like `fs::path`.

Functions in the `filesystem` namespace may fail. When functions cannot perform their assigned tasks they may throw exceptions (cf. chapter 10) or they may assign values to `error_code` objects that are passed as arguments to those functions (see section 4.3.2 below).

4.3.1 the '__file_clock' type

In section 4.2.3 it was stated that various predefined clocks are available, of which the `system_clock` refers to the clock used by the computer itself. The `filesystem` namespace uses a different clock: the `std::filesystem::__file_clock`. Time points obtained using the `__file_clock` differ from the time points obtained using the system clock: time points using the `__file_clock` are based on an epoch that (currently) lies well beyond the epoch Jan 1, 00:00:00 1970 that is used by the system clock: Fri Dec 31 23:59:59 2173. The two epochs can be positioned on a time scale with the present somewhere in between:

```
<------|-----------------------|-----------------------|------->
  system_clock's --------> present <--------    __file_clock's
   epoch starts  positive           negative     epoch starts
                   count             count
```

The `__file_clock` has its own peculiarities: the static member `now` is available, as are some non-static members: additions and subtractions of durations and the member `time_since_epoch` can all be used, and . The other members (`to_time_t, from_time_t, min` and `max`) aren't available.

Since `to_time_t` is not available for `__file_clock` how can we show the time or obtain the time's components of a `time_point<__file_clock>` object?

---

[1] http://www.boost.org/doc/libs/1_65_1/libs/filesystem/doc/index.htm

Currently, there are two ways to accomplish that: compute the correction 'by hand' or use the static `__file_clock::to_sys` function converting a `__file_clock` time point to a `time_point` as used by `system_clock, steady_clock,` and `high_resolution_clock`.

Computing the difference between the epochs we find 6'437'663'999 seconds, which we can add to the obtained time since the `__file_clock's` epoch to obtain the time since the `system_clock's` epoch. If `timePt` holds the duration since the `__file_clock` epoch then

```
6'437'663'999 + system_clock::to_time_t(
                    time_point<system_clock>{ nanoseconds(timePt) })
```

equals the number of seconds since the `system_clock's` epoch.

The potential drawback of this procedure is that, as `__file_clock's` name starts with underscores, the begin of its epoch might change. By using the `now` members of both clocks this drawback is avoided:

```
auto systemNow = system_clock::now().time_since_epoch();
auto fileNow = __file_clock::now().time_since_epoch();
time_t diff = (systemNow - fileNow) / 1'000'000'000;

time_t seconds = diff + system_clock::to_time_t(
                    time_point<system_clock>{ nanoseconds(timePt) });
```

Although being able to compute the time-shifts yourself is attractive from an understanding point of view, it's maybe also a bit (too) cumbersome for daily practices. The static function `__file_clock::to_sys` can be used to convert `__file_clock::time_points` to `system_clock:::time_points`. The `__file_clock::to_sys` function is covered in section 4.3.3.2.

4.3.2 The class 'error_code'

Objects of the class `std::error_code` encapsulate *error values*, and associated *error categories* (cf. section 10.9; `error_code` can be used after including the `<system_error>` header, but it is also available after including the `<filesystem>` header file). Traditionally error values are available as values assigned to the global `int errno` variable. By convention, when `errno's` value equals zero there's no error. This convention was adopted by `error_code`.

Error codes can be defined for many conceptually different situations. Those situations are characterized by their own *error categories*.

Error categories are used to associate `error_code` objects with the errors that are defined by those categories. Default available error categories may use values like `EADDRINUSE` (or the equivalent `enum class errc` value `address_in_use`) but new types of error categories, tailored to other contexts, can also be defined. Defining error categories is covered near the end of the **C++** Annotations (section 23.7.1). At this point two `error_category` members are briefly introduced:

- `std::string message(int err)` returning a textual description of error `err` (like *address already in use* when `err` equals `address_in_use`).
- `char const *name()` returning the name of the error category (like *generic* for the generic category);

Error category classes are singleton classes: only one object exists of each error category. In the context of the filesystem namespace the standard category `system_category` is used, and a reference to the `system_category` object is returned by the free function `std::system_category`, expecting no arguments. The public interface of the class `error_code` declares these construtors and members:

Constructors:

- `error_code() noexcept`:
  the object is initialized with error *value* 0 and the `system_category` error category. Value 0 is not considered an error;
- Copy- and move-constructors are available;
- `error_code(int ec, error_category const &cat) noexcept`:
  the object is initialized from error value `ec` (e.g., `errno`, set by a failing function), and a const reference to the applicable error *category* (provided by, e.g., `std::system_category()` or `std::generic_category()`). Here is an example defining an `error_code` object:

  ```
  error_code ec{ 5, system_category() };
  ```
- `error_code(ErrorCodeEnum value) noexcept`:
  this is a member template (cf. section 22.1.3), using template header `template <class ErrorCodeEnum>`. It initializes the object with the return value of `make_error_code(value)` (see below). In section 23.7 defining `ErrorCodeEnums` is covered. Note: `ErrorCodeEnum` as such does not exist. It is a mere placeholder for existing `ErrorCodeEnum` enumerations;

Members:

- The overloaded assignment operator and an assignment operator accepting an `ErrorCodeEnum` are available;
- `void assign(int val, error_category const &cat)`:
  assigns new values to the object's error value and category. E.g, `ec.assign(0, generic_category());`
- `error_category const &category() const noexcept`:
  returns a reference to the object's error category;
- `void clear() noexcept`:
  sets the `error_code's` value to 0 and its error category to `system_category`;
- `error_condition default_error_condition() const noexcept`:
  returns the current category's default error condition initialized with the current object's error value and error category (see section 10.9.2 for details about the class `error_condition`);
- `string message() const`:
  the message that is associated with the current object's error value is returned (equivalent to `category().message(ec.value())`);
- `explicit operator bool() const noexcept`:
  returns true if the object's error value is unequal 0 (i.e., it represents and error)
- `int value() const noexcept`:
  returns the object's error value.

Free functions:

- Two `error_code` objects can be compared for (in) equality and can be ordered (using `operator<`).

Ordering `error_codes` associated with different error categories has no meaning. But when the error categories are identical then they are compared by their error code values (cf. this `SG14 discussion summary`[2]);

- `error_code make_error_code(errc value) noexcept:`
  returns an `error_code` object initialized with `static_cast<int>(value)` and `generic_category()`. This function converts an `enum class errc` value to an `error_code`.

  Other error related enums may also be defined with which tailored `make_error_code` functions can be associated (cf. section 23.7;)

- `std::ostream &operator<<(std::ostream & os, error_code const &ec):`
  executes the following statement:

  ```
  return os << ec.category().name() << ':' << ec.value();
  ```

Several functions introduced below define an optional last `error_code &ec` parameter. Those functions have `noexcept` specifications. If those functions cannot complete their tasks, then `ec` is set to the appropriate error code, calling `ec.clear()` if no error was encountered. If no `ec` argument is provided then those functions throw a `filesystem_error` exception if they cannot complete their tasks.

4.3.3 Names of file system entries: path

Objects of the class `filesysten::path` hold names of file system entries. The class `path` is a value class: a default constructor (empty path) as well as standard copy/move construction/assignment facilities are available. In addition, the following constructors can be used:

- `path(string &&tmp);`
- `path(Type const &source):`
  any acceptable type that provides the characters of the path (e.g., `source` is a NTBS);
- `path(InputIter begin, InputIter end):`
  the characters from `begin` to `end` define the `path's` name.

A thus constructed `path` doesn't have to refer to an existing file system entry.

Path constructors expect character sequences (including NTBSs) that may consist of various (all optional) elements:

- a root-name, e.g., a disk-name (like `E:`) or device indicator (like `//nfs`);
- a root-directory, present if it is the first character after the (optional) root-name;
- filename characters (not containing directory separators). In addition the ‘single dot filename’ (`.`) represents the current directory and the ‘double dot filename’ (`..`) represents the current directory's parent directory;
- directory separators (by default the forward slash). Multiple consecutive separators are automatically merged into one separator.

---

[2] http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2018/p0824r1.html

The constructors also define a last `format ftmp = auto_format` parameter, for which in practice almost never an argument has to be provided (for its details see `cppreference`[3].)

Many functions expect `path` arguments which can usually be created from NTBSs or `std::string` objects as `path` allows promotions (cf. section 11.4). E.g., the filesystem function `absolute` expects a `const &path` argument. It can be called like this: `absolute("tmp/filename")`.

4.3.3.1 Accessors, modifiers and operators

The class `path` provides the following operators and members:

Operators:

- `path &operator/=(Type const &arg)`:
  the arguments that can be passed to the constructors can also be passed to this member. The `arg` argument is separated from the path's current content by a directory separator (unless the path is initially empty as in `cout << path{}.append("entry")`). See also the members `append` and `concat`, below. The free operator `/` accepts two `path` (promotable) arguments, returning a `path` containing both paths separated by a directory separator (e.g., `lhs / rhs` returns a `path` object containing `lhs/rhs`);
- `path &operator+=(Type const &arg)`:
  similar to `/=`, but *no* directory separator is used when adding `arg` to the current `path`;
- comparison operators: `path` objects can be compared using the (operators implied by the) == and <=> operators. Path objects are compared by lexicographical comparing their ascii-character content.

Accessors:

Accessors return specific `path` components. If a path doesn't contain the requested component then an empty `path` is returned.

- `char const *c_str()`: the path's content as an NTBS is returned;
- `path extension()` returns the dot-extension of the path's last component (including the dot);
- `path filename()` returns the last path-content of the current `path` object. See also the `stem()` accessor, below;
- `bool is_absolute()`: returns `true` if the `path` object contains an absolute path specification;
- `bool is_relative()`: returns `true` if the `path` object contains a relative path specification;
- `path parent_path()` returns the current path-content from which the last element has been removed. Note that if the `path` object contains a filename's path (like `"/usr/bin/zip"`) then `parent_path` removes `/zip` and returns `/usr/bin`, so not `zip's` parent directory, but its actual directory;
- `path relative_path()`: returns the path's content beyond the path's root-directory component of the `path` object. E.g., if the `path ulb{ "/usr/local/bin" }` is defined then `ulb.relative_path()` returns a path containing `"usr/local/bin"`;
- `path relative_path()`: returns the path's content beyond the path's root-directory component of the `path` object. E.g., if the `path ulb{ "/usr/local/bin" }` is defined then `ulb.relative_path()` returns a path containing `"usr/local/bin"`;

---

[3] http://en.cppreference.com/w/cpp/experimental/fs/path

- `path root_directory()`: returns the root-directory component of the `path` object;
- `path root_name()`: returns the root-name's component of the `path` object;
- `path root_path()`: returns the root-path component of the `path` object;
- `path stem()` returns the last path-content of the current `path` object from which the dot-extension hash been removed;
- `string()`: returns the path's content as a `std::string`.
  Similar accessors are available for the following string-types: `wstring`, `u8string`, `u16string`, `,` `u32string`, `generic_string`, `generic_wstring`, `generic_u8string`, `generic_u16string`, and `generic_u32string`;

Except for the family of `string()` and the `is_...` accessors, there are also `bool has_...` members returning `true` if the `path` contains the specified component (e.g., `has_extension` returns `true` if the `path` contains an extension).

Member functions:

- `path &append(Type const &arg)` acts like the `/=` operator;
- `path::iterator begin()` returns an iterator containing the first path component; Dereferencing a `path::iterator` returns a `path` object.
  When available root names and root directories are returned as initial components. When incrementing `path::iterators` the individual directories and finally filename components are returned. The directory separators themselves are not returned when dereferencing subsequent `path::iterators`;
- `void clear()`: the `path's` content is erased;
- `int compare(Type const &other)`:
  returns the result of lexicographically comparing the current path's content with `other`. `Other` can be a `path`, a string-type or an NTBS;
- `path &concat(Type const &arg)` acts like the `+=` operator;
- `ostream &operator<<(ostream &out, path const &path)` (stream insertion) inserts `path's` content, surrounded by double quotes, into `out`;
- `istream &operator>>(istream &in, path &path)` extracts `path's` content from `in`. The extracted path name may optionally be surrounded by double quotes. When inserting a previously extracted `path` object only one set of surrounding quotes are shown.
- `path &remove_filename()`:
  removes the last component of the stored path. If only a root-directory is stored, then the root directory is removed. Note that the last directory separator is kept, unless it is the only path element;
- `path &replace_extension(path const &replacement = path{} )`:
  replaces the extension of the last component of the stored path (including the extension's dot) with `replacement`. The extension is removed if `replacement` is empty. If the `path` calling `replace_extension` has no extension then `replacement` is added. The replacement may optionally start with a dot. The path object's extension receives only one dot;
- `path &replace_filename(path const &replacement)`:
  replaces the last component of the stored path with `replacement`, which itself may contain multiple path elements. If only a root-directory is stored, then it is replaced by `replacement`. The member's behavior is undefined if the current path object is empty;

4.3.3.2 Free functions

In addition to the `path` member functions various free functions are available. Some of these copy files. Those functions accept an optional `std::filesystem::copy_options` argument. The `enum class copy_options` defines symbolic constants that can be used to fine-tune the behavior of these functions. The enumeration supports bitwise operators (the symbols' values are shown between parentheses) and defines these symbols:

- When copying files:
  - `none` (0): report an error (default behavior);
  - `skip_existing` (1): keep the existing file, without reporting an error;
  - `overwrite_existing` (2): replace the existing file;
  - `update_existing` (4): replace the existing file only if it is older than the file being copied;
- When copying subdirectories:
  - `none` (0): skip subdirectories (default behavior);
  - `recursive` (8): recursively copy subdirectories and their content;
- When copying symlinks:
  - `none` (0): follow symlinks (default behavior);
  - `copy_symlinks` (16): copy symlinks as symlinks, not as the files they point to;
  - `skip_symlinks` (32): ignore symlinks;
- To control `copy's` behavior itself:
  - `none` (0): copy file content (default behavior);
  - `directories_only` (64): copy the directory structure, but do not copy any non-directory files;
  - `create_symlinks` (128): instead of creating copies of files, create symlinks pointing to the originals (the source path must be an absolute path unless the destination path is in the current directory);
  - `create_hard_links` (256): instead of creating copies of files, create hardlinks that resolve to the same files as the originals.

The following functions expect `path` arguments:

- `path absolute(path const &src, [, error_code &ec])`:
  a copy of `src` specified as an absolute path (i.e., starting at the filesystem's root (and maybe disk) name). It can be called like this: `absolute("tmp/filename")`, returning the (absolute) current working directory to which `absolute's` argument is appended as a final element, separated by a directory separator. Relative path indicators (like `../` and `./`) are kept. The returned `path` merely is an absolute path. If relative path indicators should be removed, then use the next function;

- `path canonical(path const &src [, error_code &ec])`:
  returns `src's` canonical path. The argument `src` must refer to an existing directory entry. Example:

  ```
  path man{ "/usr/local/bin/../../share/man" };
  cout << canonical(man) << '\n';    // shows:   "/usr/share/man"
  ```

- `void copy(path const &src, path const &dest [, copy_options opts [, error_code &ec]])`:
  `src` must exist. Copies `src` to `dest` if the `cp` program would also succeed.

  If `src` is a directory, and `dest` does not exist, `dest` is created. Directories are recursively copied if copy options `recursive` or `none` were specified;
- `bool copy_file(path const &src, path const &dest [, copy_options opts [, error_code &ec]])`:
  `src` must exist. Copies `src` to `dest` if the `cp` program would also succeed. Symbolic links are followed. The value `true` is returned if copying succeeded;
- `void copy_symlink(path const &src, path const &dest [, error_code &ec])`:
  creates the symlink `dest` as a copy of the symlink `src`;
- `bool create_directories(path const &dest [, error_code &ec])`:
  creates each component of `dest`, unless already existing. The value `true` is returned if `dest` was actually created. If `false` is returned `ec` contains an error-code, which is zero (`ec.value() == 0`) if `dest` already existed. See also `create_directory` below;
- `bool create_directory(path const &dest [, path const &existing] [, error_code &ec])`:
  `dest's` parent directory must exist. This function creates directory `dest` if it does not yet exist. The value `true` is returned if `dest` was actually created. If `false` is returned `ec` contains an error-code, which is zero (`ec.value() == 0`) if `dest` already existed. If `existing` is specified, then `dest` receives the same attributes as `existing`;
- `void create_directory_symlink(path const &dir, path const &link [, error_code &ec])`:
  like `create_symlink` (see below), but is used to create a symbolic link to a directory;
- `void create_hardlink(path const &dest, path const &link [, error_code &ec])`:
  creates a hard link from `link` to `dest`. `Dest` must exist;
- `void create_symlink(path const &dest, path const &link [, error_code &ec])`:
  creates a symbolic (soft) link from `link` to `dest`; `dest` does *not* have to exist;
- `path current_path([error_code &ec]), void current_path(path const &toPath [, error_code &ec])`:
  the former function returns the current working directory (cwd), the latter changes the cwd to `toPath`. The returned path's last character is not a slash, unless called from the root-directory;
- `bool equivalent(path const &path1, path const &path2 [, error_code &ec])`:
  `true` is returned if `path1` and `path2` refer to the same file or directory, and have identical statuses. Both paths must exist;
- `bool exists(path const &dest [, error_code &ec]), exists(file_status status)`:
  `true` is returned if `dest` exists (actually: if `status(dest[, ec])` (see below) returns `true`). Note: when iterating over directories, the iterator usually provides the entries' statuses. In those cases calling `exists(iterator->status())` is more efficient than calling `exists(*iterator)`. When `dest` is the path to a symbolic reference then `exists` returns whether the link's destination exists or not (see also the functions `status` and `symlink_status` in section 4.3.4);
- `std::unintmax_t file_size(path const &dest [, error_code &ec])`:
  returns the size in bytes of a regular file (or symlink destination);

- `std::uintmax_t hard_link_count(path const &dest [, error_code &ec])`:
  returns the number of hard links associated with `dest`;

- `time_point<__file_clock> last_write_time(path const &dest [, error_code &ec])`, `void last_write_time(path const &dest, time_point<__file_clock> newTime [, error_code &ec])`:
  the former function returns `dest's` last modification time; the latter function changes `dest's` last modification time to `newTime`. `last_write_time's` return type is defined through a `using` alias for `chrono::time_point` (cf. section 4.2.4). The returned `time_point` is guaranteed to cover all file time values that may be encountered in the current file system. The function `__file_clock::to_sys` (see below) can be used to convert `__file_clock` time points to `system_clock` time_points;

- `path read_symlink(path const &src [, error_code &ec])`:
  `src` must refer to a symbolic link or an error is generated. The link's target is returned;

- `bool remove(path const &dest [, error_code &ec])`, `std::uintmax_t remove_all(path const &dest [, error_code &ec])`:
  `remove` removes the file, symlink, or empty directory `dest`, returning `true` if `dest` could be removed; `remove_all` removes `dest` if it's a file (or symlink); and recursively removes directory `dest`, returning the number of removed entries;

- `void rename(path const &src, path const &dest [, error_code &ec])`:
  renames `src` to `dest`, as if using the standard **mv**(1) command (if `dest` exists it is overwritten);

- `void resize_file(path const &src, std::uintmax_t size [, error_code &ec])`:
  `src's` size is changed to `size` as if using the standard **truncate**(1) command;

- `space_info space(path const &src [, error_code &ec])`:
  returns information about the file system in which `src` is located;

- `path system_complete(path const &src[, error_code& ec])`:
  returns the absolute path matching `src`, using `current_path` as its base;

- `path temp_directory_path([error_code& ec])`:
  returns the path to a directory that can be used for temporary files. The directory is not created, but its name is commonly available from the environment variables `TMPDIR`, `TMP`, `TEMP`, or `TEMPDIR`. Otherwise, `/tmp` is returned.

- `time_point<system_clock> __file_clock::to_sys(time_point<__file_clock> timePoint)`:
  here is how the time returned by `last_write_time` can be represented using the `system_clock's` epoch:

```
int main()
{
    time_t seconds = system_clock::to_time_t(
                    __file_clock::to_sys(last_write_time("lastwritetime.cc"))
                );

    cout << "lastwritetime.cc's last (UTC) write time: " <<
             put_time(gmtime(&seconds), "%c") << '\n';
}
```

4.3.4 Handling directories: directory_entry

The file system is a recursive data structure. Its top-level entry is a directory (the root directory) containing plain directory entries (files, (soft) links, named sockets, etc.) and possibly also (sub)directory entries referring to nested directories which in turn may contiain plain- and (sub)directory entries.

In the `std::filesystem` namespace the elements of directories are objects of the class `directory_entry`, containing names and statuses of the entries of that directory.

The class `directory_entry` supports all standard constructors and assignment operators and in addition a constructor expecting a `path`:

```
    directory_entry(path const &entry);
```

Objects of the class `directory_entry` can be constructed by name, without requiring that those objects refer to existing entries in the computer's file system. The assignment operator is also available, as is the (`ostream`) insertion operator, inserting the object's `path` into the stream. The extraction operator is not available.

'`directory_entry`' objects may be compared using the `==`, `!=`, `<`, `<=`, `>`, and `>=` operators. These operators are then applied to their `path` objects: `directory_entry("one") == directory_entry("one")` returns `true`.

In addition to these operators the class `directory_entry` also has these member functions:

- `void assign(path const &dest)`:
  the current path is replaced by `dest` (its action is identical to that of the overloaded assignment operator);
- `void replace_filename(path const &dest)`:
  the last element of the current object's path is replaced by `dest`. If that element is empty (like when the object's path ends in a directory separator) then `dest` is appended to the current object's path;
- `path const &path() const`, `operator path const &() const`:
  the current object's path name is returned;
- `file_system::file_status status([error_code &ec])`:
  returns type and attributes of the directory entry referred to by the current object. If the current object refers to a symlink then the status of the entry the symlink refers to is returned. To obtain the status of the entry itself, even if it's a symlink use `symlink_status` (see also section 4.3.5 and 4.3.5.1 below).

4.3.4.1 Visiting directory entries: (recursive_)directory_iterator

The `filesystem` namespace has two classes simplifying directory processing: objects of the class `directory_iterator` are (input) iterators iterating over the entries of directories; and objects of the class `recursive_directory_iterator` are (input) iterators recursively visiting all entries of directories.

The classes `(recursive_)directory_iterator` provides default, copy, and move constructors. Objects of both classes may also be constructed from a `path` and an optional `error_code`. E.g.,

```
    directory_iterator(path const &dest [, error_code &ec]);
```

All members of standard input iterators (cf. section 18.2) are supported. These iterators point to `directory_entry` objects referring to entries in the computer's file system. E.g.,

```
cout << *directory_iterator{ "/home" } << '\n'; // shows the first
                                                 // entry under /home
```

End-iterators matching these objects are available through the default constructed objects of the two classes. In addition, range-based for loops can be used as shown by the next example:

```
for (auto &entry: directory_iterator("/var/log"))
    cout << entry << '\n';
```

For-statements explicitly defining iterators can also be used:

```
for (
    auto iter = directory_iterator("/var/log"),
          end = directory_iterator{};
            iter != end;
                ++iter
)
    cout << entry << '\n';
```

After constructing a `(recursive_)directory_iterator base{"/var/log"}` object it refers to the first element of its directory. Such iterators can also explicitly be defined: `auto &iter = begin(base), auto iter = begin(base), auto &iter = base` or `auto iter = base`. All these `iter` objects refer to `base's` data, and incrementing them also advances `base` to its next element:

```
recursive_directory_iterator base{ "/var/log/" };
auto iter = base;
                            // final two elements show identical paths,
                            // different from the first element.
cout << *iter << ' ' << *++iter << ' ' << *base << '\n';
```

The functions `begin` and `end` that are used in the above examples are, like `(recursive_)directory_iterator`, available in the `filesystem` namespace.

The `recursive_directory_iterator` also accepts a `directory_options` argument (see below), by default specified as `directory_options::none`:

```
recursive_directory_iterator(path const &dest,
                        directory_options options [, error_code &ec]);
```

The `enum class directory_options` defines values that are used to fine-tune the behavior of `recursive_directory_iterator` objects, supporting bitwise operators (the values of its symbols are shown between parentheses):

- `none` (0): directory symlinks are skipped, denied permission to enter a subdirectory generates an error;
- `follow_directory_symlink` (1): symlinks to subdirectories are followed;
- `skip_permission_denied` (2): directories that cannot be entered are silently skipped.

The class `recursive_directory_iterator` also has these members:

- `int depth() const`:
  returns the current iteration depth. The depth of the initial directory, specified at construction-time, equals 0;
- `void disable_recursion_pending()`:
  when called before incrementing the iterator the next directory entry is not recursively visited if it is a sub-directory. Then, after incrementing the iterator recursion is again allowed. If a recursion should end at a specific depth then this function must repeatedly be called before calling the iterator's increment operator once `depth()` returns that specific depth;
- `recursive_directory_iterator &increment(error_code &ec)`:
  acts identically to the iterator's increment operator. However, when an error occurs `operator++` throws a `filesystem_error` exception, while `increment` assigns the error to `ec`;
- `directory_options options() const`:
  returns the option(s) specified at construction-time;
- `void pop()`:
  ends processing the current directory, and continues at the next entry in the current directory's parent. When (in a for-statement, see the example below) called from the initial directory that directory's processing ends;
- `bool recursion_pending() const`:
  `true` is returned if recursive processing of sub-directories of the currently processed directory is allowed. If so, and the directory entry the iterator points at is a sub-directory then processing continues at that sub-directory at the iterator's next increment;

Here is a little program displaying all directory elements of a directory and of all its immediate sub-directories.

```
int main()
{
    recursive_directory_iterator base{ "/var/log" };

    for (auto entry = base, end = end(base); entry != end; ++entry)
    {
        cout << entry.depth() << ": " << *entry << '\n';
        if (entry.depth() == 1)
            entry.disable_recursion_pending();
    }
}
```

The above program handles entries as they come. If other strategies are needed they have to be implemented. E.g., a breadth-first strategy first visits all the non-directory entries and then visits the sub-directories. In the next example this is realized by processing each of the directories stored in `level` (initially it merely contains the starting directory). 'Processing a directory' means that its non-directory entries are directly processed while the names of its sub-directories are stored in `next`. Once all entries in `level` have been processed the names of the next level sub-directories are available in `next` and by assigning `next` to `level` all directories at the next level are processed. When reaching the most deeply nested sub-directories `next` remains empty and the `while` statement ends:

```
void breadth(path const &dir)            // starting dir.
{
        vector<path> level{ dir };          // currently processed level

        while (not level.empty())           // process all its dirs.
        {
            vector<path> next;              // dirs of the next level

            for (auto const &dir: level)    // visit all dirs at this level
            {
                cout << "At " << dir << '\n';
                                            // at each dir: visit all entries
                for (auto const &entry: directory_iterator{ dir })
                {
                    if (entry.is_directory())   // store all dirs at the current
                        next.push_back(entry);  //  level
                    else                        // or process its non-dir entry
                        cout << "   entry: " << entry << '\n';
                }
            }

            level = next;                   // continue at the next level,
        }                                   // which eventually won't exist
    }
```

4.3.5 Types (file_type) and permissions (perms) of file system elements: file_status

File system entries (represented by `path` objects), have several attributes: permissions (e.g., the owner may modifiy an entry, others may only read entries), and types (like plain files, directories, and soft-links).

Types and permissions of file system entries are available through objects of the class `file_status`. The class `file_status` is a value-class supporting copy- and move- constructors and assignment operators.

The constructor

```
    explicit file_status(file_type type = file_type::none,
                         perms permissions = perms::unknown)
```

creates the file status for a specific type of file system entry having a specific set of permissions. It also acts as default constructor.

The constructor's first parameter is an enumeration specifying the type of a file system entry represented by a `path` object:

- `not_found = -1` indicates that a file system entry whose status was requested was not found (this is not considered an error);
- `none` indicates either that the file status has not yet been evaluated, or that an error occurred when an entry's status was evaluated;
- `regular`: the entry is a regular file;
- `directory`: the entry is a directory;
- `symlink`: the entry is a symbolic link;

- `block`: the entry is a block device;
- `character`: the entry is a character device;
- `fifo`: the entry is a named pipe;
- `socket`: the entry is a socket file;
- `unknown`: the entry is an unknown file type

The constructor's second parameter defines the `enum class perms` specifying the access permissions of file system entries. The enumeration's symbols were selected so that their meanings should be more descriptive than the constants defined in the `<sys/stat.h>` header file, but other than that they have identical values. All bitwise operators can be used by values of the `enum class perms`. Here is an overview of the symbols defined by the `enum class perms`:

Permission specifiers

Symbol	Value	sys/stat.h	Meaning
none	0000		No permission bits were set
owner_read	0400	S_IRUSR	File owner has read permission
owner_write	0200	S_IWUSR	File owner has write permission
owner_exec	0100	S_IXUSR	File owner has execute/search permissions
owner_all	0700	S_IRWXU	File owner has read, write, and execute/search permissions
group_read	0040	S_IRGRP	The file's group has read permission
group_write	0020	S_IWGRP	The file's group has write permission
group_exec	0010	S_IXGRP	The file's group has execute/search permissions
group_all	0070	S_IRWXG	The file's group has read, write, and execute/search permissions
others_read	0004	S_IROTH	Other users have read permission
others_write	0002	S_IWOTH	Other users have write permission
others_exec	0001	S_IXOTH	Other users have execute/search permissions
others_all	0007	S_IRWXO	Other users have read, write, and execute/search permissions
all	0777		All users have read, write, and execute/search permissions
set_uid	04000	S_ISUID	Set user ID to file owner user ID on execution
set_gid	02000	S_ISGID	Set group ID to file's user group ID on execution
sticky_bit	01000	S_ISVTX	POSIX XSI specifies that when set on a directory only file owners may delete files even if the directory is writeable by others (used, e.g., with `/tmp`)
mask	07777		All valid permission bits.

The class `file_status` provides these members:

- `perms permissions() const` and `void permissions(perms newPerms [, perm_options opts] [, error_code &ec])`:
  the former member returns the permissions of the file system entry represented by the `file_status` object, the latter can be used to modify those permissions. The `enum class perm_options` has these values:
  - `replace`: current options are replaced by `newPerms`;
  - `add`: `newPerms` are added to the current permissions;

  - `remove`: `newPerms` are removed from the current permissions;
  - `nofollow`: when `path` refers to a symbolic link the permissions of the symbolic link instead of those of the file system entry the link refers to are updated.

- `file_type type() const` and `void type(file_type type)`:
  the former member returns the type of the file system entry represented by the `file_status` object, the latter can be used to set the type.

4.3.5.1 Obtaining the status of file system entries

The `filesystem` functions `status` and `symlink_status` retrieve or change statuses of file system entries. These functions may be called with a final (optional) `error_code` argument which is assigned an appropriate error code if they cannot perform their tasks. If the argument is omitted the members throw exceptions if they cannot perform their tasks:

- `file_status status(path const &dest [, error_code &ec])`:
  returns type and attributes of `dest`. If `dest` is a symlink the status of the link's destination is returned;
- `file_status symlink_status(path const &dest [, error_code &ec])`:
  when calling `symlink_status(dest)` the status of `dest` itself is returned. Thus, if `dest` refers to a symlink then `symlink_status` does *not* return the status of the entry `dest` refers to, but the status of `dest` itself: a symbolic link (with `file_status's type()` member returning `file_type::symlink`);
- `bool status_known(file_status const &status)`:
  returns `true` if `status` refers to a determined status (`status` itself may indicate that the entity referred to by `status` does not exist). One way of receiving `false` is by passing it a default status object: `status_known(file_status{})`;

Once a `file_status` object is obtained the file type of the entry whose status it represents can be interrogated using these functions (defined in the `filesystem` namespace, where `WHATEVER` is the requested specification):

```
bool is_WHATEVER(file_status status)
bool is_WHATEVER(path const path &entry [, error_code &ec])
```

These functions return `true` if `status` or `status` matches the requested type. Here are the available functions:

- `is_block_file`: the path refers to a block device;
- `is_character_file`: the path refers to a character device;
- `is_directory`: the path refers to a directory;
- `is_empty`: the path refers to an empty file or directory;
- `is_fifo`: the path refers to a named pipe;
- `is_other`: the path does not refer to a directory, regular file or symlink;
- `is_regular_file`: the path refers to a regular file;
- `is_socket`: the path refers to a named socket;
- `is_symlink`: the path refers to a symbolic link;

Alternatively, the `file_status::type()` member can be used in, e.g., a `switch` to select an entry matching its `file_type` return value (see the previous section (4.3.5) for a description of the symbols defined by the `file_type` enum).

Here is a little program showing how file statuses can be obtained and shown (for the *map* see section 12.4.7):

```
namespace
{
    std::unordered_map<file_type, char const *> statusMap =
    {
        { file_type::not_found, "an unknown file" },
        { file_type::none,      "not yet or erroneously evaluated "
                                                            "file type" },
        { file_type::regular,   "a regular file" },
        { file_type::directory, "a directory" },
        { file_type::symlink,   "a symbolic link" },
        { file_type::block,     "a block device" },
        { file_type::character, "a character device" },
        { file_type::fifo,      "a named pipe" },
        { file_type::socket,    "a socket file" },
        { file_type::unknown,   "an unknown file type" }
    };
}

int main()
{
    cout << oct;

    string line;
    while (true)
    {
        cout << "enter the name of a file system entry: ";
        if (not getline(cin, line) or line.empty())
            break;

        path entry{ line };

        error_code ec;
        file_status stat = status(entry, ec);

        if (not status_known(stat))
        {
            cout << "status of " << entry << " is unknown. "
                                            "Ec = " << ec << '\n';
            continue;
        }

        cout << "status of " << entry << ": type = " <<
                 statusMap[stat.type()] <<
                 ", permissions: " <<
                    static_cast<size_t>(stat.permissions()) << '\n';
    }
}
```

4.3.6 Information about the space of file systems: space_info

Every existing `path` lives in a file system, Sizes of file systems typically are quite large, but there is a limit to their sizes.

The size of file systems, the number of bytes that is currently being used and the remaining number of bytes is made available by the function `space(path const &entry [, error_code &ec])`, returning the information about the file system containing `entry` in a POD `struct space_info`.

If the `error_code` argument is provided then it is cleared if no error occurs, and set to the operating system's error code if an error has occurred. If an error occurs and the `error_code` argument was not provided then a `filesystem_error` exception is thrown, receiving `path` as its first argument and the operating system's error code as its `error_code` argument.

The returned `space_info` has three fields:

```
uintmax_t capacity;     // total size in bytes
uintmax_t free;         // number of free bytes on the file system
uintmax_t available;    // free bytes for a non-privileged process
```

If a field cannot be determined it is set to -1 (i.e., the max. value of the type `uintmax_t`).

The function can be used this way:

```
int main()
{
    path tmp{ "/tmp" };

    auto pod = space(tmp);

    cout << "The filesystem containing /tmp has a capacity of " <<
                                              pod.capacity << " bytes,\n"
        "i.e., " << pod.capacity / (1024 * 1024) << " MB.\n"
        "# free bytes: " << pod.free << "\n"
        "# available:  " << pod.available << "\n"
        "free + available:  " << pod.free + pod.available << '\n';
}
```

4.3.7 File system exceptions: filesystem_error

The `std::filesystem` namespace offers its own exception type `filesystem_error` (see also chapter 10). Its constructor has the following signature (the bracketed parameters are optional):

```
filesystem_error(string const &what,
                [path const &path1, [path const &path2,]]
                error_code ec);
```

As `filesystem` facilities are closely related to standard system functions, `errc` error code enumeration values can be used to obtain `error_codes` to pass to `filesystem_error`, as illustrated by the following program:

```
int main()
try
```

```
{
    try
    {
        throw filesystem_error{ "exception encountered", "p1", "p2",
                                make_error_code(errc::address_in_use) };
    }
    catch (filesystem_error const &fse)
    {
        cerr << "what:  " << fse.what() << "\n"
                "path1: " << fse.path1() << "\n"
                "path2: " << fse.path2() << "\n"
                "code:  " << fse.code() << '\n';

        throw;
    }
}
catch (exception const &ec)
{
    cerr << "\n"
            "plain exception's what: " << ec.what() << "\n\n";
}
```

Chapter 5

The ‘string’ Data Type

C++ offers many solutions for common problems. Most of these facilities are part of the *Standard Template Library* or they are implemented as *generic algorithms* (see chapter 19).

Among the facilities **C++** programmers have developed over and over again are those manipulating chunks of text, commonly called *strings*. The **C** programming language offers rudimentary string support.

To process text **C++** offers a `std::string` type. In **C++** the traditional **C** library functions manipulating NTB strings are deprecated in favor of using `string` objects. Many problems in **C** programs are caused by buffer overruns, boundary errors and allocation problems that can be traced back to improperly using these traditional **C** string library functions. Many of these problems can be prevented using **C++** string objects.

Actually, `string` objects are *class type* variables, and in that sense they are comparable to stream objects like `cin` and `cout`. In this section the use of `string` type objects is covered. The focus is on their definition and their use. When using `string` objects the *member function syntax* is commonly used:

```
        stringVariable.operation(argumentList)
```

For example, if `string1` and `string2` are variables of type `std::string`, then

```
        string1.compare(string2)
```

can be used to compare both strings.

In addition to the common member functions the `string` class also offers a wide variety of *operators*, like the assignment (=) and the comparison operator (==). Operators often result in code that is easy to understand and their use is generally preferred over the use of member functions offering comparable functionality. E.g., rather than writing

```
    if (string1.compare(string2) == 0)
```

the following is generally preferred:

```
    if (string1 == string2)
```

To define and use `string`-type objects, sources must include the header file `<string>`. To merely *declare* the string type the header iosfwd can be included.

In addition to `std::string`, the header file `string` defines the following string types:

- `std::wstring`, a string type consisting of `wchar_t` characters;
- `std::u16string`, a string type consisting of `char16_t` characters;
- `std::u32string`, a string type consisting of `char32_t` characters.

5.1 Operations on strings

Some of the operations that can be performed on strings return indices within the strings. Whenever such an operation fails to find an appropriate index, the *value* `string::npos` is returned. This value is a symbolic value of type `string::size_type`, which is (for all practical purposes) an (`unsigned`) `int`.

All `string` member functions accepting `string` objects as arguments also accept NTBS arguments. The same usually holds true for operators accepting `string` objects.

Some `string`-members use *iterators*. Iterators are formally introduced in section 18.2. Member functions using iterators are listed in the next section (5.2), but the iterator concept itself is not further covered by this chapter.

Strings support a large variety of members and operators. A short overview listing their capabilities is provided in this section, with subsequent sections offering a detailed discussion. The bottom line: **C++** strings are extremely versatile and there is hardly a reason for falling back on the **C** library to process text. **C++** strings handle all the required memory management and thus memory related problems, which are the #1 source of problems in **C** programs, can be prevented when **C++** strings are used. Strings do come at a price, though. The class's extensive capabilities have also turned it into a beast. It's hard to learn and master all its features and in the end you'll find that not all that you expected is actually there. For example, `std::string` doesn't offer case-insensitive comparisons. But in the end it isn't even as simple as that. It *is* there, but it is somewhat hidden and at this point in the **C++** Annotations it's too early to study into that hidden corner yet. Instead, realize that **C**'s standard library *does* offer useful functions that can be used as long as we're aware of their limitations and are able to avoid their traps. So for now, to perform a traditional case-insensitive comparison of the content of two `std::string` objects `str1` and `str2` the following will do:

```
    strcasecmp(str1.c_str(), str2.c_str());
```

Strings support the following functionality:

- `initialization`:
  when string objects are defined they are always properly initialized. In other words, they are always in a valid state. Strings may be initialized empty or already existing text can be used to initialize strings.
- `assignment`:
  strings may be given new values. New values may be assigned using member functions (like `assign`) but a plain assignment operator (i.e., =)may also be used. Furthermore, assignment *to* a character buffer is also supported.
- `conversions`:
  the partial or complete content of string objects may be interpreted as **C** strings but the string's content may also be processed as a series of raw binary bytes, not necessarily terminating in a 0-valued character. Furthermore, in many situations plain characters and **C** strings may be used where `std::string`s are accepted as well.

- `breakdown`:
  the individual characters stored in a string can be accessed using the familiar index operator (`[]`) allowing us to either access or modify information in the middle of a string.

- `comparisons`:
  strings may be compared to other strings (NTBSs) using the familiar logical comparison operators `==, !=, <, <=, >` and `>=`. There are also member functions available offering a more fine-grained comparison.

- `modification`:
  the content of strings may be modified in many ways. Operators are available to add information to string objects, to insert information in the middle of string objects, or to replace or erase (parts of) a string's content.

- `swapping`:
  the string's swapping capability allows us in principle to exchange the content of two string objects without a byte-by-byte copying operation of the string's content.

- `searching`:
  the locations of characters, sets of characters, or series of characters may be searched for from any position within the string object and either searching in a forward or backward direction.

- `housekeeping`:
  several housekeeping facilities are offered: the string's length, or its empty-state may be interrogated. But string objects may also be resized.

- `stream I/O`:
  strings may be extracted from or inserted into streams. In addition to plain string extraction a line of a text file may be read without running the risk of a buffer overrun. Since extraction and insertion operations are stream based the I/O facilities are *device independent*.

5.2 A std::string reference

In this section the string members and string-related operations are referenced. The subsections cover, respectively the string's initializers, iterators, operators, and member functions. The following terminology is used throughout this section:

- `object` is always a `string`-object;
- `argument` is a `string const &` or a `char const *` unless indicated otherwise. The content of an `argument` never is modified by the operation processing the `argument`;
- `opos` refers to an offset into an `object` string;
- `apos` refers to an offset into an `argument`;
- `on` represents a number of characters in an `object` (starting at `opos`);
- `an` represents a number of characters in an `argument` (starting at `apos`).

Both `opos` and `apos` must refer to existing offsets, or an exception (cf. chapter 10) is generated. In contrast, `an` and `on` may exceed the number of available characters, in which case only the available characters are considered.

Many members declare default values for `on, an` and `apos`. Some members declare default values for `opos`. Default offset values are 0, the default values of `on` and `an` is `string::npos`, which can be interpreted as 'the required number of characters to reach the end of the string'.

With members starting their operations at the end of the string object's content proceeding backwards, the default value of `opos` is the index of the object's *last* character, with `on` by default equal to `opos + 1`, representing the length of the substring *ending* at `opos`.

In the overview of member functions presented below it may be assumed that all these parameters accept default values unless indicated otherwise. Of course, the default argument values cannot be used if a function requires additional arguments beyond the ones otherwise accepting default values.

Some members have overloaded versions expecting an initial argument of type `char const *`. But even if that is not the case the first argument can *always* be of type `char const *` where a parameter of `std::string` is defined.

Several member functions accept *iterators*. Section 18.2 covers the technical aspects of *iterators*, but these may be ignored at this point without loss of continuity. Like `apos` and `opos`, iterators must refer to existing positions and/or to an existing range of characters within the string object's content.

All `string`-member functions computing indices return the predefined constant `string::npos` on failure.

The `s` literal suffix to indicate that a `std::string` constant is intended when a string literal (like `"hello world"`) is used. It can be used after declaring `using namespace std` or, more specific, after declaring `using namespace std::literals::string_literals`.

When string literals are used when explicitly defining or using `std::string` objects the `s`-suffix is hardly ever required, but it may come in handy when using the `auto` keyword. E.g., `auto str = "hello world"s` defines `std::string str`, whereas it would have been a `char const *` if the literal suffix had been omitted.

5.2.1 Initializers

After defining string objects they are guaranteed to be in a valid state. At *definition time* string objects may be initialized in one of the following ways: The following `string` constructors are available:

- `string object`:
  initializes `object` to an empty string. When defining a `string` this way no argument list may be specified;

- `string object(string::size_type count, char ch)`:
  initializes `object` with `count` characters `ch`. *Caveat:* to initialize a string object using this constructor do not use the curly-braces variant, but use the constructor as shown, to avoid selecting the initializer-list constructor (see below);

- `string object(string const &argument)`:
  initializes `object` with `argument`;

- `string object(std::string const &argument, string::size_type apos, string::size_type an)`:
  initializes `object` with `argument`'s content starting at index position `apos`, using at most `an` of `argument`'s characters;

- `string object(InputIterator begin, InputIterator end)`:
  initializes `object` with the characters in the range of characters defined by the two `InputIterators`.

- `string object(std::initializer_list<char> chars)`:
  initializes `object` with the characters specified in the initializer list. The string may also

directly be initialized, using the curly braced initialization. Here is an example showing both forms:

```
string str1({'h', 'e', 'l', 'l', 'o'});
string str2{ 'h', 'e', 'l', 'l', 'o' };
```

5.2.2 Iterators

See section 18.2 for details about *iterators*. As a quick introduction to iterators: an iterator acts like a pointer, and pointers can often be used in situations where iterators are requested. Iterators usually come in pairs, defining a range of entities. The begin-iterator points to the first entity, the end-iterator points just beyond the last entity of the range. Their difference is equal to the number of entities in the iterator-range.

Iterators play an important role in the context of *generic algorithms* (cf. chapter 19). The class `std::string` defines the following *iterator types*:

- `string::iterator` and `string::const_iterator`:

  these iterators are *forward iterators*. The `const_iterator` is returned by `string const` objects, the plain `iterator` is returned by non-const string objects. Characters referred to by `iterators` may be modified;

- `string::reverse_iterator` and `string::reverse_const_iterator`:

  these iterators are also *forward iterators* but when *incrementing* the iterator the *previous* character in the string object is reached. Other than that they are comparable to, respectively, `string::iterator` and `string::const_iterator`.

5.2.3 Operators

String objects may be manipulated by member functions but also by operators. Using operators often results in more natural-looking code. In cases where operators are available having equivalent functionality as member function the operator is practically always preferred.

The following operators are available for `string` objects (in the examples 'object' and 'argument' refer to existing `std::string` objects).

- plain assignment:

  a character, **C** or **C++** string may be assigned to a `string` object. The assignment operator returns its left-hand side operand. Example:

  ```
  object =  argument;
  object = "C string";
  object = 'x';
  object = 120;        // same as object = 'x'
  ```

- addition:

  the arithmetic additive assignment operator and the addition operator add text to a `string` object. The compound assignment operator returns its left-hand side operand, the addition operator returns its result in a temporary string object. When using the addition operator either the left-hand side operand or the right-hand side operand must be a `std::string` object. The other operand may be a char, a **C** string or a **C++** string. Example:

```
object += argument;
object += "hello";
object += 'x';      // integral expressions are OK

argument + otherArgument;   // two std::string objects
argument + "hello";         // using + at least one
"hello" + argument;         // std::string is required
argument + 'a';             // integral expressions are OK
'a' + argument;
```

- index operator:

  The index operator may be used to retrieve `object`’s individual characters, or to assign new values to individual characters of a non-const string object. There is no range-checking (use the `at()` member function for that). This operator returns a `char &` or `char const &`. Example:

  ```
  object[3] = argument[5];
  ```

- logical operators:

  the logical comparison operators may be applied to two string objects or to a string object and a **C** string to compare their content. These operators return a `bool` value. The `==, !=, >, >=, <,` and `<=` operators are available. The ordering operators perform a lexicographical comparison of their content using the ASCII character collating sequence. Example:

  ```
  object == object;           // true
  object != (object + 'x');   // true
  object <= (object + 'x');   // true
  ```

- stream related operators:

  the insertion-operator (cf. section 3.1.4) may be used to insert a `string` object into an `ostream`, the extraction-operator may be used to extract a string object from an `istream`. The extraction operator by default first ignores all whitespace characters and then extracts all consecutively non-blank characters from an `istream`. Instead of a string a character array may be extracted as well, but the advantage of using a string object should be clear: the destination string object is automatically resized to the required number of characters. Example:

  ```
  cin >> object;
  cout << object;
  ```

5.2.4 Member functions

The `std::string` class offers many member function as well as additional non-member functions that should be considered part of the string class. All these functions are listed below in alphabetic order.

The symbolic value `string::npos` is defined by the string class. It represents ‘index-not-found’ when returned by member functions returning string offset positions. Example: when calling ‘`object.find('x')`’ (see below) on a string object not containing the character `'x'`, `npos` is returned, as the requested position does not exist.

The final 0-byte used in **C** strings to indicate the end of an NTBS is *not* considered part of a **C++** string, and so the member function will return `npos`, rather than `length()` when looking for 0 in a string object containing the characters of a **C** string.

Here are the standard functions that operate on objects of the class string. When a parameter of `size_t` is mentioned it may be interpreted as a parameter of type `string::size_type`, but without defining a default argument value. The type `size_type` should be read as `string::size_type`. With `size_type` the default argument values mentioned in section 5.2 apply. All quoted functions are member functions of the class `std::string`, except where indicated otherwise.

- `char &at(size_t opos):`
  a reference to the character at the indicated position is returned. When called with `string const` objects a `char const &` is returned. The member function performs range-checking, raising an exception (that by default aborts the program) if an invalid index is passed.
- `string &append(InputIterator begin, InputIterator end):`
  the characters in the range defined by `begin` and `end` are appended to the current string object.
- `string &append(string const &argument, size_type apos, size_type an):`
  `argument` (or a substring) is appended to the current string object.
- `string &append(char const *argument, size_type an):`
  the first `an` characters of `argument` are appended to the string object.
- `string &append(size_type n, char ch):`
  `n` characters `ch` are appended to the current string object.
- `string &assign(string const &argument, size_type apos, size_type an):`
  `argument` (or a substring) is assigned to the string object. If `argument` is of type `char const *` and one additional argument is provided the second argument is interpreted as a value initializing `an`, using 0 to initialize `apos`.
- `string &assign(size_type n, char ch):`
  `n` characters `ch` are assigned to the current string object.
- `char &back():`
  returns a reference to the last `char` stored inside the string object. The result is undefined for empty strings.
- `string::iterator begin():`
  an iterator referring to the first character of the current string object is returned. With `const` string objects a `const_iterator` is returned.
- `size_type capacity() const:`
  the number of characters that can currently be stored in the string object without needing to resize it is returned.
- `string::const_iterator cbegin():`
  a `const_iterator` referring to the first character of the current string object is returned.
- `string::const_iterator cend():`
  a `const_iterator` referring to the end of the current string object is returned.
- `void clear():`
  the string's content is erased.
- `int compare(string const &argument) const:`
  the text stored in the current string object and the text stored in `argument` is compared using a lexicographical comparison using the ASCII character collating sequence. zero is returned if

the two strings have identical content, a negative value is returned if the text in the current object should be ordered *before* the text in `argument`; a positive value is returned if the text in the current object should be ordered *beyond* the text in `argument`.

- `int compare(size_t opos, size_t on, string const &argument) const`:
  a substring of the text stored in the current string object is compared to the text stored in `argument`. At most `on` characters starting at offset `opos` are compared to the text in `argument`.

- `int compare(size_t opos, size_t on, string const &argument, size_type apos, size_type an)`:
  a substring of the text stored in the current string object is compared to a substring of the text stored in `argument`. At most `on` characters of the current string object, starting at offset `opos`, are compared to at most `an` characters of `argument`, starting at offset `apos`. In this case `argument` *must* be a string object.

- `int compare(size_t opos, size_t on, char const *argument, size_t an)`:
  a substring of the text stored in the current string object is compared to a substring of the text stored in `argument`. At most `on` characters of the current string object starting at offset `opos` are compared to at most `an` characters of `argument`. `Argument` must have at least `an` characters. The characters may have arbitrary values: 0-valued characters have no special meanings.

- `size_t copy(char *argument, size_t on, size_type opos) const`:
  the content of the current string object are (partially) copied into `argument`. The actual number of characters copied is returned. The second argument, specifying the number of characters to copy, from the current string object is required. No 0-valued character is appended to the copied string but can be appended to the copied text using an idiom like the following:

  ```
  argument[object.copy(argument, string::npos)] = 0;
  ```

  Of course, the programmer should make sure that `argument`'s size is large enough to accommodate the additional 0-byte.

- `string::const_reverse_iterator crbegin()`:
  a `const_reverse_iterator` referring to the last character of the current string object is returned.

- `string::const_reverse_iterator crend()`:
  a `const_reverse_iterator` referring to the begin of the current string object is returned.

- `char const *c_str() const`:
  the content of the current string object as an NTBS.

- `char const *data() const`:
  the raw content of the current string object are returned. Since this member does not return an NTBS (as `c_str` does), it can be used to retrieve any kind of information stored inside the current string object including, e.g., series of 0-bytes:

  ```
  string s(2, 0);
  cout << static_cast<int>(s.data()[1]) << '\n';
  ```

- `bool empty() const`:
  `true` is returned if the current string object contains no data.

- `string::iterator end()`:
  an iterator referring to the position just beyond the last character of the current string object is returned. With `const` string objects a `const_iterator` is returned.

- `string &erase(size_type opos, size_type on)`:
  a (sub)string of the information stored in the current string object is erased.

- `string::iterator erase(string::iterator begin, string::iterator end)`:
  the parameter `end` is optional. If omitted the value returned by the current object's `end` member is used. The characters defined by the `begin` and `end` iterators are erased. The iterator `begin` is returned, which is then referring to the position immediately following the last erased character.

- `size_t find(string const &argument, size_type opos) const`:
  the first index in the current string object is returned where `argument` is found.

- `size_t find(char const *argument, size_type opos, size_type an) const`:
  the first index in the current string object is returned where `argument` is found. When all three arguments are specified the first argument *must* be a `char const *`.

- `size_t find(char ch, size_type opos) const`:
  the first index in the current string object is returned where `ch` is found.

- `size_t find_first_of(string const &argument, size_type opos) const`:
  the first index in the current string object is returned whose character matches any character from `argument`.

- `size_type find_first_of(char const *argument, size_type opos, size_type an) const`:
  the first index in the current string object is returned whose character matches any character from `argument`. If `opos` is provided it refers to the first index in the current string object where the search for `argument` should start. If omitted, the string object is completely scanned. If `an` is provided it indicates the number of characters of the `char const *` argument that should be used in the search. It defines a substring starting at the beginning of `argument`. If omitted, all of `argument`'s characters are used.

- `size_type find_first_of(char ch, size_type opos)`:
  the first index in the current string object is returned whose character is equal to `ch`.

- `size_t find_first_not_of(string const &argument, size_type opos) const`:
  the first index in the current string object is returned whose character does not match any character from `argument`.

- `size_type find_first_not_of(char const *argument, size_type opos, size_type an) const`:
  the first index in the current string object is returned whose character does not match any character from `argument`. The `opos` and `an` parameters are handled as with `find_first_of`

- `size_t find_first_not_of(char ch, size_type opos) const`:
  the first index in the current string object is returned whose character is unequal to `ch`.

- `size_t find_last_of(string const &argument, size_type opos) const`:
  the last index in the current string object is returned whose character matches any character from `argument`.

- `size_type find_last_of(char const *argument, size_type opos, size_type an) const`:
  the last index in the current string object is returned whose character matches any character from `argument`. If `opos` is provided it refers to the last index in the current string object where the search for `argument` should start (searching backward towards the beginning of the current object). If omitted, the string object is scanned completely. If `an` is provided it indicates the number of characters of the `char const *` argument that should be used in the search. It defines a substring starting at the beginning of `argument`. If omitted, all of `argument`'s characters are used.

- `size_type find_last_of(char ch, size_type opos)`:
  the last index in the current string object is returned whose character is equal to `ch`.

- `size_t find_last_not_of(string const &argument, size_type opos) const`:
  the last index in the current string object is returned whose character does not match any character from `argument`.

- `size_type find_last_not_of(char const *argument, size_type opos, size_type an) const`:
  the last index in the current string object is returned whose character does not match any character from `argument`. The `opos` and `an` parameters are handled as with `find_last_of`.

- `size_t find_last_not_of(char ch, size_type opos) const`:
  the last index in the current string object is returned whose character is unequal to `ch`.

- `char &front()`:
  returns a reference to the first `char` stored inside the string object. The result is undefined for empty strings.

- `allocator_type get_allocator()`:
  returns the allocator of the class `std::string`

- `istream &std::getline(istream &istr, string &object, char delimiter = '\n')`:
  Note: this is *not* a member function of the class `string`.
  A line of text is read from `istr`. All characters until `delimiter` (or the end of the stream, whichever comes first) are read from `istr` and are stored in `object`. If the delimiter is encountered it is removed from the stream, but is not stored in `object`.
  If the delimiter is not found, `istr.eof` returns `true` (see section 6.3.1). Since streams may be interpreted as `bool` values (cf. section 6.3.1) a commonly encountered idiom to read all lines from a stream successively into a string object `line` looks like this:

  ```
  while (getline(istr, line))
      process(line);
  ```

  The content of the last line, whether or not it was terminated by a delimiter, is eventually also assigned to `object`.

- `string &insert(size_t opos, string const &argument, size_type apos, size_type an)`:
  a (sub)string of `argument` is inserted into the current string object at the current string object’s index position `opos`. Arguments for `apos` and `an` must either both be provided or they must both be omitted.

- `string &insert(size_t opos, char const *argument, size_type an)`:
  `argument` (of type `char const *`) is inserted at index `opos` into the current string object.

- `string &insert(size_t opos, size_t count, char ch)`:
  `Count` characters `ch` are inserted at index `opos` into the current string object.

- `string::iterator insert(string::iterator begin, char ch)`:
  the character `ch` is inserted at the current object’s position referred to by `begin`. `Begin` is returned.

- `string::iterator insert(string::iterator begin, size_t count, char ch)`:
  `Count` characters `ch` are inserted at the current object’s position referred to by `begin`. `Begin` is returned.

- `string::iterator insert(string::iterator begin, InputIterator abegin, InputIterator aend)`:
  the characters in the range defined by the `InputIterators` `abegin` and `aend` are inserted at the current object’s position referred to by `begin`. `Begin` is returned.

- `size_t length() const`:
  the number of characters stored in the current string object is returned.

- `size_t max_size() const`:
  the maximum number of characters that can be stored in the current string object is returned.

- `void pop_back()`:
  The string's last character is removed from the string object.

- `void push_back(char ch)`:
  The character `ch` is appended to the string object.

- `string::reverse_iterator rbegin()`:
  a reverse iterator referring to the last character of the current string object is returned. With `const` string objects a `reverse_const_iterator` is returned.

- `string::reverse_iterator rend()`:
  a reverse iterator referring to the position just before the first character of the current string object is returned. With `const` string objects a `reverse_const_iterator` is returned.

- `string &replace(size_t opos, size_t on, string const &argument, size_type apos, size_type an)`:
  a (sub)string of characters in `object` are replaced by the (subset of) characters of `argument`. If `on` is specified as 0 `argument` is inserted into `object` at offset `opos`.

- `string &replace(size_t opos, size_t on, char const *argument, size_type an)`:
  a series of characters in `object` are replaced by the first `an` characters of `char const *` argument.

- `string &replace(size_t opos, size_t on, size_type count, char ch)`:
  `on` characters of the current string object, starting at index position `opos`, are replaced by `count` characters `ch`.

- `string &replace(string::iterator begin, string::iterator end, string const &argument)`:
  the series of characters in the current string object defined by the iterators `begin` and `end` are replaced by `argument`. If `argument` is a `char const *`, an additional argument `an` may be used, specifying the number of characters of `argument` that are used in the replacement.

- `string &replace(string::iterator begin, string::iterator end, size_type count, char ch)`:
  the series of characters in the current string object defined by the iterators `begin` and `end` are replaced by `count` characters having values `ch`.

- `string &replace(string::iterator begin, string::iterator end, InputIterator abegin, InputIterator aend)`:
  the series of characters in the current string object defined by the iterators `begin` and `end` are replaced by the characters in the range defined by the `InputIterators abegin` and `aend`.

- `void reserve(size_t request)`:
  the current string object's capacity is changed to at least `request`. After calling this member, `capacity`'s return value will be at least `request`. A request for a smaller size than the value returned by `capacity` is ignored. A `std::length_error` exception is thrown if `request` exceeds the value returned by `max_size` (`std::length_error` is defined in the `stdexcept` header). Calling `reserve()` has the effect of redefining a string's capacity: when enlarging the capacity extra memory is allocated, but not immediately available to the program. This is illustrated by the exception thrown by the string's `at()` member when trying to access an element exceeding the string's `size` but not the string's `capacity`.

- `void resize(size_t size, char ch = 0)`:
  the current string object is resized to `size` characters. If the string object is resized to a size larger than its current size the additional characters will be initialized to `ch`. If it is reduced in size the characters having the highest indices are chopped off.

- `size_t rfind(string const &argument, size_type opos) const`:
  the last index in the current string object where `argument` is found is returned. Searching proceeds from the current object’s offset `opos` back to its beginning.

- `size_t rfind(char const *argument, size_type opos, size_type an) const`:
  the last index in the current string object where `argument` is found is returned. Searching proceeds from the current object’s offset `opos` back to its beginning. The parameter `an` specifies the length of the substring of `argument` to look for, starting at `argument`’s beginning.

- `size_t rfind(char ch, size_type opos)const`:
  the last index in the current string object where `ch` is found is returned. Searching proceeds from the current object’s offset `opos` back to its beginning.

- `void shrink_to_fit()`:
  optionally reduces the amount of memory allocated by a vector to its current size. The implementor is free to ignore or otherwise optimize this request. In order to guarantee a ‘shrink to fit’ operation the

  ```
  string{ stringObject }.swap(stringObject)
  ```

  idiom can be used.

- `size_t size() const`:
  the number of characters stored in the current string object is returned. This member is a synonym of `length()`.

- `string substr(size_type opos, size_type on) const`:
  a substring of the current string object of at most `on` characters starting at index `opos` is returned.

- `void swap(string &argument)`:
  the content of the current string object are swapped with the content of `argument`. For this member `argument` must be a string object and cannot be a `char const *`.

5.2.5 Conversion functions

Several string conversion functions are available operating on or producing `std::string` objects. These functions are listed below in alphabetic order. They are not member functions, but class-less (free) functions declared in the `std` namespace. The `<string>` header file must be included before they can be used.

- `float stof(std::string const &str, size_t *pos = 0)`:
  Initial whitespace characters in `str` are ignored. Then the following sequences of characters are converted to a `float` value, which is returned:
  - A decimal floating point constant:
    - An optional + or - character
    - A series of decimal digits, possibly containing one decimal point character
    - An optional e or E character, followed by an optional - or + character, followed by a series of decimal digits

  - A hexadecimal floating point constant:
    - An optional + or - character
    - 0x or 0X
    - A series of hexadecimal digits, possibly containing one decimal point character
    - An optional p or P character, followed by an optional - or + character, followed by a series of decimal digits
  - An infinity expression:
    - An optional + or - character
    - The words `inf` or `infinity` (case insensitive words)
  - A 'not a number' expression:
    - An optional + or - character
    - The words `nan` or `nan(alphanumeric character sequence)` (`nan` is a case insensitive word), resulting in a `NaN` floating point value

  If `pos != 0` the index of the first character in `str` which was not converted is returned in `*pos`. A `std::invalid_argument` exception is thrown if the characters in `str` could not be converted to a `float`, a `std::out_of_range` exception is thrown if the converted value would have exceeded the range of `float` values.

- `double stod(std::string const &str, size_t *pos = 0)`:
  A conversion as described with `stof` is performed, but now to a value of type `double`.

- `double stold(std::string const &str, size_t *pos = 0)`:
  A conversion as described with `stof` is performed, but now to a value of type `long double`.

- `int stoi(std::string const &str, size_t *pos = 0, int base = 10)`:
  Initial whitespace characters in `str` are ignored. Then all characters representing numeric constants of the number system whose `base` is specified are converted to an `int` value, which is returned. An optional + or - character may prefix the numeric characters. Values starting with 0 are automatically interpreted as octal values, values starting with 0x or 0X as hexadecimal characters. The value `base` must be between 2 and 36. If `pos != 0` the index of the first character in `str` which was not converted is returned in `*pos`. A `std::invalid_argument` exception is thrown if the characters in `str` could not be converted to an `int`, a `std::out_of_range` exception is thrown if the converted value would have exceeded the range of `int` values.

  Here is an example of its use:

  ```
  int value = stoi(" -123"s);  // assigns value -123
  value = stoi(" 123"s, 0, 5); // assigns value 38
  ```

- `long stol(std::string const &str, size_t *pos = 0, int base = 10)`:
  A conversion as described with `stoi` is performed, but now to a value of type `long`.

- `long long stoll(std::string const &str, size_t *pos = 0, int base = 10)`:
  A conversion as described with `stoi` is performed, but now to a value of type `long long`.

- `unsigned long stoul(std::string const &str, size_t *pos = 0, int base = 10)`:
  A conversion as described with `stoi` is performed, but now to a value of type `unsigned long`.

- `unsigned long long stoull(std::string const &str, size_t *pos = 0, int base = 10)`:
  A conversion as described with `stoul` is performed, but now to a value of type `unsigned long long`.

- `std::string to_string(Type value)`:
  Type can be of the types `int`, `long`, `long long`, `unsigned`, `unsigned long`, `unsigned long long`, `float`, `double`, or `long double`. The value of the argument is converted to a textual representation, which is returned as a `std::string` value.
- `std::wstring to_wstring(Type value)`:
  The conversion as described at `to_string` is performed, returning a `std::wstring`.

Chapter 6

The IO-stream Library

Extending the standard stream (`FILE`) approach, well known from the **C** programming language, **C++** offers an *input/output* (I/O) library based on `class` concepts.

All **C++** I/O facilities are defined in the namespace `std`. The `std::` prefix is omitted below, except for situations where this would result in ambiguities.

Earlier (in chapter 3) we've seen several examples of the use of the **C++** I/O library, in particular showing insertion operator (<<) and the extraction operator (>>). In this chapter we'll cover I/O in more detail.

The discussion of input and output facilities provided by the **C++** programming language heavily uses the `class` concept and the notion of member functions. Although class construction has not yet been covered (for that see chapter 7) and although *inheritance* is not covered formally before chapter 13, it is quite possible to discuss I/O facilities long before the technical background of class construction has been covered.

Most **C++** I/O classes have names starting with `basic_` (like `basic_ios`). However, these `basic_` names are not regularly found in **C++** programs, as most classes are also defined using `typedef` definitions like:

```
        typedef basic_ios<char>       ios;
```

Since **C++** supports various kinds of character types (e.g., `char`, `wchar_t`), I/O facilities were developed using the *template* mechanism allowing for easy conversions to character types other than the traditional `char` type. As elaborated in chapter 21, this also allows the construction of generic software, that could thereupon be used for any particular type representing characters. So, analogously to the above `typedef` there exists a

```
        typedef basic_ios<wchar_t>    wios;
```

This type definition can be used for the `wchar_t` type. Because of the existence of these type definitions, the `basic_` prefix was omitted from the **C++** Annotations without loss of continuity. The **C++** Annotations primarily focus on the standard 8-bits `char` type.

Iostream objects can*not* be declared using standard forward declarations, like:

```
    class std::ostream;     // now erroneous
```

Instead, to declare iostream classes the `<iosfwd>` header file should be included:

```
#include <iosfwd>       // correct way to declare iostream classes
```

Using **C++** I/O offers the additional advantage of *type safety*. Objects (or plain values) are inserted into streams. Compare this to the situation commonly encountered in **C** where the `fprintf` function is used to indicate by a format string what kind of value to expect where. Compared to this latter situation **C++**'s *iostream* approach immediately uses the objects where their values should appear, as in

```
cout << "There were " << nMaidens << " virgins present\n";
```

The compiler notices the type of the `nMaidens` variable, inserting its proper value at the appropriate place in the sentence inserted into the `cout` iostream.

Compare this to the situation encountered in **C**. Although **C** compilers are getting smarter and smarter, and although a well-designed **C** compiler may warn you for a mismatch between a format specifier and the type of a variable encountered in the corresponding position of the argument list of a `printf` statement, it can't do much more than *warn* you. The *type safety* seen in **C++** *prevents* you from making type mismatches, as there are no types to match.

Apart from this, *iostreams* offer more or less the same set of possibilities as the standard `FILE`-based I/O used in **C**: files can be opened, closed, positioned, read, written, etc.. In **C++** the basic `FILE` structure, as used in **C**, is still available. But **C++** adds to this I/O based on classes, resulting in type safety, extensibility, and a clean design.

In the ANSI/ISO standard the intent was to create architecture independent I/O. Previous implementations of the iostreams library did not always comply with the standard, resulting in many extensions to the standard. The I/O sections of previously developed software may have to be partially rewritten. This is tough for those who are now forced to modify old software, but every feature and extension that was once available can be rebuilt easily using ANSI/ISO standard conforming I/O. Not all of these reimplementations can be covered in this chapter, as many reimplementations rely on inheritance and polymorphism, which topics are formally covered by chapters 13 and 14. Selected reimplementations are provided in chapter 25, and in this chapter references to particular sections in other chapters are given where appropriate. This chapter is organized as follows (see also Figure 6.1):

- The `class ios_base` is the foundation upon which the iostreams I/O library was built. It defines the core of all I/O operations and offers, among other things, facilities for inspecting the state of I/O streams and for output formatting.

- The class `ios` was directly derived from `ios_base`. Every class of the I/O library doing input or output is itself *derived* from this `ios` class, and so *inherits* its (and, by implication, `ios_base`'s) capabilities. The reader is urged to keep this in mind while reading this chapter. The concept of inheritance is not discussed here, but rather in chapter 13.

  The class `ios` is important in that it implements the communication with a *buffer* that is used by streams. This buffer is a `streambuf` object which is responsible for the actual I/O to/from the underlying *device*. Consequently `iostream` objects do not perform I/O operations themselves, but leave these to the (stream)buffer objects with which they are associated.

- Next, basic **C++** output facilities are discussed. The basic class used for output operations is `ostream`, defining the insertion operator as well as other facilities writing information to streams. Apart from inserting information into files it is possible to insert information into memory buffers, for which the `ostringstream` class is available. Formatting output is to a great extent possible using the facilities defined in the `ios` class, but it is also possible to *insert formatting commands* directly into streams using *manipulators*. This aspect of **C++** output is discussed as well.

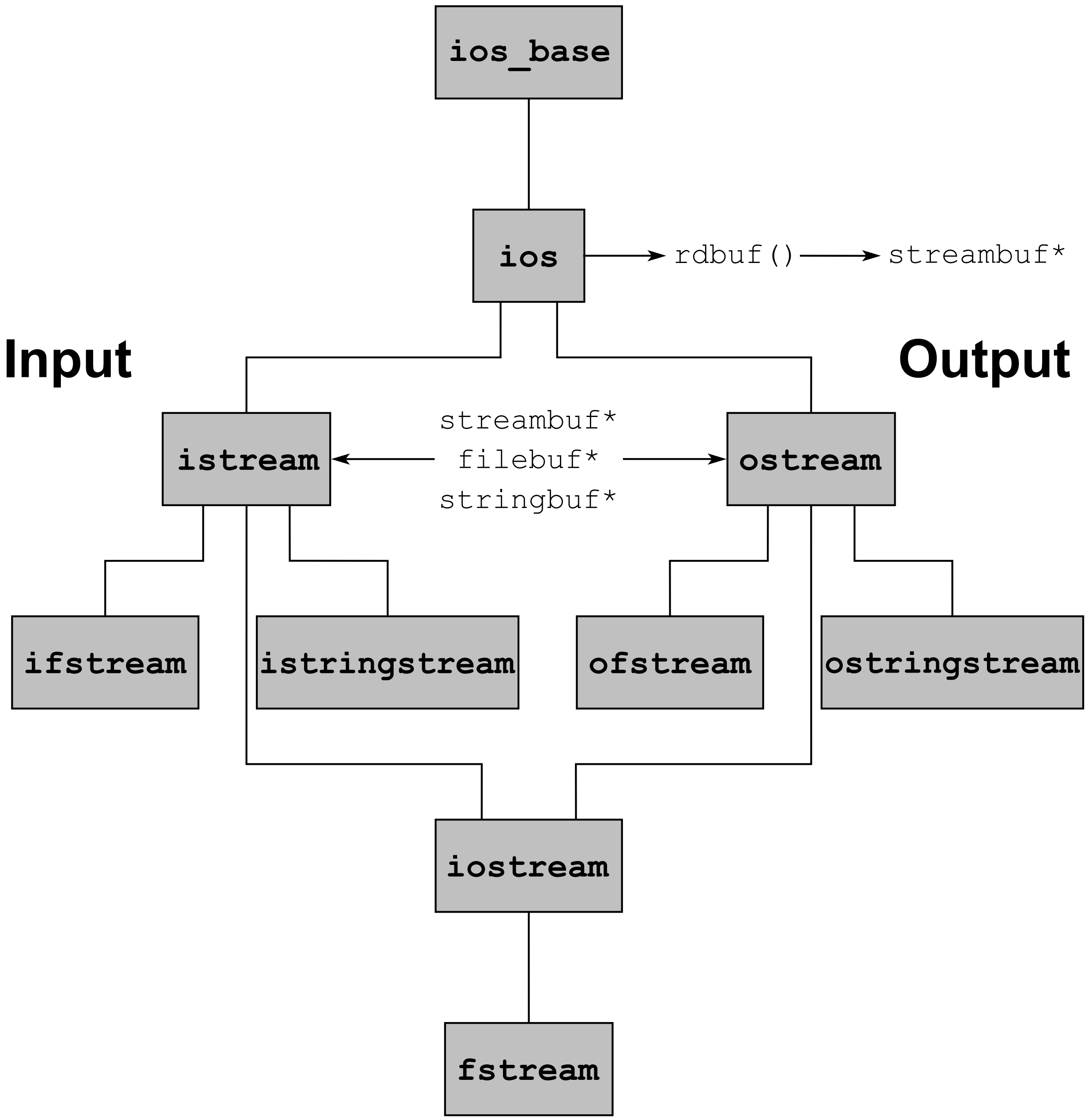
ios_base
ios
rdbuf()
streambuf*
Input
Output
istream
streambuf*
filebuf*
stringbuf*
ostream
ifstream
istringstream
ofstream
ostringstream
iostream
fstream

Figure 6.1: Central I/O Classes

- Basic **C++** input facilities are implemented by the `istream` class. This class defines the extraction operator and related input facilities. Comparably to inserting information into memory buffers (using `ostringstream`) a class `istringstream` is available to extract information from memory buffers.
- Finally, several advanced I/O-related topics are discussed. E.g., reading and writing from the same stream and mixing **C** and **C++** I/O using `filebuf` objects. Other I/O related topics are covered elsewhere in the **C++** Annotations, e.g., in chapter 25.

Stream objects have a limited but important role: they are the interface between, on the one hand, the objects to be input or output and, on the other hand, the `streambuf`, which is responsible for the actual input and output to the device accessed by a `streambuf` object.

This approach allows us to construct a new kind of `streambuf` for a new kind of device, and use that streambuf in combination with the 'good old' `istream`- and `ostream`-class facilities. It is important to understand the distinction between the formatting roles of iostream objects and the buffering interface to an external device as implemented in a `streambuf` object. Interfacing to new devices (like *sockets* or *file descriptors*) requires the construction of a new kind of `streambuf`, rather than a new kind of `istream` or `ostream` object. A *wrapper class* may be constructed around the `istream` or `ostream` classes, though, to ease the access to a special device. This is how the stringstream classes were constructed.

6.1 Special header files

Several iostream related header files are available. Depending on the situation at hand, the following header files should be used:

- `iosfwd`: sources should include this header file if only a declaration of the stream classes is required. For example, if a function defines a reference parameter to an `ostream` then the compiler does not need to know exactly what an `ostream` is. When declaring such a function the `ostream` class merely needs to be be declared. One cannot use

  ```
  class std::ostream; // erroneous declaration

  void someFunction(std::ostream &str);
  ```

  but, instead, one should use:

  ```
  #include <iosfwd>   // correctly declares class ostream

  void someFunction(std::ostream &str);
  ```

- `<ios>`: sources should include this header file when using types and facilites (like `ios::off_type`, see below) defined in the `ios` class.
- `<streambuf>`: sources should include this header file when using `streambuf` or `filebuf` classes. See sections 14.8 and 14.8.2.
- `<istream>`: sources should include this preprocessor directive when using the class `istream` or when using classes that do both input and output. See section 6.5.1.
- `<ostream>`: sources should include this header file when using the class `ostream` class or when using classes that do both input and output. See section 6.4.1.
- `<iostream>`: sources should include this header file when using the global stream objects (like `cin` and `cout`).

- `<fstream>`: sources should include this header file when using the file stream classes. See sections 6.4.2, 6.5.2, and 6.6.3.
- `<sstream>`: sources should include this header file when using the string stream classes. See sections 6.4.3 and 6.5.3.
- `<iomanip>`: sources should include this header file when using parameterized manipulators. See section 6.3.2.

6.2 The foundation: the class 'ios_base'

The class `std::ios_base` forms the foundation of all I/O operations, and defines, among other things, facilities for inspecting the state of I/O streams and most output formatting facilities. Every stream class of the I/O library is, through the class `ios`, *derived* from this class, and *inherits* its capabilities. As `ios_base` is the foundation on which all **C++** I/O was built, we introduce it here as the first class of the **C++** I/O library.

Note that, as in **C**, I/O in **C++** is *not* part of the language (although it *is* part of the ANSI/ISO standard on **C++**). Although it is technically possible to ignore all predefined I/O facilities, nobody does so, and the I/O library therefore represents a *de facto* I/O standard for **C++**. Also note that, as mentioned before, the iostream classes themselves are not responsible for the eventual I/O, but delegate this to an auxiliary class: the class `streambuf` or its derivatives.

It is neither possible nor required to construct an `ios_base` object directly. Its construction is always a side-effect of constructing an object further down the class hierarchy, like `std::ios`. `Ios` is the next class down the iostream hierarchy (see Figure 6.1). Since all stream classes in turn inherit from `ios`, and thus also from `ios_base`, the distinction between `ios_base` and `ios` is in practice not important. Therefore, facilities actually provided by `ios_base` will be discussed as facilities provided by `ios`. The reader who is interested in the true class in which a particular facility is defined should consult the relevant header files (e.g., `ios_base.h` and `basic_ios.h`).

6.3 Interfacing 'streambuf' objects: the class 'ios'

The `std::ios` class is derived directly from `ios_base`, and it defines *de facto* the foundation for all stream classes of the **C++** I/O library.

Although it *is* possible to construct an `ios` object directly, this is seldom done. The purpose of the class `ios` is to provide the facilities of the class `basic_ios`, and to add several new facilites, all related to the `streambuf` object which is managed by objects of the class `ios`.

All other stream classes are either directly or indirectly derived from `ios`. This implies, as explained in chapter 13, that all facilities of the classes `ios` and `ios_base` are also available to other stream classes. Before discussing these additional stream classes, the features offered by the class `ios` (and by implication: by `ios_base`) are now introduced.

In some cases it may be required to include `ios` explicitly. An example is the situations where the formatting flags themselves (cf. section 6.3.2.2) are referred to in source code.

The class `ios` offers several member functions, most of which are related to formatting. Other frequently used member functions are:

- `std::streambuf *ios::rdbuf()`:
  A pointer to the `streambuf` object forming the interface between the `ios` object and the device

with which the `ios` object communicates is returned. See sections 14.8 and 25.1.2 for more information about the `class streambuf`.

- `std::streambuf *ios::rdbuf(std::streambuf *new):`

  The current `ios` object is associated with another `streambuf` object. A pointer to the `ios` object's original `streambuf` object is returned. The object to which this pointer points is not destroyed when the `stream` object goes out of scope, but is owned by the caller of `rdbuf`.

- `std::ostream *ios::tie():`
  A pointer to the `ostream` object that is currently tied to the `ios` object is returned (see the next member). The return value 0 indicates that currently no `ostream` object is tied to the `ios` object. See section 6.5.5 for details.

- `std::ostream *ios::tie(std::ostream *outs):`

  The ostream object is tied to current `ios` object. This means that the `ostream` object is *flushed* every time before an input or output action is performed by the current `ios` object. A pointer to the `ios` object's original `ostream` object is returned. To break the tie, pass the argument 0. See section 6.5.5 for an example.

6.3.1 Condition states

Operations on streams may fail for various reasons. Whenever an operation fails, further operations on the stream are suspended. It is possible to inspect, set and possibly clear the condition state of streams, allowing a program to repair the problem rather than having to abort. The members that are available for interrogating or manipulating the stream's state are described in the current section.

Conditions are represented by the following *condition flags*:

- `ios::badbit`:
  if this flag has been raised an illegal operation has been requested at the level of the `streambuf` object to which the stream interfaces. See the member functions below for some examples.
- `ios::eofbit`:
  if this flag has been raised, the `ios` object has sensed end of file.
- `ios::failbit`:
  if this flag has been raised, an operation performed by the stream object has failed (like an attempt to extract an `int` when no numeric characters are available on input). In this case the stream itself could not perform the operation that was requested of it.
- `ios::goodbit`:
  this flag is raised when none of the other three condition flags were raised.

Several condition member functions are available to manipulate or determine the states of `ios` objects. Originally they returned `int` values, but their current return type is `bool`:

- `bool ios::bad():`

  the value `true` is returned when the stream's `badbit` has been set and `false` otherwise. If `true` is returned it indicates that an illegal operation has been requested at the level of the `streambuf` object to which the stream interfaces. What does this mean? It indicates that the `streambuf` itself is behaving unexpectedly. Consider the following example:

  ```
  std::ostream error(0);
  ```

Here an `ostream` object is constructed *without* providing it with a working `streambuf` object. Since this ‘`streambuf`’ will never operate properly, its `badbit` flag is raised from the very beginning: `error.bad()` returns `true`.

- `bool ios::eof()`:

  the value `true` is returned when end of file (`EOF`) has been sensed (i.e., the `eofbit` flag has been set) and `false` otherwise. Assume we’re reading lines line-by-line from `cin`, but the last line is not terminated by a final `\n` character. In that case `std::getline` attempting to read the `\n` delimiter hits end-of-file first. This raises the `eofbit` flag and `cin.eof()` returns `true`. For example, assume `std::string str` and `main` executing the statements:

  ```
  getline(cin, str);
  cout << cin.eof();
  ```

  Then

  ```
  echo "hello world" | program
  ```

  prints the value 0 (no EOF sensed). But after

  ```
  echo -n "hello world" | program
  ```

  the value 1 (EOF sensed) is printed.

- `bool ios::fail()`:

  the value `true` is returned when `bad` returns `true` or when the `failbit` flag was set. The value `false` is returned otherwise. In the above example, `cin.fail()` returns `false`, whether we terminate the final line with a delimiter or not (as we’ve read a line). However, executing *another* `getline` results in raising the `failbit` flag, causing `cin::fail()` to return `true`. In general: `fail` returns `true` if the requested stream operation failed. A simple example showing this consists of an attempt to extract an `int` when the input stream contains the text `hello world`. The value `not fail()` is returned by the `bool` interpretation of a stream object (see below).

- `ios::good()`:

  the value of the `goodbit` flag is returned. It equals `true` when none of the other condition flags (`badbit, eofbit, failbit`) was raised. Consider the following little program:

  ```
  #include <iostream>
  #include <string>

  using namespace std;

  void state()
  {
      cout << "\n"
              "Bad: " << cin.bad() << " "
              "Fail: " << cin.fail() << " "
              "Eof: " << cin.eof() << " "
              "Good: " << cin.good() << '\n';
  }

  int main()
  {
      string line;
  ```

```
    int x;

    cin >> x;
    state();

    cin.clear();
    getline(cin, line);
    state();

    getline(cin, line);
    state();
}
```

When this program processes a file having two lines, containing, respectively, `hello` and `world`, while the second line is not terminated by a `\n` character the following is shown:

```
    Bad: 0 Fail: 1 Eof: 0 Good: 0

    Bad: 0 Fail: 0 Eof: 0 Good: 1

    Bad: 0 Fail: 0 Eof: 1 Good: 0
```

Thus, extracting `x` fails (`good` returning `false`). Then, the error state is cleared, and the first line is successfully read (`good` returning `true`). Finally the second line is read (incompletely): `good` returning `false`, and `eof` returning `true`.

- Interpreting streams as `bool` values:

  streams may be used in expressions expecting logical values. Some examples are:

  ```
  if (cin)                // cin itself interpreted as bool
  if (cin >> x)           // cin interpreted as bool after an extraction
  if (getline(cin, str))  // getline returning cin
  ```

  When interpreting a stream as a logical value, it is actually '`not fail()`' that is interpreted. The above examples may therefore be rewritten as:

  ```
  if (not cin.fail())
  if (not (cin >> x).fail())
  if (not getline(cin, str).fail())
  ```

  The former incantation, however, is used almost exclusively.

The following members are available to manage error states:

- `void ios::clear()`:

  When an error condition has occurred, and the condition can be repaired, then `clear` can be used to clear the error state of the file. An overloaded version exists accepting state flags, that are set after first clearing the current set of flags: `clear(int state)`. Its return type is `void`

- `ios::iostate ios::rdstate()`:

  The current set of flags that are set for an `ios` object are returned (as an `int`). To test for a particular flag, use the bitwise and operator:

  ```
  if (!(iosObject.rdstate() & ios::failbit))
  {
      // last operation didn't fail
  }
  ```

Note that this test cannot be performed for the `goodbit` flag as its value equals zero. To test for ‘good’ use a construction like:

```
if (iosObject.rdstate() == ios::goodbit)
{
    // state is `good'
}
```

- `void ios::setstate(ios::iostate state)`:

  A stream may be assigned a certain set of states using `setstate`. Its return type is `void`. E.g.,

  ```
  cin.setstate(ios::failbit);     // set state to `fail'
  ```

  To set multiple flags in one `setstate()` call use the `bitor` operator:

  ```
  cin.setstate(ios::failbit | ios::eofbit)
  ```

  The member `clear` is a shortcut to clear all error flags. Of course, clearing the flags doesn’t automatically mean the error condition has been cleared too. The strategy should be:

  - An error condition is detected,
  - The error is repaired
  - The member `clear` is called.

C++ supports an *exception* mechanism to handle exceptional situations. According to the ANSI/ISO standard, exceptions can be used with stream objects. Exceptions are covered in chapter 10. Using exceptions with stream objects is covered in section 10.7.

6.3.2 Formatting output and input

The way information is written to streams (or, occasionally, read from streams) is controlled by *formatting flags*.

Formatting is used when it is necessary to, e.g., set the width of an output field or input buffer and to determine the form (e.g., the *radix*) in which values are displayed. Most formatting features belong to the realm of the `ios` class. Formatting is controlled by flags, defined by the `ios` class. These flags may be manipulated in two ways: using specialized member functions or using *manipulators*, which are directly inserted into or extracted from streams. There is no special reason for using either method; usually both methods are possible. In the following overview the various member functions are first introduced. Following this the flags and manipulators themselves are covered. Examples are provided showing how the flags can be manipulated and what their effects are.

Many manipulators are parameterless and are available once a stream header file (e.g., `iostream`) has been included. Some manipulators require arguments. To use the latter manipulators the header file `iomanip` must be included.

6.3.2.1 Format modifying member functions

Several *member functions* are available manipulating the I/O formatting flags. Instead of using the members listed below *manipulators* are often available that may directly be inserted into or extracted from streams. The available members are listed in alphabetical order, but the most important ones in practice are setf, unsetf and width.

- `ios &ios::copyfmt(ios &obj)`:
  all format flags of `obj` are copied to the current `ios` object. The current `ios` object is returned.

- `ios::fill() const`:
  the current padding character is returned. By default, this is the blank space.

- `ios::fill(char padding)`:

  the padding character is redefined, the padding character that was used before the redefinition is returned. Instead of using this member function the `setfill` *manipulator* may be inserted directly into an `ostream`. Example:

  ```
  cout.fill('0');          // use '0' as padding char
  cout << setfill('+');    // use '+' as padding char
  ```

- `ios::fmtflags ios::flags() const`:
  the current set of flags controlling the format state of the stream for which the member function is called is returned. To inspect whether a particular flag was set, use the `bit_and` operator. Example:

  ```
  if (cout.flags() & ios::hex)
      cout << "Integral values are printed as hex numbers\n"
  ```

- `ios::fmtflags ios::flags(ios::fmtflags flagset)`:

  the *previous* set of flags are returned and the new set of flags are defined by `flagset`. Multiple flags are specified using the `bitor` operator. Example:

  ```
          // change the representation to hexadecimal
  cout.flags(ios::hex | cout.flags() & ~ios::dec);
  ```

- `int ios::precision() const`:
  the number of significant digits used when outputting floating point values is returned (default: 6).

- `int ios::precision(int signif)`:

  the number of significant digits to use when outputting real values is set to `signif`. The previously used number of significant digits is returned. If the number of required digits exceeds `signif` then the number is displayed in ‘scientific’ notation (cf. section 6.3.2.2). Manipulator: `setprecision`. Example:

  ```
  cout.precision(3);          // 3 digits precision
  cout << setprecision(3);    // same, using the manipulator

  cout << 1.23 << " " << 12.3 << " " << 123.12 << " " << 1234.3 << '\n';
  // displays: 1.23 12.3 123 1.23e+03
  ```

- `ios::fmtflags ios::setf(ios::fmtflags flags)`:

  sets one or more formatting flags (use the `bitor` operator to combine multiple flags). Already set flags are not affected. The *previous* set of flags is returned. Instead of using this member function the manipulator `setiosflags` may be used. Examples are provided in the next section (6.3.2.2).

- `ios::fmtflags ios::setf(ios::fmtflags flags, ios::fmtflags mask)`:

  clears all flags mentioned in `mask` and sets the flags specified in `flags`. The *previous* set of flags is returned. Some examples are (but see the next section (6.3.2.2) for a more thorough discussion):

  ```
          // left-adjust information in wide fields:
  cout.setf(ios::left, ios::adjustfield);

          // display integral values as hexadecimal numbers:
  ```

```
cout.setf(ios::hex, ios::basefield);

        // display floating point values in scientific notation:
cout.setf(ios::scientific, ios::floatfield);
```

- `ios::fmtflags ios::unsetf(fmtflags flags)`:

  the specified formatting flags are cleared (leaving the remaining flags unaltered) and returns the *previous* set of flags. A request to unset an active default flag (e.g., `cout.unsetf(ios::dec)`) is ignored. Instead of this member function the manipulator `resetiosflags` may also be used. Example:

  ```
  cout << 12.24;              // displays  12.24
  cout.setf(ios::fixed);
  cout << 12.24;              // displays  12.240000
  cout.unsetf(ios::fixed);    // undo a previous ios::fixed setting.
  cout << 12.24;              // displays  12.24
  cout << resetiosflags(ios::fixed);  // using manipulator rather
                                      // than unsetf
  ```

- `int ios::width() const`:

  the currently active output field width to use on the next insertion is returned. The default value is 0, meaning ‘as many characters as needed to write the value’.

- `int ios::width(int nchars)`:

  the field width of the next insertion operation is set to `nchars`, returning the previously used field width. This setting is not persistent. It is reset to 0 after every insertion operation. Manipulator: `std::setw(int)`. Example:

  ```
  cout.width(5);
  cout << 12;                     // using 5 chars field width
  cout << setw(12) << "hello";    // using 12 chars field width
  ```

6.3.2.2 Formatting flags

Most *formatting flags* are related to outputting information. Information can be written to output streams in basically two ways: using *binary output* information is written directly to an output stream, without converting it first to some human-readable format and using *formatted output* by which values stored in the computer’s memory are converted to human-readable text first. Formatting flags are used to define the way this conversion takes place. In this section all formatting flags are covered. Formatting flags may be (un)set using member functions, but often manipulators having the same effect may also be used. For each of the flags it is shown how they can be controlled by a member function or -if available- a manipulator.

To display information in wide fields:

- `ios::internal`:

  to add fill characters (blanks by default) between the minus sign of negative numbers and the value itself. Other values and data types are right-adjusted. Manipulator: `std::internal`. Example:

  ```
  cout.setf(ios::internal, ios::adjustfield);
  cout << internal;       // same, using the manipulator

  cout << '\'' << setw(5) << -5 << "'\n";  // displays '-   5'
  ```

- `ios::left`:
  to left-adjust values in fields that are wider than needed to display the values. Manipulator: `std::left`. Example:

  ```
  cout.setf(ios::left, ios::adjustfield);
  cout << left;            // same, using the manipulator

  cout << '\'' << setw(5) << "hi" << "'\n";  // displays 'hi   '
  ```

- `ios::right`:
  to right-adjust values in fields that are wider than needed to display the values. Manipulator: `std::right`. This is the default. Example:

  ```
  cout.setf(ios::right, ios::adjustfield);
  cout << right;           // same, using the manipulator

  cout << '\'' << setw(5) << "hi" << "'\n";  // displays '   hi'
  ```

Using various number representations:

- `ios::dec`:
  to display integral values as decimal numbers. Manipulator: `std::dec`. This is the default. Example:

  ```
  cout.setf(ios::dec, ios::basefield);
  cout << dec;             // same, using the manipulator
  cout << 0x10;            // displays 16
  ```

- `ios::hex`:
  to display integral values as hexadecimal numbers. Manipulator: `std::hex`. Example:

  ```
  cout.setf(ios::hex, ios::basefield);
  cout << hex;             // same, using the manipulator
  cout << 16;              // displays 10
  ```

- `ios::oct`:
  to display integral values as octal numbers. Manipulator: `std::oct`. Example:

  ```
  cout.setf(ios::oct, ios::basefield);
  cout << oct;             // same, using the manipulator
  cout << 16;              // displays 20
  ```

- `std::setbase(int radix)`:
  This is a manipulator that can be used to change the number representation to decimal, hexadecimal or octal. Example:

  ```
  cout << setbase(8);      // octal numbers, use 10 for
                           // decimal, 16 for hexadecimal
  cout << 16;              // displays 20
  ```

Fine-tuning displaying values:

- `ios::boolalpha`:
  logical values may be displayed as text using the text '`true`' for the `true` logical value,

and '`false`' for the `false` logical value using `boolalpha`. By default this flag is not set. Complementary flag: `ios::noboolalpha`. Manipulators: `std::boolalpha` and `std::noboolalpha`. Example:

```
cout.setf(ios::boolalpha);
cout << boolalpha;       // same, using the manipulator
cout << (1 == 1);        // displays true
```

- `ios::showbase`:
  to display the numeric base of integral values. With hexadecimal values the `0x` prefix is used, with octal values the prefix `0`. For the (default) decimal value no particular prefix is used. Complementary flag: `ios::noshowbase`. Manipulators: `std::showbase` and `std::noshowbase`. Example:

```
cout.setf(ios::showbase);
cout << showbase;        // same, using the manipulator
cout << hex << 16;       // displays 0x10
```

- `ios::showpos`:
  to display the + sign with positive decimal (only) values. Complementary flag: `ios::noshowpos`. Manipulators: `std::showpos` and `std::noshowpos`. Example:

```
cout.setf(ios::showpos);
cout << showpos;             // same, using the manipulator
cout << 16;                  // displays +16
cout.unsetf(ios::showpos);   // Undo showpos
cout << 16;                  // displays 16
```

- `ios::uppercase`:
  to display letters in hexadecimal values using capital letters. Complementary flag: `ios::nouppercase`. Manipulators: `std::uppercase` and `std::nouppercase`. By default lower case letters are used. Example:

```
cout.setf(ios::uppercase);
cout << uppercase;             // same, using the manipulator
cout << hex << showbase <<
        3735928559;            // displays 0XDEADBEEF
```

Displaying floating point numbers

- `ios::fixed`:

  to display real values using a fixed decimal point (e.g., 12.25 rather than 1.225e+01), the `fixed` formatting flag is used. It can be used to set a fixed number of digits behind the decimal point. Manipulator: `fixed`. Example:

```
cout.setf(ios::fixed, ios::floatfield);
cout.precision(3);          // 3 digits behind the .

    // Alternatively:
cout << setiosflags(ios::fixed) << setprecision(3);

cout << 3.0 << " " << 3.01 << " " << 3.001 << '\n';
     << 3.0004 << " " << 3.0005 << " " << 3.0006 << '\n'
    // Results in:
    // 3.000 3.010 3.001
    // 3.000 3.001 3.001
```

The example shows that 3.0005 is rounded away from zero, becoming 3.001 (likewise -3.0005 becomes -3.001). First setting precision and then `fixed` has the same effect.

- `ios::scientific`:
  to display real values in *scientific notation* (e.g., 1.24e+03). Manipulator: `std::scientific`. Example:

  ```
  cout.setf(ios::scientific, ios::floatfield);
  cout << scientific;         // same, using the manipulator
  cout << 12.25;              // displays 1.22500e+01
  ```

- `ios::showpoint`:
  to display a trailing decimal point *and* trailing decimal zeros when real numbers are displayed. Complementary flag: `ios::noshowpoint`. Manipulators: `std::showpoint`, `std::noshowpoint`. Example:

  ```
  cout << fixed << setprecision(3);   // 3 digits behind .

  cout.setf(ios::showpoint);      // set the flag
  cout << showpoint;              // same, using the manipulator

  cout << 16.0 << ", " << 16.1 << ", " << 16;
  // displays: 16.000, 16.100, 16
  ```

  Note that the final 16 is an integral rather than a floating point number, so it has no decimal point. So `showpoint` has no effect. If `ios::showpoint` is not active trailing zeros are discarded. If the fraction is zero the decimal point is discarded as well. Example:

  ```
  cout.unsetf(ios::fixed, ios::showpoint);    // unset the flags

  cout << 16.0 << ", " << 16.1;
  // displays: 16, 16.1
  ```

Handling whitespace and flushing streams

- `std::endl`:
  manipulator inserting a newline character and flushing the stream. Often flushing the stream is not required and doing so would needlessly slow down I/O processing. Consequently, using `endl` should be avoided (in favor of inserting `'\n'`) unless flushing the stream is explicitly intended. Note that streams are automatically flushed when the program terminates or when a stream is 'tied' to another stream (cf. `tie` in section 6.3). Example:

  ```
  cout << "hello" << endl;    // prefer: << '\n';
  ```

- `std::ends`:
  manipulator inserting a 0-byte into a stream. It is usually used in combination with memory-streams (cf. section 6.4.3).

- `std::flush`:
  a stream may be flushed using this member. Often flushing the stream is not required and doing so would needlessly slow down I/O processing. Consequently, using `flush` should be avoided unless it is explicitly required to do so. Note that streams are automatically flushed when the program terminates or when a stream is 'tied' to another stream (cf. `tie` in section 6.3). Example:

  ```
  cout << "hello" << flush;    // avoid if possible.
  ```

- `ios::skipws`:
  leading whitespace characters (blanks, tabs, newlines, etc.) are skipped when a value is extracted from a stream. This is the default. If the flag is not set, leading whitespace characters are not skipped. Manipulator: `std::skipws`. Example:

  ```
  cin.setf(ios::skipws);  // to unset, use
                          //  cin.unsetf(ios::skipws)

  cin >> skipws;          // same, using the manipulator
  int value;
  cin >> value;           // skips initial blanks
  ```

- `ios::unitbuf`:
  the stream for which this flag is set flushes its buffer after every output operation Often flushing a stream is not required and doing so would needlessly slow down I/O processing. Consequently, setting `unitbuf` should be avoided unless flushing the stream is explicitly intended. Note that streams are automatically flushed when the program terminates or when a stream is 'tied' to another stream (cf. `tie` in section 6.3). Complementary flag: `ios::nounitbuf`. Manipulators: `std::unitbuf`, `std::nounitbuf`. Example:

  ```
  cout.setf(ios::unitbuf);
  cout << unitbuf;            // same, using the manipulator

  cout.write("xyz", 3);       // flush follows write.
  ```

- `std::ws`:
  manipulator removing all whitespace characters (blanks, tabs, newlines, etc.) at the current file position. White space characters are removed if present even if the flag `ios::noskipws` has been set. Example (assume the input contains 4 blank characters followed by the character `X`):

  ```
  cin >> ws;      // skip whitespace
  cin.get();      // returns 'X'
  ```

6.4 Output

In **C++** output is primarily based on the `std::ostream` class. The `ostream` class defines the basic operators and members inserting information into streams: the *insertion operator* (<<), and special members like `write` writing unformatted information to streams.

The class `ostream` acts as *base class* for several other classes, all offering the functionality of the `ostream` class, but adding their own specialties. In the upcoming sections the following classes are discussed:

- The class `ostream`, offering the basic output facilities;
- The class `ofstream`, allowing us to write files (comparable to **C**'s `fopen(filename, "w")`);
- The class `ostringstream`, allowing us to write information to memory (comparable to **C**'s `sprintf` function).

6.4.1 Basic output: the class 'ostream'

The class `ostream` defines basic output facilities. The `cout`, `clog` and `cerr` objects are all `ostream` objects. All facilities related to output as defined by the `ios` class are also available in the `ostream` class.

We may define `ostream` objects using the following *ostream constructor*:

- `std::ostream object(std::streambuf *sb)`:

  this constructor creates an `ostream` object which is a wrapper around an existing `std::streambuf` object. It isn't possible to define a plain `ostream` object (e.g., using `std::ostream out;`) that can thereupon be used for insertions. When `cout` or its friends are used, we are actually using a predefined `ostream` object that has already been defined for us and interfaces to the standard output stream using a (also predefined) `streambuf` object handling the actual interfacing.

  It *is*, however, possible to define an `ostream` object passing it a 0-pointer. Such an object cannot be used for insertions (i.e., it raises its `ios::bad` flag when something is inserted into it), but it may be given a `streambuf` later. Thus it may be preliminary constructed, suspending its use until an appropriate `streambuf` becomes available (see also section 14.8.3).

To define the `ostream` class in **C++** sources, the `<ostream>` header file must be included. To use the predefined `ostream` objects (`std::cerr, std::cout` etc.) the `<iostream>` header file must be included.

6.4.1.1 Writing to 'ostream' objects

The class `ostream` supports both formatted and *binary output*.

The *insertion operator* (<<) is used to insert values in a type safe way into `ostream` objects. This is called formatted output, as binary values which are stored in the computer's memory are converted to human-readable ASCII characters according to certain formatting rules.

The insertion operator points to the `ostream` object to receive the information. The normal associativity of << remains unaltered, so when a statement like

```
cout << "hello " << "world";
```

is encountered, the leftmost two operands are evaluated first (`cout << "hello "`), and an `ostream &` object, which is actually the same `cout` object, is returned. Now, the statement is reduced to

```
cout << "world";
```

and the second string is inserted into `cout`.

The << operator has a lot of (overloaded) variants, so many types of variables can be inserted into `ostream` objects. There is an overloaded <<-operator expecting an `int`, a `double`, a pointer, etc. etc.. Each operator returns the `ostream` object into which the information so far has been inserted, and can thus immediately be followed by the next insertion.

Streams lack facilities for formatted output like **C**'s `printf` and `vprintf` functions. Although it is not difficult to implement these facilities in the world of streams, `printf`-like functionality is hardly ever required in **C++** programs. Furthermore, as it is potentially type-*unsafe*, it might be better to avoid this functionality completely.

When binary files must be written, normally no text-formatting is used or required: an `int` value should be written as a series of raw bytes, not as a series of ASCII numeric characters 0 to 9. The following member functions of `ostream` objects may be used to write 'binary files':

- `ostream& put(char c)`:
  to write a single character to the output stream. Since a character is a byte, this member function could also be used for writing a single character to a text-file.
- `ostream& write(char const *buffer, int length)`:
  to write at most `length` bytes, stored in the `char const *buffer` to the `ostream` object. Bytes are written as they are stored in the buffer, no formatting is done whatsoever. Note that the first argument is a `char const *`: a *type cast* is required to write any other type. For example, to write an `int` as an unformatted series of byte-values use:

  ```
  int x;
  out.write(reinterpret_cast<char const *>(&x), sizeof(int));
  ```

  The bytes written by the above `write` call are written to the `ostream` in an order depending on the *endian-ness* of the underlying hardware. Big-endian computers write the most significant byte(s) of multi-byte values first, little-endian computers first write the least significant byte(s).

6.4.1.2 'ostream' positioning

Although not every `ostream` object supports repositioning, they usually do. This means that it is possible to rewrite a section of the stream which was written earlier. Repositioning is frequently used in database applications where it must be possible to access the information in the database at random.

The current position can be obtained and modified using the following members:

- `ios::pos_type tellp()`:
  the current (absolute) position in the file where the next write-operation to the stream will take place is returned.
- `ostream &seekp(ios::off_type step, ios::seekdir org)`:
  modifies a stream's actual position. The function expects an `off_type step` representing the number of bytes the current stream position is moved with respect to `org`. The `step` value may be negative, zero or positive.

  The origin of the step, `org` is a value in the `ios::seekdir` enumeration. Its values are:

  - `ios::beg`:
    the stepsize is computed relative to the beginning of the stream. This value is used by default.
  - `ios::cur`:
    the stepsize is computed relative to the current position of the stream (as returned by `tellp`).
  - `ios::end`:
    the stepsize is interpreted relative to the current end position of the stream.

  It is OK to seek or write beyond the last file position. Writing bytes to a location beyond `EOF` will pad the intermediate bytes with 0-valued bytes: null-bytes. Seeking before `ios::beg` raises the `ios::fail` flag.

6.4.1.3 ‘ostream’ flushing

Unless the `ios::unitbuf` flag has been set, information written to an `ostream` object is not immediately written to the physical stream. Rather, an internal buffer is filled during the write-operations, and when full it is flushed.

The stream’s internal buffer can be flushed under program control:

- `ostream& flush()`:
  any buffered information stored internally by the `ostream` object is flushed to the device to which the `ostream` object interfaces. A stream is flushed automatically when:
  - the object ceases to exist;
  - the `endl` or `flush` *manipulators* (see section 6.3.2.2) are inserted into an `ostream` object;
  - a stream supporting the `close`-operation is explicitly closed (e.g., a `std::ofstream` object, cf. section 6.4.2).

6.4.2 Output to files: the class ‘ofstream’

The `std::ofstream` class is derived from the `ostream` class: it has the same capabilities as the `ostream` class, but can be used to access files or create files for writing.

In order to use the `ofstream` class in **C++** sources, the `<fstream>` header file must be included. Including `fstream` does not automatically make available the standard streams `cin`, `cout` and `cerr`. Include `iostream` to declare these standard streams.

The following constructors are available for `ofstream` objects:

- `ofstream object`:

  this is the basic constructor. It defines an `ofstream` object which may be associated with an actual file later, using its `open()` member (see below).

- `ofstream object(char const *name, ios::openmode mode = ios::out)`:

  this constructor defines an `ofstream` object and associates it immediately with the file named `name` using output mode `mode`. Section 6.4.2.1 provides an overview of available output modes. Example:

  ```
  ofstream out("/tmp/scratch");
  ```

It is not possible to open an `ofstream` using a *file descriptor*. The reason for this is (apparently) that file descriptors are not universally available over different operating systems. Fortunately, file descriptors can be used (indirectly) with a `std::streambuf` object (and in some implementations: with a `std::filebuf` object, which is also a `streambuf`). `Streambuf` objects are discussed in section 14.8, `filebuf` objects are discussed in section 14.8.2.

Instead of directly associating an `ofstream` object with a file, the object can be constructed first, and opened later.

- `void open(char const *name, ios::openmode mode = ios::out)`:
  associates an `ofstream` object with an actual file. If the `ios::fail` flag was set before calling `open` and opening succeeds the flag is cleared. Opening an already open stream fails. To reassociate a stream with another file it must first be closed:

  ```
  ofstream out("/tmp/out");
  ```

```
out << "hello\n";
out.close();        // flushes and closes out
out.open("/tmp/out2");
out << "world\n";
```

- `void close()`:
  closes the `ofstream` object. The function sets the `ios::fail` flag of the closed object. Closing the file flushes any buffered information to the associated file. A file is automatically closed when the associated `ofstream` object ceases to exist.

- `bool is_open() const`:
  assume a stream was properly constructed, but it has not yet been attached to a file. E.g., the statement `ofstream ostr` was executed. When we now check its status through `good()`, a non-zero (i.e., *OK*) value is returned. The 'good' status here indicates that the stream object has been constructed properly. It doesn't mean the file is also open. To test whether a stream is actually open, `is_open` should be called. If it returns `true`, the stream is open. Example:

```
#include <fstream>
#include <iostream>

using namespace std;

int main()
{
    ofstream of;

    cout << "of's open state: " << boolalpha << of.is_open() << '\n';

    of.open("/dev/null");       // on Unix systems

    cout << "of's open state: " << of.is_open() << '\n';
}
/*
    Generated output:
of's open state: false
of's open state: true
*/
```

6.4.2.1 Modes for opening stream objects

The following file modes or file flags are available when constructing or opening `ofstream` (or `istream`, see section 6.5.2) objects. The values are of type `ios::openmode`. Flags may be combined using the `bitor` operator.

- `ios::app`:
  reposition the stream to its end before every output command (see also `ios::ate` below). The file is created if it doesn't yet exist. When opening a stream in this mode any existing content of the file is kept.

- `ios::ate`:
  start initially at the end of the file. Note that any existing content is *only* kept if some other flag tells the object to do so. For example `ofstream out("gone", ios::ate)` *rewrites* the file `gone`, because the implied `ios::out` causes the rewriting. If rewriting of an existing file should be prevented, the `ios::in` mode should be specified too. However, when `ios::in` is specified the file must already exist. The `ate` mode only initially positions the file at the end

of file position. After that information may be written in the middle of the file using `seekp`. When the `app` mode is used information is *only* written at end of file (effectively ignoring `seekp` operations).

- `ios::binary`:
  open a file in binary mode (used on systems distinguishing text- and binary files, like MS-Windows).

- `ios::in`:
  open the file for reading. The file must exist.

- `ios::out`:
  open the file for writing. Create it if it doesn't yet exist. If it exists, the file is rewritten.

- `ios::trunc`:
  start initially with an empty file. Any existing content of the file is lost.

The following combinations of file flags have special meanings:

```
in | out:           The stream may be read and written. However, the
                    file must exist.
in | out | trunc:   The stream may be read and written. It is
                    (re)created empty first.
```

An interesting subtlety is that the `open` members of the `ifstream, ofstream` and `fstream` classes have a second parameter of type `ios::openmode`. In contrast to this, the `bitor` operator returns an `int` when applied to two enum-values. The question why the `bitor` operator may nevertheless be used here is answered in a later chapter (cf. section 11.12).

6.4.3 Output to memory: the class 'ostringstream'

To write information to memory using `stream` facilities, `std::ostringstream` objects should be used. As the class `ostringstream` is derived from the class `ostream` all `ostream`'s facilities are available to `ostringstream` objects as well. To use and define `ostringstream` objects the header file `<sstream>` must be included. In addition the class `ostringstream` offers the following constructors and members:

- `ostringstream ostr(string const &init, ios::openmode mode = ios::out)`:
  when specifying `openmode` as `ios::ate`, the `ostringstream` object is initialized by the `string init` and remaining insertions are appended to the content of the `ostringstream` object.

- `ostringstream ostr(ios::openmode mode = ios::out)`:
  this constructor can also be used as default constructor. Alternatively it allows, e.g., forced additions at the end of the information stored in the object so far (using `ios::app`). Example:

  ```
  std::ostringstream out;
  ```

- `std::string str() const`:
  a copy of the string that is stored inside the `ostringstream` object is returned.

- `void str(std::string const &str)`:
  the current object is reinitialized with new initial content.

The following example illustrates the use of the `ostringstream` class: several values are inserted into the object. Then, the text contained by the `ostringstream` object is stored in a `std::string`, whose length and content are thereupon printed. Such `ostringstream` objects are most often used for doing 'type to string' conversions, like converting `int` values to text. Formatting flags can be used with `ostringstreams` as well, as they are part of the `ostream` class.

Here is an example showing an `ostringstream` object being used:

```
#include <iostream>
#include <sstream>

using namespace std;

int main()
{
    ostringstream ostr("hello ", ios::ate);

    cout << ostr.str() << '\n';

    ostr.setf(ios::showbase);
    ostr.setf(ios::hex, ios::basefield);
    ostr << 12345;

    cout << ostr.str() << '\n';

    ostr << " -- ";
    ostr.unsetf(ios::hex);
    ostr << 12;

    cout << ostr.str() << '\n';

    ostr.str("new text");
    cout << ostr.str() << '\n';

    ostr.seekp(4, ios::beg);
    ostr << "world";
    cout << ostr.str() << '\n';
}
/*
    Output from this program:
hello
hello 0x3039
hello 0x3039 -- 12
new text
new world
*/
```

6.4.4 The 'put_time' manipulator

The manipulator `std::put_time(std::tm const *specs, char const *fmt)` can be used to insert time specifications into `std::ostream` objects.

Time specifications are provided in `std::tm` objects, and the way the time should be displayed is defined by the *format string* `fmt`.

Starting with a `chrono::time_point` the following steps must be performed to insert the time point's time into a `std::ostream`:

- Obtain a `time_point` (e.g.: `system_clock{}.now()`);
- Pass the time point to the clock's `to_time_t` function, saving the returned `time_t` value:

  ```
  time_t secs = system_clock::to_time_t( system_clock{}.now() );
  ```

- Pass `sec's` address to either `std::localtime` or `std::gmtime`. These functions return `std::tm` structs containing the required time components expressed in, respectively, the computer's local time or GMT;
- Pass the return value of either `localtime` or `gmtime` together with a format string (e.g., `"%c"`) to `put_time`, inserting it into an `std::ostream`:

  ```
                  // displays, e.g., Mon Nov  4 21:34:59 2019
  time_t secs = system_clock::to_time_t( system_clock{}.now() );
  std::cout << std::put_time(std::localtime(&secs), "%c") << '\n';
  ```

A simple function returning `put_time's` return value and expecting a `time_point` and format string can be defined which handles the above two statements. E.g., (omitting the `std::` and `std::chrono::` specifications for brevity):

```
auto localTime(time_point<system_clock> const &tp, char const *fmt)
{
    time_t secs = system_clock::to_time_t( tp );
    return put_time(localtime(&secs), fmt);
}
            // used as:
cout << localTime(system_clock{}.now(), "%c") << '\n';
```

Many more format specifiers are recognized by `put_time`. Specifiers start with `%`. To display a percent character as part of the format string write it twice: `%%`. In addition to the standard escape sequences, `%n` can be used instead of `\n`, and `%t` can be used instead of `\t`.

Year specifiers

Specifier	Meaning	std::tm field(s)
%Y	year as a 4 digit decimal number	tm_year
%EY	year in an alternative representation	tm_year
%y	last 2 digits of year as a decimal number (range [00,99])	tm_year
%Oy	last 2 digits of year using an alternative numeric system	tm_year
%Ey	year as offset from locale's alternative calendar period %EC (locale-dependent)	tm_year
%C	first 2 digits of year as a decimal number (range [00,99])	tm_year
%EC	name of the base year (period) in the locale's alternative representation	tm_year
%G	ISO 8601 week-based year, i.e. the year that contains the specified week	tm_year, tm_wday, tm_yday
%g	last 2 digits of ISO 8601 week-based year (range [00,99])	tm_year, tm_wday, tm_yday

Month specifiers

Specifier	Meaning	std::tm field(s)
%b	abbreviated month name, e.g. Oct	tm_mon
%m	month as a decimal number (range [01,12])	tm_mon
%Om	month using an alternative numeric system	tm_mon

Week specifiers

Specifier	Meaning	std::tm field(s)
%U	week of the year as a decimal number (Sunday is the first day of the week) (range [00,53])	tm_year, tm_wday, tm_yday
%OU	week of the year, as by %U, using an alternative numeric system	tm_year, tm_wday, tm_yday
%W	week of the year as a decimal number (Monday is the first day of the week) (range [00,53])	tm_year, tm_wday, tm_yday
%OW	week of the year, as by %W, using an alternative numeric system	tm_year, tm_wday, tm_yday
%V	ISO 8601 week of the year (range [01,53])	tm_year, tm_wday, tm_yday
%OV	week of the year, as by %V, using an alternative numeric system	tm_year, tm_wday, tm_yday

Day of the year/month specifiers

Specifier	Meaning	std::tm field(s)
%j	day of the year as a decimal number (range [001,366])	tm_yday
%d	day of the month as a decimal number (range [01,31])	tm_mday
%Od	zero-based day of the month using an alternative numeric system	tm_mday
%e	day of the month as a decimal number (range [1,31])	tm_mday
%Oe	one-based day of the month using an alternative numeric system	tm_mday

Day of the week specifiers

Specifier	Meaning	std::tm field(s)
%a	abbreviated weekday name, e.g. Fri	tm_wday
%A	full weekday name, e.g. Friday	tm_wday
%w	weekday as a decimal number, where Sunday is 0 (range [0-6])	tm_wday
%Ow	weekday, where Sunday is 0, using an alternative numeric system	tm_wday
%u	weekday as a decimal number, where Monday is 1 (ISO 8601 format) (range [1-7])	tm_wday
%Ou	weekday, where Monday is 1, using an alternative numeric system	tm_wday

Hour, minute, second specifiers

Specifier	Meaning	std::tm field(s)
%H	hour as a decimal number, 24 hour clock (range [00-23])	tm_hour
%OH	hour from 24-hour clock using an alternative numeric system	tm_hour
%I	hour as a decimal number, 12 hour clock (range [01,12])	tm_hour
%OI	hour from 12-hour clock using the alternative numeric system	tm_hour
%M	minute as a decimal number (range [00,59])	tm_min
%OM	minute using an alternative numeric system	tm_min
%S	second as a decimal number (range [00,60])	tm_sec
%OS	second using an alternative numeric system	tm_sec

Additional specifiers

Specifier	Meaning	std::tm field(s)
%c	standard date and time string, e.g. Sun Oct 17 04:41:13 2010	all
%Ec	alternative date and time string	all
%x	localized date representation	all
%Ex	alternative date representation	all
%X	localized time representation	all
%EX	alternative time representation	all
%D	equivalent to `"%m/%d/%y"`	tm_mon, tm_mday, tm_year
%F	equivalent to `"%Y-%m-%d"` (the ISO 8601 date format)	tm_mon, tm_mday, tm_year
%r	localized 12-hour clock time	tm_hour, tm_min, tm_sec
%R	equivalent to `"%H:%M"`	tm_hour, tm_min
%T	equivalent to `"%H:%M:%S"` (the ISO 8601 time format)	tm_hour, tm_min, tm_sec
%p	localized a.m. or p.m.	tm_hour
%z	offset from UTC in the ISO 8601 format (e.g. -0430; no characters if time zone information is not available)	tm_isdst
%Z	time zone name or abbreviation (no characters if time zone information is not available)	tm_isdst

6.5 Input

In **C++** input is primarily based on the `std::istream` class. The `istream` class defines the basic operators and members extracting information from streams: the *extraction operator* (>>), and special members like `istream::read` reading unformatted information from streams.

The class `istream` acts as *base class* for several other classes, all offering the functionality of the `istream` class, but adding their own specialties. In the upcoming sections the following classes are discussed:

- The class `istream`, offering the basic facilities for doing input;
- The class `ifstream`, allowing us to read files (comparable to **C**'s `fopen(filename, "r")`);
- The class `istringstream`, allowing us to extract information from memory rather than from file (comparable to **C**'s `sscanf` function).

6.5.1 Basic input: the class 'istream'

The class `istream` defines basic input facilities. The `cin` object, is an `istream` object. All facilities related to input as defined by the `ios` class are also available in the `istream` class.

We may define `istream` objects using the following *istream constructor*:

- `istream object(streambuf *sb)`:

  this constructor can be used to construct a wrapper around an existing `std::streambuf` object. Similarly to `ostream` objects, `istream` objects may be defined by passing it initially a 0-pointer. See section 6.4.1 for a discussion, see also section 14.8.3, and see chapter 25 for examples.

To define the `istream` class in **C++** sources, the `<istream>` header file must be included. To use the predefined `istream` object `cin`, the `<iostream>` header file must be included.

6.5.1.1 Reading from 'istream' objects

The class `istream` supports both formatted and unformatted (*binary*) input. The *extraction operator* (`operator>>`) is used to extract values in a type safe way from `istream` objects. This is called formatted input, whereby human-readable ASCII characters are converted, according to certain formatting rules, to binary values.

The extraction operator points to the objects or variables to receive new values. The normal associativity of >> remains unaltered, so when a statement like

```
cin >> x >> y;
```

is encountered, the leftmost two operands are evaluated first (`cin >> x`), and an `istream &` object, which is actually the same `cin` object, is returned. Now, the statement is reduced to

```
cin >> y
```

and the `y` variable is extracted from `cin`.

The >> operator has many (overloaded) variants and thus many types of variables can be extracted from `istream` objects. There is an overloaded >> available for the extraction of an `int`, of a `double`, of a string, of an array of characters, possibly to the location pointed at by a pointer, etc., etc.. String or character array extraction by default first skips all whitespace characters, and then extracts all consecutive non-whitespace characters. Once an extraction operator has been processed the `istream` object from which the information was extracted is returned and it can immediately be used for additional `istream` operations that appear in the same expression.

Streams do not support facilities for formatted input as offered by **C**'s `scanf` and `vscanf` functions. Although it is not difficult to add such facilities to the world of streams, `scanf`-like functionality is in practice never needed in **C++** programs. Furthermore, as it is potentially type-*unsafe*, it is better to avoid using **C**-type formatted input.

When binary files must be read, the information should normally not be formatted: an `int` value should be read as a series of unaltered bytes, not as a series of ASCII numeric characters 0 to 9. The following member functions for reading information from `istream` objects are available:

- `int gcount() const`:
  the number of characters read from the input stream by the last unformatted input operation is returned.
- `int get()`:
  the next available single character is returned as an unsigned `char` value using an `int` return type. `EOF` is returned if no more character are available.
- `istream &get(char &ch)`:
  the next single character read from the input stream is stored in `ch`. The member function returns the stream itself which may be inspected to determine whether a character was obtained or not.
- `istream &get(char *buffer, int len, char delim = '\n')`:
  At most `len - 1` characters are read from the input stream into the array starting at `buffer`, which should be at least `len` bytes long. Reading also stops when the delimiter `delim` is encountered. However, the delimiter itself is *not removed* from the input stream.

  Having stored the characters into `buffer`, a 0-valued character is written beyond the last character stored into the `buffer`. The functions `eof` and `fail` (see section 6.3.1) return 0 (`false`) if the delimiter was encountered before reading `len - 1` characters or if the delimiter was not encountered after reading `len - 1` characters. It is OK to specifiy a 0-valued character delimiter: this way NTBSs may be read from a (binary) file.
- `istream &getline(char *buffer, int len, char delim = '\n')`:
  this member function operates analogously to the `get` member function, but `getline` removes `delim` from the stream if it is actually encountered. The delimiter itself, if encountered, is *not* stored in the `buffer`. If `delim` was *not* found (before reading `len - 1` characters) the `fail` member function, and possibly also `eof` returns true. Realize that the `std::string` class also offers a function `std::getline` which is generally preferred over this `getline` member function that is described here (see section 5.2.4).
- `istream &ignore()`:
  one character is skipped from the input stream.
- `istream &ignore(int n)`:
  `n` characters are skipped from the input stream.
- `istream &ignore(int n, int delim)`:
  at most `n` characters are skipped but skipping characters stops after having removed `delim` from the input stream.
- `int peek()`:
  this function returns the next available input character, but does not actually remove the character from the input stream. `EOF` is returned if no more characters are available.
- `istream &putback(char ch)`:
  The character `ch` is 'pushed back' into the input stream, to be read again as the next available character. `EOF` is returned if this is not allowed. Normally, it is OK to put back one character. Example:

  ```
  string value;
  ```

```
cin >> value;
cin.putback('X');
                // displays: X
cout << static_cast<char>(cin.get());
```

- `istream &read(char *buffer, int len)`:
  At most `len` bytes are read from the input stream into the buffer. If `EOF` is encountered first, fewer bytes are read, with the member function `eof` returning `true`. This function is commonly used when reading *binary* files. Section 6.5.2 contains an example in which this member function is used. The member function `gcount()` may be used to determine the number of characters that were retrieved by `read`.
- `istream &readsome(char *buffer, int len)`:
  at most `len` bytes are read from the input stream into the buffer. All available characters are read into the buffer, but if `EOF` is encountered, fewer bytes are read, without setting the `ios::eofbit` or `ios::failbit`.
- `istream &unget()`:
  the last character that was read from the stream is put back.

6.5.1.2 'istream' positioning

Although not every `istream` object supports repositioning, some do. This means that it is possible to read the same section of a stream repeatedly. Repositioning is frequently used in *database applications* where it must be possible to access the information in the database randomly.

The current position can be obtained and modified using the following members:

- `ios::pos_type tellg()`:
  the stream's current (absolute) position where the stream's next read-operation will take place is returned.
- `istream &seekg(ios::off_type step, ios::seekdir org)`:
  modifies a stream's actual position. The function expects an `off_type step` representing the number of bytes the current stream position is moved with respect to `org`. The `step` value may be negative, zero or positive.

  The origin of the step, `org` is a value in the `ios::seekdir` enumeration. Its values are:

  - `ios::beg`:
    the stepsize is computed relative to the beginning of the stream. This value is used by default.
  - `ios::cur`:
    the stepsize is computed relative to the current position of the stream (as returned by `tellp`).
  - `ios::end`:
    the stepsize is interpreted relative to the current end position of the stream.

  It is OK to seek beyond the last file position. Seeking before `ios::beg` raises the `ios::failbit` flag.

6.5.2 Input from files: the class 'ifstream'

The `std::ifstream` class is derived from the `istream` class: it has the same capabilities as the `istream` class, but can be used to access files for reading.

In order to use the `ifstream` class in **C++** sources, the `<fstream>` header file must be included. Including `fstream` does not automatically make available the standard streams `cin`, `cout` and `cerr`. Include `iostream` to declare these standard streams.

The following constructors are available for `ifstream` objects:

- `ifstream object`:

  this is the basic constructor. It defines an `ifstream` object which may be associated with an actual file later, using its `open()` member (see below).

- `ifstream object(char const *name, ios::openmode mode = ios::in)`:

  this constructor can be used to define an `ifstream` object and associate it immediately with the file named `name` using input mode `mode`. Section 6.4.2.1 provides an overview of available input modes. Example:

  ```
  ifstream in("/tmp/input");
  ```

Instead of directly associating an `ifstream` object with a file, the object can be constructed first, and opened later.

- `void open(char const *name, ios::openmode mode = ios::in)`:
  associates an `ifstream` object with an actual file. If the `ios::fail` flag was set before calling `open` and opening succeeds the flag is cleared. Opening an already open stream fails. To reassociate a stream with another file it must first be closed:

  ```
  ifstream in("/tmp/in");
  in >> variable;
  in.close();        // closes in
  in.open("/tmp/in2");
  in >> anotherVariable;
  ```

- `void close()`:
  closes the `ifstream` object. The function sets the `ios::fail` flag of the closed object. Closing the file flushes any buffered information to the associated file. A file is automatically closed when the associated `ifstream` object ceases to exist.

- `bool is_open() const`:
  assume a stream was properly constructed, but it has not yet been attached to a file. E.g., the statement `ifstream ostr` was executed. When we now check its status through `good()`, a non-zero (i.e., *OK*) value is returned. The 'good' status here indicates that the stream object has been constructed properly. It doesn't mean the file is also open. To test whether a stream is actually open, `is_open` should be called. If it returns `true`, the stream is open. Also see the example in section 6.4.2. The following example illustrates reading from a binary file (see also section 6.5.1.1):

  ```
  #include <fstream>
  using namespace std;

  int main(int argc, char **argv)
  {
      ifstream in(argv[1]);
      double   value;

      // reads double in raw, binary form from file.
      in.read(reinterpret_cast<char *>(&value), sizeof(double));
  }
  ```

6.5.3 Input from memory: the class 'istringstream'

To read information from memory using `stream` facilities, `std::istringstream` objects should be used. As the class `istringstream` is derived from the class `istream` all `istream`'s facilities are available to `istringstream` objects as well. To use and define `istringstream` objects the header file `<sstream>` must be included. In addition the class `istringstream` offers the following constructors and members:

- `istringstream istr(string const &init, ios::openmode mode = ios::in)`:
  the object is initialized with `init`'s content
- `istringstream istr(ios::openmode mode = ios::in)`:
  this constructor is usually used as the default constructor. Example:

  ```
  std::istringstream in;
  ```
- `void str(std::string const &str)`:
  the current object is reinitialized with new initial content.

The following example illustrates the use of the `istringstream` class: several values are extracted from the object. Such `istringstream` objects are most often used for doing 'string to type' conversions, like converting text to `int` values (cf. **C**'s `atoi` function). Formatting flags can be used with `istringstreams` as well, as they are part of the `istream` class. In the example note especially the use of the member `seekg`:

```
#include <iostream>
#include <sstream>
using namespace std;

int main()
{
    istringstream istr("123 345");  // store some text.
    int x;

    istr.seekg(2);              // skip "12"
    istr >> x;                  // extract int
    cout << x << '\n';          // write it out
    istr.seekg(0);              // retry from the beginning
    istr >> x;                  // extract int
    cout << x << '\n';          // write it out
    istr.str("666");            // store another text
    istr >> x;                  // extract it
    cout << x << '\n';          // write it out
}
/*
    output of this program:
3
123
666
*/
```

6.5.4 Copying streams

Usually, files are copied either by reading a source file character by character or line by line. The basic *mold* to process streams is as follows:

- Continuous loop:
  1. read from the stream
  2. if reading did not succeed (i.e., `fail` returns `true`), `break` from the loop
  3. process the information that was read

Note that reading must *precede* testing, as it is only possible to know after actually attempting to read from a file whether the reading succeeded or not. Of course, variations are possible: `getline(istream &, string &)` (see section 6.5.1.1) returns an `istream &`, so here reading and testing may be contracted using one expression. Nevertheless, the above mold represents the general case. So, the following program may be used to copy `cin` to `cout`:

```
#include <iostream>
using namespace::std;

int main()
{
    while (true)
    {
        char c;

        cin.get(c);
        if (cin.fail())
            break;
        cout << c;
    }
}
```

Contraction is possible here by combining `get` with the `if`-statement, resulting in:

```
    if (!cin.get(c))
        break;
```

Even so, this would still follow the basic rule: ‘read first, test later’.

Simply copying a file isn’t required very often. More often a situation is encountered where a file is processed up to a certain point, followed by plain copying the file’s remaining information. The next program illustrates this. Using `ignore` to skip the first line (for the sake of the example it is assumed that the first line is at most 80 characters long), the second statement uses yet another overloaded version of the <<-operator, in which a `streambuf` pointer is inserted into a stream. As the member `rdbuf` returns a stream’s `streambuf *`, we have a simple means of inserting a stream’s content into an `ostream`:

```
    #include <iostream>
    using namespace std;

    int main()
    {
        cin.ignore(80, '\n');   // skip the first line and...
        cout << cin.rdbuf();    // copy the rest through the streambuf *
    }
```

This way of copying streams only assumes the existence of a `streambuf` object. Consequently it can be used with all specializations of the `streambuf` class.

6.5.5 Coupling streams

Ostream objects can be *coupled* to `ios` objects using the `tie` member function. Tying results in flushing the `ostream`'s buffer whenever an input or output operation is performed on the `ios` object to which the `ostream` object is tied. By default `cout` is tied to `cin` (using `cin.tie(cout)`). This tie means that whenever an operation on `cin` is requested, `cout` is flushed first. To break the tie, `ios::tie(0)` can be called. In the example: `cin.tie(0)`.

Another useful coupling of streams is shown by the tie between `cerr` and `cout`. Because of the tie standard output and error messages written to the screen are shown in sync with the time at which they were generated:

```
#include <iostream>
using namespace std;

int main()
{
    cerr.tie(0);        // untie
    cout << "first (buffered) line to cout ";
    cerr << "first (unbuffered) line to cerr\n";
    cout << "\n";

    cerr.tie(&cout);    // tie cout to cerr
    cout << "second (buffered) line to cout ";
    cerr << "second (unbuffered) line to cerr\n";
    cout << "\n";
}
/*
    Generated output:

    first (unbuffered) line to cerr
    first (buffered) line to cout
    second (buffered) line to cout second (unbuffered) line to cerr
*/
```

An alternative way to couple streams is to make streams use a common `streambuf` object. This can be implemented using the `ios::rdbuf(streambuf *)` member function. This way two streams can use, e.g. their own formatting, one stream can be used for input, the other for output, and redirection using the stream library rather than operating system calls can be implemented. See the next sections for examples.

6.6 Advanced topics

6.6.1 Moving streams

Stream classes (e.g.,, all stream classes covered in this chapter) are movable and can be swapped. This implies that factory functions can be designed for stream classes. Here is an example:

```
ofstream out(string const &name)
{
    ofstream ret(name);             // construct ofstream
    return ret;                     // return value optimization, but
}                                    // OK as moving is supported

int main()
{
    ofstream mine(out("out"));       // return value optimizations, but
                                     // OK as moving is supported

    ofstream base("base");
    ofstream other;

    base.swap(other);                // swapping streams is OK

    other = std::move(base);         // moving streams is OK

    // other = base;                 // this would fail: copy assignment
                                     // is not available for streams
}
```

6.6.2 Redirecting streams

Using `ios::rdbuf` streams can be forced to share their `streambuf` objects. Thus information written to one stream is actually written to another stream; a phenomenon normally called *redirection*. Redirection is commonly implemented at the operating system level, and sometimes that is still necessary (see section 25.2.3).

A common situation where redirection is useful is when error messages should be written to file rather than to the standard error stream, usually indicated by its file descriptor number 2. In the Unix operating system using the `bash` shell, this can be realized as follows:

```
program 2>/tmp/error.log
```

Following this command any error messages written by `program` are written to `/tmp/error.log`, instead of appearing on the screen.

Here is an example showing how this can be implemented using `streambuf` objects. Assume `program` expects an argument defining the name of the file to write the error messages to. It could be called as follows:

```
program /tmp/error.log
```

The program looks like this, an explanation is provided below the program's source text:

```
#include <iostream>
#include <fstream>
using namespace std;

int main(int argc, char **argv)
{
    ofstream errlog;                                // 1
    streambuf *cerr_buffer = 0;                     // 2

    if (argc == 2)
    {
        errlog.open(argv[1]);                         // 3
        cerr_buffer = cerr.rdbuf(errlog.rdbuf());    // 4
    }
    else
    {
        cerr << "Missing log filename\n";
        return 1;
    }

    cerr << "Several messages to stderr, msg 1\n";
    cerr << "Several messages to stderr, msg 2\n";

    cout << "Now inspect the contents of " <<
            argv[1] << "... [Enter] ";
    cin.get();                                        // 5

    cerr << "Several messages to stderr, msg 3\n";

    cerr.rdbuf(cerr_buffer);                          // 6
    cerr << "Done\n";                                 // 7
}
/*
    Generated output on file argv[1]

    at cin.get():

Several messages to stderr, msg 1
Several messages to stderr, msg 2

    at the end of the program:

Several messages to stderr, msg 1
Several messages to stderr, msg 2
Several messages to stderr, msg 3
*/
```

- At lines 1-2 local variables are defined: `errlog` is the `ofstream` to write the error messages to, and `cerr_buffer` is a pointer to a `streambuf`, to point to the original `cerr` buffer.

- At line 3 the alternate error stream is opened.

- At line 4 redirection takes place: `cerr` now writes to the `streambuf` defined by `errlog`. It is important that the original buffer used by `cerr` is saved, as explained below.

- At line 5 we pause. At this point, two lines were written to the alternate error file. We get a chance to take a look at its content: there were indeed two lines written to the file.

- At line 6 the redirection is terminated. This is very important, as the `errlog` object is destroyed at the end of `main`. If `cerr`'s buffer would not have been restored, then at that point `cerr` would refer to a non-existing `streambuf` object, which might produce unexpected results. It is the responsibility of the programmer to make sure that an original `streambuf` is saved before redirection, and is restored when the redirection ends.

- Finally, at line 7, `Done` is again written to the screen, as the redirection has been terminated.

6.6.3 Reading AND Writing streams

Streams can be read *and* written using `std::fstream` objects. As with `ifstream` and `ofstream` objects, its constructor expects the name of the file to be opened:

```
        fstream inout("iofile", ios::in | ios::out);
```

Note the use of the constants `ios::in` and `ios::out`, indicating that the file must be opened for both reading and writing. Multiple mode indicators may be used, concatenated by the `bitor` operator. Alternatively, instead of `ios::out`, `ios::app` could have been used and mere writing would become appending (at the end of the file).

Reading and writing to the same file is always a bit awkward: what to do when the file may not yet exist, but if it already exists it should not be rewritten? Having fought with this problem for some time I now use the following approach:

```
    #include <fstream>
    #include <iostream>
    #include <string>

    using namespace std;

    int main()
    {
        fstream rw("fname", ios::out | ios::in);

        if (!rw)            // file didn't exist yet
        {
            rw.clear();     // try again, creating it using ios::trunc
            rw.open("fname", ios::out | ios::trunc | ios::in);
        }

        if (!rw)            // can't even create it: bail out
        {
            cerr << "Opening `fname' failed miserably" << '\n';
            return 1;
        }

        cerr << "We're at: " << rw.tellp() << '\n';

                            // write something
        rw << "Hello world" << '\n';

        rw.seekg(0);        // go back and read what's written

        string s;
        getline(rw, s);

        cout << "Read: " << s << '\n';
    }
```

Under this approach if the first construction attempt fails `fname` doesn't exist yet. But then `open` can be attempted using the `ios::trunc` flag. If the file already existed, the construction would have succeeded. By specifying `ios::ate` when defining `rw`, the initial read/write action would by default have taken place at `EOF`.

Under **DOS**-like operating systems that use the multiple character sequence `\r\n` to separate lines in text files the flag `ios::binary` is required to process binary files ensuring that `\r\n` combinations are processed as two characters. In general, `ios::binary` should be specified when binary (non-text) files are to be processed. By default files are opened as text files. Unix operating systems do not distinguish text files from binary files.

With `fstream` objects, combinations of file flags are used to make sure that a stream is or is not (re)created empty when opened. See section 6.4.2.1 for details.

Once a file has been opened in read and write mode, the << operator can be used to insert information into the file, while the >> operator may be used to extract information from the file. These operations may be performed in any order, but a `seekg` or `seekp` operation is required when switching between insertions and extractions. The seek operation is used to activate the stream's data used for reading or those used for writing (and *vice versa*). The `istream` and `ostream` parts of `fstream` objects share the stream's data buffer and by performing the seek operation the stream either activates its `istream` or its `ostream` part. If the seek is omitted, reading after writing and writing after reading simply fails. The example shows a whitespace-delimited word being read from a file, writing another string to the file, just beyond the point where the just read word terminated. Finally yet another string is read which is found just beyond the location where the just written strings ended:

```
fstream f("filename", ios::in | ios::out);
string  str;

f >> str;       // read the first word

                // write a well known text
f.seekg(0, ios::cur);
f << "hello world";

f.seekp(0, ios::cur);
f >> str;       // and read again
```

Since a *seek* or *clear* operation is required when alternating between read and write (extraction and insertion) operations on the same file it is not possible to execute a series of << and >> operations in one expression statement.

Of course, random insertions and extractions are hardly ever used. Generally, insertions and extractions occur at well-known locations in a file. In those cases, the position where insertions or extractions are required can be controlled and monitored by the `seekg`, `seekp`, `tellg` and `tellp` members (see sections 6.4.1.2 and 6.5.1.2).

Error conditions (see section 6.3.1) occurring due to, e.g., reading beyond end of file, reaching end of file, or positioning before begin of file, can be cleared by the `clear` member function. Following `clear` processing may continue. E.g.,

```
fstream f("filename", ios::in | ios::out);
string  str;

f.seekg(-10);   // this fails, but...
f.clear();      // processing f continues

f >> str;       // read the first word
```

A situation where files are both read and written is seen in *database* applications, using files consisting of records having fixed sizes, and where locations and sizes of pieces of information are known. For example, the following program adds text lines to a (possibly existing) file. It can also be used to retrieve a particular line, given its order-number in the file. A *binary file* `index` allows for the quick retrieval of the location of lines.

```
#include <iostream>
#include <fstream>
#include <string>
#include <climits>
using namespace std;

void err(char const *msg)
{
    cout << msg << '\n';
}

void err(char const *msg, long value)
{
    cout << msg << value << '\n';
}

void read(fstream &index, fstream &strings)
{
    int idx;

    if (!(cin >> idx))                          // read index
    {
        cin.clear();                            // allow reading again
        cin.ignore(INT_MAX, '\n');              // skip the line
        return err("line number expected");
    }

    index.seekg(idx * sizeof(long));            // go to index-offset

    long offset;

    if
    (
        !index.read                             // read the line-offset
        (
            reinterpret_cast<char *>(&offset),
            sizeof(long)
        )
    )
        return err("no offset for line", idx);

    if (!strings.seekg(offset))                 // go to the line's offset
        return err("can't get string offset ", offset);

    string line;

    if (!getline(strings, line))                // read the line
        return err("no line at ", offset);

    cout << "Got line: " << line << '\n';       // show the line
}
```

```
void write(fstream &index, fstream &strings)
{
    string line;

    if (!getline(cin, line))                   // read the line
        return err("line missing");

    strings.seekp(0, ios::end);                // to strings
    index.seekp(0, ios::end);                  // to index

    long offset = strings.tellp();

    if
    (
        !index.write                           // write the offset to index
        (
            reinterpret_cast<char *>(&offset),
            sizeof(long)
        )
    )
        return err("Writing failed to index: ", offset);

    if (!(strings << line << '\n'))            // write the line itself
        return err("Writing to `strings' failed");
                                               // confirm writing the line
    cout << "Write at offset " << offset << " line: " << line << '\n';
}

int main()
{
    fstream index("index", ios::trunc | ios::in | ios::out);
    fstream strings("strings", ios::trunc | ios::in | ios::out);

    cout << "enter `r <number>' to read line <number> or "
                            "w <line>' to write a line\n"
            "or enter `q' to quit.\n";

    while (true)
    {
        cout << "r <nr>, w <line>, q ? ";        // show prompt

        index.clear();
        strings.clear();

        string cmd;
        cin >> cmd;                              // read cmd

        if (cmd == "q")                          // process the cmd.
            return 0;

        if (cmd == "r")
            read(index, strings);
        else if (cmd == "w")
            write(index, strings);
        else if (cin.eof())
        {
                cout << "\n"
                        "Unexpected end-of-file\n";
                return 1;
            }
            else
                cout << "Unknown command: " << cmd << '\n';
        }
    }
```

Another example showing reading *and* writing of files is provided by the next program. It also illustrates the processing of NTBSs:

```
    #include <iostream>
    #include <fstream>
    using namespace std;

    int main()
    {                                         // r/w the file
        fstream f("hello", ios::in | ios::out | ios::trunc);

        f.write("hello", 6);                  // write 2 NTB strings
        f.write("hello", 6);

        f.seekg(0, ios::beg);                 // reset to begin of file

        char buffer[100];                     // or: char *buffer = new char[100]
        char c;
                                              // read the first `hello'
        cout << f.get(buffer, sizeof(buffer), 0).tellg() << '\n';
        f >> c;                               // read the NTB delim

                                              // and read the second `hello'
        cout << f.get(buffer + 6, sizeof(buffer) - 6, 0).tellg() << '\n';

        buffer[5] = ' ';                      // change asciiz to ' '
        cout << buffer << '\n';               // show 2 times `hello'
    }
    /*
        Generated output:
    5
    11
    hello hello
    */
```

A completely different way to read and write streams may be implemented using `streambuf` members. All considerations mentioned so far remain valid (e.g., before a read operation following a write operation `seekg` must be used). When `streambuf` objects are used, either an `istream` is associated with the `streambuf` object of another `ostream` object, or an `ostream` object is associated with the `streambuf` object of another `istream` object. Here is the previous program again, now using *associated streams*:

```
    #include <iostream>
    #include <fstream>
    #include <string>
    using namespace std;
```

```
void err(char const *msg);      // see earlier example
void err(char const *msg, long value);

void read(istream &index, istream &strings)
{
    index.clear();
    strings.clear();

    // insert the body of the read() function of the earlier example
}


void write(ostream &index, ostream &strings)
{
    index.clear();
    strings.clear();

    // insert the body of the write() function of the earlier example
}

int main()
{
    ifstream index_in("index", ios::trunc | ios::in | ios::out);
    ifstream strings_in("strings", ios::trunc | ios::in | ios::out);
    ostream  index_out(index_in.rdbuf());
    ostream  strings_out(strings_in.rdbuf());

    cout << "enter `r <number>' to read line <number> or "
                            "w <line>' to write a line\n"
            "or enter `q' to quit.\n";

    while (true)
    {
        cout << "r <nr>, w <line>, q ? ";       // show prompt

        string cmd;

        cin >> cmd;                             // read cmd

        if (cmd == "q")                         // process the cmd.
            return 0;

        if (cmd == "r")
            read(index_in, strings_in);
        else if (cmd == "w")
            write(index_out, strings_out);
        else
            cout << "Unknown command: " << cmd << '\n';
    }
}
```

In this example

- the streams associated with the `streambuf` objects of existing streams are not `ifstream` or `ofstream` objects but basic `istream` and `ostream` objects.

- The `streambuf` object is not defined by an `ifstream` or `ofstream` object. Instead it is defined outside of the streams, using a `filebuf` (cf. section 14.8.2) and constructions like:

  ```
  filebuf fb("index", ios::in | ios::out | ios::trunc);
  istream index_in(&fb);
  ostream index_out(&fb);
  ```

- An `ifstream` object can be constructed using stream modes normally used with `ofstream` objects. Conversely, an `ofstream` objects can be constructed using stream modes normally used with `ifstream` objects.
- If `istream` and `ostreams` share a `streambuf`, then their read and write pointers (should) point to the shared buffer: they are tightly coupled.
- The advantage of using an external (separate) `streambuf` over a predefined `fstream` object is (of course) that it opens the possibility of using `stream` objects with specialized `streambuf` objects. These `streambuf` objects may specifically be constructed to control and interface particular devices. Elaborating this (see also section 14.8) is left as an exercise to the reader.

Chapter 7

Classes

The **C** programming language offers two methods for structuring data of different types. The **C** `struct` holds data members of various types, and the **C** `union` also defines data members of various types. However, a union's data members all occupy the same location in memory and the programmer may decide on which one to use.

In this chapter classes are introduced. A `class` is a kind of `struct`, but its content is by default inaccessible to the outside world, whereas the content of a **C++** `struct` is by default accessible to the outside world. In **C++** `struct`s find little use: they are mainly used to aggregate data within the context of classes or to define elaborate return values. Often a **C++** `struct` merely contains *plain old data* (POD, cf. section 9.10). In **C++** the `class` is the main data structuring device, by default enforcing two core concepts of current-day software engineering: *data hiding* and *encapsulation* (cf. sections 3.2.1 and 7.1.1).

The `union` is another data structuring device the language offers. The traditional **C** union is still available, but **C++** also offers *unrestricted unions*. Unrestricted unions are unions whose data fields may be of class types. The **C++** Annotations covers these unrestricted unions in section 9.9, after having introduced several other new concepts of **C++**,

C++ extends the **C** `struct` and `union` concepts by allowing the definition of *member* functions (introduced in this chapter) within these data types. Member functions are functions that can only be used with objects of these data types or within the scope of these data types. Some of these member functions are special in that they are always, usually automatically, called when an object starts its life (the so-called *constructor*) or ends its life (the so-called *destructor*). These and other types of member functions, as well as the design and construction of, and philosophy behind, classes are introduced in this chapter.

We step-by-step construct a class `Person`, which could be used in a database application to store a person's name, address and phone number.

Let's start by creating a `class Person` right away. From the onset, it is important to make the distinction between the class *interface* and its *implementation*. A class may loosely be defined as 'a set of data and all the functions operating on those data'. This definition is later refined but for now it is sufficient to get us started.

A class interface is a definition, defining the organization of objects of that class. Normally a definition results in memory reservation. E.g., when defining `int variable` the compiler ensures that some memory is reserved in the final program storing `variable`'s values. Although it is a definition no memory is set aside by the compiler once it has processed the class definition. But a class definition follows the *one definition rule*: in **C++** entities may be defined only once. As a *class definition* does not imply that memory is being reserved the term *class interface* is preferred instead.

Class interfaces are normally contained in a class *header file*, e.g., `person.h`. We'll start our `class Person` interface here (cf section 7.7 for an explanation of the `const` keywords behind some of the class's member functions):

```
#include <string>

class Person
{
    std::string d_name;          // name of person
    std::string d_address;       // address field
    std::string d_phone;         // telephone number
    size_t      d_mass;          // the mass in kg.

    public:                      // member functions
        void setName(std::string const &name);
        void setAddress(std::string const &address);
        void setPhone(std::string const &phone);
        void setMass(size_t mass);

        std::string const &name()    const;
        std::string const &address() const;
        std::string const &phone()   const;
        size_t mass()                const;
};
```

The member functions that are *declared* in the interface must still be implemented. The implementation of these members is properly called their definition.

In addition to member *functions* classes also commonly define the *data* that are manipulated by those member functions. These data are called the *data members*. In `Person` they are `d_name`, `d_address`, `d_phone` and `d_mass`. Data members should be given private access rights. Since the class uses private access rights by default they are usually simply listed at the top of the class interface.

All communication between the outer world and the class data is routed through the class's member functions. Data members may receive new values (e.g., using `setName`) or they may be retrieved for inspection (e.g., using `name`). Functions merely returning values stored inside the object, not allowing the caller to modify these internally stored values, are called *accessors*.

Syntactically there is only a marginal difference between a class and a struct. Classes by default define *private* members, structs define *public* members. Conceptually, though, there are differences. In **C++** structs are used in the way they are used in **C**: to aggregate data, which are all freely accessible. Classes, on the other hand, hide their data from access by the outside world (which is aptly called *data hiding*) and offer member functions to define the communication between the outer world and the class's data members.

Following *Lakos* (Lakos, J., 2001) **Large-Scale C++ Software Design** (Addison-Wesley) I suggest the following setup of class interfaces:

- All data members have *private access rights*, and are placed at the top of the interface.
- All data members start with `d_`, followed by a name suggesting their meaning (in chapter 8 we'll also encounter data members starting with `s_`).
- Non-private data members *do* exist, but one should be hesitant to define non-private access rights for data members (see also chapter 13).

- Two broad categories of member functions are *manipulators* and *accessors*. Manipulators allow the users of objects to modify the internal data of the objects. By convention, manipulators start with `set`. E.g., `setName`.
- With *accessors*, a `get`-prefix is still frequently encountered, e.g., `getName`. However, following the conventions promoted by the **Qt** (see `http://www.trolltech.com`) *Graphical User Interface Toolkit*, the `get`-prefix is now deprecated. So, rather than defining the member `getAddress`, it should simply be named `address`.
- Normally (exceptions exist) the public member functions of a class are listed first, immediately following the class's data members. They are the important elements of the interface as they define the features the class is offering to its users. It's a matter of convention to list them high up in the interface. The keyword `private` is needed beyond the public members to switch back from public members to private access rights which nicely separates the members that may be used 'by the general public' from the class's own support members.

Style conventions usually take a long time to develop. There is nothing obligatory about them, though. I suggest that readers who have compelling reasons *not* to follow the above style conventions use their own. All others are strongly advised to adopt the above style conventions.

Finally, referring back to section 3.1.2 that

```
using namespace std;
```

must be used in most (if not all) examples of source code. As explained in sections 7.11 and 7.11.1 the `using` directive should follow the preprocessor directive(s) including the header files, using a setup like the following:

```
#include <iostream>
#include "person.h"

using namespace std;

int main()
{
    ...
}
```

7.1 The constructor

C++ classes usually contain two special categories of member functions which are essential to the proper working of classes. These categories are the constructors and the destructor. The *destructor*'s primary task is to return memory allocated by an object to the common pool when an object goes 'out of scope'. Allocation of memory is discussed in chapter 9, and an in-depth coverage of destructors is therefore postponed until we reach that chapter. In the current chapter the emphasis is on the class's internal organization and on its constructors.

Constructors are recognized by their names which are equal to their class names. Constructors do not specify return values, not even `void`. E.g., the class `Person` may define a constructor `Person::Person()`. The **C++** run-time system ensures that the constructor of a class is called when a variable of the class is defined. It is possible to define a class lacking any constructor. In that case the compiler defines a default constructor that is called when an object of that class is defined. What actually happens in that case depends on the data members that are defined by that class (cf. section 7.3.1).

Objects may be defined locally or globally. However, in **C++** most objects are defined locally. Globally defined objects are hardly ever required and are somewhat deprecated.

When a function defines a local object, that object's constructor is called every time the function is called. The object's constructor is activated at the point where the object is defined (a subtlety is that an object may be defined implicitly as, e.g., a temporary variable in an expression).

When an object is defined as a static object it is constructed when the program starts. In this case its constructor is called even before the function `main` starts. Example:

```
#include <iostream>
using namespace std;

class Demo
{
    public:
        Demo();
};

Demo::Demo()
{
    cout << "Demo constructor called\n";
}

Demo d;

int main()
{}

/*
    Generated output:
Demo constructor called
*/
```

The program contains one global object of the class `Demo` with `main` having an empty body. Nonetheless, the program produces some output generated by the constructor of the globally defined `Demo` object.

Constructors have a very important and well-defined role. They must ensure that all the class's data members have sensible or at least well-defined values once the object has been constructed. We'll get back to this important task shortly. The *default constructor* has no argument. It is defined by the compiler unless another constructor is defined and unless its definition is suppressed (cf. section 7.6). If a default constructor is required in addition to another constructor then the default constructor must explicitly be defined as well. **C++** provides special syntax to realize that without much effort, which is also covered by section 7.6.

7.1.1 A first application

Our example class `Person` has three string data members and a `size_t d_mass` data member. Access to these data members is controlled by interface functions.

Whenever an object is defined the class's constructor(s) ensure that its data members are given 'sensible' values. Thus, objects never suffer from uninitialized values. Data members may be given new values, but that should never be directly allowed. It is a core principle (called *data hiding*) of good class design that its data members are private. The modification of data members is therefore fully controlled by member functions and thus, indirectly, by the class-designer. The class *encapsulates* all actions performed on its data members and due to this *encapsulation* the class object may assume the 'responsibility' for its own data-integrity. Here is a minimal definition of `Person`'s manipulating members:

```
#include "person.h"                 // given earlier
using namespace std;

void Person::setName(string const &name)
{
    d_name = name;
}
void Person::setAddress(string const &address)
{
    d_address = address;
}
void Person::setPhone(string const &phone)
{
    d_phone = phone;
}
void Person::setMass(size_t mass)
{
    d_mass = mass;
}
```

It's a minimal definition in that no checks are performed. But it should be clear that checks are easy to implement. E.g., to ensure that a phone number only contains digits one could define:

```
void Person::setPhone(string const &phone)
{
    if (phone.empty())
        d_phone = " - not available -";
    else if (phone.find_first_not_of("0123456789") == string::npos)
        d_phone = phone;
    else
        cout << "A phone number may only contain digits\n";
}
```

Note the double negation in this implementation. Double negations are very hard to read, and an encapsulating member `bool hasOnly` handles the test, and improves `setPhone's` readability:

```
bool Person::hasOnly(char const *characters, string const &object)
{
                    // object only contains 'characters'
    return object.find_first_not_of(characters) == string::npos;
}
```

and `setPhone` becomes:

```
void Person::setPhone(string const &phone)
{
    if (phone.empty())
        d_phone = " - not available -";
    else if (hasOnly("0123456789", phone))
```

```
            d_phone = phone;
        else
            cout << "A phone number may only contain digits\n";
    }
```

Since `hasOnly` is an encapsulated member function we can ensure that it's only used with non-empty string objects, so `hasOnly` itself doesn't have to check for that.

Access to the data members is controlled by *accessor* members. Accessors ensure that data members cannot suffer from uncontrolled modifications. Since accessors conceptually do not modify the object's data (but only retrieve the data) these member functions are given the predicate `const`. They are called *const member functions*, which, as they are guaranteed not to modify their object's data, are available to both modifiable and constant objects (cf. section 7.7).

To prevent *backdoors* we must also make sure that the data member is not modifiable through an accessor's return value. For values of built-in primitive types that's easy, as they are usually returned by value, which are copies of the values found in variables. But since objects may be fairly large making copies is usually prevented by returning objects by reference. A backdoor is created by returning a data member by reference, as in the following example, showing the allowed abuse below the function definition:

```
    string &Person::name() const
    {
        return d_name;
    }

    Person somebody;
    somebody.setName("Nemo");

    somebody.name() = "Eve";    // Oops, backdoor changing the name
```

To prevent the backdoor objects are returned as *const references* from accessors. Here are the implementations of `Person`'s accessors:

```
    #include "person.h"                  // given earlier
    using namespace std;

    string const &Person::name() const
    {
        return d_name;
    }
    string const &Person::address() const
    {
       return d_address;
    }
    string const &Person::phone() const
    {
       return d_phone;
    }
    size_t Person::mass() const
    {
       return d_mass;
    }
```

The `Person` class interface remains the starting point for the class design: its member functions define what can be asked of a `Person` object. In the end the implementation of its members merely is a technicality allowing `Person` objects to do their jobs.

The next example shows how the class `Person` may be used. An object is initialized and passed to a function `printperson()`, printing the person's data. Note the reference operator in the parameter list of the function `printperson`. Only a reference to an existing `Person` object is passed to the function, rather than a complete object. The fact that `printperson` does not modify its argument is evident from the fact that the parameter is declared `const`.

```
    #include <iostream>
    #include "person.h"                 // given earlier
    using namespace std;

    void printperson(Person const &p)
    {
        cout << "Name    : " << p.name()      << "\n"
                "Address : " << p.address()   << "\n"
                "Phone   : " << p.phone()     << "\n"
                "Mass  : " << p.mass()   << '\n';
    }

    int main()
    {
        Person p;

        p.setName("Linus Torvalds");
        p.setAddress("E-mail: Torvalds@cs.helsinki.fi");
        p.setPhone("");
        p.setMass(75);           // kg.

        printperson(p);
    }
/*
    Produced output:

Name    : Linus Torvalds
Address : E-mail: Torvalds@cs.helsinki.fi
Phone   :  - not available -
Mass  : 75

*/
```

7.1.2 Constructors: with and without arguments

The class `Person`'s constructor so far has not received any parameters. **C++** allows constructors to be defined with or without parameter lists. The arguments are supplied when an object is defined.

For the class `Person` a constructor expecting three strings and a `size_t` might be useful. Representing, respectively, the person's name, address, phone number and mass. This constructor can be implemented like this (but see also section 7.3.1):

```
    Person::Person(string const &name, string const &address,
                   string const &phone, size_t mass)
    {
        d_name = name;
        d_address = address;
        setPhone(phone);
        d_mass = mass;
    }
```

It must of course also be declared in the class interface:

```
    class Person
    {
        // data members (not altered)

        public:
            Person(std::string const &name, std::string const &address,
                   std::string const &phone, size_t mass);

            // rest of the class interface (not altered)
    };
```

Now that this constructor has been declared, the default constructor must explicitly be declared as well if we still want to be able to construct a plain `Person` object without any specific initial values for its data members. The class `Person` would thus support two constructors, and the part declaring the constructors now becomes:

```
    class Person
    {
        // data members
        public:
            Person();
            Person(std::string const &name, std::string const &address,
                   std::string const &phone, size_t mass);

            // additional members
    };
```

In this case, the default constructor doesn't have to do very much, as it doesn't have to initialize the `string` data members of the `Person` object. As these data members are objects themselves, they are initialized to empty strings by their own default constructor. However, there is also a `size_t` data member. That member is a variable of a built-in type and such variabes do not have constructors and so are not initialized automatically. Therefore, unless the value of the `d_mass` data member is explicitly initialized its value is:

- a *random* value for local `Person` objects;
- 0 for global and static `Person` objects.

The 0-value might not be too bad, but normally we don't want a *random* value for our data members. So, even the default constructor has a job to do: initializing the data members which are not initialized to sensible values automatically. Its implementation can be:

```
    Person::Person()
    {
        d_mass = 0;
    }
```

Using constructors with and without arguments is illustrated next. The object `karel` is initialized by the constructor defining a non-empty parameter list while the default constructor is used for the `anon` object. When constructing objects using constructors requiring arguments you are advised to surround the arguments by curly braces. Parentheses can often also be used, and sometimes even *have* to be used (cf. section 12.4.2), but mindlessly using parentheses instead of curly braces may easily result in unexpected problems (cf. section 7.2). Hence the advice to prefer curly braces rather than parentheses. Here's the example showing two constructor-calls:

```
int main()
{
    Person karel{ "Karel", "Rietveldlaan 37", "542 6044", 70 };
    Person anon;
}
```

The two `Person` objects are defined when `main` starts as they are *local* objects, living only for as long as `main` is active.

If `Person` objects must be definable using other arguments, corresponding constructors must be added to `Person`'s interface. Apart from overloading class constructors it is also possible to provide constructors with default argument values. These default arguments must be specified with the constructor declarations in the class interface, like so:

```
class Person
{
    public:
        Person(std::string const &name,
               std::string const &address = "--unknown--",
               std::string const &phone   = "--unknown--",
               size_t mass = 0);

};
```

Often, constructors use highly similar implementions. This results from the fact that the constructor's parameters are often defined for convenience: a constructor not requiring a `phone` number but requiring a `mass` cannot be defined using default arguments, since `phone` is not the constructor's last parameter. Consequently a special constructor is required not having `phone` in its parameter list. However, this doesn't necessarily mean that constructors must duplicate their code, as constructors may call each other (called *constructor delegation*). Constructor delegation is illustrated in section 7.4.1 below.

7.1.2.1 The order of construction

The possibility to pass arguments to constructors allows us to monitor the construction order of objects during program execution. This is illustrated by the next program using a class `Test`. The program defines a global `Test` object and two local `Test` objects. The order of construction is as expected: first global, then main's first local object, then `func`'s local object, and then, finally, `main`'s second local object:

```
#include <iostream>
#include <string>
using namespace std;

class Test
```

```
    {
        public:
            Test(string const &name);   // constructor with an argument
    };

    Test::Test(string const &name)
    {
        cout << "Test object " << name << " created" << '\n';
    }

    Test globaltest("global");

    void func()
    {
        Test functest("func");
    }

    int main()
    {
        Test first{ "main first" };
        func();
        Test second{ "main second" };
    }
/*
    Generated output:
Test object global created
Test object main first created
Test object func created
Test object main second created
*/
```

7.2 Ambiguity resolution

Calling constructors using parentheses may result in unexpected surprises. Assume the following class interface is available:

```
    class Data
    {
        public:
            Data();
            Data(int one);
            Data(int one, int two);

            void display();
    };
```

The intention is to define two objects of the class Data, using, respectively, the first and second constructors, while using parentheses in the object definitions. Your code looks like this (and compiles correctly):

```
    #include "data.h"
    int main()
    {
        Data d1();
        Data d2(argc);
    }
```

Now it's time to make some good use of the `Data` objects. Let's add two statements to `main`:

```
        d1.display();
        d2.display();
```

But, surprise, the compiler complains about the first of these two:

error: request for member 'display' in 'd1', which is of non-class type 'Data()'

What's going on here? First of all, notice the data type the compiler refers to: `Data()`, rather than `Data`. What are those `()` doing there?

Before answering that question, let's broaden our story somewhat. We know that somewhere in a library a *factory function* `dataFactory` exists. A factory function creates and returns an object of a certain type. This `dataFactory` function returns a `Data` object, constructed using `Data`'s default constructor. Hence, `dataFactory` needs no arguments. We want to use `dataFactory` in our program, but must declare the function. So we add the declaration to `main`, as that's the only location where `dataFactory` will be used. It's a function, not requiring arguments, returning a `Data` object:

```
        Data dataFactory();
```

This, however, looks remarkably similar to our `d1` object definition:

```
        Data d1();
```

We found the source of our problem: `Data d1()` apparently is *not* the definition of a `d1` object, but the *declaration* of a function, returning a `Data` object. So, what's happening here and how should we define a `Data` object using `Data`'s default constructor?

First: what's happening here is that the compiler, when confronted with `Data d1()`, actually had a choice. It could either define a `Data` object, or declare a function. It declares a function.

In fact, we're encountering an ambiguity in **C++**'s grammar here, which is solved, according to the language's standard, by always letting a declaration prevail over a definition. We'll encounter more situations where this ambiguity occurs later on in this section.

Second: there are several ways we can solve this ambiguity the way we want it to be solved. To define an object using its default constructor:

- merely mention it (like `int x`): `Data d1`;
- use the curly-brace initialization: `Data d1{}`;
- use the assignment operator and an anonymous default constructed `Data` object: `Data d1 = Data{}`, or possibly `Data d1 = Data()`.

7.2.1 Types 'Data' vs. 'Data()'

`Data()` in the above context defines a default constructed anonymous `Data` object. This takes us back to the compiler error. According to the compiler, our original `d1` apparently was not of type `Data`, but of type `Data()`. So what's that?

Let's first have a look at our second constructor. It expects an `int`. We would like to define another `Data` object, using the second constructor, but want to pass the default `int` value to the constructor, using `int()`. We know this defines a default `int` value, as `cout << int() << '\n'` nicely displays 0, and `int x = int()` also initialized x to 0. So we define `'Data di(int())'` in `main`.

Not good: again the compiler complains when we try to use `di`. After `'di.display()'` the compiler tells us:

error: request for member 'display' in 'di', which is of non-class type 'Data(int (*)())'

Oops, again not as expected.... Didn't we pass 0? Why the sudden pointer? It's that same 'use a declaration when possible' strategy again. The notation `Type()` not only represents the default value of type `Type`, but it's also a shorthand notation for an anonymous pointer to a function, not expecting arguments, and returning a `Type` value, which you can verify by defining `'int (*ip)() = nullptr'`, and passing `ip` as argument to `di`: `di(ip)` compiles fine.

So why doesn't the error occur when inserting `int()` or assigning `int()` to `int x`? In these latter cases nothing is declared. Rather, '`cout`' and '`int x =`' require expressions determining values, which is provided by `int()`'s 'natural' interpretation. But with `'Data di(int())'` the compiler again has a choice, and (by design) it chooses a declaration because the declaration takes priority. Now `int()`'s interpretation as an anonymous pointer is available and therefore used.

Likewise, if `int x` has been defined, `'Data b1(int(x))'` declares `b1` as a function, expecting an `int` (as `int(x)` represents a type), while `'Data b2((int)x)'` defines `b2` as a `Data` object, using the constructor expecting a single `int` value.

Again, to use default entities, values or objects, prefer `{}` over `()`: `Data di{ int{} }` defines `di` of type `Data`, calling the `Data(int x)` constructor and uses `int's` default value 0.

7.2.2 Superfluous parentheses

Let's play some more. At some point in our program we defined `int b`. Then, in a compound statement we need to construct an anonymous `Data` object, initialized using `b`, followed by displaying `b`:

```
int b = 18;
{
    Data(b);
    cout << b;
}
```

About that `cout` statement the compiler tells us (I modified the error message to reveal its meaning):

error: cannot bind 'std::ostream & << Data const &'

Here we didn't insert `int b` but `Data b`. Had we omitted the compound statement, the compiler would have complained about a doubly defined `b` entity, as `Data(b)` simply means `Data b`, a `Data` object constructed by default. The compiler may omit superfluous parentheses when parsing a definition or declaration.

Of course, the question now becomes how a temporary object `Data`, initialized with `int b` can be defined. Remember that the compiler may remove superfluous parentheses. So, what we need to do is to pass an `int` to the anonymous `Data` object, without using the `int`'s name.

- We can use a cast: `Data(static_cast<int>(b));`

- We can use a curly-brace initialization: `Data{ b }`.

Values and types make big differences. Consider the following definitions:

```
Data (*d4)(int);     // 1
Data (*d5)(3);       // 2
```

Definition 1 should cause no problems: it's a pointer to a function, expecting an `int`, returning a `Data` object. Hence, `d4` is a pointer variable.

Definition 2 is slightly more complex. Yes, it's a pointer. But it has nothing to do with a function. So what's that argument list containing 3 doing there? Well, it's not an argument list. It's an initialization that looks like an argument list. Remember that variables can be initialized using the assignment statement, by parentheses or by curly parentheses. So instead of '`(3)`' we could have written '`= 3`' or '`{3}`'. Let's pick the first alternative, resulting in:

```
Data (*d5) = 3;
```

Now we get to 'play compiler' again. Removing some superfluous parentheses we get:

```
Data *d5 = 3;
```

It's a pointer to a `Data` object, initialized to 3. This is semantically incorrect, but that's only clear after the syntactical analysis. If I had initially written

```
 Data (*d5)(&d1);      // 2
```

the fun resulting from contrasting `int` and `3` would most likely have been spoiled.

7.2.3 Existing types

Once a type name has been defined it also prevails over identifiers representing variables, if the compiler is given a choice. This, too, can result in interesting constructions.

Assume a function `process` expecting an `int` exists in a library. We want to use this function to process some `int` data values. So in `main` `process` is declared and called:

```
int process(int Data);
process(argc);
```

No problems here. But unfortunately we once decided to 'beautify' our code, by throwing in some superfluous parentheses, like so:

```
int process(int (Data));
process(argc);
```

Now we're in trouble. The compiler now generates an error, caused by its rule to let declarations prevail over definitions. `Data` now becomes the name of the `class Data`, and analogous to `int (x)` the parameter `int (Data)` is parsed as `int (*)(Data)`: a pointer to a function, expecting a `Data` object, returning an `int`.

Here is another example. When, instead of declaring

```
int process(int Data[10]);
```

we declare, e.g., to emphasize the fact that an array is passed to `process`:

```
int process(int (Data[10]));
```

the `process` function does not expect a pointer to `int` values, but a pointer to a function expecting a pointer to `Data` elements, returning an `int`.

To summarize the findings in the 'Ambiguity Resolution' section:

- The compiler will try to remove superfluous parentheses;
- But if the parenthesized construction represents a type, it will try to use the type;
- More in general: when possible the compiler will interpret a syntactic construction as a declaration, rather than as a definition (of an object or variable).
- Most problems that result from the compiler interpreting constructions as declarations are caused by us using parentheses. As a rule of thumb: use curly braces, rather than parentheses when constructing objects (or values).

7.3 Objects inside objects: composition

In the class `Person` objects are used as data members. This construction technique is called *composition*.

Composition is neither extraordinary nor **C++** specific: in **C** a `struct` or `union` field is commonly used in other compound types. In **C++** it requires some special thought as their initialization sometimes is subject to restrictions, as discussed in the next few sections.

7.3.1 Composition and (const) objects: (const) member initializers

Unless specified otherwise object data members of classes are initialized by their default constructors. Using the default constructor might not always be the optimal way to intialize an object and it might not even be possible: a class might simply not define a default constructor.

Earlier we've encountered the following constructor of the `Person`:

```
Person::Person(string const &name, string const &address,
               string const &phone, size_t mass)
{
    d_name = name;
    d_address = address;
    d_phone = phone;
    d_mass = mass;
}
```

Think briefly about what is going on in this constructor. In the constructor's body we encounter assignments to string objects. Since assignments are used in the constructor's body their left-hand side objects must exist. But when objects are coming into existence constructors *must* have been called. The initialization of those objects is thereupon immediately undone by the body of `Person`'s constructor. That is not only inefficient but sometimes downright impossible. Assume that the class interface mentions a `string const` data member: a data member whose value is not supposed to change at all (like a birthday, which usually doesn't change very much and is therefore a good candidate for a `string const` data member). Constructing a birthday object and providing it with an initial value is OK, but changing the initial value isn't.

The body of a constructor allows assignments to data members. The *initialization* of data members happens before that. **C++** defines the *member initializer* syntax allowing us to specify the way data members are initialized at construction time. Member initializers are specified as a list of constructor specifications between a colon following a constructor's parameter list and the opening curly brace of a constructor's body, as follows:

```
Person::Person(string const &name, string const &address,
               string const &phone, size_t mass)
:
    d_name(name),
    d_address(address),
    d_phone(phone),
    d_mass(mass)
{}
```

In this example the member initialization used parentheses surrounding the intialization expression. Instead of parentheses *curly braces* may also be used. E.g., `d_name` could also be initialized this way:

```
    d_name{ name },
```

Member initialization *always* occurs when objects are composed in classes: if *no* constructors are mentioned in the member initializer list the default constructors of the objects are called. Note that this only holds true for *objects*. Data members of primitive data types are *not* initialized automatically.

Member initialization can, however, also be used for primitive data members, like `int` and `double`. The above example shows the initialization of the data member `d_mass` from the parameter `mass`. When member initializers are used the data member could even have the same name as the constructor's parameter (although this is deprecated) as there is no ambiguity and the first (left) identifier used in a member initializer is always a data member that is initialized whereas the identifier between parentheses is interpreted as the parameter.

The *order* in which class type data members are initialized is defined by the order in which those members are defined in the composing class interface. If the order of the initialization in the constructor differs from the order in the class interface, the compiler complains, and reorders the initialization so as to match the order of the class interface.

Member initializers should be used as often as possible. As shown it may be required to use them (e.g., to initialize const data members, or to initialize objects of classes lacking default constructors) but *not* using member initializers also results in inefficient code as the default constructor of a data member is always automatically called unless an explicit member initializer is specified. Reassignment in the constructor's body following default construction is then clearly inefficient. Of course, sometimes it is fine to use the default constructor, but in those cases the explicit member initializer can be omitted.

As a rule of thumb: if a value is assigned to a data member in the constructor's body then try to avoid that assignment in favor of using a member initializer.

7.3.2 Composition and reference objects: reference member initializers

Apart from using member initializers to initialize composed objects (be they `const` objects or not), there is another situation where member initializers must be used. Consider the following situation.

A program uses an object of the class `Configfile`, defined in `main` to access the information in a configuration file. The configuration file contains parameters of the program which may be set by changing the values in the configuration file, rather than by supplying command line arguments.

Assume another object used in `main` is an object of the class `Process`, doing 'all the work'. What possibilities do we have to tell the object of the class `Process` that an object of the class `Configfile` exists?

- The objects could have been declared as *global* objects. This *is* a possibility, but not a very good one, since all the advantages of local objects are lost.
- The `Configfile` object may be passed to the `Process` object at construction time. Bluntly passing an object (i.e., by value) might not be a very good idea, since the object must be copied into the `Configfile` parameter, and then a data member of the `Process` class can be used to make the `Configfile` object accessible throughout the `Process` class. This might involve yet another object-copying task, as in the following situation:

  ```
  Process::Process(Configfile conf)    // a copy from the caller
  {
      d_conf = conf;                   // copying to d_conf member
  }
  ```

- The copy-instructions can be avoided if *pointers* to the `Configfile` objects are used, as in:

  ```
  Process::Process(Configfile *conf)   // pointer to external object
  {
      d_conf = conf;                   // d_conf is a Configfile *
  }
  ```

  This construction as such is OK, but forces us to use the '`->`' field selector operator, rather than the '`.`' operator, which is (disputably) awkward. Conceptually one tends to think of the `Configfile` object as an object, and not as a pointer to an object. In **C** this would probably have been the preferred method, but in **C++** we can do better.

- Rather than using value or pointer parameters, the `Configfile` parameter could be defined as a *reference parameter* of `Process`'s constructor. Next, use a `Config` reference data member in the `class Process`.

But a reference variable cannot be initialized using an assignment, and so the following is incorrect:

```
Process::Process(Configfile &conf)
{
    d_conf = conf;        // wrong: no assignment
}
```

The statement `d_conf = conf` fails, because it is not an initialization, but an assignment of one `Configfile` object (i.e., `conf`), to another (`d_conf`). An assignment to a reference variable is actually an assignment to the variable the reference variable refers to. But which variable does `d_conf` refer to? To no variable at all, since we haven't initialized `d_conf`. After all, the whole purpose of the statement `d_conf = conf` was to initialize `d_conf`....

How to initialize `d_conf`? We once again use the member initializer syntax. Here is the correct way to initialize `d_conf`:

```
Process::Process(Configfile &conf)
:
    d_conf(conf)      // initializing reference member
{}
```

The above syntax must be used in all cases where reference data members are used. E.g., if `d_ir` would have been an `int` reference data member, a construction like

```
Process::Process(int &ir)
:
    d_ir(ir)
{}
```

would have been required.

7.4 Data member initializers

Non-static data members of classes are usually initialized by the class's constructors. Frequently (but not always) the same initializations are used by different constructors, resulting in multiple points where the initializations are performed, which in turn complicates class maintenance.

Consider a class defining several data members: a pointer to data, a data member storing the number of data elements the pointer points at, a data member storing the sequence number of the object. The class also offer a basic set of constructors, as shown in the following class interface:

```
class Container
{
    Data *d_data;
    size_t d_size;
    size_t d_nr;

    static size_t s_nObjects;

    public:
        Container();
        Container(Container const &other);
        Container(Data *data, size_t size);
        Container(Container &&tmp);
};
```

The initial values of the data members are easy to describe, but somewhat hard to implement. Consider the initial situation and assume the default constructor is used: all data members should be set to 0, except for `d_nr` which must be given the value `++s_nObjects`. Since these are *non*-default actions, we can't declare the default constructor using `= default`, but we must provide an actual implementation:

```
Container()
:
    d_data(0),
        d_size(0),
        d_nr(++s_nObjects)
    {}
```

In fact, *all* constructors require us to state the `d_nr(++s_nObjects)` initialization. So if `d_data`'s type would have been a (move aware) class type, we would still have to provide implementations for all of the above constructors.

C++, however, also supports *data member initializers*, simplifying the initialization of non-static data members. Data member initializers allow us to assign initial values to data members. The compiler must be able to compute these initial values from initialization expressions, but the initial values do not have to be constant expressions. So `++s_nObjects` can be an initial value.

Using data member initializers for the class `Container` we get:

```
    class Container
    {
        Data *d_data = 0;
        size_t d_size = 0;
        size_t d_nr = ++s_nObjects;

        static size_t s_nObjects;

        public:
            Container() = default;
            Container(Container const &other);
            Container(Data *data, size_t size);
            Container(Container &&tmp);
    };
```

Note that the data member initializations are recognized by the compiler, and are applied to its implementation of the default constructor. In fact, all constructors will apply the data member initializations, unless explicitly initialized otherwise. E.g., the move-constructor may now be implemented like this:

```
    Container(Container &&tmp)
    :
        d_data(tmp.d_data),
        d_size(tmp.d_size)
    {
        tmp.d_data = 0;
    }
```

Although `d_nr`'s intialization is left out of the implementation it *is* initialized due to the data member initialization provided in the class's interface.

An *aggregate* is an array or a `class` (usually a `struct` with no user-defined constructors, no private or protected non-static data members, no base classes (cf. chapter 13), and no virtual functions (cf. chapter 14)). E.g.,

```
    struct POD      // defining aggregate POD
    {
        int first = 5;
        double second = 1.28;
        std::string hello{ "hello" };
    };
```

To initialize such aggregates *braced initializer lists* can be used. In fact, their use is preferred over using the older form (using parentheses), as using braces avoids confusion with function declarations. E.g.,

```
POD pod{ 4, 13.5, "hi there" };
```

When using braced-initializer lists not all data members need to be initialized. Specification may stop at any data member, in which case the default (or explicitly defined initialization values) of the remaining data members are used. E.g.,

```
POD pod{ 4 };   // uses second: 1.28, hello: "hello"
```

7.4.1 Delegating constructors

Often constructors are specializations of each other, allowing objects to be constructed specifying only subsets of arguments for all of its data members, using default argument values for the remaining data members.

Before the C++11 standard common practice was to define a member like `init` performing all initializations common to constructors. Such an `init` function, however, cannot be used to initialize `const` or reference data members, nor can it be used to perform so-called *base class* initializations (cf. chapter 13).

Here is an example where such an `init` function might have been used. A class `Stat` is designed as a wrapper class around **C**'s **stat**(2) function. The class might define three constructors: one expecting no arguments and initializing all data members to appropriate values; a second one doing the same, but it calls `stat` for the filename provided to the constructor; and a third one expecting a filename and a search path for the provided file name. Instead of repeating the initialization code in each constructor, the common code can be factorized into a member `init` which is called by the constructors.

C++ offers an alternative by allowing constructors to call each other. This is called *delegating constructors* which is illustrated by the next example:

```
class Stat
{
    public:
        Stat()
        :
            Stat("", "")        // no filename/searchpath
        {}
        Stat(std::string const &fileName)
        :
            Stat(fileName, "")  // only a filename
        {}
        Stat(std::string const &fileName, std::string const &searchPath)
        :
            d_filename(fileName),
            d_searchPath(searchPath)
        {
            // remaining actions to be performed by the constructor
        }
};
```

C++ allows static const integral data members to be initialized within the class interfaces (cf. chapter 8). The C++11 standard adds to this the facility to define default initializations for plain data members in class interfaces (these data members may or may not be `const` or of integral types, but (of course) they cannot be reference data members).

These default initializations may be overruled by constructors. E.g., if the class `Stat` uses a data member `bool d_hasPath` which is `false` by default but the third constructor (see above) should initialize it to `true` then the following approach is possible:

```
class Stat
{
    bool d_hasPath = false;

    public:
        Stat(std::string const &fileName, std::string const &searchPath)
        :
            d_hasPath(true)     // overrule the interface-specified
        {}                      // value
};
```

Here `d_hasPath` receives its value only once: it's always initialized to `false` except when the shown constructor is used in which case it is initialized to `true`.

7.5 Uniform initialization

When defining variables and objects they may immediately be given initial values. Class type objects are always initialized using one of their available constructors. **C** already supports the array and struct *initializer list* consisting of a list of constant expressions surrounded by a pair of curly braces.

C++ supports a comparable initialization, called *uniform initialization*. It uses the following syntax:

```
Type object{ value list };
```

When defining objects using a list of objects each individual object may use its own uniform initialization.

The advantage of uniform initialization over using constructors is that using constructor arguments may sometimes result in an ambiguity as constructing an object may sometimes be confused with using the object's overloaded function call operator (cf. section 11.10). As initializer lists can only be used with *plain old data* (POD) types (cf. section 9.10) and with classes that are 'initializer list aware' (like `std::vector`) the ambiguity does not arise when initializer lists are used.

Uniform initialization can be used to initialize an object or variable, but also to initialize data members in a constructor or implicitly in the return statement of functions. Examples:

```
class Person
{
    // data members
    public:
        Person(std::string const &name, size_t mass)
        :
            d_name {name},
            d_mass {mass}
            {}

            Person copy() const
            {
                return {d_name, d_mass};
            }
    };
```

Object definitions may be encountered in unexpected places, easily resulting in (human) confusion. Consider a function '`func`' and a very simple class `Fun` (`struct` is used, as data hiding is not an issue here; in-class implementations are used for brevity):

```
    void func();

    struct Fun
    {
        Fun(void (*f)())
        {
            std::cout << "Constructor\n";
        };

        void process()
        {
            std::cout << "process\n";
        }
    };
```

Assume that in `main` a `Fun` object is defined as follows:

```
    Fun fun(func);
```

Running this program displays `Constructor`, confirming that the object `fun` is constructed.

Next we change this line of code, intending to call `process` from an anonymous `Fun` object:

```
    Fun(func).process();
```

As expected, `Constructor` appears, followed by the text `process`.

What about just defining an anonymous `Fun` object? We do:

```
    Fun(func);
```

Now we're in for a surprise. The compiler complains that `Fun`'s default constructor is missing. Why's that? Insert some blanks immediately after `Fun` and you get `Fun (func)`. Parentheses around an identifier are OK, and are stripped off once the parenthesized expression has been parsed. In this case: `(func)` equals `func`, and so we have `Fun func`: the definition of a `Fun func` object, using `Fun`'s default constructor (which isn't provided).

So why does `Fun(func).process()` compile? In this case we have a member selector operator, whose left-hand operand must be an class-type object. The object must exist, and `Fun(func)` represents that object. It's not the name of an existing object, but a constructor expecting a function like `func` exists. The compiler now creates an anonymous `Fun`, passing it `func` as its argument.

Clearly, in this example, parentheses cannot be used to create an anonymous `Fun` object. However, the uniform initialization *can* be used. To define the anonymous `Fun` object use this syntax:

```
Fun{ func };
```

(which can also be used to immediately call one of its members. E.g., `Fun{func}.process()`).

Although the uniform intialization syntax is slightly different from the syntax of an initializer list (the latter using the assignment operator) the compiler nevertheless uses the initializer list if a constructor supporting an initializer list is available. As an example consider:

```
class Vector
{
    public:
        Vector(size_t size);
        Vector(std::initializer_list<int> const &values);
};

Vector vi = {4};
```

When defining `vi` the constructor expecting the initializer list is called rather than the constructor expecting a `size_t` argument. If the latter constructor is required the definition using the standard constructor syntax must be used. I.e., `Vector vi(4)`.

Initializer lists are themselves objects that may be constructed using another initializer list. However, values stored in an initializer list are immutable. Once the initializer list has been defined their values remain as-is.

Before using initializer lists the `initializer_list` header file must be included.

Initializer lists support a basic set of member functions and constructors:

- `initializer_list<Type> object`:
  defines `object` as an empty initializer list
- `initializer_list<Type> object { list of Type values }`:
  defines `object` as an initializer list containing `Type` values
- `initializer_list<Type> object(other)`:
  initializes `object` using the values stored in `other`
- `size_t size() const`:
  returns the number of elements in the initializer list
- `Type const *begin() const`:
  returns a pointer to the first element of the initializer list
- `Type const *end() const`:
  returns a pointer just beyond the location of the last element of the initializer list

7.6 Defaulted and deleted class members

In everyday class design two situations are frequently encountered:

- A class offering constructors explicitly has to define a default constructor;

- A class (e.g., a class implementing a stream) cannot initialize objects by copying the values from an existing object of that class (called *copy construction*) and cannot assign objects to each other.

Once a class defines at least one constructor its default constructor is not automatically defined by the compiler. **C++** relaxes that restriction somewhat by offering the '`= default`' syntax. A class specifying '`= default`' with its default constructor declaration indicates that the trivial default constructor should be provided by the compiler. A trivial default constructor performs the following actions:

- Its data members of built-in or primitive types are not initialized;
- Its composed (class type) data members are initialized by their default constructors.
- If the class is derived from a base class (cf. chapter 13) the base class is initialized by its default constructor.

Trivial implementations can also be provided for the *copy constructor*, the *overloaded assignment operator*, and the *destructor*. Those members are introduced in chapter 9.

Conversely, situations exist where some (otherwise automatically provided) members should *not* be made available. This is realized by specifying '`= delete`'. Using `= default` and `= delete` is illustrated by the following example. The default constructor receives its trivial implementation, copy-construction is prevented:

```
class Strings
{
    public:
        Strings() = default;
        Strings(std::string const *sp, size_t size);

        Strings(Strings const &other) = delete;
};
```

7.7 Const member functions and const objects

The keyword `const` is often used behind the parameter list of member functions. This keyword indicates that a member function does not alter the data members of its object. Such member functions are called *const member functions*. In the class `Person`, we see that the accessor functions were declared `const`:

```
class Person
{
    public:
        std::string const &name()    const;
        std::string const &address() const;
        std::string const &phone()   const;
        size_t mass()              const;
};
```

The rule of thumb given in section 3.1.1 applies here too: whichever appears to the *left* of the keyword `const`, is not altered. With member functions this should be interpreted as 'doesn't alter its own data'.

When implementing a const member function the `const` attribute must be repeated:

```
string const &Person::name() const
{
    return d_name;
}
```

The compiler prevents the data members of a class from being modified by one of its const member functions. Therefore a statement like

```
d_name[0] = toupper(static_cast<unsigned char>(d_name[0]));
```

results in a compiler error when added to the above function's definition.

`Const` member functions are used to prevent inadvertent data modification. Except for constructors and the destructor (cf. chapter 9) only const member functions can be used with (plain, references or pointers to) `const` objects.

Const objects are frequently encountered as `const &` parameters of functions. Inside such functions only the object's const members may be used. Here is an example:

```
void displayMass(ostream &out, Person const &person)
{
    out << person.name() << " weighs " << person.mass() << " kg.\n";
}
```

Since `person` is defined as a `Person const &` the function `displayMass` cannot call, e.g., `person.setMass(75)`.

The `const` member function attribute can be used to overload member functions. When functions are overloaded by their `const` attribute the compiler uses the member function matching most closely the const-qualification of the object:

- When the object is a `const` object, only `const` member functions can be used.
- When the object is not a `const` object, non-`const` member functions are used, *unless* only a `const` member function is available. In that case, the `const` member function is used.

The next example illustrates how (non) `const` member functions are selected:

```
#include <iostream>
using namespace std;

class Members
{
    public:
        Members();
        void member();
        void member() const;
};

Members::Members()
{}
void Members::member()
```

```
{
    cout << "non const member\n";
}
void Members::member() const
{
    cout << "const member\n";
}

int main()
{
    Members const constObject;
    Members       nonConstObject;

    constObject.member();
    nonConstObject.member();
}
/*
        Generated output:

    const member
    non const member
*/
```

As a general principle of design: member functions should always be given the `const` attribute, unless they actually modify the object's data.

7.7.1 Anonymous objects

Sometimes objects are used because they offer a certain functionality. The objects only exist because of their functionality, and nothing in the objects themselves is ever changed. The following class `Print` offers a facility to print a string, using a configurable prefix and suffix. A partial class interface could be:

```
class Print
{
    public:
        Print(ostream &out);
        void print(std::string const &prefix, std::string const &text,
                 std::string const &suffix) const;
};
```

An interface like this would allow us to do things like:

```
Print print{ cout };
for (int idx = 0; idx != argc; ++idx)
    print.print("arg: ", argv[idx], "\n");
```

This works fine, but it could greatly be improved if we could pass `print`'s invariant arguments to `Print`'s constructor. This would simplify `print`'s prototype (only one argument would need to be passed rather than three) and we could wrap the above code in a function expecting a `Print` object:

```
void allArgs(Print const &print, int argc, char **argv)
```

```
{
    for (int idx = 0; idx != argc; ++idx)
        print.print(argv[idx]);
}
```

The above is a fairly generic piece of code, at least it is with respect to `Print`. Since `prefix` and `suffix` don't change they can be passed to the constructor which could be given the prototype:

```
Print(ostream &out, string const &prefix = "", string const &suffix = "");
```

Now `allArgs` may be used as follows:

```
Print p1{ cout, "arg: ", "\n" };     // prints to cout
Print p2{ cerr, "err: --", "--\n" };// prints to cerr

allArgs(p1, argc, argv);             // prints to cout
allArgs(p2, argc, argv);             // prints to cerr
```

But now we note that `p1` and `p2` are only used inside the `allArgs` function. Furthermore, as we can see from `print`'s prototype, `print` doesn't modify the internal data of the `Print` object it is using.

In such situations it is actually not necessary to define objects before they are used. Instead *anonymous objects* may be used. Anonymous objects can be used:

- to initialize a function parameter which is a `const` reference to an object;
- if the object is *only* used inside the function call.

When passing anonymous objects as arguments of `const &` parameters of functions they are considered constant as they merely exist for passing the information of (class type) objects to those functions. This way, they cannot be modified, nor may their non-const member functions be used. Of course, a `const_cast` could be used to cast away the const reference's constness, but that's considered bad practice on behalf of the function receiving the anonymous objects. Also, any modification to the anonymous object is lost once the function returns as the anonymous object ceases to exist after calling the function. These anonymous objects used to initialize const references should not be confused with passing anonymous objects to parameters defined as rvalue references (section 3.3.2) which have a completely different purpose in life. Rvalue references primarily exist to be 'swallowed' by functions receiving them. Thus, the information made available by rvalue references outlives the rvalue reference objects which are also anonymous.

Anonymous objects are defined when a constructor is used without providing a name for the constructed object. Here is the corresponding example:

```
allArgs(Print{ cout, "arg: ", "\n" }, argc, argv);    // prints to cout
allArgs(Print{ cerr, "err: --", "--\n" }, argc, argv);// prints to cerr
```

In this situation the `Print` objects are constructed and immediately passed as first arguments to the `allArgs` functions, where they are accessible as the function's `print` parameter. While the `allArgs` function is executing they can be used, but once the function has completed, the anonymous `Print` objects are no longer accessible.

7.7.1.1 Subtleties with anonymous objects

Anonymous objects can be used to initialize function parameters that are `const` references to objects. These objects are created just before such a function is called, and are destroyed once the function has terminated. **C++**'s grammar allows us to use anonymous objects in other situations as well. Consider the following snippet of code:

```
int main()
{
    // initial statements
    Print{ "hello", "world" };       // assume a matching constructor
                                     // is available
    // later statements
}
```

In this example an anonymous `Print` object is constructed, and it is immediately destroyed thereafter. So, following the 'initial statements' our `Print` object is constructed. Then it is destroyed again followed by the execution of the 'later statements'.

The example illustrates that the standard lifetime rules do not apply to anonymous objects. Their lifetimes are limited to the *statements*, rather than to the *end of the block* in which they are defined.

Plain anonymous object are at least useful in one situation. Assume we want to put *markers* in our code producing some output when the program's execution reaches a certain point. An object's constructor could be implemented so as to provide that marker-functionality allowing us to put markers in our code by defining anonymous, rather than named objects.

C++'s grammar contains another remarkable characteristic illustrated by the next example:

```
int main(int argc, char **argv)
{
          // assume a matching constructor is available:
    Print p{ cout, "", "" };            // 1
    allArgs(Print{ p }, argc, argv);    // 2
}
```

In this example a non-anonymous object `p` is constructed in statement 1, which is then used in statement 2 to *initialize* an anonymous object. The anonymous object, in turn, is then used to initialize `allArgs`'s `const` reference parameter. This use of an existing object to initialize another object is common practice, and is based on the existence of a so-called *copy constructor*. A copy constructor creates an object (as it is a constructor) using an existing object's characteristics to initialize the data of the object that's created. Copy constructors are discussed in depth in chapter 9, but presently only the concept of a copy constructor is used.

In the above example a copy constructor is used to initialize an anonymous object. The anonymous object was then used to initialize a parameter of a function. However, when we try to apply the same trick (i.e., using an existing object to initialize an anonymous object) to a plain statement, the compiler generates an error: the object `p` can't be redefined (in statement 3, below):

```
int main(int argc, char *argv[])
{
    Print p{ "", "" };                  // 1
    allArgs(Print(p), argc, argv);      // 2
    Print(p);                           // 3 error!
}
```

Does this mean that using an existing object to initialize an anonymous object that is used as function argument is OK, while an existing object can't be used to initialize an anonymous object in a plain statement?

The compiler actually provides us with the answer to this apparent contradiction. About statement 3 the compiler reports something like:

```
error: redeclaration of 'Print p'
```

which solves the problem when realizing that within a compound statement objects and variables may be defined. Inside a compound statement, a *type name* followed by a `variable name` is the grammatical form of a variable definition. *Parentheses* can be used to break priorities, but if there are no priorities to break, they have no effect, and are simply ignored by the compiler. In statement 3 the parentheses allowed us to get rid of the blank that's required between a type name and the variable name, but to the compiler we wrote

```
    Print (p);
```

which is, since the parentheses are superfluous, equal to

```
    Print p;
```

thus producing `p`'s redeclaration.

As a further example: when we define a variable using a built-in type (e.g., `double`) using superfluous parentheses the compiler quietly removes these parentheses for us:

```
double ((((a))));       // weird, but OK.
```

To summarize our findings about anonymous variables:

- Anonymous objects are great for initializing `const` reference parameters.
- The same syntax, however, can also be used in stand-alone statements, in which they are interpreted as variable definitions if our intention actually was to initialize an anonymous object using an existing object.
- Since this may cause confusion, it's probably best to restrict the use of anonymous objects to the first (and main) form: initializing function parameters.

7.8 The keyword 'inline'

Let us take another look at the implementation of the function `Person::name()`:

```
std::string const &Person::name() const
{
    return d_name;
}
```

This function is used to retrieve the name field of an object of the class `Person`. Example:

```
void showName(Person const &person)
{
    cout << person.name();
}
```

To insert `person`'s name the following actions are performed:

- The function `Person::name()` is called.
- This function returns `person`'s `d_name` as a reference.
- The referenced name is inserted into `cout`.

Especially the first part of these actions causes some time loss, since an extra function call is necessary to retrieve the value of the `name` field. Sometimes a faster procedure immediately making the `d_name` data member available is preferred without ever actually calling a function `name`. This can be realized using `inline` functions. An inline function is a request to the compiler to insert the function's code at the location of the function's call. This may speed up execution by avoiding a function call, which typically comes with some (stack handling and parameter passing) overhead. Note that `inline` is a *request* to the compiler: the compiler may decide to ignore it, and *will* probably ignore it when the function's body contains much code. Good programming discipline suggests to be aware of this, and to avoid `inline` unless the function's body is fairly small. More on this in section 7.8.2.

7.8.1 Defining members inline

Inline functions may be implemented *in the class interface itself*. For the class `Person` this results in the following implementation of `name`:

```
class Person
{
    public:
        std::string const &name() const
        {
            return d_name;
        }
};
```

Note that the inline code of the function `name` now literally occurs inline in the interface of the class `Person`. The keyword `const` is again added to the function's header.

Although members can be defined *in-class* (i.e., inside the class interface itself), it is considered bad practice for the following reasons:

- Defining members inside the interface contaminates the interface with implementations. The interface's purpose is to document what functionality the class offers. Mixing member declarations and implementation details complicates understanding the interface. Readers need to skip implementation details which takes time and makes it hard to grab the 'broad picture', and thus to understand at a glance what functionality the class's objects are offering.
- In-class implementations of private member functions may usually be avoided altogether (as they are private members). They should be moved to the internal header file (*unless* inline public members use such inline private members).
- Although members that are eligible for inline-coding should remain inline, situations do exist where such inline members migrate from an inline to a non-inline definition. In-class inline definitions still need editing (sometimes considerable editing) before they can be compiled. This additional editing is undesirable.

Because of the above considerations inline members should not be defined in-class. Rather, they should be defined following the class interface. The `Person::name` member is therefore preferably defined as follows:

```
class Person
{
    public:
        std::string const &name() const;
};

inline std::string const &Person::name() const
{
    return d_name;
}
```

If it is ever necessary to cancel `Person::name`'s inline implementation, then this becomes its non-inline implementation:

```
#include "person.ih"

std::string const &Person::name() const
{
    return d_name;
}
```

Only the `inline` keyword needs to be removed to obtain the correct non-inline implementation.

Defining members inline has the following effect: whenever an inline-defined function is called, the compiler may *insert the function's body* at the location of the function call. It may be that the function itself is never actually called.

This construction, where the function code itself is inserted rather than a call to the function, is called an inline function. Note that using inline functions may result in multiple occurrences of the code of those functions in a program: one copy for each invocation of the inline function. This is probably OK if the function is a small one, and needs to be executed fast. It's not so desirable if the code of the function is extensive. The compiler knows this too, and handles the use of inline functions as a *request* rather than a *command*. If the compiler considers the function too long, it will not grant the request. Instead it will treat the function as a normal function.

7.8.2 When to use inline functions

When should inline functions be used, and when not? There are some rules of thumb which may be followed:

- In general inline functions should **not** be used. *Voilà*; that's simple, isn't it?
- Consider defining a function inline once a fully developed and tested program runs too slowly and shows 'bottlenecks' in certain functions, and the bottleneck is removed by defining inline members. A profiler, which runs a program and determines where most of the time is spent, is necessary to perform such optimizations.
- Defining inline functions may be considered when they consist of one very simple statement (such as the return statement in the function `Person::name`).

- When a function is defined inline, its implementation is inserted in the code wherever the function is used. As a consequence, when the *implementation* of the inline function changes, all sources using the inline function must be recompiled. In practice that means that all functions must be recompiled that include (either directly or indirectly) the header file of the class in which the inline function is defined. Not a very attractive prospect.

- It is only useful to implement an inline function when the time spent during a function call is long compared to the time spent by the function's body. An example of an inline function which hardly affects the program's speed is:

  ```
  inline void Person::printname() const
  {
      cout << d_name << '\n';
  }
  ```

  This function contains only one statement. However, the statement takes a relatively long time to execute. In general, functions which perform input and output take lots of time. The effect of the conversion of this function `printname()` to inline would therefore lead to an insignificant gain in execution time.

All inline functions have one disadvantage: the actual code is inserted by the compiler and must therefore be known at compile-time. Therefore, as mentioned earlier, an inline function can never be located in a run-time library. Practically this means that an inline function is found near the interface of a class, usually in the same header file. The result is a header file which not only shows the **declaration** of a class, but also part of its **implementation**, thus always blurring the distinction between interface and implementation.

7.8.2.1 A prelude: when NOT to use inline functions

As a prelude to chapter 14 (Polymorphism), there is one situation in which inline functions should definitely be avoided. At this point in the **C++** Annotations it's a bit too early to expose the full details, but since the keyword `inline` is the topic of this section this is considered the appropriate location for the advice.

There are situations where the compiler is confronted with so-called *vague linkage* (cf. `http://gcc.gnu.org/onlinedocs/gcc-4.6.0/gcc/Vague-Linkage.html`). These situations occur when the compiler does not have a clear indication in what object file to put its compiled code. This happens, e.g., with inline functions, which are usually encountered in multiple source files. Since the compiler may insert the code of ordinary inline functions in places where these functions are called, vague linking is usually no problem with these ordinary functions.

However, as explained in chapter 14, when using polymorphism the compiler must ignore the `inline` keyword and define so-called *virtual members* as true (*out-of-line*) functions. In this situation the vague linkage may cause problems, as the compiler must decide in what object `s` to put their code. Usually that's not a big problem as long as the function is at least called once. But virtual functions are special in the sense that they may very well never be explicitly called. On some architectures (e.g., armel) the compiler may fail to compile such inline virtual functions. This may result in missing symbols in programs using them. To make matters slightly more complex: the problem may emerge when shared libraries are used, but not when static libraries are used.

To avoid all of these problems virtual functions should *never* be defined inline, but they should always be defined *out-of-line*. I.e., they should be defined in source files.

7.8.3 Inline variables

In addition to inline functions, inline variables can be defined (and identically initialized) in multiple translation units. E.g., a header file could contain

```
inline int value = 15;                          // OK

class Demo
{
    // static int s_value = 15;                 // ERROR
    static int constexpr s_value = 15;          // OK

    static int s_inline;                        // OK: see below: the inline
                                                //   definition follows the
                                                //   class declaration
};
inline int Demo::s_inline = 20;                 // OK
```

7.9 Local classes: classes inside functions

Classes are usually defined at the global or namespace level. However, it is entirely possible to define a local class, i.e., inside a function. Such classes are called *local classes*.

Local classes can be very useful in advanced applications involving inheritance or templates (cf. section 13.8). At this point in the **C++** Annotations they have limited use, although their main features can be described. At the end of this section an example is provided.

- Local classes may use almost all characteristics of normal classes. They may have constructors, destructors, data members, and member functions;
- Local classes cannot define static data members. Static member functions, however, *can* be defined.
- Since a local class may define static member functions, it is possible to define *nested functions* in **C++** somewhat comparable to the way programming languages like **Pascal** allow nested functions to be defined.
- If a local class needs access to a constant integral value, a local *enum* can be used. The `enum` may be anonymous, exposing only the `enum` values.
- Local classes cannot directly access the non-static variables of their surrounding context. For example, in the example shown below the class `Local` cannot directly access `main`'s `argc` parameter.
- Local classes may directly access global data and static variables defined by their surrounding function. This includes variables defined in the anonymous namespace of the source file containing the local class.
- Local class objects can be defined inside the function body, but they cannot leave the function as objects of their own type. I.e., a local class name cannot be used for either the return type or for the parameter types of its surrounding function.
- As a prelude to *inheritance* (chapter 13): a local class may be derived from an existing class allowing the surrounding function to return a dynamically allocated locally constructed class object, pointer or reference via a base class pointer or reference.

```
#include <iostream>
#include <string>

using namespace std;

int main(int argc, char **argv)
{
    static size_t staticValue = 0;

    class Local
    {
        int d_argc;             // non-static data members OK

        public:
            enum                // enums OK
            {
                VALUE = 5
            };
            Local(int argc)     // constructors and member functions OK
            :                   // in-class implementation required
                d_argc(argc)
            {
                                // global data: accessible
                cout << "Local constructor\n";
                                // static function variables: accessible
                staticValue += 5;
            }
            static void hello() // static member functions: OK
            {
                cout << "hello world\n";
            }
    };
    Local::hello();             // call Local static member
    Local loc{ argc };          // define object of a local class.
}
```

7.10 The keyword ‘mutable’

Earlier, in section 7.7, the concepts of const member functions and const objects were introduced.

C++ also allows the declaration of data members which may be modified, even by const member function. Declarations of such data members start with the keyword `mutable`.

Mutable should be used for those data members that may be modified without logically changing the object, which might therefore still be considered a constant object.

An example of a situation where `mutable` is appropriately used is found in the implementation of a string class. Consider the `std::string`’s `c_str` and `data` members. The actual data returned by the two members are identical, but `c_str` must ensure that the returned string is terminated by an 0-byte. As a string object has both a length and a capacity an easy way to implement `c_str` is to ensure that the string’s capacity exceeds its length by at least one character. This invariant allows `c_str` to be implemented as follows:

```
    char const *string::c_str() const
```

```
{
    d_data[d_length] = 0;
    return d_data;
}
```

This implementation logically does not modify the object's data as the bytes beyond the object's initial (length) characters have undefined values. But in order to use this implementation `d_data` must be declared `mutable`:

```
mutable char *d_data;
```

The keyword `mutable` is also useful in classes implementing, e.g., reference counting. Consider a class implementing reference counting for strings. The object doing the reference counting might be a const object, but the class may define a copy constructor. Since const objects can't be modified, how would the copy constructor be able to increment the reference count? Here the `mutable` keyword may profitably be used, as it can be incremented and decremented, even though its object is a const object.

The keyword `mutable` should sparingly be used. Data modified by const member functions should never logically modify the object, and it should be easy to demonstrate this. As a rule of thumb: do not use `mutable` unless there is a very clear reason (the object is logically not altered) for violating this rule.

7.11 Header file organization

In section 2.5.10 the requirements for header files when a **C++** program also uses **C** functions were discussed. Header files containing class interfaces have additional requirements.

First, source files. With the exception of the occasional classless function, source files contain the code of member functions of classes. Basically, there are two approaches:

- All required header files for a member function are included in each individual source file.
- All required header files (for all member functions of a class) are included in a header file that is included by each of the source files defining class members.

The first alternative has the advantage of economy for the compiler: it only needs to read the header files that are necessary for a particular source file. It has the disadvantage that the program developer must include multiple header files again and again in source files: it both takes time to type the `include`-directives and to think about the header files which are needed in a particular source file.

The second alternative has the advantage of economy for the program developer: the header file of the class accumulates header files, so it tends to become more and more generally useful. It has the disadvantage that the compiler frequently has to process many header files which aren't actually used by the function to compile.

With computers running faster and faster (and compilers getting smarter and smarter) I think the second alternative is to be preferred over the first alternative. So, as a starting point source files of a particular class `MyClass` could be organized according to the following example:

```
#include <myclass.h>

int MyClass::aMemberFunction()
{}
```

There is only one `include`-directive. Note that the directive refers to a header file in a directory mentioned in the `INCLUDE`-file environment variable. Local header files (using `#include "myclass.h"`) could be used too, but that tends to complicate the organization of the class header file itself somewhat.

The organization of the header file itself requires some attention. Consider the following example, in which two classes `File` and `String` are used.

Assume the `File` class has a member `gets(String &destination)`, while the class `String` has a member function `getLine(File &file)`. The (partial) header file for the `class String` is then:

```
#ifndef STRING_H_
#define STRING_H_

#include <project/file.h>   // to know about a File

class String
{
    public:
        void getLine(File &file);
};
#endif
```

Unfortunately a similar setup is required for the class `File`:

```
#ifndef FILE_H_
#define FILE_H_

#include <project/string.h>   // to know about a String

class File
{
    public:
        void gets(String &string);
};
#endif
```

Now we have created a problem. The compiler, trying to compile the source file of the function `File::gets` proceeds as follows:

- The header file `project/file.h` is opened to be read;
- `FILE_H_` is defined
- The header file `project/string.h` is opened to be read
- `STRING_H_` is defined
- The header file `project/file.h` is (again) opened to be read
- Apparently, `FILE_H_` is already defined, so the remainder of `project/file.h` is skipped.
- The interface of the class `String` is now parsed.
- In the class interface a reference to a `File` object is encountered.
- As the `class File` hasn't been parsed yet, a `File` is still an undefined type, and the compiler quits with an error.

The solution to this problem is to use a *forward class reference before* the class interface, and to include the corresponding class header file *beyond* the class interface. So we get:

```
#ifndef STRING_H_
#define STRING_H_

class File;                 // forward reference

class String
{
    public:
        void getLine(File &file);
};

#include <project/file.h>   // to know about a File

#endif
```

A similar setup is required for the class `File`:

```
#ifndef FILE_H_
#define FILE_H_

class String;               // forward reference

class File
{
    public:
        void gets(String &string);
};

#include <project/string.h>   // to know about a String

#endif
```

This works well in all situations where either references or pointers to other classes are involved and with (non-inline) member functions having class-type return values or parameters.

This setup doesn't work with composition, nor with in-class inline member functions. Assume the class `File` has a *composed* data member of the class `String`. In that case, the class interface of the class `File` *must* include the header file of the class `String` before the class interface itself, because otherwise the compiler can't tell how big a `File` object is. A `File` object contains a `String` member, but the compiler can't determine the size of that `String` data member and thus, by implication, it can't determine the size of a `File` object.

In cases where classes contain composed objects (or are derived from other classes, see chapter 13) the header files of the classes of the composed objects must have been read *before* the class interface itself. In such a case the `class File` might be defined as follows:

```
#ifndef FILE_H_
#define FILE_H_

#include <project/string.h>     // to know about a String

class File
```

```
{
    String d_line;              // composition !

    public:
        void gets(String &string);
};
#endif
```

The class `String` can't declare a `File` object as a composed member: such a situation would again result in an undefined class while compiling the sources of these classes.

All remaining header files (appearing below the class interface itself) are required only because they are used by the class's source files.

This approach allows us to introduce yet another refinement:

- Header files defining a class interface should *declare* what can be declared before defining the class interface itself. So, classes that are mentioned in a class interface should be specified using forward declarations *unless*
    - They are a *base class* of the current class (see chapter 13);
    - They are the class types of composed data members;
    - They are used in inline member functions.

  In particular: additional actual header files are *not* required for:
    - class-type return values of functions;
    - class-type value parameters of functions.

  Class header files of objects that are either composed or inherited or that are used in inline functions, *must* be known to the compiler before the interface of the current class starts. The information in the header file itself is protected by the `#ifndef ... #endif` construction introduced in section 2.5.10.

- Program sources in which the class is used only need to include this header file. *Lakos*, (2001) refines this process even further. See his book **Large-Scale C++ Software Design** for further details. This header file should be made available in a well-known location, such as a directory or subdirectory of the standard `INCLUDE` path.

- To implement member functions the class's header file is required and usually additional header files (like the `string` header file) as well. The class header file itself as well as these additional header files should be included in a separate internal header file (for which the extension `.ih` ('internal header') is suggested).

  The `.ih` file should be defined in the same directory as the source files of the class. It has the following characteristics:
    - There is *no* need for a protective `#ifndef` .. `#endif` shield, as the header file is never included by other header files.
    - The standard `.h` header file defining the class interface is included.
    - The header files of all classes used as forward references in the standard `.h` header file are included.
    - Finally, all other header files that are required in the source files of the class are included.

  An example of such a header file organization is:
    - First part, e.g., `/usr/local/include/myheaders/file.h`:

      ```
      #ifndef FILE_H_
      ```

```
#define FILE_H_

#include <fstream>      // for composed 'ifstream'

class Buffer;           // forward reference

class File              // class interface
{
    std::ifstream d_instream;

    public:
        void gets(Buffer &buffer);
};
#endif
```

– Second part, e.g., `~/myproject/file/file.ih`, where all sources of the class File are stored:

```
#include <myheaders/file.h> // make the class File known

#include <buffer.h>         // make Buffer known to File
#include <string>           // used by members of the class
#include <sys/stat.h>       // File.
```

7.11.1 Using namespaces in header files

When entities from namespaces are used in header files, no `using` directive should be specified in those header files if they are to be used as general header files declaring classes or other entities from a library. When the `using` directive is used in a header file then users of such a header file are forced to accept and use the declarations in all code that includes the particular header file.

For example, if in a namespace `special` an object `Inserter cout` is declared, then `special::cout` is of course a different object than `std::cout`. Now, if a class `Flaw` is constructed, in which the constructor expects a reference to a `special::Inserter`, then the class should be constructed as follows:

```
class special::Inserter;

class Flaw
{
    public:
        Flaw(special::Inserter &ins);
};
```

Now the person designing the class `Flaw` may be in a lazy mood, and might get bored by continuously having to prefix `special::` before every entity from that namespace. So, the following construction is used:

```
using namespace special;

class Inserter;
class Flaw
{
    public:
        Flaw(Inserter &ins);
};
```

This works fine, up to the point where somebody wants to include `flaw.h` in other source files: because of the `using` directive, this latter person is now by implication also `using namespace special`, which could produce unwanted or unexpected effects:

```
#include <flaw.h>
#include <iostream>

using std::cout;

int main()
{
    cout << "starting\n";        // won't compile
}
```

The compiler is confronted with two interpretations for `cout`: first, because of the `using` directive in the `flaw.h` header file, it considers `cout` a `special::Inserter`, then, because of the `using` directive in the user program, it considers `cout` a `std::ostream`. Consequently, the compiler reports an error.

As a rule of thumb, header files intended for general use should not contain `using` declarations. This rule does not hold true for header files which are only included by the sources of a class: here the programmer is free to apply as many `using` declarations as desired, as these directives never reach other sources.

7.11.2 Modules

Since the introduction of header files in the **C** language header files have been the main tool for declaring elements that are not defined but are used in source files. E.g., when using `printf` in `main` the preprocessor directive `#include <stdio.h>` had to be specified.

This method still works in **C++**, but gradually proved to be inefficient. One reason being that header files have to be processed again for every source file of a set of source files each including that header file. The drawback of this approach quickly becomes apparent once classes are used, as the compiler will repeatedly have to process the class's header file for each source file using that class. Usually it's not just that one header file, but header files tend to include other header files, resulting in an avalanche of header files that must be processed by the compiler again and again for every single source file that the compiler must compile. If a typical source file includes h header files, and s source files must be compiled, then that results in a significant compilation load, as the compiler must process $s * h$ header files.

Precompiled headers offered an initial attempt to reduce this excessive workload. But precompiled headers have problems of their own: they're enormously big (a precompiled header file of less than 100 bytes can easily result in a precompiled header of 25 MB or more), and they're kind of fragile: simply recompiling a header if it's younger than its precompiled form may quickly result in much overhead, e.g., if merely some comment is added to the header.

Another common defense mechanism encountered in traditional headers is the use of *include guards*, ensuring that a header file is processed once if it is included by multiple other header files. Such include guards are macros, and were extensively discussed in section 7.11. Include guards work, but completely depend on the uniqueness of the guard-identifier, which is usually a long name, written in capitals using several underscores to increase the probability of their uniqueness.

By offering *modules* the C++20 standard provides solutions to the problems mentioned above. At the time of this writing the Gnu `g++` compiler (still) experiences problems with modules. Once these problems have been solved a separate chapter about modules will definitely be added to the **C++** Annotations.

7.12 Sizeof applied to class data members

In **C++** the well-known `sizeof` operator can be applied to data members of classes without the need to specify an object as well. Consider:

```
class Data
{
    std::string d_name;
    ...
};
```

To obtain the size of `Data`'s `d_name` member the following expression can be used:

```
sizeof(Data::d_name);
```

However, note that the compiler observes data protection here as well. `Sizeof(Data::d_name)` can only be used where `d_name` may be visible as well, i.e., by `Data`'s member functions and friends.

Chapter 8

Static Data And Functions

In the previous chapters we provided examples of classes where each object had its own set of data members data. Each of the class's member functions could access any member of any object of its class.

In some situations it may be desirable to define *common data fields*, that may be accessed by *all* objects of the class. For example, the name of the startup directory, used by a program that recursively scans the directory tree of a disk. A second example is a variable that indicates whether some specific initialization has occurred. In that case the object that was constructed first would perform the initialization and would set the flag to 'done'.

Such situations are also encountered in **C**, where several functions need to access the same variable. A common solution in **C** is to define all these functions in one source file and to define the variable `static`: the variable name is invisible outside the scope of the source file. This approach is quite valid, but violates our philosophy of using only one function per source file. Another **C**-solution is to give the variable in question an unusual name, e.g., `_6uldv8`, hoping that other program parts won't use this name by accident. Neither the first, nor the second legacy **C** solution is elegant.

C++ solves the problem by defining `static members`: data and functions, common to all objects of a class and (when defined in the private section) inaccessible outside of the class. These static members are this chapter's topic.

Static members cannot be defined as virtual functions. A virtual member function is an ordinary member in that it has a `this` pointer. As static member functions have no `this` pointer, they cannot be declared virtual.

8.1 Static data

Any data member of a class can be declared `static`; be it in the `public` or `private` section of the class interface. Such a data member is created and initialized only once, in contrast to non-static data members which are created again and again for each object of the class.

Static data members are created as soon as the program starts. Even though they're created at the very beginning of a program's execution cycle they are nevertheless true members of their classes.

It is suggested to prefix the names of static member with `s_` so they may easily be distinguished (in class member functions) from the class's data members (which should preferably start with `d_`).

Public static data members are global variables. They may be accessed by *all of the program's code*, simply by using their class names, the scope resolution operator and their member names. Example:

```
class Test
{
    static int s_private_int;

    public:
        static int s_public_int;
};

int main()
{
    Test::s_public_int = 145;   // OK
    Test::s_private_int = 12;   // wrong, don't touch
                                // the private parts
}
```

The example does not present an executable program. It merely illustrates the *interface*, and not the *implementation* of `static` data members, which is discussed next.

8.1.1 Private static data

To illustrate the use of a static data member which is a private variable in a class, consider the following:

```
class Directory
{
    static char s_path[];

    public:
        // constructors, destructors, etc.
};
```

The data member `s_path[]` is a private static data member. During the program's execution only *one* `Directory::s_path[]` exists, even though multiple objects of the class `Directory` may exist. This data member could be inspected or altered by the constructor, destructor or by any other member function of the class `Directory`.

Since constructors are called for each new object of a class, static data members are not *initialized* by constructors. At most they are *modified*. The reason for this is that static data members exist *before* any constructor of the class has been called. Static data members are initialized when they are defined, outside of any member function, exactly like the initialization of ordinary (non-class) global variables.

The definition and initialization of a static data member usually occurs in one of the source files of the class functions, preferably in a source file dedicated to the definition of static data members, called `data.cc`.

The data member `s_path[]`, used above, could thus be defined and initialized as follows in a file `data.cc`:

```
#include "directory.ih"

char Directory::s_path[200] = "/usr/local";
```

In the class interface the static member is actually only *declared*. In its implementation (definition) its type and class name are explicitly mentioned. Note also that the size specification can be left out of the interface, as shown above. However, its size *is* (either explicitly or implicitly) required when it is defined.

Note that *any* source file could contain the definition of the static data members of a class. A separate `data.cc` source file is advised, but the source file containing, e.g., `main()` could be used as well. Of course, any source file defining static data of a class must also include the header file of that class, in order for the static data member to be known to the compiler.

A second example of a useful private static data member is given below. Assume that a class `Graphics` defines the communication of a program with a graphics-capable device (e.g., a VGA screen). The initialization of the device, which in this case would be to switch from text mode to graphics mode, is an action of the constructor and depends on a `static` flag variable `s_nobjects`. The variable `s_nobjects` simply counts the number of `Graphics` objects which are present at one time. Similarly, the destructor of the class may switch back from graphics mode to text mode when the last `Graphics` object ceases to exist. The class interface for this `Graphics` class might be:

```
class Graphics
{
    static int s_nobjects;              // counts # of objects

    public:
        Graphics();
        ~Graphics();                    // other members not shown.
    private:
        void setgraphicsmode();         // switch to graphics mode
        void settextmode();             // switch to text-mode
}
```

The purpose of the variable `s_nobjects` is to count the number of objects existing at a particular moment in time. When the first object is created, the graphics device is initialized. At the destruction of the last `Graphics` object, the switch from graphics mode to text mode is made:

```
int Graphics::s_nobjects = 0;           // the static data member

Graphics::Graphics()
{
    if (!s_nobjects++)
        setgraphicsmode();
}

Graphics::~Graphics()
{
    if (!--s_nobjects)
        settextmode();
}
```

Obviously, when the class `Graphics` would define more than one constructor, each constructor would need to increase the variable `s_nobjects` and would possibly have to initialize the graphics mode.

8.1.2 Public static data

Data members could also be declared in the public section of a class. This, however, is deprecated (as it violates the principle of data hiding). The static data member `s_path[]` (cf. section 8.1) could be declared in the public section of the class definition. This would allow all the program's code to access this variable directly:

```
int main()
{
    getcwd(Directory::s_path, 199);
}
```

A declaration is not a definition. Consequently the variable `s_path` still has to be defined. This implies that some source file still needs to contain `s_path[]` array's definition.

8.1.3 Initializing static const data

Static `const` data members should be initialized like any other static data member: in source files defining these data members.

Usually, if these data members are of integral or built-in primitive data types the compiler accepts in-class initializations of such data members. However, there is no formal rule requiring the compiler to do so. Compilations may or may not succeed depending on the optimizations used by the compiler (e.g., using `-O2` may result in a successful compilation, but `-O0` (no-optimizations) may fail to compile, but then maybe only when shared libraries are used...).

In-class initializations of integer constant values (e.g., of types `char`, `int`, `long`, etc, maybe `unsigned`) is nevertheless possible using (e.g., anonymous) enums. The following example illustrates how this can be done:

```
class X
{
    public:
        enum         { s_x = 34 };
        enum: size_t { s_maxWidth = 100 };
};
```

To avoid confusion caused by different compiler options static data members should always explicitly be defined and initialized in a source file, whether or not `const`.

8.1.4 Generalized constant expressions (constexpr)

In **C** macros are often used to let the preprocessor perform simple calculations. These *macro functions* may have arguments, as illustrated in the next example:

```
#define xabs(x) ((x) < 0 ? -(x) : (x))
```

The disadvantages of macros are well-known. The main reason for avoiding macros is that they are not parsed by the compiler, but are processed by the preprocessor resulting in mere text replacements and thus avoid type-safety or syntactic checks of the macro definition by itself. Furthermore, since macros are processed by the preprocessor their use is unconditional, without acknowledging the context in which they are applied. `NULL` is an infamous example. Ever tried to define an `enum` symbol `NULL`? or `EOF`? Chances are that, if you did, the compiler threw strange error messages at you.

Generalized const expressions can be used as an alternative.

Generalized const expressions are recognized by the modifier `constexpr` (a keyword), that is applied to the expression's type.

There is a small syntactic difference between the use of the `const` modifier and the use of the `constexpr` modifier. While the `const` modifier can be applied to definitions and declarations alike, the `constexpr` modifier can only be applied to definitions:

```
extern int const externInt;      // OK: declaration of const int
extern int constexpr error;      // ERROR: not a definition
```

Variables defined with the `constexpr` modifier have constant (immutable) values. But generalized const expressions are not just used to define constant variables; they have other applications as well. The `constexpr` keyword is usually applied to functions, turning the function into a *constant-expression function*.

A constant-expression function should not be confused with a function returning a `const` value (although a constant-expression function *does* return a (const) value). A constant expression function has the following characteristics:

- it returns a value;
- its return type is given the `constexpr` modifier;
- its body consists of one single return statement (but see also the notes at end of this section)

Such functions are also called *named constant expressions with parameters*.

These constant expression functions may or may not be called with arguments that have been evaluated at compile-time (not just 'const arguments', as a `const` parameter value is not evaluated at compile-time). If they are called with compile-time evaluated arguments then the returned value is considered a `const` value as well.

This allows us to encapsulate expressions that can be evaluated at compile-time in functions, and it allows us to use these functions in situations where previously the expressions themselves had to be used. The encapsulation reduces the number of occurrences of the expressions to one, simplifying maintenance and reduces the probability of errors.

If arguments that could not be compile-time evaluated are passed to constant-expression functions, then these functions act like any other function, in that their return values are no longer considered constant expressions.

Assume some two-dimensional arrays must be converted to one-dimensional arrays. The one-dimensional array must have `nrows * ncols + nrows + ncols + 1` elements, to store row, column, and total marginals, as well as the elements of the source array itself. Furthermore assume that `nrows` and `ncols` have been defined as globally available `size_t const` values (they could be a class's static data). The one-dimensional arrays are data members of a class or struct, or they are also defined as global arrays.

Now that constant-expression functions are available the expression returning the number of the required elements can be encapsulated in such a function:

```
size_t const nRows = 45;
size_t const nCols = 10;

size_t constexpr nElements(size_t rows, size_t cols)
{
    return rows * cols + rows + cols + 1;
}

    ....

int intLinear[ nElements(nRows, nCols) ];

struct Linear
{
    double d_linear[ nElements(nRows, nCols) ];
};
```

If another part of the program needs to use a linear array for an array of different sizes then the constant-expression function can also be used. E.g.,

```
string stringLinear[ nElements(10, 4) ];
```

Constant-expression functions can be used in other constant expression functions as well. The following constant-expression function returns half the value, rounded upwards, that is returned by `nElements`:

```
size_t constexpr halfNElements(size_t rows, size_t cols)
{
    return (nElements(rows, cols) + 1) >> 1;
}
```

Classes should not expose their data members to external software, so as to reduce coupling between classes and external software. But if a class defines a `static const size_t` data member then that member's value could very well be used to define entities living outside of the class's scope, like the number of elements of an array or to define the value of some enum. In situations like these constant-expression functions are the perfect tool to maintain proper data hiding:

```
class Data
{
    static size_t const s_size = 7;

    public:
        static size_t constexpr size();
        size_t constexpr mSize();
};

size_t constexpr Data::size()
{
    return s_size;
}

size_t constexpr Data::mSize()
{
    return size();
}

double data[ Data::size() ];        // OK: 7 elements
short data2[ Data().mSize() ];      // also OK: see below
```

Please note the following:

- Constant-expression functions are implicitly declared inline;
- Non-static constant-expression member functions are implicitly `const`, and a `const` member modifier for them is optional;
- Constant values (e.g., static constant data members) used by constant-expression functions must be known by the time the compiler encounters the functions' definitions. That's why `s_size` was initialized in `Data`'s class interface.

Since the C++14 standard the requirements of `constexpr` functions have been relaxed. Starting at this standard, `constexpr` functions may

- define any kind of variable except for `static` or `thread_local` variables;
- define variables without initializers;
- use conditional statements (`if` and `switch`);
- use repetition statements, including the range-based `for` statement;
- use expressions changing the values of objects that are local to the `constexpr` function;

In addition, C++14 allows `constexpr` member functions to be non-const. But note that non-const `constexpr` member functions can only modify data members of objects that were defined local to the `constexpr` function calling the non-const `constexpr` member function.

8.1.4.1 Constant expression data

As we've seen, (member) functions and variables of primitive data types can be defined using the `constexpr` modifier. What about class-type objects?

Objects of classes are values of class type, and like values of primitive types they can be defined with the `constexpr` specifier. Constant expression class-type objects must be initialized with constant expression arguments; the constructor that is actually used must itself have been declared with the `constexpr` modifier. Note again that the `constexpr` constructor's definition must have been seen by the compiler before the `constexpr` object can be constructed:

```
class ConstExpr
{
    public:
        constexpr ConstExpr(int x);
};

ConstExpr ok{ 7 };              // OK: not declared as constexpr

constexpr ConstExpr err{ 7 };   // ERROR: constructor's definition
                                //        not yet seen

constexpr ConstExpr::ConstExpr(int x)
{}

constexpr ConstExpr ok{ 7 };                  // OK: definition seen
constexpr ConstExpr okToo = ConstExpr{ 7 }; // also OK
```

A constant-expression constructor has the following characteristics:

- it is declared with the `constexpr` modifier;

- its member initializers only use constant expressions;
- its body is empty.

An object constructed with a constant-expression constructor is called a *user-defined literal*. Destructors and copy constructors of user-defined literals must be trivial.

The `constexpr` characteristic of user-defined literals may or may not be maintained by its class's members. If a member is not declared with a `constexpr` return value, then using that member does not result in a constant-expression. If a member *does* declare a `constexpr` return value then that member's return value is considered a `constexpr` if it is by itself a constant expression function. To maintain its `constexpr` characteristics it can refer to its classes' data members *only* if its object has been defined with the `constexpr` modifier, as illustrated by the example:

```
class Data
{
    int d_x;

    public:
        constexpr Data(int x)
        :
            d_x(x)
        {}

        int constexpr cMember()
        {
            return d_x;
        }

        int member() const
        {
            return d_x;
        }
};

Data d1{ 0 };           // OK, but not a constant expression

enum e1 {
    ERR = d1.cMember()  // ERROR: cMember(): no constant
};                      //        expression anymore

constexpr Data d2{ 0 }; // OK, constant expression

enum e2 {
    OK = d2.cMember(),  // OK: cMember(): now a constant
                        //                expression
    ERR = d2.member(),  // ERR: member(): not a constant
};                      //                expression
```

8.2 Static member functions

In addition to static data members, **C++** allows us to define *static member functions*. Similar to static data that are shared by all objects of the class, static member functions also exist without any associated object of their class.

Static member functions can access all static members of their class, but *also* the members (`private` or `public`) of objects of their class *if* they are informed about the existence of these objects (as in the upcoming example). As static member functions are not associated with any object of their class they do not have a `this` pointer. In fact, a static member function is completely comparable to a global function, not associated with any class (i.e., in practice they are. See the next section (8.2.1) for a subtle note). Since static member functions do not require an associated object, static member functions declared in the public section of a class interface may be called without specifying an object of its class. The following example illustrates this characteristic of static member functions:

```
class Directory
{
    string d_currentPath;
    static char s_path[];

    public:
        static void setpath(char const *newpath);
        static void preset(Directory &dir, char const *newpath);
};
inline void Directory::preset(Directory &dir, char const *newpath)
{
                                                // see the text below
    dir.d_currentPath = newpath;                // 1
}

char Directory::s_path[200] = "/usr/local";     // 2

void Directory::setpath(char const *newpath)
{
    if (strlen(newpath) >= 200)
        throw "newpath too long";

    strcpy(s_path, newpath);                    // 3
}

int main()
{
    Directory dir;

    Directory::setpath("/etc");                 // 4
    dir.setpath("/etc");                        // 5

    Directory::preset(dir, "/usr/local/bin");   // 6
    dir.preset(dir, "/usr/local/bin");          // 7
}
```

- at 1 a static member function modifies a private data member of an object. However, the object whose member must be modified is given to the member function as a reference parameter.

  Note that static member functions can be defined as inline functions.

- at 2 a relatively long array is defined to be able to accommodate long paths. Alternatively, a `string` or a pointer to dynamic memory could be used.

- at 3 a (possibly longer, but not too long) new pathname is stored in the static data member `s_path[]`. Note that only static members are used.

- at 4, `setpath()` is called. It is a static member, so no object is required. But the compiler must know to which class the function belongs, so the class is mentioned using the scope resolution operator.
- at 5, the same is implemented as in 4. Here `dir` is used to tell the compiler that we're talking about a function in the `Directory` class. Static member functions *can* be called as normal member functions, but this does not imply that the static member function receives the object's address as a `this` pointer. Here the member-call syntax is used as an alternative for the classname plus scope resolution operator syntax.
- at 6, `currentPath` is altered. As in 4, the class and the scope resolution operator are used.
- at 7, the same is implemented as in 6. But here `dir` is used to tell the compiler that we're talking about a function in the `Directory` class. Here in particular note that this is *not* using `preset()` as an ordinary member function of `dir`: the function still has no `this`-pointer, so `dir` must be passed as argument to inform the static member function `preset` about the object whose `currentPath` member it should modify.

In the example only public static member functions were used. **C++** also allows the definition of private static member functions. Such functions can only be called by member functions of their class.

8.2.1 Calling conventions

As noted in the previous section, static (public) member functions are comparable to classless functions. However, formally this statement is not true, as the **C++** standard does not prescribe the same calling conventions for static member functions as for classless global functions.

In practice the calling conventions are identical, implying that the address of a static member function could be used as an argument of functions having parameters that are pointers to (global) functions.

If unpleasant surprises must be avoided at all cost, it is suggested to create global classless *wrapper functions* around static member functions that must be used as *call back* functions for other functions.

Recognizing that the traditional situations in which call back functions are used in **C** are tackled in **C++** using template algorithms (cf. chapter 19), let's assume that we have a class `Person` having data members representing the person's name, address, phone and mass. Furthermore, assume we want to sort an array of pointers to `Person` objects, by comparing the `Person` objects these pointers point to. Keeping things simple, we assume that the following public static member exists:

```
    int Person::compare(Person const *const *p1, Person const *const *p2);
```

A useful characteristic of this member is that it may directly inspect the required data members of the two `Person` objects passed to the member function using pointers to pointers (double pointers).

Most compilers allow us to pass this function's address as the address of the comparison function for the standard **C** `qsort()` function. E.g.,

```
    qsort
    (
        personArray, nPersons, sizeof(Person *),
        reinterpret_cast<int(*)(void const *, void const *)>(Person::compare)
    );
```

However, if the compiler uses different calling conventions for static members and for classless functions, this might not work. In such a case, a classless wrapper function like the following may be used profitably:

```
int compareWrapper(void const *p1, void const *p2)
{
    return
        Person::compare
        (
            static_cast<Person const *const *>(p1),
            static_cast<Person const *const *>(p2)
        );
}
```

resulting in the following call of the `qsort()` function:

```
qsort(personArray, nPersons, sizeof(Person *), compareWrapper);
```

Note:

- The wrapper function takes care of any mismatch in the calling conventions of static member functions and classless functions;
- The wrapper function handles the required type casts;
- The wrapper function might perform small additional services (like dereferencing pointers if the static member function expects references to `Person` objects rather than double pointers);
- As an aside: in **C++** programs functions like `qsort()`, requiring the specification of call back functions are seldom used. Instead using existing generic template algorithms is preferred (cf. chapter 19).

Chapter 9

Classes And Memory Allocation

In contrast to the set of functions that handle memory allocation in **C** (i.e., `malloc` etc.), memory allocation in **C++** is handled by the operators `new` and `delete`. Important differences between `malloc` and `new` are:

- The function `malloc` doesn't 'know' what the allocated memory will be used for. E.g., when memory for `int`s is allocated, the programmer must supply the correct expression using a multiplication by `sizeof(int)`. In contrast, `new` requires a type to be specified; the `sizeof` expression is implicitly handled by the compiler. Using `new` is therefore *type safe*.
- Memory allocated by `malloc` is initialized by `calloc`, initializing the allocated characters to a configurable initial value. This is not very useful when objects are available. As operator `new` knows about the type of the allocated entity it may (and will) call the constructor of an allocated class type object. This constructor may be also supplied with arguments.
- All **C**-allocation functions must be inspected for `NULL`-returns. This is not required anymore when `new` is used. In fact, `new`'s behavior when confronted with failing memory allocation is configurable through the use of a *new_handler* (cf. section 9.2.2).

A comparable relationship exists between `free` and `delete`: `delete` makes sure that when an object is deallocated, its destructor is automatically called.

The automatic calling of constructors and destructors when objects are created and destroyed has consequences which we shall discuss in this chapter. Many problems encountered during **C** program development are caused by incorrect memory allocation or memory leaks: memory is not allocated, not freed, not initialized, boundaries are overwritten, etc.. **C++** does not 'magically' solve these problems, but it *does* provide us with tools to prevent these kinds of problems.

As a consequence of `malloc` and friends becoming deprecated the very frequently used `str...` functions, like `strdup`, that are all `malloc` based, should be avoided in **C++** programs. Instead, the facilities of the `string` class and operators `new` and `delete` should be used.

Memory allocation procedures influence the way classes dynamically allocating their own memory should be designed. Therefore, in this chapter these topics are discussed in addition to discussions about operators `new` and `delete`. We'll first cover the peculiarities of operators `new` and `delete`, followed by a discussion about:

- the destructor: the member function that's called when an object ceases to exist;
- the assignment operator, allowing us to assign an object to another object of its own class;

- the `this` pointer, allowing explicit references to the object for which a member function was called;
- the copy constructor: the constructor creating a copy of an object;
- the move constructor: a constructor creating an object from an anonymous temporary object.

9.1 Operators 'new' and 'delete'

C++ defines two operators to allocate memory and to return it to the 'common pool'. These operators are, respectively, `new` and `delete`.

Here is a simple example illustrating their use. An `int` pointer variable points to memory allocated by operator `new`. This memory is later released by operator `delete`.

```
int *ip = new int;
delete ip;
```

Here are some characteristics of operators `new` and `delete`:

- `new` and `delete` are *operators* and therefore do not require parentheses, as required for *functions* like `malloc` and `free`;
- `new` returns a pointer to the kind of memory that's asked for by its operand (e.g., it returns a pointer to an `int`);
- `new` uses a *type* as its operand, which has the important benefit that the correct amount of memory, given the type of the object to be allocated, is made available;
- as a consequence, `new` is a type safe operator as it always returns a pointer to the type that was mentioned as its operand. In addition, the type of the receiving pointer must match the type specified with operator `new`;
- `new` may fail, but this is normally of *no* concern to the programmer. In particular, the program does *not* have to test the success of the memory allocation, as is required for `malloc` and friends. Section 9.2.2 delves into this aspect of `new`;
- `delete` returns `void`;
- for each call to `new` a matching `delete` should eventually be executed, lest a memory leak occurs;
- `delete` can safely operate on a 0-pointer (doing nothing);
- otherwise `delete` must only be used to return memory allocated by `new`. It should *not* be used to return memory allocated by `malloc` and friends.
- in **C++** `malloc` and friends are *deprecated* and should be avoided.

Operator `new` can be used to allocate primitive types but also to allocate objects. When a primitive type or a `struct` type without a constructor is allocated the allocated memory is *not* guaranteed to be initialized to 0, but an initialization expression may be provided:

```
int *v1 = new int;           // not guaranteed to be initialized to 0
int *v1 = new int();         // initialized to 0
int *v2 = new int(3);        // initialized to 3
int *v3 = new int(3 * *v2); // initialized to 9
```

When a class-type object is allocated, the arguments of its constructor (if any) are specified immediately following the type specification in the `new` expression and the object is initialized by to the thus specified constructor. For example, to allocate `string` objects the following statements could be used:

```
string *s1 = new string;            // uses the default constructor
string *s2 = new string{};          // same
string *s3 = new string(4, ' ');    // initializes to 4 blanks.
```

In addition to using `new` to allocate memory for a single entity or an array of entities (see the next section) there also exists a variant allocating *raw memory*: `operator new(sizeInBytes)`. Raw memory is returned as a `void *`. Here `new` allocates a block of memory for unspecified purpose. Although raw memory may consist of multiple characters it should not be interpreted as an array of characters. Since raw memory returned by `new` is returned as a `void *` its return value can be assigned to a `void *` variable. More often it is assigned to a `char *` variable, using a cast. Here is an example:

```
char *chPtr = static_cast<char *>(operator new(numberOfBytes));
```

The use of raw memory is frequently encountered in combination with the *placement new* operator, discussed in section 9.1.5.

9.1.1 Allocating arrays

Operator `new[]` is used to allocate arrays. The generic notation `new[]` is used in the **C++** Annotations. Actually, the number of elements to be allocated must be specified between the square brackets and it must, in turn, be *prefixed* by the type of the entities that must be allocated. Example:

```
int *intarr = new int[20];          // allocates 20 ints
string *stringarr = new string[10]; // allocates 10 strings.
```

Operator `new` is a different operator than operator `new[]`. A consequence of this difference is discussed in the next section (9.1.2).

Arrays allocated by operator `new[]` are called *dynamic arrays*. They are constructed during the execution of a program, and their lifetime may exceed the lifetime of the function in which they were created. Dynamically allocated arrays may last for as long as the program runs.

When `new[]` is used to allocate an array of primitive values or an array of objects, `new[]` must be specified with a type and an (unsigned) expression between its square brackets. The type and expression together are used by the compiler to determine the required size of the block of memory to make available. When `new[]` is used the array's elements are stored consecutively in memory. An array index expression may thereafter be used to access the array's individual elements: `intarr[0]` represents the first `int` value, immediately followed by `intarr[1]`, and so on until the last element (`intarr[19]`).

With non-class types (primitive types, POD types without constructors) the block of memory returned by operator `new[]` is *not* guaranteed to be initialized to 0. Alternatively, adding `()` to the `new` expression *will* initialize the block of memory to zeroes. E.g.,

```
struct POD
{
    int iVal;
    double dVal;
};
new POD[5]();        // returns a pointer to 5 0-initialized PODs
new double[9]();     // returns a pointer to 9 0-initialized doubles
```

If there are members of the `struct POD` that are explicitly initialized in the struct's interface (e.g., `int iVal = 12`), or if the struct uses composition, and the composed data member's type defines a default constructor, then initializations in the struct's interface and initializations performed by the composed data member's constructor takes precedence over the 0-initialization. Here is an example:

```
struct Data
{
    int value = 100;
};
struct POD
{
    int iVal = 12;
    double dVal;
    Data data;
};

POD *pp = new POD[5]();
```

Here, `pp` points to five `POD` objects, each having their `iVal` data members initialized to 12, their `dVal` data members initialized to 0, and their `data.value` members initialized to 100.

When operator `new[]` is used to allocate arrays of objects of class types defining default constructors these constructors are automatically used. Consequently `new string[20]` results in a block of 20 *initialized* `string` objects. A non-default constructor cannot be called, but often it is possible to work around that (as discussed in section 13.8).

The expression between brackets of operator `new[]` represents the number of elements of the array to allocate. The **C++** standard allows allocation of 0-sized arrays. The statement `new int[0]` is correct **C++**. However, it is also pointless and confusing and should be avoided. It is pointless as it doesn't refer to any element at all, it is confusing as the returned pointer has a useless non-0 value. A pointer intending to point to an array of values should be initialized (like any pointer that isn't yet pointing to memory) to 0, allowing for expressions like `if (ptr) ...`

Without using operator `new[]`, arrays of variable sizes can also be constructed as *local arrays*. Such arrays are not dynamic arrays and their lifetimes are restricted to the lifetime of the block in which they were defined.

Once allocated, all arrays have fixed sizes. There is no *simple* way to enlarge or shrink arrays. **C++** has no operator '`renew`'. Section 9.1.3 illustrates how to enlarge arrays.

9.1.2 Deleting arrays

Dynamically allocated arrays are deleted using operator `delete[]`. It expects a pointer to a block of memory, previously allocated by operator `new[]`.

When operator `delete[]`'s operand is a pointer to an array of objects two actions are performed:

- First, the class's destructor is called for each of the objects in the array. The destructor, as explained later in this chapter, performs all kinds of cleanup operations that are required by the time the object ceases to exist.

- Second, the memory pointed at by the pointer is returned to the common pool.

Here is an example showing how to allocate and delete an array of 10 string objects:

```
std::string *sp = new std::string[10];
delete[] sp;
```

No special action is performed if a dynamically allocated array of primitive typed values is deleted. Following `int *it = new int[10]` the statement `delete[] it` simply returns the memory pointed at by `it`. Realize that, as a pointer is a primitive type, deleting a dynamically allocated array of pointers to objects does *not* result in the proper destruction of the objects the array's elements point at. So, the following example results in a *memory leak*:

```
string **sp = new string *[5];
for (size_t idx = 0; idx != 5; ++idx)
    sp[idx] = new string;
delete[] sp;            // MEMORY LEAK !
```

In this example the only action performed by `delete[]` is to return an area the size of five pointers to strings to the common pool.

Here's how the destruction in such cases *should* be performed:

- Call `delete` for each of the array's elements;
- Delete the array itself

Example:

```
for (size_t idx = 0; idx != 5; ++idx)
    delete sp[idx];
delete[] sp;
```

One of the consequences is of course that by the time the memory is going to be returned not only the pointer must be available but also the number of elements it contains. This can easily be accomplished by storing pointer and number of elements in a simple class and then using an object of that class.

Operator `delete[]` is a different operator than operator `delete`. The rule of thumb is: if `new[]` was used, also use `delete[]`.

9.1.3 Enlarging arrays

Once allocated, all arrays have fixed sizes. There is no simple way to enlarge or shrink arrays. **C++** has no `renew` operator. The basic steps to take when enlarging an array are the following:

- Allocate a new block of memory of larger size;
- Copy the old array content to the new array;
- Delete the old array;
- Let the pointer to the array point to the newly allocated array.

Static and local arrays cannot be resized. Resizing is only possible for dynamically allocated arrays. Example:

```
#include <string>
using namespace std;

string *enlarge(string *old, size_t oldsize, size_t newsize)
{
    string *tmp = new string[newsize];  // allocate larger array

    for (size_t idx = 0; idx != oldsize; ++idx)
        tmp[idx] = old[idx];            // copy old to tmp

    delete[] old;                       // delete the old array
    return tmp;                         // return new array
}

int main()
{
    string *arr = new string[4];        // initially: array of 4 strings
    arr = enlarge(arr, 4, 6);           // enlarge arr to 6 elements.
}
```

The procedure to enlarge shown in the example also has several drawbacks.

- The new array requires `newsize` constructors to be called;
- Having initialized the strings in the new array, `oldsize` of them are immediately reassigned to the corresponding values in the original array;
- All the objects in the old arrays are destroyed.

Depending on the context various solutions exist to improve the efficiency of this rather inefficient procedure. An array of pointers could be used (requiring only the pointers to be copied, no destruction, no superfluous initialization) or raw memory in combination with the placement new operator could be used (an array of objects remains available, no destruction, no superfluous construction).

9.1.4 Managing 'raw' memory

As we've seen operator `new` allocates the memory for an object and subsequently initializes that object by calling one of its constructors. Likewise, operator `delete` calls an object's destructor and subsequently returns the memory allocated by operator `new` to the common pool.

In the next section we'll encounter another use of `new`, allowing us to initialize objects in so-called *raw memory*: memory merely consisting of bytes that have been made available by either static or dynamic allocation.

Raw memory is made available by `operator new(sizeInBytes)` and also by `operator new[](sizeInBytes)`. The returned memory should not be interpreted as an array of any kind but just a series of memory locations that were dynamically made available. No initialization whatsoever is performed by these variants of `new`.

Both variants return `void *s` so (static) casts are required to use the return values as memory of some type.

Here are two examples:

```
                                // room for 5 ints:
    int *ip = static_cast<int *>(operator new(5 * sizeof(int)));
                                // same as the previous example:
    int *ip2 = static_cast<int *>(operator new[](5 * sizeof(int)));
                                // room for 5 strings:
    string *sp = static_cast<string *>(operator new(5 * sizeof(string)));
```

As `operator new` has no concept of data types the size of the intended data type must be specified when allocating raw memory for a certain number of objects of an intended type. The use of `operator new` therefore somewhat resembles the use of `malloc`.

The counterpart of `operator new` is `operator delete`. `Operator delete` (or, equivalently, `operator delete[]`), expects a `void *` (so a pointer to any type can be passed to it). The pointer is interpreted as a pointer to raw memory which is returned to the common pool without any further action. In particular, no destructors are called by `operator delete`. The use of `operator delete` therefore resembles the use of `free`. To return the memory pointed at by the abovementioned variables `ip` and `sp` `operator delete` should be used:

```
                    // delete raw memory allocated by operator new
    operator delete(ip);
    operator delete[](ip2);
    operator delete(sp);
```

9.1.5 The ‘placement new’ operator

A remarkable form of operator `new` is called the *placement new* operator. Before using placement `new` the `<memory>` header file must be included.

Placement `new` is passed an existing block of memory into which `new` initializes an object or value. The block of memory should be large enough to contain the object, but apart from that there are no further requirements. It is easy to determine how much memory is used by en entity (object or variable) of type `Type`: the `sizeof` operator returns the number of bytes used by an `Type` entity.

Entities may of course dynamically allocate memory for their own use. Dynamically allocated memory, however, is not part of the entity’s memory ‘footprint’ but it is always made available externally to the entity itself. This is why `sizeof` returns the same value when applied to different `string` objects that return different length and capacity values.

The placement `new` operator uses the following syntax (using `Type` to indicate the used data type):

```
    Type *new(void *memory) Type{ arguments };
```

Here, `memory` is a block of memory of at least `sizeof(Type)` bytes and `Type(arguments)` is any constructor of the class `Type`.

The placement `new` operator is useful in situations where classes set aside memory to be used later. This is used, e.g., by `std::string` to change its capacity. Calling `string::reserve` may enlarge that capacity without making memory beyond the string’s length immediately available to the `string` object’s users. But the object itself *may* use its additional memory. E.g, when information is added to a `string` object it can draw memory from its capacity rather than performing a reallocation for each single character that is added to its content.

Let's apply that philosophy to a class `Strings` storing `std::string` objects. The class defines a `string *d_memory` accessing the memory holding its `d_size` string objects as well as `d_capacity - d_size` reserved memory. Assuming that a default constructor initializes `d_capacity` to 1, doubling `d_capacity` whenever an additional `string` must be stored, the class must support the following essential operations:

- doubling its capacity when all its spare memory (e.g., made available by `reserve`) has been consumed;
- adding another `string` object
- properly deleting the installed strings and memory when a `Strings` object ceases to exist.

The private member `void Strings::reserve` is called when the current capacity must be enlarged to `d_capacity`. It operates as follows: First new, raw, memory is allocated (line 1). This memory is in no way initialized with strings. Then the available strings in the old memory are copied into the newly allocated raw memory using placement new (line 2). Next, the old memory is deleted (line 3).

```
void Strings::reserve()
{
    using std::string;

    string *newMemory = static_cast<string *>(                  // 1
                            operator new(d_capacity * sizeof(string)));
    for (size_t idx = 0; idx != d_size; ++idx)                  // 2
        new (newMemory + idx) string{ d_memory[idx] };
    destroy();                                                  // 3
    d_memory = newMemory;
}
```

The member `append` adds another `string` object to a `Strings` object. A (public) member `reserve(request)` (enlarging `d_capacity` if necessary and if enlarged calling `reserve()`) ensures that the `String` object's capacity is sufficient. Then placement `new` is used to install the latest string into the raw memory's appropriate location:

```
void Strings::append(std::string const &next)
{
    reserve(d_size + 1);
    new (d_memory + d_size) std::string{ next };
    ++d_size;
}
```

At the end of the `String` object's lifetime, and during enlarging operations all currently used dynamically allocated memory must be returned. This is made the responsibility of the member `destroy`, which is called by the class's destructor and by `reserve()`. More about the destructor itself in the next section, but the implementation of the support member `destroy` is discussed below.

With placement `new` an interesting situation is encountered. Objects, possibly themselves allocating memory, are installed in memory that may or may not have been allocated dynamically, but that is usually not completely filled with such objects. So a simple `delete[]` can't be used. On the other hand, a `delete` for each of the objects that *are* available can't be used either, since those `delete` operations would also try to delete the memory of the objects themselves, which wasn't dynamically allocated.

This peculiar situation is solved in a peculiar way, only encountered in cases where placement `new` is used: memory allocated by objects initialized using placement `new` is returned by *explicitly* calling the object's destructor. The destructor is declared as a member having as its name the class name preceded by a tilde, not using any arguments. So, `std::string`'s destructor is named `~string`. An object's destructor *only* returns memory allocated by the object itself and, despite of its name, does *not* destroy its object. Any memory allocated by the *strings* stored in our class `Strings` is therefore properly destroyed by explicitly calling their destructors. Following this `d_memory` is back to its initial status: it again points to raw memory. This raw memory is then returned to the common pool by `operator delete`:

```
void Strings::destroy()
{
    for (std::string *sp = d_memory + d_size; sp-- != d_memory; )
        sp->~string();

    operator delete(d_memory);
}
```

So far, so good. All is well as long as we're using only one object. What about allocating an array of objects? Initialization is performed as usual. But as with `delete`, `delete[]` cannot be called when the buffer was allocated statically. Instead, when multiple objects were initialized using placement `new` in combination with a statically allocated buffer all the objects' destructors must be called explicitly, as in the following example:

```
    using std::string;

    char buffer[3 * sizeof(string)];
    string *sp = new(buffer) string [3];

    for (size_t idx = 0; idx < 3; ++idx)
        sp[idx].~string();
```

9.2 The destructor

Comparable to the constructor, classes may define a *destructor*. This function is the constructor's counterpart in the sense that it is invoked when an object ceases to exist. A destructor is usually called automatically, but that's not always true. The destructors of dynamically allocated objects are not automatically activated, but in addition to that: when a program is interrupted by an `exit` call, only the destructors of already initialized global objects are called. In that situation destructors of objects defined *locally* by functions are also *not* called. This is one (good) reason for avoiding `exit` in **C++** programs.

Destructors obey the following syntactical requirements:

- a destructor's name is equal to its class name prefixed by a tilde;
- a destructor has no arguments;
- a destructor has no return value.

Destructors are declared in their class interfaces. Example:

```
    class Strings
```

```
{
    public:
        Strings();
        ~Strings();     // the destructor
};
```

By convention the constructors are declared first. The destructor is declared next, to be followed by other member functions.

A destructor's main task is to ensure that memory allocated by an object is properly returned when the object ceases to exist. Consider the following interface of the class `Strings`:

```
class Strings
{
    std::string *d_string;
    size_t d_size;

    public:
        Strings();
        Strings(char const *const *cStrings, size_t n);
        ~Strings();

        std::string const &at(size_t idx) const;
        size_t size() const;
};
```

The constructor's task is to initialize the data fields of the object. E.g, its constructors are defined as follows:

```
Strings::Strings()
:
    d_string(0),
    d_size(0)
{}

Strings::Strings(char const *const *cStrings, size_t size)
:
    d_string(new string[size]),
    d_size(size)
{
    for (size_t idx = 0; idx != size; ++idx)
        d_string[idx] = cStrings[idx];
}
```

As objects of the class `Strings` allocate memory a destructor is clearly required. Destructors may or may not be called automatically, but note that destructors are *only* called (or, in the case of dynamically allocated objects: should only be called) for fully constructed objects.

C++ considers objects 'fully constructed' once at least one of its constructors could normally complete. It used to be *the* constructor, but as **C++** supports constructor delegation, multiple constructors can be activated for a single object; hence 'at least one constructor'. The remaining rules apply to fully constructed objects;

- Destructors of local non-static objects are called automatically when the execution flow leaves the block in which they were defined; the destructors of objects defined somewhere in the outer block of a function are called just before the function terminates.

- Destructors of static or global objects are called when the program itself terminates.
- The destructor of a dynamically allocated object is called by `delete` using the object's address as its operand;
- The destructors of a dynamically allocated array of objects are called by `delete[]` using the address of the array's first element as its operand;
- The destructor of an object initialized by placement `new` is activated by explicitly calling the object's destructor.

The destructor's task is to ensure that all memory that is dynamically allocated and controlled only by the object itself is returned. The task of the `Strings`'s destructor would therefore be to delete the memory to which `d_string` points. Its implementation is:

```
Strings::~Strings()
{
    delete[] d_string;
}
```

The next example shows `Strings` at work. In `process` a `Strings store` is created, and its data are displayed. It returns a dynamically allocated `Strings` object to `main`. A `Strings *` receives the address of the allocated object and deletes the object again. Another `Strings` object is then created in a block of memory made available locally in `main`, and an explicit call to `~Strings` is required to return the memory allocated by that object. In the example only once a `Strings` object is automatically destroyed: the local `Strings` object defined by `process`. The other two `Strings` objects require explicit actions to prevent memory leaks.

```
#include "strings.h"
#include <iostream>

using namespace std;;

void display(Strings const &store)
{
    for (size_t idx = 0; idx != store.size(); ++idx)
        cout << store.at(idx) << '\n';
}

Strings *process(char *argv[], size_t argc)
{
    Strings store{ argv, argc };
    display(store);
    return new Strings{ argv, argc };
}

int main(int argc, char *argv[])
{
    Strings *sp = process(argv, argc);
    delete sp;

    char buffer[sizeof(Strings)];
    sp = new (buffer) Strings{ argv, static_cast<size_t>(argc) };
    sp->~Strings();
}
```

9.2.1 Object pointers revisited

Operators `new` and `delete` are used when an object or variable is allocated. One of the advantages of the operators `new` and `delete` over functions like `malloc` and `free` is that `new` and `delete` call the corresponding object constructors and destructors.

The allocation of an object by operator `new` is a two-step process. First the memory for the object itself is allocated. Then its constructor is called, initializing the object. Analogously to the construction of an object, the destruction is also a two-step process: first, the destructor of the class is called deleting the memory controlled by the object. Then the memory used by the object itself is freed.

Dynamically allocated arrays of objects can also be handled by `new` and `delete`. When allocating an array of objects using operator `new` the default constructor is called for each object in the array. In cases like this operator `delete[]` must be used to ensure that the destructor is called for each of the objects in array.

However, the addresses returned by `new Type` and `new Type[size]` are of identical types, in both cases a `Type *`. Consequently it cannot be determined by the type of the pointer whether a pointer to dynamically allocated memory points to a single entity or to an array of entities.

What happens if `delete` rather than `delete[]` is used? Consider the following situation, in which the destructor `~Strings` is modified so that it tells us that it is called. In a `main` function an array of two `Strings` objects is allocated using `new`, to be deleted by `delete[]`. Next, the same actions are repeated, albeit that the `delete` operator is called without `[]`:

```
    #include <iostream>
    #include "strings.h"
    using namespace std;

    Strings::~Strings()
    {
        cout << "Strings destructor called" << '\n';
    }

    int main()
    {
        Strings *a  = new Strings[2];

        cout << "Destruction with []'s" << '\n';
        delete[] a;

        a = new Strings[2];

        cout << "Destruction without []'s" << '\n';
        delete a;
    }
/*
    Generated output:
Destruction with []'s
Strings destructor called
Strings destructor called
Destruction without []'s
Strings destructor called
*/
```

From the generated output, we see that the destructors of the individual `Strings` objects are called when `delete[]` is used, while only the first object's destructor is called if the `[]` is omitted.

Conversely, if `delete[]` is called in a situation where `delete` should have been called the results are unpredictable, and the program will most likely crash. This problematic behavior is caused by the way the run-time system stores information about the size of the allocated array (usually right *before* the array's first element). If a single object is allocated the array-specific information is not available, but it is nevertheless assumed present by `delete[]`. Thus this latter operator encounters bogus values in the memory locations just before the array's first element. It then dutifully interprets the value it encounters there as size information, usually causing the program to fail.

If no destructor is defined, a *trivial destructor* is defined by the compiler. The trivial destructor ensures that the destructors of composed objects (as well as the destructors of *base classes* if a class is a derived class, cf. chapter 13) are called. This has serious implications: objects allocating memory create memory leaks unless precautionary measures are taken (by defining an appropriate destructor). Consider the following program:

```
#include <iostream>
#include "strings.h"
using namespace std;

Strings::~Strings()
{
    cout << "Strings destructor called" << '\n';
}

int main()
{
    Strings **ptr = new Strings* [2];

    ptr[0] = new Strings[2];
    ptr[1] = new Strings[2];

    delete[] ptr;
}
```

This program produces no output at all. Why is this? The variable `ptr` is defined as a pointer to a pointer. The dynamically allocated array therefore consists of pointer variables and pointers are of a primitive type. No destructors exist for primitive typed variables. Consequently only the array itself is returned, and no `Strings` destructor is called.

Of course, we don't want this, but require the `Strings` objects pointed to by the elements of `ptr` to be deleted too. In this case we have two options:

- In a for-statement visit all the elements of the `ptr` array, calling `delete` for each of the array's elements. This procedure was demonstrated in the previous section.
- A wrapper class is designed around a pointer (to, e.g., an object of some class, like `Strings`). Rather than using a pointer to a pointer to `Strings` objects a pointer to an array of wrapper-class objects is used. As a result `delete[] ptr` calls the destructor of each of the wrapper class objects, in turn calling the `Strings` destructor for their `d_strings` members. Example:

    ```
    #include <iostream>
    using namespace std;

    class Strings   // partially implemented
    {
    ```

```
    public:
        ~Strings();
};

inline Strings::~Strings()
{
    cout << "destructor called\n";
}

class Wrapper
{
    Strings *d_strings;

    public:
        Wrapper();
        ~Wrapper();
};

inline Wrapper::Wrapper()
:
    d_strings(new Strings{})
{}
inline Wrapper::~Wrapper()
{
    delete d_strings;
}

int main()
{
    auto ptr = new Strings *[4];
    // ... code assigning `new Strings' to ptr's elements
    delete[] ptr;               // memory leak: ~Strings() not called

    cout << "===========\n";
    delete[] new Wrapper[4];    // OK: 4 x destructor called
}
/*
    Generated output:
===========
destructor called
destructor called
destructor called
destructor called
*/
```

9.2.2 The function set_new_handler()

The **C++** run-time system ensures that when memory allocation fails an error function is activated. By default this function throws a *bad_alloc* exception (see section 10.8), terminating the program. Therefore it is not necessary to check the return value of operator `new`. Operator `new`'s default behavior may be modified in various ways. One way to modify its behavior is to redefine the function that's called when memory allocation fails. Such a function must comply with the following requirements:

- it has no parameters;

- its return type is `void`.

A redefined error function might, e.g., print a message and terminate the program. The user-written error function becomes part of the allocation system through the function `set_new_handler`.

Such an error function is illustrated below[1]:

```
#include <iostream>
#include <string>

using namespace std;

void outOfMemory()
{
    cout << "Memory exhausted. Program terminates." << '\n';
    exit(1);
}

int main()
{
    long allocated = 0;

    set_new_handler(outOfMemory);       // install error function

    while (true)                        // eat up all memory
    {
        new int [100000]();
        allocated += 100000 * sizeof(int);
        cout << "Allocated " << allocated << " bytes\n";
    }
}
```

Once the new error function has been installed it is automatically invoked when memory allocation fails, and the program is terminated. Memory allocation may fail in indirectly called code as well, e.g., when constructing or using streams or when strings are duplicated by low-level functions.

So far for the theory. On some systems the 'out of memory' condition may actually never be reached, as the operating system may interfere before the run-time support system gets a chance to stop the program.

The traditional memory allocation functions (like `strdup`, `malloc`, `realloc` etc.) do not trigger the `new` handler when memory allocation fails and should be avoided in **C++** programs.

9.3 The assignment operator

In **C++** struct and class type objects can be directly assigned new values in the same way as this is possible in **C**. The default action of such an assignment for non-class type data members is a straight byte-by-byte copy from one data member to another. For now we'll use the following simple class `Person`:

```
class Person
```

---

[1] This implementation applies to the GNU **C/C++** requirements. Actually using the program given in the next example is not advised, as it probably enormously slows down your computer due to the resulting use of the operating system's *swap area*.

```
{
    char *d_name;
    char *d_address;
    char *d_phone;

    public:
        Person();
        Person(char const *name, char const *addr, char const *phone);
        ~Person();
    private:
        char *strdupnew(char const *src);   // returns a copy of src.
};

// strdupnew is easily implemented, here is its inline implementation:
inline char *Person::strdupnew(char const *src)
{
    return strcpy(new char [strlen(src) + 1], src);
}
```

`Person`'s data members are initialized to zeroes or to copies of the NTBSs passed to `Person`'s constructor, using some variant of `strdup`. The allocated memory is eventually returned by `Person`'s destructor.

Now consider the consequences of using `Person` objects in the following example:

```
void tmpPerson(Person const &person)
{
    Person tmp;
    tmp = person;
}
```

Here's what happens when `tmpPerson` is called:

- it expects a reference to a `Person` as its parameter `person`.
- it defines a local object `tmp`, whose data members are initialized to zeroes.
- the object referenced by `person` is copied to `tmp`: `sizeof(Person)` number of bytes are copied from `person` to `tmp`.

Now a potentially dangerous situation has been created. The actual values in `person` are *pointers*, pointing to allocated memory. After the assignment this memory is addressed by two objects: `person` *and* `tmp`.

- The potentially dangerous situation develops into an acutely dangerous situation once the function `tmpPerson` terminates: `tmp` is destroyed. The destructor of the class `Person` releases the memory pointed to by the fields `d_name`, `d_address` and `d_phone`: unfortunately, this memory is also pointed at by `person`....

This problematic assignment is illustrated in Figure 9.1.

Having executed `tmpPerson`, the object referenced by `person` now contains pointers to deleted memory.

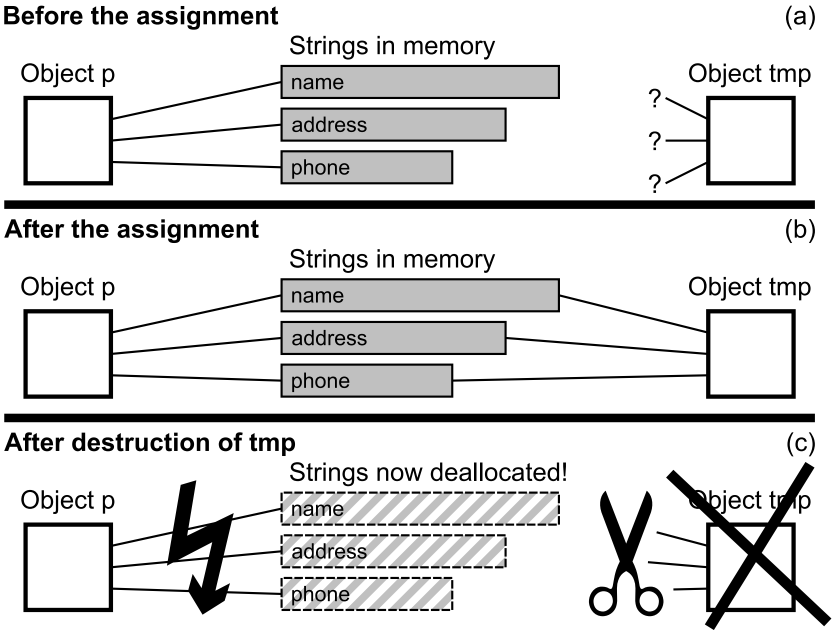
Before the assignment
(a)
Strings in memory
Object p
name
address
phone
Object tmp
?
?
?
After the assignment
(b)
Strings in memory
Object p
name
address
phone
Object tmp
After destruction of tmp
(c)
Strings now deallocated!
Object p
name
address
phone
Object tmp

Figure 9.1: Private data and public interface functions of the class Person, using byte-by-byte assignment

This is undoubtedly not a desired effect of using a function like `tmpPerson`. The deleted memory is likely to be reused by subsequent allocations. The pointer members of `person` have effectively become *wild pointers*, as they don't point to allocated memory anymore. In general it can be concluded that

> *every class containing pointer data members is a potential candidate for trouble*.

Fortunately, it is possible to prevent these troubles, as discussed next.

9.3.1 Overloading the assignment operator

Obviously, the right way to assign one `Person` object to another, is **not** to copy the content of the object bytewise. A better way is to make an equivalent object. One having its own allocated memory containing copies of the original strings.

The way to assign a `Person` object to another is illustrated in Figure 9.2. There are several ways to assign a `Person` object to another. One way would be to define a special member function to handle the assignment. The purpose of this member function would be to create a copy of an object having its own `name`, `address` and `phone` strings. Such a member function could be:

```
void Person::assign(Person const &other)
{
        // delete our own previously used memory
    delete[] d_name;
    delete[] d_address;
    delete[] d_phone;

        // copy the other Person's data
    d_name    = strdupnew(other.d_name);
```

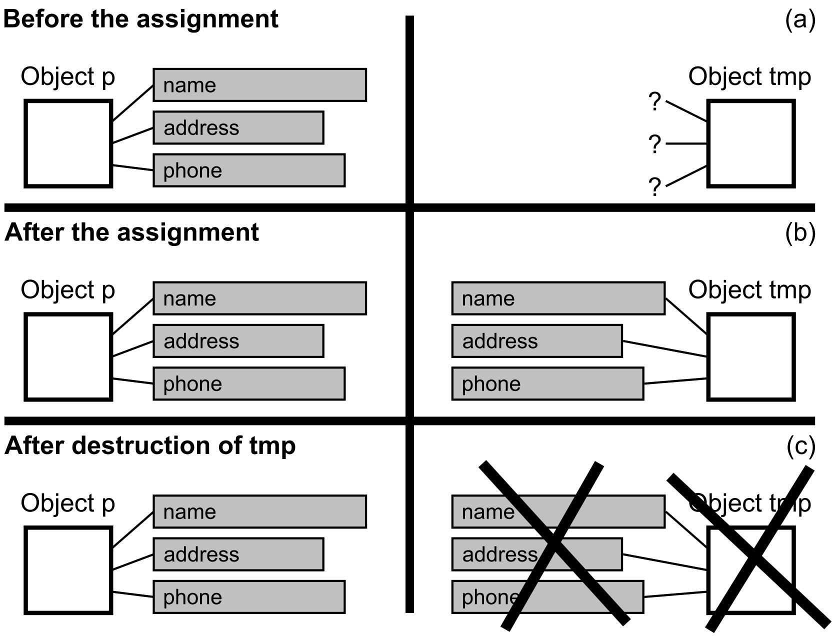
Before the assignment
(a)
Object p
name
address
phone
Object tmp
?
?
?
After the assignment
(b)
Object p
name
address
phone
name
address
phone
Object tmp
After destruction of tmp
(c)
Object p
name
address
phone
name
address
phone
Object tmp

Figure 9.2: Private data and public interface functions of the class Person, using the 'correct' assignment.

```
        d_address = strdupnew(other.d_address);
        d_phone   = strdupnew(other.d_phone);
    }
```

Using `assign` we could rewrite the offending function `tmpPerson`:

```
    void tmpPerson(Person const &person)
    {
        Person tmp;

            // tmp (having its own memory) holds a copy of person
        tmp.assign(person);

            // now it doesn't matter that tmp is destroyed..
    }
```

This solution is valid, although it only tackles a symptom. It requires the programmer to use a specific member function instead of the assignment operator. The original problem (assignment produces wild pointers) is still not solved. Since it is hard to 'strictly adhere to a rule' a way to solve the original problem is of course preferred.

Fortunately a solution exists using *operator overloading*: the possibility **C++** offers to redefine the actions of an operator in a given context. Operator overloading was briefly mentioned earlier, when the operators << and >> were redefined to be used with streams (like `cin`, `cout` and `cerr`), see section 3.1.4.

Overloading the assignment operator is probably the most common form of operator overloading in **C++**. A word of warning is appropriate, though. The fact that **C++** allows operator overloading does not mean that this feature should indiscriminately be used. Here's what you should keep in mind:

- operator overloading should be used in situations where an operator has a defined action, but this default action has undesired side effects in a given context. A clear example is the above assignment operator in the context of the class `Person`.

- operator overloading can be used in situations where the operator is commonly applied and no surprise is introduced when it's redefined. An example where operator overloading is appropriately used is found in the class `std::string`: assigning one string object to another provides the destination string with a copy of the content of the source string. No surprises here.
- in all other cases a member function should be defined instead of redefining an operator.

An operator should simply do what it is designed to do. The phrase that's often encountered in the context of operator overloading is *do as the `int`s do*. The way operators behave when applied to `int`s is what is expected, all other implementations probably cause surprises and confusion. Therefore, overloading the insertion (<<) and extraction (>>) operators in the context of streams is probably ill-chosen: the stream operations have nothing in common with bitwise shift operations.

9.3.1.1 The member 'operator=()'

To add operator overloading to a class, the class interface is simply provided with a (usually *public*) member function naming the particular operator. That member function is thereupon implemented.

To overload the assignment operator =, a member `operator=(Class const &rhs)` is added to the class interface. Note that the function name consists of two parts: the keyword `operator`, followed by the operator itself. When we augment a class interface with a member function `operator=`, then that operator is *redefined* for the class, which prevents the default operator from being used. In the previous section the function `assign` was provided to solve the problems resulting from using the default assignment operator. Rather than using an ordinary member function **C++** commonly uses a dedicated operator generalizing the operator's default behavior to the class in which it is defined.

The `assign` member mentioned before may be redefined as follows (the member `operator=` presented below is a first, rather unsophisticated, version of the overloaded assignment operator. It will shortly be improved):

```
class Person
{
    public:                             // extension of the class Person
                                        // earlier members are assumed.
        void operator=(Person const &other);
};
```

Its implementation could be

```
void Person::operator=(Person const &other)
{
    delete[] d_name;                      // delete old data
    delete[] d_address;
    delete[] d_phone;

    d_name = strdupnew(other.d_name);   // duplicate other's data
    d_address = strdupnew(other.d_address);
    d_phone = strdupnew(other.d_phone);
}
```

This member's actions are similar to those of the previously mentioned member `assign`, but this member is automatically called when the assignment operator = is used. Actually there are *two* ways to call overloaded operators as shown in the next example:

```
void tmpPerson(Person const &person)
{
    Person tmp;

    tmp = person;
    tmp.operator=(person);  // the same thing
}
```

Overloaded operators are seldom called explicitly, but explicit calls must be used (rather than using the plain operator syntax) when you explicitly *want* to call the overloaded operator from a pointer to an object (it is also possible to dereference the pointer first and then use the plain operator syntax, see the next example):

```
void tmpPerson(Person const &person)
{
    Person *tmp = new Person;

    tmp->operator=(person);
    *tmp = person;          // yes, also possible...

    delete tmp;
}
```

9.4 The 'this' pointer

A member function of a given class is always called in combination with an object of its class. There is always an implicit 'substrate' for the function to act on. **C++** defines a keyword, `this`, to reach this substrate.

The `this` keyword is a pointer variable that always contains the address of the object for which the member function was called. The `this` pointer is implicitly declared by each member function (whether `public, protected`, or `private`). The `this` pointer is a constant pointer to an object of the member function's class. For example, the members of the class `Person` implicitly declare:

```
extern Person *const this;
```

A member function like `Person::name` could be implemented in two ways: with or without using the `this` pointer:

```
char const *Person::name() const    // implicitly using `this'
{
    return d_name;
}

char const *Person::name() const    // explicitly using `this'
{
    return this->d_name;
}
```

The `this` pointer is seldom explicitly used, but situations do exist where the `this` pointer is actually required (cf. chapter 16).

9.4.1 Sequential assignments and this

C++'s syntax allows for sequential assignments, with the assignment operator associating from right to left. In statements like:

```
a = b = c;
```

the expression `b = c` is evaluated first, and its result in turn is assigned to `a`.

The implementation of the overloaded assignment operator we've encountered thus far does not permit such constructions, as it returns `void`.

This imperfection can easily be remedied using the `this` pointer. The overloaded assignment operator expects a reference to an object of its class. It can also *return* a reference to an object of its class. This reference can then be used as an argument in sequential assignments.

The overloaded assignment operator commonly returns a reference to the current object (i.e., `*this`). The next version of the overloaded assignment operator for the class `Person` thus becomes:

```
Person &Person::operator=(Person const &other)
{
    delete[] d_address;
    delete[] d_name;
    delete[] d_phone;

    d_address = strdupnew(other.d_address);
    d_name = strdupnew(other.d_name);
    d_phone = strdupnew(other.d_phone);

    // return current object as a reference
    return *this;
}
```

Overloaded operators may themselves be overloaded. Consider the `string` class, having overloaded assignment operators `operator=(std::string const &rhs)`, `operator=(char const *rhs)`, and several more overloaded versions. These additional overloaded versions are there to handle different situations which are, as usual, recognized by their argument types. These overloaded versions all follow the same mold: when necessary dynamically allocated memory controlled by the object is deleted; new values are assigned using the overloaded operator's parameter values and `*this` is returned.

9.5 The copy constructor: initialization vs. assignment

Consider the class `Strings`, introduced in section 9.2, once again. As it contains several primitive type data members as well as a pointer to dynamically allocated memory it needs a constructor, a destructor, and an overloaded assignment operator. In fact the class offers two constructors: in addition to the default constructor it offers a constructor expecting a `char const *const *` and a `size_t`.

Now consider the following code fragment. The statement references are discussed following the example:

```
int main(int argc, char **argv)
```

```
{
    Strings s1(argv, argc);      // (1)
    Strings s2;                  // (2)
    Strings s3(s1);              // (3)

    s2 = s1;                          // (4)
}
```

- At 1 we see an initialization. The object `s1` is initialized using `main`'s parameters: `Strings`'s second constructor is used.
- At 2 `Strings`'s *default constructor* is used, initializing an empty `Strings` object.
- At 3 yet another `Strings` object is created, using a constructor accepting an existing `Strings` object. This form of initializations has not yet been discussed. It is called a *copy construction* and the constructor performing the initialization is called the *copy constructor*. Copy constructions are also encountered in the following form:

  ```
  Strings s3 = s1;
  ```

  This is a *construction* and therefore an *initialization*. It is not an *assignment* as an assignment needs a left-hand operand that has already been defined. **C++** allows the assignment syntax to be used for constructors having only one parameter. It is somewhat deprecated, though.
- At 4 we see a plain assignment.

In the above example three objects were defined, each using a different constructor. The actually used constructor was deduced from the constructor's argument list.

The copy constructor encountered here is new. It does not result in a compilation error even though it hasn't been declared in the class interface. This takes us to the following rule:

> A copy constructor is (almost) always available, even if it isn't declared in the class's interface.

The reason for the '(almost)' is given in section 9.7.1.

The copy constructor made available by the compiler is also called the trivial copy constructor. Its use can easily be suppressed (using the `= delete` idiom). The trivial copy constructor performs a byte-wise copy operation of the existing object's primitive data to the newly created object, calls copy constructors to intialize the object's class data members from their counterparts in the existing object and, when inheritance is used, calls the copy constructors of the base class(es) to initialize the new object's base classes.

Consequently, in the above example the trivial copy constructor is used. As it performs a byte-by-byte copy operation of the object's primitive type data members that is exactly what happens at statement 3. By the time `s3` ceases to exist its destructor deletes its array of strings. Unfortunately `d_string` is of a primitive data type and so it also deletes `s1`'s data. Once again we encounter wild pointers as a result of an object going out of scope.

The remedy is easy: instead of using the trivial copy constructor a copy constructor must explicitly be added to the class's interface and its definition must prevent the wild pointers, comparably to the way this was realized in the overloaded assignment operator. An object's dynamically allocated memory is *duplicated*, so that it contains its own allocated data. But note that if a class also reserves extra (raw) memory, i.e., if it supports extra memory capacity, then that unused extra capacity is not made available in the copy-constructed object.

Copy construction can therefore be used to shed excess capacity. The copy constructor is simpler than the overloaded assignment operator in that it doesn't have to delete previously allocated memory. Since the object is going to be created no memory has already been allocated.

`Strings`'s copy constructor can be implemented as follows:

```
Strings::Strings(Strings const &other)
:
    d_string(new string[other.d_size]),
    d_size(other.d_size)
{
    for (size_t idx = 0; idx != d_size; ++idx)
        d_string[idx] = other.d_string[idx];
}
```

The copy constructor is always called when an object is initialized using another object of its class. Apart from the plain copy construction that we encountered thus far, here are other situations where the copy constructor is used:

- it is used when a function defines a class type value parameter rather than a pointer or a reference. The function's argument initializes the function's parameter using the copy constructor. Example:

  ```
  void process(Strings store) // no pointer, no reference
  {
      store.at(3) = "modified";   // doesn't modify `outer'
  }

  int main(int argc, char **argv)
  {
      Strings outer(argv, argc);
      process(outer);
  }
  ```

- it is used when a function defines a class type value return type. Example:

  ```
  Strings copy(Strings const &store)
  {
      return store;
  }
  ```

Here `store` is used to initialize `copy`'s return value. The returned `Strings` object is a temporary, anonymous object that may be immediately used by code calling `copy` but no assumptions can be made about its lifetime thereafter.

9.6 Revising the assignment operator

The overloaded assignment operator has characteristics also encountered with the copy constructor and the destructor:

- The *copying of (private) data* occurs (1) in the copy constructor and (2) in the overloaded assignment function.

- Allocated memory is deleted (1) in the overloaded assignment function and (2) in the destructor.

The copy constructor and the destructor clearly are required. If the overloaded assignment operator also needs to return allocated memory and to assign new values to its data members couldn't the destructor and copy constructor be used for that?

As we've seen in our discussion of the destructor (section 9.2) the destructor can explicitly be called, but that doesn't hold true for the (copy) constructor. But let's briefly summarize what an overloaded assignment operator is supposed to do:

- It should delete the dynamically allocated memory controlled by the current object;
- It should reassign the current object's data members using a provided existing object of its class.

The second part surely looks a lot like copy construction. Copy construction becomes even more attractive after realizing that the copy constructor also initializes any reference data members the class might have. Realizing the copy construction part is easy: just define a local object and initialize it using the assignment operator's const reference parameter, like this:

```
Strings &operator=(Strings const &other)
{
    Strings tmp(other);
    // more to follow
    return *this;
}
```

You may think the optimization `operator=(Strings tmp)` is attractive, but let's postpone that for a little while (at least until section 9.7).

Now that we've done the copying part, what about the deleting part? And isn't there another slight problem as well? After all we copied all right, but not into our intended (current, `*this`) object.

At this point it's time to introduce *swapping*. Swapping two variables means that the two variables exchange their values. We'll discuss swapping in detail in the next section, but let's for now assume that we've added a member `swap(Strings &other)` to our class `Strings`. This allows us to complete `String`'s `operator=` implementation:

```
Strings &operator=(Strings const &other)
{
    Strings tmp(other);
    swap(tmp);
    return *this;
}
```

This implementation of `operator=` is generic: it can be applied to every class whose objects are swappable. How does it work?

- The information in the `other` object is used to initialize a local `tmp` object. This takes care of the copying part of the assignment operator;
- Calling `swap` ensures that the current object receives its new values (with `tmp` receiving the current object's original values);

- When `operator=` terminates its local `tmp` object ceases to exist and its destructor is called. As it by now contains the data previously owned by the current object, the current object's original data are now destroyed, effectively completing the destruction part of the assignment operation.

Nice?

9.6.1 Swapping

Many classes (e.g., `std::string`) offer `swap` members allowing us to swap two of their objects. The *Standard Template Library* (STL, cf. chapter 18) offers various functions related to swapping. There is even a `swap` *generic algorithm* (cf. section 19.1.62), which is commonly implemented using the assignment operator. When implementing a `swap` member for our class `Strings` it could be used, provided that all of `String`'s data members can be swapped. As this is true (*why* this is true is discussed shortly) we can augment `class Strings` with a `swap` member:

```
void Strings::swap(Strings &other)
{
    swap(d_string, other.d_string);
    swap(d_size, other.d_size);
}
```

Having added this member to `Strings` the copy-and-swap implementation of `String::operator=` can now be used.

When two variables (e.g., `double one` and `double two`) are swapped, each one holds the other one's value after the swap. So, if `one == 12.50` and `two == -3.14` then after `swap(one, two)` `one == -3.14` and `two == 12.50`.

Variables of primitive data types (pointers and the built-in types) can be swapped, class-type objects can be swapped if their classes offer a `swap` member.

So should we provide our classes with a swap member, and if so, how should it be implemented?

The above example (`Strings::swap`) shows the standard way to implement a `swap` member: each of its data members are swapped in turn. But there are situations where a class cannot implement a swap member this way, even if the class only defines data members of primitive data types. Consider the situation depicted in figure 9.3.

In this figure there are four objects, each object has a pointer pointing to the next object. The basic organization of such a class looks like this:

```
class List
{
    List *d_next;
    ...
};
```

Initially four objects have their `d_next` pointer set to the next object: 1 to 2, 2 to 3, 3 to 4. This is shown in the upper half of the figure. At the bottom half it is shown what happens if objects 2 and 3 are swapped: 3's `d_next` point is now at object 2, which still points to 4; 2's `d_next` pointer points to 3's address, but 2's `d_next` is now at object 3, which is therefore pointing to itself. Bad news!

Another situation where swapping of objects goes wrong happens with classes having data members pointing or referring to data members of the same object. Such a situation is shown in figure 9.4.

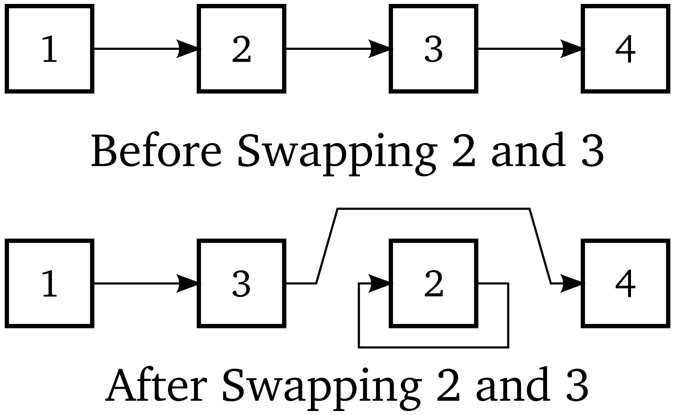
1
2
3
4
Before Swapping 2 and 3
1
3
2
4
After Swapping 2 and 3

Figure 9.3: Swapping a linked list

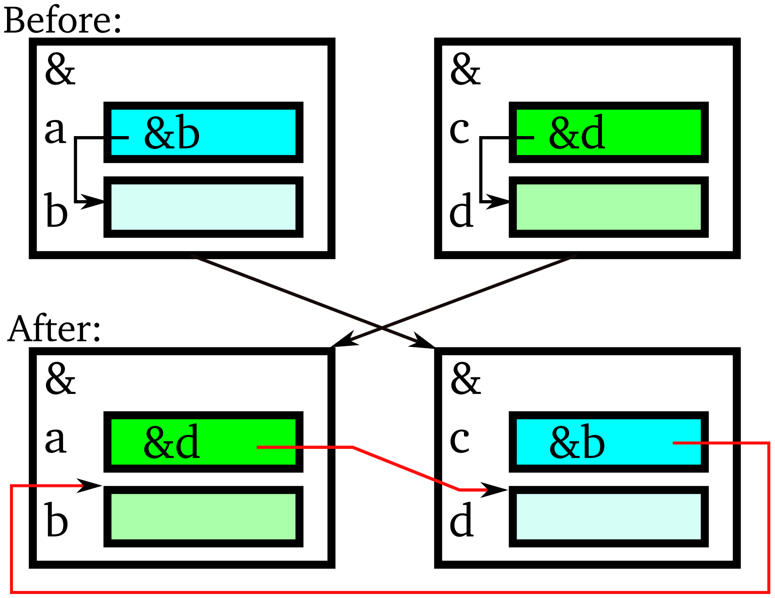
Before:
&
a
&b
b
&
c
&d
d
After:
&
a
&d
b
&
c
&b
d

Figure 9.4: Swapping objects with self-referential data

Here, objects have two data members, as in the following class setup:

```
class SelfRef
{
    size_t *d_ownPtr;        // initialized to &d_data
    size_t d_data;
};
```

The top-half of figure 9.4 shows two objects; their upper data members pointing to their lower data members. But if these objects are swapped then the situation shown in the figure's bottom half is encountered. Here the values at addresses a and c are swapped, and so, rather than pointing to their bottom data members they suddenly point to other object's data members. Again: bad news.

The common cause of these failing swapping operations is easily recognized: simple swapping operations must be avoided when data members point or refer to data that is involved in the swapping. If, in figure 9.4 the a and c data members would point to information outside of the two objects (e.g., if they would point to dynamically allocated memory) then the simple swapping would succeed.

However, the difficulty encountered with swapping `SelfRef` objects does not imply that two `SelfRef` objects cannot be swapped; it only means that we must be careful when designing `swap` members. Here is an implementation of `SelfRef::swap`:

```
void SelfRef::swap(SelfRef &other)
{
    swap(d_data, other.d_data);
}
```

In this implementation swapping leaves the self-referential data member as-is, and merely swaps the remaining data. A similar `swap` member could be designed for the linked list shown in figure 9.3.

9.6.1.1 Fast swapping

As we've seen with placement `new` objects can be constructed in blocks of memory of `sizeof(Class)` bytes large. And so, two objects of the same class each occupy `sizeof(Class)` bytes.

If objects of our class can be swapped, and if our class's data members do not refer to data actually involved in the swapping operation then a very fast swapping method that is based on the fact that we know how large our objects are can be implemented.

In this fast-swap method we merely swap the content of the `sizeof(Class)` bytes. This procedure may be applied to classes whose objects may be swapped using a member-by-member swapping operation and can (in practice, although this probably overstretches the allowed operations as described by the **C++** ANSI/ISO standard) also be used in classes having reference data members. It simply defines a buffer of `sizeof(Class)` bytes and performs a circular `memcpy` operation. Here is its implementation for a hypothetical class `Class`. It results in very fast swapping:

```
#include <cstring>

void Class::swap(Class &other)
{
    char buffer[sizeof(Class)];
    memcpy(buffer, &other, sizeof(Class));
    memcpy(static_cast<void *>(&other), this,   sizeof(Class));
```

```
        memcpy(static_cast<void *>(this), buffer, sizeof(Class));
    }
```

The `static_cast` for `memcpy's` destination address is used to prevent a compiler complaint: since `Class` is a class-type, the compiler (rightly) warns against bluntly copying bytes. But using `memcpy` is fine if you're `Class's` developer and know what you're doing.

Here is a simple example of a class defining a reference data member and offering a `swap` member implemented like the one above. The reference data members are initialized to external streams. After running the program `one` contains two *hello to 1* lines, `two` contains two *hello to 2* lines (for brevity all members of `Reference` are defined inline):

```
    #include <fstream>
    #include <cstring>

    class Reference
    {
        std::ostream &d_out;

        public:
            Reference(std::ostream &out)
            :
                d_out(out)
            {}
            void swap(Reference &other)
            {
                char buffer[sizeof(Reference)];
                memcpy(buffer, this, sizeof(Reference));
                memcpy(static_cast<void *>(this), &other, sizeof(Reference));
                memcpy(static_cast<void *>(&other), buffer,
                                                    sizeof(Reference));
            }
            std::ostream &out()
            {
                return d_out;
            }
    };

    int main()
    {
        std::ofstream one{ "one" };
        std::ofstream two{ "two" };

        Reference ref1{ one };          // ref1/ref2 hold references to
        Reference ref2{ two };          // the streams

        ref1.out() << "hello to 1\n";   // generate some output
        ref2.out() << "hello to 2\n";

        ref1.swap(ref2);

        ref2.out() << "hello to 1\n";   // more output
        ref1.out() << "hello to 2\n";
    }
```

Fast swapping should only be used for self-defined classes for which it can be proven that fast-swapping does not corrupt its objects, when swapped.

9.7 Moving data

Traditionally, **C++** offered two ways to assign the information pointed to by a data member of a temporary object to an *lvalue* object. Either a copy constructor or reference counting had to be used. In addition to these two methods **C++** now also supports *move semantics*, allowing *transfer* of the data pointed to by a temporary object to its destination.

Moving information is based on the concept of anonymous (temporary) data. Temporary values are returned by functions like `operator-()` and `operator+(Type const &lhs, Type const &rhs)`, and in general by functions returning their results 'by value' instead of returning references or pointers.

Anonymous values are always short-lived. When the returned values are primitive types (`int`, `double`, etc.) nothing special happens, but if a class-type object is returned by value then its destructor can be called immediately following the function call that produced the value. In any case, the value itself becomes inaccessible immediately after the call. Of course, a temporary return value may be bound to a reference (lvalue or rvalue), but as far as the compiler is concerned the value now has a name, which by itself ends its status as a temporary value.

In this section we concentrate on anonymous temporary values and show how they can be used to improve the efficiency of object construction and assignment. These special construction and assignment methods are known as *move construction* and *move assignment*. Classes supporting move operations are called *move-aware*.

Classes allocating their own memory usually benefit from becoming move-aware. But a class does not have to use dynamic memory allocation before it can benefit from move operations. Most classes using composition (or inheritance where the base class uses composition) can benefit from move operations as well.

Movable parameters for class `Class` take the form `Class &&tmp`. The parameter is an *rvalue reference*, and a rvalue reference only binds to an anonymous temporary value. The compiler is required to call functions offering movable parameters whenever possible. This happens when the class defines functions supporting `Class &&` parameters and an anonymous temporary value is passed to such functions. Once a temporary value has a name (which already happens inside functions defining `Class const &` or `Class &&tmp` parameters as within such functions the names of these parameters are available) it is no longer an *anonymous* temporary value, and within such functions the compiler no longer calls functions expecting anonymous temporary values when the parameters are used as arguments.

The next example (using inline member implementations for brevity) illustrates what happens if a non-const object, a temporary object and a const object are passed to functions `fun` for which these kinds of parameters were defined. Each of these functions call a function `gun` for which these kinds of parameters were also defined. The first time `fun` is called it (as expected) calls `gun(Class &)`. Then `fun(Class &&)` is called as its argument is an anonymous (temporary) object. However, inside `fun` the anonymous value has received a name, and so it isn't anonymous anymore. Consequently, `gun(Class &)` is called once again. Finally `fun(Class const &)` is called, and (as expected) `gun(Class const &)` is now called.

```
#include <iostream>

using namespace std;

class Class
```

```
{
    public:
    Class()
    {};
    void fun(Class const &other)
    {
        cout << "fun: Class const &\n";
        gun(other);
    }
    void fun(Class &other)
    {
        cout << "fun: Class &\n";
        gun(other);
    }
    void fun(Class &&tmp)
    {
        cout << "fun: Class &&\n";
        gun(tmp);
    }
    void gun(Class const &other)
    {
        cout << "gun: Class const &\n";
    }
    void gun(Class &other)
    {
        cout << "gun: Class &\n";
    }
    void gun(Class &&tmp)
    {
        cout << "gun: Class &&\n";
    }
};

int main()
{
    Class c1;

    c1.fun(c1);
    c1.fun(Class());

    Class const c0;
    c1.fun(c0);
}
```

Generally it is pointless to define a function having an rvalue reference return type. The compiler decides whether or not to use an overloaded member expecting an rvalue reference on the basis of the provided argument. If it is an anonymous temporary it calls the function defining the rvalue reference parameter, if such a function is available. An rvalue reference return type is used, e.g., with the `std::move` call, to keep the rvalue reference nature of its argument, which is known to be a temporary anonymous object. Such a situation can be exploited also in a situation where a temporary object is passed to (and returned from) a function which must be able to modify the temporary object. The alternative, passing a `const &`, is less attractive as it requires a `const_cast` before the object can be modified. Here is an example:

```
    std::string &&doubleString(std::string &&tmp)
```

```
{
    tmp += tmp;
    return std::move(tmp);
}
```

This allows us to do something like

```
std::cout << doubleString("hello "s);
```

to insert `hello hello` into `cout`.

The compiler, when selecting a function to call applies a fairly simple algorithm, and also considers copy elision. This is covered shortly (section 9.8).

9.7.1 The move constructor (dynamic data)

Our class `Strings` has, among other members, a data member `string *d_string`. Clearly, `Strings` should define a copy constructor, a destructor and an overloaded assignment operator.

Now consider the following function `loadStrings(std::istream &in)` extracting the strings for a `Strings` object from `in`. Next, the `Strings` object filled by `loadStrings` is returned by value. The function `loadStrings` returns a temporary object, which can then used to initialize an external `Strings` object:

```
Strings loadStrings(std::istream &in)
{
    Strings ret;
    // load the strings into 'ret'
    return ret;
}
// usage:
Strings store(loadStrings(cin));
```

In this example two full copies of a `Strings` object are required:

- initializing `loadString`'s value return type from its local `Strings ret` object;
- initializing `store` from `loadString`'s return value

We can improve the above procedure by defining a *move constructor*. Here is the declaration of the `Strings` class move constructor:

```
Strings(Strings &&tmp);
```

Move constructors of classes using dynamic memory allocation are allowed to assign the values of pointer data members to their own pointer data members without requiring them to make a copy of the source's data. Next, the temporary's pointer value is set to zero to prevent its destructor from destroying data now owned by the just constructed object. The move constructor has *grabbed* or *stolen* the data from the temporary object. This is OK as the temporary object cannot be referred to again (as it is anonymous, it cannot be accessed by other code) and the temporary objects cease to exist shortly after the constructor's call. Here is the implementation of `Strings` move constructor:

```
Strings::Strings(Strings &&tmp)
```

```
    :
        d_string(tmp.d_string),
        d_size(tmp.d_size),
        d_capacity(tmp.d_capacity)
    {
        tmp.d_string = 0;
        tmp.d_size = 0;
        tmp.d_capacity = 0;
    }
```

Move construction (in general: moving) must leave the object from which information was moved in a valid state. It is not specified in what way that valid state must be realized, but a good rule of thumb might be to return the object to its default constructed state. Therefore its `d_size` and `d_capacity` are also set to 0 when its `d_string` pointer is set to 0.

In section 9.5 it was stated that the copy constructor is almost always available. *Almost* always as the declaration of a move constructor suppresses the default availability of the copy constructor. The default copy constructor is also suppressed if a *move assignment operator* is declared (cf. section 9.7.3).

The following example shows a simple class `Class`, declaring a move constructor. In the `main` function following the class interface a `Class` object is defined which is then passed to the constructor of a second `Class` object. Compilation fails with the compiler reporting:

```
    error: cannot bind 'Class' lvalue to 'Class&&'
    error:   initializing argument 1 of 'Class::Class(Class&&)'
```

```
class Class
{
    public:
        Class() = default;
        Class(Class &&tmp)
        {}
};

int main()
{
    Class one;
    Class two{ one };
}
```

The cure is easy: after declaring a (possibly `default`) copy constructor the error disappears:

```
class Class
{
    public:
        Class() = default;
        Class(Class const &other) = default;
        Class(Class &&tmp)
        {}
};

int main()
{
    Class one;
    Class two{ one };
}
```

9.7.2 The move constructor (composition)

Classes not using pointer members pointing to memory controlled by its objects (and not having base classes doing so, see chapter 13) may also benefit from overloaded members expecting rvalue references. The class benefits from move operations when one or more of the composed data members themselves support move operations.

Move operations cannot be implemented if the class type of a composed data member does not support moving or copying. Currently, `stream` classes fall into this category.

An example of a move-aware class is the class `std:string`. A class `Person` could use composition by defining `std::string d_name` and `std::string d_address`. Its move constructor would then have the following prototype:

```
    Person(Person &&tmp);
```

However, the following implementation of this move constructor is incorrect:

```
    Person::Person(Person &&tmp)
    :
        d_name(tmp.d_name),
        d_address(tmp.d_address)
    {}
```

It is incorrect as `string`'s copy constructors rather than `string`'s move constructors are called. If you're wondering why this happens then remember that move operations are *only* performed for anonymous objects. To the compiler anything having a name isn't anonymous. And so, by implication, having available a rvalue reference does *not* mean that we're referring to an anonymous object. But we *know* that the move constructor is only called for anonymous arguments. To use the corresponding `string` move operations we have to inform the compiler that we're talking about anonymous data members as well. For this a cast could be used (e.g., `static_cast<Person &&>(tmp)`), but the C++-0x standard provides the function `std::move` to anonymize a named object. The correct implementation of `Person`'s move construction is, therefore:

```
    Person::Person(Person &&tmp)
    :
        d_name( std::move(tmp.d_name) ),
        d_address( std::move(tmp.d_address) )
    {}
```

The function `std::move` is (indirectly) declared by many header files. If no header is already declaring `std::move` then include `utility`.

When a class using composition not only contains class type data members but also other types of data (pointers, references, primitive data types), then these other data types can be initialized as usual. Primitive data type members can simply be copied; references can be initialized as usual and pointers may use move operations as discussed in the previous section.

The compiler never calls move operations for variables having names. Let's consider the implications of this by looking at the next example, assuming the class `Class` offers a move constructor and a copy constructor:

```
Class factory();

void fun(Class const &other);   // a
void fun(Class &&tmp);          // b

void callee(Class &&tmp)
{
    fun(tmp);                   // 1
}

int main()
{
    callee(factory());
}
```

- At 1 function a is called. At first sight this might be surprising, but `fun`'s argument is not an *anonymous* temporary object but a *named* temporary object.

Realizing that `fun(tmp)` might be called twice the compiler's choice is understandable. If `tmp`'s data would have been grabbed at the first call, the second call would receive `tmp` without any data. But at the last call we might know that `tmp` is never used again and so we might like to ensure that `fun(Class &&)` is called. For this, once again, `std::move` is used:

```
fun(std::move(tmp));            // last call!
```

9.7.3 Move-assignment

In addition to the overloaded assignment operator a *move assignment* operator may be implemented for classes supporting move operations. In this case, if the class supports swapping the implementation is surprisingly simple. No copy construction is required and the move assignment operator can simply be implemented like this:

```
Class &operator=(Class &&tmp)
{
    swap(tmp);
    return *this;
}
```

If swapping is not supported then the assignment can be performed for each of the data members in turn, using `std::move` as shown in the previous section with a class `Person`. Here is an example showing how to do this with that class `Person`:

```
Person &operator=(Person &&tmp)
{
    d_name = std::move(tmp.d_name);
    d_address = std::move(tmp.d_address);
    return *this;
}
```

As noted previously (section 9.7.1) declaring a move assignment operator suppresses the default availability of the copy constructor. It is made available again by declaring the copy constructor in the class's interface (and of course by providing an explicit implementation or by using the `= default` default implementation).

9.7.4 Revising the assignment operator (part II)

Now that we've familiarized ourselves with the overloaded assignment operator and the move-assignment, let's once again have a look at their implementations for a class `Class`, supporting swapping through its `swap` member. Here is the generic implementation of the overloaded assignment operator:

```
Class &operator=(Class const &other)
{
    Class tmp{ other };
    swap(tmp);
    return *this;
}
```

and this is the move-assignment operator:

```
Class &operator=(Class &&tmp)
{
    swap(tmp);
    return *this;
}
```

They look remarkably similar in the sense that the overloaded assignment operator's code is identical to the move-assignment operator's code once a copy of the `other` object is available. Since the overloaded assignment operator's `tmp` object really is nothing but a temporary `Class` object we can use this fact by implementing the overloaded assignment operator in terms of the move-assignment. Here is a second revision of the overloaded assignment operator:

```
Class &operator=(Class const &other)
{
    Class tmp{ other };
    return *this = std::move(tmp);
}
```

9.7.5 Moving and the destructor

Once a class becomes a *move-aware* class one should realize that its destructor still performs its job as implemented. Consequently, when moving pointer values from a temporary source to a destination the move constructor should make sure that the temporary's pointer value is set to zero, to prevent doubly freeing memory.

If a class defines pointers to pointer data members there usually is not only a pointer that is moved, but also a `size_t` defining the number of elements in the array of pointers.

Once again, consider the class `Strings`. Its destructor is implemented like this:

```
Strings::~Strings()
{
    for (string **end = d_string + d_size; end-- != d_string; )
        delete *end;
    delete[] d_string;
}
```

The move constructor (and other move operations!) must realize that the destructor not only deletes `d_string`, but also considers `d_size`. A member implementing move operations should therefore not only set `d_string` to zero but also `d_size`. The previously shown move constructor for `Strings` is therefore incorrect. Its improved implementation is:

```
Strings::Strings(Strings &&tmp)
:
    d_string(tmp.d_string),
    d_size(tmp.d_size),
    d_capacity(tmp.d_capacity)
{
    tmp.d_string = 0;
    tmp.d_size = 0;
}
```

If operations by the destructor all depend on `d_string` having a non-zero value then variations of the above approach are possible. The move operations could merely set `d_string` to 0, testing whether `d_string == 0` in the destructor (and if so, end the destructor's actions). In the latter variant the `d_size` assignment can be omitted.

9.7.6 Move-only classes

Classes may very well allow move semantics without offering copy semantics. Most stream classes belong to this category. Extending their definition with move semantics greatly enhances their usability. Once move semantics becomes available for such classes, so called *factory functions* (functions returning an object constructed by the function) can easily be implemented. E.g.,

```
// assume char *filename
ifstream inStream(openIstream(filename));
```

For this example to work an `ifstream` constructor must offer a move constructor. This ensures that only one object refers to the open `istream`.

Once classes offer move semantics their objects can also safely be stored in standard containers (cf. chapter 12). When such containers perform reallocations (e.g., when their sizes are enlarged) they use the object's move constructors rather than their copy constructors. As move-only classes suppress copy semantics containers storing objects of move-only classes implement the correct behavior in that it is impossible to assign such containers to each other.

9.7.7 Default move constructors and assignment operators

As we've seen, classes by default offer a copy constructor and assignment operator. These class members are implemented so as to provide basic support: data members of primitive data types are copied byte-by-byte, but for class type data members their corresponding copy constructors c.q. assignment operators are called. The compiler also attempts to provide default implementations for move constructors and move assignment operators. However, the default constructors and assignment operators cannot always be provided.

These are the rules the compiler applies when deciding what to provide or not to provide:

- If the copy constructor or the copy assignment operator is declared, then the default move constructor and move assignment operator are suppressed; their use is replaced by the corresponding copy operation (constructor or assignment operator);

- If the move constructor or the move assignment operator is declared then the copy constructor and the copy assignment operator are implicitly declared as deleted, and can therefore not be used anymore;
- If *either* the move constructor *or* the move assignment operator is declared, then (in addition to suppressing the copy operations) the default implementation of the other move-member is also suppressed;
- In all other cases the default copy and move constructors *and* the default copy and assignment operators are provided.

If default implementations of copy or move constructors or assignment operators are suppressed, but they should be available, then it's easy to provide the default implementations by specifying the required signatures, to which the specification '`= default`' is added.

Here is an example of a class offering all defaults: constructor, copy constructor, move constructor, copy assignment operator and move assignment operator:

```
class Defaults
{
    int d_x;
    Mov d_mov;
};
```

Assuming that `Mov` is a class offering move operations in addition to the standard copy operations, then the following actions are performed on the destination's `d_mov` and `d_x`:

```
Defaults factory();

int main()
{                               Mov operation:    d_x:
                                ---------------------------
  Defaults one;                 Mov(),            undefined
  Defaults two(one);            Mov(Mov const &), one.d_x
  Defaults three(factory());    Mov(Mov &&tmp),   tmp.d_x

  one = two;                    Mov::operator=(   two.d_x
                                     Mov const &),

  one = factory();              Mov::operator=(   tmp.d_x
                                     Mov &&tmp)
}
```

If, `Defaults` declares at least one constructor (not being the copy- or move constructor) as well as the copy assignment operators then only the default copy- and declared assignment operator are available. E.g.:

```
class Defaults
{
    int d_x;
    Mov d_mov;

    public:
        Defaults(int x);
        Defaults &operator=(Default const &rhs);
};

Defaults factory();

int main()
{                              Mov operation:    resulting d_x:
                               --------------------------------
  Defaults one;                ERROR: not available
  Defaults two(one);           Mov(Mov const &),        one.d_x
  Defaults three(factory());   Mov(Mov const &),        one.d_x

  one = two;                   Mov::operatpr=(          two.d_x
                                    Mov const &)
  one = factory();             Mov::operator=(          tmp.d_x
                                    Mov const &)
}
```

To reestablish the defaults, append `= default` to the appropriate declarations:

```
class Defaults
{
    int d_x;
    Mov d_mov;

    public:
        Defaults()              = default;
        Defaults(int x);
        // Defaults(Default const &) remains available (by default)

        Defaults(Defaults &&tmp) = default;

        Defaults &operator=(Defaults const &rhs);
        Defaults &operator=(Defaults &&tmp) = default;
};
```

Be cautious declaring defaults, as default implementations copy data members of primitive types byte-by-byte from the source object to the destination object. This is likely to cause problems with pointer type data members.

The `= default` suffix can only be used when declaring constructors or assignment operators in the class's public section.

9.7.8 Moving: implications for class design

Here are some general rules to apply when designing classes offering value semantics (i.e., classes whose objects can be used to initialize other objects of their class and that can be asssigned to other objects of their class):

- Classes using pointers to dynamically allocated memory, owned by the class's objects must be provided with a copy constructor, an overloaded copy assignment operator and a destructor;
- Classes using pointers to dynamically allocated memory, owned by the class's objects, should be provided with a move constructor and a move assignment operator;

- Classes using composition may benefit from move constructors and move assignment operators as well. Some classes support neither move nor copy construction and assignment (for example: stream classes don't). If your class contains data members of such class types then defining move operations is pointless.

In the previous sections we've also encountered an important design principle that can be applied to move-aware classes:

> *Whenever a member of a class receives a* `const &` *to an object of its own class and creates a copy of that object to perform its actual actions on, then that function's implementation can be implemented by an overloaded function expecting an rvalue reference.*

The former function can now call the latter by passing `std::move(tmp)` to it. The advantages of this design principle should be clear: there is only one implementation of the actual actions, and the class automatically becomes *move-aware* with respect to the involved function.

We've seen an initial example of the use of this principle in section 9.7.4. Of course, the principle cannot be applied to the copy constructor itself, as you need a copy constructor to make a copy. The copy- and move constructors must always be implemented independently from each other.

9.8 Copy Elision and Return Value Optimization

When the compiler selects a member function (or constructor) it applies a simple set of rules, matching arguments with parameter types.

Below two tables are shown. The first table should be used in cases where a function argument has a name, the second table should be used in cases where the argument is anonymous. In each table select the const or non-const column and then use the topmost overloaded function that is available having the specified parameter type.

The tables do not handle functions defining value parameters. If a function has overloads expecting, respectively, a value parameter and some form of reference parameter the compiler reports an ambiguity when such a function is called. In the following selection procedure we may assume, without loss of generality, that this ambiguity does not occur and that all parameter types are reference parameters.

Parameter types matching a function's argument of type `T` if the argument is:

- a *named* argument (an lvalue or a named rvalue)

	the argument is:	
	non-const	const
Use the topmost	(T &)	
available function	(T const &)	(T const &)

  Example: for an `int x` argument a function `fun(int &)` is selected rather than a function `fun(int const &)`. If no `fun(int &)` is available the `fun(int const &)` function is used. If neither is available (and `fun(int)` hasn't been defined instead) the compiler reports an error.

- an *anonymous* argument (an anonymous temporary or a literal value)

	the argument is:	
	non-const	const
Use the topmost	(T &&)	
available function	(T const &)	(T const &)

> Example: when the return value of an `int arg()` function is passed to a function `fun` for which various overloaded versions are available `fun(int &&)` is selected. If this function is unavailable but `fun(int const &)` is, then the latter function is used. If none of these two functions is available the compiler reports an error.

The tables show that eventually *all* arguments can be used with a function specifying a `T const &` parameter. For *anonymous* arguments a similar *catch all* is available having a higher priority: `T const &&` matches all anonymous arguments. Functions having this signature are normally not defined as their implementations are (should be) identical to the implementations of the functions expecting a `T const &` parameter. Since the temporary can apparently not be modified a function defining a `T const &&` parameter has no alternative but to copy the temporary's resources. As this task is already performed by functions expecting a `T const &`, there is no need for implementing functions expecting `T const &&` parameters, and it's considered bad style if you do.

As we've seen the move constructor grabs the information from a temporary for its own use. That is OK as the temporary is going to be destroyed after that anyway. It also means that the temporary's data members are modified.

Having defined appropriate copy and/or move constructors it may be somewhat surprising to learn that the compiler may decide to stay clear of a copy or move operation. After all making *no* copy and *not* moving is more efficient than copying or moving.

The option the compiler has to avoid making copies (or perform move operations) is called *copy elision* or *return value optimization*. In all situations where copy or move constructions are appropriate the compiler may apply copy elision. Here are the rules. In sequence the compiler considers the following options, stopping once an option can be selected:

- if a copy or move constructor exists, try copy elision
- if a move constructor exists, move.
- if a copy constructor exists, copy.
- report an error

All modern compilers apply copy elision. Here are some examples where it may be encountered:

```
class Elide;

Elide fun()         // 1
{
    Elide ret;
    return ret;
}

void gun(Elide par);

Elide elide(fun()); // 2

gun(fun());         // 3
```

- At 1 `ret` may never exist. Instead of using `ret` and copying `ret` eventually to `fun`'s return value it may directly use the area used to contain `fun`'s return value.
- At 2 `fun`'s return value may never exist. Instead of defining an area containing `fun`'s return value and copying that return value to `elide` the compiler may decide to use `elide` to create `fun`'s return value in.

- At 3 the compiler may decide to do the same for gun's `par` parameter: `fun`'s return value is directly created in `par`'s area, thus eliding the copy operation from `fun`'s return value to `par`.

9.9 Unrestricted Unions

We end this chapter about abstract containers with a small detour, introducing extensions to the `union` concept. Although unions themselves aren't 'abstract containers', having covered containers puts us in a good position to introduce and illustrate *unrestricted unions*.

Whereas traditional unions can only contain primitive data, unrestricted unions allow addition of data fields of types for which non-trivial constructors were defined. Such data fields commonly are of class-types. Here is an example of such an unrestricted union:

```
union Union
{
    int u_int;
    std::string u_string;
};
```

One of its fields is defined as a `std::string` (having a constructor), turning this union into an *unrestricted* union. As an unrestricted union defines at least one field of a type having a constructor the question becomes how these unions can be constructed and destroyed.

The destructor of a union consisting of, e.g. a `std::string` and an `int` should of course not call the `string`'s destructor if the union's last (or only) use referred to its `int` field. Likewise, when the `std::string` field is used, and processing switches from the `std::string` to the `int` field, `std::string`'s destructor should be called before any assignment to the `int` field takes place.

The compiler does not solve the issue for us, and in fact does not at all implement default constructors or destructors for unrestricted unions. If we try to define an unrestricted union like the one shown above, an error message is issued. E.g.,

```
error: use of deleted function 'Union::Union()'
error: 'Union::Union()' is implicitly deleted because the default
        definition would be ill-formed:
error: union member 'Union::u_string' with non-trivial
        'std::basic_string<...>::basic_string() ...'
```

9.9.1 Implementing the destructor

Although the compiler won't provide (default) implementations for constructors and destructors of unrestricted unions, *we* can (and *must*). The task isn't difficult, but there are some caveats.

Consider our unrestricted union's destructor. It clearly should destroy `u_string`'s data if that is its currently active field; but it should do nothing if `u_int` is its currently active field. But how does the destructor know what field to destroy? It doesn't, as the unrestricted union contains no information about what field is currently active.

This problem is tackled by embedding the unrestricted union in a larger aggregate (like a class or a struct) where it becomes a regular data member. We still consider the unrestricted union a data type by itself, but its use requires caution. The surrounding class is provided with a *d_field* data member keeping track of the currently active union-field. The `d_field` value is an enumeration value which is defined by the union. The actual use of the unrestricted union is completely controlled by the aggregate, freeing the aggregate's users from any administration related to the unrestricted union.

Using this design we start out with an explicit and empty implementation of the destructor, as there's no way to tell the destructor itself what field to destroy:

```
Data::Union::~Union()
{};
```

Nevertheless, unrestricted unions must properly destroy their class-type fields. Since an unrestricted union itself doesn't know what its active field is, it must be informed about that by its surrounding class. To simplify the generalization to other types a static array of pointers to functions destroying the current field's value is used. This array is defined in the union's private section as

```
static void (Union::*s_destroy[])();
```

and it is initialized as:

```
void (Union::*Union::s_destroy[])() =
{
    &Union::destroyText,
    &Union::destroyValue
};
```

Primitive data types normally don't need any special attention when they go out of scope, so `destroyValue` can be defined as an empty function:

```
void Union::destroyValue()
{}
```

On the other hand, the member `destroyText` must explicitly call `u_text's` destructor:

```
void Union::destroyText()
{
    u_text.std::string::~string();
}
```

Proper destruction can now be realized by a single function `void destroy(Field field)` which simply calls the appropriate function:

```
void Union::destroy(Field type)
{
    (this->*s_destroy[type])();
}
```

Since the unrestricted union is defined as a data member of a surrounding class, the surrounding class's destructor is responsible for the proper destruction of its unrestricted union. As the surrounding class keeps track of the currently active unrestricted union's field its implementation is easy:

```
Data::~Data()
{
    d_union.destroy(d_field);
}
```

9.9.2 Embedding an unrestricted union in a surrounding class

The unrestricted union becomes a data member of the surrounding aggregate (e.g., `class Data`). The `class Data` is provided with a data member `Union::Field d_field` and `Data`'s users might query the currently active field from, e.g., an accessor `field`:

```
class Data
{
    Union::Field d_field;
    Union d_union;

    public:
        Data(int value = 0);
        Data(Data const &other);
        Data(Data &&tmp);
        Data(std::string const &text);

        ~Data();                // empty body

        Union::Field field() const;
        ...
};
```

`Data`'s constructors receive `int` or `string` values. To pass these values to `d_union`, we need `Union` constructors for the various union fields.

The unrestricted union itself starts out like this:

```
union Union
{
    enum Field
    {
        TEXT,
        VALUE
    };

    private:
        std::string u_text;
        int u_value;

    public:
        Union(Union const &other) = delete;
        ~Union();               // empty

        Union(int value);
        Union(std::string const &text);

        Union(Union const &other, Field type);
        Union(Union &&tmp, Field type);
        ...
};
```

The last two `Union` constructors are comparable to the standard copy- and move constructors. With unrestricted unions, however, the existing union's actual type needs to be specified so that the correct field is initialized. To simplify the generalization to other types we apply a procedure that is comparable to the procedure we followed for destroying an understricted union: we define a static array of pointers to copy-functions. This array is declared in the union's private section as

```
static void (Union::*s_copy[])(Union const &other);
```

and it is defined as:

```
void (Union::*Union::s_copy[])(Union const &other) =
{
    &Union::copyText,
    &Union::copyValue
};
```

The `copyText` and `copyValue` private members are responsible for copying `other's` data fields. However, there is a little snag. Although basic types can directly be assigned, class-type fields cannot. Destination fields cannot be initialized using member initializers as the field to initialize depends on the `Field` type that's passed to the constructor. Because of that the initialization must be performed inside the constructors' bodies. At that point the data fields are merely a series of uninitialized bytes, and so placement new is used to copy-construct class-type fields. Here are the implementations of the copy functions:

```
void Union::copyValue(Union const &other)
{
    u_value = other.u_value;
}

void Union::copyText(Union const &other)
{
    new(&u_text) string{ other.u_text };
}
```

When implementing the union's move constructor other considerations must be taken into account. Since we're free to do whatever we want with the move constructor's `Union &&tmp` object, we can simply grab its current field, and store a `VALUE` type of value into `tmp`. For that we use the `Union's` `swap` facility, the current object's field, another `Union` object, and the other `Union's` field type (swapping is discussed in the next section). Of course, if there isn't any primitive typed field this doesn't work. In that case field-specific move functions must be used, comparable to the ones used when copy-constructing a `Union` object.

Now we're ready for the constructors' implementations:

```
Union::Union(std::string const &text)
:
    u_text(text)
{}

Union::Union(int value)
:
    u_value(value)
{}

Union::Union(Union &&tmp, Field type)
{
    swap(VALUE, tmp, type);
}

Union::Union(Union const &other, Field type)
{
    (this->*s_copy[type])(other);
}

Data::Data(Data const &other)
:
    d_field(other.d_field),
    d_union(other.d_union, d_field)
{}

Data::Data(int value)
:
    d_field(Union::VALUE),
    d_union(value)
{}

Data::Data(Data const &other)
:
    d_field(other.d_field),
    d_union(other.d_union, d_field)
{}
```

9.9.3 Swapping unrestricted unions

Unrestricted unions should define a non-throwing `swap` member. It needs three arguments: the current object's field, another union object, and that union's field. The prototype of our unrestricted union's `swap` member, therefore, is:

```
void swap(Field current, Union &other, Field next);
```

To implement it similar considerations as encountered with the copy constructor apply. An unrestricted union having k fields must support $k * k$ different swap situations. Representing these in a $k * k$ matrix we note that the diagonal elements refer to swapping identical elements for which no special considerations apply (assuming swapping of identical data types is supported). The lower-triangle elements are identical to their transposed upper-triangle elements, and so they can use those elements after reverting the current and other union objects. All field-specific swap functions can be organized in a *k x k* static matrix of pointers to swapping members. For `Union` the declaration of that matrix is

```
static void (Union::*s_swap[][2])(Union &other);
```

and its definition is

```
void (Union::*Union::s_swap[][2])(Union &other) =
{
  {  &Union::swap2Text,     &Union::swapTextValue},
  {  &Union::swapValueText, &Union::swap2Value},
};
```

The diagonal and lower-triangle elements are straightforwardly implemented. E.g.,

```
void Union::swap2Text(Union &other)
{
    u_text.swap(other.u_text);
}

void Union::swapValueText(Union &other)
{
    other.swapTextValue(*this);
}
```

but implementing the upper-triangle elements requires some thought. To install a class-type field placement new must again be used. But this time we're not copying but moving, as the current object is going to lose its content. Like swapping, moving should always succeed. Following the move construction the other object has received the current object's data. As the current object keeps its valid state after the move, it must also explicitly be destroyed to properly end its lifetime. Here is the implementation of `swapTextValue`:

```
void Union::swapTextValue(Union &other)
{
    int value = other.u_value;  // save the int value
                                // install string at other
    new(&other.u_text) string{ std::move(u_text) };
    u_text.~string();           // remove the old field's union

    u_value = value;            // store current's new value
}
```

When an unrestricted union has multiple class-type fields then when swapping move construction must be applied to both unrestricted unions. This requires a temporary. Assume an unrestricted union supports fields of classes `This` and `That` then to swap unrestricted unions using, respectively the `This` and `That` fields we do as follows:

```
void ThisThat::swapThisThat(ThisThat &other)
{
    This tmp{ std::move(u_this) };  // save the current object
    u_this.~This();                 // properly destroy it

                                    // install the other object at
                                    // this object
    new(&u_that) That{ std::move(other.u_that) };
    other.u_that.~That();           // properly destroy the other
                                    // object

                                    // install this object's original
                                    // value at the other object
    new(&other.u_this) This{ std::move(tmp) };

}                                   // tmp is automatically destroyed
```

Now that unrestricted unions can be swapped, their `swap` member can be used by `swap` members of surrounding classes. E.g.,

```
void Data::swap(Data &other)
{
        d_union.swap(d_field, other.d_union, other.d_field);

        Union::Field field = d_field;   // swap the fields
        d_field = other.d_field;
        other.d_field = field;
    }
```

9.9.4 Assignment

There are two ways to assign a `Data` object to another one: copy assignment and move assignment. Their implementations are standard:

```
    Data &Data::operator=(Data const &other)    // copy-assignment
    {
        Data tmp{ other };
        swap(tmp);
        return *this;
    }

    Data &Data::operator=(Data &&tmp)           // move-assignment
    {
        swap(tmp);
        return *this;
    }
```

Since `swap` has already been defined the assignment operators need no further attention: they are implemented using their standard implementations.

When unrestricted unions are used outside of surrounding classes a situation may arise where two unrestricted unions are directly assigned to each other. In that case the unions' active fields must somehow be available. Since `operator=` can only be defined having one parameter, simply passing an unrestricted union as its rvalue would lack information about the lvalue's and rvalue's active fields. Instead two members are suggested: `copy`, doing copy assignment and `move`, doing move assignment. Their implementations closely resemble those of the standard assignment operators:

```
    void Union::copy(Field type, Union const &other, Field next)
    {
        Union tmp{ other, next };   // create a copy
        swap(type, tmp, next);      // swap *this and tmp
        tmp.destroy(type);          // destroy tmp
    }

    void Union::move(Field type, Union &&tmp, Field next)
    {
        swap(type, tmp, next);
    }
```

In the source distribution you'll find a directory `yo/memory/examples/unions`. It contains a small demo-program in which `Union` and `Data` are used.

9.10 Aggregate Data Types

C++ inherited the struct concept from **C** and extended it with the class concept. Structs are still used in **C++**, mainly to store and pass around aggregates of different data types. A commonly used term for these structs is *aggregate* (in some languages known as *plain old data* (pod)). Aggregates are commonly used in **C++** programs to merely combine data in dedicated (struct) types. E.g., when a function must return a `double`, a `bool` and `std::string` these three different data types may be aggregated using a `struct` that merely exists to pass along values. Data protection and functionality is hardly ever an issue. For such cases **C** and **C++** use `structs`. But as a **C++** `struct` is just a `class` with special access rights some members (constructors, destructor, overloaded assignment operator) may implicitly be defined. The aggregates capitalizes on this concept by requiring that its definition remains as simple as possible. Aggregates show the following characteristics:

- there are no user provided constructors or user provided inherited constructors (cf. chapter 13);
- its non-static data members have public access rights;
- no virtual members;
- when using inheritance, the base classes aren't virtual and only public inheritance is used.

Aggregates can also be arrays, in which case the array elements are the aggregate's elements. If an aggregate is a `struct` its direct base classes are its elements (if any), followed by the `struct's` data members, in their declaration order. Here is an example:

```
struct Outer
{
    struct Inner
    {
        int     d_int;
        double  d_double;
    };

    std::string d_string;
    Inner d_inner;
};

Outer out{ "hello", { 1, 12.5} };
```

`Outer out's d_string` is initialized with `hello"`, its `d_inner` member has two data members: `d_int` is initialized to 1, `d_double` to 12.5.

(Designated) initializer lists can also be used (cf. section 3.3.5). Also, often *structured binding declarations* (cf. section 3.3.7.1) can be used to avoid explicitly defining an aggregate data type.

9.11 Conclusion

Four important extensions to classes were introduced in this chapter: the destructor, the copy constructor, the move constructor and the overloaded assignment operator. In addition the importance of *swapping*, especially in combination with the overloaded assignment operator, was stressed.

Classes having pointer data members, pointing to dynamically allocated memory controlled by the objects of those classes, are potential sources of memory leaks. The extensions introduced in this chapter implement the standard defense against such memory leaks.

Encapsulation (data hiding) allows us to ensure that the object's data integrity is maintained. The automatic activation of constructors and destructors greatly enhance our capabilities to ensure the data integrity of objects doing dynamic memory allocation.

A simple conclusion is therefore that classes whose objects allocate memory controlled by themselves must at least implement a *destructor*, an *overloaded assignment operator* and a *copy constructor*. Implementing a *move constructor* remains optional, but it allows us to use *factory functions* with classes *not* allowing copy construction and/or assignment.

In the end, assuming the availability of at least a copy or move constructor, the compiler might avoid them using *copy elision*. The compiler is free to use copy elision wherever possible; it is, however, never a requirement. The compiler may therefore always decide not to use copy elision. In all situations where otherwise a copy or move constructor would have been used the compiler may consider to use copy elision.

Chapter 10

Exceptions

C supports several ways for a program to react to situations breaking the normal unhampered flow of a program:

- The function may notice the abnormality and issue a message. This is probably the least disastrous reaction a program may show.
- The function in which the abnormality is observed may decide to stop its intended task, returning an error code to its caller. This is a great example of postponing decisions: now the *calling function* is faced with a problem. Of course the calling function may act similarly, by passing the error code up to *its* caller.
- The function may decide that things are going out of hand, and may call `exit` to terminate the program completely. A tough way to handle a problem if only because the destructors of local objects aren't activated.
- The function may use a combination of the functions `setjmp` and `longjmp` to enforce non-local exits. This mechanism implements a kind of `goto` jump, allowing the program to continue at an outer level, skipping the intermediate levels which would have to be visited if a series of returns from nested functions would have been used.

In **C++** all these flow-breaking methods are still available. However, of the mentioned alternatives, `setjmp` and `longjmp` isn't frequently encountered in **C++** (or even in **C**) programs, due to the fact that the program flow is completely disrupted.

C++ offers *exceptions* as the preferred alternative to, e.g., `setjmp` and `longjmp`. Exceptions allow **C++** programs to perform a controlled non-local return, without the disadvantages of `longjmp` and `setjmp`.

Exceptions are the proper way to bail out of a situation which cannot be handled easily by a function itself, but which is not disastrous enough for a program to terminate completely. Also, exceptions provide a flexible layer of control between the short-range `return` and the crude `exit`.

In this chapter exceptions are covered. First an example is given of the different impact exceptions and the `setjmp/longjmp` combination have on programs. This example is followed by a discussion of the formal aspects of exceptions. In this part the guarantees our software should be able to offer when confronted with exceptions are presented. Exceptions and their guarantees have consequences for constructors and destructors. We'll encounter these consequences at the end of this chapter.

10.1 Exception syntax

Before contrasting the traditional **C** way of handling non-local gotos with exceptions let's introduce the syntactic elements that are involved when using exceptions.

- Exceptions are generated by a `throw` statement. The keyword `throw`, followed by an expression of a certain type, throws the expression value as an exception. In **C++** anything having value semantics may be thrown as an exception: an `int`, a `bool`, a `string`, etc. However, there also exists a *standard exception* type (cf. section 10.8) that may be used as *base class* (cf. chapter 13) when defining new exception types.
- Exceptions are generated within a well-defined local environment, called a `try`-block. The run-time support system ensures that all of the program's code is itself surrounded by a *global* `try` *block*. Thus, every exception generated by our code will always reach the boundary of at least one `try`-block. A program terminates when an exception reaches the boundary of the global `try` block, and when this happens destructors of local and global objects that were alive at the point where the exception was generated are not called. This is not a desirable situation and therefore all exceptions should be generated within a `try`-block explicitly defined by the program. Here is an example of a string exception thrown from within a `try`-block:

```
try
{
    // any code can be defined here
    if (someConditionIsTrue)
        throw "this is the std::string exception"s;
    // any code can be defined here
}
```

- `catch`: Immediately following the `try`-block, one or more `catch`-clauses must be defined. A `catch`-clause consists of a catch-header defining the type of the exception it can catch followed by a compound statement defining what to do with the caught exception:

```
catch (string const &msg)
{
    // statements in which the caught string object are handled
}
```

  Multiple `catch` clauses may appear underneath each other, one for each exception type that has to be caught. In general the `catch` clauses may appear in any order, but there are exceptions requiring a specific order. To avoid confusion it's best to put a `catch` clause for the most general exception last. At most *one* exception clause will be activated. **C++** does not support a **Java**-style `finally`-clause activated after completing a catch clause.

10.2 An example using exceptions

In the following examples the same basic program is used. The program uses two classes, `Outer` and `Inner`.

First, an `Outer` object is defined in `main`, and its member `Outer::fun` is called. Then, in `Outer::fun` an `Inner` object is defined. Having defined the `Inner` object, its member `Inner::fun` is called.

That's about it. The function `Outer::fun` terminates calling `inner`'s destructor. Then the program terminates, activating `outer`'s destructor. Here is the basic program:

```
#include <iostream>
using namespace std;

class Inner
{
    public:
        Inner();
        ~Inner();
        void fun();
};
Inner::Inner()
{
    cout << "Inner constructor\n";
}
Inner::~Inner()
{
    cout << "Inner destructor\n";
}
void Inner::fun()
{
    cout << "Inner fun\n";
}

class Outer
{
    public:
        Outer();
        ~Outer();
        void fun();
};
Outer::Outer()
{
    cout << "Outer constructor\n";
}
Outer::~Outer()
{
    cout << "Outer destructor\n";
}
void Outer::fun()
{
    Inner in;
    cout << "Outer fun\n";
    in.fun();
}

int main()
{
    Outer out;
    out.fun();
}

/*
    Generated output:
Outer constructor
Inner constructor
Outer fun
```

```
    Inner fun
    Inner destructor
    Outer destructor
    */
```

After compiling and running, the program's output is entirely as expected: the destructors are called in their correct order (reversing the calling sequence of the constructors).

Now let's focus our attention on two variants in which we simulate a non-fatal disastrous event in the `Inner::fun` function. This event must supposedly be handled near `main`'s end.

We'll consider two variants. In the first variant the event is handled by `setjmp` and `longjmp`; in the second variant the event is handled using **C++**'s exception mechanism.

10.2.1 Anachronisms: 'setjmp' and 'longjmp'

The basic program from the previous section is slightly modified to contain a variable `jmp_buf jmpBuf` used by `setjmp` and `longjmp`.

The function `Inner::fun` calls `longjmp`, simulating a disastrous event, to be handled near `main`'s end. In `main` a target location for the long jump is defined through the function `setjmp`. `Setjmp`'s zero return indicates the initialization of the `jmp_buf` variable, in which case `Outer::fun` is called. This situation represents the 'normal flow'.

The program's return value is zero *only* if `Outer::fun` terminates normally. The program, however, is designed in such a way that this won't happen: `Inner::fun` calls `longjmp`. As a result the execution flow returns to the `setjmp` function. In this case it does *not* return a zero return value. Consequently, after calling `Inner::fun` from `Outer::fun` `main`'s `if`-statement is entered and the program terminates with return value 1. Try to follow these steps when studying the following program source, which is a direct modification of the basic program given in section 10.2:

```
    #include <iostream>
    #include <setjmp.h>
    #include <cstdlib>

    using namespace std;

    jmp_buf jmpBuf;

    class Inner
    {
        public:
            Inner();
            ~Inner();
            void fun();
    };

    Inner::Inner()
    {
        cout << "Inner constructor\n";
    }
    void Inner::fun()
    {
        cout << "Inner fun\n";
        longjmp(jmpBuf, 0);
    }
    Inner::~Inner()
    {
        cout << "Inner destructor\n";
    }

    class Outer
    {
        public:
            Outer();
            ~Outer();
            void fun();
    };

    Outer::Outer()
    {
        cout << "Outer constructor\n";
    }
    Outer::~Outer()
    {
        cout << "Outer destructor\n";
    }
    void Outer::fun()
    {
        Inner in;
        cout << "Outer fun\n";
        in.fun();
    }

    int main()
    {
        Outer out;

        if (setjmp(jmpBuf) != 0)
            return 1;

        out.fun();
    }
    /*
        Generated output:
    Outer constructor
    Inner constructor
    Outer fun
    Inner fun
    Outer destructor
    */
```

This program's output clearly shows that `inner`'s destructor is not called. This is a direct consequence of the non-local jump performed by `longjmp`. Processing proceeds immediately from the `longjmp` call inside `Inner::fun` to `setjmp` in `main`. There, its return value is unequal zero, and the program terminates with return value 1. Because of the non-local jump `Inner::~Inner` is never executed: upon return to `main`'s `setjmp` the existing stack is simply broken down disregarding any destructors waiting to be called.

This example illustrates that the destructors of objects can easily be skipped when `longjmp` and `setjmp` are used and **C++** programs should therefore avoid those functions like the plague.

10.2.2 Exceptions: the preferred alternative

Exceptions are **C++**'s answer to the problems caused by `setjmp` and `longjmp`. Here is an example using exceptions. The program is once again derived from the basic program of section 10.2:

```
#include <iostream>
using namespace std;

class Inner
{
    public:
        Inner();
        ~Inner();
        void fun();
};
Inner::Inner()
{
    cout << "Inner constructor\n";
}
Inner::~Inner()
{
    cout << "Inner destructor\n";
}
void Inner::fun()
{
    cout << "Inner fun\n";
    throw 1;
    cout << "This statement is not executed\n";
}

class Outer
{
    public:
        Outer();
        ~Outer();
        void fun();
};

Outer::Outer()
{
    cout << "Outer constructor\n";
}
Outer::~Outer()
{
    cout << "Outer destructor\n";
}
void Outer::fun()
{
    Inner in;
    cout << "Outer fun\n";
    in.fun();
}

int main()
{
        Outer out;
        try
        {
            out.fun();
        }
        catch (int x)
        {}
    }
    /*
        Generated output:
    Outer constructor
    Inner constructor
    Outer fun
    Inner fun
    Inner destructor
    Outer destructor
    */
```

`Inner::fun` now throws an `int` exception where a `longjmp` was previously used. Since `in.fun` is called by `out.fun`, the exception is generated within the `try` block surrounding the `out.fun` call. As an `int` value was thrown this value reappears in the `catch` clause beyond the `try` block.

Now `Inner::fun` terminates by throwing an exception instead of calling `longjmp`. The exception is caught in `main`, and the program terminates. Now we see that `inner`'s destructor is properly called. It is interesting to note that `Inner::fun`'s execution really terminates at the `throw` statement: The `cout` statement, placed just beyond the `throw` statement, isn't executed.

What did this example teach us?

- Exceptions provide a means to break a function's (and program's) normal flow without having to use a cascade of `return`-statements, and without the need to terminate the program using blunt tools like the function `exit`.
- Exceptions do not disrupt the proper activation of destructors. Since `setjmp` and `longjmp` *do* distrupt the proper activation of destructors their use is strongly deprecated in **C++**.

10.3 Throwing exceptions

Exceptions are generated by `throw` statements. The `throw` keyword is followed by an expression, defining the thrown exception value. Example:

```
    throw "Hello world";        // throws a char *
    throw 18;                   // throws an int
    throw string{ "hello" };    // throws a string
```

Local objects cease to exist when a function terminates. This is no different for exceptions.

Objects defined locally in functions are automatically destroyed once exceptions thrown by these functions leave these functions. This also happens to objects thrown as exceptions. However, just before leaving the function context the object is copied and it is this copy that eventually reaches the appropriate `catch` clause.

The following examples illustrates this process. `Object::fun` defines a local `Object toThrow`, that is thrown as an exception. The exception is caught in `main`. But by then the object originally thrown doesn't exist anymore, and `main` received a copy:

```
#include <iostream>
#include <string>
using namespace std;

class Object
{
    string d_name;

    public:
        Object(string name)
        :
            d_name(name)
        {
            cout << "Constructor of " << d_name << "\n";
        }
        Object(Object const &other)
        :
            d_name(other.d_name + " (copy)")
        {
            cout << "Copy constructor for " << d_name << "\n";
        }
        ~Object()
        {
            cout << "Destructor of " << d_name << "\n";
        }
        void fun()
        {
            Object toThrow("'local object'");
            cout << "Calling fun of " << d_name << "\n";
            throw toThrow;
        }
        void hello()
        {
            cout << "Hello by " << d_name << "\n";
        }
};

int main()
{
    Object out{ "'main object'" };
    try
    {
        out.fun();
    }
    catch (Object o)
    {
        cout << "Caught exception\n";
        o.hello();
    }
}
```

`Object`'s copy constructor is special in that it defines its name as the other object's name to which the string `" (copy)"` is appended. This allow us to monitor the construction and destruction of objects more closely. `Object::fun` generates an exception, and throws its locally defined object. Just before throwing the exception the program has produced the following output:

```
Constructor of 'main object'
Constructor of 'local object'
Calling fun of 'main object'
```

When the exception is generated the next line of output is produced:

```
Copy constructor for 'local object' (copy)
```

The local object is passed to `throw` where it is treated as a value argument, creating a copy of `toThrow`. This copy is thrown as the exception, and the local `toThrow` object ceases to exist. The thrown exception is now caught by the `catch` clause, defining an `Object` value parameter. Since this is a *value* parameter yet another copy is created. Thus, the program writes the following text:

```
Destructor of 'local object'
Copy constructor for 'local object' (copy) (copy)
```

The `catch` block now displays:

```
Caught exception
```

Following this `o`'s `hello` member is called, showing us that we indeed received a *copy of the copy* of the original `toThrow` object:

```
Hello by 'local object' (copy) (copy)
```

Then the program terminates and its remaining objects are now destroyed, reversing their order of creation:

```
Destructor of 'local object' (copy) (copy)
Destructor of 'local object' (copy)
Destructor of 'main object'
```

The copy created by the `catch` clause clearly is superfluous. It can be avoided by defining object *reference parameters* in `catch` clauses: '`catch (Object &o)`'. The program now produces the following output:

```
Constructor of 'main object'
Constructor of 'local object'
Calling fun of 'main object'
Copy constructor for 'local object' (copy)
Destructor of 'local object'
Caught exception
Hello by 'local object' (copy)
Destructor of 'local object' (copy)
Destructor of 'main object'
```

Only a single copy of `toThrow` was created.

It's a bad idea to throw a *pointer* to a locally defined object. The pointer is thrown, but the object to which the pointer refers ceases to exist once the exception is thrown. The catcher receives a wild pointer. Bad news....

Let's summarize the above findings:

- Local objects are thrown as copied objects;

- Don't throw pointers to local objects;
- It is possible to throw pointers to *dynamically* generated objects. In this case one must take care that the generated object is properly deleted by the exception handler to prevent a memory leak.

Exceptions are thrown in situations where a function can't complete its assigned task, but the program is still able to continue. Imagine a program offering an interactive calculator. The program expects numeric expressions, which are evaluated. Expressions may show syntactic errors or it may be mathematically impossible to evaluate them. Maybe the calculator allows us to define and use variables and the user might refer to non-existing variables: plenty of reasons for the expression evaluation to fail, and so many reasons for exceptions to be thrown. None of those should terminate the program. Instead, the program's user is informed about the nature of the problem and is invited to enter another expression. Example:

```
if (!parse(expressionBuffer))           // parsing failed
    throw "Syntax error in expression";

if (!lookup(variableName))              // variable not found
    throw "Variable not defined";

if (divisionByZero())                   // unable to do division
    throw "Division by zero is not defined";
```

Where these `throw` statements are located is irrelevant: they may be found deeply nested inside the program, or at a more superficial level. Furthermore, *functions* may be used to generate the exception to be thrown. An `Exception` object might support stream-like insertion operations allowing us to do, e.g.,

```
if (!lookup(variableName))
    throw Exception() << "Undefined variable '" << variableName << "';
```

10.3.1 The empty 'throw' statement

Sometimes it is required to inspect a thrown exception. An exception catcher may decide to ignore the exception, to process the exception, to rethrow it after inspection or to change it into another kind of exception. For example, in a server-client application the client may submit requests to the server by entering them into a queue. Normally every request is eventually answered by the server. The server may reply that the request was successfully processed, or that some sort of error has occurred. On the other hand, the server may have died, and the client should be able to discover this calamity, by not waiting indefinitely for the server to reply.

In this situation an intermediate exception handler is called for. A thrown exception is first inspected at the middle level. If possible it is processed there. If it is not possible to process the exception at the middle level, it is passed on, unaltered, to a more superficial level, where the really tough exceptions are handled.

By placing an *empty* `throw` statement in the exception handler's code the received exception is passed on to the next level that might be able to process that particular type of exception. The *rethrown* exception is never handled by one of its neighboring exception handlers; it is always transferred to an exception handler at a more superficial level.

In our server-client situation a function

```
initialExceptionHandler(string &exception)
```

could be designed to handle the `string` exception. The received message is inspected. If it's a simple message it's processed, otherwise the exception is passed on to an outer level. In `initialExceptionHandler`'s implementation the empty `throw` statement is used:

```
void initialExceptionHandler(string &exception)
{
    if (!plainMessage(exception))
        throw;

    handleTheMessage(exception);
}
```

Below (section 10.5), the empty `throw` statement is used to pass on the exception received by a `catch`-block. Therefore, a function like `initialExceptionHandler` can be used for a variety of thrown exceptions, as long as their types match `initialExceptionHandler`'s parameter, which is a string.

The next example jumps slightly ahead, using some of the topics covered in chapter 14. The example may be skipped, though, without loss of continuity.

A basic exception handling class can be constructed from which specific exception types are derived. Suppose we have a class `Exception`, having a member function `ExceptionType Exception::severity`. This member function tells us (little wonder!) the severity of a thrown exception. It might be `Info`, `Notice`, `Warning`, `Error` or `Fatal`. The information contained in the exception depends on its severity and is processed by a function `handle`. In addition, all exceptions support a member function like `textMsg`, returning textual information about the exception in a `string`.

By defining a polymorphic function `handle` it can be made to behave differently, depending on the nature of a thrown exception, when called from a basic `Exception` pointer or reference.

In this case, a program may throw any of these five exception types. Assuming that the classes `Message` and `Warning` were derived from the class `Exception`, then the `handle` function matching the exception type will automatically be called by the following exception catcher:

```
//
catch(Exception &ex)
{
    cout << e.textMsg() << '\n';

    if
    (
        ex.severity() != ExceptionType::Warning
        &&
        ex.severity() != ExceptionType::Message
    )
        throw;              // Pass on other types of Exceptions

    ex.handle();            // Process a message or a warning
}
```

Now anywhere in the `try` block preceding the exception handler `Exception` objects or objects of one of its derived classes may be thrown. All those exceptions will be caught by the above handler. E.g.,

```
throw Info{};
```

```
    throw Warning{};
    throw Notice{};
    throw Error{};
    throw Fatal{};
```

10.4 The try block

The `try`-block surrounds `throw` statements. Remember that a program is always surrounded by a global `try` block, so `throw` statements may appear anywhere in your code. More often, though, `throw` statements are used in function bodies and such functions may be called from within `try` blocks.

A `try` block is defined by the keyword `try` followed by a compound statement. This block, in turn, *must* be followed by at least one `catch` handler:

```
    try
    {
                // any statements here
    }
    catch(...)  // at least one catch clause here
    {}
```

`Try`-blocks are commonly nested, creating exception *levels*. For example, `main`'s code is surrounded by a `try`-block, forming an outer level handling exceptions. Within `main`'s `try`-block functions are called which may also contain `try`-blocks, forming the next exception level. As we have seen (section 10.3.1), exceptions thrown in inner level `try`-blocks may or may not be processed at that level. By placing an empty `throw` statement in an exception handler, the thrown exception is passed on to the next (outer) level.

10.5 Catching exceptions

A `catch` clause consists of the keyword `catch` followed by a parameter list defining one parameter specifying type and (parameter) name of the exception caught by that particular `catch` handler. This name may then be used as a variable in the compound statement following the `catch` clause. Example:

```
    catch (string &message)
    {
        // code to handle the message
    }
```

Primitive types and objects may be thrown as exceptions. It's a bad idea to throw a pointer or reference to a local object, but a pointer to a *dynamically* allocated object may be thrown if the exception handler deletes the allocated memory to prevent a memory leak. Nevertheless, throwing such a pointer is dangerous as the exception handler won't be able to distinguish dynamically allocated memory from non-dynamically allocated memory, as illustrated by the next example:

```
    try
    {
        static int x;
        int *xp = &x;

        if (condition1)
            throw xp;

        xp = new int(0);
        if (condition2)
            throw xp;
    }
    catch (int *ptr)
    {
        // delete ptr or not?
    }
```

Close attention should be paid to the nature of the parameter of the exception handler, to make sure that when pointers to dynamically allocated memory are thrown the memory is returned once the handler has processed the pointer. In general pointers should not be thrown as exceptions. If dynamically allocated memory must be passed to an exception handler then the pointer should be wrapped in a smart pointer, like `unique_ptr` or `shared_ptr` (cf. sections 18.3 and 18.4).

Multiple `catch` handlers may follow a `try` block, each handler defining its own exception type. The *order* of the exception handlers is important. When an exception is thrown, the first exception handler matching the type of the thrown exception is used and remaining exception handlers are ignored. Eventually at most one exception handler following a `try`-block is activated. Normally this is of no concern as each exception has its own unique type.

Example: if exception handlers are defined for `char *`s and `void *`s then NTBSs are caught by the former handler. Note that a `char *` can also be considered a `void *`, but the exception type matching procedure is smart enough to use the `char *` handler with the thrown NTBS. Handlers should be designed very type specific to catch the correspondingly typed exception. For example, `int`-exceptions are not caught by `double`-catchers, `char`-exceptions are not caught by `int`-catchers. Here is a little example illustrating that the order of the catchers is not important for types not having any hierarchal relationship to each other (i.e., `int` is not derived from `double`; `string` is not derived from an NTBS):

```
#include <iostream>
using namespace std;

int main()
{
    while (true)
    {
        try
        {
            string s;
            cout << "Enter a,c,i,s for ascii-z, char, int, string "
                                                    "exception\n";
            getline(cin, s);
            switch (s[0])
            {
                case 'a':
                    throw "ascii-z";
                case 'c':
                    throw 'c';
                case 'i':
                    throw 12;
                case 's':
                    throw string{};
            }
        }
        catch (string const &)
        {
            cout << "string caught\n";
        }
        catch (char const *)
        {
            cout << "ASCII-Z string caught\n";
        }
        catch (double)
        {
            cout << "isn't caught at all\n";
        }
        catch (int)
        {
            cout << "int caught\n";
        }
        catch (char)
        {
            cout << "char caught\n";
        }
    }
}
```

Rather than defining specific exception handlers a specific class can be designed whose objects contain information about the exception. Such an approach was mentioned earlier, in section 10.3.1. Using this approach, there's only one handler required, since we *know* we don't throw other types of exceptions:

```
    try
    {
        // code throws only Exception objects
    }
    catch (Exception &ex)
    {
        ex.handle();
    }
```

When the code of an exception handler has been processed, execution continues beyond the last exception handler directly following the matching `try`-block (assuming the handler doesn't itself use flow control statements (like `return` or `throw`) to break the default flow of execution). The following cases can be distinguished:

- If *no* exception was thrown within the `try`-block no exception handler is activated, and execution continues from the last statement in the `try`-block to the first statement beyond the last `catch`-block.
- If an exception *was* thrown within the `try`-block but neither the current level nor another level contains an appropriate exception handler, the program's default exception handler is called, aborting the program.
- If an exception was thrown from the `try`-block and an appropriate exception handler is avail-

able, then the code of that exception handler is executed. Following that, the program's execution continues at the first statement beyond the last `catch`-block.

All statements in a `try` block following an executed `throw`-statement are ignored. However, objects that were successfully constructed within the `try` block before executing the `throw` statement *are* destroyed before any exception handler's code is executed.

10.5.1 The default catcher

At a certain level of the program only a limited set of handlers may actually be required. Exceptions whose types belong to that limited set are processed, all other exceptions are passed on to exception handlers of an outer level `try` block.

An intermediate type of exception handling may be implemented using the default exception handler, which must be (due to the hierarchal nature of exception catchers, discussed in section 10.5) placed beyond all other, more specific exception handlers.

This default exception handler cannot determine the actual type of the thrown exception and cannot determine the exception's value but it may execute some statements, and thus do some default processing. Moreover, the caught exception is not lost, and the default exception handler may use the empty `throw` statement (see section 10.3.1) to pass the exception on to an outer level, where it's actually processed. Here is an example showing this use of a default exception handler:

```
#include <iostream>
using namespace std;

int main()
{
    try
    {
        try
        {
            throw 12.25;    // no specific handler for doubles
        }
        catch (int value)
        {
            cout << "Inner level: caught int\n";
        }
        catch (...)
        {
            cout << "Inner level: generic handling of exceptions\n";
            throw;
        }
    }
    catch(double d)
    {
        cout << "Outer level may use the thrown double: " << d << '\n';
    }
}
/*
    Generated output:
Inner level: generic handling of exceptions
Outer level may use the thrown double: 12.25
*/
```

The program's output illustrates that an empty `throw` statement in a default exception handler throws the received exception to the next (outer) level of exception catchers, keeping type and value of the thrown exception.

Thus, basic or generic exception handling can be accomplished at an inner level, while specific handling, based on the type of the thrown expression, can be provided at an outer level. Additionally, particularly in multi-threaded programs (cf. chapter 20), thrown exceptions can be transferred between threads after converting `std::exception` objects to `std::exception_ptr` objects. This proceduce can even be used from inside the default catcher. Refer to section 20.12.1 for further coverage of the class `std::exception_ptr`.

10.6 Functions that cannot throw exceptions: the 'noexcept' keyword

Once a function has been defined it's often called from other functions. If called functions are not defined in the same source file as calling functions the called functions must be declared, for which header files are often used. Those called functions might throw exceptions, which might be unacceptible to the function calling those other functions. E.g., functions like `swap` and destructors may not throw exceptions.

Functions that may not throw exceptions can be declared and defined by specifying the `noexcept` keyword (see section 10.9 for examples of function declarations specifying `noexcept`).

When using `noecept` there's a slight run-time overhead penalty because the function needs an overall `try-catch` block catching any eception that might be thrown by its (called) code. When an exception is caught (violating the `noexcept` specification) then the `catch` clause calls `std::terminate`, ending the program.

In addition to using a plain `noexcept`, it can also be given an argument that is evaluated compile-time (e.g., `void fun() noexcept(sizeof(int) == 4)`): if the evaluation returns `true` then the `noexcept` requirement is used; if the evaluation returns `false`, then the `noexcept` requirement is ignored. Examples of this advanced use of `noexcept` are provided in section 23.8.

10.7 Iostreams and exceptions

The **C++** I/O library was used well before exceptions were available in **C++**. Hence, normally the classes of the iostream library do not throw exceptions. However, it is possible to modify that behavior using the `ios::exceptions` member function. This function has two overloaded versions:

- `ios::iostate exceptions()`:
  this member returns the state flags for which the stream will throw exceptions;
- `void exceptions(ios::iostate state)`

  this member causes the stream to throw an exception when state `state` is observed.

In the I/O library, exceptions are objects of the class `ios::failure`, derived from `ios::exception`. A `std::string const &message` may be specified when defining a `failure` object. Its message may then be retrieved using its `virtual char const *what() const` member.

Exceptions should be used in exceptional circumstances. Therefore, we think it is questionable to have stream objects throw exceptions for fairly normal situations like `EOF`. Using exceptions to handle input errors might be defensible (e.g., in situations where input errors should not occur and imply a corrupted file) but often aborting the program with an appropriate error message would probably be the more appropriate action. As an example consider the following interactive program using exceptions to catch incorrect input:

```
#include <iostream>
#include <climits>
using namespace::std;

int main()
{
    cin.exceptions(ios::failbit);   // throw exception on fail
    while (true)
    {
        try
        {
            cout << "enter a number: ";
            int value;
            cin >> value;
            cout << "you entered " << value << '\n';
        }
        catch (ios::failure const &problem)
        {
            cout << problem.what() << '\n';
            cin.clear();
            cin.ignore(INT_MAX, '\n');  // ignore the faulty line
        }
    }
}
```

By default, exceptions raised from within `ostream` objects are caught by these objects, which set their `ios::badbit` as a result. See also the paragraph on this issue in section 14.8.

10.8 Standard exceptions

All data types may be thrown as exceptions. Several additional exception classes are now defined by the **C++** standard. Before using those additional exception classes the `<stdexcept>` header file must be included.

All of these *standard exceptions* are class types by themselves, but also offer all facilities of the `std::exception` class and objects of the standard exception classes may also be considered objects of the `std::exception` class.

The `std::exception` class offers the member

```
char const *what() const;
```

describing in a short textual message the nature of the exception.

C++ defines the following standard exception classes:

- `std::bad_alloc` (this requires the `<new>` header file): thrown when `operator new` fails;
- `std::bad_array_new_length` (this requires the `<new>` header file): thrown when an illegal array size is requested when using `new Type[...]`. Illegal sizes are negative values, values

that exceed an implementation defined maximum, the number of initializer clauses exceeds the specified number of array elements (e.g., `new int[2]{ 1, 2, 3 }`);

- `std::bad_cast` (this requires the `<typeinfo>` header file): thrown in the context of *polymorphism* (see section 14.6.1);
- `std::bad_exception` (this requires the `<exception>` header file): thrown when a function tries to generate another type of exception than declared in its function throw list;
- `std::bad_typeid` (this requires the `<typeinfo>` header file): also thrown in the context of *polymorphism* (see section 14.6.2);

All additional exception classes were derived from `std::exception`. The constructors of all these additional classes accept `std::string const &` arguments summarizing the reason for the exception (retrieved by the `exception::what` member). The additionally defined exception classes are:

- `std::domain_error`: a (mathematical) domain error is detected;
- `std::invalid_argument`: the argument of a function has an invalid value;
- `std::length_error`: thrown when an object would have exceeded its maximum permitted length;
- `std::logic_error`: a logic error should be thrown when a problem is detected in the internal logic of the program. Example: a function like **C**'s `printf` is called with more arguments than there are format specifiers in its format string;
- `std::out_of_range`: thrown when an argument exceeds its permitted range. Example: thrown by `at` members when their arguments exceed the range of admissible index values;
- `std::overflow_error`: an overflow error should be thrown when an arithmetic overflow is detected. Example: dividing a value by a very small value;
- `std::range_error`: a range error should be thrown when an internal computation results in a value exceeding a permissible range;
- `std::runtime_error`: a runtime error should be thrown when a problem is encountered that can only be detected while the program is being executed. Example: a non-integral is entered when the program's input expects an integral value.
- `std::underflow_error`: an underflow error should be thrown when an arithmetic underflow is detected. Example: dividing a very small value by a very large value.
- `std::tx_exception<Type>`: derived from `std::runtime_error`. This exception can be thrown from an `atomic_cancel` compound statement (cf. section 20.14) to undo statements executed so far.

10.8.1 Standard exceptions: to use or not to use?

Since values of any type may be thrown as exceptions, you may wonder when to throw values of standard exception types and (if ever) when to throw values of other types.

Current practice in the C++ community is to throw exceptions only in exceptional situations. In that respect C++'s philosophy about using exceptions differs markedly from the way exceptions are used in, e.g., Java, where exceptions are often encountered in situations C++ doesn't consider exceptional. Another common practice is to follow a 'conceptual' style when designing software. A nice characteristic of exceptions is that exceptions can be thrown at a point where your source shows what's happening: throwing an `std::out_of_range` exception is nice for the software maintainer, as the reason for the exception is immediately recognized.

At the catch-clause the semantical context usually isn't very relevant anymore and by catching a std::exception and showing its `what()` content the program's *user* is informed about what happened.

But throwing values of other types can also be useful. What about a situation where you want to throw an exception and catch it at some shallow level? In between there may be various levels of software provided by external software libraries over which the software engineer has no control. At those levels exceptions (std::exceptions) could be generated too, and those exceptions might also be caught by the library's code. When throwing a standard exception type it may be hard to convince yourself that that exception isn't caught by the externally provided software. Assuming that no catch-alls are used (i.e., `catch (...)`) then throwing an exception from the `std::exception` family might not be a very good idea. In such cases throwing a value from a simple, maybe empty, `enum` works fine:

```
enum HorribleEvent
{};

... at some deep level:
    throw HorribleEvent{};

... at some shallow level:
catch (HorribleEvent hs)
{
    ...
}
```

Other examples can easily be found: design a class holding a message and an error (exit) code: where necessary throw an object of that class, catch it in the catch clause of main's try block and you can be sure that all objects defined at intermediate levels are neatly destroyed, and at the end you show the error message and return the exit code embedded in your non-exception object.

So, the advice is to use `std::exception` types when available, and clearly do the required job. But if an exception is used to simply bail out of an unpleasant situation, or if there's a chance that externally provided code might catch `std:exceptions` then consider throwing objects or values of other types.

10.9 System error, error_category, and error_condition

The class `std::system_error` is derived from `std::runtime_error`, which in turn is derived from `std::exception`

Before using the class `system_error` or related classes the `<system_error>` header file must be included.

`System_error` exceptions can be thrown when errors occur having associated (system) *error values*. Such errors are typically associated with low-level (like operating system) functions, but other types of errors (e.g., bad user input, non-existing requests) can also be handled.

In addition to error codes (cf. section 4.3.2) and error categories (covered below) error *conditions* are distinguished. Error conditions specify platform independent types of errors like syntax errors or non-existing requests.

When constructing `system_error` objects error codes and error categories may be specified. First

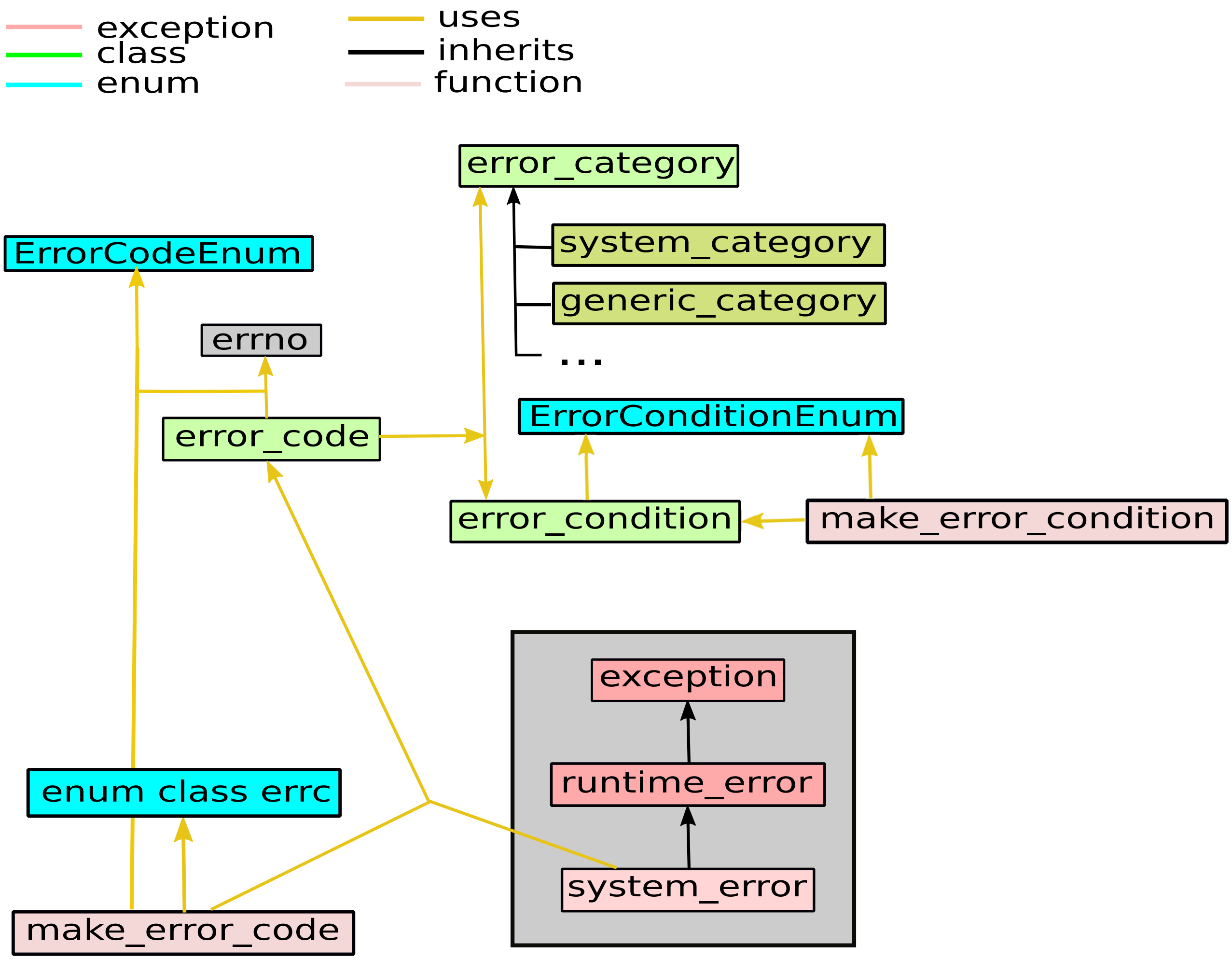
exception
class
enum
uses
inherits
function
error_category
system_category
generic_category
...
ErrorCodeEnum
errno
error_code
ErrorConditionEnum
error_condition
make_error_condition
exception
runtime_error
system_error
enum class errc
make_error_code

Figure 10.1: System_error: associated components

we'll look at the classes `error_condition` and `error_category`, then `system_error` itself is covered in more detail.

Figure 10.1 illustrates how the various components interact.

As shown in figure 10.1 the class `error_category` uses the class `error_condition` and the class `error_condition` uses the class `error_category`. As a consequence of this circular dependency between these two classes these classes should be approached as one single class: when covering `error_category` the class `error_condition` should be known and vice versa. This circular dependency among these classes is unfortunate and an example of bad class design.

As `system_error` is eventually derived from `exception` it offers the standard `what` member. It also contains an `error_code`.

In POSIX systems the `errno` variable is associated with many, often rather cryptic, symbols. The predefined `enum class errc` attempts to provide intuitively more appealing symbols. Since its symbols are defined in a strongly typed enumeration, they cannot directly be used when defining a matching `error_code`. Instead, a `make_error_code` function converts `enum class errc` values and values of newly defined error code enumerations (called `ErrorCodeEnum` below) to `error_code` objects.

The `enum class errc` defined in the `std` namespace defines symbols whose values are equal to the traditional error code values used by **C** but describe the errors in a less cryptic way. E.g.,

```
enum class errc
{
    address_family_not_supported, // EAFNOSUPPORT
    address_in_use,               // EADDRINUSE
    address_not_available,        // EADDRNOTAVAIL
    already_connected,            // EISCONN
    argument_list_too_long,       // E2BIG
    argument_out_of_domain,       // EDOM
    bad_address,                  // EFAULT
    ...
};
```

Values of `ErrorCodeEnums` can be passed to matching `make_error_code` functions. Defining your own `ErrorCodeEnum` enumeration is covered in section 23.7.

Now that the general outline has been presented, it's time to have a closer look at the various components shown in figure 10.1.

10.9.1 The class 'std::error_category'

Objects of the class `std::error_category` identify sources of sets of error codes. New error categories for new error code enumerations can also be defined (cf. section 23.7).

Error categories are designed as *singletons*: only one object of each class can exist. Because of this `error_categories` are equal when the addresses of `error_category` objects are equal. Error category objects are returned by functions (see below) or by static `instance()` members of error category classes.

Error category classes define several members. Most are declared *virtual* (cf. chapter 14), meaning that those members may be redefined in error category classes we ourselves design:

- `virtual error_condition default_error_condition(int ev) const noexcept`:
  returns an `error_condition` object (cf. section 10.9.2) initialized with error value `ev` and the current (i.e., `*this`) `error_category`;
- `virtual bool equivalent(error_code const &code, int condition) const noexcept`:
  returns `true` if the equivalence between the error condition that is associated with the `error_code` object and the `error_condition_enum` value that is specified (as an `int` value) as the function's second argument could be establisted;
- `virtual bool equivalent(int ev, error_condition const &condition) const noexcept`:
  returns `true` if the equivalence of an `error_condition` object that is constructed from the `ErrorConditionEnum` value that is associated with the `ErrorCategoryEnum` value that was passed (as `int`) to the function and the `error_condition` object that was passed to the function as its second argument could be established;
- `virtual string message(int ev) const`:
  This member returns a string describing the error condition denoted by `ev`, which should be a (cast to `int`) value of the category's error condition enumeration;
- `virtual char const *name() const noexcept`:
  This member returns the name of the error category as NTBS (like `generic`);
- `bool operator<(error_category const &rhs) const noexcept`:
  returns `less<const error_category*>()(this, &rhs)`.

- Error category objects can be compared for (in)equality.

The functions returning predefined error categories are:

- `error_category const &generic_category() noexcept`:
  returns a reference to the *generic* `error_category` object. The returned object's `name` member returns a pointer to the string `"generic"`;
- `error_category const &system_category() noexcept`:
  returns a reference to the *operating system* `error_category` object: it is used for errors reported by the operating system. The object's `name` member returns a pointer to the string `"system"`;
- `error_category const &iostream_category() noexcept`:
  returns a reference to the *iostream* `error_category` object: it is used for errors reported by stream objects. The object's `name` member returns a pointer to the string `"iostream"`;
- `error_category const &future_category() noexcept`:
  returns a reference to the *future* `error_category` object: it is used for errors reported by 'future' objects (cf. section 20.8). The object's `name` member returns a pointer to the string `"future"`;

10.9.2 The class 'std::error_condition'

`Error_condition` objects contain information about 'higher level' types of errors. They are supposed to be platform independent like syntax errors or non-existing requests.

Error condition objects are returned by the member `default_error_condition` of the classes `error_code` and `error_category`, and they are returned by the function `std::error_condition make_error_condition(ErrorConditionEnum ec)`. The type name `ErrorConditionEnum` is a formal name for an `enum class` that enumerates the 'higher level' error types. The `error_condition` objects returned by `make_error_condition` are initialized with `ec` and the `error_category` that uses the `ErrorConditionEnum`. Defining your own `ErrorConditionEnum` is covered in section 23.7.

Constructors:

- `error_condition() noexcept`:
  the object's value is initialized to 'no error' (i.e., 0) and a `system_category` error category;
- The copy constructor is available;
- `error_condition(int ec, error_category const &cat) noexcept`:
  the object's value is initialized to `ec` and error category `cat`. It is the responsibility of the caller to ensure that `ec` represents a (cast to `int`) value of `cat's` error condition enumeration;
- `error_condition(ErrorConditionEnum value) noexcept`:
  this is a member template (cf. section 22.1.3), using template header `template <class ErrorConditionEnum>`. It initializes the object with the return value of `make_error_condition(value)`;

Members:

- The copy assignment operator and an assignment operator accepting an `ErrorConditionEnum` are available;

- `void assign(int val, error_category const &cat)`:
  assigns new values to the current object's *value* and *category* data members;
- `error_category const &category() const noexcept`:
  returns a reference to the object's error category (note that this is a reference to the category's singleton object);
- `void clear() noexcept`:
  after calling this member *value* is set to 0 and the object's error *category* set to `generic_category`;
- `string message() const`:
  returns `category().message(value());`
- `explicit operator bool() const noexcept`:
  returns `true` if `value()` returns a non-zero value (so its semantic meaning is 'the object represents an error');
- `int value() const noexcept`:
  returns the object's error value.

Two `error_condition` objects can be compared for (in)equality, and can be ordered using `operator<`. Ordering is pointless if the two objects refer to different error categories. If the categories of two objects are different they are considered different.

10.9.3 The class system_error

`System_error` objects can be constructed from `error_codes` or from error values (`ints`) and matching error category objects, optionally followed by a standard textual description of the nature of the encountered error.

Here is the class's public interface:

```
class system_error: public runtime_error
 {
     public:
         system_error(error_code ec);
         system_error(error_code ec, string const &what_arg);
         system_error(error_code ec, char const *what_arg);

         system_error(int ev, error_category const &ecat);
         system_error(int ev, error_category const &ecat,
                             char const *what_arg);
         system_error(int ev, error_category const &ecat,
                             string const &what_arg);

         error_code const &code() const noexcept;
         char const *what() const noexcept;
 }
```

The `ev` values often are the values of the `errno` variable as set upon failure by system level functions like **chmod**(2).

Note that the first three constructors shown in the interface receive an `error_code` object as their first arguments. As one of the `error_code` constructors also expects an `int` and and `error_category` argument, the second set of three constructors could also be used instead of the first set of three constructors. E.g.,

```
    system_error(errno, system_category(), "context of the error");
    // identical to:
    system_error(error_code(errno, system_category()),
                                          "context of the error");
```

The second set of three constructors are primarily used when an existing function already returns an `error_code`. E.g.,

```
    system_error(make_error_code(errc::bad_address),
                                          "context of the error");
    // or maybe:
    system_error(make_error_code(static_cast<errc>(errno)),
                                          "context of the error");
```

In addition to the standard `what` member, the `system_error` class also offers a member `code` returning a const reference to the exception's error code.

The NTBS returned by `system_error's what` member may be formatted by a `system_error` object:

```
    what_arg + ": " + code().message()
```

Note that, although `system_error` was derived from `runtime_error`, you'll lose the `code` member when catching a `std::exception` object. Of course, downcasting is possible, but that's a stopgap. Therefore, if a `system_error` is thrown, a matching `catch(system_error const &)` clause must be provided to retrieve the value returned by the `code` member. This, and the rather complex organization of the classes that are involved when using `system_error` result in a very complex, and hard to generalize exception handling. In essence, what you obtain at the cost of high complexity is a facility for categorizing `int` or `enum` error values. Additional coverage of the involved complexities is provided in chapter 23, in particular section 23.7 (for a flexible alternative, see the class `FBB::Exception` in the author's `Bobcat library`[1]).

10.10 Exception guarantees

Software should be *exception safe*: the program should continue to work according to its specifications in the face of exceptions. It is not always easy to realize exception safety. In this section some guidelines and terminology is introduced when discussing exception safety.

Since exceptions may be generated from within all **C++** functions, exceptions may be generated in many situations. Not all of these situations are immediately and intuitively recognized as situations where exceptions can be thrown. Consider the following function and ask yourself at which points exceptions may be thrown:

```
    void fun()
    {
        X x;
        cout << x;
```

---

[1] http://fbb-git.gitlab.io/bobcat/

```
        X *xp = new X{ x };
        cout << (x + *xp);
        delete xp;
    }
```

If it can be assumed that `cout` as used above does not throw an exception there are at least 13 opportunities for exceptions to be thrown:

- `X x`: the default constructor could throw an exception (#1)
- `cout << x`: the overloaded insertion operator could throw an exception (#2), but its rhs argument might not be an `X` but, e.g., an `int`, and so `X::operator int() const` could be called which offers yet another opportunity for an exception (#3).
- `*xp = new X{ x }`: the copy constructor may throw an exception (#4) and operator new (#5a) too. But did you realize that this latter exception might not be thrown from `::new`, but from, e.g., `X`'s own overload of `operator new`? (#5b)
- `cout << (x + *xp)`: we might be seduced into thinking that two `X` objects are added. But it doesn't have to be that way. A separate class Y might exist and `X` may have a conversion operator `operator Y() const`, and `operator+(Y const &lhs, X const &rhs)`, `operator+(X const &lhs, Y const &rhs)`, and `operator+(X const &lhs, X const &rhs)` might all exist. So, if the conversion operator exists, then depending on the kind of overload of `operator+` that is defined either the addition's left-hand side operand (#6), right-hand side operand (#7), or `operator+` itself (#8) may throw an exception. The resulting value may again be of any type and so the overloaded `cout << return-type-of-operator+` operator may throw an exception (#9). Since `operator+` returns a temporary object it is destroyed shortly after its use. `X`'s destructor *could* throw an exception (#10).
- `delete xp`: whenever `operator new` is overloaded `operator delete` should be overloaded as well and may throw an exception (#11). And of course, `X`'s destructor might again throw an exception (#12).
- `}`: when the function terminates the local `x` object is destroyed: again an exception could be thrown (#13).

It is stressed here (and further discussed in section 10.12) that although it is possible for exceptions to leave destructors this would violate the **C++** standard and so it must be prevented in well-behaving **C++** programs.

How can we expect to create working programs when exceptions might be thrown in so many situations?

Exceptions may be generated in a great many situations, but serious problems are prevented when we're able to provide at least one of the following exception guarantees:

- The *basic guarantee*: no resources are leaked. In practice this means: all allocated memory is properly returned when exceptions are thrown.
- The *strong guarantee*: the program's state remains unaltered when an exception is thrown (as an example: the canonical form of the overloaded assignment operator provides this guarantee)
- The *nothrow* guarantee: this applies to code for which it can be proven that no exception can be thrown from it.

10.10.1 The basic guarantee

The *basic guarantee* dictates that functions that fail to complete their assigned tasks must return all allocated resources, usually memory, before terminating. Since practically all functions and operators may throw exceptions and since a function may repeatedly allocate resources the blueprint of a function allocating resources shown below defines a try block to catch all exceptions that might be thrown. The catch handler's task is to return all allocated resources and then rethrow the exception.

```
void allocator(X **xDest, Y **yDest)
{
    X *xp = 0;              // non-throwing preamble
    Y *yp = 0;

    try                     // this part might throw
    {
        xp = new X[nX];     // alternatively: allocate one object
        yp = new Y[nY];
    }
    catch(...)
    {
        delete xp;
        throw;
    }

    delete[] *xDest;        // non-throwing postamble
    *xDest = xp;
    delete[] *yDest;
    *yDest = yp;
}
```

In the pre-try code the pointers to receive the addresses returned by the operator `new` calls are initialized to 0. Since the catch handler must be able to return allocated memory they must be available outside of the `try` block. If the allocation succeeds the memory pointed to by the destination pointers is returned and then the pointers are given new values.

Allocation and or initialization might fail. If allocation fails `new` throws a `std::bad_alloc` exception and the catch handler simply deletes 0-pointers which is OK.

If allocation succeeds but the construction of (some) of the objects fails by throwing an exception then the following is *guaranteed* to happen:

- The destructors of all successfully allocated objects are called;
- The dynamically allocated memory to contain the objects is returned

Consequently, there is no memory leak when `new` fails. Inside the above `try` block `new X` may fail: this does not affect the 0-pointers and so the catch handler merely deletes 0 pointers. When `new Y` fails `xp` points to allocated memory and so it must be returned. This happens inside the catch handler. The final pointer (here: `yp`) will only be unequal zero when `new Y` properly completes, so there's no need for the catch handler to return the memory pointed at by `yp`.

10.10.2 The strong guarantee

The *strong guarantee* dictates that an object's state should not change in the face of exceptions. This is realized by performing all operations that might throw on a separate copy of the data. If all this succeeds then the current object and its (now successfully modified) copy are swapped. An example of this approach can be observed in the canonical overloaded assignment operator:

```
Class &operator=(Class const &other)
{
    Class tmp(other);
    swap(tmp);
    return *this;
}
```

The copy construction might throw an exception, but this keeps the current object's state intact. If the copy construction succeeds `swap` swaps the current object's content with `tmp`'s content and returns a reference to the current object. For this to succeed it must be guaranteed that `swap` won't throw an exception. Returning a reference (or a value of a primitive data type) is also guaranteed not to throw exceptions. The canonical form of the overloaded assignment operator therefore meets the requirements of the strong guarantee.

Some rules of thumb were formulated that relate to the strong guarantee (cf. Sutter, H., *Exceptional C++*, Addison-Wesley, 2000). E.g.,

- All the code that might throw an exception affecting the current state of an object should perform its tasks separately from the data controlled by the object. Once this code has performed its tasks without throwing an exception replace the object's data by the new data.
- Member functions modifying their object's data should not return original (contained) objects by value.

The canonical assignment operator is a good example of the first rule of thumb. Another example is found in classes storing objects. Consider a class `PersonDb` storing multiple `Person` objects. Such a class might offer a member `void add(Person const &next)`. A plain implementation of this function (merely intended to show the application of the first rule of thumb, but otherwise completely disregarding efficiency considerations) might be:

```
Person *PersonDb::newAppend(Person const &next)
{
    Person *tmp = 0;
    try
    {
        tmp = new Person[d_size + 1];
        for (size_t idx = 0; idx < d_size; ++idx)
            tmp[idx] = d_data[idx];
        tmp[d_size] = next;
        return tmp;
    }
    catch (...)
    {
        delete[] tmp;
        throw;
    }
}

void PersonDb::add(Person const &next)
{
    Person *tmp = newAppend(next);
    delete[] d_data;
```

```
        d_data = tmp;
        ++d_size;
    }
```

The (private) `newAppend` member's task is to create a copy of the currently allocated `Person` objects, including the data of the next `Person` object. Its `catch` handler catches any exception that might be thrown during the allocation or copy process and returns all memory allocated so far, rethrowing the exception at the end. The function is *exception neutral* as it propagates all its exceptions to its caller. The function also doesn't modify the `PersonDb` object's data, so it meets the strong exception guarantee. Returning from `newAppend` the member `add` may now modify its data. Its existing data are returned and its `d_data` pointer is made to point to the newly created array of `Person` objects. Finally its `d_size` is incremented. As these three steps don't throw exceptions `add` too meets the strong guarantee.

The second rule of thumb (member functions modifying their object's data should not return original (contained) objects by value) may be illustrated using a member `PersonDb::erase(size_t idx)`. Here is an implementation attempting to return the original `d_data[idx]` object:

```
    Person PersonData::erase(size_t idx)
    {
        if (idx >= d_size)
            throw "Array bounds exceeded"s;
        Person ret(d_data[idx]);
        Person *tmp = copyAllBut(idx);
        delete[] d_data;
        d_data = tmp;
        --d_size;
        return ret;
    }
```

Although copy elision usually prevents the use of the copy constructor when returning `ret`, this is not guaranteed to happen. Furthermore, a copy constructor *may* throw an exception. If that happens the function has irrevocably mutated the `PersonDb`'s data, thus losing the strong guarantee.

Rather than returning `d_data[idx]` by value it might be assigned to an external `Person` object before mutating `PersonDb`'s data:

```
    void PersonData::erase(Person *dest, size_t idx)
    {
        if (idx >= d_size)
            throw "Array bounds exceeded"s;
        *dest = d_data[idx];
        Person *tmp = copyAllBut(idx);
        delete[] d_data;
        d_data = tmp;
        --d_size;
    }
```

This modification works, but changes the original assignment of creating a member returning the original object. However, both functions suffer from a task overload as they modify `PersonDb`'s data and also return an original object. In situations like these the *one-function-one-responsibility* rule of thumb should be kept in mind: a function should have a single, well defined responsibility.

The preferred approach is to retrieve `PersonDb`'s objects using a member like `Person const &at(size_t idx) const` and to erase an object using a member like `void PersonData::erase(size_t idx)`.

10.10.3 The nothrow guarantee

Exception safety can only be realized if some functions and operations are guaranteed *not* to throw exceptions. This is called the *nothrow guarantee*. An example of a function that must offer the nothrow guarantee is the `swap` function. Consider once again the canonical overloaded assignment operator:

```
Class &operator=(Class const &other)
{
    Class tmp(other);
    swap(tmp);
    return *this;
}
```

If `swap` were allowed to throw exceptions then it would most likely leave the current object in a partially swapped state. As a result the current object's state would most likely have been changed. As `tmp` has been destroyed by the time a catch handler receives the thrown exception it becomes very difficult (as in: impossible) to retrieve the object's original state. Losing the strong guarantee as a consequence.

The `swap` function must therefore offer the nothrow guarantee. It must have been designed as if using the following prototype (see also section 23.8):

```
void Class::swap(Class &other) noexcept;
```

Likewise, `operator delete` and `operator delete[]` offer the nothrow guarantee, and according to the **C++** standard destructors may themselves not throw exceptions (if they do their behavior is formally undefined, see also section 10.12 below).

Since the **C** programming language does not define the exception concept functions from the standard **C** library offer the nothrow guarantee by implication. This allowed us to define the generic `swap` function in section 9.6 using `memcpy`.

Operations on primitive types offer the nothrow guarantee. Pointers may be reassigned, references may be returned etc. etc. without having to worry about exceptions that might be thrown.

10.11 Function try blocks

Exceptions may be generated from inside constructors. How can exceptions generated in such situations be caught by the constructor itself, rather than outside the constructor? The intuitive solution, nesting the object construction in a `try` block does not solve the problem. The exception by then has left the constructor and the object we intended to construct isn't visible anymore.

Using a nested `try` block is illustrated in the next example, where `main` defines an object of class `PersonDb`. Assuming that `PersonDb`'s constructor throws an exception, there is no way we can access the resources that might have been allocated by `PersonDb`'s constructor from the catch handler as the `pdb` object is out of scope:

```
int main(int argc, char **argv)
{
    try
    {
        PersonDb pdb{ argc, argv }; // may throw exceptions
```

```
            ...                         // main()'s other code
        }
        catch(...)                      // and/or other handlers
        {
            ...                         // pdb is inaccessible from here
        }
    }
```

Although all objects and variables defined inside a `try` block are inaccessible from its associated catch handlers, object data members were available before starting the `try` block and so they may be accessed from a catch handler. In the following example the catch handler in `PersonDb`'s constructor is able to access its `d_data` member:

```
    PersonDb::PersonDb(int argc, char **argv)
    :
        d_data(0),
        d_size(0)
    {
        try
        {
            initialize(argc, argv);
        }
        catch(...)
        {
            // d_data, d_size: accessible
        }
    }
```

Unfortunately, this does not help us much. The `initialize` member is unable to reassign `d_data` and `d_size` if `PersonDb const pdb` was defined; the `initialize` member should at least offer the basic exception guarantee and return any resources it has acquired before terminating due to a thrown exception; and although `d_data` and `d_size` offer the nothrow guarantee as they are of primitive data types a class type data member might throw an exception, possibly resulting in violation of the basic guarantee.

In the next implementation of `PersonDb` assume that constructor receives a pointer to an already allocated block of `Person` objects. The `PersonDb` object takes ownership of the allocated memory and it is therefore responsible for the allocated memory's eventual destruction. Moreover, `d_data` and `d_size` are also used by a composed object `PersonDbSupport`, having a constructor expecting a `Person const *` and `size_t` argument. Our next implementation may then look something like this:

```
    PersonDb::PersonDb(Person *pData, size_t size)
    :
        d_data(pData),
        d_size(size),
        d_support(d_data, d_size)
    {
        // no further actions
    }
```

This setup allows us to define a `PersonDb const &pdb`. Unfortunately, `PersonDb` cannot offer the basic guarantee. If `PersonDbSupport`'s constructor throws an exception it isn't caught although `d_data` already points to allocated memory.

The *function try block* offers a solution for this problem. A function try block consists of a `try` block and its associated handlers. The function `try` block starts *immediately* after the function header, and its block defines the function body. With constructors base class and data member initializers may be placed between the `try` keyword and the opening curly brace. Here is our final implementation of `PersonDb`, now offering the basic guarantee:

```
PersonDb::PersonDb(Person *pData, size_t size)
try
:
    d_data(pData),
    d_size(size),
    d_support(d_data, d_size)
{}
catch (...)
{
    delete[] d_data;
}
```

Let's have a look at a stripped-down example. A constructor defines a function try block. The exception thrown by the `Throw` object is initially caught by the object itself. Then it is rethrown. The surrounding `Composer`'s constructor also defines a function try block, `Throw`'s rethrown exception is properly caught by `Composer`'s exception handler, even though the exception was generated from within its member initializer list:

```
#include <iostream>

class Throw
{
    public:
        Throw(int value)
        try
        {
            throw value;
        }
        catch(...)
        {
            std::cout << "Throw's exception handled locally by Throw()\n";
            throw;
        }
};

class Composer
{
    Throw d_t;
    public:
        Composer()
        try             // NOTE: try precedes initializer list
        :
            d_t(5)
        {}
        catch(...)
        {
            std::cout << "Composer() caught exception as well\n";
        }
};
```

```
int main()
{
    Composer c;
}
```

When running this example, we're in for a nasty surprise: the program runs and then breaks with an *abort exception*. Here is the output it produces, the last two lines being added by the system's final catch-all handler, catching all remaining uncaught exceptions:

```
Throw's exception handled locally by Throw()
Composer() caught exception as well
terminate called after throwing an instance of 'int'
Abort
```

The reason for this is documented in the **C++** standard: at the end of a catch-handler belonging to a constructor or destructor function try block, the original exception is automatically rethrown.

The exception is not rethrown if the handler itself throws another exception, offering the constructor or destructor a way to replace a thrown exception by another one. The exception is only rethrown if it reaches the end of the catch handler of a constructor or destructor function try block. Exceptions caught by nested catch handlers are not automatically rethrown.

As only constructors and destructors rethrow exceptions caught by their function try block catch handlers the run-time error encountered in the above example may simply be repaired by providing `main` with its own function try block:

```
int main()
try
{
    Composer c;
}
catch (...)
{}
```

Now the program runs as planned, producing the following output:

```
Throw's exception handled locally by Throw()
Composer() caught exception as well
```

A final note: if a function defining a function try block also declares an exception throw list then only the types of rethrown exceptions must match the types mentioned in the throw list.

10.12 Exceptions in constructors and destructors

Object destructors are only activated for completely constructed objects. Although this may sound like a truism, there is a subtlety here. If the construction of an object fails for some reason, the object's destructor is *not* called when the object goes out of scope. This could happen if an exception that is generated by the constructor is not caught by the constructor. If the exception is thrown when the object has already allocated some memory, then that memory is not returned: its destructor isn't called as the object's construction wasn't successfully completed.

The following example illustrates this situation in its prototypical form. The constructor of the class `Incomplete` first displays a message and then throws an exception. Its destructor also displays a message:

```
class Incomplete
{
    public:
        Incomplete()
        {
            cerr << "Allocated some memory\n";
            throw 0;
        }
        ~Incomplete()
        {
            cerr << "Destroying the allocated memory\n";
        }
};
```

Next, `main()` creates an `Incomplete` object inside a `try` block. Any exception that may be generated is subsequently caught:

```
int main()
{
    try
    {
        cerr << "Creating `Incomplete' object\n";
        Incomplete{};
        cerr << "Object constructed\n";
    }
    catch(...)
    {
        cerr << "Caught exception\n";
    }
}
```

When this program is run, it produces the following output:

```
Creating `Incomplete' object
Allocated some memory
Caught exception
```

Thus, if `Incomplete`'s constructor would actually have allocated some memory, the program would suffer from a memory leak. To prevent this from happening, the following counter measures are available:

- Prevent the exceptions from leaving the constructor.
  If part of the constructor's body may generate exceptions, then this part may be surrounded by a `try` block, allowing the exception to be caught by the constructor itself. This approach is defensible when the constructor is able to repair the cause of the exception and to complete its construction as a valid object.
- If an exception is generated by a base class constructor or by a member initializing constructor then a `try` block within the constructor's body won't be able to catch the thrown exception. This *always* results in the exception leaving the constructor and the object is not considered to

have been properly constructed. A `try` block may include the member initializers, and the `try` block's compound statement becomes the constructor's body as in the following example:

```
class Incomplete2
{
    Composed d_composed;
    public:
        Incomplete2()
        try
        :
            d_composed(/* arguments */)
        {
            // body
        }
        catch (...)
        {}
};
```

An exception thrown by either the member initializers or the body results in the execution never reaching the body's closing curly brace. Instead the catch clause is reached. Since the constructor's body isn't properly completed the object is not considered properly constructed and eventually the object's destructor won't be called.

The catch clause of a constructor's function `try` block behaves slightly different than a catch clause of an ordinary function `try` block. An exception reaching a constructor's function `try` block may be transformed into another exception (which is thrown from the catch clause) but if no exception is explicitly thrown from the catch clause the exception originally reaching the catch clause is always rethrown. Consequently, there's no way to confine an exception thrown from a base class constructor or from a member initializer to the constructor: such an exception *always* propagates to a more shallow block and in that case the object's construction is always considered incomplete.

Consequently, if incompletely constructed objects throw exceptions then the constructor's catch clause is responsible for preventing memory (generally: resource) leaks. There are several ways to realize this:

- When multiple inheritance is used: if initial base classes have properly been constructed and a later base class throws, then the initial base class objects are automatically destroyed (as they are themselves fully constructed objects)
- When composition is used: already constructed composed objects are automatically destroyed (as they are fully constructed objects)
- Instead of using plain pointers *smart pointers* (cf. section 18.4) should be used to manage dynamically allocated memory. In this case, if the constructor throws either before or after the allocation of the dynamic memory, then allocated memory is properly returned as `shared_ptr` objects are, after all, objects.
- If plain pointer data members *must* be used then the constructor's body should first, in its member initialization section, initialize its plain pointer data members. Then, in its body it can dynamically allocate memory, reassigning the plain pointer data members. The constructor must be provided with a function try block whose generic catch clause deletes the memory pointed at by the class's plain pointer data members. Example:

```
class Incomplete2
{
    Composed d_composed;
    char *d_cp;          // plain pointers
```

```
        int *d_ip;

        public:
            Incomplete2(size_t nChars, size_t nInts)
            try
            :
                d_composed(/* arguments */),    // might throw
                d_cp(0),
                d_ip(0)
            {
                preamble();                     // might throw
                d_cp = new char[nChars];        // might throw
                d_ip = new int[nChars];         // might throw
                postamble();                    // might throw
            }
            catch (...)
            {
                delete[] d_cp;                  // clean up
                delete[] d_ip;
            }
    };
```

On the other hand, since **C++** supports constructor delegation an object may have been completely constructed according to the **C++** run-time system, but yet its constructor may have thrown an exception. This happens if a delegated constructor successfully completes (after which the object is considered 'completely constructed'), but the constructor itself throws an exception, as illustrated by the next example:

```
    class Delegate
    {
        public:
            Delegate()
            :
                Delegate(0)
            {
                throw 12;       // throws but completely constructed
            }
            Delegate(int x)         // completes OK
            {}
    };
    int main()
    try
    {
        Delegate del;           // throws

    } // del's destructor is called here
    catch (...)
    {}
```

In this example it is the responsibility of `Delegate`'s designer to ensure that the throwing default constructor does not invalidate the actions performed by `Delegate`'s destructor. E.g., if the delegated constructor allocates memory to be deleted by the destructor, then the default constructor should either leave the memory as-is, or it can delete the memory and set the corresponding pointer to zero thereafter. In any case, it is `Delegate`'s responsibility to ensure that the object remains in a valid state, even though it throws an exception.

According to the **C++** standard exceptions thrown by destructors may not leave their bodies. Providing a destructor with a function `try` block is therefore a violation of the standard: exceptions caught by a function `try` block's catch clause have already left the destructor's body. If --in violation of the standard-- the destructor *is* provided with a function `try` block and an exception is caught by the `try` block then that exception is rethrown, similar to what happens in catch clauses of constructor functions' `try` blocks.

The consequences of an exception leaving the destructor's body is not defined, and may result in unexpected behavior. Consider the following example:

Assume a carpenter builds a cupboard having a single drawer. The cupboard is finished, and a customer, buying the cupboard, finds that the cupboard can be used as expected. Satisfied with the cupboard, the customer asks the carpenter to build another cupboard, this time having *two* drawers. When the second cupboard is finished, the customer takes it home and is utterly amazed when the second cupboard completely collapses immediately after it is used for the first time.

Weird story? Then consider the following program:

```
int main()
{
    try
    {
        cerr << "Creating Cupboard1\n";
        Cupboard1{};
        cerr << "Beyond Cupboard1 object\n";
    }
    catch (...)
    {
        cerr << "Cupboard1 behaves as expected\n";
    }
    try
    {
        cerr << "Creating Cupboard2\n";
        Cupboard2{};
        cerr << "Beyond Cupboard2 object\n";
    }
    catch (...)
    {
        cerr << "Cupboard2 behaves as expected\n";
    }
}
```

When this program is run it produces the following output:

```
Creating Cupboard1
Drawer 1 used
Cupboard1 behaves as expected
Creating Cupboard2
Drawer 2 used
Drawer 1 used
terminate called after throwing an instance of 'int'
Abort
```

The final `Abort` indicates that the program has aborted instead of displaying a message like `Cupboard2 behaves as expected`.

Let's have a look at the three classes involved. The class `Drawer` has no particular characteristics, except that its destructor throws an exception:

```
class Drawer
{
    size_t d_nr;
    public:
        Drawer(size_t nr)
        :
            d_nr(nr)
        {}
        ~Drawer()
        {
            cerr << "Drawer " << d_nr << " used\n";
            throw 0;
        }
};
```

The class `Cupboard1` has no special characteristics at all. It merely has a single composed `Drawer` object:

```
class Cupboard1
{
    Drawer left;
    public:
        Cupboard1()
        :
            left(1)
        {}
};
```

The class `Cupboard2` is constructed comparably, but it has two composed `Drawer` objects:

```
class Cupboard2
{
    Drawer left;
    Drawer right;
    public:
        Cupboard2()
        :
            left(1),
            right(2)
        {}
};
```

When `Cupboard1`'s destructor is called `Drawer`'s destructor is eventually called to destroy its composed object. This destructor throws an exception, which is caught beyond the program's first `try` block. This behavior is completely as expected.

A subtlety here is that `Cupboard1`'s destructor (and hence `Drawer`'s destructor) is activated *immediately* subsequent to its construction. Its destructor is called immediately subsequent to its construction as `Cupboard1()` defines an anonymous object. As a result the `Beyond Cupboard1 object` text is never inserted into `std::cerr`.

Because of `Drawer`'s destructor throwing an exception a problem occurs when `Cupboard2`'s destructor is called. Of its two composed objects, the second `Drawer`'s destructor is called first. This destructor throws an exception, which ought to be caught beyond the program's second `try` block. However, although the flow of control by then has left the context of `Cupboard2`'s destructor, that object hasn't completely been destroyed yet as the destructor of its other (left) `Drawer` still has to be called.

Normally that would not be a big problem: once an exception is thrown from `Cupboard2`'s destructor any remaining actions would simply be ignored, albeit that (as both drawers are properly constructed objects) `left`'s destructor would still have to be called.

This happens here too and `left`'s destructor *also* needs to throw an exception. But as we've already left the context of the second `try` block, the current flow control is now thoroughly mixed up, and the program has no other option but to abort. It does so by calling `terminate()`, which in turn calls `abort()`. Here we have our collapsing cupboard having two drawers, even though the cupboard having one drawer behaves perfectly.

The program aborts since there are multiple composed objects whose destructors throw exceptions leaving the destructors. In this situation one of the composed objects would throw an exception by the time the program's flow control has already left its proper context causing the program to abort.

The **C++** standard therefore understandably stipulates that exceptions may *never* leave destructors. Here is the skeleton of a destructor whose code might throw exceptions. No function `try` block but all the destructor's actions are encapsulated in a `try` block nested under the destructor's body.

```
Class::~Class()
{
    try
    {
        maybe_throw_exceptions();
    }
    catch (...)
    {}
}
```

Chapter 11

More Operator Overloading

Having covered the overloaded assignment operator in chapter 9, and having shown several examples of other overloaded operators as well (i.e., the insertion and extraction operators in chapters 3 and 6), we now take a look at operator overloading in general.

11.1 Overloading ‘operator[]()’

As our next example of operator overloading, we introduce a class `IntArray` encapsulating an array of `int`s. Indexing the array elements is possible using the standard array index operator `[]`, but additionally checks for array bounds overflow are performed. Furthermore, the index operator (`operator[]`) is interesting in that it can be used in expressions as both lvalue and as rvalue.

Here is an example showing the basic use of the class:

```
int main()
{
    IntArray x{ 20 };                // 20 ints

    for (int i = 0; i < 20; i++)
        x[i] = i * 2;                // assign the elements

    for (int i = 0; i <= 20; i++)    // produces boundary overflow
        cout << "At index " << i << ": value is " << x[i] << '\n';
}
```

First, the constructor is used to create an object containing 20 `int`s. The elements stored in the object can be assigned or retrieved. The first `for`-loop assigns values to the elements using the index operator, the second `for`-loop retrieves the values but also results in a run-time error once the non-existing value `x[20]` is addressed. The `IntArray` class interface is:

```
#include <cstddef>

class IntArray
{
    int     *d_data;
    size_t d_size;
```

```
        public:
            IntArray(size_t size = 1);
            IntArray(IntArray const &other);
            ~IntArray();
            IntArray &operator=(IntArray const &other);

                                                // overloaded index operators:
            int &operator[](size_t index);              // first
            int operator[](size_t index) const;         // second

            void swap(IntArray &other);         // trivial

        private:
            void boundary(size_t index) const;
            int &operatorIndex(size_t index) const;
    };
```

This class has the following characteristics:

- One of its constructors has a `size_t` parameter having a default argument value, specifying the number of `int` elements in the object.
- The class internally uses a pointer to reach allocated memory. Hence, the necessary tools are provided: a copy constructor, an overloaded assignment operator and a destructor.
- Note that there are two overloaded index operators. Why are there two?

  The first overloaded index operator allows us to reach and modify the elements of non-constant `IntArray` objects. This overloaded operator's prototype is a function returning *a reference* to an `int`. This allows us to use expressions like `x[10]` as rvalues *or* lvalues.

  With non-const `IntArray` objects `operator[]` can therefore be used to retrieve and to assign values. The return value of the non-const `operator[]` member is *not* an `int const &`, but an `int &`. In this situation we don't use `const`, as we must be able to modify the element we want to access when the operator is used as lvalue.

  This whole scheme fails if there's nothing to assign. Consider the situation where we have an `IntArray const stable(5)`. Such an object is an immutable *const* object. The compiler detects this and refuses to compile this object definition if only the non-const `operator[]` is available. Hence the second overloaded index operator is added to the class's interface. Here the return value is an `int`, rather than an `int &`, and the member function itself is a `const` member function. This second form of the overloaded index operator is automatically used by the compiler with `const` objects. It is used for value *retrieval* instead of value assignment. That, of course, is precisely what we want when using `const` objects. In this situation members are overloaded only by their `const` attribute. This form of function overloading was introduced earlier in the **C++** Annotations (sections 2.5.4 and 7.7).

  Note the difference between the return types of the two overloaded index operators: `int &` and `int`. Here, using a value return type for the const-index operator is OK, because the return type is a simple built-in type: returning a copy of the requested value is likely more efficient than returning a const reference, which must be dereferenced whenever it is used. However, for more complex return types (generally: objects) value return types should be avoided and the const index operator should define a `Type const &` return type instead of a `Type` value return type.

  Since `IntArray` stores values of a primitive type `IntArray`'s `operator[] const` could also have defined a value return type. However, with objects one usually doesn't want the extra copying that's implied with value return types. In those cases `const &` return values are preferred for `const` member functions. So, in the `IntArray` class an `int` return value could have been used as well, resulting in the following prototype:

```
int IntArray::operator[](size_t index) const;
```

- As there is only one pointer data member, the destruction of the memory allocated by the object is a simple `delete[] data`.

Now, the implementation of the members (omitting the trivial implementation of `swap`, cf. chapter 9) are:

```
#include "intarray.ih"

IntArray::IntArray(size_t size)
:
    d_size(size)
{
    if (d_size < 1)
        throw "IntArray: size of array must be >= 1"s;

    d_data = new int[d_size];
}

IntArray::IntArray(IntArray const &other)
:
    d_size(other.d_size),
    d_data(new int[d_size])
{
    memcpy(d_data, other.d_data, d_size * sizeof(int));
}

IntArray::~IntArray()
{
    delete[] d_data;
}

IntArray &IntArray::operator=(IntArray const &other)
{
    IntArray tmp(other);
    swap(tmp);
    return *this;
}

int &IntArray::operatorIndex(size_t index) const
{
    boundary(index);
    return d_data[index];
}

int &IntArray::operator[](size_t index)
{
    return operatorIndex(index);
}

int IntArray::operator[](size_t index) const
```

```
{
    return operatorIndex(index);
}

void IntArray::boundary(size_t index) const
{
    if (index < d_size)
        return;
    ostringstream out;
    out  << "IntArray: boundary overflow, index = " <<
            index << ", should be < " << d_size << '\n';
    throw out.str();
}
```

Note how the `operator[]` members were implemented: as non-const members may call const member functions and as the implementation of the `const` member function is identical to the non-const member function's implementation both `operator[]` members could be defined inline using an auxiliary function `int &operatorIndex(size_t index) const`. A `const` member function may return a non-const reference (or pointer) return value, referring to one of the data members of its object. Of course, this is a potentially dangerous backdoor that may break data hiding. However, the members in the public interface prevent this breach and so the two public `operator[]` members may themselves safely call the same `int &operatorIndex() const` member, that defines a *private backdoor*.

11.2 Overloading insertion and extraction operators

Classes may be adapted in such a way that their objects may be inserted into and extracted from, respectively, a `std::ostream` and `std::istream`.

The class `std::ostream` defines insertion operators for primitive types, such as `int`, `char *`, etc.. In this section we learn how to extend the existing functionality of classes (in particular `std::istream` and `std::ostream`) in such a way that they can be used also in combination with classes developed much later in history.

In particular we will show how the insertion operator can be overloaded allowing the insertion of any type of object, say `Person` (see chapter 9), into an `ostream`. Having defined such an overloaded operator we're able to use the following code:

```
Person kr("Kernighan and Ritchie", "unknown", "unknown");

cout << "Name, address and phone number of Person kr:\n" << kr << '\n';
```

The statement `cout << kr` uses `operator<<`. This member function has two operands: an `ostream &` and a `Person &`. The required action is defined in an overloaded *free function* `operator<<` expecting two arguments:

```
                            // declared in `person.h'
std::ostream &operator<<(std::ostream &out, Person const &person);

                            // defined in some source file
ostream &operator<<(ostream &out, Person const &person)
{
    return
```

```
        out <<
            "Name:    " << person.name() << ", "
            "Address: " << person.address() << ", "
            "Phone:   " << person.phone();
    }
```

The free function `operator<<` has the following noteworthy characteristics:

- The function returns a reference to an `ostream` object, to enable 'chaining' of the insertion operator.
- The two operands of `operator<<` are passed to the free function as its arguments. In the example, the parameter `out` was initialized by `cout`, the parameter `person` by `kr`.

In order to overload the *extraction* operator for, e.g., the `Person` class, members are needed modifying the class's private data members. Such *modifiers* are normally offered by the class interface. For the `Person` class these members could be the following:

```
    void setName(char const *name);
    void setAddress(char const *address);
    void setPhone(char const *phone);
```

These members may easily be implemented: the memory pointed to by the corresponding data member must be deleted, and the data member should point to a copy of the text pointed to by the parameter. E.g.,

```
    void Person::setAddress(char const *address)
    {
        delete[] d_address;
        d_address = strdupnew(address);
    }
```

A more elaborate function should check the reasonableness of the new address (`address` also shouldn't be a 0-pointer). This however, is not further pursued here. Instead, let's have a look at the final `operator>>`. A simple implementation is:

```
    istream &operator>>(istream &in, Person &person)
    {
        string name;
        string address;
        string phone;

        if (in >> name >> address >> phone)    // extract three strings
        {
            person.setName(name.c_str());
            person.setAddress(address.c_str());
            person.setPhone(phone.c_str());
        }
        return in;
    }
```

Note the stepwise approach that is followed here. First, the required information is extracted using available extraction operators. Then, if that succeeds, *modifiers* are used to modify the data members of the object to be extracted. Finally, the stream object itself is returned as a reference.

11.3 Conversion operators

A class may be constructed around a built-in type. E.g., a class `String`, constructed around the `char *` type. Such a class may define all kinds of operations, like assignments. Take a look at the following class interface, designed after the `string` class:

```
    class String
    {
        char *d_string;

        public:
            String();
            String(char const *arg);
            ~String();
            String(String const &other);
            String &operator=(String const &rvalue);
            String &operator=(char const *rvalue);
    };
```

Objects of this class can be initialized from a `char const *`, and also from a `String` itself. There is an overloaded assignment operator, allowing the assignment from a `String` object and from a `char const *`[1].

Usually, in classes that are less directly linked to their data than this `String` class, there will be an *accessor member function*, like a member `char const *String::c_str() const`. However, the need to use this latter member doesn't appeal to our intuition when an array of `String` objects is defined by, e.g., a class `StringArray`. If this latter class provides the `operator[]` to access individual `String` members, it would most likely offer at least the following class interface:

```
    class StringArray
    {
        String *d_store;
        size_t d_n;

        public:
            StringArray(size_t size);
            StringArray(StringArray const &other);
            StringArray &operator=(StringArray const &rvalue);
            ~StringArray();

            String &operator[](size_t index);
    };
```

This interface allows us to assign `String` elements to each other:

```
    StringArray sa{ 10 };

    sa[4] = sa[3];  // String to String assignment
```

But it is also possible to assign a `char const *` to an element of `sa`:

```
    sa[3] = "hello world";
```

---

[1] Note that the assignment from a `char const *` also allows the null-pointer. An assignment like `stringObject = 0` is perfectly in order.

Here, the following steps are taken:

- First, `sa[3]` is evaluated. This results in a `String` reference.
- Next, the `String` class is inspected for an overloaded assignment, expecting a `char const *` to its right-hand side. This operator is found, and the string object `sa[3]` receives its new value.

Now we try to do it the other way around: how to *access* the `char const *` that's stored in `sa[3]`? The following attempt fails:

```
char const *cp = sa[3];
```

It fails since we would need an overloaded assignment operator for the 'class' `char const *`. Unfortunately, there isn't such a class, and therefore we can't build that overloaded assignment operator (see also section 11.14). Furthermore, *casting* won't work as the compiler doesn't know how to cast a `String` to a `char const *`. How to proceed?

One possibility is to define an accessor member function `c_str()`:

```
char const *cp = sa[3].c_str()
```

This compiles fine but looks clumsy.... A far better approach would be to use a *conversion operator*.

A *conversion operator* is a kind of overloaded operator, but this time the overloading is used to cast the object to another type. In class interfaces, the general form of a conversion operator is:

```
operator <type>() const;
```

Conversion operators usually are `const` member functions: they are automatically called when their objects are used as *rvalues* in expressions having a `type` *lvalue*. Using a conversion operator a `String` object may be interpreted as a `char const *` rvalue, allowing us to perform the above assignment.

Conversion operators are somewhat dangerous. The conversion is automatically performed by the compiler and unless its use is perfectly transparent it may confuse those who read code in which conversion operators are used. E.g., novice **C++** programmers are frequently confused by statements like '`if (cin) ...`'.

As a rule of thumb: classes should define at most one conversion operator. Multiple conversion operators may be defined but frequently result in ambiguous code. E.g., if a class defines `operator bool() const` and `operator int() const` then passing an object of this class to a function expecting a `size_t` argument results in an ambiguity as an `int` and a `bool` may both be used to initialize a `size_t`.

In the current example, the class `String` could define the following conversion operator for `char const *`:

```
String::operator char const *() const
{
    return d_string;
}
```

Notes:

- Conversion operators do not define return types. The conversion operator returns a value of the type specified beyond the `operator` keyword.

- In certain situations (e.g., when a `String` argument is passed to a function specifying an ellipsis parameter) the compiler needs a hand to disambiguate our intentions. A `static_cast` solves the problem.
- With *template functions* conversion operators may not work immediately as expected. For example, when defining a conversion operator `X::operator std::string const() const` then `cout << X()` won't compile. The reason for this is explained in section 21.9, but a shortcut allowing the conversion operator to work is to define the following overloaded `operator<<` function:

```
std::ostream &operator<<(std::ostream &out, std::string const &str)
{
    return out.write(str.data(), str.length());
}
```

Conversion operators are also used when objects of classes defining conversion operators are inserted into streams. Realize that the right hand sides of insertion operators are function parameters that are initialized by the operator's right hand side arguments. The rules are simple:

- If a class `X` defining a conversion operator also defines an insertion operator accepting an `X` object the insertion operator is used;
- Otherwise, if the type returned by the conversion operator is insertable then the conversion operator is used;
- Otherwise, a compilation error results. Note that this happens if the type returned by the conversion operator itself defines a conversion operator to a type that may be inserted into a stream.

In the following example an object of class `Insertable` is directly inserted; an object of the class `Convertor` uses the conversion operator; an object of the class `Error` cannot be inserted since it does not define an insertion operator and the type returned by its conversion operator cannot be inserted either (`Text` *does* define an `operator int() const`, but the fact that a `Text` itself cannot be inserted causes the error):

```
#include <iostream>
#include <string>
using namespace std;

struct Insertable
{
    operator int() const
    {
        cout << "op int()\n";
        return 0;
    }
};
ostream &operator<<(ostream &out, Insertable const &ins)
{
    return out << "insertion operator";
}
struct Convertor
{
    operator Insertable() const
    {
        return Insertable();
        }
    };
    struct Text
    {
        operator int() const
        {
            return 1;
        }
    };
    struct Error
    {
        operator Text() const
        {
            return Text{};
        }
    };

    int main()
    {
        Insertable insertable;
        cout << insertable << '\n';
        Convertor convertor;
        cout << convertor << '\n';
        Error error;
        cout << error << '\n';
    }
```

Some final remarks regarding conversion operators:

- A conversion operator should be a 'natural extension' of the facilities of the object. For example, the stream classes define `operator bool()`, allowing constructions like `if (cin)`.
- A conversion operator should return an *rvalue*. It should do so to enforce data-hiding and because it is the intended use of the conversion operator. Defining a conversion operator as an *lvalue* (e.g., defining an `operator int &()` conversion operator) opens up a back door, and the operator can only be used as *lvalue* when explicitly called (as in: `x.operator int&() = 5`). Don't use it.
- Conversion operators should be defined as `const` member functions as they don't modify their object's data members.
- Conversion operators returning composed objects should return const references to these objects whenever possible to avoid calling the composed object's copy constructor.

11.4 The keyword 'explicit'

Conversions are not only performed by conversion operators, but also by constructors accepting one argument (i.e., constructors having one or multiple parameters, specifying default argument values for all parameters or for all but the first parameter).

Assume a data base class `DataBase` is defined in which `Person` objects can be stored. It defines a `Person *d_data` pointer, and so it offers a copy constructor and an overloaded assignment operator.

In addition to the copy constructor `DataBase` offers a default constructor and several additional constructors:

- `DataBase(Person const &)`: the `DataBase` initially contains a single `Person` object;
- `DataBase(istream &in)`: the data about multiple persons are read from `in`.
- `DataBase(size_t count, istream &in = cin)`: the data of `count` persons are read from `in`, by default the standard input stream.

The above constructors all are perfectly reasonable. But they also allow the compiler to compile the following code without producing any warning at all:

```
    DataBase db;
    DataBase db2;
    Person person;

    db2 = db;           // 1
    db2 = person;       // 2
    db2 = 10;           // 3
    db2 = cin;          // 4
```

Statement 1 is perfectly reasonable: `db` is used to redefine `db2`. Statement 2 might be understandable since we designed `DataBase` to contain `Person` objects. Nevertheless, we might question the logic that's used here as a `Person` is not some kind of `DataBase`. The logic becomes even more opaque when looking at statements 3 and 4. Statement 3 in effect waits for the data of 10 persons to appear at the standard input stream. Nothing like that is suggested by `db2 = 10`.

Implicit promotions are used with statements 2 through 4. Since constructors accepting, respectively a `Person`, an `istream`, and a `size_t` and an `istream` have been defined for `DataBase` and since the assignment operator expects a `DataBase` right-hand side (rhs) argument the compiler first converts the rhs arguments to anonymous `DataBase` objects which are then assigned to `db2`.

It is good practice to prevent implicit promotions by using the `explicit` modifier when declaring a constructor. Constructors using the `explicit` modifier can only be used to construct objects explicitly. Statements 2-4 would not have compiled if the constructors expecting one argument would have been declared using `explicit`. E.g.,

```
    explicit DataBase(Person const &person);
    explicit DataBase(size_t count, std:istream &in);
```

Having declared all constructors accepting one argument as `explicit` the above assignments would have required the explicit specification of the appropriate constructors, thus clarifying the programmer's intent:

```
    DataBase db;
    DataBase db2;
    Person person;

    db2 = db;                   // 1
    db2 = DataBase{ person };   // 2
    db2 = DataBase{ 10 };       // 3
    db2 = DataBase{ cin };      // 4
```

As a rule of thumb prefix one argument constructors with the `explicit` keyword unless implicit promotions are perfectly natural (`string`'s `char const *` accepting constructor is a case in point).

11.4.1 Explicit conversion operators

In addition to explicit constructors, **C++** supports *explicit conversion operators*.

For example, a class might define `operator bool() const` returning `true` if an object of that class is in a usable state and `false` if not. Since the type `bool` is an arithmetic type this could result in unexpected or unintended behavior. Consider:

```
void process(bool value);

class StreamHandler
{
    public:
        operator bool() const;      // true: object is fit for use
        ...
};

int fun(StreamHandler &sh)
{
    int sx;

    if (sh)                         // intended use of operator bool()
        ... use sh as usual; also use `sx'

    process(sh);                    // typo: `sx' was intended
}
```

In this example `process` unintentionally receives the value returned by `operator bool` using the implicit conversion from `bool` to `int`.

When defining `explicit` conversion operators implicit conversions like the one shown in the example are prevented. Such conversion operators can only be used in situations where the converted type is explicitly required (as in the condition clauses of `if` or `while` statements), or is explicitly requested using a `static_cast`. To declare an explicit bool conversion operator in class `StreamHandler`'s interface replace the above declaration by:

```
        explicit operator bool() const;
```

Since the C++14 standard `istreams` define an `explicit operator bool() const`. As a consequence:

```
while (cin.get(ch)) // compiles OK
    ;

bool fun1()
{
    return cin;     // 'bool = istream' won't compile as
}                   // istream defines 'explicit operator bool'

bool fun1()
{
    return static_cast<bool>(cin); // compiles OK
}
```

11.5 Overloading increment and decrement operators

Overloading the increment operator (`operator++`) and decrement operator (`operator--`) introduces a small problem: there are two versions of each operator, as they may be used as *postfix operator* (e.g., `x++`) or as *prefix operator* (e.g., `++x`).

Used as *postfix* operator, the value's object is returned as an *rvalue*, temporary const object and the post-incremented variable itself disappears from view. Used as *prefix* operator, the variable is incremented, and its value is returned as *lvalue* and it may be altered again by modifying the prefix operator's return value. Whereas these characteristics are not *required* when the operator is overloaded, it is strongly advised to implement these characteristics in any overloaded increment or decrement operator.

Suppose we define a *wrapper class* around the `size_t` value type. Such a class could offer the following (partially shown) interface:

```
class Unsigned
{
    size_t d_value;

    public:
        Unsigned();
        explicit Unsigned(size_t init);

        Unsigned &operator++();
}
```

The class's last member declares the *prefix* overloaded increment operator. The returned *lvalue* is `Unsigned &`. The member is easily implemented:

```
Unsigned &Unsigned::operator++()
{
    ++d_value;
    return *this;
}
```

To define the *postfix* operator, an overloaded version of the operator is defined, expecting a (dummy) `int` argument. This might be considered a *kludge*, or an acceptable application of function overloading. Whatever your opinion in this matter, the following can be concluded:

- Overloaded increment and decrement operators *without parameters* are *prefix* operators, and should return *references* to the current object.
- Overloaded increment and decrement operators *having an int parameter* are *postfix* operators, and should return a value which is a copy of the object at the point where its postfix operator is used.

The postfix increment operator is declared as follows in the class `Unsigned`'s interface:

```
Unsigned operator++(int);
```

It may be implemented as follows:

```
Unsigned Unsigned::operator++(int)
```

```
    {
        Unsigned tmp{ *this };
        ++d_value;
        return tmp;
    }
```

Note that the operator's parameter is not used. It is only part of the implementation to *disambiguate* the prefix- and postfix operators in implementations and declarations.

In the above example the statement incrementing the current object offers the *nothrow* guarantee as it only involves an operation on a primitive type. If the initial copy construction throws then the original object is not modified, if the return statement throws the object has safely been modified. But incrementing an object could itself throw exceptions. How to implement the increment operators in that case? Once again, `swap` is our friend. Here are the pre- and postfix operators offering the strong guarantee when the member `increment` performing the increment operation may throw:

```
    Unsigned &Unsigned::operator++()
    {
        Unsigned tmp{ *this };
        tmp.increment();
        swap(tmp);
        return *this;
    }
    Unsigned Unsigned::operator++(int)
    {
        Unsigned tmp{ *this };
        tmp.increment();
        swap(tmp);
        return tmp;
    }
```

Both operators first create copies of the current objects. These copies are incremented and then swapped with the current objects. If `increment` throws the current objects remain unaltered; the swap operations ensure that the correct objects are returned (the incremented object for the prefix operator, the original object for the postfix operator) and that the current objects become the incremented objects.

When calling the increment or decrement operator using its full member function name then any `int` argument passed to the function results in calling the postfix operator. Omitting the argument results in calling the prefix operator. Example:

```
    Unsigned uns{ 13 };

    uns.operator++();     // prefix-incrementing uns
    uns.operator++(0);    // postfix-incrementing uns
```

Both the prefix and postfix increment and decrement operators are deprecated when applied to `bool` type of variables. In situations where a postfix increment operator could be useful the `std::exchange` (cf. section 19.1.11) should be used.

11.6 Overloading binary operators

In various classes overloading binary operators (like `operator+`) can be a very natural extension of the class's functionality. For example, the `std::string` class has various overloaded `operator+`

members.

Most binary operators come in two flavors: the plain binary operator (like the `+` operator) and the compound binary assignment operator (like `operator+=`). Whereas the plain binary operators return values, the compound binary assignment operators usually return references to the objects for which the operators were called. For example, with `std::string` objects the following code (annotations below the example) may be used:

```
std::string s1;
std::string s2;
std::string s3;

s1 = s2 += s3;                  // 1
(s2 += s3) + " postfix";        // 2
s1 = "prefix " + s3;            // 3
"prefix " + s3 + "postfix";     // 4
```

- at `// 1` the content of `s3` is added to `s2`. Next, `s2` is returned, and its new content is assigned to `s1`. Note that `+=` returns `s2`.
- at `// 2` the content of `s3` is also added to `s2`, but as `+=` returns `s2` itself, it's possible to add some more to `s2`
- at `// 3` the `+` operator returns a `std::string` containing the concatenation of the text `prefix` and the content of `s3`. This string returned by the `+` operator is thereupon assigned to `s1`.
- at `// 4` the `+` operator is applied twice. The effect is:
  1. The first `+` returns a `std::string` containing the concatenation of the text `prefix` and the content of `s3`.
  2. The second `+` operator takes this returned string as its left hand value, and returns a string containing the concatenated text of its left and right hand operands.
  3. The string returned by the second `+` operator represents the value of the expression.

Now consider the following code, in which a class `Binary` supports an overloaded `operator+`:

```
class Binary
{
    public:
        Binary();
        Binary(int value);
        Binary operator+(Binary const &rhs);
};

int main()
{
    Binary b1;
    Binary b2{ 5 };

    b1 = b2 + 3;            // 1
    b1 = 3 + b2;            // 2
}
```

Compilation of this little program fails for statement `// 2`, with the compiler reporting an error like:

```
error: no match for 'operator+' in '3 + b2'
```

Why is statement `// 1` compiled correctly whereas statement `// 2` won't compile?

In order to understand this remember *promotions*. As we have seen in section 11.4, constructors expecting single arguments may implicitly be activated when an argument of an appropriate type is provided. We've already encountered this with `std::string` objects, where NTBSs may be used to initialize `std::string` objects.

Analogously, in statement `// 1`, `operator+` is called, using `b2` as its left-hand side operand. This operator expects another `Binary` object as its right-hand side operand. However, an `int` is provided. But as a constructor `Binary(int)` exists, the `int` value can be promoted to a `Binary` object. Next, this `Binary` object is passed as argument to the `operator+` member.

Unfortunately, in statement `// 2` promotions are not available: here the `+` operator is applied to an `int`-type lvalue. An `int` is a primitive type and primitive types have no knowledge of 'constructors', 'member functions' or 'promotions'.

How, then, are promotions of left-hand operands implemented in statements like `"prefix " + s3`? Since promotions can be applied to function arguments, we must make sure that both operands of binary operators are arguments. This implies that plain binary operators supporting promotions for either their left-hand side operand or right-hand side operand should be declared as *free operators*, also called *free functions*.

Functions like the plain binary operators conceptually belong to the class for which they implement these operators. Consequently they should be declared in the class's header file. We cover their implementations shortly, but here is our first revision of the declaration of the class `Binary`, declaring an overloaded `+` operator as a free function:

```
class Binary
{
    public:
        Binary();
        Binary(int value);
};

Binary operator+(Binary const &lhs, Binary const &rhs);
```

After defining binary operators as free functions, several promotions are available:

- If the left-hand operand is of the intended class type, the right hand argument is promoted whenever possible;
- If the right-hand operand is of the intended class type, the left hand argument is promoted whenever possible;
- No promotions occur when neither operand is of the intended class type;
- An ambiguity occurs when promotions to different classes are possible for the two operands. For example:

  ```
  class A;

  class B
  {
      public:
          B(A const &a);
  };
  ```

```
class A
{
    public:
        A();
        A(B const &b);
};

A operator+(A const &a, B const &b);
B operator+(B const &b, A const &a);

int main()
{
    A a;

    a + a;
};
```

> Here, both overloaded + operators are possible candidates when compiling the statement `a + a`. The ambiguity must be solved by explicitly promoting one of the arguments, e.g., `a + B{a}`, which enables the compiler to resolve the ambiguity to the first overloaded + operator.

The next step consists of implementing the required overloaded binary compound assignment operators, having the form `@=`, where `@` represents a binary operator. As these operators *always* have left-hand side operands which are object of their own classes, they are implemented as genuine member functions. Compound assignment operators usually return references to the objects for which the binary compound assignment operators were requested, as these objects might be modified in the same statement. E.g., `(s2 += s3) + " postfix"`.

Here is our second revision of the class `Binary`, showing the declaration of the plain binary operator as well as the corresponding compound assignment operator:

```
class Binary
{
    public:
        Binary();
        Binary(int value);

        Binary &operator+=(Binary const &rhs);
};

Binary operator+(Binary const &lhs, Binary const &rhs);
```

How should the compound addition assignment operator be implemented? When implementing compound binary assignment operators the strong guarantee should always be kept in mind: if the operation might throw use a temporary object and swap. Here is our implementation of the compound assignment operator:

```
Binary &Binary::operator+=(Binary const &rhs)
{
    Binary tmp{ *this };
    tmp.add(rhs);           // this might throw
    swap(tmp);
    return *this;
}
```

It's easy to implement the free binary operator: the `lhs` argument is copied into a `Binary tmp` to which the `rhs` operand is added. Then `tmp` is returned, using copy elision. The class `Binary` declares the free binary operator as a friend (cf. chapter 15), so it can call `Binary's add` member:

```
class Binary
{
    friend Binary operator+(Binary const &lhs, Binary const &rhs);

    public:
        Binary();
        Binary(int value);

        Binary &operator+=(Binary const &other);

    private:
        void add(Binary const &other);
};
```

The binary operator's implementation becomes:

```
Binary operator+(Binary const &lhs, Binary const &rhs)
{
    Binary tmp{ lhs };
    tmp.add(rhs);
    return tmp;
}
```

If the class `Binary` is move-aware then it's attractive to add move-aware binary operators. In this case we also need operators whose left-hand side operands are rvalue references. When a class is move aware various interesting implementations are suddenly possible, which we encounter below, and in the next (sub)section. First have a look at the signature of such a binary operator (which should also be declared as a friend in the class interface):

```
Binary operator+(Binary &&lhs, Binary const &rhs);
```

Since the lhs operand is an rvalue reference, we can modify it *ad lib*. Binary operators are commonly designed as factory functions, returning objects created by those operators. However, the (modified) object referred to by `lhs` should itself *not* be returned. As stated in the C++ standard,

> A temporary object bound to a reference parameter in a function call persists until the completion of the full-expression containing the call.

and furthermore:

> The lifetime of a temporary bound to the returned value in a function return statement is not extended; the temporary is destroyed at the end of the full-expression in the return statement.

In other words, a temporary object cannot itself be returned as the function's return value: a `Binary &&` return type should therefore not be used. Therefore functions implementing binary operators are factory functions (note, however, that the returned object may be constructed using the class's move constructor whenever a temporary object has to be returned).

Alternatively, the binary operator can first create an object by move constructing it from the operator's lhs operand, performing the binary operation on that object and the operator's rhs operand, and then return the modified object (allowing the compiler to apply copy elision). It's a matter of taste which one is preferred.

Here are the two implementations. Because of copy elision the explicitly defined `ret` object is created in the location of the return value. Both implementations, although they appear to be different, show identical run-time behavior:

```
            // first implementation: modify lhs
Binary operator+(Binary &&lhs, Binary const &rhs)
{
    lhs.add(rhs);
    return std::move(lhs);
}
            // second implementation: move construct ret from lhs
Binary operator+(Binary &&lhs, Binary const &rhs)
{
    Binary ret{ std::move(lhs) };
    ret.add(rhs);
    return ret;
}
```

Now, when executing expressions like (all `Binary` objects) `b1 + b2 + b3` the following functions are called:

```
copy operator+          = b1 + b2
Copy constructor        = tmp(b1)
    adding              = tmp.add(b2)
copy elision            : tmp is returned from b1 + b2

move operator+          = tmp + b3
adding                  = tmp.add(b3)
Move construction       = tmp2(move(tmp)) is returned
```

But we're not there yet: in the next section we encounter possibilities for several more interesting implementations, in the context of compound assignment operators.

11.6.1 Member function reference bindings (& and &&)

We've seen that binary operators (like `operator+`) can be implemented very efficiently, but require at least move constructors.

An expression like

```
Binary{} + varB + varC + varD
```

therefore returns a move constructed object representing `Binary{} + varB`, then another move constructed object receiving the first return value and `varC`, and finally yet another move constructed object receiving the second returned object and `varD` as its arguments.

Now consider the situation where we have a function defining a `Binary &&` parameter, and a second `Binary const &` parameter. Inside that function these values need to be added, and their sum is then passed as argument to two other functions. We *could* do this:

```
void fun1(Binary &&lhs, Binary const &rhs)
{
    lhs += rhs;
    fun2(lhs);
    fun3(lhs);
}
```

But realize that when using `operator+=` we first construct a copy of the current object, so a temporary object is available to perform the addition on, and then swap the temporary object with the current object to commit the results. But wait! Our lhs operand already *is* a temporary object. So why create another?

In this example another temporary object is indeed not required: `lhs` remains in existence until `fun1` ends. But different from the binary operators the binary compound assignment operators don't have explicitly defined left-hand side operands. But we still can inform the compiler that a particular *member* (so, not merely compound assignment operators) should only be used when the objects calling those members is an anonymous temporary object, or a non-anonymous (modifiable or non-modifiable) object. For this we use *reference bindings* a.k.a. *reference qualifiers*.

Reference bindings consist of a reference token (`&`), optionally preceded by `const`, or an rvalue reference token (`&&`). Such reference qualifiers are immediately affixed to the function's head (this applies to the declaration and the implementation alike). Functions provided with rvalue reference bindings are selected by the compiler when used by anonymous temporary objects, whereas functions provided with lvalue reference bindings are selected by the compiler when used by other types of objects.

Reference qualifiers allow us to fine-tune our implementations of compund assignment operators like `operator+=`. If we know that the object calling the compound assignment operator is itself a temporary, then there's no need for a separate temporary object. The operator may directly perform its operation and could then return itself as an rvalue reference. Here is the implementation of `operator+=` tailored to being used by temporary objects:

```
Binary &&Binary::operator+=(Binary const &rhs) &&
{
    add(rhs);                    // directly add rhs to *this,
    return std::move(*this);     // return the temporary object itself
}
```

This implementation is about as fast as it gets. But be careful: in the previous section we learned that a temporary is destroyed at the end of the full expression of a return stattement. In this case, however, the temporary already exists, and so (also see the previous section) it should persist until the expression containing the (`operator+=`) function call is completed. As a consequence,

```
cout << (Binary{} += existingBinary) << '\n';
```

is OK, but

```
Binary &&rref = (Binary{} += existingBinary);
cout << rref << '\n';
```

is not, since `rref` becomes a dangling reference immediately after its initialization.

A full-proof alternative implementation of the rvalue-reference bound `operator+=` returns a move-constructed copy:

```
Binary Binary::operator+=(Binary const &rhs) &&
{
    add(rhs);                       // directly add rhs to *this,
    return std::move(*this);        // return a move constructed copy
}
```

The price to pay for this full-proof implementation is an extra move construction. Now, using the previous example (using `rref`), `operator+=` returns a copy of the `Binary{}` temporary, which is still a temporary object which can safely be referred to by `rref`.

Which implementation to use may be a matter of choice: if users of `Binary` know what they're doing then the former implementation can be used, since these users will never use the above `rref` initialization. If you're not so sure about your users, use the latter implementation: formally your users will do something they shouldn't do, but there's no penalty for that.

For the compound assignment operator called by an lvalue reference (i.e., a named object) we use the implementation for `operator+=` from the previous section (note the reference qualifier):

```
Binary &Binary::operator+=(Binary const &other) &
{
    Binary tmp(*this);
    tmp.add(other);      // this might throw
    swap(tmp);
    return *this;
}
```

With this implementation adding `Binary` objects to each other (e.g., `b1 += b2 += b3`) boils down to

```
operator+=    (&)       = b2 += b3
Copy constructor        = tmp(b2)
    adding              = tmp.add(b3)
    swap                = b2 <-> tmp
return                  = b2

operator+=    (&)       = b1 += b2
Copy constructor        = tmp(b1)
    adding              = tmp.add(b2)
    swap                = b1 <-> tmp
return                  = b1
```

When the leftmost object is a temporary then a copy construction and swap call are replaced by the construction of an anonymous object. E.g., with `Binary{} += b2 += b3` we observe:

```
operator+=    (&)       = b2 += b3
Copy constructor        = tmp(b2)
    adding              = tmp.add(b3)
    swap                = b2 <-> tmp

Anonymous object        = Binary{}

operator+=    (&&)      = Binary{} += b2
    adding              = add(b2)

return                  = move(Binary{})
```

For `Binary &Binary::operator+=(Binary const &other) &` an alternative implementation exists, merely using a single return statement, but in fact requiring two extra function calls. It's a matter of taste whether you prefer writing less code or executing fewer function calls:

```
Binary &Binary::operator+=(Binary const &other) &
{
    return *this = Binary{ *this } += rhs;
}
```

Notice that the implementations of `operator+` and `operator+=` are independent of the actual definition of the class `Binary`. Adding standard binary operators to a class (i.e., operators operating on arguments of their own class types) can therefore easily be realized.

11.6.2 The three-way comparison operator '<=>'

The `C++20` standard added the *three-way comparison* operator <=>, also known as the *spaceship operator*, to the language.

This operator is closely related to comparison classes, covered in section 18.7. At this point we focus on using the `std::strong_ordering` class: the examples of the spaceship operator presented in this section all return `strong_ordering` objects. These objects are

- `strong_ordering::equal` if both operands are equal;
- `strong_ordering::less` if the left-hand side operand is smaller than the right-hand side operand;
- `strong_ordering::greater` if the left-hand side operand is greater than the right-hand side operand.

Standard operand conversions are handled by the compiler. Note that

- if one of the operands is of type `bool`, then the other operand must also be of type `bool`;
- narrowing conversions, except from integral types to floating point types, are not allowed;
- when the operands are of identical enumeration types their values are converted to the underlying numeric integral type, which values are then compared.

Other standard conversions, like lvalue transformations and qualification conversions (cf. section 21.4), are automatically performed.

Now about the spaceship operator itself. Why would you want it? Of course, if it's defined then you can use it. As it's available for integral numeric types the following correctly compiles:

```
auto isp =    3 <=> 4;
```

whereafter `isp's` value can be compared to available outcome-values:

```
cout << ( isp == strong_ordering::less ? "less\n" : "not less\n" );
```

But that by itself doesn't make the spaceship operator all too interesting. What *does* make it interesting is that, in combination with `operator==`, it handles *all* comparison operators. So after providing a class with `operator==` and `operator<=>` its objects can be compared for equality, inequality, and they can be ordered by `<, <=, >,` and `>=`. As an example consider books. To book owners the titles and author names are the books' important characterstics. To sort them on book shelfs we must use `operator<`, to find a particular book we use `operator==`, to determine whether two books are different we use `operator!=` and if you want to order them in an country where Arabic is the main language you might want to sort them using `operator>` considering that the prevalent reading order in those countries is from right to left. Ignoring constructors, destructors and other members, then this is the interface of our class `Book` (note the inclusion of the `<compare>` header file, containing the declarations of the comparison classes):

```
#include <string>
#include <compare>

class Book
{
    friend bool operator==(Book const &lhs, Book const &rhs);
    friend std::strong_ordering operator<=>(Book const &lhs,
                                            Book const &rhs);
    std::string d_author;
    std::string d_title;

    // ...
};
```

Both friend-functions are easy to implement:

```
bool operator==(Book const &lhs, Book const &rhs)
{
    return lhs.d_author == rhs.d_author and lhs.d_title == rhs.d_title;
}

strong_ordering operator<=>(Book const &lhs, Book const &rhs)
{
    return lhs.d_author < rhs.d_author  ? strong_ordering::less     :
           lhs.d_author > rhs.d_author  ? strong_ordering::greater  :
           lhs.d_title  < rhs.d_title   ? strong_ordering::less     :
           lhs.d_title  > rhs.d_title   ? strong_ordering::greater  :
                                          strong_ordering::equal;
}
```

And that's it! Now all comparison operators (and of course the spaceship operator itself) are available. The following now compiles flawlessly:

```
void books(Book const &b1, Book const &b2)
{
    cout << (b1 == b2) << (b1 != b2) << (b1 <  b2) <<
            (b1 <= b2) << (b1 >  b2) << (b1 >= b2) << '\n';
}
```

calling `books` for two identical books inserts 100101 into `cout`.

The spaceship operator is available for integral numeric types and may have been defined for class types. E.g., it is defined for `std::string`. It is not automatically available for floating point types.

11.7 Overloading ‘operator new(size_t)’

When `operator new` is overloaded, it must define a `void *` return type, and its first parameter must be of type `size_t`. The default `operator new` defines only one parameter, but overloaded versions may define multiple parameters. The first one is not explicitly specified but is deduced from the size of objects of the class for which `operator new` is overloaded. In this section overloading `operator new` is discussed. Overloading `new[]` is discussed in section 11.9.

It is possible to define multiple versions of the `operator new`, as long as each version defines its own unique set of arguments. When overloaded `operator new` members must dynamically allocate memory they can do so using the global `operator new`, applying the scope resolution operator `::`. In the next example the overloaded `operator new` of the class `String` initializes the substrate of dynamically allocated `String` objects to 0-bytes:

```
#include <cstring>
#include <iosfwd>

class String
{
    std::string *d_data;

    public:
        void *operator new(size_t size)
        {
            return memset(::operator new(size), 0, size);
        }
        bool empty() const
        {
            return d_data == 0;
        }
};
```

The above `operator new` is used in the following program, illustrating that even though `String`’s default constructor does nothing the object’s data member `d_data` is initialized to zero:

```
#include "string.h"
#include <iostream>
using namespace std;

int main()
{
    String *sp = new String;

    cout << boolalpha << sp->empty() << '\n';    // shows: true
}
```

At `new String` the following took place:

- First, `String::operator new` was called, allocating and initializing a block of memory, the size of a `String` object.
- Next, a pointer to this block of memory was passed to the (default) `String` constructor. Since no constructor was defined, the constructor itself didn’t do anything at all.

As `String::operator new` initialized the allocated memory to zero bytes the allocated `String` object's `d_data` member had already been initialized to a 0-pointer by the time it started to exist.

All member functions (including constructors and destructors) we've encountered so far define a (hidden) pointer to the object on which they should operate. This hidden pointer becomes the function's `this` pointer.

In the next example of *pseudo* **C++** *code*, the pointer is explicitly shown to illustrate what's happening when `operator new` is used. In the first part a `String` object `str` is directly defined, in the second part of the example the (overloaded) `operator new` is used:

```
String::String(String *const this);     // real prototype of the default
                                        // constructor

String *sp = new String;                // This statement is implemented
                                        // as follows:

String *sp = static_cast<String *>(              // allocation
                    String::operator new(sizeof(String))
             );
String::String{ sp };                            // initialization
```

In the above fragment the member functions were treated as *object-less* member functions of the class `String`. Such members are called *static member functions* (cf. chapter 8). Actually, `operator new` *is* such a static member function. Since it has no `this` pointer it cannot reach data members of the object for which it is expected to make memory available. It can only allocate and initialize the allocated memory, but cannot reach the object's data members by name as there is as yet no data object layout defined.

Following the allocation, the memory is passed (as the `this` pointer) to the constructor for further processing.

`Operator new` can have multiple parameters. The first parameter is initialized as an implicit argument and is always a `size_t` parameter. Additional overloaded operators may define additional parameters. An interesting additional `operator new` is the *placement new* operator. With the placement new operator a block of memory has already been set aside and one of the class's constructors is used to initialize that memory. Overloading placement new requires an `operator new` having two parameters: `size_t` and `char *`, pointing to the memory that was already available. The `size_t` parameter is implicitly initialized, but the remaining parameters must explicitly be initialized using arguments to `operator new`. Hence we reach the familiar syntactical form of the placement new operator in use:

```
char buffer[sizeof(String)];         // predefined memory
String *sp = new(buffer) String;     // placement new call
```

The declaration of the placement new operator in our class `String` looks like this:

```
void *operator new(size_t size, char *memory);
```

It could be implemented like this (also initializing the `String`'s memory to 0-bytes):

```
void *String::operator new(size_t size, char *memory)
{
    return memset(memory, 0, size);
}
```

Any other overloaded version of `operator new` could also be defined. Here is an example showing the use and definition of an overloaded `operator new` storing the object’s address immediately in an existing array of pointers to `String` objects (assuming the array is large enough):

```
    // use:
String *next(String **pointers, size_t *idx)
{
    return new(pointers, (*idx)++) String;
}

    // implementation:
void *String::operator new(size_t size, String **pointers, size_t idx)
{
    return pointers[idx] = ::operator new(size);
}
```

11.8 Overloading ‘operator delete(void ∗)’

The `delete` operator may also be overloaded. In fact it’s good practice to overload `operator delete` whenever `operator new` is also overloaded.

`Operator delete` must define a `void *` parameter. A second overloaded version defining a second parameter of type `size_t` is related to overloading `operator new[]` and is discussed in section 11.9.

Overloaded `operator delete` members return `void`.

The ‘home-made’ `operator delete` is called when deleting a dynamically allocated object after executing the destructor of the associated class. So, the statement

```
delete ptr;
```

with `ptr` being a pointer to an object of the class `String` for which the operator `delete` was overloaded, is a shorthand for the following statements:

```
ptr->~String(); // call the class's destructor

                // and do things with the memory pointed to by ptr
String::operator delete(ptr);
```

The overloaded `operator delete` may do whatever it wants to do with the memory pointed to by `ptr`. It could, e.g., simply delete it. If that would be the preferred thing to do, then the default `delete` operator can be called using the `::` scope resolution operator. For example:

```
void String::operator delete(void *ptr)
{
    // any operation considered necessary, then, maybe:
    ::delete ptr;
}
```

To declare the above overloaded `operator delete` simply add the following line to the class’s interface:

```
void operator delete(void *ptr);
```

Like `operator new` `operator delete` is a static member function (see also chapter 8).

11.9 Operators 'new[]' and 'delete[]'

In sections 9.1.1, 9.1.2 and 9.2.1 `operator new[]` and `operator delete[]` were introduced. Like `operator new` and `operator delete` the operators `new[]` and `delete[]` may be overloaded.

As it is possible to overload `new[]` and `delete[]` as well as `operator new` and `operator delete`, one should be careful in selecting the appropriate set of operators. The following rule of thumb should always be applied:

> If `new` is used to allocate memory, `delete` should be used to deallocate memory. If `new[]` is used to allocate memory, `delete[]` should be used to deallocate memory.

By default these operators act as follows:

- `operator new` is used to allocate a single object or primitive value. With an object, the object's constructor is called.
- `operator delete` is used to return the memory allocated by `operator new`. Again, with class-type objects, the class's destructor is called.
- `operator new[]` is used to allocate a series of primitive values or objects. If a series of objects is allocated, the class's default constructor is called to initialize each object individually.
- `operator delete[]` is used to delete the memory previously allocated by `new[]`. *If* objects were previously allocated, then the destructor is called for each individual object. Be careful, though, when pointers to objects were allocated. If *pointers to objects* were allocated the destructors of the objects to which the allocated pointers point won't automatically be called. A pointer is a primitive type and so no further action is taken when it is returned to the common pool.

11.9.1 Overloading 'new[]'

To overload `operator new[]` in a class (e.g., in the class `String`) add the following line to the class's interface:

```
void *operator new[](size_t size);
```

The member's `size` parameter is implicitly provided and is initialized by **C++**'s run-time system to the amount of memory that must be allocated. Like the simple one-object `operator new` it should return a `void *`. The number of objects that must be initialized can easily be computed from `size / sizeof(String)` (and of course replacing `String` by the appropriate class name when overloading `operator new[]` for another class). The overloaded `new[]` member may allocate raw memory using e.g., the default `operator new[]` or the default `operator new`:

```
void *operator new[](size_t size)
{
    return ::operator new[](size);
    // alternatively:
    // return ::operator new(size);
}
```

Before returning the allocated memory the overloaded `operator new[]` has a chance to do something special. It could, e.g., initialize the memory to zero-bytes.

Once the overloaded `operator new[]` has been defined, it is automatically used in statements like:

```
String *op = new String[12];
```

Like `operator new` additional overloads of `operator new[]` may be defined. One opportunity for an `operator new[]` overload is overloading *placement new* specifically for arrays of objects. This operator is available by default but becomes unavailable once at least one overloaded `operator new[]` is defined. Implementing placement `new` is not difficult. Here is an example, initializing the available memory to 0-bytes before returning:

```
void *String::operator new[](size_t size, char *memory)
{
    return memset(memory, 0, size);
}
```

To use this overloaded operator, the second parameter must again be provided, as in:

```
char buffer[12 * sizeof(String)];
String *sp = new(buffer) String[12];
```

11.9.2 Overloading 'delete[]'

To overload `operator delete[]` in a class `String` add the following line to the class's interface:

```
void operator delete[](void *memory);
```

Its parameter is initialized to the address of a block of memory previously allocated by `String::new[]`.

There are some subtleties to be aware of when implementing `operator delete[]`. Although the addresses returned by `new` and `new[]` point to the allocated object(s), there is an additional `size_t` value available immediately before the address returned by `new` and `new[]`. This `size_t` value is part of the allocated block and contains the actual size of the block. This of course does not hold true for the placement `new` operator.

When a class defines a destructor the `size_t` value preceding the address returned by `new[]` does not contain the size of the allocated block, but the *number* of objects specified when calling `new[]`. Normally that is of no interest, but when overloading `operator delete[]` it might become a useful piece of information. In those cases `operator delete[]` does *not* receive the address returned by `new[]` but rather the address of the initial `size_t` value. Whether this is at all useful is not clear. By the time `delete[]`'s code is executed all objects have already been destroyed, so `operator delete[]` is only to determine how many objects were destroyed but the objects themselves cannot be used anymore.

Here is an example showing this behavior of `operator delete[]` for a minimal `Demo` class:

```
struct Demo
{
    size_t idx;
    Demo()
```

```
        {
            cout << "default cons\n";
        }
        ~Demo()
        {
            cout << "destructor\n";
        }
        void *operator new[](size_t size)
        {
            return ::operator new(size);
        }
        void operator delete[](void *vp)
        {
            cout << "delete[] for: " << vp << '\n';
            ::operator delete[](vp);
        }
};

int main()
{
    Demo *xp;
    cout << ((int *)(xp = new Demo[3]))[-1] << '\n';
    cout << xp << '\n';
    cout << "==================\n";
    delete[] xp;
}
// This program displays (your 0x?????? addresses might differ, but
// the difference between the two should be sizeof(size_t)):
//  default cons
//  default cons
//  default cons
//  3
//  0x8bdd00c
//  ==================
//  destructor
//  destructor
//  destructor
//  delete[] for: 0x8bdd008
```

Having overloaded `operator delete[]` for a class `String`, it will be used automatically in statements like:

```
    delete[] new String[5];
```

Operator `delete[]` may also be overloaded using an additional `size_t` parameter:

```
void operator delete[](void *p, size_t size);
```

Here `size` is automatically initialized to the size (in bytes) of the block of memory to which `void *p` points. If this form is defined, then `void operator[](void *)` should *not* be defined, to avoid ambiguities. An example of this latter form of `operator delete[]` is:

```
void String::operator delete[](void *p, size_t size)
{
        cout << "deleting " << size << " bytes\n";
        ::operator delete[](ptr);
    }
```

Additional overloads of `operator delete[]` may be defined, but to use them they must explicitly be called as static member functions (cf. chapter 8). Example:

```
        // declaration:
    void String::operator delete[](void *p, ostream &out);
        // usage:
    String *xp = new String[3];
    String::operator delete[](xp, cout);
```

11.9.3 The ‘operator delete(void *, size_t)’ family

As we’ve seen classes may overload their `operator delete` and `operator delete[]` members.

Since the C++14 standard the global `void operator delete(void *, size_t size)` and `void operator delete[](void *, size_t size)` functions can also be overloaded.

When a global sized deallocation function is defined, it is automatically used instead of the default, non-sized deallocation function. The performance of programs may improve if a sized deallocation function is available (cf. `http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2013/n3663.html`).

11.9.4 ‘new[]’, ‘delete[]’ and exceptions

When an exception is thrown while executing a `new[]` expression, what will happen? In this section we’ll show that `new[]` is exception safe even when only some of the objects were properly constructed.

To begin, `new[]` might throw while trying to allocate the required memory. In this case a `bad_alloc` is thrown and we don’t leak as nothing was allocated.

Having allocated the required memory the class’s default constructor is going to be used for each of the objects in turn. At some point a constructor might throw. What happens next is defined by the **C++** standard: the destructors of the already constructed objects are called and the memory allocated for the objects themselves is returned to the common pool. Assuming that the failing constructor offers the basic guarantee `new[]` is therefore exception safe even if a constructor may throw.

The following example illustrates this behavior. A request to allocate and initialize five objects is made, but after constructing two objects construction fails by throwing an exception. The output shows that the destructors of properly constructed objects are called and that the allocated *substrate memory* is properly returned:

```
    #include <iostream>
    using namespace std;

    static size_t count = 0;

    class X
    {
        int x;

        public:
            X()
            {
                if (count == 2)
                    throw 1;
                cout << "Object " << ++count << '\n';
            }
            ~X()
            {
                cout << "Destroyed " << this << "\n";
            }
            void *operator new[](size_t size)
            {
                cout << "Allocating objects: " << size << " bytes\n";
                return ::operator new(size);
            }
            void operator delete[](void *mem)
            {
                cout << "Deleting memory at " << mem << ", containing: " <<
                    *static_cast<int *>(mem) << "\n";
                ::operator delete(mem);
            }
    };

    int main()
    try
    {
        X *xp = new X[5];
        cout << "Memory at " << xp << '\n';
        delete[] xp;
    }
    catch (...)
    {
        cout << "Caught exception.\n";
    }
    // Output from this program (your 0x??? addresses might differ)
    //  Allocating objects: 24 bytes
    //  Object 1
    //  Object 2
    //  Destroyed 0x8428010
    //  Destroyed 0x842800c
    //  Deleting memory at 0x8428008, containing: 5
    //  Caught exception.
```

11.10 Function Objects

Function Objects are created by overloading the *function call operator* `operator()`. By defining the function call operator an object masquerades as a function, hence the term *function objects*. Function objects are also known as *functors*.

Function objects are important when using *generic algorithms*. The use of function objects is preferred over alternatives like pointers to functions. The fact that they are important in the context of generic algorithms leaves us with a didactic dilemma. At this point in the **C++** Annotations it would have been nice if generic algorithms would already have been covered, but for the discussion of the generic algorithms knowledge of function objects is required. This bootstrapping problem is solved in a well known way: by ignoring the dependency for the time being, for now concentrating on the function object concept.

Function objects are objects for which `operator()` has been defined. Function objects are not just used in combination with generic algorithms, but also as a (preferred) alternative to pointers to functions.

Function objects are frequently used to implement *predicate* functions. Predicate functions return boolean values. Predicate functions and predicate function objects are commonly referred to as 'predicates'. Predicates are frequently used by generic algorithms such as the count_if generic algorithm, covered in chapter 19, returning the number of times its function object has returned `true`. In the *standard template library* two kinds of predicates are used: *unary predicates* receive one argument, *binary predicates* receive two arguments.

Assume we have a class `Person` and an array of `Person` objects. Further assume that the array is not sorted. A well known procedure for finding a particular `Person` object in the array is to use the function `lsearch`, which performs a *linear search* in an array. Example:

```
Person &target = targetPerson();    // determine the person to find
Person *pArray;
size_t n = fillPerson(&pArray);

cout << "The target person is";

if (!lsearch(&target, pArray, &n, sizeof(Person), compareFunction))
    cout << " not";
cout << "found\n";
```

The function `targetPerson` determines the person we're looking for, and `fillPerson` is called to fill the array. Then `lsearch` is used to locate the target person.

The comparison function must be available, as its address is one of the arguments of `lsearch`. It must be a real function having an address. If it is defined inline then the compiler has no choice but to ignore that request as inline functions don't have addresses. `CompareFunction` could be implemented like this:

```
int compareFunction(void const *p1, void const *p2)
{
    return *static_cast<Person const *>(p1)      // lsearch wants 0
            !=                                   // for equal objects
            *static_cast<Person const *>(p2);
}
```

This, of course, assumes that the `operator!=` has been overloaded in the class `Person`. But overloading `operator!=` is no big deal, so let's assume that that operator is actually available.

On average `n / 2` times *at least* the following actions take place:

1. The two arguments of the compare function are pushed on the stack;
2. The value of the final parameter of `lsearch` is determined, producing `compareFunction`'s address;
3. The compare function is called;

4. Then, inside the compare function the address of the right-hand argument of the `Person::operator!=` argument is pushed on the stack;
5. `Person::operator!=` is evaluated;
6. The argument of the `Person::operator!=` function is popped off the stack;
7. The two arguments of the compare function are popped off the stack.

Using function objects results in a different picture. Assume we have constructed a function `PersonSearch`, having the following prototype (this, however, is not the preferred approach. Normally a generic algorithm is preferred over a home-made function. But for now we focus on `PersonSearch` to illustrate the use and implementation of a function object):

```
Person const *PersonSearch(Person *base, size_t nmemb,
                           Person const &target);
```

This function can be used as follows:

```
Person &target = targetPerson();
Person *pArray;
size_t n = fillPerson(&pArray);

cout << "The target person is";

if (!PersonSearch(pArray, n, target))
    cout << " not";

cout << "found\n";
```

So far, not much has been changed. We've replaced the call to `lsearch` with a call to another function: `PersonSearch`. Now look at `PersonSearch` itself:

```
Person const *PersonSearch(Person *base, size_t nmemb,
                            Person const &target)
{
    for (int idx = 0; idx < nmemb; ++idx)
        if (target(base[idx]))
            return base + idx;
    return 0;
}
```

`PersonSearch` implements a plain linear search. However, in the for-loop we see `target(base[idx])`. Here `target` is used as a *function object*. Its implementation is simple:

```
bool Person::operator()(Person const &other) const
{
    return *this == other;
}
```

Note the somewhat peculiar syntax: `operator()`. The first set of parentheses define the operator that is overloaded: the function call operator. The second set of parentheses define the parameters that are required for this overloaded operator. In the class header file this overloaded operator is declared as:

```
bool operator()(Person const &other) const;
```

Clearly `Person::operator()` is a simple function. It contains but one statement, and we could consider defining it inline. Assuming we do, then this is what happens when `operator()` is called:

1. The address of the right-hand argument of the `Person::operator==` argument is pushed on the stack;
2. The `operator==` function is evaluated (which probably also is a *semantic* improvement over calling `operator!=` when looking for an object *equal to* a specified target object);
3. The argument of `Person::operator==` argument is popped off the stack.

Due to the fact that `operator()` is an inline function, it is not actually called. Instead `operator==` is called immediately. Moreover, the required stack operations are fairly modest.

Function objects may truly be defined inline. Functions that are called indirectly (i.e., using pointers to functions) can never be defined inline as their addresses must be known. Therefore, even if the function object needs to do very little work it is defined as an ordinary function if it is going to be called through pointers. The overhead of performing the indirect call may annihilate the advantage of the flexibility of calling functions indirectly. In these cases using inline function objects can result in an increase of a program's efficiency.

An added benefit of function objects is that they may access the private data of their objects. In a search algorithm where a compare function is used (as with `lsearch`) the target and array elements are passed to the compare function using pointers, involving extra stack handling. Using function objects, the target person doesn't vary within a single search task. Therefore, the target person could be passed to the function object's class constructor. This is in fact what happens in the expression `target(base[idx])` receiving as its only argument the subsequent elements of the array to search.

11.10.1 Constructing manipulators

In chapter 6 we saw constructions like `cout << hex << 13 <<` to display the value 13 in hexadecimal format. One may wonder by what magic the `hex` manipulator accomplishes this. In this section the construction of manipulators like `hex` is covered.

Actually the construction of a manipulator is rather simple. To start, a definition of the manipulator is needed. Let's assume we want to create a manipulator `w10` which sets the field width of the next field to be written by the `ostream` object to 10. This manipulator is constructed as a function. The `w10` function needs to know about the `ostream` object in which the width must be set. By providing the function with an `ostream &` parameter, it obtains this knowledge. Now that the function knows about the `ostream` object we're referring to, it can set the width in that object.

Next, it must be possible to use the manipulator in an insertion sequence. This implies that the return value of the manipulator must be a reference to an `ostream` object also.

From the above considerations we're now able to construct our `w10` function:

```
#include <ostream>
#include <iomanip>

std::ostream &w10(std::ostream &str)
{
    return str << std::setw(10);
}
```

The `w10` function can of course be used in a 'stand alone' mode, but it can also be used as a manipulator. E.g.,

```
    #include <iostream>
    #include <iomanip>

    using namespace std;

    extern ostream &w10(ostream &str);

    int main()
    {
        w10(cout) << 3 << " ships sailed to America\n";
        cout << "And " << w10 << 3 << " more ships sailed too.\n";
    }
```

The `w10` function can be used as a manipulator because the `class ostream` has an overloaded `operator<<` accepting a pointer to a function expecting an `ostream &` and returning an `ostream &`. Its definition is:

```
ostream& operator<<(ostream &(*func)(ostream &str))
{
    return (*func)(*this);
}
```

In addition to the above overloaded `operator<<` another one is defined

```
ios_base &operator<<(ios_base &(*func)(ios_base &base))
{
    (*func)(*this);
    return *this;
}
```

This latter function is used when inserting, e.g., `hex` or `internal`.

The above procedure does not work for manipulators requiring arguments. It is of course possible to overload `operator<<` to accept an `ostream` reference and the address of a function expecting an `ostream &` and, e.g., an `int`, but while the address of such a function may be specified with the <<-operator, the arguments itself cannot be specified. So, one wonders how the following construction has been implemented:

```
cout << setprecision(3)
```

In this case the manipulator is defined as a macro. Macro's, however, are the realm of the preprocessor, and may easily suffer from unwelcome side-effects. In **C++** programs they should be avoided whenever possible. The following section introduces a way to implement manipulators requiring arguments without resorting to macros, but using anonymous objects.

11.10.1.1 Manipulators requiring arguments

Manipulators taking arguments are implemented as macros: they are handled by the preprocessor, and are not available beyond the preprocessing stage.

Manipulators, maybe requiring arguments, can also be defined without using macros. One solution, suitable for modifying globally available objects (like `cin`, or `cout`) is based on using anonymous objects:

- First, a class is defined, e.g. `Align`, whose constructor expects the arguments configuring the required manipulation. In our example representing, respectively, a field width and an alignment type.
- The class also supports an overloaded insertion (or extraction) operator. E.g.,

  ```
  ostream &operator<<(ostream &ostr, Align const &align)
  ```
- Next, the (anonymous) object is inserted into a stream. The insertion operator passes the stream to `Align::align`, allowing that member to configure (and return) the provided stream.

Here is an example of a little program using such a *home-made* manipulator expecting multiple arguments:

```
#include <iostream>
#include <iomanip>

class Align
{
    unsigned d_width;
    std::ios::fmtflags d_alignment;

    public:
        Align(unsigned width, std::ios::fmtflags alignment);
        std::ostream &operator()(std::ostream &ostr) const;
};

Align::Align(unsigned width, std::ios::fmtflags alignment)
:
    d_width(width),
    d_alignment(alignment)
{}

std::ostream &Align::operator()(std::ostream &ostr) const
{
    ostr.setf(d_alignment, std::ios::adjustfield);
    return ostr << std::setw(d_width);
}

std::ostream &operator<<(std::ostream &ostr, Align &&align)
{
    return align(ostr);
}

using namespace std;

int main()
{
    cout
        << "`" << Align{ 5, ios::left } << "hi" << "'"
        << "`" << Align{ 10, ios::right } << "there" << "'\n";
}

/*
    Generated output:
```

```
        `hi    '`     there'
    */
```

When (local) objects must be manipulated, then the class that must provide manipulators may define function call operators receiving the required arguments. E.g., consider a class `Matrix` that should allow its users to specify the value and line separators when inserting the matrix into an `ostream`.

Two data members (e.g., `char const *d_valueSep` and `char const *d_lineSep`) are defined (and initialized to acceptable values). The insertion function inserts `d_valueSep` between values, and `d_lineSep` at the end of inserted rows. The member `operator()(char const *valueSep, char const *lineSep)` simply assigns values to the corresponding data members.

Given an object `Matrix matrix`, then at this point `matrix(" ", "\n")` can be called. The function call operator should probably not insert the matrix, as the responsibility of manipulators is to manipulate, not to insert. So, to insert a matrix a statement like

```
        cout << matrix(" ", "\n") << matrix << '\n';
```

should probably be used. The manipulator (i.e., function call operator) assigns the proper values to `d_valueSep` and `d_lineSep`, which are then used during the actual insertion.

The return value of the function call operator remains to be specified. The return value should be insertable, but in fact should not insert anything at all. An empty NTBS could be returned, but that's a bit kludge-like. Instead the address of a manipulator function, not performing any action, can be returned. Here's the implementation of such an empty manipulator:

```
        // static       (alternatively a free function could be used)
        std::ostream &Matrix::nop(std::ostream &out)
        {
            return out;
        }
```

Thus, the implementation of the `Matrix's` manipulator becomes:

```
        std::ostream &(
            *Matrix::operator()(char const *valueSep, char const *lineSep) )
                                                            (std::ostream &)
        {
            d_valueSep = valueSep;
            d_lineSep = lineSep;
            return nop;
        }
```

Instead (probably a matter of taste) of returning the address of an empty function the manipulator could first set the required insertion-specific values and could then return itself: the `Matrix` would be inserted according to the just assigned values to the insertion variables:

```
        Matrix const &Matrix::operator()
            (char const *valueSep, char const *lineSep)
        {
            d_valueSep = valueSep;
            d_lineSep = lineSep;
            return *this;
        }
```

In this case the insertion statement is simplified to

```
cout << matrix(" ", "\n") << '\n';
```

11.11 Lambda expressions

C++ supports *lambda expressions*. As we'll see in chapter 19 *generic algorithms* often accept arguments that can either be function objects or plain functions. Examples are the `sort` (cf. section 19.1.59) and `find_if` (cf. section 19.1.17) generic algorithms. As a rule of thumb: when a called function must remember its state a function object is appropriate, otherwise a plain function can be used.

Frequently the function or function object is not readily available, and it must be defined in or near the location where it is used. This is commonly realized by defining a class or function in the anonymous namespace (say: class or function A), passing an A to the code needing A. If that code is itself a member function of the class B, then A's implementation might benefit from having access to the members of class B.

This scheme usually results in a significant amount of code (defining the class), or it results in complex code (to make available software elements that aren't automatically accessible to A's code). It may also result in code that is irrelevant at the current level of specification. Nested classes don't solve these problems either. Moreover, nested classes can't be used in templates.

lambda expressions solve these problems. A lambda expression defines an anonymous function object which may immediately be passed to functions expecting function object arguments, as explained in the next few sections.

According to the C++ standard, lambda expressions *provide a concise way to create simple function objects*. The emphasis here is on *simple*: a lambda expression's size should be comparable to the size of inline-functions: just one or maybe two statements. If you need more code, then encapsulate that code in a separate function which is then called from inside the lambda expression's compound statement, or consider designing a separate function object.

11.11.1 Lambda expressions: syntax

A lambda expression defines an anonymous function object, also called a *closure object* or simply a *closure*.

When a lambda expression is evaluated it results in a temporary function object (the closure object). This temporary function object is of a unique anonymous class type, called its *closure type*.

Lambda expressions are used inside blocks, classes or namespaces (i.e., pretty much anywhere you like). Their implied closure type is defined in the smallest block, class or namespace scope containing the lambda expression. The closure object's visibility starts at its point of definition and ends where its closure type ends (i.e., their visibility is identical to the visibility of plain variables).

The closure type defines a `const` public inline function call operator. Here is an example of a lambda expression:

```
[]                      // the `lambda-introducer'
(int x, int y)          // the `lambda-declarator'
{                       // a normal compound-statement
    return x * y;
}
```

The function (formally: the function call operator of the closure type created by this lambda expression) expects two `int` arguments and returns their product. This function is an inline `const` member of its closure type. Its `const` attribute is removed if the lambda expression specifies `mutable`. E.g.,

```
[](int x, int y) mutable
...
```

The lambda-declarator may be omitted if no parameters are defined, but when specifying `mutable` (or `constexpr`, see below) a lambda-declarator must be specified (at least as an empty set of parentheses). The parameters in a lambda declarator cannot be given default arguments.

Declarator specifiers can be `mutable`, `constexpr`, or both. A `constexpr` lambda-expression is itself a `constexpr`, which may be compile-time evaluated if its arguments qualify as const-expressions. By implication, if a lambda-expression is defined inside a `constexpr` function then the lambda-expression itself is a `constexpr`, and the `constexpr` declarator specifier is not required. Thus, the following function definitions are identical:

```
int constexpr change10(int n)
{
    return [n]
           {
               return n > 10 ? n - 10 : n + 10;
           }();
}

int constexpr change10(int n)
{
    return [n] () constexpr
           {
               return n > 10 ? n - 10 : n + 10;
           }();
}
```

A closure object as defined by the previous lambda expression could for example be used in combination with the `accumulate` generic algorithm (cf. section 19.1.1) to compute the product of a series of `int` values stored in a vector:

```
cout << accumulate(vi.begin(), vi.end(), 1,
            [] (int x, int y)
            {
                return x * y;
            }
        );
```

This lambda expression implicitly defines its return type as `decltype(x * y)`. Implicit return types can be used in these cases:

- the lambda expression does not contain a `return` statement (i.e., it's a void lambda expression);
- the lambda expression contains a single `return` statement; or
- the lambda expression contains multiple `return` statements returning values of identical types (e.g., all `int` values).

If there are multiple `return` statements returning values of different types then the lambda expression's return type must explicitly be specified using a late-specified return type, (cf. section 3.3.7):

```
[](bool neg, double y) -> int
{
    return neg ? -y : y;
}
```

Variables visible at the location of a lambda expression may be accessible from inside the lambda expression's compound statement. Which variables and how they are accessed depends on the content of the lambda-introducer.

When the lambda expression is defined inside a class member function the lambda-introducer may contain `this` or `*this`; where used in the following overview this class-context is assumed.

Global variables are always accessible, and can be modified if their definitions allow so (this in general holds true in the following overview: when stated that 'variables can be modified' then that only applies to variables that themselves allow modifications).

Local variables of the lambda expression's surrounding function may also be specified inside the lambda-introducer. The specification `local` is used to refer to any comma-separated list of local variables of the surrounding function that are visible at the lambda expression's point of definition. There is no required ordering of the `this, *this` and `local` specifications.

Finally, where in the following overview `mutable` is mentioned it must be specified, where `mutable_opt` is specified it is optional.

Access globals, maybe data members and local variables:

- `[] mutable_opt` limits access to merely global variables;
- `[this] mutable_opt` allows access to all the object's data members, which can be modified.
- `[*this]` provides access to all the object's members, which cannot be modified.
- `[*this] mutable` is like `[*this]` but modifiable copies are used inside the lambda expression without affecting the object's own data.
- `[local] [this, local] [*this, local]`: like the previous `[...]` specifications, but `local` is immutably accessed.
- `[local] mutable, [this, local] mutable, [*this, local] mutable`: like the previous `[...]` specifications, but `local` is available as a local copy, which can be modified without affecting the surrounding function's local variable.
- `[&local] mutable_opt, [this, &local] mutable_opt, [*this, &local] mutable_opt`: like the previous `[...]` specifications, but `local` is available by modifiable reference of the surrounding function's local variable.

The following specifications must use `=` as the first element of the lambda-introducer. It allows accessing local variables by value, unless...:

- `[=], [=, this], [=, *this]`: the 'local const' specifier: local variables are visible, but cannot be modified.
- `[=] mutable, [=, this] mutable, [=, *this] mutable`: local variables are visible as modifiable copies. The original local variables themselves are not affected.

- `[=, &local] mutable_opt`: like the previous `[= ...]` specifications, but `local` is accessed by modifiable reference.

The following specifications must use `&` as the first element of the lambda-introducer. It allows accessing local variables by reference, unless...:

- `[&] mutable_opt`, `[&, this], mutable_opt`: the 'local reference specifier: local variables are visible as modifiable references. When the lambda expression is defined inside a class member function the object's members are accessible and modifiable.
- `[&, *this] mutable_opt`: local variables are visible as modifiable references, data members are visible but cannot be modified.
- `[&, local] mutable_opt`, `[&, this, local] mutable_opt`, `[&, *this, local] mutable_opt`: like the previous `[& ...]` specifications, but `local` is accessed as a modifiable copy, not affecting the surrounding function's local variable.

Even when not specified, lambda expressions implicitly capture their `this` pointers, and class members are always accessed relative to `this`. But when members are called asynchronously (cf. chapter 20) a problem may arise, because the asynchronously called lambda function may refer to members of an object whose lifetime ended shortly after asynchronously calling the lambda function. This potential problem is solved by using '`*this`' in the lambda-capture if it starts with `=`, e.g., `[=, *this]` (in addition, variables may still also be captured, as usual). When specifying '`*this`' the object to which `this` refers is *explicitly captured*: if the object's scope ends it is not immediately destroyed, but its lifetime is extended by the lambda-expression for the duration of that expression. In order to use the '`*this`' specification, the object must be available. Consider the following example:

```
struct S2
{
    double ohseven = .007;

    auto f()
    {
        return [this]                       // (1, see below)
               {
                     return [*this]         // (2)
                            {
                                return ohseven; // OK
                            };
               }();                         // (3)
    }

    auto g()
    {
        return []
               {
                     return [*this]
                     {
                         // error: *this not captured by
                         // the outer lambda-expression
                     };
                }();
    }
};
```

Although lambda expressions are anonymous function objects, they *can* be assigned to variables. Often, the variable is defined using the keyword `auto`. E.g.,

```
auto sqr = [](int x)
           {
               return x * x;
           };
```

The lifetime of such lambda expressions is equal to the lifetime of the variable receiving the lambda expression as its value.

Note also that defining a lambda expression is different from calling its function operator. The function `S2::f()` returns what the lamba expression (1)'s function call operator returns: its function call operator is called by using `()` (at (3)). What it in fact returns is another anonymous function object (defined at `(2)`). As that's just a function object, to retrieve its value it must still be called from `f's` return value using something like this:

```
S2 s2;
s2.f()();
```

Here, the second set of parentheses activates the returned function object's function call operator. Had the parentheses been omitted at (3) then `S2::f()` would have returned a mere anonymous function object (defined at (1)), in which case it would require three sets of parentheses to retrieve `ohseven's` value: `s2.f()()()`.

11.11.2 Using lambda expressions

Now that the syntax of lambda expressions have been covered let's see how they can be used in various situations.

First we consider named lambda expressions. Named lambda expressions nicely fit in the niche of local functions: when a function needs to perform computations which are at a conceptually lower level than the function's task itself, then it's attractive to encapsulate these computations in a separate support function and call the support function where needed. Although support functions can be defined in anonymous namespaces, that quickly becomes awkward when the requiring function is a class member and the support function also must access the class's members.

In that case a named lambda expression can be used: it can be defined inside a requiring function, and it may be given full access to the surrounding class. The name to which the lambda expression is assigned becomes the name of a function which can be called from the surrounding function. Here is an example, converting a numeric IP address to a dotted decimal string, which can also be accessed directly from an `Dotted` object (all implementations in-class to conserve space):

```
class Dotted
{
    std::string d_dotted;

    public:
        std::string const &dotted() const
        {
            return d_dotted;
        }
        std::string const &dotted(size_t ip)
        {
                auto octet =
                    [](size_t idx, size_t numeric)
                    {
                        return to_string(numeric >> idx * 8 & 0xff);
                    };

                d_dotted =
                        octet(3, ip) + '.' + octet(2, ip) + '.' +
                        octet(1, ip) + '.' + octet(0, ip);

                return d_dotted;
            }
    };
```

Next we consider the use of generic algorithms, like the `for_each` (cf. section 19.1.18):

```
    void showSum(vector<int> const &vi)
    {
        int total = 0;
        for_each(
            vi.begin(), vi.end(),
            [&](int x)
            {
                total += x;
            }
        );
        std::cout << total << '\n';
    }
```

Here the variable `int total` is passed to the lambda expression by reference and is directly accessed by the function. Its parameter list merely defines an `int x`, which is initialized in sequence by each of the values stored in `vi`. Once the generic algorithm has completed `showSum`'s variable `total` has received a value that is equal to the sum of all the vector's values. It has outlived the lambda expression and its value is displayed.

But although generic algorithms are extremely useful, there may not always be one that fits the task at hand. Furthermore, an algorithm like `for_each` looks a bit unwieldy, now that the language offers range-based for-loops. So let's try this, instead of the above implementation:

```
    void showSum(vector<int> const &vi)
    {
        int total = 0;
        for (auto el: vi)
            [&](int x)
            {
                total += x;
            };

        std::cout << total << '\n';
    }
```

But when `showSum` is now called, its `cout` statement consistently reports 0. What's happening here?

When a generic algorithm is given a lambda function, its implementation instantiates a reference to a function. The referenced function is thereupon called from within the generic algorithm. But, in the above example the range-based for-loop's nested statement merely represents the *definition* of a lambda function. Nothing is actually called, and hence `total` remains equal to 0.

Thus, to make the above example work we not only must *define* the lambda expression, but we must also *call* the lambda function. We can do this by giving the lambda function a *name*, and then call the lambda function by its given name:

```
void showSum(vector<int> const &vi)
{
    int total = 0;
    for (auto el: vi)
    {
        auto lambda = [&](int x)
                        {
                            total += x;
                        };

        lambda(el);
    }
    std::cout << total << '\n';
}
```

In fact, there is no need to give the lambda function a name: the `auto lambda` definition represents the lambda function, which could also directly be called. The syntax for doing this may look a bit weird, but there's nothing wrong with it, and it allows us to drop the compound statement, required in the last example, completely. Here goes:

```
void showSum(vector<int> const &vi)
{
    int total = 0;
    for (auto el: vi)
        [&](int x)
        {
            total += x;
        }(el);          // immediately append the
                        // argument list to the lambda
                        // function's definition
    std::cout << total << '\n';
}
```

Lambda expressions can also be used to prevent spurious returns from `condition_variable's` `wait` calls (cf. section 20.4.3).

The class `condition_variable` allows us to do so by offering `wait` members expecting a lock *and* a predicate. The predicate checks the data's state, and returns `true` if the data's state allows the data's processing. Here is an alternative implementation of the `down` member shown in section 20.4.3, checking for the data's actual availability:

```
void down()
{
    unique_lock<mutex> lock(sem_mutex);
    condition.wait(lock,
        [&]()
        {
            return semaphore != 0
            }
        );
        --semaphore;
    }
```

The lambda expression ensures that `wait` only returns once `semaphore` has been incremented.

Lambda expression are primarily used to obtain functors that are used in a very localized section of a program. Since they are used inside an existing function we should realize that once we use lambda functions multiple aggregation levels are mixed. Normally a function implements a task which can be described at its own aggregation level using just a few sentences. E.g., “the function `std::sort` sorts a data structure by comparing its elements in a way that is appropriate to the context where `sort` is called”. By using an existing comparison method the aggregation level is kept, and the statement is clear by itself. E.g.,

```
    sort(data.begin(), data.end(), greater<DataType>());
```

If an existing comparison method is not available, a tailor-made function object must be created. This could be realized using a lambda expression. E.g.,

```
    sort(data.begin(), data.end(),
        [&](DataType const &lhs, DataType const &rhs)
        {
            return lhs.greater(rhs);
        }
    );
```

Looking at the latter example, we should realize that here two different aggregation levels are mixed: at the top level the intent is to sort the elements in `data`, but at the nested level (inside the lambda expression) something completely different happens. Inside the lambda expression we define how a the decision is made about which of the two objects is the greater. Code exhibiting such mixed aggregation levels is hard to read, and should be avoided.

On the other hand: lambda expressions also simplify code because the overhead of defining tailor-made functors is avoided. The advice, therefore, is to use lambda expressions sparingly. *When* they are used make sure that their sizes remain small. As a rule of thumb: lambda expressions should be treated like in-line functions, and should merely consist of one, or maybe occasionally two expressions.

A special group of lambda expressions is known as *generic lambda expressions*. As generic lambda expressions are in fact *class templates*, their coverage is postponed until chapter 22.

11.12 The case of [io]fstream::open()

Earlier, in section 6.4.2.1, it was noted that the `[io]fstream::open` members expect an `ios::openmode` value as their final argument. E.g., to open an `fstream` object for writing you could do as follows:

```
    fstream out;
    out.open("/tmp/out", ios::out);
```

Combinations are also possible. To open an `fstream` object for *both* reading and writing the following stanza is often seen:

```
fstream out;
out.open("/tmp/out", ios::in | ios::out);
```

When trying to combine enum values using a 'home made' `enum` we may run into problems. Consider the following:

```
enum Permission
{
    READ =      1 << 0,
    WRITE =     1 << 1,
    EXECUTE =   1 << 2
};

void setPermission(Permission permission);

int main()
{
    setPermission(READ | WRITE);
}
```

When offering this little program to the compiler it replies with an error message like this:

```
invalid conversion from 'int' to 'Permission'
```

The question is of course: why is it OK to combine `ios::openmode` values passing these combined values to the stream's `open` member, but not OK to combine `Permission` values.

Combining enum values using arithmetic operators results in `int`-typed values. *Conceptually* this never was our intention. Conceptually it can be considered correct to combine enum values if the resulting value conceptually makes sense as a value that is still within the original enumeration domain. Note that after adding a value `READWRITE = READ | WRITE` to the above `enum` we're still not allowed to specify `READ | WRITE` as an argument to `setPermission`.

To answer the question about combining enumeration values and yet stay within the enumeration's domain we turn to operator overloading. Up to this point operator overloading has been applied to class types. Free functions like `operator<<` have been overloaded, and those overloads are conceptually within the domain of their class.

As **C++** is a strongly typed language realize that defining an `enum` is really something beyond the mere association of `int`-values with symbolic names. An enumeration type is really a type of its own, and as with any type its operators can be overloaded. When writing `READ | WRITE` the compiler performs the default conversion from enum values to `int` values and applies the operator to `ints`. It does so when it has no alternative.

But it is also possible to overload the enum type's operators. Thus we may ensure that we'll remain within the enum's domain even though the resulting value wasn't defined by the enum. The advantage of type-safety and conceptual clarity is considered to outweigh the somewhat peculiar introduction of values hitherto not defined by the enum.

Here is an example of such an overloaded operator:

```
Permission operator|(Permission left, Permission right)
{
    return static_cast<Permission>(static_cast<int>(left) | right);
}
```

Other operators can easily and analogously be constructed.

Operators like the above were defined for the `ios::openmode` enumeration type, allowing us to specify `ios::in | ios::out` as argument to `open` while specifying the corresponding parameter as `ios::openmode` as well. Clearly, operator overloading can be used in many situations, not necessarily only involving class-types.

11.13 User-defined literals

In addition to the well-known literals, like numerical constants (with or without suffixes), character constants and string (textual) literals, **C++** also supports *user-defined literals*, also known as *extensible literals*.

A user-defined literal is defined by a function (see also section 23.3) that must be defined at namespace scope. Such a function is called a literal operator. A literal operator cannot be a class member function. The names of a literal operator must start with an underscore, and a literal operator is used (called) by *suffixing* its name (including the underscore) to the argument that must be passed to it . Assuming `_NM2km` (nautical mile to km) is the name of a literal operator, then it could be called as `100_NM2km`, producing, e.g., the value 185.2.

Using `Type` to represent the return type of the literal operator its generic declaration looks like this:

```
    Type operator "" _identifier(parameter-list);
```

The blank space trailing the empty string is required. The parameter lists of literal operators can be:

- `unsigned long long int`. It is used as, e.g., `123_identifier`. The argument to this literal operator can be decimal constants, binary constants (initial 0b), octal constants (initial 0) and hexadecimal constants (initial 0x);
- `long double`. It is used as, e.g., `12.25_NM2km`;
- `char const *text`. The `text` argument is an NTBS. It is used as, e.g., `1234_pental`. The argument must *not* be given double quotes, and must represent a numeric constant, as also expected by literal operators defining `unsigned long long int` parameters.
- `char const *text, size_t len`. Here, the compiler determines `len` as if it had called `strlen(text)`. It is used as, e.g., `"hello"_nVowels`;
- `wchar_t const *text, size_t len`, same as the previous one, but accepting a string of `wchar_t` characters. It is used as, e.g., `L"1234"_charSum`;
- `char16_t const *text, size_t len`, same as the previous one, but accepting a string of `char16_t` characters. It is used as, e.g., `u"utf 16"_uc`;
- `char32_t const *text, size_t len`, same as the previous one, but accepting a string of `char32_t` characters. It is used as, e.g., `U"UTF 32"_lc`;

If literal operators are overloaded the compiler will pick the literal operator requiring the least 'effort'. E.g., 120 is processed by a literal operator defining an `unsigned long long int` parameter and not by its overloaded version, defining a `char const *` parameter. But if overloaded literal operators exist defining `char const *` and `long double` parameters then the operator defining a `char const *` parameter is used when the argument 120 is provided, while the operator defining a `long double` parameter is used with the argument 120.3.

A literator operator can define any return type. Here is an example of a definition of the `_NM2km` literal operator:

```
double operator "" _NM2km(char const *nm)
{
    return std::stod(nm) * 1.852;
}

double value = 120_NM2km;   // example of use
```

Of course, the argument could also have been a `long double` constant. Here's an alternative implementation, explicitly expecting a `long double`:

```
double constexpr operator "" _NM2km(long double nm)
{
    return nm * 1.852;
}

double value = 450.5_NM2km;   // example of use
```

A numeric constant can also be processed completely at compile-time. Section 23.3 provides the details of this type of literal operator.

Arguments to literal operators are themselves always constants. A literal operator like `_NM2km` cannot be used to convert, e.g., the value of a variable. A literal operator, although it is defined as a function, cannot be called like a function. The following examples therefore result in compilation errors:

```
double speed;

speed_NM2km;         // no identifier 'speed_NM2km'
_NM2km(speed);       // no function _NM2km
_NM2km(120.3);       // no function _NM2km
```

11.14 Overloadable operators

The following operators can be overloaded:

```
+       -       *       /       %       ^       &       |
~       !       ,       =       <=>     <       >       <=
>=      ++      --      <<      >>      ==      !=      &&
||      +=      -=      *=      /=      %=      ^=      &=
|=      <<=     >>=     []      ()      ->      ->*     new
new[]   delete  delete[]
```

Several operators have *textual alternatives*:

textual alternative	operator
`and`	`&&`
`and_eq`	`&=`
`bitand`	`&`
`bitor`	`|`
`compl`	`~`
`not`	`!`
`not_eq`	`!=`
`or`	`||`
`or_eq`	`|=`
`xor`	`^`
`xor_eq`	`^=`

'Textual' alternatives of operators are also overloadable (e.g., `operator and`). However, note that textual alternatives are not *additional* operators. So, within the same context `operator&&` and `operator and` can not *both* be overloaded.

Several of these operators may only be overloaded as member functions *within* a class. This holds true for the `'='`, the `'[]'`, the `'()'` and the `'->'` operators. Consequently, it isn't possible to redefine, e.g., the assignment operator globally in such a way that it accepts a `char const *` as an `lvalue` and a `String &` as an *rvalue*. Fortunately, that isn't necessary either, as we have seen in section 11.3.

Finally, the following operators cannot be overloaded:

```
    .       .*      ::      ?:      sizeof  typeid
```

Chapter 12

Abstract Containers

C++ offers several predefined datatypes, all part of the Standard Template Library, which can be used to implement solutions to frequently occurring problems. The datatypes discussed in this chapter are all *containers*: you can put stuff inside them, and you can retrieve the stored information from them.

The interesting part is that the kind of data that can be stored inside these containers has been left unspecified at the time the containers were constructed. That's why they are spoken of as *abstract* containers.

Abstract containers rely heavily on *templates*, covered in chapter 21 and beyond. To use abstract containers, only a minimal grasp of the template concept is required. In **C++** a template is in fact a recipe for constructing a function or a complete class. The recipe tries to abstract the functionality of the class or function as much as possible from the data on which the class or function operates. As the data types on which the templates operate were not known when the template was implemented, the datatypes are either inferred from the context in which a function template is used, or they are mentioned explicitly when a class template is used (the term that's used here is *instantiated*). In situations where the types are explicitly mentioned, the *angle bracket notation* is used to indicate which data types are required. For example, below (in section 12.2) we'll encounter the `pair` container, which requires the explicit mentioning of two data types. Here is a `pair` object containing both an `int` and a `string`:

```
    pair<int, string> myPair;
```

The object `myPair` is defined as an object holding both an `int` and a `string`.

The angle bracket notation is used intensively in the upcoming discussion of abstract containers. Actually, understanding this part of templates is the only real requirement for using abstract containers. Now that we've introduced this notation, we can postpone the more thorough discussion of templates to chapter 21, and concentrate on their use in this chapter.

Most abstract containers are *sequential* containers: they contain data that can be stored and retrieved in some sequential way. Examples are the `array`, implementing a fixed-sized array; a `vector`, implementing an extendable array; the `list`, implementing a data structure that allows for the easy insertion or deletion of data; the `queue`, also called a *FIFO* (first in, first out) structure, in which the first element that is entered is the first element to be retrieved again; and the `stack`, which is a *first in, last out* (FILO or LIFO) structure.

In addition to sequential containers several special containers are available. The `pair` is a basic container in which a pair of values (of types that are left open for further specification) can be stored, like two strings, two ints, a string and a double, etc.. Pairs are often used to return data elements that naturally come in pairs. For example, the `map` is an abstract container storing keys and their associated values. Elements of these maps are returned as `pairs`.

A variant of the `pair` is the `complex` container, implementing operations that are defined on complex numbers.

A `tuple` (cf. section 22.6) generalizes the `pair` container to a data structure accommodating any number of different data types.

All abstract containers described in this chapter as well as the `string` and stream datatypes (cf. chapters 5 and 6) are part of the Standard Template Library.

All but the unordered containers support the following basic set of operators:

- The overloaded assignment operator, so we can assign two containers of the same types to each other. If the container's data type supports move assignment, then assignment of an anonymous temporary container to a destination container will use move assignment when assigning new values to the destination container's element. Overloaded assignment is *also* supported by the unordered containers;
- Tests for equality: == and != The equality operator applied to two containers returns `true` if the two containers have the same number of elements, which are pairwise equal according to the equality operator of the contained data type. The inequality operator does the opposite;
- Ordering operators: <, <=, > and >=. The < operator returns `true` if each element in the left-hand side container is less than each corresponding element in the right-hand side container. Additional elements in either the left-hand side container or the right-hand side container are ignored.

```
container left;
container right;

left = {0, 2, 4};
right = {1, 3};             // left < right

right = {1, 3, 6, 1, 2};    // left < right
```

Note that before a user-defined type (usually a `class`-type) can be stored in a container, the user-defined type should at least support:

- A default value (e.g., a default constructor)
- The equality operator (==)
- The less-than operator (<)

Sequential containers can also be initialized using *initializer lists*.

Most containers (exceptions are the stack (section 12.4.11), priority_queue (section 12.4.5), and queue (section 12.4.4) containers) support members to determine their maximum sizes (through their member function max_size).

Virtually all containers support copy construction. If the container supports copy construction and the container's data type supports move construction, then move construction is automatically used for the container's data elements when a container is initialized with an anonymous temporary container.

Closely linked to the standard template library are the *generic algorithms*. These algorithms may be used to perform frequently occurring tasks or more complex tasks than is possible with the containers themselves, like counting, filling, merging, filtering etc.. An overview of generic algorithms and their applications is given in chapter 19. Generic algorithms usually rely on the availability of *iterators*, representing begin and end-points for processing data stored inside containers. The abstract containers usually support constructors and members expecting iterators, and they often have members returning iterators (comparable to the `string::begin` and `string::end` members). In this chapter the iterator concept is not further investigated. Refer to chapter 18 for this.

Containers often collect data during their lifetimes. When a container goes out of scope, its destructor tries to destroy its data elements. This only succeeds if the data elements themselves are stored inside the container. If the data elements of containers are pointers to dynamically allocated memory then the memory pointed to by these pointers is not destroyed, resulting in a memory leak. A consequence of this scheme is that the data stored in a container should often be considered the 'property' of the container: the container should be able to destroy its data elements when the container's destructor is called. So, normally containers should not contain pointers to data. Also, a container should not be required to contain `const` data, as `const` data prevent the use of many of the container's members, like the assignment operator.

12.1 Notations used in this chapter

In this chapter about containers, the following notational conventions are used:

- Containers live in the standard namespace. In code examples this will be clearly visible, but in the text `std::` is usually omitted.
- A container without angle brackets represents any container of that type. Mentally add the required type in angle bracket notation. E.g., `pair` may represent `pair<string, int>`.
- The notation `Type` represents the generic type. `Type` could be `int`, `string`, etc.
- Identifiers `object` and `container` represent objects of the container type under discussion.
- The identifier `value` represents a value of the type that is stored in the container.
- Simple, one-letter identifiers, like `n` represent unsigned values.
- Longer identifiers represent iteratoriterators. Examples are `pos`, `from`, `beyond`

Some containers, e.g., the `map` container, contain pairs of values, usually called 'keys' and 'values'. For such containers the following notational convention is used in addition:

- The identifier `key` indicates a value of the used key-type
- The identifier `keyvalue` indicates a value of the '`value_type`' used with the particular container.

12.2 The 'pair' container

The `pair` container is a rather basic container. It is used to store two elements, called `first` and `second`, and that's about it. Before using `pair` containers the header file `<utility>` must be included.

The `pair`'s data types are specified when the `pair` object is defined (or declared) using the template's angle bracket notation (cf. chapter 21). Examples:

```
pair<string, string> piper("PA28", "PH-ANI");
pair<string, string> cessna("C172", "PH-ANG");
```

here, the variables `piper` and `cessna` are defined as `pair` variables containing two `strings`. Both strings can be retrieved using the `first` and `second` fields of the `pair` type:

```
cout << piper.first << '\n' <<      // shows 'PA28'
        cessna.second << '\n';      // shows 'PH-ANG'
```

The `first` and `second` members can also be used to reassign values:

```
cessna.first = "C152";
cessna.second = "PH-ANW";
```

If a `pair` object must be completely reassigned, an *anonymous* pair object can be used as the right-hand operand of the assignment. An anonymous variable defines a temporary variable (which receives no name) solely for the purpose of (re)assigning another variable of the same type. Its generic form is

```
type(initializer list)
```

Note that when a `pair` object is used the type specification is not completed by just mentioning the containername `pair`. It also requires the specification of the data types which are stored within the pair. For this the (template) angle bracket notation is used again. E.g., the reassignment of the `cessna` pair variable could have been accomplished as follows:

```
cessna = pair<string, string>("C152", "PH-ANW");
```

In cases like these, the `type` specification can become quite elaborate, which has caused a revival of interest in the possibilities offered by the `typedef` keyword. If many `pair<type1, type2>` clauses are used in a source, the typing effort may be reduced and readability might be improved by first defining a name for the clause, and then using the defined name later. E.g.,

```
typedef pair<string, string> pairStrStr;

cessna = pairStrStr("C152", "PH-ANW");
```

All abstract containers are class templates, and the types for which class templates are initialized are commonly specified between pointed brackets following the class template's name. However, the compiler may be able to deduce the container's types from the types of arguments that are specified when constructing the container. E.g., when defining

```
pair values{ 1, 1.5 };
```

the compiler deduces that `values.first` is an `int` and `values.second` is a `double`. Sometimes the class template's types cannot be deduced. In those cases the intended types must explicitly be specified:

```
pair<int, double> values;
```

Although the compiler will deduce types whenever it can, it might not deduce the types we had in mind. Had we defined

```
    pair cessna{ "C172", "PH-BVL" };
```

then the compilation would succeed, but an expression like `cout << cessna.first.length()` would not compile, as `"C172"` is a NTBS, and hence `cessna.first` is a `char *`. In this case simply appending an `s` to the NTBSs fixes the problem, but such a simple fix might not always be available. Section 12.4.2 has contains more information about deducing template parameter types.

Apart from this (and the basic set of operations (assignment and comparisons)) the `pair` offers no further functionality. It is, however, a basic ingredient of the upcoming abstract containers `map`, `multimap` and `hash_map`.

C++ also offers a *generalized pair* container: the *tuple*, covered in section 22.6.

12.3 Allocators

Most containers use a special object for allocating the memory that is managed by them. This object is called an allocator, and it's type is (usually by default) specified when a container is constructed. A container's allocator can be obtained using the container's `get_allocator` member, which returns a copy of the allocator used by the container. Allocators offer the following members:

- `value_type *address(value_type &object)`

  returns the address of `object`.

- `value_type *allocate(size_t count)`

  allocates raw memory for holding `count` values of the container's `value_type`.

- `void construct(value_type *object, Arg &&...args)`

  using placement new, uses the arguments following `object` to install a value at `object`.

- `void destroy(value_type *object)`

  calls `object`'s destructor (but doesn't deallocate `object`'s own memory).

- `void deallocate(value_type *object, size_t count)`

  calls `operator delete` to delete object's memory, previously allocated by `allocate`.

- `size_t max_size()`

  returns the maximum number of elements that `allocate` can allocate.

Here is an example, using the allocator of a vector of strings (see section 12.4.2 below for a description of the `vector` container):

```
#include <iostream>
#include <vector>
#include <string>

using namespace std;
```

```
int main()
{
    vector<string> vs;

    auto allocator = vs.get_allocator();        // get the allocator

    string *sp = allocator.allocate(3);         // alloc. space for 3 strings

    allocator.construct(&sp[0], "hello world"); // initialize 1st string
    allocator.construct(&sp[1], sp[0]);         // use the copy constructor
    allocator.construct(&sp[2], 12, '=');       // string of 12 = chars

    cout << sp[0] << '\n' <<                    // show the strings
            sp[1] << '\n' <<
            sp[2] << '\n' <<
            "could have allocated " << allocator.max_size() << " strings\n";

    for (size_t idx = 0; idx != 3; ++idx)
        allocator.destroy(sp + idx);            // delete the string's
                                                // contents

    allocator.deallocate(sp, 3);                // and delete sp itself again.
}
```

12.4 Available Containers

12.4.1 The ‘array’ container

The `array` class implements a fixed-size array. Before using the `array` container the `<array>` header file must be included.

To define a `std::array` both the data type of its elements and its size must be specified: the data type is given after an opening angle bracket, immediately following the ‘`array`’ container name. The array’s size is provided after the data type specification. Finally, a closing angle bracket completes the array’s type. Specifications like this are common practice with containers. The combination of `array`, type and size defines a *type*. As a result, `array<string, 4>` defines another type than `array<string, 5>`, and a function explicitly defining an `array<Type, N>` parameter will not accept an `array<Type, M>` argument if `N` and `M` are unequal.

The array’s size may may be defined as 0 (although such an array probably has little use as it cannot store any element). The elements of an array are stored contiguously. If `array<Type, N> arr` has been defined, then `&arr[n] + m == &arr[n + m]`, assuming than `0 <= n < N` and `0 <= n + m < N`.

The following constructors, operators, and member functions are available:

- Constructors:
  - The copy and move constructors are available;
  - An `array` may be constructed with a fixed number `N` of default elements:

    ```
    array<string, N> object;
    ```

  - An initial subset of the elements of an array may be initialized using a brace delimited initializer list:

    ```
    array<double, 4> dArr = {1.2, 2.4};
    ```

    Here `dArr` is defined as an array of 4 element, with `dArr[0]` and `dArr[1]` initialized to, respectively 1.2 and 2.4, and `dArr[2]` and `dArr[3]` initialized to 0. An attractive characteristic of arrays (and other containers) is that containers initialize their data elements to the data type's default value. The data type's *default constructor* is used for this initialization. With non-class data types the value 0 is used. So, for an `array<double, 4>` array we know that all but its explicitly initialized elements are initialized to zero.

- In addition to the standard operators for containers, the `array` supports the index operator, which can be used to retrieve or reassign individual elements of the array. Note that the elements which are indexed must exist. For example, having defined an empty array a statement like `iarr[0] = 18` produces an error, as the array is empty. Note that `operator[]` does *not* respect its array bounds. If you want run-time array bound checking, use the array's `at` member.

- The `array` class offers the following member functions:

  - `Type &at(size_t idx)`:
    returns a reference to the array's element at index position `idx`. If `idx` exceeds the array's size a `std::out_of_range` exception is thrown.
  - `Type &back()`:
    returns a reference to the last element in the array. It is the responsibility of the programmer to use the member only if the array is not empty.
  - `array::iterator begin()`:
    returns an iterator pointing to the first element in the array, returning `end` if the array is empty.
  - `array::const_iterator cbegin()`:
    returns a const_iterator pointing to the first element in the array, returning `cend` if the array is empty.
  - `array::const_iterator cend()`:
    returns a const_iterator pointing just beyond the array's last element.
  - `array::const_reverse_iterator crbegin()`:
    returns a const_reverse_iterator pointing to the last element in the array, returning `crend` if the array is empty.
  - `array::const_reverse_iterator crend()`:
    returns a const_reverse_iterator pointing just before the array's first element.
  - `value_type *data()`:
    returns a pointer to the array's first data element. With a const array a `value_type const *` is returned.
  - `bool empty()`:
    returns `true` if the array contains no elements.
  - `array::iterator end()`:
    returns an iterator pointing beyond the last element in the array.
  - `void fill(Type const &item)`:
    fills all the array's elements with a copy of `item`
  - `Type &front()`:
    returns a reference to the first element in the array. It is the responsibility of the programmer to use the member only if the array is not empty.
  - `array::reverse_iterator rbegin()`:
    this member returns a reverse_iterator pointing to the last element in the array.

  - `array::reverse_iterator rend()`:
    returns a reverse_iterator pointing before the first element in the array.
  - `constexpr size_t size()`:
    returns the number of elements the array contains.
  - `void swap(<array<Type, N> &other)`:
    swaps the content of the current and other array. The array other's data type and size must be equal to the data type and size of the object calling `swap`.

Using an `array` rather than a standard **C** style array offers several advantages:

- All its elements are immediately initialized;
- Introspection is possible (e.g., `size` can be used);
- The `array` container can be used in the context of templates, there code is developed that operates on data types that become available only after the code itself has been developed;
- Since `array` supports reverse iterators, it can be immediately be used with generic algorithms performing 'reversed' operations (e.g., to perform a descending rather than ascending sort (cf. section 19.1.59))

In general, when looking for a sequential data structure, the `array` or `vector` (introduced in the next section) should be your 'weapon of choice'. Only if these containers demonstrably do not fit the problem at hand you should use another type of container.

12.4.2 The 'vector' container

The `vector` class implements an expandable array. Before using the `vector` container the `<vector>` header file must be included.

The following constructors, operators, and member functions are available:

- Constructors:
  - The copy and move constructors are available;
  - A `vector` may be constructed empty:

    ```
    vector<string> object;
    ```

  - A vector may be initialized to a certain number of elements:

    ```
    vector<string> object(5, "Hello"s); // initialize to 5 Hello's,
    vector<string> container(10);        // and to 10 empty strings
    vector<string> names = {"george", "frank", "tony", "karel"};
    ```

    Note the difference between `vector<int> first(5)` and `vector<int> second{ 5 }`. The vector `first` contains five elements, initialized to 0, while the vector `second` contains one element, initialized to 5. Referring back to section 12.2: with the latter definition the compiler is able to deduce the vector's template parameter type (`int`), so the latter definition could also have been written as `vector second{ 5 }`.
    An ambiguity might be observed when looking at

    ```
    vector object{ vector{ 1 } };
    ```

    Did we define a `vector<int>` or a `vector<vector<int>>`? The standard considers this a `vector<int>`: it is initialized using the vector's move constructor from an abstract `vector<int>`.

- A vector may be initialized using iterators. To initialize a vector with elements 5 until 10 (including the last one) of an existing `vector<string>` the following construction may be used:

  ```
  extern vector<string> container;
  vector<string> object(&container[5], &container[11]);
  ```

  Note here that the last element pointed to by the second iterator (`&container[11]`) is *not* stored in `object`. This is a simple example of the use of *iterators*, in which the used range of values starts at the first value, and includes all elements up to but not including the element to which the second iterator refers. The standard notation for this is `[begin, end)`.

- In addition to the standard operators for containers, the `vector` supports the index operator, which can be used to retrieve or reassign individual elements of the vector. Note that the elements which are indexed must exist. For example, having defined an empty vector a statement like `ivect[0] = 18` produces an error, as the vector is empty. So, the vector is *not* automatically expanded, and `operator[]` does *not* respect its array bounds. In this case the vector should be resized first, or `ivect.push_back(18)` should be used (see below). If you need run-time array bound checking, use the vector's `at` member.

- The `vector` class offers the following member functions:
  - `void assign(...)`:
    assigns new content to the vector:
    * `assign(iterator begin, iterator end)` assigns the values at the iterator range `[begin, end)` to the vector;
    * `assign(size_type n, value_type const &val)` assigns `n` copies of `val` to the vector;
    * `assign(initializer_list<value_type> values)` assigns the values in the initializer list to the vector.
  - `Type &at(size_t idx)`:
    returns a reference to the vector's element at index position `idx`. If `idx` exceeds the vector's size a `std::out_of_range` exception is thrown.
  - `Type &back()`:
    returns a reference to the last element in the vector. It is the responsibility of the programmer to use the member only if the vector is not empty.
  - `vector::iterator begin()`:
    returns an iterator pointing to the first element in the vector, returning `end` if the vector is empty.
  - `size_t capacity()`:
    Number of elements for which memory has been allocated. It returns at least the value returned by `size`
  - `vector::const_iterator cbegin()`:
    returns a const_iterator pointing to the first element in the vector, returning `cend` if the vector is empty.
  - `vector::const_iterator cend()`:
    returns a const_iterator pointing just beyond the vector's last element.
  - `void clear()`:
    erases all the vector's elements.
  - `vector::const_reverse_iterator crbegin()`:
    returns a const_reverse_iterator pointing to the last element in the vector, returning `crend` if the vector is empty.
  - `vector::const_reverse_iterator crend()`:
    returns a const_reverse_iterator pointing just before the vector's first element.

- `value_type *data()`:
  returns a pointer to the vector's first data element.
- `iterator emplace(const_iterator position, Args &&...args)`:
  a `value_type` object is constructed from the arguments specified after `position`, and the newly created element is inserted at `position`. Different from `insert`, which expects an existing object of the container's value type (and inserts the provided argument into the container) using copy or move construction or assignment, `emplace` uses its arguments to *construct* such an object immediately at the intended location of the container, without requiring copy or move construction or assignment.
- `void emplace_back(Args &&...args)`:
  a `value_type` object is constructed from the member's arguments, and the newly created element is inserted beyond the vector's last element.
- `bool empty()`:
  returns `true` if the vector contains no elements.
- `vector::iterator end()`:
  returns an iterator pointing beyond the last element in the vector.
- `vector::iterator erase()`:
  erases a specific range of elements in the vector:
  - `erase(pos)` erases the element pointed to by the iterator `pos`. The iterator `++pos` is returned.
  - `erase(first, beyond)` erases elements indicated by the iterator range `[first, beyond)`, returning `beyond`.
- `Type &front()`:
  returns a reference to the first element in the vector. It is the responsibility of the programmer to use the member only if the vector is not empty.
- `allocator_type get_allocator() const`:
  returns a copy of the allocator object used by the `vector` object.
- `... insert()`:
  elements may be inserted starting at a certain position. The return value depends on the version of `insert()` that is called:
  - `vector::iterator insert(pos)` inserts a default value of type `Type` at `pos`, `pos` is returned.
  - `vector::iterator insert(pos, value)` inserts `value` at `pos`, `pos` is returned.
  - `void insert(pos, first, beyond)` inserts the elements in the iterator range `[first, beyond)`.
  - `void insert(pos, n, value)` inserts `n` elements having value `value` at position `pos`.
- `size_t max_size()`:
  returns the maximum number of elements this `vector` may contain.
- `void pop_back()`:
  removes the last element from the vector. Avoid calling this member on an empty vector: although nothing is returned its internally maintained count of number of available elements is reduced, causing the vector's `size()` member to return the (when cast to `int`) value -1, and then -2, etc., etc.
- `void push_back(value)`:
  adds `value` to the end of the vector.
- `vector::reverse_iterator rbegin()`:
  this member returns a reverse_iterator pointing to the last element in the vector.
- `vector::reverse_iterator rend()`:
  returns an iterator pointing before the first element in the vector.

- `void reserve(size_t request)`:
  if `request` is less than or equal to `capacity`, this call has no effect. Otherwise, it is a request to allocate additional memory. If the call is successful, then `capacity` returns a value of at least `request`. Otherwise, `capacity` is unchanged. In either case, `size`'s return value won't change, until a function like `resize` is called, actually changing the number of accessible elements.
- `void resize()`:
  can be used to alter the number of elements that are currently stored in the vector:
  * `resize(n, value)` may be used to resize the vector to a size of `n`. `Value` is optional. If the vector is expanded and `value` is not provided, the additional elements are initialized to the default value of the used data type, otherwise `value` is used to initialize extra elements.
- `void shrink_to_fit()`:
  optionally reduces the amount of memory allocated by a vector to its current size. The implementor is free to ignore or otherwise optimize this request. In order to guarantee a 'shrink to fit' operation the

  ```
  vector<Type>(vectorObject).swap(vectorObject)
  ```

  idiom can be used.
- `size_t size()`:
  returns the number of elements in the vector.
- `void swap()`:
  swaps two vectors using identical data types. Example:

  ```
  #include <iostream>
  #include <vector>
  using namespace std;

  int main()
  {
      vector<int> v1(7);
      vector<int> v2(10);

      v1.swap(v2);
      cout << v1.size() << " " << v2.size() << '\n';
  }
  /*
      Produced output:
  10 7
  */
  ```

12.4.3 The 'list' container

The `list` container implements a list data structure. Before using a `list` container the header file `<list>` must be included.

The organization of a `list` is shown in figure 12.1. Figure 12.1 shows that a list consists of separate list-elements, connected by pointers. The list can be traversed in two directions: starting at *Front* the list may be traversed from left to right, until the 0-pointer is reached at the end of the rightmost list-element. The list can also be traversed from right to left: starting at *Back*, the list is traversed from right to left, until eventually the 0-pointer emanating from the leftmost list-element is reached.

As a subtlety note that the representation given in figure 12.1 is not necessarily used in actual implementations of the list. For example, consider the following little program:

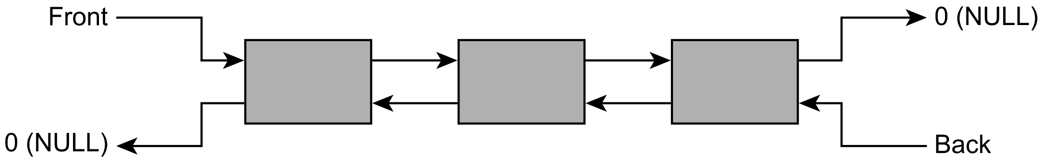

Figure 12.1: A list data-structure

```
int main()
{
    list<int> l;
    cout << "size: " << l.size() << ", first element: " <<
            l.front() << '\n';
}
```

When this program is run it might actually produce the output:

```
size: 0, first element: 0
```

Its front element can even be assigned a value. In this case the implementor has chosen to provide the list with a hidden element. The list actually is a *circular* list, where the hidden element serves as terminating element, replacing the 0-pointers in figure 12.1. As noted, this is a subtlety, which doesn't affect the conceptual notion of a list as a data structure ending in 0-pointers. Note also that it is well known that various implementations of list-structures are possible (cf. Aho, A.V., Hopcroft J.E. and Ullman, J.D., (1983) *Data Structures and Algorithms* (Addison-Wesley)).

Both lists and vectors are often appropriate data structures in situations where an unknown number of data elements must be stored. However, there are some rules of thumb to follow when selecting the appropriate data structure.

- When most accesses are random, a `vector` is the preferred data structure. Example: in a program counting character frequencies in a textfile, a `vector<int> frequencies(256)` is the datastructure of choice, as the values of the received characters can be used as indices into the `frequencies` vector.
- The previous example illustrates a second rule of thumb, also favoring the `vector`: if the number of elements is known in advance (and does not notably change during the lifetime of the program), the vector is also preferred over the list.
- In cases where insertions or deletions prevail and the data structure is large the list is generally preferred.

At present lists aren't as useful anymore as they used to be (when computers were much slower and more memory-constrained). Except maybe for some rare cases, a `vector` should be the preferred container; even when implementing algorithms traditionally using lists.

Other considerations related to the choice between lists and vectors should also be given some thought. Although it is true that the vector is able to grow dynamically, the dynamic growth requires data-copying. Clearly, copying a million large data structures takes a considerable amount of time, even on fast computers. On the other hand, inserting a large number of elements in a list doesn't require us to copy non-involved data. Inserting a new element in a list merely requires us to juggle some pointers. In figure 12.2 this is shown: a new element is inserted between the second and third element, creating a new list of four elements. Removing an element from a list is also

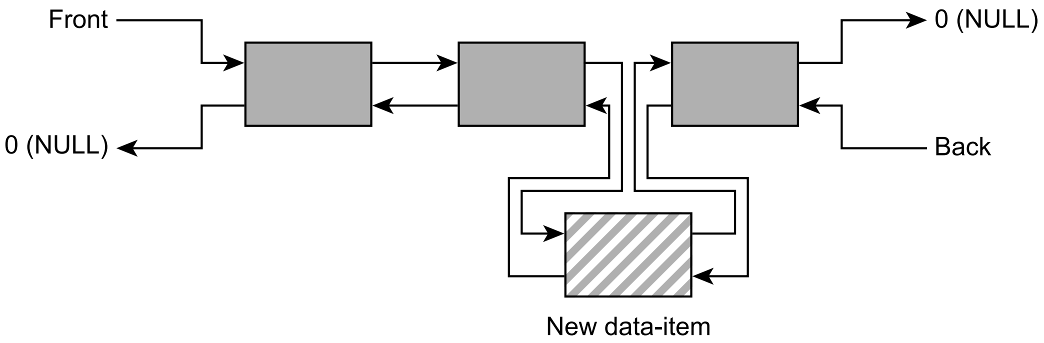

Figure 12.2: Adding a new element to a list

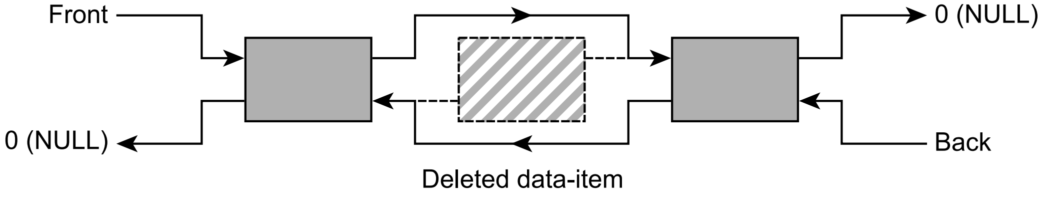

Figure 12.3: Removing an element from a list

fairly easy. Starting again from the situation shown in figure 12.1, figure 12.3 shows what happens if element two is removed from our list. Again: only pointers need to be juggled. In this case it's even simpler than adding an element: only two pointers need to be rerouted. To summarize the comparison between lists and vectors: it's probably best to conclude that there is no clear-cut answer to the question what data structure to prefer. There are rules of thumb, which may be adhered to. But if worse comes to worst, a profiler may be required to find out what's best.

The `list` container offers the following constructors, operators, and member functions:

- Constructors:
  - The copy and move constructors are available;
  - A `list` may be constructed empty:

    ```
    list<string> object;
    ```

    As with the `vector`, it is an error to refer to an element of an empty list.
  - A list may be initialized to a certain number of elements. By default, if the initialization value is not explicitly mentioned, the default value or default constructor for the actual data type is used. For example:

    ```
    list<string> object(5, "Hello"s); // initialize to 5 Hello's
    list<string> container(10);       // and to 10 empty strings
    ```
  - A list may be initialized using a two iterators. To initialize a list with elements 5 until 10 (including the last one) of a `vector<string>` the following construction may be used:

    ```
    extern vector<string> container;
    list<string> object(&container[5], &container[11]);
    ```
- The `list` does not offer specialized operators, apart from the standard operators for containers.

- The following member functions are available:
  - `void assign(...)`:

    assigns new content to the list:
    - `assign(iterator begin, iterator end)` assigns the values at the iterator range `[begin, end)` to the list;
    - `assign(size_type n, value_type const &val)` assigns `n` copies of `val` to the list;
  - `Type &back()`:
    returns a reference to the last element in the list. It is the responsibility of the programmer to use this member only if the list is not empty.
  - `list::iterator begin()`:
    returns an iterator pointing to the first element in the list, returning `end` if the list is empty.
  - `void clear()`:
    erases all elements from the list.
  - `bool empty()`:
    returns `true` if the list contains no elements.
  - `list::iterator end()`:
    returns an iterator pointing beyond the last element in the list.
  - `list::iterator erase()`:
    erases a specific range of elements in the list:
    - `erase(pos)` erases the element pointed to by `pos`. The iterator `++pos` is returned.
    - `erase(first, beyond)` erases elements indicated by the iterator range `[first, beyond)`. `Beyond` is returned.
  - `Type &front()`:
    returns a reference to the first element in the list. It is the responsibility of the programmer to use this member only if the list is not empty.
  - `allocator_type get_allocator() const`:
    returns a copy of the allocator object used by the `list` object.
  - `... insert()`:
    inserts elements into the list. The return value depends on the version of `insert` that is called:
    - `list::iterator insert(pos)` inserts a default value of type `Type` at `pos`, `pos` is returned.
    - `list::iterator insert(pos, value)` inserts `value` at `pos`, `pos` is returned.
    - `void insert(pos, first, beyond)` inserts the elements in the iterator range `[first, beyond)`.
    - `void insert(pos, n, value)` inserts `n` elements having value `value` at position `pos`.
  - `size_t max_size()`:
    returns the maximum number of elements this `list` may contain.
  - `void merge(list<Type> other)`:
    this member function assumes that the current and other lists are sorted (see below, the member `sort`). Based on that assumption, it inserts the elements of `other` into the current list in such a way that the modified list remains sorted. If both list are not sorted, the resulting list will be ordered ‘as much as possible’, given the initial ordering of the elements in the two lists. `list<Type>::merge` uses `Type::operator<` to sort the data in the list, which operator must therefore be available. The next example illustrates the

use of the `merge` member: the list '`object`' is not sorted, so the resulting list is ordered 'as much as possible'.

```
#include <iostream>
#include <string>
#include <list>
using namespace std;

void showlist(list<string> &target)
{
    for
    (
        list<string>::iterator from = target.begin();
        from != target.end();
        ++from
    )
        cout << *from << " ";

    cout << '\n';
}

int main()
{
    list<string> first;
    list<string> second;

    first.push_back("alpha"s);
    first.push_back("bravo"s);
    first.push_back("golf"s);
    first.push_back("quebec"s);

    second.push_back("oscar"s);
    second.push_back("mike"s);
    second.push_back("november"s);
    second.push_back("zulu"s);

    first.merge(second);
    showlist(first);
}
```

A subtlety is that `merge` doesn't alter the list if the list itself is used as argument: `object.merge(object)` won't change the list '`object`'.

- `void pop_back()`:
  removes the last element from the list. The program aborts when called on an empty list.
- `void pop_front()`:
  removes the first element from the list. The program aborts when called on an empty list.
- `void push_back(value)`:
  adds `value` to the end of the list.
- `void push_front(value)`:
  adds `value` before the first element of the list.
- `list::reverse_iterator rbegin()`:
  returns a reverse_iterator pointing to the last element in the list.
- `void remove(value)`:
  removes all occurrences of `value` from the list. In the following example, the two strings '`Hello`' are removed from the list `object`:

```
#include <iostream>
#include <string>
#include <list>
using namespace std;

int main()
{
    list<string> object;

    object.push_back("Hello"s);
    object.push_back("World"s);
    object.push_back("Hello"s);
    object.push_back("World"s);

    object.remove("Hello"s);

    while (object.size())
    {
        cout << object.front() << '\n';
        object.pop_front();
    }
}
/*
        Generated output:
    World
    World
*/
```

- `void remove_if(Predicate pred)`:
  removes all occurrences from the list for which the predicate function or function object `pred` returns `true`. For each of the objects stored in the list the predicate is called as `pred(*iter)`, where `iter` represents the iterator used internally by `remove_if`. If a function `pred` is used, its prototype should be `bool pred(value_type const &object)`.
- `list::reverse_iterator rend()`:
  this member returns a reverse_iterator pointing before the first element in the list.
- `void resize()`:
  alters the number of elements that are currently stored in the list:
  * `resize(n, value)` may be used to resize the list to a size of `n`. `Value` is optional. If the list is expanded and `value` is not provided, the extra elements are initialized to the default value of the used data type, otherwise `value` is used to initialize extra elements.
- `void reverse()`:
  reverses the order of the elements in the list. The element `back` becomes `front` and *vice versa*.
- `size_t size()`:
  returns the number of elements in the list.
- `void sort()`:
  sorts the list. An example of its use is given at the description of the `unique` member function below. `list<Type>::sort` uses `Type::operator<` to sort the data in the list, which must therefore be available.
- `void splice(pos, object)`:
  transfers the content of `object` to the current list, starting the insertion at the iterator

position `pos` of the object using the `splice` member. Following `splice`, `object` is empty. For example:

```
#include <iostream>
#include <string>
#include <list>
using namespace std;

int main()
{
    list<string> object;

    object.push_front("Hello"s);
    object.push_back("World"s);

    list<string> argument(object);

    object.splice(++object.begin(), argument);

    cout << "Object contains " << object.size() << " elements, " <<
            "Argument contains " << argument.size() <<
            " elements,\n";

    while (object.size())
    {
        cout << object.front() << '\n';
        object.pop_front();
    }
}
```

Alternatively, `argument` may be followed by an iterator of `argument`, indicating the first element of `argument` that should be spliced, or by two iterators `begin` and `end` defining the iterator-range `[begin, end)` on `argument` that should be spliced into `object`.

- `void swap()`:
  swaps two lists using identical data types.
- `void unique()`:
  operating on a sorted list, this member function removes all consecutively identical elements from the list. `list<Type>::unique` uses `Type::operator==` to identify identical data elements, which operator must therefore be available. Here's an example removing all multiply occurring words from the list:

```
#include <iostream>
#include <string>
#include <list>
using namespace std;
                        // see the merge() example
void showlist(list<string> &target)
{
    for
    (
        list<string>::iterator from = target.begin();
        from != target.end();
        ++from
    )
        cout << *from << " ";

    cout << '\n';
}


int main()
{
    string
        array[] =
        {
            "charlie",
            "alpha",
            "bravo",
            "alpha"
        };

    list<string>
        target
        (
            array, array + sizeof(array)
            / sizeof(string)
        );

    cout << "Initially we have:\n";
    showlist(target);

    target.sort();
    cout << "After sort() we have:\n";
    showlist(target);

    target.unique();
    cout << "After unique() we have:\n";
    showlist(target);
}
/*
    Generated output:

    Initially we have:
    charlie alpha bravo alpha
    After sort() we have:
    alpha alpha bravo charlie
    After unique() we have:
    alpha bravo charlie
*/
```

12.4.4 The ‘queue’ container

The `queue` class implements a queue data structure. Before using a `queue` container the header file `<queue>` must be included.

A queue is depicted in figure 12.4. In figure 12.4 it is shown that a queue has one point (the *back*) where items can be added to the queue, and one point (the *front*) where items can be removed (read) from the queue. A `queue` is therefore also called a *FIFO* data structure, for *first in, first out*. It is most often used in situations where events should be handled in the same order as they are generated.

The following constructors, operators, and member functions are available for the `queue` container:

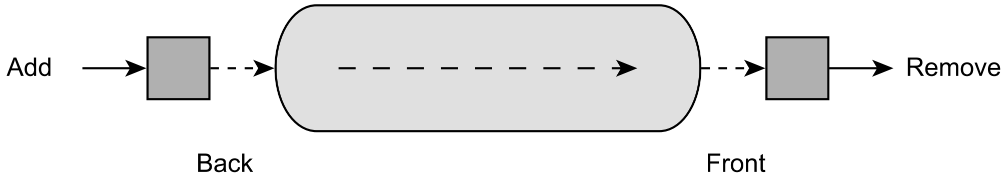

Figure 12.4: A queue data-structure

- Constructors:
  - The copy and move constructors are available;
  - A `queue` may be constructed empty:

    ```
    queue<string> object;
    ```

    As with the `vector`, it is an error to refer to an element of an empty queue.
- The `queue` container only supports the basic container operators.
- The following member functions are available for queues:
  - `Type &back()`:
    returns a reference to the last element in the queue. It is the responsibility of the programmer to use the member only if the queue is not empty.
  - `bool empty()`:
    returns `true` if the queue contains no elements.
  - `Type &front()`:
    returns a reference to the first element in the queue. It is the responsibility of the programmer to use the member only if the queue is not empty.
  - `void pop()`:
    removes the element at the front of the queue. Note that the element is *not* returned by this member. Avoid calling this member on an empty queue: although nothing is returned its internally maintained count of number of available elements is reduced, causing the queue's `size()` member to return the (when cast to `int`) value -1, and then -2, etc., etc. One might wonder why `pop` returns `void`, instead of a value of type `Type` (cf. `front`). One reason is found in the principles of good software design: functions should perform one task. Combining the removal and return of the removed element breaks this principle. Moreover, when this principle is abandoned `pop`'s implementation is always flawed. Consider the prototypical implementation of a `pop` member that is supposed to return the just popped value:

    ```
    Type queue::pop()
    {
        Type ret{ front() };
        erase_front();
        return ret;
    }
    ```

    The venom, as usual, is in the tail: since `queue` has no control over `Type`'s behavior the final statement (`return ret`) might throw. By that time the queue's front element has already been removed from the queue and so it is lost. Thus, a `Type` returning `pop` member cannot offer the *strong guarantee* and consequently `pop` should not return the former `front` element. Because of all this, we must first use `front` and then `pop` to obtain and remove the queue's front element.
  - `void push(value)`:
    this member adds `value` to the back of the queue.

  - `size_t size()`:
    returns the number of elements in the queue.

Note that the queue does not support iterators or an index operator. The only elements that can be accessed are its front and back element. A queue can be emptied by:

- repeatedly removing its front element;
- assigning an empty queue using the same data type to it;
- having its destructor called.

12.4.5 The 'priority_queue' container

The `priority_queue` class implements a priority queue data structure. Before using a `priority_queue` container the `<queue>` header file must have been included.

A priority queue is identical to a `queue`, but allows the entry of data elements according to *priority rules*. A real-life priority queue is found, e.g., at airport check-in terminals. At a terminal the passengers normally stand in line to wait for their turn to check in, but late passengers are usually allowed to jump the queue: they receive a higher priority than other passengers.

The priority queue uses `operator<` of the data type stored in the priority queue to decide about the priority of the data elements. The *smaller* the value, the *lower* the priority. So, the priority queue *could* be used to sort values while they arrive. A simple example of such a priority queue application is the following program: it reads words from `cin` and writes a sorted list of words to `cout`:

```
#include <iostream>
#include <string>
#include <queue>
using namespace std;

int main()
{
    priority_queue<string> q;
    string word;

    while (cin >> word)
        q.push(word);

    while (q.size())
    {
        cout << q.top() << '\n';
        q.pop();
    }
}
```

Unfortunately, the words are listed in reversed order: because of the underlying <-operator the words appearing later in the ASCII-sequence appear first in the priority queue. A solution to that problem is to define a *wrapper class* around the `string` datatype, reversing `string`'s `operator<`. Here is the modified program:

```
#include <iostream>
#include <string>
```

```
#include <queue>

class Text
{
    std::string d_s;

    public:
        Text(std::string const &str)
        :
            d_s(str)
        {}
        operator std::string const &() const
        {
            return d_s;
        }
        bool operator<(Text const &right) const
        {
            return d_s > right.d_s;
        }
};

using namespace std;

int main()
{
    priority_queue<Text> q;
    string word;

    while (cin >> word)
        q.push(word);

    while (q.size())
    {
        word = q.top();
        cout << word << '\n';
        q.pop();
    }
}
```

Other possibilities to achieve the same exist. One would be to store the content of the priority queue in, e.g., a vector, from which the elements can be read in reversed order.

The following constructors, operators, and member functions are available for the `priority_queue` container:

- Constructors:
    - The copy and move constructors are available;
    - A `priority_queue` may be constructed empty:

      `priority_queue<string> object;`
- The `priority_queue` only supports the basic operators of containers.
- The following member functions are available for priority queues:
    - `bool empty()`:
      returns `true` if the priority queue contains no elements.

  - `void pop()`:
    removes the element at the top of the priority queue. Note that the element is *not* returned by this member. As with the `queue` avoid calling this member on an empty priority queue (cf. section 12.4.4.)
  - `void push(value)`:
    inserts `value` at the appropriate position in the priority queue.
  - `size_t size()`:
    returns the number of elements in the priority queue.
  - `Type &top()`:
    returns a reference to the first element of the priority queue. It is the responsibility of the programmer to use the member only if the priority queue is not empty.

Note that the priority queue does not support iterators or an index operator. The only element that can be accessed is its top element. A priority queue can be emptied by:

- repeatedly removing its top element;
- assigning an empty queue using the same data type to it;
- having its destructor called.

12.4.6 The 'deque' container

The `deque` (pronounce: 'deck') class implements a doubly ended queue data structure (deque). Before using a `deque` container the header file `<deque>` must be included.

A `deque` is comparable to a queue, but it allows for reading and writing at both ends. Actually, the `deque` data type supports a lot more functionality than the `queue`, as illustrated by the following overview of available member functions. A `deque` is a combination of a `vector` and two queues, operating at both ends of the vector. In situations where random insertions and the addition and/or removal of elements at one or both sides of the vector occurs frequently using a `deque` should be considered.

The following constructors, operators, and member functions are available for deques:

- Constructors:
  - The copy and move constructors are available;
  - A `deque` may be constructed empty:

    ```
    deque<string> object;
    ```

    As with the `vector`, it is an error to refer to an element of an empty deque.
  - A deque may be initialized to a certain number of elements. By default, if the initialization value is not explicitly mentioned, the default value or default constructor for the actual data type is used. For example:

    ```
    deque<string> object(5, "Hello"s), // initialize to 5 Hello's
    deque<string> container(10);       // and to 10 empty strings
    ```
  - A deque may be initialized using two iterators. To initialize a deque with elements 5 until 10 (including the last one) of a `vector<string>` the following construction may be used:

    ```
    extern vector<string> container;
    deque<string> object(&container[5], &container[11]);
    ```

- In addition to the standard operators for containers, the deque supports the index operator, which may be used to retrieve or reassign random elements of the deque. Note that the indexed elements must exist.
- The following member functions are available for deques:
  - `void assign(...)`:

    assigns new content to the deque:

    - `assign(iterator begin, iterator end)` assigns the values at the iterator range `[begin, end)` to the deque;
    - `assign(size_type n, value_type const &val)` assigns `n` copies of `val` to the deque;
  - `Type &at(size_t idx)`:

    returns a reference to the deque's element at index position `idx`. If `idx` exceeds the deque's size a `std::out_of_range` exception is thrown.
  - `Type &back()`:
    returns a reference to the last element in the deque. It is the responsibility of the programmer to use the member only if the deque is not empty.
  - `deque::iterator begin()`:
    returns an iterator pointing to the first element in the deque.
  - `deque::const_iterator cbegin()`:

    returns a const_iterator pointing to the first element in the deque, returning `cend` if the deque is empty.
  - `deque::const_iterator cend()`:

    returns a const_iterator pointing just beyond the deque's last element.
  - `void clear()`:
    erases all elements in the deque.
  - `deque::const_reverse_iterator crbegin()`:

    returns a const_reverse_iterator pointing to the last element in the deque, returning `crend` if the deque is empty.
  - `deque::const_reverse_iterator crend()`:

    returns a const_reverse_iterator pointing just before the deque's first element.
  - `iterator emplace(const_iterator position, Args &&...args)`

    a `value_type` object is constructed from the arguments specified after `position`, and the newly created element is inserted at `position`.
  - `void emplace_back(Args &&...args)`

    a `value_type` object is constructed from the member's arguments, and the newly created element is inserted beyond the deque's last element.
  - `void emplace_front(Args &&...args)`

    a `value_type` object is constructed from the member's arguments, and the newly created element is inserted before the deque's first element.
  - `bool empty()`:
    returns `true` if the deque contains no elements.
  - `deque::iterator end()`:
    returns an iterator pointing beyond the last element in the deque.
  - `deque::iterator erase()`:
    the member can be used to erase a specific range of elements in the deque:
    - `erase(pos)` erases the element pointed to by `pos`. The iterator `++pos` is returned.

  - `erase(first, beyond)` erases elements indicated by the iterator range `[first, beyond)`. `Beyond` is returned.

- `Type &front()`:
  returns a reference to the first element in the deque. It is the responsibility of the programmer to use the member only if the deque is not empty.
- `allocator_type get_allocator() const`:
  returns a copy of the allocator object used by the `deque` object.
- `... insert()`:
  inserts elements starting at a certain position. The return value depends on the version of `insert` that is called:
  - `deque::iterator insert(pos)` inserts a default value of type `Type` at `pos`, `pos` is returned.
  - `deque::iterator insert(pos, value)` inserts `value` at `pos`, `pos` is returned.
  - `void insert(pos, first, beyond)` inserts the elements in the iterator range `[first, beyond)`.
  - `void insert(pos, n, value)` inserts `n` elements having value `value` starting at iterator position `pos`.
- `size_t max_size()`:
  returns the maximum number of elements this `deque` may contain.
- `void pop_back()`:
  removes the last element from the deque. Avoid calling this member on an empty deque: although nothing is returned its internally maintained count of number of available elements is reduced, causing the deque's `size()` member to return the (when cast to `int`) value -1, and then -2, etc., etc.
- `void pop_front()`:
  removes the first element from the deque. Avoid calling this member on an empty deque: as with `pop_back()` its internally maintained count of number of available elements is reduced
- `void push_back(value)`:
  adds `value` to the end of the deque.
- `void push_front(value)`:
  adds `value` before the first element of the deque.
- `deque::reverse_iterator rbegin()`:
  returns a reverse_iterator pointing to the last element in the deque.
- `deque::reverse_iterator rend()`:
  this member returns a reverse_iterator pointing before the first element in the deque.
- `void resize()`:
  alters the number of elements that are currently stored in the deque:
  - `resize(n, value)` may be used to resize the deque to a size of `n`. `Value` is optional. If the deque is expanded and `value` is not provided, the additional elements are initialized to the default value of the used data type, otherwise `value` is used to initialize extra elements.
- `void shrink_to_fit()`:
  optionally reduces the amount of memory allocated by a deque to its current size. The implementor is free to ignore or otherwise optimize this request. In order to guarantee a 'shrink to fit' operation `deque<Type>(dequeObject).swap(dequeObject)` idiom can be used.
- `size_t size()`:
  returns the number of elements in the deque.
- `void swap(argument)`:
  swaps two deques using identical data types.

12.4.7 The 'map' container

The `map` class offers a (sorted) associative array. Before using a `map` container the `<map>` header file must be included.

A `map` is filled with *key, value* pairs, which may be of any container-accepted type. Since types are associated with both the key and the value, we must specify *two types* in the angle bracket notation, comparable to the specification we've seen with the `pair` container (cf. section 12.2). The first type represents the key's type, the second type represents the value's type. For example, a `map` in which the key is a `string` and the value is a `double` can be defined as follows:

```
map<string, double> object;
```

The *key* is used to access its associated information. That information is called the *value*. For example, a phone book uses the names of people as the key, and uses the telephone number and maybe other information (e.g., the zip-code, the address, the profession) as value. Since a `map` sorts its keys, the `key`'s `operator<` must be defined, and it must be sensible to use it. For example, it is generally a bad idea to use pointers for keys, as sorting pointers is something different than sorting the values pointed at by those pointers. In addition to the *key, value* types, a third type defines the comparison class, used to compare two keys. By default, the comparison class is `std::less<KeyType` (cf. section 18.1.2), using the key type's `operator<` to compare two key values. For key type `KeyType` and value type `ValueType` the map's type definition, therefore, looks like this:

```
map<KeyType, ValueType, std::less<KeyType>>
```

The two fundamental operations on maps are the storage of *key, value* combinations, and the retrieval of values, given their keys. The index operator using a key as the index, can be used for both. If the index operator is used as *lvalue*, the expression's `rvalue` is inserted into the map. If it is used as *rvalue*, the key's associated value is retrieved. Each key can be stored only once in a `map`. If the same key is entered again, the new value replaces the formerly stored value, which is lost.

A specific *key, value* combination can implicitly or explicitly be inserted into a `map`. If explicit insertion is required, the *key, value* combination must be constructed first. For this, every `map` defines a `value_type` which may be used to create values that can be stored in the `map`. For example, a value for a `map<string, int>` can be constructed as follows:

```
map<string, int>::value_type siValue{ "Hello", 1 };
```

The `value_type` is associated with the `map<string, int>`: the type of the key is `string`, the type of the value is `int`. Anonymous `value_type` objects are also often used. E.g.,

```
map<string, int>::value_type{ "Hello", 1 };
```

Instead of using the line `map<string, int>::value_type(...)` over and over again, a `typedef` is frequently used to reduce typing and to improve readability:

```
typedef map<string, int>::value_type StringIntValue
```

Using this typedef, values for the `map<string, int>` may now be constructed using:

```
StringIntValue{ "Hello", 1 };
```

Alternatively, `pairs` may be used to represent *key, value* combinations used by maps:

```
pair<string, int>{ "Hello", 1 };
```

12.4.7.1 The ‘map’ constructors

The following constructors are available for the `map` container:

- The copy and move constructors are available;
- A `map` may be constructed empty:

  ```
  map<string, int> object;
  ```

  Note that the values stored in maps may be containers themselves. For example, the following defines a `map` in which the value is a `pair`: a container nested under another container:

  ```
      map<string, pair<string, string>> object;
  ```

  Note the use of the two consecutive closing angle brackets, which does not result in ambiguities as their syntactical context differs from their use as binary operators in expressions.

- A map may be initialized using two iterators. The iterators may either point to `value_type` values for the map to be constructed, or to plain `pair` objects. If pairs are used, their `first` element represents the type of the keys, and their `second` element represents the type of the values. Example:

  ```
  pair<string, int> pa[] =
  {
      pair<string,int>("one", 1),
      pair<string,int>("two", 2),
      pair<string,int>("three", 3),
  };

  map<string, int> object(&pa[0], &pa[3]);
  ```

  In this example, `map<string, int>::value_type` could have been written instead of `pair<string, int>` as well.

  If `begin` represents the first iterator that is used to construct a map and if `end` represents the second iterator, `[begin, end)` will be used to initialize the map. Maybe contrary to intuition, the `map` constructor only enters *new* keys. If the last element of `pa` would have been `"one", 3`, only *two* elements would have entered the `map`: `"one", 1` and `"two", 2`. The value `"one", 3` would silently have been ignored.

  The `map` receives its own copies of the data to which the iterators point as illustrated by the following example:

  ```
      #include <iostream>
      #include <map>
      using namespace std;

      class MyClass
      {
          public:
              MyClass()
              {
                  cout << "MyClass constructor\n";
              }
              MyClass(MyClass const &other)
              {
  ```

```
                cout << "MyClass copy constructor\n";
            }
            ~MyClass()
            {
                cout << "MyClass destructor\n";
            }
    };

    int main()
    {
        pair<string, MyClass> pairs[] =
        {
            pair<string, MyClass>{ "one", MyClass{} }
        };
        cout << "pairs constructed\n";

        map<string, MyClass> mapsm{ &pairs[0], &pairs[1] };
        cout << "mapsm constructed\n";
    }
    /*
        Generated output:
    MyClass constructor
    MyClass copy constructor
    MyClass destructor
    pairs constructed
    MyClass copy constructor
    mapsm constructed
    MyClass destructor
    MyClass destructor
    */
```

When tracing the output of this program, we see that, first, the constructor of a `MyClass` object is called to initialize the anonymous element of the array `pairs`. This object is then copied into the first element of the array `pairs` by the copy constructor. Next, the original element is not required anymore and is destroyed. At that point the array `pairs` has been constructed. Thereupon, the `map` constructs a temporary `pair` object, which is used to construct the map element. Having constructed the map element, the temporary `pair` object is destroyed. Eventually, when the program terminates, the `pair` element stored in the `map` is destroyed too.

12.4.7.2 The 'map' operators

The map supports, in addition to the standard operators for containers, the index operator.

The index operator may be used to retrieve or reassign individual elements of the map. The argument of the index operator is called a *key*.

If the provided key is not available in the `map`, a new data element is automatically added to the `map` using the default value or default constructor to initialize the value part of the new element. This default value is returned if the index operator is used as an rvalue.

When initializing a new or reassigning another element of the map, the type of the right-hand side of the assignment operator must be equal to (or promotable to) the type of the map's value part. E.g., to add or change the value of element `"two"` in a map, the following statement can be used:

```
mapsm["two"] = MyClass{};
```

12.4.7.3 The ‘map’ public members

The following member functions are available for the `map` container:

- `mapped_type &at(key_type const &key)`:
  returns a reference to the map’s `mapped_type` associated with `key`. If the key is not stored in the `map` an `std::out_of_range` exception is thrown.

- `map::iterator begin()`:
  returns an iterator pointing to the first element of the map.

- `map::const_iterator cbegin()`:
  returns a const_iterator pointing to the first element in the map, returning `cend` if the map is empty.

- `map::const_iterator cend()`:
  returns a const_iterator pointing just beyond the map’s last element.

- `void clear()`:
  erases all elements from the map.

- `size_t count(key)`:
  returns 1 if the provided key is available in the `map`, otherwise 0 is returned.

- `map::reverse_iterator crbegin() const`:
  reverse_iterator returns a reverse_iterator pointing to the last element of the map.

- `map::reverse_iterator crend()`:
  returns an iterator pointing before the first element of the map.

- `pair<iterator, bool> emplace(Args &&...args)`:
  a `value_type` object is constructed from `emplace`’s arguments. If the `map` already contained an object using the same `key_type` value, then a `std::pair` is returned containing an iterator pointing to the object using the same `key_type` value and the value `false`. If no such `key_type` value was found, the newly constructed object is inserted into the `map`, and the returned `std::pair` contains an iterator pointing to the newly inserted `value_type` as well as the value `true`.

- `iterator emplace_hint(const_iterator position, Args &&...args)`:
  a `value_type` object is constructed from the member’s arguments, and the newly created element is inserted into the `map`, unless the (at `args`) provided key already exists. The implementation may or may not use `position` as a *hint* to start looking for an insertion point. The returned `iterator` points to the `value_type` using the provided key. It may refer to an already existing `value_type` or to a newly added `value_type`; an existing `value_type` is not replaced. If a new value *was* added, then the container’s size has been incremented when `emplace_hint` returns.

- `bool empty()`:
  returns `true` if the map contains no elements.

- `map::iterator end()`:
  returns an iterator pointing beyond the last element of the map.

- `pair<map::iterator, map::iterator> equal_range(key)`:
  this member returns a pair of iterators, being respectively the return values of the member functions `lower_bound` and `upper_bound`, introduced below. An example illustrating these member functions is given at the discussion of the member function `upper_bound`.

- `... erase()`:
  erases a specific element or range of elements from the map:
  - `bool erase(key)` erases the element having the given `key` from the `map`. `True` is returned if the value was removed, `false` if the map did not contain an element using the given `key`.
  - `void erase(pos)` erases the element pointed to by the iterator `pos`.
  - `void erase(first, beyond)` erases all elements indicated by the iterator range `[first, beyond)`.
- `map::iterator find(key)`:
  returns an iterator to the element having the given key. If the element isn't available, `end` is returned. The following example illustrates the use of the `find` member function:

```
#include <iostream>
#include <map>
using namespace std;

int main()
{
    map<string, int> object;

    object["one"] = 1;

    map<string, int>::iterator it = object.find("one");

    cout << "`one' " <<
            (it == object.end() ? "not " : "") << "found\n";

    it = object.find("three");

    cout << "`three' " <<
            (it == object.end() ? "not " : "") << "found\n";
}
/*
    Generated output:
`one' found
`three' not found
*/
```

- `allocator_type get_allocator() const`:
  returns a copy of the allocator object used by the `map` object.
- `... insert()`:
  inserts elements into the map. Values associated with already existing keys, however, are not replaced by new values. Its return value depends on the version of `insert` that is called:
  - `pair<map::iterator, bool> insert(keyvalue)` inserts a new `value_type` into the map. The return value is a `pair<map::iterator, bool>`. If the returned `bool` field is `true`, `keyvalue` was inserted into the map. The value `false` indicates that the key that was specified in `keyvalue` was already available in the map, and so `keyvalue` was not inserted into the map. In both cases the `map::iterator` field points to the data element having the `key` that was specified in `keyvalue`. The use of this variant of `insert` is illustrated by the following example:

```
#include <iostream>
#include <string>
```

```
#include <map>
using namespace std;

int main()
{
    pair<string, int> pa[] =
    {
        pair<string,int>("one", 10),
        pair<string,int>("two", 20),
        pair<string,int>("three", 30),
    };
    map<string, int> object(&pa[0], &pa[3]);

            // {four, 40} and `true' is returned
    pair<map<string, int>::iterator, bool>
        ret = object.insert
                (
                    map<string, int>::value_type
                    ("four", 40)
                );

    cout << boolalpha;

    cout << ret.first->first << " " <<
        ret.first->second << " " <<
        ret.second << " " << object["four"] << '\n';

            // {four, 40} and `false' is returned
    ret = object.insert
                (
                    map<string, int>::value_type
                    ("four", 0)
                );

    cout << ret.first->first << " " <<
        ret.first->second << " " <<
        ret.second << " " << object["four"] << '\n';
}
/*
    Generated output:

    four 40 true 40
    four 40 false 40
*/
```

Note the somewhat peculiar constructions like

```
cout << ret.first->first << " " << ret.first->second << ...
```

Note that '`ret`' is equal to the `pair` returned by the `insert` member function. Its '`first`' field is an iterator into the `map<string, int>`, so it can be considered a pointer to a `map<string, int>::value_type`. These value types themselves are pairs too, having '`first`' and '`second`' fields. Consequently, '`ret.first->first`' is the *key* of the map value (a `string`), and '`ret.first->second`' is the *value* (an `int`).

- `map::iterator insert(pos, keyvalue)`. This way a `map::value_type` may also be inserted into the map. `pos` is ignored, and an iterator to the inserted element is returned.

  - `void insert(first, beyond)` inserts the (`map::value_type`) elements pointed to by the iterator range `[first, beyond)`. Values that were already present are not replaced.

- `key_compare key_comp()`:
  returns a copy of the object used by the `map` to compare keys. The type `map<KeyType, ValueType>::key_compare` is defined by the map container and `key_compare`'s parameters have types `KeyType const &`. The comparison function returns `true` if the first key argument should be ordered before the second key argument. To compare keys *and* values, use `value_comp`, listed below.

- `map::iterator lower_bound(key)`:
  returns an iterator pointing to the first `keyvalue` element of which the `key` is at least equal to the specified `key`. If no such element exists, the function returns `end`.

- `size_t max_size()`:
  returns the maximum number of elements this `map` may contain.

- `map::reverse_iterator rbegin()`:
  returns a reverse_iterator pointing to the last element of the map.

- `map::reverse_iterator rend()`:
  returns an iterator pointing before the first element of the map.

- `size_t size()`:
  returns the number of elements in the map.

- `void swap(argument)`:
  swaps two maps using identical key/value types.

- `map::iterator upper_bound(key)`:
  returns an iterator pointing to the first `keyvalue` element having a `key` exceeding the specified `key`. If no such element exists, the function returns `end`. The following example illustrates the member functions `equal_range`, `lower_bound` and `upper_bound`:

```
#include <iostream>
#include <map>
using namespace std;

int main()
{
    pair<string, int> pa[] =
    {
        pair<string,int>("one", 10),
        pair<string,int>("two", 20),
        pair<string,int>("three", 30),
    };
    map<string, int> object(&pa[0], &pa[3]);
    map<string, int>::iterator it;

    if ((it = object.lower_bound("tw")) != object.end())
        cout << "lower-bound `tw' is available, it is: " <<
                it->first << '\n';

    if (object.lower_bound("twoo") == object.end())
        cout << "lower-bound `twoo' not available" << '\n';

    cout << "lower-bound two: " <<
            object.lower_bound("two")->first <<
            " is available\n";
        if ((it = object.upper_bound("tw")) != object.end())
            cout << "upper-bound `tw' is available, it is: " <<
                    it->first << '\n';

        if (object.upper_bound("twoo") == object.end())
            cout << "upper-bound `twoo' not available" << '\n';

        if (object.upper_bound("two") == object.end())
            cout << "upper-bound `two' not available" << '\n';

        pair
        <
            map<string, int>::iterator,
            map<string, int>::iterator
        >
            p = object.equal_range("two");

        cout << "equal range: `first' points to " <<
                    p.first->first << ", `second' is " <<
            (
                p.second == object.end() ?
                    "not available"
                :
                    p.second->first
            ) <<
            '\n';
    }
    /*
        Generated output:

            lower-bound `tw' is available, it is: two
            lower-bound `twoo' not available
            lower-bound two: two is available
            upper-bound `tw' is available, it is: two
            upper-bound `twoo' not available
            upper-bound `two' not available
            equal range: `first' points to two, `second' is not available
    */
```

- `value_compare value_comp()`:
  returns a copy of the object used by the `map` to compare keys. The type `map<KeyType, ValueType>::value_compare` is defined by the map container and `value_compare`'s parameters have types `value_type const &`. The comparison function returns `true` if the first key argument should be ordered before the second key argument. The `Value_Type` elements of the `value_type` objects passed to this member are not used by the returned function.

12.4.7.4 The 'map': a simple example

As mentioned at the beginning of section 12.4.7, the `map` represents a sorted associative array. In a `map` the keys are sorted. If an application must visit all elements in a map the `begin` and `end` iterators must be used.

The following example illustrates how to make a simple table listing all keys and values found in a map:

```
#include <iostream>
#include <iomanip>
#include <map>

using namespace std;

int main()
{
    pair<string, int>
        pa[] =
        {
            pair<string,int>("one", 10),
            pair<string,int>("two", 20),
            pair<string,int>("three", 30),
        };
    map<string, int>
        object(&pa[0], &pa[3]);

    for
    (
        map<string, int>::iterator it = object.begin();
            it != object.end();
                ++it
    )
        cout << setw(5) << it->first.c_str() <<
                setw(5) << it->second << '\n';
}
/*
    Generated output:
  one   10
three   30
  two   20
*/
```

12.4.8 The 'multimap' container

Like the `map`, the `multimap` class implements a (sorted) associative array. Before using a `multimap` container the header file `<map>` must be included.

The main difference between the `map` and the `multimap` is that the multimap supports multiple values associated with the same key, whereas the map contains single-valued keys. Note that the multimap also accepts multiple identical values associated with identical keys.

The `map` and the `multimap` have the same set of constructors and member functions, with the exception of the index operator which is not supported with the multimap. This is understandable: if multiple entries of the same key are allowed, which of the possible values should be returned for `object[key]`?

Refer to section 12.4.7 for an overview of the `multimap` member functions. Some member functions, however, deserve additional attention when used in the context of the `multimap` container. These members are discussed below.

- `size_t map::count(key)`:
  returns the number of entries in the multimap associated with the given `key`.

- `... erase()`:
  erases elements from the map:
  - `size_t erase(key)` erases all elements having the given `key`. The number of erased elements is returned.
  - `void erase(pos)` erases the single element pointed to by `pos`. Other elements possibly having the same keys are not erased.
  - `void erase(first, beyond)` erases all elements indicated by the iterator range `[first, beyond)`.
- `pair<multimap::iterator, multimap::iterator> equal_range(key)`:
  returns a pair of iterators, being respectively the return values of `lower_bound` and `upper_bound`, introduced below. The function provides a simple means to determine all elements in the `multimap` that have the same `keys`. An example illustrating the use of these member functions is given at the end of this section.
- `multimap::iterator find(key)`:
  this member returns an iterator pointing to the first value whose key is `key`. If the element isn't available, `end` is returned. The iterator could be incremented to visit all elements having the same `key` until it is either `end`, or the iterator's `first` member is not equal to `key` anymore.
- `multimap::iterator insert()`:
  this member function normally succeeds, and so a *multimap::iterator* is returned, instead of a `pair<multimap::iterator, bool>` as returned with the `map` container. The returned iterator points to the newly added element.

Although the functions `lower_bound` and `upper_bound` act identically in the `map` and `multimap` containers, their operation in a `multimap` deserves some additional attention. The next example illustrates `lower_bound`, `upper_bound` and `equal_range` applied to a `multimap`:

```
#include <iostream>
#include <map>
using namespace std;

int main()
{
    pair<string, int> pa[] =
    {
        pair<string,int>("alpha", 1),
        pair<string,int>("bravo", 2),
        pair<string,int>("charlie", 3),
        pair<string,int>("bravo", 6),   // unordered `bravo' values
        pair<string,int>("delta", 5),
        pair<string,int>("bravo", 4),
    };
    multimap<string, int> object(&pa[0], &pa[6]);

    typedef multimap<string, int>::iterator msiIterator;

    msiIterator it = object.lower_bound("brava");

    cout << "Lower bound for `brava': " <<
            it->first << ", " << it->second << '\n';

    it = object.upper_bound("bravu");
```

```
        cout << "Upper bound for `bravu': " <<
                it->first << ", " << it->second << '\n';

        pair<msiIterator, msiIterator>
            itPair = object.equal_range("bravo");

        cout << "Equal range for `bravo':\n";
        for (it = itPair.first; it != itPair.second; ++it)
            cout << it->first << ", " << it->second << '\n';
        cout << "Upper bound: " << it->first << ", " << it->second << '\n';

        cout << "Equal range for `brav':\n";
        itPair = object.equal_range("brav");
        for (it = itPair.first; it != itPair.second; ++it)
            cout << it->first << ", " << it->second << '\n';
        cout << "Upper bound: " << it->first << ", " << it->second << '\n';
    }
    /*
        Generated output:

        Lower bound for `brava': bravo, 2
        Upper bound for `bravu': charlie, 3
        Equal range for `bravo':
        bravo, 2
        bravo, 6
        bravo, 4
        Upper bound: charlie, 3
        Equal range for `brav':
        Upper bound: bravo, 2
    */
```

In particular note the following characteristics:

- `lower_bound` and `upper_bound` produce the same result for non-existing keys: they both return the first element having a key that exceeds the provided key.
- Although the keys are ordered in the `multimap`, the values for equal keys are not ordered: they are retrieved in the order in which they were entered.

12.4.9 The 'set' container

The `set` class implements a sorted collection of values. Before using `set` containers the `<set>` header file must be included.

A set contains unique values (of a container-acceptable type). Each value is stored only once.

A specific value can be explicitly created: Every `set` defines a `value_type` which may be used to create values that can be stored in the `set`. For example, a value for a `set<string>` can be constructed as follows:

```
    set<string>::value_type setValue{ "Hello" };
```

Like the `std::map` container, the `std::set` also has an additional parameter declaring the class that is used for comparing values in the set. For value type `ValueType` the set's type definition, therefore, looks like this:

```
set<ValueType, std::less<ValueType>>
```

The `value_type` is associated with the `set<string>`. Anonymous `value_type` objects are also often used. E.g.,

```
set<string>::value_type{ "Hello" };
```

Instead of using the line `set<string>::value_type(...)` over and over again, a `typedef` is often used to reduce typing and to improve readability:

```
typedef set<string>::value_type StringSetValue
```

Using this typedef, values for the `set<string>` may be constructed as follows:

```
StringSetValue{ "Hello" };
```

Alternatively, values of the set's type may be used immediately. In that case the value of type `Type` is implicitly converted to a `set<Type>::value_type`.

The following constructors, operators, and member functions are available for the `set` container:

- Constructors:
  - The copy and move constructors are available;
  - A `set` may be constructed empty:

    ```
    set<int> object;
    ```
  - A set may be initialized using two iterators. For example:

    ```
    int intarr[] = {1, 2, 3, 4, 5};

    set<int> object{ &intarr[0], &intarr[5] };
    ```

  Note that all values in the set must be different: it is not possible to store the same value repeatedly when the set is constructed. If the same value occurs repeatedly, only the first instance of the value is entered into the set; the remaining values are silently ignored.

  Like the map, the `set` receives its own copy of the data it contains.

- The `set` container only supports the standard set of operators that are available for containers.

- The `set` class has the following member functions:
  - `set::iterator begin()`:
    returns an iterator pointing to the first element of the set. If the set is empty `end` is returned.
  - `void clear()`:
    erases all elements from the set.
  - `size_t count(value)`:
    returns 1 if the specified value is available in the `set`, otherwise 0 is returned.
  - `bool empty()`:
    returns `true` if the set contains no elements.
  - `set::iterator end()`:
    returns an iterator pointing beyond the last element of the set.

- `pair<set::iterator, set::iterator> equal_range(value)`:
  this member returns a pair of iterators, being respectively the return values of the member functions `lower_bound` and `upper_bound`, introduced below.
- `... erase()`:
  erases a specific element or range of elements from the set:
  - `bool erase(value)` erases the element having the given `value` from the `set`. `True` is returned if the value was removed, `false` if the set did not contain an element '`value`'.
  - `void erase(pos)` erases the element pointed to by the iterator `pos`.
  - `void erase(first, beyond)` erases all elements indicated by the iterator range `[first, beyond)`.
- `set::iterator find(value)`:
  returns an iterator to the element having the given value. If the element isn't available, `end` is returned.
- `allocator_type get_allocator() const`:
  returns a copy of the allocator object used by the `set` object.
- `... insert()`:
  inserts elements into the `set`. If the element already exists, the existing element is left untouched and the element to be inserted is ignored. The return value depends on the version of `insert` that is called:
  - `pair<set::iterator, bool> insert(value)` inserts a new `set::value_type` into the set. The return value is a `pair<set::iterator, bool>`. If the returned `bool` field is `true`, `value` was inserted into the set. The value `false` indicates that the value that was specified was already available in the set, and so the provided `value` was not inserted into the set. In both cases the `set::iterator` field points to the data element in the `set` having the specified `value`.
  - `set::iterator insert(pos, value)`. This way a `set::value_type` may also be inserted into the set. `pos` is ignored, and an iterator to the inserted element is returned.
  - `void insert(first, beyond)` inserts the (`set::value_type`) elements pointed to by the iterator range `[first, beyond)` into the set. Values that were already present are not replaced.
- `key_compare key_comp()`:
  returns a copy of the object used by the `set` to compare keys. The type `set<ValueType>::key_compare` is defined by the set container and `key_compare`'s parameters have types `ValueType const &`. The comparison function returns `true` if its first argument should be ordered before its second argument.
- `set::iterator lower_bound(value)`:
  returns an iterator pointing to the first `value` element of which the `value` is at least equal to the specified `value`. If no such element exists, the function returns `end`.
- `size_t max_size()`:
  returns the maximum number of elements this `set` may contain.
- `set::reverse_iterator rbegin()`:
  returns a reverse_iterator pointing to the last element of the set.
- `set::reverse_iterator rend`:
  returns a reverse_iterator pointing before the first element of the set.
- `size_t size()`:
  returns the number of elements in the set.
- `void swap(argument)`:
  swaps two sets (`argument` being the second set) that use identical data types.

  - `set::iterator upper_bound(value)`:
    returns an iterator pointing to the first `value` element having a `value` exceeding the specified `value`. If no such element exists, the function returns `end`.
  - `value_compare value_comp()`:
    returns a copy of the object used by the `set` to compare values. The type `set<ValueType>::value_compare` is defined by the set container and `value_compare`'s parameters have types `ValueType const &`. The comparison function returns `true` if its first argument should be ordered before its second argument. Its operation is identical to that of a `key_compare` object, returned by `key_comp`.

12.4.10 The 'multiset' container

Like the `set`, the `multiset` class implements a sorted collection of values. Before using `multiset` containers the header file `<set>` must be included.

The main difference between the `set` and the `multiset` is that the `multiset` supports multiple entries of the same value, whereas the `set` contains unique values.

The `set` and the `multiset` have the same set of constructors and member functions. Refer to section 12.4.9 for an overview of the member functions that can be used with the `multiset`. Some member functions, however, behave slightly different than their counterparts of the `set` container. Those members are:

- `size_t count(value)`:
  returns the number of entries in the multiset associated with the given `value`.
- `... erase()`:
  erases elements from the set:
  - `size_t erase(value)` erases all elements having the given `value`. The number of erased elements is returned.
  - `void erase(pos)` erases the element pointed to by the iterator `pos`. Other elements possibly having the same values are not erased.
  - `void erase(first, beyond)` erases all elements indicated by the iterator range `[first, beyond)`.
- `pair<multiset::iterator, multiset::iterator> equal_range(value)`:
  returns a pair of iterators, being respectively the return values of `lower_bound` and `upper_bound`, introduced below. The function provides a simple means to determine all elements in the `multiset` that have the same `values`.
- `multiset::iterator find(value)`:
  returns an iterator pointing to the first element having the specified value. If the element isn't available, `end` is returned. The iterator could be incremented to visit all elements having the given `value` until it is either `end`, or the iterator doesn't point to '`value`' anymore.
- `... insert()`:
  this member function normally succeeds and returns a *multiset::iterator* rather than a `pair<multiset::iterator, bool>` as returned with the `set` container. The returned iterator points to the newly added element.

Although the functions `lower_bound` and `upper_bound` act identically in the `set` and `multiset` containers, their operation in a `multiset` deserves some additional attention. With a `multiset` container `lower_bound` and `upper_bound` produce the same result for non-existing keys: they both return the first element having a key exceeding the provided key.

Here is an example showing the use of various member functions of a multiset:

```
#include <iostream>
#include <set>

using namespace std;

int main()
{
    string
        sa[] =
        {
            "alpha",
            "echo",
            "hotel",
            "mike",
            "romeo"
        };

    multiset<string>
        object(&sa[0], &sa[5]);

    object.insert("echo");
    object.insert("echo");

    multiset<string>::iterator
        it = object.find("echo");

    for (; it != object.end(); ++it)
        cout << *it << " ";
    cout << '\n';

    cout << "Multiset::equal_range(\"ech\")\n";
    pair
    <
        multiset<string>::iterator,
        multiset<string>::iterator
    >
        itpair = object.equal_range("ech");

    if (itpair.first != object.end())
        cout << "lower_bound() points at " << *itpair.first << '\n';
    for (; itpair.first != itpair.second; ++itpair.first)
        cout << *itpair.first << " ";

    cout << '\n' <<
            object.count("ech") << " occurrences of 'ech'" << '\n';

    cout << "Multiset::equal_range(\"echo\")\n";
    itpair = object.equal_range("echo");

    for (; itpair.first != itpair.second; ++itpair.first)
        cout << *itpair.first << " ";

    cout << '\n' <<
```

```
                object.count("echo") << " occurrences of 'echo'" << '\n';

        cout << "Multiset::equal_range(\"echoo\")\n";
        itpair = object.equal_range("echoo");

        for (; itpair.first != itpair.second; ++itpair.first)
            cout << *itpair.first << " ";

        cout << '\n' <<
                object.count("echoo") << " occurrences of 'echoo'" << '\n';
    }
    /*
        Generated output:

        echo echo echo hotel mike romeo
        Multiset::equal_range("ech")
        lower_bound() points at echo

        0 occurrences of 'ech'
        Multiset::equal_range("echo")
        echo echo echo
        3 occurrences of 'echo'
        Multiset::equal_range("echoo")

        0 occurrences of 'echoo'
    */
```

12.4.11 The ‘stack’ container

The `stack` class implements a stack data structure. Before using `stack` containers the header file `<stack>` must be included.

A stack is also called a first in, last out (FILO or LIFO) data structure as the first item to enter the stack is the last item to leave. A stack is an extremely useful data structure in situations where data must temporarily remain available. For example, programs maintain a stack to store local variables of functions: the lifetime of these variables is determined by the time these functions are active, contrary to global (or static local) variables, which live for as long as the program itself lives. Another example is found in calculators using the *Reverse Polish Notation* (RPN), in which the operands of operators are kept in a stack, whereas operators pop their operands off the stack and push the results of their work back onto the stack.

As an example of the use of a stack, consider figure 12.5, in which the content of the stack is shown while the expression `(3 + 4) * 2` is evaluated. In the RPN this expression becomes `3 4 + 2 *`, and figure 12.5 shows the stack content after each *token* (i.e., the operands and the operators) is read from the input. Notice that each operand is indeed pushed on the stack, while each operator changes the content of the stack. The expression is evaluated in five steps. The caret between the tokens in the expressions shown on the first line of figure 12.5 shows what token has just been read. The next line shows the actual stack-content, and the final line shows the steps for referential purposes. Note that at step 2, two numbers have been pushed on the stack. The first number (`3`) is now at the bottom of the stack. Next, in step 3, the `+` operator is read. The operator pops two operands (so that the stack is empty at that moment), calculates their sum, and pushes the resulting value (`7`) on the stack. Then, in step 4, the number `2` is read, which is dutifully pushed on the stack again. Finally, in step 5 the final operator `*` is read, which pops the values `2` and `7` from the stack, computes their product, and pushes the result back on the stack. This result (`14`) could then be popped to be displayed on some medium.

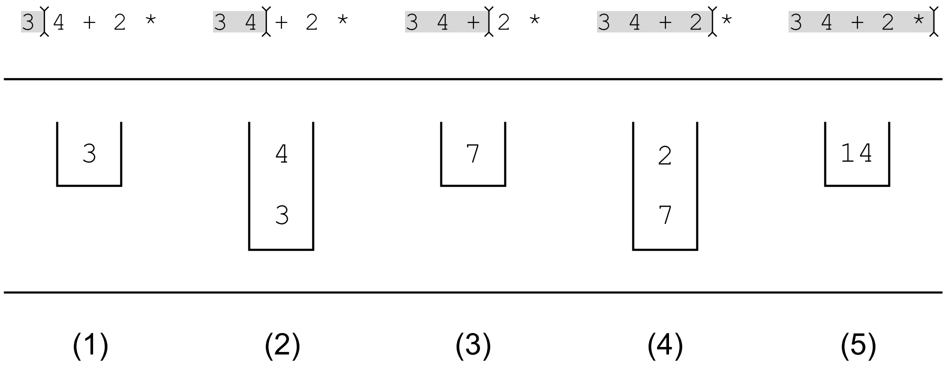

Figure 12.5: The content of a stack while evaluating `3 4 + 2 *`

From figure 12.5 we see that a stack has one location (the *top*) where items can be pushed onto and popped off the stack. This top element is the stack's only immediately visible element. It may be accessed and modified directly.

Bearing this model of the stack in mind, let's see what we formally can do with the `stack` container. For the `stack`, the following constructors, operators, and member functions are available:

- Constructors:
  - The copy and move constructors are available;
  - A `stack` may be constructed empty:

    `stack<string> object;`
- Only the basic set of container operators are supported by the `stack`
- The following member functions are available for stacks:
  - `bool empty()`:
    this member returns `true` if the stack contains no elements.
  - `void pop()`:
    removes the element at the top of the stack. Note that the popped element is *not* returned by this member. Refer to section 12.4.4 for a discussion about the reason why `pop` has return type `void` and why `pop` should not be called on an empty `stack`.
  - `void push(value)`:
    places `value` at the top of the stack, hiding the other elements from view.
  - `size_t size()`:
    this member returns the number of elements in the stack.
  - `Type &top()`:
    this member returns a reference to the stack's top (and only visible) element. It is the responsibility of the programmer to use this member only if the stack is not empty.

The stack does not support iterators or an index operator. The only elements that can be accessed is its top element. To empty a stack:

- repeatedly remove its front element;
- assign an empty stack to it;
- have its destructor called (e.g., by ending its lifetime).

12.4.12 The ‘unordered_map’ container (‘hash table’)

In **C++** hash tables are available as objects of the class `unordered_map`.

Before using `unordered_map` or `unordered_multimap` containers the header file `<unordered_map>` must be included.

The `unordered_map` class implements an associative array in which the elements are stored according to some *hashing* scheme. As discussed, the map is a sorted data structure. The keys in maps are sorted using the `operator<` of the key's data type. Generally, this is not the fastest way to either store or retrieve data. The main benefit of sorting is that a listing of sorted keys appeals more to humans than an unsorted list. However, a by far faster way to store and retrieve data is to use *hashing*.

Hashing uses a function (called the *hash function*) to compute an (unsigned) number from the key, which number is thereupon used as an index in the table storing the keys and their values. This number is called the *bucket number*. Retrieval of a key is as simple as computing the hash value of the provided key, and looking in the table at the computed index location: if the key is present, it is stored in the table, at the computed bucket location and its value can be returned. If it's not present, the key is not currently stored in the container.

Collisions occur when a computed index position is already occupied by another element. For these situations the abstract containers have solutions available. A simple solution, used by `unordered_maps`, consists of using *linear chaining*, which uses linked list to store colliding table elements.

The term *unordered_map* is used rather than *hash* to avoid name collisions with hash tables developed before they were added to the language.

Because of the hashing method, the *efficiency* of a `unordered_map` in terms of speed should greatly exceed the efficiency of the `map`. Comparable conclusions may be drawn for the `unordered_set`, the `unordered_multimap` and the `unordered_multiset`.

12.4.12.1 The ‘unordered_map’ constructors

When defining an `unordered_map` type five template arguments must be specified :

- a KeyType (becoming `unordered_map::key_type`),
- a ValueType (becoming `unordered_map::mapped_type`),
- the type of an object computing a hash value from a key value (becoming `unordered_map::hasher`), and
- the type of an object that can compare two keys for equality (becoming `unordered_map::key_equal`).
- the type of its allocator. This is usually left unspecified, using the allocator provided by default by the implementor.

The generic definition of an `unordered_map` container looks like this:

```
std::unordered_map <KeyType, ValueType, hash type, predicate type,
                    allocator type>
```

When `KeyType` is `std::string` or a built-in type then default types are available for the hash type and the predicate type. In practice the allocator type is not specified, as the default allocator suffices.

In these cases an `unordered_map` object can be defined by merely specifying the key- and value types, like this:

```
std::unordered_map<std::string, ValueType> hash(size_t size = implSize);
```

Here, `implSize` is the container's default initial size, which is specified by the implementor. The map's size is automatically enlarged by the `unordered_map` when necessary, in which case the container *rehashes* all its elements. In practice the default `size` argument provided by the implementor is completely satisfactory.

The `KeyType` frequently consists of text. So, a `unordered_map` using a `std::string KeyType` is frequently used. Be careful not to use a plain `char const * key_type` as two `char const *` values pointing to equal **C**-strings stored at different locations are considered to be different keys, as their pointer values rather than their textual content are compared. Here is an example showing how a `char const * KeyType` can be used. Note that in the example no arguments are specified when constructing `months`, since default values and constructors are available:

```
#include <unordered_map>
#include <iostream>
#include <string>
#include <cstring>

using namespace std;

struct EqualCp
{
    bool operator()(char const *l, char const *r) const
    {
        return strcmp(l, r) == 0;
    }
};
struct HashCp
{
    size_t operator()(char const *str) const
    {
        return std::hash<std::string>()(str);
    }
};
int main()
{
    unordered_map<char const *, int, HashCp, EqualCp> months;
    // or explicitly:
        unordered_map<char const *, int, HashCp, EqualCp>
                                  monthsTwo(61, HashCp(), EqualCp());

    months["april"] = 30;
    months["november"] = 31;

    string apr("april");    // different pointers, same string

    cout << "april     -> " << months["april"] << '\n' <<
            "april     -> " << months[apr.c_str()] << '\n';
}
```

If other `KeyTypes` must be used, then the `unordered_map`'s constructor requires (constant references to) a hash function object, computing a hash value from a key value, and a predicate function object, returning `true` if two `unordered_map::key_type` objects are identical. A *generic algorithm* (see chapter 19) exists performing tests of equality (i.e., `equal_to`). These tests can be used if the key's data type supports the equality operator. Alternatively, an overloaded `operator==` or specialized function object could be constructed returning `true` if two keys are equal and `false` otherwise.

Constructors

The `unordered_map` supports the following constructors:

- The copy and move constructors are available;
- `explicit unordered_map(size_type n = implSize, hasher const &hf = hasher(), key_equal const &eql = key_equal(), allocator_type const &alloc = allocator_type())`: this constructor can also be used as default constructor;
- `unordered_map(const_iterator begin, const_iterator end, size_type n = implSize, hasher const &hf = hasher(), key_equal const &eql = key_equal(), allocator_type const &alloc = allocator_type())`: this constructor expects two iterators specifying a range of `unordered_map::value_type const` objects, and
- `unordered_map(initializer_list<value_type> initList, size_type n = implSize, hasher const &hf = hasher(), key_equal const &eql = key_equal(), allocator_type const &alloc = allocator_type())`: a constructor expecting an `initializer_list` of `unordered_map::value_type` values.

The following example shows a program using an unordered_map containing the names of the months of the year and the number of days these months (usually) have. Then, using the subscript operator the days in several months are displayed (the predicate used here is the generic algorithm `equal_to<string>`, which is provided by the compiler as the default fourth argument of the `unordered_map` constructor):

```
#include <unordered_map>
#include <iostream>
#include <string>
using namespace std;

int main()
{
    unordered_map<string, int> months;

    months["january"] = 31;
    months["february"] = 28;
    months["march"] = 31;
    months["april"] = 30;
    months["may"] = 31;
    months["june"] = 30;
    months["july"] = 31;
    months["august"] = 31;
    months["september"] = 30;
    months["october"] = 31;
    months["november"] = 30;
    months["december"] = 31;
    cout << "september -> " << months["september"] << '\n' <<
            "april     -> " << months["april"] << '\n' <<
            "june      -> " << months["june"] << '\n' <<
            "november  -> " << months["november"] << '\n';
}
/*
    Generated output:
september -> 30
april     -> 30
june      -> 30
november  -> 30
*/
```

12.4.12.2 The 'unordered_map' public members

The `unordered_map` supports the index operator operating identically to the `map`'s index operator: a (const) reference to the `ValueType` associated with the provided `KeyType`'s value is returned. If not yet available, the key is added to the `unordered_map`, and a default `ValueType` value is returned. In addition, it supports `operator==`.

The `unordered_map` provides the following member functions (`key_type, value_type` etc. refer to the types defined by the `unordered_map`):

- `mapped_type &at(key_type const &key)`:
  returns a reference to the unordered_map's `mapped_type` associated with `key`. If the key is not stored in the `unordered_map` a `std::out_of_range` exception is thrown.
- `unordered_map::iterator begin()`:
  returns an iterator pointing to the first element in the unordered_map, returning `end` if the unordered_map is empty.
- `size_t bucket(key_type const &key)`:
  returns the index location where `key` is stored. If `key` wasn't stored yet `bucket` adds `value_type(key, Value())` before returning its index position.
- `size_t bucket_count()`:
  returns the number of slots used by the containers. Each slot may contain one (or more, in case of collisions) `value_type` objects.
- `size_t bucket_size(size_t index)`:
  returns the number of `value_type` objects stored at bucket position `index`.
- `unordered_map::const_iterator cbegin()`:
  returns a const_iterator pointing to the first element in the unordered_map, returning `cend` if the unordered_map is empty.
- `unordered_map::const_iterator cend()`:
  returns a const_iterator pointing just beyond the unordered_map's last element.
- `void clear()`:
  erases all the unordered_map's elements.
- `size_t count(key_type const &key)`:
  returns the number of times a `value_type` object using `key_type key` is stored in the `unordered_map` (which is either one or zero).

- `pair<iterator, bool> emplace(Args &&...args)`:
  a `value_type` object is constructed from `emplace`'s arguments. If the `unordered_map` already contained an object using the same `key_type` value, then a `std::pair` is returned containing an iterator pointing to the object using the same `key_type` value and the value `false`. If no such `key_type` value was found, the newly constructed object is inserted into the `unordered_map`, and the returned `std::pair` contains an iterator pointing to the newly inserted inserted `value_type` as well as the value `true`.
- `iterator emplace_hint(const_iterator position, Args &&...args)`:
  a `value_type` object is constructed from the member's arguments, and the newly created element is inserted into the `unordered_map`, unless the (at `args`) provided key already exists. The implementation may or may not use `position` as a *hint* to start looking for an insertion point. The returned `iterator` points to the `value_type` using the provided key. It may refer to an already existing `value_type` or to a newly added `value_type`; an existing `value_type` is not replaced. If a new value *was* added, then the container's size has been incremented when `emplace_hint` returns.
- `bool empty()`:
  returns `true` if the unordered_map contains no elements.
- `unordered_map::iterator end()`:
  returns an iterator pointing beyond the last element in the unordered_map.
- `pair<iterator, iterator> equal_range(key)`:
  this member returns a pair of iterators defining the range of elements having a key that is equal to `key`. With the `unordered_map` this range includes at most one element.
- `unordered_map::iterator erase()`:
  erases a specific range of elements in the unordered_map:
  - `erase(pos)` erases the element pointed to by the iterator `pos`. The iterator `++pos` is returned.
  - `erase(first, beyond)` erases elements indicated by the iterator range `[first, beyond)`, returning `beyond`.
- `iterator find(key)`:
  returns an iterator to the element having the given key. If the element isn't available, `end` is returned.
- `allocator_type get_allocator() const`:
  returns a copy of the allocator object used by the `unordered_map` object.
- `hasher hash_function() const`:
  returns a copy of the hash function object used by the `unordered_map` object.
- `... insert()`:

  elements may be inserted starting at a certain position. No insertion is performed if the provided key is already in use. The return value depends on the version of `insert()` that is called. When a `pair<iterator, bool>` is returned, then the `pair's first` member is an iterator pointing to the element having a key that is equal to the key of the provided `value_type`, the `pair's second` member is `true` if `value` was actually inserted into the container, and `false` if not.

  - `pair<iterator, bool> insert(value_type const &value)` attempts to insert `value`.
  - `pair<iterator, bool> insert(value_type &&tmp)` attempts to insert `value` using `value_type`'s move constructor.

  - `pair<iterator, bool> insert(const_iterator hint, value_type const &value)` attempts to insert `value`, possibly using `hint` as a starting point when trying to insert `value`.
  - `pair<iterator, bool> insert(const_iterator hint, value_type &&tmp)` attempts to insert a `value` using `value_type`'s move constructor, and possibly using `hint` as a starting point when trying to insert `value`.
  - `void insert(first, beyond)` tries to insert the elements in the iterator range `[first, beyond)`.
  - `void insert(initializer_list <value_type> iniList)` attempts to insert the elements in `iniList` into the container.

- `hasher key_eq() const`:
  returns a copy of the `key_equal` function object used by the `unordered_map` object.
- `float load_factor() const`:
  returns the container's current load factor, i.e. `size / bucket_count`.
- `size_t max_bucket_count()`:
  returns the maximum number of buckets this `unordered_map` may contain.
- `float max_load_factor() const`:
  identical to `load_factor`.
- `void max_load_factor(float max)`:
  changes the current maximum load factor to `max`. When a load factor of `max` is reached, the container will enlarge its `bucket_count`, followed by a rehash of its elements. Note that the container's default maximum load factor equals 1.0
- `size_t max_size()`:
  returns the maximum number of elements this `unordered_map` may contain.
- `void rehash(size_t size)`:
  if `size` exceeds the current bucket count, then the bucket count is increased to `size`, followed by a rehash of its elements.
- `void reserve(size_t request)`:
  if `request` is less than or equal to the current bucket count, this call has no effect. Otherwise, the bucket count is increased to a value of at least `request`, followed by a rehash of the container's elements.
- `size_t size()`:
  returns the number of elements in the unordered_map.
- `void swap(unordered_map &other)`:
  swaps the content of the current and the other `unordered_map`.

12.4.12.3 The 'unordered_multimap' container

The `unordered_multimap` allows multiple objects using the same keys to be stored in an unordered map. The `unordered_multimap` container offers the same set of members and constructors as the `unordered_map`, but without the unique-key restriction imposed upon the `unordered_map`.

The `unordered_multimap` does not offer `operator[]` and does not offer `at` members.

Below all members are described whose behavior differs from the behavior of the corresponding `unordered_map` members:

- `at`

    not supported by the `unordered_multimap` container

- `size_t count(key_type const &key)`:
  returns the number of times a `value_type` object using `key_type key` is stored in the `unordered_map`. This member is commonly used to verify whether `key` is available in the `unordered_multimap`.

- `iterator emplace(Args &&...args)`:
  a `value_type` object is constructed from `emplace`'s arguments. The returned `iterator` points to the newly inserted inserted `value_type`.

- `iterator emplace_hint(const_iterator position, Args &&...args)`:
  a `value_type` object is constructed from the member's arguments, and the newly created element is inserted into the `unordered_multimap`. The implementation may or may not use `position` as a *hint* to start looking for an insertion point. The returned `iterator` points to the `value_type` using the provided key.

- `pair<iterator, iterator> equal_range(key)`:
  this member returns a pair of iterators defining the range of elements having a key that is equal to `key`.

- `iterator find(key)`:
  returns an iterator to an element having the given key. If no such element is available, `end` is returned.

- `... insert()`:

  elements may be inserted starting at a certain position. The return value depends on the version of `insert()` that is called. When an `iterator` is returned, then it points to the element that was inserted.

  - `iterator insert(value_type const &value)` inserts `value`.
  - `iterator insert(value_type &&tmp)` inserts `value` using `value_type`'s move constructor.
  - `iterator insert(const_iterator hint, value_type const &value)` inserts `value`, possibly using `hint` as a starting point when trying to insert `value`.
  - `iterator insert(const_iterator hint, value_type &&tmp)` inserts `value` using `value_type`'s move constructor, and possibly using `hint` as a starting point when trying to insert `value`.
  - `void insert(first, beyond)` inserts the elements in the iterator range `[first, beyond)`.
  - `void insert(initializer_list <value_type> iniList)` inserts the elements in `iniList` into the container.

12.4.13 The 'unordered_set' container

The *set* container, like the `map` container, orders its elements. If ordering is not an issue, but fast lookups are, then a hash-based set and/or multi-set may be preferred. **C++** provides such hash-based sets and multi-sets: the `unordered_set` and `unordered_multiset`.

Before using these hash-based set containers the header file `<unordered_set>` must be included.

Elements stored in the `unordered_set` are immutable, but they can be inserted and removed from the container. Different from the `unordered_map`, the `unordered_set` does not use a `ValueType`. The set merely stores elements, and the stored element itself is its own key.

The `unordered_set` has the same constructors as the `unordered_map`, but the set's `value_type` is equal to its `key_type`.

When defining an `unordered_set` type four template arguments must be specified :

- a KeyType (becoming `unordered_set::key_type`),
- the type of an object computing a hash value from a key value (becoming `unordered_set::hasher`), and
- the type of an object that can compare two keys for equality (becoming `unordered_set::key_equal`).
- the type of its allocator. This is usually left unspecified, using the allocator provided by default by the implementor.

The generic definition of an `unordered_set` container looks like this:

```
std::unordered_set <KeyType, hash type, predicate type, allocator type>
```

When `KeyType` is `std::string` or a built-in type then default types are available for the hash type and the predicate type. In practice the allocator type is not specified, as the default allocator suffices. In these cases an `unordered_set` object can be defined by merely specifying the key- and value types, like this:

```
std::unordered_set<std::string> rawSet(size_t size = implSize);
```

Here, `implSize` is the container's default initial size, which is specified by the implementor. The set's size is automatically enlarged when necessary, in which case the container *rehashes* all its elements. In practice the default `size` argument provided by the implementor is completely satisfactory.

The `unordered_set` supports the following constructors:

- The copy and move constructors are available;
- `explicit unordered_set(size_type n = implSize, hasher const &hf = hasher(), key_equal const &eql = key_equal(), allocator_type const &alloc = allocator_type())`: this constructor can also be used as default constructor;
- `unordered_set(const_iterator begin, const_iterator end, size_type n = implSize, hasher const &hf = hasher(), key_equal const &eql = key_equal(), allocator_type const &alloc = allocator_type())`: this constructor expects two iterators specifying a range of `unordered_set::value_type const` objects, and
- `unordered_set(initializer_list<value_type> initList, size_type n = implSize, hasher const &hf = hasher(), key_equal const &eql = key_equal(), allocator_type const &alloc = allocator_type())`: a constructor expecting an `initializer_list` of `unordered_set::value_type` values.

The `unordered_set` does not offer an index operator, and it does not offer an `at` member. Other than those, it offers the same members as the `unordered_map`. Below the members whose behavior differs from the behavior of the `unordered_map` are discussed. For a description of the remaining members, please refer to section 12.4.12.2.

- `iterator emplace(Args &&...args)`:
  a `value_type` object is constructed from `emplace`'s arguments. It is added to the set if it is unique, and an iterator to the `value_type` is returned.

- `iterator emplace_hint(const_iterator position, Args &&...args)`:
  a `value_type` object is constructed from the member's arguments, and if the newly created element is unique it is inserted into the `unordered_set`. The implementation may or may not use `position` as a *hint* to start looking for an insertion point. The returned `iterator` points to the `value_type`.
- `unordered_set::iterator erase()`:
  erases a specific range of elements in the unordered_set:
  - `erase(key_type const &key)` erases `key` from the set. An iterator pointing to the next element is returned.
  - `erase(pos)` erases the element pointed to by the iterator `pos`. The iterator `++pos` is returned.
  - `erase(first, beyond)` erases elements indicated by the iterator range `[first, beyond)`, returning `beyond`.

12.4.13.1 The 'unordered_multiset' container

The `unordered_multiset` allows multiple objects using the same keys to be stored in an unordered set. The `unordered_multiset` container offers the same set of members and constructors as the `unordered_set`, but without the unique-key restriction imposed upon the `unordered_set`.

Below all members are described whose behavior differs from the behavior of the corresponding `unordered_set` members:

- `size_t count(key_type const &key)`:
  returns the number of times a `value_type` object using `key_type key` is stored in the `unordered_set`. This member is commonly used to verify whether `key` is available in the `unordered_multiset`.
- `iterator emplace(Args &&...args)`:
  a `value_type` object is constructed from `emplace`'s arguments. The returned `iterator` points to the newly inserted inserted `value_type`.
- `iterator emplace_hint(const_iterator position, Args &&...args)`:
  a `value_type` object is constructed from the member's arguments, and the newly created element is inserted into the `unordered_multiset`. The implementation may or may not use `position` as a *hint* to start looking for an insertion point. The returned `iterator` points to the `value_type` using the provided key.
- `pair<iterator, iterator> equal_range(key)`:
  this member returns a pair of iterators defining the range of elements having a key that is equal to `key`.
- `iterator find(key)`:
  returns an iterator to an element having the given key. If no such element is available, `end` is returned.
- `... insert()`:

  elements may be inserted starting at a certain position. The return value depends on the version of `insert()` that is called. When an `iterator` is returned, then it points to the element that was inserted.

  - `iterator insert(value_type const &value)` inserts `value`.
  - `iterator insert(value_type &&tmp)` inserts `value` using `value_type`'s move constructor.

- `iterator insert(const_iterator hint, value_type const &value)` inserts `value`, possibly using `hint` as a starting point when trying to insert `value`.
- `iterator insert(const_iterator hint, value_type &&tmp)` inserts `value` using `value_type`'s move constructor, and possibly using `hint` as a starting point when trying to insert `value`.
- `void insert(first, beyond)` inserts the elements in the iterator range `[first, beyond)`.
- `void insert(initializer_list <value_type> iniList)` inserts the elements in `iniList` into the container.

12.4.14 Heterogeneous lookup

The associative containers offered by **C++** allow us to find a value (or values) matching a given key. Traditionally, the type of the key used for the lookup must match the container's key type.

Since the C++14 standard arbitrary lookup key types can be used provided a comparison operator is available to compare that type with the container's key type. Thus, a `char const *` key (or any other type for which an `operator<` overload for `std::string` is available) can be used to lookup values in a `map<std::string, ValueType>`. This is called *heterogeneous lookup*.

Heterogeneous lookup is allowed when the comparator given to the associative container does allow this. The standard library classes `std::less` and `std::greater` were augmented to allow heterogeneous lookup.

12.5 The 'complex' container

The `complex` container defines the standard operations that can be performed on complex numbers. Before using `complex` containers the header file `<complex>` must be included.

The complex number's real and imaginary types are specified as the container's data type. Examples:

```
complex<double>
complex<int>
complex<float>
```

Note that the real and imaginary parts of complex numbers have the same datatypes.

When initializing (or assigning) a complex object, the imaginary part may be omitted from the initialization or assignment resulting in its value being 0 (zero). By default, both parts are zero.

Below it is silently assumed that the used `complex` type is `complex<double>`. Given this assumption, complex numbers may be initialized as follows:

- `target`: A default initialization: real and imaginary parts are 0.
- `target(1)`: The real part is 1, imaginary part is 0
- `target(0, 3.5)`: The real part is 0, imaginary part is 3.5
- `target(source)`: `target` is initialized with the values of `source`.

Anonymous complex values may also be used. In the next example two anonymous complex values are pushed on a stack of complex numbers, to be popped again thereafter:

```
#include <iostream>
#include <complex>
#include <stack>

using namespace std;

int main()
{
    stack<complex<double>>
        cstack;

    cstack.push(complex<double>(3.14, 2.71));
    cstack.push(complex<double>(-3.14, -2.71));

    while (cstack.size())
    {
        cout << cstack.top().real() << ", " <<
                cstack.top().imag() << "i" << '\n';
        cstack.pop();
    }
}
/*
    Generated output:
-3.14, -2.71i
3.14, 2.71i
*/
```

The following member functions and operators are defined for complex numbers (below, `value` may be either a primitive scalar type or a `complex` object):

- Apart from the standard container operators, the following operators are supported from the `complex` container.
  - `complex operator+(value)`:
    this member returns the sum of the current `complex` container and `value`.
  - `complex operator-(value)`:
    this member returns the difference between the current `complex` container and `value`.
  - `complex operator*(value)`:
    this member returns the product of the current `complex` container and `value`.
  - `complex operator/(value)`:
    this member returns the quotient of the current `complex` container and `value`.
  - `complex operator+=(value)`:
    this member adds `value` to the current `complex` container, returning the new value.
  - `complex operator-=(value)`:
    this member subtracts `value` from the current `complex` container, returning the new value.
  - `complex operator*=(value)`:
    this member multiplies the current `complex` container by `value`, returning the new value
  - `complex operator/=(value)`:
    this member divides the current `complex` container by `value`, returning the new value.

- `Type real()`:
  returns the real part of a complex number.
- `Type imag()`:
  returns the imaginary part of a complex number.
- Several mathematical functions are available for the `complex` container, such as `abs`, `arg`, `conj`, `cos`, `cosh`, `exp`, `log`, `norm`, `polar`, `pow`, `sin`, `sinh` and `sqrt`. All these functions are free functions, not member functions, accepting complex numbers as their arguments. For example,

  ```
  abs(complex<double>(3, -5));
  pow(target, complex<int>(2, 3));
  ```

- Complex numbers may be extracted from `istream` objects and inserted into `ostream` objects. The insertion results in an ordered pair `(x, y)`, in which `x` represents the real part and `y` the imaginary part of the complex number. The same form may also be used when extracting a complex number from an `istream` object. However, simpler forms are also allowed. E.g., when extracting `1.2345` the imaginary part is set to 0.

Chapter 13

Inheritance

When programming in **C**, programming problems are commonly approached using a top-down structured approach: functions and actions of the program are defined in terms of sub-functions, which again are defined in sub-sub-functions, etc.. This yields a hierarchy of code: `main` at the top, followed by a level of functions which are called from `main`, etc..

In **C++** the relationship between code and data is also frequently defined in terms of dependencies among *classes*. This looks like *composition* (see section 7.3), where objects of a class contain objects of another class as their data. But the relation described here is of a different kind: a class can be *defined* in terms of an older, pre-existing, class. This produces a new class having all the functionality of the older class, and additionally defining its own specific functionality. Instead of composition, where a given class *contains* another class, we here refer to *derivation*, where a given class *is* or *is-implemented-in-terms-of* another class.

Another term for derivation is *inheritance*: the new class inherits the functionality of an existing class, while the existing class does not appear as a data member in the interface of the new class. When discussing inheritance the existing class is called the *base class*, while the new class is called the *derived class*.

Derivation of classes is often used when the methodology of **C++** program development is fully exploited. In this chapter we first address the syntactic possibilities offered by **C++** for deriving classes. Following this we address some of the specific possibilities offered by class derivation (inheritance).

As we have seen in the introductory chapter (see section 2.4), in the object-oriented approach to problem solving classes are identified during the problem analysis. Under this approach objects of the defined classes represent entities that can be observed in the problem at hand. The classes are placed in a hierarchy, with the top-level class containing limited functionality. Each new derivation (and hence descent in the class hierarchy) adds new functionality compared to yet existing classes.

In this chapter we shall use a simple vehicle classification system to build a hierarchy of classes. The first class is `Vehicle`, which implements as its functionality the possibility to set or retrieve the mass of a vehicle. The next level in the object hierarchy are land-, water- and air vehicles.

The initial object hierarchy is illustrated in Figure 13.1.

This chapter mainly focuses on the technicalities of class derivation. The distinction between inheritance used to create derived classes whose objects should be considered objects of the base class and inheritance used to implement derived classes *in-terms-of* their base classes is postponed until the next chapter (14).

Inheritance (and polymorphism, cf. chapter 14) can be used with classes and structs. It is not defined for unions.

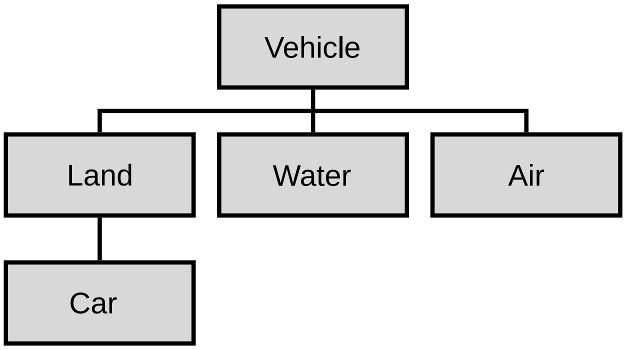

Figure 13.1: Initial object hierarchy of vehicles.

13.1 Related types

The relationship between the proposed classes representing different kinds of vehicles is further investigated here. The figure shows the object hierarchy: a `Car` is a special case of a `Land` vehicle, which in turn is a special case of a `Vehicle`.

The class `Vehicle` represents the 'greatest common divisor' in the classification system. `Vehicle` is given limited functionality: it can store and retrieve a vehicle's mass:

```
class Vehicle
{
    size_t d_mass;

    public:
        Vehicle();
        Vehicle(size_t mass);

        size_t mass() const;
        void setMass(size_t mass);
};
```

Using this class, the vehicle's mass can be defined as soon as the corresponding object has been created. At a later stage the mass can be changed or retrieved.

To represent vehicles traveling over land, a new class `Land` can be defined offering `Vehicle`'s functionality and adding its own specific functionality. Assume we are interested in the speed of land vehicles *and* in their mass. The relationship between `Vehicle`s and `Land`s could of course be represented by composition but that would be awkward: composition suggests that a `Land` vehicle *is-implemented-in-terms-of*, i.e., *contains*, a `Vehicle`, while the natural relationship clearly is that the `Land` vehicle *is* a kind of `Vehicle`.

A relationship in terms of composition would also somewhat complicate our `Land` class's design. Consider the following example showing a class `Land` using composition (only the `setMass` functionality is shown):

```
class Land
{
    Vehicle d_v;        // composed Vehicle
    public:
        void setMass(size_t mass);
};
```

```
void Land::setMass(size_t mass)
{
    d_v.setMass(mass);
}
```

Using composition, the `Land::setMass` function only passes its argument on to `Vehicle::setMass`. Thus, as far as mass handling is concerned, `Land::setMass` introduces no extra functionality, just extra code. Clearly this code duplication is superfluous: a `Land` object *is* a `Vehicle`; to state that a `Land` object *contains* a `Vehicle` is at least somewhat peculiar.

The intended relationship is represented better by inheritance. A rule of thumb for choosing between inheritance and composition distinguishes between *is-a* and *has-a* relationships. A truck *is* a vehicle, so `Truck` should probably derive from `Vehicle`. On the other hand, a truck *has* an engine; if you need to model engines in your system, you should probably express this by composing an `Engine` class inside the `Truck` class.

Following the above rule of thumb, `Land` is *derived* from the base class `Vehicle`:

```
class Land: public Vehicle
{
    size_t d_speed;
    public:
        Land();
        Land(size_t mass, size_t speed);

        void setSpeed(size_t speed);
        size_t speed() const;
};
```

To derive a class (e.g., `Land`) from another class (e.g., `Vehicle`) postfix the class name `Land` in its interface by `: public Vehicle`:

```
class Land: public Vehicle
```

The class `Land` now contains all the functionality of its base class `Vehicle` as well as its own features. Here those features are a constructor expecting two arguments and member functions to access the `d_speed` data member. Here is an example showing the possibilities of the derived class `Land`:

```
Land veh{ 1200, 145 };

int main()
{
    cout << "Vehicle weighs " << veh.mass() << ";\n"
            "its speed is " << veh.speed() << '\n';
}
```

This example illustrates two features of derivation.

- First, `mass` is not mentioned as a member in `Land`'s interface. Nevertheless it is used in `veh.mass`. This member function is an implicit part of the class, inherited from its 'parent' vehicle.

- Second, although the derived class `Land` contains the functionality of `Vehicle`, the `Vehicle`'s private members remain private: they can only be accessed by `Vehicle`'s own member functions. This means that `Land`'s member functions *must* use `Vehicle`'s member functions (like `mass` and `setMass`) to address the `mass` field. Here there's no difference between the access rights granted to `Land` and the access rights granted to other code outside of the class `Vehicle`. The class `Vehicle` *encapsulates* the specific `Vehicle` characteristics, and data hiding is one way to realize encapsulation.

Encapsulation is a core principle of good class design. Encapsulation reduces the dependencies among classes improving the maintainability and testability of classes and allowing us to modify classes without the need to modify depending code. By strictly complying with the principle of data hiding a class's internal data organization may change without requiring depending code to be changed as well. E.g., a class `Lines` originally storing **C**-strings could at some point have its data organization changed. It could abandon its `char **` storage in favor of a `vector<string>` based storage. When `Lines` uses perfect data hiding depending source code may use the new `Lines` class without requiring any modification at all.

As a rule of thumb, derived classes must be fully recompiled (but don't have to be modified) when the *data organization* (i.e., the data members) of their base classes change. Adding new member *functions* to the base class doesn't alter the data organization so no recompilation is needed when new member *functions* are added.

There is one subtle exception to this rule of thumb: if a new member function is added to a base class and that function happens to be declared as the first *virtual* member function of the base class (cf. chapter 14 for a discussion of the virtual member function concept) then that *also* changes the data organization of the base class.

Now that `Land` has been derived from `Vehicle` we're ready for our next class derivation. We'll define a class `Car` to represent automobiles. Agreeing that a `Car` object is a `Land` vehicle, and that a `Car` has a brand name it's easy to design the class `Car`:

```
class Car: public Land
{
    std::string d_brandName;

    public:
        Car();
        Car(size_t mass, size_t speed, std::string const &name);

        std::string const &brandName() const;
};
```

In the above class definition, `Car` was derived from `Land`, which in turn is derived from `Vehicle`. This is called *nested derivation*: `Land` is called `Car`'s *direct base class*, while `Vehicle` is called `Car`'s *indirect base class*.

13.1.1 Inheritance depth: desirable?

Now that `Car` has been derived from `Land` and `Land` has been derived from `Vehicle` we might easily be seduced into thinking that these class hierarchies are the way to go when designing classes. But maybe we should temper our enthusiasm.

Repeatedly deriving classes from classes quickly results in big, complex class hierarchies that are hard to understand, hard to use and hard to maintain. Hard to understand and use as users of our derived class now also have to learn all its (indirect) base class features as well. Hard to maintain because all those classes are very closely coupled. While it may be true that when data hiding is meticulously adhered to derived classes do not have to be modified when their base classes alter their data organization, it also quickly becomes practically infeasible to change those base classes once more and more (derived) classes depend on their current organization.

What initially looks like a big gain, inheriting the base class's interface, thus becomes a liability. The base class's interface is hardly ever completely required and in the end a class may benefit from explicitly defining its own member functions rather than obtaining them through inheritance.

Often classes can be defined *in-terms-of* existing classes: some of their features are used, but others need to be shielded off. Consider the `stack` container: it is commonly implemented in-terms-of a `deque`, returning `deque::back`'s value as `stack::top`'s value.

When using inheritance to implement an *is-a* relationship make sure to get the 'direction of use' right: inheritance aiming at implementing an *is-a* relationship should focus on the base class: the base class facilities aren't there to be used by the derived class, but the derived class facilities should redefine (reimplement) the base class facilities using polymorphism (which is the topic of the next chapter), allowing code to use the derived class facilities polymorphically through the base class. We've seen this approach when studying streams: the base class (e.g., `ostream`) is used time and again. The facilities defined by classes derived from `ostream` (like `ofstream` and `ostringstream`) are then used by code only relying on the facilities offered by the `ostream` class, never using the derived classes directly.

When designing classes always aim at the lowest possible coupling. Big class hierarchies usually indicate poor understanding of robust class design. When a class's interface is only partially used and if the derived class is implemented in terms of another class consider using composition rather than inheritance and define the appropriate interface members in terms of the members offered by the composed objects.

13.2 Access rights: public, private, protected

Early in the **C++** Annotations (cf. section 3.2.1) we encountered two important design principles when developing classes: *data hiding* and *encapsulation*. Data hiding restricts control over an object's data to the members of its class, encapsulation is used to restrict access to the functionality of objects. Both principles are invaluable tools for maintaining data integrity.

The keyword `private` starts sections in class interfaces in which members are declared which can only be accessed by members of the class itself. This is our main tool for realizing data hiding. According to established good practices of class design the public sections are populated with member functions offering a clean interface to the class's functionality. These members allow users to communicate with objects; leaving it to the objects how requests sent to objects are handled. In a well-designed class its objects are in full control of their data.

Inheritance doesn't change these principles, nor does it change the way the '`private`' and '`protected`' keywords operate. A derived class does not have access to a base class's private section.

Sometimes this is a bit too restrictive. Consider a class implementing a random number generating `streambuf` (cf. chapter 6). Such a `streambuf` can be used to construct an `istream irand`, after which extractions from `irand` produces series of random numbers, like in the next example in which 10 random numbers are generated using stream I/O:

```
    RandBuf buffer;
    istream irand(&buffer);
```

```
for (size_t idx = 0; idx != 10; ++idx)
{
    size_t next;
    irand >> next;
    cout << "next random number: " << next << '\n';
}
```

The question is, how many random numbers should `irand` be able to generate? Fortunately, there's no need to answer this question, as `RandBuf` can be made responsible for generating the next random number. RandBuf, therefore, operates as follows:

- It generates a random number;
- It is passed in textual form to its base class `streambuf`;
- The `istream` object extracts this random number, merely using `streambuf`'s interface;

(this process is repeated for subsequent random numbers).

Once `RandBuf` has stored the text representation of the next random number in some buffer, it must tell its base class (`streambuf`) where to find the random number's characters. For this `streambuf` offers a member `setg`, expecting the location and size of the buffer holding the random number's characters.

The member `setg` clearly cannot be declared in `streambuf`'s private section, as `RandBuf` must use it to prepare for the extraction of the next random number. But it should also not be in `streambuf`'s public section, as that could easily result in unexpected behavior by `irand`. Consider the following hypothetical example:

```
RandBuf randBuf;
istream irand(&randBuf);

char buffer[] = "12";
randBuf.setg(buffer, ...);  // setg public: buffer now contains 12

size_t next;
irand >> next;              // not a *random* value, but 12.
```

Clearly there is a close connection between `streambuf` and its derived class `RandBuf`. By allowing `RandBuf` to specify the buffer from which `streambuf` reads characters `RandBuf` remains in control, denying other parts of the program to break its well-defined behavior.

This close connection between base- and derived-classes is realized by a third keyword related to the accessibility of class members: `protected`. Here is how the member `setg` could have been be declared in a class `streambuf`:

```
class streambuf
{
    // private data here (as usual)
    protected:
        void setg(... parameters ...);  // available to derived classes

    public:
        // public members here
};
```

Protected members are members that can be accessed by derived classes, but are not part of a class's public interface.

Avoid the temptation to declare *data members* in a class's protected section: it's a sure sign of bad class design as it needlessly results in tight coupling of base and derived classes. The principle of data hiding should not be abandoned now that the keyword `protected` has been introduced. If a derived class (but not other parts of the software) should be given access to its base class's data, use member functions: accessors and modifiers declared in the base class's protected section. This enforces the intended restricted access without resulting in tightly coupled classes.

13.2.1 Public, protected and private derivation

With inheritance public derivation is frequently used. When public derivation is used the access rights of the base class's interface remains unaltered in the derived class. But the type of inheritance may also be defined as *private* or *protected*.

Protected derivation is used when the keyword `protected` is put in front of the derived class's base class:

```
class Derived: protected Base
```

When protected derivation is used all the base class's public and protected members become protected members in the derived class. The derived class may access all the base class's public and protected members. Classes that are in turn derived from the derived class view the base class's members as protected. Any other code (outside of the inheritance tree) is unable to access the base class's members.

Private derivation is used when the keyword `private` is put in front of the derived class's base class:

```
class Derived: private Base
```

When private derivation is used all the base class's members turn into private members in the derived class. The derived class members may access all base class public and protected members but base class members cannot be used elsewhere.

Public derivation should be used to define an *is-a* relationship between a derived class and a base class: the derived class object *is-a* base class object allowing the derived class object to be used polymorphically as a base class object in code expecting a base class object. Private inheritance is used in situations where a derived class object is defined in-terms-of the base class where composition cannot be used. There's little documented use for protected inheritance, but one could maybe encounter protected inheritance when defining a base class that is itself a derived class making its base class members available to classes derived from it.

Combinations of inheritance types do occur. For example, when designing a stream-class it is usually derived from `std::istream` or `std::ostream`. However, before a stream can be constructed, a `std::streambuf` must be available. Taking advantage of the fact that the inheritance order is defined in the class interface, we use multiple inheritance (see section 13.6) to derive the class from both `std::streambuf` and (then) from `std::ostream`. To the class's users it is a `std::ostream` and not a `std::streambuf`. So private derivation is used for the latter, and public derivation for the former class:

```
class Derived: private std::streambuf, public std::ostream
```

13.2.2 Promoting access rights

When private or protected derivation is used, users of derived class objects are denied access to the base class members. Private derivation denies access to all base class members to users of the derived class, protected derivation does the same, but allows classes that are in turn derived from the derived class to access the base class's public and protected members.

In some situations this scheme is too restrictive. Consider a class `RandStream` derived privately from a class `RandBuf` which is itself derived from `std::streambuf` and also publicly from `istream`:

```
class RandBuf: public std::streambuf
{
    // implements a buffer for random numbers
};
class RandStream: private RandBuf, public std::istream
{
    // implements a stream to extract random values from
};
```

Such a class could be used to extract, e.g., random numbers using the standard `istream` interface.

Although the `RandStream` class is constructed with the functionality of `istream` objects in mind, some of the members of the class `std::streambuf` may be considered useful by themselves. E.g., the function `streambuf::in_avail` returns a lower bound to the number of characters that can be read immediately. The standard way to make this function available is to define a *shadow member* calling the base class's member:

```
class RandStream: private RandBuf, public std::istream
{
    // implements a stream to extract random values from
    public:
        std::streamsize in_avail();
};
inline std::streamsize RandStream::in_avail()
{
    return std::streambuf::in_avail();
}
```

This looks like a lot of work for just making available a member from the protected or private base classes. If the intent is to make available the `in_avail` member *access promotion* can be used. Access promotion allows us to specify which members of private (or protected) base classes become available in the protected (or public) interface of the derived class. Here is the above example, now using access promotion:

```
class RandStream: private RandBuf, public std::istream
{
    // implements a stream to extract random values from
    public:
        using std::streambuf::in_avail;
};
```

It should be noted that access promotion makes available all overloaded versions of the declared base class member. So, if `streambuf` would offer not only `in_avail` but also, e.g., `in_avail(size_t *)` *both* members would become part of the public interface.

13.3 The constructor of a derived class

A derived class inherits functionality from its base class (or base classes, as **C++** supports multiple inheritance, cf. section 13.6). When a derived class object is constructed it is built on top of its base class object. As a consequence the base class must have been constructed before the actual derived class elements can be initialized. This results in some requirements that must be observed when defining derived class constructors.

A constructor exists to initialize the object's data members. A derived class constructor is also responsible for the proper initialization of its base class. Looking at the definition of the class `Land` introduced earlier (section 13.1), its constructor could simply be defined as follows:

```
Land::Land(size_t mass, size_t speed)
{
    setMass(mass);
    setSpeed(speed);
}
```

However, this implementation has several disadvantages.

- When constructing a derived class object a base class constructor is *always* called before any action is performed on the derived class object itself. By default the base class's default constructor is going to be called.
- Using the base class constructor only to reassign new values to its data members in the derived class constructor's body usually is inefficient, but sometimes sheer impossible as in situations where base class reference or `const` data members must be initialized. In those cases a specialized base class constructor must be used instead of the base class default constructor.

A derived class's base class may be initialized using a dedicated base class constructor by calling the base class constructor in the derived class constructor's initializer clause. Calling a base class constructor in a constructor's initializer clause is called a *base class initializer*. The base class initializer must be called before initializing any of the derived class's data members and when using the base class initializer none of the derived class data members may be used. When constructing a derived class object the base class is constructed first and only after that construction has successfully completed the derived class data members are available for initialization. `Land`'s constructor may therefore be improved:

```
Land::Land(size_t mass, size_t speed)
:
    Vehicle(mass),
    d_speed(speed)
{}
```

Derived class constructors always by default call their base class's default constructor. This is of course not correct for a derived class's copy constructor. Assuming that the class `Land` must be provided with a copy constructor its `Land const &other` parameter also represents the other object's base class:

```
Land::Land(Land const &other)   // assume a copy constructor is needed
:
    Vehicle(other),             // copy-construct the base class part.
    d_speed(other.d_speed)      // copy-construct Land's data members
{}
```

13.3.1 Move construction

As with classes using composition derived classes may benefit from defining a move constructor. A derived class may offer a move constructor for two reasons:

- it supports move construction for its data members
- its base class is move-aware

The design of move constructors moving data members was covered in section 9.7. A move constructor for a derived class whose base class is move-aware must *anonymize* the rvalue reference before passing it to the base class move constructor. The `std::move` function should be used when implementing the move constructor to move the information in base classes or composed objects to their new destination object.

The first example shows the move constructor for the class `Car`, assuming it has a movable `char *d_brandName` data member and assuming that `Land` is a move-aware class. The second example shows the move constructor for the class `Land`, assuming that it does not itself have movable data members, but that its `Vehicle` base class is move-aware:

```
Car::Car(Car &&tmp)
:
    Land(std::move(tmp)),           // anonymize `tmp'
    d_brandName(tmp.d_brandName)    // move the char *'s value
{
    tmp.d_brandName = 0;
}

Land(Land &&tmp)
:
    Vehicle(std::move(tmp)),    // move-aware Vehicle
    d_speed(tmp.d_speed)        // plain copying of plain data
{}
```

13.3.2 Move assignment

Derived classes may also benefit from move assignment operations. If the derived class and its base class support swapping then the implementation is simple, following the standard shown earlier in section 9.7.3. For the class `Car` this could boil down to:

```
Car &Car::operator=(Car &&tmp)
{
    swap(tmp);
    return *this;
}
```

If swapping is not supported then `std::move` can be used to call the base class's move assignment operator:

```
Car &Car::operator=(Car &&tmp)
{
    static_cast<Land &>(*this) = std::move(tmp);
    // move Car's own data members next
```

```
        return *this;
    }
```

13.3.3 Inheriting constructors

Derived classes can be constructed without explicitly defining derived class constructors. In those cases the available base class constructors are called.

This feature is either used or not. It is not possible to omit some of the derived class constructors, using the corresponding base class constructors instead. To use this feature for classes that are derived from multiple base classes (cf. section 13.6) all the base class constructors must have different signatures. Considering the complexities that are involved here it's probably best to avoid using base class constructors for classes using multiple inheritance.

The construction of derived class objects can be delegated to base class constructor(s) using the following syntax:

```
    class BaseClass
    {
        public:
            // BaseClass constructor(s)
    };

    class DerivedClass: public BaseClass
    {
        public:
            using BaseClass::BaseClass; // No DerivedClass constructors
                                        // are defined
    };
```

13.3.4 Aggregate Initializations

Aggregates (e.g., structs) can be initialized using the familiar curly-brace notation. Curly brace notations can also be used when initializing base-structs of derived-structs. Each base-level struct receives its own set of curly braces while initializing the derived-level struct. Here is an example:

```
    struct Base
    {
        int value;
    };
    struct Derived: public Base
    {
        string text;
    };

    // Initializiation of a Derived object:

    Derived der{{value}, "hello world"};
    //          -------
    //          initialization of Derived's base struct.
```

13.4 The destructor of a derived class

Destructors of classes are automatically called when an object is destroyed. This also holds true for objects of classes derived from other classes. Assume we have the following situation:

```
class Base
{
    public:
        ~Base();
};

class Derived: public Base
{
    public:
        ~Derived();
};

int main()
{
    Derived derived;
}
```

At the end of `main`, the `derived` object ceases to exists. Hence, its destructor (`~Derived`) is called. However, since `derived` is also a `Base` object, the `~Base` destructor is called as well. The base class destructor is never explicitly called from the derived class destructor.

Constructors and destructors are called in a stack-like fashion: when `derived` is constructed, the appropriate base class constructor is called first, then the appropriate derived class constructor is called. When the object `derived` is destroyed, its destructor is called first, automatically followed by the activation of the `Base` class destructor. A derived class destructor is always called before its base class destructor is called.

When the construction of a derived class object did not successfully complete (i.e., the constructor threw an exception) then its destructor is not called. However, the destructors of properly constructed base classes *will* be called if a derived class constructor throws an exception. This, of course, is how it should be: a properly constructed object should also be destroyed, eventually. Example:

```
#include <iostream>
struct Base
{
    ~Base()
    {
        std::cout << "Base destructor\n";
    }
};
struct Derived: public Base
{
    Derived()
    {
        throw 1;    // at this time Base has been constructed
    }
};
int main()
{
    try
```

```
        {
            Derived d;
        }
        catch(...)
        {}
    }
    /*
        This program displays `Base destructor'
    */
```

13.5 Redefining member functions

Derived classes may redefine base class members. Let's assume that a vehicle classification system must also cover trucks, consisting of two parts: the front part, the tractor, pulls the rear part, the trailer. Both the tractor and the trailer have their own mass, and the `mass` function should return the combined mass.

The definition of a `Truck` starts with a class definition. Our initial `Truck` class is derived from `Car` but it is then expanded to hold one more `size_t` field representing the additional mass information. Here we choose to represent the mass of the tractor in the `Car` class and to store the mass of a full truck (tractor + trailer) in its own `d_mass` data member:

```
    class Truck: public Car
    {
        size_t d_mass;

        public:
            Truck();
            Truck(size_t tractor_mass, size_t speed, char const *name,
                  size_t trailer_mass);

            void setMass(size_t tractor_mass, size_t trailer_mass);
            size_t mass() const;
    };

    Truck::Truck(size_t tractor_mass, size_t speed, char const *name,
                 size_t trailer_mass)
    :
        Car(tractor_mass, speed, name),
        d_mass(tractor_mass + trailer_mass)
    {}
```

Note that the class `Truck` now contains two functions already present in the base class `Car`: `setMass` and `mass`.

- The redefinition of `setMass` poses no problems: this function is simply redefined to perform actions which are specific to a `Truck` object.
- Redefining `setMass`, however, *hides* `Car::setMass`. For a `Truck` only the `setMass` function having two `size_t` arguments can be used.
- The `Vehicle`'s `setMass` function remains available for a `Truck`, but it must now be called *explicitly*, as `Car::setMass` is hidden from view. This latter function is hidden, even though

`Car::setMass` has only one `size_t` argument. To implement `Truck::setMass` we could write:

```
void Truck::setMass(size_t tractor_mass, size_t trailer_mass)
{
    d_mass = tractor_mass + trailer_mass;
    Car::setMass(tractor_mass);     // note: Car:: is required
}
```

- Outside of the class `Car::setMass` is accessed using the scope resolution operator. So, if a `Truck truck` needs to set its `Car` mass, it must use

  ```
  truck.Car::setMass(x);
  ```

- An alternative to using the scope resolution operator is to add a member having the same function prototype as the base class member to the derived class's interface. This derived class member could be implemented inline to call the base class member. E.g., we add the following member to the `class Truck`:

  ```
  // in the interface:
  void setMass(size_t tractor_mass);

  // below the interface:
  inline void Truck::setMass(size_t tractor_mass)
  {
      (d_mass -= Car::mass()) += tractor_mass;
      Car::setMass(tractor_mass);
  }
  ```

  Now the single argument `setMass` member function can be used by `Truck` objects without using the scope resolution operator. As the function is defined inline, no overhead of an additional function call is involved.

- To prevent hiding the base class members a `using` declaration may be added to the derived class interface. The relevant section of `Truck`'s class interface then becomes:

  ```
  class Truck: public Car
  {
      public:
          using Car::setMass;
          void setMass(size_t tractor_mass, size_t trailer_mass);
  };
  ```

  A using declaration imports (all overloaded versions of) the mentioned member function directly into the derived class's interface. If a base class member has a signature that is identical to a derived class member then compilation fails (a `using Car::mass` declaration cannot be added to `Truck`'s interface). Now code may use `truck.setMass(5000)` as well as `truck.setMass(5000, 2000)`.

  Using declarations obey access rights. To prevent non-class members from using `setMass(5000)` without a scope resolution operator but allowing derived class members to do so the `using Car::setMass` declaration should be put in the class `Truck`'s private section.

- The function `mass` is also already defined in `Car`, as it was inherited from `Vehicle`. In this case, the class `Truck` *redefines* this member function to return the truck's full mass:

  ```
  size_t Truck::mass() const
  {
      return d_mass;
  }
  ```

Example:

```
int main()
{
    Land vehicle{ 1200, 145 };
    Truck lorry{ 3000, 120, "Juggernaut", 2500 };

    lorry.Vehicle::setMass(4000);

    cout << '\n' << "Tractor weighs " <<
                    lorry.Vehicle::mass() << '\n' <<
        "Truck + trailer weighs " << lorry.mass() << '\n' <<
        "Speed is " << lorry.speed() << '\n' <<
        "Name is " << lorry.name() << '\n';
}
```

The class `Truck` was derived from `Car`. However, one might question this class design. Since a truck is conceived of as a combination of a tractor and a trailer it is probably better defined using a mixed design, using inheritance for the tractor part (inheriting from `Car`, and composition for the trailer part).

This redesign changes our point of view from a `Truck` *being* a `Car` (and some strangely added data members) to a `Truck` still *being* an `Car` (the tractor) and *containing* a `Vehicle` (the trailer).

`Truck`'s interface is now very specific, not requiring users to study `Car`'s and `Vehicle`'s interfaces and it opens up possibilities for defining 'road trains': tractors towing multiple trailers. Here is an example of such an alternate class setup:

```
class Truck: public Car    // the tractor
{
    Vehicle d_trailer;      // use vector<Vehicle> for road trains

    public:
        Truck();
        Truck(size_t tractor_mass, size_t speed, char const *name,
              size_t trailer_mass);

        void setMass(size_t tractor_mass, size_t trailer_mass);
        void setTractorMass(size_t tractor_mass);
        void setTrailerMass(size_t trailer_mass);

        size_t tractorMass() const;
        size_t trailerMass() const;
    // consider:
        Vehicle const &trailer() const;
};
```

13.6 Multiple inheritance

Except for the class `Randbuf` classes thus far have always been derived from a single base class. In addition to single inheritance **C++** also supports *multiple inheritance*. In multiple inheritance a class is derived from several base classes and hence inherits functionality from multiple parent classes at the same time.

When using multiple inheritance it should be defensible to consider the newly derived class an instantiation of both base classes. Otherwise, composition is more appropriate. In general, linear derivation (using only one base class) is used much more frequently than multiple derivation. Good class design dictates that a class should have a single, well described responsibility and that principle often conflicts with multiple inheritance where we can state that objects of class `Derived` are *both* `Base1` *and* `Base2` objects.

But then, consider *the* prototype of an object for which multiple inheritance was used to its extreme: the *Swiss army knife*! This object *is* a knife, it *is* a pair of scissors, it *is* a can-opener, it *is* a corkscrew, it *is* ....

The 'Swiss army knife' is an extreme example of multiple inheritance. In **C++** there *are* various good arguments for using multiple inheritance as well, without violating the 'one class, one responsibility' principle. We postpone those arguments until the next chapter. The current section concentrates on the technical details of constructing classes using multiple inheritance.

How to construct a 'Swiss army knife' in **C++**? First we need (at least) two base classes. For example, let's assume we are designing a toolkit allowing us to construct an instrument panel of an aircraft's cockpit. We design all kinds of instruments, like an artificial horizon and an altimeter. One of the components that is often seen in aircraft is a *nav-com set*: a combination of a navigational beacon receiver (the 'nav' part) and a radio communication unit (the 'com'-part). To define the nav-com set, we start by designing the `NavSet` class (assume the existence of the classes `Intercom, VHF_Dial` and `Message`):

```
class NavSet
{
    public:
        NavSet(Intercom &intercom, VHF_Dial &dial);

        size_t activeFrequency() const;
        size_t standByFrequency() const;

        void setStandByFrequency(size_t freq);
        size_t toggleActiveStandby();
        void setVolume(size_t level);
        void identEmphasis(bool on_off);
};
```

Next we design the class `ComSet`:

```
class ComSet
{
    public:
        ComSet(Intercom &intercom);

        size_t frequency() const;
        size_t passiveFrequency() const;

        void setPassiveFrequency(size_t freq);
        size_t toggleFrequencies();

        void setAudioLevel(size_t level);
        void powerOn(bool on_off);
        void testState(bool on_off);
        void transmit(Message &message);
};
```

Using objects of this class we can receive messages, transmitted though the `Intercom`, but we can also *transmit* messages using a `Message` object that's passed to the `ComSet` object using its `transmit` member function.

Now we're ready to construct our `NavCom` set:

```
class NavComSet: public ComSet, public NavSet
{
    public:
        NavComSet(Intercom &intercom, VHF_Dial &dial);
};
```

Done. Now we have defined a `NavComSet` which is *both* a `NavSet` *and* a `ComSet`: the facilities of both base classes are now available in the derived class using multiple inheritance.

Please note the following:

- The keyword `public` is present before both base class names (`NavSet` and `ComSet`). By default inheritance uses *private derivation* and the keyword `public` must be repeated before each of the base class specifications. Base classes are not required to use the same derivation type. One base class could have `public` derivation and another base class could use `private` derivation.
- The multiply derived class `NavComSet` introduces no additional functionality of its own, but merely combines two existing classes into a new aggregate class. Thus, **C++** offers the possibility to simply sweep multiple simple classes into one more complex class.
- Here is the implementation of The `NavComSet` constructor:

  ```
  NavComSet::NavComSet(Intercom &intercom, VHF_Dial &dial)
  :
      ComSet(intercom),
      NavSet(intercom, dial)
  {}
  ```

  The constructor requires no extra code: Its purpose is to activate the constructors of its base classes. The order in which the base class initializers are called is *not* dictated by their calling order in the constructor's code, but by the ordering of the base classes in the class interface.
- The `NavComSet` class definition requires no additional data members or member functions: here (and often) the inherited interfaces provide all the required functionality and data for the multiply derived class to operate properly.

Of course, while defining the base classes, we made life easy on ourselves by strictly using different member function names. So, there is a function `setVolume` in the `NavSet` class and a function `setAudioLevel` in the `ComSet` class. A bit cheating, since we could expect that both units in fact have a composed object `Amplifier`, handling the volume setting. A revised class might offer an `Amplifier &amplifier() const` member function, and leave it to the application to set up its own interface to the amplifier. Alternatively, a revised class could define members for setting the volume of either the `NavSet` or the `ComSet` parts.

In situations where two base classes offer identically named members special provisions need to be made to prevent ambiguity:

- The intended base class can explicitly be specified using the base class name and scope resolution operator:

  ```
  NavComSet navcom(intercom, dial);
  ```

```
navcom.NavSet::setVolume(5);    // sets the NavSet volume level
navcom.ComSet::setVolume(5);    // sets the ComSet volume level
```

- The class interface is provided with member functions that can be called unambiguously. These additional members are usually defined `inline`:

```
class NavComSet: public ComSet, public NavSet
{
    public:
        NavComSet(Intercom &intercom, VHF_Dial &dial);
        void comVolume(size_t volume);
        void navVolume(size_t volume);
};
inline void NavComSet::comVolume(size_t volume)
{
    ComSet::setVolume(volume);
}
inline void NavComSet::navVolume(size_t volume)
{
    NavSet::setVolume(volume);
}
```

- If the `NavComSet` class is obtained from a third party, and cannot be modified, a disambiguating wrapper class may be used:

```
class MyNavComSet: public NavComSet
{
    public:
        MyNavComSet(Intercom &intercom, VHF_Dial &dial);
        void comVolume(size_t volume);
        void navVolume(size_t volume);
};
inline MyNavComSet::MyNavComSet(Intercom &intercom, VHF_Dial &dial)
:
    NavComSet(intercom, dial);
{}
inline void MyNavComSet::comVolume(size_t volume)
{
    ComSet::setVolume(volume);
}
inline void MyNavComSet::navVolume(size_t volume)
{
    NavSet::setVolume(volume);
}
```

13.7 Conversions between base classes and derived classes

When public inheritance is used to define classes, an object of a derived class *is* at the same time an object of the base class. This has important consequences for object assignment and for the situation where pointers or references to such objects are used. Both situations are now discussed.

13.7.1 Conversions with object assignments

Continuing our discussion of the `NavCom` class, introduced in section 13.6, we now define two objects, a base class and a derived class object:

```
ComSet com(intercom);
NavComSet navcom(intercom2, dial2);
```

The object `navcom` is constructed using an `Intercom` and a `VHF_Dial` object. However, a `NavComSet` is at the same time a `ComSet`, allowing the assignment *from* `navcom` (a derived class object) *to* `com` (a base class object):

```
com = navcom;
```

The effect of this assignment is that the object `com` now communicates with `intercom2`. As a `ComSet` does not have a `VHF_Dial`, the `navcom`'s `dial` is ignored by the assignment. When assigning a base class object from a derived class object only the base class data members are assigned, other data members are dropped, a phenomenon called *slicing*. In situations like these slicing probably does not have serious consequences, but when passing derived class objects to functions defining base class parameters or when returning derived class objects from functions returning base class objects slicing also occurs and might have unwelcome side-effects.

The assignment from a base class object to a derived class object is problematic. In a statement like

```
navcom = com;
```

it isn't clear how to reassign the `NavComSet`'s `VHF_Dial` data member as they are missing in the `ComSet` object `com`. Such an assignment is therefore refused by the compiler. Although derived class objects are also base class objects, the reverse does not hold true: a base class object is not also a derived class object.

The following general rule applies: in assignments in which base class objects and derived class objects are involved, assignments in which data are dropped are legal (called *slicing*). Assignments in which data remain unspecified are *not* allowed. Of course, it is possible to overload an assignment operator to allow the assignment of a derived class object from a base class object. To compile the statement

```
navcom = com;
```

the class `NavComSet` must have defined an overloaded assignment operator accepting a `ComSet` object for its argument. In that case it's up to the programmer to decide what the assignment operator will do with the missing data.

13.7.2 Conversions with pointer assignments

We return to our `Vehicle` classes, and define the following objects and pointer variable:

```
Land land(1200, 130);
Car car(500, 75, "Daf");
Truck truck(2600, 120, "Mercedes", 6000);
Vehicle *vp;
```

Now we can assign the addresses of the three objects of the derived classes to the `Vehicle` pointer:

```
vp = &land;
vp = &car;
vp = &truck;
```

Each of these assignments is acceptable. However, an implicit conversion of the derived class to the base class `Vehicle` is used, since `vp` is defined as a pointer to a `Vehicle`. Hence, when using `vp` only the member functions manipulating `mass` can be called as this is the `Vehicle`'s *only* functionality. As far as the compiler can tell this is the object `vp` points to.

The same holds true for references to `Vehicles`. If, e.g., a function is defined having a `Vehicle` reference parameter, the function may be passed an object of a class derived from `Vehicle`. Inside the function, the specific `Vehicle` members remain accessible. This analogy between pointers and references holds true in general. Remember that a reference is nothing but a pointer in disguise: it mimics a plain variable, but actually it is a pointer.

This restricted functionality has an important consequence for the class `Truck`. Following `vp = &truck`, `vp` points to a `Truck` object. So, `vp->mass()` returns 2600 instead of 8600 (the combined mass of the cabin and of the trailer: 2600 + 6000), which would have been returned by `truck.mass()`.

When a function is called using a pointer to an object, then the *type of the pointer* (and not the type of the object) determines which member functions are available and can be executed. In other words, **C++** implicitly converts the type of an object reached through a pointer to the pointer's type.

If the actual type of the object pointed to by a pointer is known, an explicit type cast can be used to access the full set of member functions that are available for the object:

```
Truck truck;
Vehicle *vp;

vp = &truck;        // vp now points to a truck object

Truck *trp;

trp = static_cast<Truck *>(vp);
cout << "Make: " << trp->name() << '\n';
```

Here, the second to last statement specifically casts a `Vehicle *` variable to a `Truck *`. As usual (when using casts), this code is not without risk. It *only* works if `vp` really points to a `Truck`. Otherwise the program may produce unexpected results.

13.8 Using non-default constructors with new[]

An often heard complaint is that operator `new[]` calls the default constructor of a class to initialize the allocated objects. For example, to allocate an array of 10 strings we can do

```
new string[10];
```

but it is not possible to use another constructor. Assuming that we'd want to initialize the strings with the text `hello world`, we can't write something like:

```
new string{ "hello world" }[10];
```

The initialization of a dynamically allocated object usually consists of a two-step process: first the array is allocated (implicitly calling the default constructor); second the array's elements are initialized, as in the following little example:

```
    string *sp = new string[10];
    fill(sp, sp + 10, string{ "hello world" });
```

These approaches all suffer from 'double initializations', comparable to not using member initializers in constructors.

One way to avoid double initialization is to use inheritance. Inheritance can profitably be used to call non-default constructors in combination with operator `new[]`. The approach capitalizes on the following:

- A base class pointer may point to a derived class object;
- A derived class without (non-static) data members has the same size as its base class.

The above also suggests a possible approach:

- Derive a simple, member-less class from the class we're interested in;
- Use the appropriate base class initializer in its default constructor;
- Allocate the required number of derived class objects, and assign `new[]`'s return expression to a pointer to base class objects.

Here is a simple example, producing 10 lines containing the text `hello world`:

```
#include <iostream>
#include <string>
#include <algorithm>
#include <iterator>

using namespace std;

struct Xstr: public string
{
    Xstr()
    :
        string("hello world")
    {}
};

int main()
{
    string *sp = new Xstr[10];
    copy(sp, sp + 10, ostream_iterator<string>{ cout, "\n" });
}
```

Of course, the above example is fairly unsophisticated, but it's easy to polish the example: the class `Xstr` can be defined in an anonymous namespace, accessible only to a function `getString()` which may be given a `size_t nObjects` parameter, allowing users to specify the number of `hello world`-initialized strings they would like to allocate.

Instead of hard-coding the base class arguments it's also possible to use variables or functions providing the appropriate values for the base class constructor's arguments. In the next example a *local class* `Xstr` is defined inside a function `nStrings(size_t nObjects, char const *fname)`, expecting the number of `string` objects to allocate and the name of a file whose subsequent lines are used to initialize the objects. The local class is invisible outside of the function `nStrings`, so no special namespace safeguards are required.

As discussed in section 7.9, members of local classes cannot access local variables from their surrounding function. However, they can access global and static data defined by the surrounding function.

Using a local class neatly allows us to hide the implementation details within the function `nStrings`, which simply opens the file, allocates the objects, and closes the file again. Since the local class is derived from `string`, it can use any `string` constructor for its base class initializer. In this particular case it doesn't even do that, as copy elision ensures that `Xstr's` base class `string` in fact is the `string` returned by `nextLine`. That latter function's `string` subsequently receives the lines of the just opened stream. As `nextLine` is a static member function, it's available to `Xstr` default constructor's member initializers even though at that time the `Xstr` object isn't available yet.

```
#include <fstream>
#include <iostream>
#include <string>
#include <algorithm>
#include <iterator>

using namespace std;

string *nStrings(size_t size, char const *fname)
{
    static thread_local ifstream in;

    struct Xstr: public string
    {
        Xstr()
        :
            string(nextLine())
        {}
        static string nextLine()
        {
            string line;

            getline(in, line);
            return line;        // copy elision turns this
        }                       // into Xstr's base class string
    };
    in.open(fname);
    string *sp = new Xstr[size];
    in.close();

    return sp;
}

int main()
{
    string *sp = nStrings(10, "nstrings.cc");
    copy(sp, sp + 10, ostream_iterator<string>{ cout, "\n" });
}
```

When this program is run, it displays the first 10 lines of the file `nstrings.cc`.

Note that the example defines a `static thread_local ifstream` object. Thread_local variables are formally introduced in chapter 20. The `thread_local` specification assures that the function can safely be used, even in multithreaded programs.

A completely different way to avoid the double initialization (not using inheritance) is to use placement new (cf. section 9.1.5): simply allocate the required amount of memory followed by the proper in-place allocation of the objects, using the appropriate constructors. In the next example a pair of static `construct/destroy` members are used to perform the required initialization. In the example `construct` expects an `istream` that provides the initialization strings for objects of a class `String` simply containing a `std::string` object. `Construct` first allocates enough memory for the `n String` objects plus room for an initial `size_t` value. This initial `size_t` value is then initialized with `n`. Next, in a `for` statement, lines are read from the provided stream and the lines are passed to the constructors, using placement new calls. Finally the address of the first `String` object is returned. Then, the destruction of the objects is handled by the member `destroy`. It retrieves the number of objects to destroy from the `size_t` it finds just before the location of the address of the first object to destroy. The objects are then destroyed by explicitly calling their destructors. Finally the raw memory, originally allocated by `construct` is returned.

```
#include <fstream>
#include <iostream>
#include <string>
using namespace std;

class String
{
    union Ptrs
    {
        void *vp;
        String *sp;
        size_t *np;
    };

    std::string d_str;

    public:
        String(std::string const &txt)
        :
            d_str(txt)
        {}
        ~String()
        {
            cout << "destructor: " << d_str << '\n';
        }
        static String *construct(istream &in, size_t n)
        {
            Ptrs p = {operator new(n * sizeof(String) + sizeof(size_t))};
            *p.np++ = n;

            string line;
            for (size_t idx = 0; idx != n; ++idx)
            {
                getline(in, line);
                new(p.sp + idx) String{ line };
            }

            return p.sp;
        }
        static void destroy(String *sp)
        {
            Ptrs p = {sp};
            --p.np;
            for (size_t n = *p.np; n--; )
                sp++->~String();

            operator delete(p.vp);
        }
};

int main()
{
    String *sp = String::construct(cin, 5);

    String::destroy(sp);
}

/*
    After providing 5 lines containing, respectively
        alpha, bravo, charley, delta, echo
    the program displays:
                destructor: alpha
                destructor: bravo
                destructor: charley
                destructor: delta
                destructor: echo
*/
```

Chapter 14

Polymorphism

Using inheritance classes may be derived from other classes, called base classes. In the previous chapter we saw that base class pointers may be used to point to derived class objects. We also saw that when a base class pointer points to an object of a derived class the pointer's type, rather than the object's type, determines which member functions are visible. So when a `Vehicle *vp`, points to a `Car` object `Car`'s `speed` or `brandName` members can't be used.

In the previous chapter two fundamental ways classes may be related to each other were discussed: a class may be *implemented-in-terms-of* another class and it can be stated that a derived class *is-a* base class. The former relationship is usually implemented using composition, the latter is usually implemented using a special form of inheritance, called *polymorphism*, the topic of this chapter.

An *is-a* relationship between classes allows us to apply the *Liskov Substitution Principle* (*LSP*) according to which a derived class object may be passed to and used by code expecting a pointer or reference to a base class object. In the **C++** Annotations so far the LSP has been applied many times. Every time an `ostringstream, ofstream` or `fstream` was passed to functions expecting an `ostream` we've been applying this principle. In this chapter we'll discover how to design our own classes accordingly.

LSP is implemented using a technique called *polymorphism*: although a base class pointer is used it performs actions defined in the (derived) class of the object it actually points to. So, a `Vehicle *vp` might behave like a `Car *` when pointing to a `Car`[1].

Polymorphism is implemented using a feature called *late binding*. It's called that way because the decision *which* function to call (a base class function or a function of a derived class) cannot be made at *compile-time*, but is postponed until the program is actually executed: only then it is determined which member function will actually be called.

In **C++** late binding is *not* the default way functions are called. By default *static binding* (or *early binding*) is used. With static binding the functions that are called are determined by the compiler, merely using the class types of objects, object pointers or object references.

Late binding is an inherently different (and slightly slower) process as it is decided at run-time, rather than at compile-time what function is going to be called. As **C++** supports *both* late- and early-binding **C++** programmers are offered an option as to what kind of binding to use. Choices can be optimized to the situations at hand. Many other languages offering object oriented facilities (e.g., **Java**) only or by default offer late binding. **C++** programmers should be keenly aware of this. Expecting early binding and getting late binding may easily produce nasty bugs.

---

[1] In one of the StarTrek movies, Capt. Kirk was in trouble, as usual. He met an extremely beautiful lady who, however, later on changed into a hideous troll. Kirk was quite surprised, but the lady told him: "Didn't you know I am a polymorph?"

Let's look at a simple example to start appreciating the differences between late and early binding. The example merely illustrates. Explanations of *why* things are as shown are shortly provided.

Consider the following little program:

```
#include <iostream>
using namespace std;

class Base
{
    protected:
        void hello()
        {
            cout << "base hello\n";
        }
    public:
        void process()
        {
            hello();
        }
};
class Derived: public Base
{
    protected:
        void hello()
        {
            cout << "derived hello\n";
        }
};
int main()
{
    Derived derived;

    derived.process();
}
```

The important characteristic of the above program is the `Base::process` function, calling `hello`. As `process` is the only member that is defined in the public interface it is the only member that can be called by code not belonging to the two classes. The class `Derived`, derived from `Base` clearly inherits `Base`'s interface and so `process` is also available in `Derived`. So the `Derived` object in `main` is able to call `process`, but not `hello`.

So far, so good. Nothing new, all this was covered in the previous chapter. One may wonder why `Derived` was defined at all. It was presumably defined to create an implementation of `hello` that's appropriate for `Derived` but differing from `Base::hello`'s implementation. `Derived`'s author's reasoning was as follows: `Base`'s implementation of `hello` is not appropriate; a `Derived` class object can remedy that by providing an appropriate implementation. Furthermore our author reasoned:

> "since the type of an object determines the interface that is used, `process` must call `Derived::hello` as `hello` is called via `process` from a `Derived` class object".

Unfortunately our author's reasoning is flawed, due to static binding. When `Base::process` was compiled static binding caused the compiler to bind the `hello` call to `Base::hello()`.

The author *intended* to create a `Derived` class that `is-a` `Base` class. That only partially succeeded: `Base`'s interface was inherited, but after that `Derived` has relinquished all control over what happens. Once we're in `process` we're only able to see `Base`'s member implementations. Polymorphism offers a way out, allowing us to redefine (in a derived class) members of a base class allowing these redefined members to be used from the base class's interface.

This is the essence of LSP: public inheritance should not be used to reuse the base class members (in derived classes) but to be reused (by the base class, polymorphically using derived class members reimplementing base class members).

Take a second to appreciate the implications of the above little program. The `hello` and `process` members aren't too impressive, but the implications of the example are. The `process` member could implement directory travel, `hello` could define the action to perform when encountering a file. `Base::hello` might simply show the name of a file, but `Derived::hello` might delete the file; might only list its name if its younger than a certain age; might list its name if it contains a certain text; etc., etc.. Up to now `Derived` would have to implement `process`'s actions itself; Up to now code expecting a `Base` class reference or pointer could only perform `Base`'s actions. Polymorphism allows us to reimplement members of base classes and to use those reimplemented members in code expecting base class references or pointers. Using polymorphism existing code may be reused by derived classes reimplementing the appropriate members of their base classes. It's about time to uncover how this magic can be realized.

Polymorphism, which is not the default in **C++**, solves the problem and allows the author of the classes to reach its goal. For the curious reader: prefix `void hello()` in the `Base` class with the keyword `virtual` and recompile. Running the modified program produces the intended and expected `derived hello`. Why this happens is explained next.

14.1 Virtual functions

By default the behavior of a member function called via a pointer or reference is determined by the implementation of that function in the pointer's or reference's class. E.g., a `Vehicle *` activates `Vehicle`'s member functions, even when pointing to an object of a derived class. This is known as as *early* or *static* binding: the function to call is determined at compile-time. In **C++** *late* or *dynamic* binding is realized using *virtual member functions*.

A member function becomes a virtual member function when its declaration starts with the keyword `virtual`. It is stressed once again that in **C++**, different from several other object oriented languages, this is *not* the default situation. By default *static* binding is used.

Once a function is declared `virtual` in a base class, it remains virtual in all derived classes. The keyword `virtual` should not be mentioned for members in derived classes which are declared virtual in base classes. In derived classes those members should be provided with the `override` indicator, allowing the compiler to verify that you're indeed referring to an existing virtual member function.

In the vehicle classification system (see section 13.1), let's concentrate on the members `mass` and `setMass`. These members define the *user interface* of the class `Vehicle`. What we would like to accomplish is that this user interface can be used for `Vehicle` and for any class inheriting from `Vehicle`, since objects of those classes are themselves also `Vehicles`.

If we can define the user interface of our base class (e.g., `Vehicle`) such that it remains usable irrespective of the classes we derive from `Vehicle` our software achieves an enormous reusability: we design or software around `Vehicle's` user interface, and our software will also properly function for derived classes. Using plain inheritance doesn't accomplish this. If we define

```
std::ostream &operator<<(std::ostream &out, Vehicle const &vehicle)
{
    return out << "Vehicle's mass is " << vehicle.mass() << " kg.";
    }
```

and `Vehicle's` member `mass` returns 0, but `Car's` member `mass` returns 1000, then twice a mass of 0 is reported when the following program is executed:

```
    int main()
    {
        Vehicle vehicle;
        Car vw(1000);

        cout << vehicle << '\n' << vw << endl;
    }
```

We've defined an overloaded insertion operator, but since it only knows about `Vehicle's` user interface, '`cout << vw`' will use `vw's Vehicle's` user interface as well, thus displaying a mass of 0.

Reusability is enhanced if we add a *redefinable interface* to the base class's interface. A redefinable interface allows derived classes to fill in their own implementation, without affecting the user interface. At the same time the user interface will behave according to the derived class's wishes, and not just to the base class's default implementation.

Members of the reusable interface should be declared in the class's private sections: conceptually they merely belong to their own classes (cf. section 14.7). In the base class these members should be declared `virtual`. These members can be redefined (overridden) by derived classes, and should there be provided with `override` indicators.

We keep our user interface (`mass`), and add the redefinable member `vmass` to `Vehicle's` interface:

```
    class Vehicle
    {
        public:
            size_t mass() const;
            size_t si_mass() const;     // see below

        private:
            virtual size_t vmass() const;
    };
```

Separating the user interface from the redefinable interface is a sensible thing to do. It allows us to fine-tune the user interface (only one point of maintenance), while at the same time allowing us to standardize the expected behavior of the members of the redefinable interface. E.g., in many countries the International system of units is used, using the kilogram as the unit for mass. Some countries use other units (like the *lbs*: 1 kg being approx. 2.2046 lbs). By separating the user interface from the redefinable interface we can use one standard for the redefinable interface, and keep the flexibility of transforming the information *ad-lib* in the user interface.

Just to maintain a clean separation of user- and redefinable interface we might consider adding another accessor to `Vehicle`, providing the `si_mass`, simply implemented like this:

```
    size_t Vehicle::si_mass() const
    {
        return vmass();
    }
```

If `Vehicle` supports a member `d_massFactor` then its `mass` member can be implemented like this:

```
size_t Vehicle::mass()
{
    return d_massFactor * si_mass();
}
```

`Vehicle` itself could define `vmass` so that it returns a token value. E.g.,

```
size_t Vehicle::vmass()
{
    return 0;
}
```

Now let's have a look at the class `Car`. It is derived from `Vehicle`, and it inherits `Vehicle's` user interface. It also has a data member `size_t d_mass`, and it implements its own reusable interface:

```
class Car: public Vehicle
{
    ...
    private:
        size_t vmass() override;
}
```

If `Car` constructors require us to specify the car's mass (stored in `d_mass`), then `Car` simply implements its `vmass` member like this:

```
size_t Car::vmass() const
{
    return d_mass;
}
```

The class `Truck`, inheriting from `Car` needs two mass values: the tractor's mass and the trailer's mass. The tractor's mass is passed to its `Car` base class, the trailor's mass is passed to its `Vehicle d_trailor` data member. `Truck`, too, overrides `vmass`, this time returning the sum of its tractor and trailor masses:

```
size_t Truck::vmass() const
{
    return Car::si_mass() + d_trailer.si_mass();
}
```

Once a class member has been declared `virtual` it becomes a virtual member in all derived classes, whether or not these members are provided with the `override` indicator. But `override` *should* be used, as it allows to compiler to catch typos when writing down the derived class interface.

A member function may be declared `virtual` *anywhere* in a class hierarchy, but this probably defeats the underlying polymorphic class design, as the original base class is no longer capable of completely covering the redefinable interfaces of derived classes. If, e.g, `mass` is declared virtual in `Car`, but not in `Vehicle`, then the specific characteristics of virtual member functions would only be available for `Car` objects and for objects of classes derived from `Car`. For a `Vehicle` pointer or reference static binding would remain to be used.

The effect of late binding (polymorphism) is illustrated below:

```
void showInfo(Vehicle &vehicle)
{
    cout << "Info: " << vehicle << '\n';
}

int main()
{
    Car car(1200);              // car with mass 1200
    Truck truck(6000, 115,        // truck with cabin mass 6000,
          "Scania", 15000);       // speed 115, make Scania,
                                  // trailer mass 15000

    showInfo(car);               // see (1) below
    showInfo(truck);              // see (2) below

    Vehicle *vp = &truck;
    cout << vp->speed() << '\n';// see (3) below
}
```

Now that `mass` is defined `virtual`, late binding is used:

- at (1), `Car`'s mass is displayed;
- at (2) `Truck`'s mass is displayed;
- at (3) a syntax error is generated. The member `speed` is not a member of `Vehicle`, and hence not callable via a `Vehicle*`.

The example illustrates that when a pointer to a class is used *only the members of that class can be called*. A member's `virtual` characteristic only influences the type of binding (early vs. late), not the set of member functions that is visible to the pointer.

Through virtual members derived classes may redefine the behavior performed by functions called from base class members or from pointers or references to base class objects. This redefinition of base class members by derived classes is called *overriding members*.

14.2 Virtual destructors

When an object ceases to exist the object's destructor is called. Now consider the following code fragment (cf. section 13.1):

```
Vehicle *vp = new Land{ 1000, 120 };

delete vp;          // object destroyed
```

Here `delete` is applied to a base class pointer. As the base class defines the available interface `delete vp` calls `~Vehicle` and `~Land` remains out of sight. Assuming that `Land` allocates memory a memory leak results. Freeing memory is not the only action destructors can perform. In general they may perform any action that's necessary when an object ceases to exist. But here none of the actions defined by `~Land` are performed. Bad news....

In **C++** this problem is solved by *virtual destructors*. A destructor can be declared `virtual`. When a base class destructor is declared virtual then the destructor of the actual class pointed to by a base class pointer `bp` is going to be called when `delete bp` is executed. Thus, late binding is realized for destructors even though the destructors of derived classes have unique names. Example:

```
class Vehicle
{
    public:
        virtual ~Vehicle();      // all derived class destructors are
                                 // now virtual as well.
};
```

By declaring a virtual destructor, the above `delete` operation (`delete vp`) correctly calls `Land`'s destructor, rather than `Vehicle`'s destructor.

Once a destructor is called it performs as usual, whether or not it is a virtual destructor. So, `~Land` first executes its own statements and then calls `~Vehicle`. Thus, the above `delete vp` statement uses late binding to call `~Vehicle` and from this point on the object destruction proceeds as usual.

Destructors should always be defined `virtual` in classes designed as a base class from which other classes are going to be derived. Often those destructors themselves have no tasks to perform. In these cases the virtual destructor is given an empty body. For example, the definition of `Vehicle::~Vehicle()` may be as simple as:

```
Vehicle::~Vehicle()
{}
```

Resist the temptation to define virtual destructors (even empty destructors) inline as this complicates class maintenance. Section 14.11 discusses the reason behind this rule of thumb.

14.3 Pure virtual functions

The base class `Vehicle` is provided with its own concrete implementations of its virtual members (`mass` and `setMass`). However, virtual member functions do not necessarily *have* to be implemented in base classes.

When the implementations of virtual members are omitted from base classes the class imposes requirements upon derived classes. The derived classes are required to provide the 'missing implementations'.

This approach, in some languages (like **C#, Delphi** and **Java**) known as an *interface*, defines a *protocol*. Derived classes *must* obey the protocol by implementing the as yet not implemented members. If a class contains at least one member whose implementation is missing no objects of that class can be defined.

Such incompletely defined classes are always base classes. They enforce a protocol by merely declaring names, return values and arguments of some of their members. These classes are call *abstract classes* or *abstract base classes*. Derived classes become non-abstract classes by implementing the as yet not implemented members.

Abstract base classes are the foundation of many *design patterns* (cf. *Gamma et al.* (1995)) , allowing the programmer to create highly *reusable software*. Some of these design patterns are covered by the **C++** Annotations (e.g, the *Template Method* in section 25.2), but for a thorough discussion of design patterns the reader is referred to Gamma *et al.*'s book.

Members that are merely declared in base classes are called *pure virtual functions*. A virtual member becomes a pure virtual member by postfixing `= 0` to its declaration (i.e., by replacing the semicolon ending its declaration by '`= 0;`'). Example:

```
#include <iosfwd>
class Base
{
    public:
        virtual ~Base();
        virtual std::ostream &insertInto(std::ostream &out) const = 0;
};
inline std::ostream &operator<<(std::ostream &out, Base const &base)
{
    return base.insertInto(out);
}
```

All classes derived from `Base` *must* implement the `insertInto` member function, or their objects cannot be constructed. This is neat: all objects of class types derived from `Base` can now always be inserted into `ostream` objects.

Could the virtual destructor of a base class ever be a pure virtual function? The answer to this question is no. First of all, there is no need to enforce the availability of destructors in derived classes as destructors are provided by default (unless a destructor is declared with the `= delete` attribute). Second, if it is a pure virtual member its implementation does not exist. However, derived class destructors eventually call their base class destructors. How could they call base class destructors if their implementations are lacking? More about this in the next section.

Often, but not necessarily, pure virtual member functions are `const` member functions. This allows the construction of constant derived class objects. In other situations this might not be necessary (or realistic), and non-constant member functions might be required. The general rule for `const` member functions also applies to pure virtual functions: if the member function alters the object's data members, it cannot be a `const` member function.

Abstract base classes frequently don't have data members. However, once a base class declares a pure virtual member it *must* be declared identically in derived classes. If the implementation of a pure virtual function in a derived class alters the derived class object's data, then *that* function cannot be declared as a `const` member. Therefore, the author of an abstract base class should carefully consider whether a pure virtual member function should be a `const` member function or not.

14.3.1 Implementing pure virtual functions

Pure virtual member functions may be implemented. To implement a pure virtual member function, provide it with its normal `= 0;` specification, but implement it as well. Since the `= 0;` ends in a semicolon, the pure virtual member is always at most a declaration in its class, but an implementation may either be provided outside from its interface (maybe using `inline`).

Pure virtual member functions may be called from derived class objects or from its class or derived class members by specifying the base class and scope resolution operator together with the member to be called. Example:

```
#include <iostream>

class Base
{
    public:
        virtual ~Base();
        virtual void pureimp() = 0;
};
Base::~Base()
{}
void Base::pureimp()
{
    std::cout << "Base::pureimp() called\n";
}
class Derived: public Base
{
    public:
        virtual void pureimp();
};
inline void Derived::pureimp()
{
    Base::pureimp();
    std::cout << "Derived::pureimp() called\n";
}
int main()
{
    Derived derived;

    derived.pureimp();
    derived.Base::pureimp();

    Derived *dp = &derived;

    dp->pureimp();
    dp->Base::pureimp();
}
// Output:
//      Base::pureimp() called
//      Derived::pureimp() called
//      Base::pureimp() called
//      Base::pureimp() called
//      Derived::pureimp() called
//      Base::pureimp() called
```

Implementing a pure virtual member has limited use. One could argue that the pure virtual member function's implementation may be used to perform tasks that can already be performed at the base class level. However, there is no guarantee that the base class virtual member function is actually going to be called. Therefore base class specific tasks could as well be offered by a separate member, without blurring the distinction between a member doing some work and a pure virtual member enforcing a protocol.

14.4 Explicit virtual overrides

Consider the following situations:

- A class `Value` is a *value* class. It offers a copy constructor, an overloaded assignment operator, maybe move operations, and a public, non-virtual constructor. In section 14.7 it is argued that such classes are not suited as base classes. New classes should not inherit from `Value`. How to enforce this?

- A polymorphic class `Base` defines a virtual member `v_process(int32_t)`. A class derived from `Base` needs to override this member, but the author mistakingly defined `v_proces(int32_t)`. How to prevent such errors, breaking the polymorphic behavior of the derived class?
- A class `Derived`, derived from a polymorphic `Base` class overrides the member `Base::v_process`, but classes that are in turn derived from `Derived` should no longer override `v_process`, but *may* override other virtual members like `v_call` and `v_display`. How to enforce this restricted polymorphic character for classes derived from `Derived`?

Two special identifiers, `final` and `override` are used to realize the above. These identifiers are special in the sense that they only require their special meanings in specific contexts. Outside of this context they are just plain identifiers, allowing the programmer to define a variable like `bool final`.

The identifier `final` can be applied to class declarations to indicate that the class cannot be used as a base class. E.g.:

```
class Base1 final               // cannot be a base class
{};
class Derived1: public Base1    // ERR: Base1 is final
{};

class Base2                     // OK as base class
{};
class Derived2 final: public Base2  // OK, but Derived2 can't be
{};                                 //     used as a base class
class Derived: public Derived2      // ERR: Derived2 is final
{};
```

The identifier `final` can also be added to virtual member declarations. This indicates that those virtual members cannot be overridden by derived classes. The restricted polymorphic character of a class, mentioned above, can thus be realized as follows:

```
class Base
{
    virtual int v_process();    // define polymorphic behavior
    virtual int v_call();
    virtual int v_display();
};
class Derived: public Base      // Derived restricts polymorphism
{                               // to v_call and v_display
    virtual int v_process() final;
};
class Derived2: public Derived
{
    // int v_process();            No go: Derived:v_process is final
    virtual int v_display();    // OK to override
};
```

To allow the compiler to detect typos, differences in parameter types, or differences in member function modifiers (e.g., `const` vs. non-`const`) the identifier `override` can (should) be appended to derived class members overriding base class members. E.g.,

```
class Base
{
    virtual int v_process();
    virtual int v_call() const;
    virtual int v_display(std::ostream &out);
};
class Derived: public Base
{
    virtual int v_proces() override;    // ERR: v_proces != v_process
    virtual int v_call() override;      // ERR: not const
                                        // ERR: parameter types differ
    virtual int v_display(std::istream &out) override;
};
```

14.5 Virtual functions and multiple inheritance

In chapter 6 we encountered the class `fstream`, one class offering features of `ifstream` and `ofstream`. In chapter 13 we learned that a class may be derived from multiple base classes. Such a derived class inherits the properties of all its base classes. Polymorphism can also be used in combination with multiple inheritance.

Consider what would happen if more than one 'path' leads from the derived class up to its (base) classes. This is illustrated in the next (fictitious) example where a class `Derived` is doubly derived from `Base`:

```
class Base
{
    int d_field;
    public:
        void setfield(int val);
        int field() const;
};
inline void Base::setfield(int val)
{
    d_field = val;
}
inline int Base::field() const
{
    return d_field;
}
class Derived: public Base, public Base
{};
```

Due to the double derivation, `Base`'s functionality now occurs twice in `Derived`. This results in ambiguity: when the function `setfield()` is called for a `Derived` class object, which function will that be as there are two of them? The scope resolution operator won't come to the rescue and so the **C++** compiler cannot compile the above example and (correctly) identifies an error.

The above code clearly duplicates its base class in the derivation, which can of course easily be avoided by not doubly deriving from `Base` (or by using composition (!)). But duplication of a base class can also occur through nested inheritance, where an object is derived from, e.g., a `Car` and from an `Air` (cf. section 13.1). Such a class would be needed to represent, e.g., a flying car[2]. An `AirCar`

---

[2] such as the one in James Bond vs. the Man with the Golden Gun...

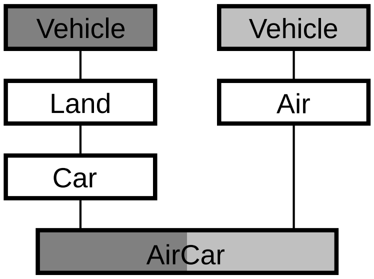

Figure 14.1: Duplication of a base class in multiple derivation.

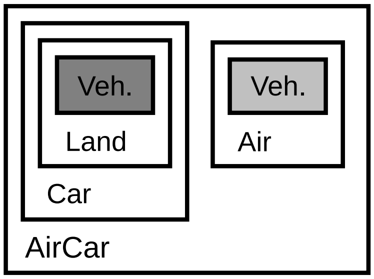

Figure 14.2: Internal organization of an `AirCar` object.

would ultimately contain two `Vehicles`, and hence two `mass` fields, two `setMass()` functions and two `mass()` functions. Is this what we want?

14.5.1 Ambiguity in multiple inheritance

Let's investigate closer why an `AirCar` introduces ambiguity, when derived from `Car` and `Air`.

- An `AirCar` is a `Car`, hence a `Land`, and hence a `Vehicle`.
- However, an `AirCar` is also an `Air`, and hence a `Vehicle`.

The duplication of `Vehicle` data is further illustrated in Figure 14.1. The internal organization of an `AirCar` is shown in Figure 14.2 The **C++** compiler detects the ambiguity in an `AirCar` object, and will therefore not compile statements like:

```
AirCar jBond;
cout << jBond.mass() << '\n';
```

Which member function `mass` to call cannot be determined by the compiler but the programmer has two possibilities to resolve the ambiguity for the compiler:

- First, the function call where the ambiguity originates can be modified. The ambiguity is resolved using the scope resolution operator:

  ```
  // let's hope that the mass is kept in the Car
  // part of the object..
  cout << jBond.Car::mass() << '\n';
  ```

  The scope resolution operator and the class name are put right before the name of the member function.

- Second, a dedicated function `mass` could be created for the class `AirCar`:

  ```
  int AirCar::mass() const
  {
      return Car::mass();
  }
  ```

The second possibility is preferred as it does not require the compiler to flag an error; nor does it require the programmer using the class `AirCar` to take special precautions.

However, there exists a more elegant solution, discussed in the next section.

14.5.2 Virtual base classes

As illustrated in Figure 14.2, an `AirCar` represents *two* `Vehicle`s. This not only results in an ambiguity about which function to use to access the `mass` data, but it also defines two `mass` fields in an `AirCar`. This is slightly redundant, since we can assume that an `AirCar` has but one mass.

It is, however, possible to define an `AirCar` as a class consisting of but one `Vehicle` and yet using multiple derivation. This is realized by defining the base classes that are multiply mentioned in a derived class's inheritance tree as a *virtual base class*.

For the class `AirCar` this implies a small change when deriving an `AirCar` from `Land` and `Air` classes:

```
class Land: virtual public Vehicle
{
    // etc
};
class Car: public Land
{
    // etc
};
class Air: virtual public Vehicle
{
    // etc
};
class AirCar: public Car, public Air
{
};
```

Virtual derivation ensures that a `Vehicle` is only added once to a derived class. This means that the route along which a `Vehicle` is added to an `AirCar` is no longer depending on its direct base classes; we can only state that an `AirCar` is a `Vehicle`. The internal organization of an `AirCar` after virtual derivation is shown in Figure 14.3.

When a class `Third` inherits from a base class `Second` which in turn inherits from a base class `First` then the `First` class constructor called by the `Second` class constructor is also used when this `Second` constructor is used when constructing a `Third` object. Example:

```
class First
{
    public:
        First(int x);
```

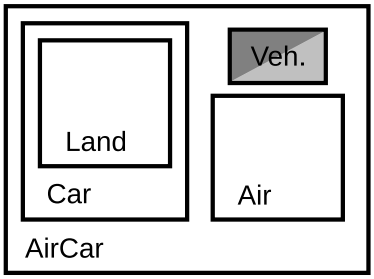

Figure 14.3: Internal organization of an `AirCar` object when the base classes are virtual.

```
};
class Second: public First
{
    public:
        Second(int x)
        :
            First(x)
        {}
};
class Third: public Second
{
    public:
        Third(int x)
        :
            Second(x)           // calls First(x)
        {}
};
```

The above no longer holds true when `Second` uses virtual derivation. When `Second` uses virtual derivation its base class constructor is *ignored* when `Second`'s constructor is called from `Third`. Instead `Second` by default calls `First`'s default constructor. This is illustrated by the next example:

```
class First
{
    public:
        First()
        {
            cout << "First()\n";
        }
        First(int x);
};
class Second: public virtual First      // note: virtual
{
    public:
        Second(int x)
        :
            First(x)
        {}
};
class Third: public Second
{
    public:
        Third(int x)
```

```
            :
                Second(x)
            {}
    };
    int main()
    {
        Third third{ 3 };   // displays `First()'
    }
```

When constructing `Third` `First`'s default constructor is used by default. `Third`'s constructor, however, may overrule this default behavior by explicitly specifying the constructor to use. Since the `First` object must be available before `Second` can be constructed it must be specified first. To call `First(int)` when constructing `Third(int)` the latter constructor can be defined as follows:

```
    class Third: public Second
    {
        public:
            Third(int x)
            :
                First(x),           // now First(int) is called.
                Second(x)
            {}
    };
```

This behavior may seem puzzling when simple linear inheritance is used but it makes sense when multiple inheritance is used with base classes using virtual inheritance. Consider `AirCar`: when `Air` and `Car` both virtually inherit from `Vehicle` will `Air` and `Car` both initialize the common `Vehicle` object? If so, which one is going to be called first? What if `Air` and `Car` use different `Vehicle` constructors? All these questions can be avoided by passing the responsibility for the initialization of a common base class to the class eventually using the common base class object. In the above example `Third`. Hence `Third` is provided an opportunity to specify the constructor to use when initializing `First`.

Multiple inheritance may also be used to inherit from classes that do not all use virtual inheritance. Assume we have two classes, `Derived1` and `Derived2`, both (possibly virtually) derived from `Base`.

We now address the question which constructors will be called when calling a constructor of the class `Final:  public Derived1, public Derived2`.

To distinguish the involved constructors `Base1` indicates the `Base` class constructor called as base class initializer for `Derived1` (and analogously: `Base2` called from `Derived2`). A plain `Base` indicates `Base`'s default constructor.

`Derived1` and `Derived2` indicate the base class initializers used when constructing a `Final` object.

Now we're ready to distinguish the various cases when constructing an object of the class `Final: public Derived1, public Derived2`:

- classes:

  ```
  Derived1: public Base
  Derived2: public Base
  ```

  This is normal, non virtual multiple derivation. The following constructors are called in the order shown:

  `Base1,`

```
    Derived1,
    Base2,
    Derived2
```

- classes:

  ```
  Derived1: public Base
  Derived2: virtual public Base
  ```

  Only `Derived2` uses virtual derivation. `Derived2`'s base class constructor is ignored. Instead, `Base` is called and it is called prior to any other constructor:

  ```
  Base,
  Base1,
  Derived1,
  Derived2
  ```

  As only one class uses virtual derivation, *two* `Base` class objects remain available in the eventual `Final` class.

- classes:

  ```
  Derived1: virtual public Base
  Derived2: public Base
  ```

  Only `Derived1` uses virtual derivation. `Derived1`'s base class constructor is ignored. Instead, `Base` is called and it is called prior to any other constructor. Different from the first (non-virtual) case `Base` is now called, rather than `Base1`:

  ```
  Base,
  Derived1,
  Base2,
  Derived2
  ```

- classes:

  ```
  Derived1: virtual public Base
  Derived2: virtual public Base
  ```

  Both base classes use virtual derivation and so only *one* `Base` class object will be present in the `Final` class object. The following constructors are called in the order shown:

  ```
  Base,
  Derived1,
  Derived2
  ```

Virtual derivation is, in contrast to virtual functions, a pure compile-time issue. Virtual inheritance merely defines how the compiler defines a class's data organization and construction process.

14.5.3 When virtual derivation is not appropriate

Virtual inheritance can be used to merge multiply occurring base classes. However, situations may be encountered where multiple occurrences of base classes is appropriate. Consider the definition of a `Truck` (cf. section 13.5):

```
class Truck: public Car
```

```
{
    int d_trailer_mass;

    public:
        Truck();
        Truck(int engine_mass, int sp, char const *nm,
               int trailer_mass);

        void setMass(int engine_mass, int trailer_mass);
        int mass() const;
};
Truck::Truck(int engine_mass, int sp, char const *nm,
              int trailer_mass)
:
    Car(engine_mass, sp, nm)
{
    d_trailer_mass = trailer_mass;
}
int Truck::mass() const
{
    return                  // sum of:
        Car::mass() +    //   engine part plus
        trailer_mass;         //   the trailer
}
```

This definition shows how a `Truck` object is constructed to contain two mass fields: one via its derivation from `Car` and one via its own `int d_trailer_mass` data member. Such a definition is of course valid, but it could also be rewritten. We could derive a `Truck` from a `Car` *and* from a `Vehicle`, thereby explicitly requesting the double presence of a `Vehicle`; one for the mass of the engine and cabin, and one for the mass of the trailer. A slight complication is that a class organization like

```
class Truck: public Car, public Vehicle
```

is not accepted by the **C++** compiler. As a `Vehicle` is already part of a `Car`, it is therefore not needed once again. This organization may, however be forced using a small trick. By creating an additional class inheriting from `Vehicle` and deriving `Truck` from that additional class rather than directly from `Vehicle` the problem is solved. Simply derive a class `TrailerVeh` from `Vehicle`, and then `Truck` from `Car` and `TrailerVeh`:

```
class TrailerVeh: public Vehicle
{
    public:
        TrailerVeh(int mass)
        :
            Vehicle(mass)
        {}
};
class Truck: public Car, public TrailerVeh
{
    public:
        Truck();
        Truck(int engine_mass, int sp, char const *nm, int trailer_mass);
        void setMass(int engine_mass, int trailer_mass);
        int mass() const;
};
```

```
inline Truck::Truck(int engine_mass, int sp, char const *nm,
                    int trailer_mass)
:
    Car(engine_mass, sp, nm),
    TrailerVeh(trailer_mass)
{}
inline int Truck::mass() const
{
    return                       // sum of:
        Car::mass() +         //   engine part plus
        TrailerVeh::mass();   //   the trailer
}
```

14.6 Run-time type identification

C++ offers two ways to retrieve types of objects and expressions at run-time. The possibilities of **C++**'s run-time type identification are limited compared to languages like **Java**. Usually static type checking and static type identification is used in **C++**. Static type checking is possibly safer and certainly more efficient than run-time type identification and should therefore be preferred over run-time type identification. But situations exist where run-time type identification is appropriate. **C++** offers run-time type identification through the *dynamic cast* and `typeid` operators.

- A `dynamic_cast` is used to convert a base class pointer or reference to a derived class pointer or reference. This is also known as *down-casting*.
- The `typeid` operator returns the actual type of an expression.

These operators can be used with objects of classes having at least one virtual member function.

14.6.1 The dynamic_cast operator

The `dynamic_cast<>` operator is used to convert a base class pointer or reference to, respectively, a derived class pointer or reference. This is also called *down-casting* as direction of the cast is *down* the inheritance tree.

A dynamic cast's actions are determined run-time; it can only be used if the base class declares at least one virtual member function. For the dynamic cast to succeed, the destination class's `Vtable` must be equal to the `Vtable` to which the dynamic cast's argument refers to, lest the cast fails and returns 0 (if a dynamic cast of a pointer was requested) or throws a `std::bad_cast` exception (if a dynamic cast of a reference was requested).

In the following example a pointer to the class `Derived` is obtained from the `Base` class pointer `bp`:

```
class Base
{
    public:
        virtual ~Base();
};
class Derived: public Base
{
    public:
        char const *toString();
};
inline char const *Derived::toString()
{
    return "Derived object";
}
int main()
{
    Base *bp;
    Derived *dp,
    Derived d;

    bp = &d;

    dp = dynamic_cast<Derived *>(bp);

    if (dp)
        cout << dp->toString() << '\n';
    else
        cout << "dynamic cast conversion failed\n";
}
```

In the condition of the above `if` statement the success of the dynamic cast is verified. This verification is performed at *run-time*, as the actual class of the objects to which the pointer points is only known by then.

If a base class pointer is provided, the dynamic cast operator returns 0 on failure and a pointer to the requested derived class on success.

Assume a `vector<Base *>` is used. The pointers of such a vector may point to objects of various classes, all derived from `Base`. A dynamic cast returns a pointer to the specified class if the base class pointer indeed points to an object of the specified class and returns 0 otherwise.

We could determine the actual class of an object a pointer points to by performing a series of checks to find the derived class to which a base class pointer points. Example:

```
class Base
{
    public:
        virtual ~Base();
};
class Derived1: public Base;
class Derived2: public Base;

int main()
{
    vector<Base *> vb(initializeBase());

    Base *bp = vb.front();

    if (dynamic_cast<Derived1 *>(bp))
        cout << "bp points to a Derived1 class object\n";
    else if (dynamic_cast<Derived2 *>(bp))
        cout << "bp points to a Derived2 class object\n";
}
```

Alternatively, a reference to a base class object may be available. In this case the `dynamic_cast` operator throws an exception if the down casting fails. Example:

```
#include <iostream>
#include <typeinfo>

class Base
{
    public:
        virtual ~Base();
        virtual char const *toString();
};
inline char const *Base::toString()
{
    return "Base::toString() called";
}
class Derived1: public Base
{};
class Derived2: public Base
{};

Base::~Base()
{}
void process(Base &b)
{
    try
    {
        std::cout << dynamic_cast<Derived1 &>(b).toString() << '\n';
    }
    catch (std::bad_cast)
    {}
    try
    {
        std::cout << dynamic_cast<Derived2 &>(b).toString() << '\n';
    }
    catch (std::bad_cast)
    {
        std::cout << "Bad cast to Derived2\n";
    }
}
int main()
{
    Derived1 d;
    process(d);
}
/*
    Generated output:

    Base::toString() called
    Bad cast to Derived2
*/
```

In this example the value `std::bad_cast` is used. A `std::bad_cast` exception is thrown if the dynamic cast of a reference to a derived class object fails.

Note the form of the `catch` clause: `bad_cast` is the name of a type. Section 17.4.1 describes how such a type can be defined.

The dynamic cast operator is a useful tool when an existing base class cannot or should not be modified (e.g., when the sources are not available), and a derived class may be modified instead. Code receiving a base class pointer or reference may then perform a dynamic cast to the derived class to access the derived class's functionality.

You may wonder in what way the behavior of the `dynamic_cast` differs from that of the `static_cast`.

When the `static_cast` is used, we tell the compiler that it must convert a pointer or reference to its expression type to a pointer or reference of its destination type. This holds true whether the base class declares virtual members or not. Consequently, all the `static_cast`'s actions can be determined by the compiler, and the following compiles fine:

```
class Base
{
    // maybe or not virtual members
};
class Derived1: public Base
{};
class Derived2: public Base
{};

int main()
{
    Derived1 derived1;
    Base *bp = &derived1;

    Derived1 &d1ref = static_cast<Derived1 &>(*bp);
    Derived2 &d2ref = static_cast<Derived2 &>(*bp);
}
```

Pay attention to the second `static_cast`: here the `Base` class object is cast to a `Derived2` class reference. The compiler has no problems with this, as `Base` and `Derived2` are related by inheritance.

Semantically, however, it makes no sense as `bp` in fact points to a `Derived1` class object. This is detected by a `dynamic_cast`. A `dynamic_cast`, like the `static_cast`, converts related pointer or reference types, but the `dynamic_cast` provides a run-time safeguard. The dynamic cast fails when the requested type doesn't match the actual type of the object we're pointing at. In addition, the `dynamic_cast`'s use is much more restricted than the `static_cast`'s use, as the `dynamic_cast` can only be used for downcasting to derived classes having virtual members.

In the end a dynamic cast is a cast, and casts should be avoided whenever possible. When the need for dynamic casting arises ask yourself whether the base class has correctly been designed. In situations where code expects a base class reference or pointer the base class interface should be all that is required and using a dynamic cast should not be necessary. Maybe the base class's virtual interface can be modified so as to prevent the use of dynamic casts. Start frowning when encountering code using dynamic casts. When using dynamic casts in your own code always properly document why the dynamic cast was appropriately used and was not avoided.

14.6.2 The 'typeid' operator

As with the `dynamic_cast` operator, `typeid` is usually applied to references to base class objects that refer to derived class objects. `Typeid` should only be used with base classes offering virtual members.

Before using `typeid` the `<typeinfo>` header file must be included.

The `typeid` operator returns an object of type `type_info`. Different compilers may offer different implementations of the class `type_info`, but at the very least `typeid` must offer the following interface:

```
class type_info
{
    public:
        virtual ~type_info();
        int operator==(type_info const &other) const;
        int operator!=(type_info const &other) const;
        bool before(type_info const &rhs) const;
        char const *name() const;
    private:
        type_info(type_info const &other);
        type_info &operator=(type_info const &other);
};
```

Note that this class has a private copy constructor and a private overloaded assignment operator. This prevents code from constructing `type_info` objects and prevents code from assigning `type_info` objects to each other. Instead, `type_info` objects are constructed and returned by the `typeid` operator.

If the `typeid` operator is passed a base class reference it is able to return the actual name of the type the reference refers to. Example:

```
class Base;
class Derived: public Base;

Derived d;
Base    &br = d;

cout << typeid(br).name() << '\n';
```

In this example the `typeid` operator is given a base class reference. It prints the text "`Derived`", being the class name of the class `br` actually refers to. If `Base` does not contain virtual functions, the text "`Base`" is printed.

The `typeid` operator can be used to determine the name of the actual type of expressions, not just of class type objects. For example:

```
cout << typeid(12).name() << '\n';     // prints:  int
cout << typeid(12.23).name() << '\n';  // prints:  double
```

Note, however, that the above example is suggestive at most. It *may* print `int` and `double`, but this is not necessarily the case. If portability is required, make sure no tests against these static, built-in text-strings are required. Check out what your compiler produces in case of doubt.

In situations where the `typeid` operator is applied to determine the type of a derived class, a base class *reference* should be used as the argument of the `typeid` operator. Consider the following example:

```
class Base;     // contains at least one virtual function
class Derived: public Base;
```

```
Base *bp = new Derived;     // base class pointer to derived object

if (typeid(bp) == typeid(Derived *))    // 1: false
    ...
if (typeid(bp) == typeid(Base *))       // 2: true
    ...
if (typeid(bp) == typeid(Derived))      // 3: false
    ...
if (typeid(bp) == typeid(Base))         // 4: false
    ...
if (typeid(*bp) == typeid(Derived))     // 5: true
    ...
if (typeid(*bp) == typeid(Base))        // 6: false
    ...

Base &br = *bp;

if (typeid(br) == typeid(Derived))      // 7: true
    ...
if (typeid(br) == typeid(Base))         // 8: false
    ...
```

Here, `(1)` returns `false` as a `Base *` is not a `Derived *`. `(2)` returns `true`, as the two pointer types are the same, `(3)` and `(4)` return `false` as pointers to objects are not the objects themselves.

On the other hand, if `*bp` is used in the above expressions, then `(1)` and `(2)` return `false` as an object (or reference to an object) is not a pointer to an object, whereas `(5)` now returns `true`: `*bp` actually refers to a `Derived` class object, and `typeid(*bp)` returns `typeid(Derived)`. A similar result is obtained if a base class reference is used: `7` returning `true` and `8` returning `false`.

The `type_info::before(type_info const &rhs)` member is used to determine the *collating order* of classes. This is useful when comparing two *types* for equality. The function returns a nonzero value if `*this` precedes `rhs` in the hierarchy or collating order of the used types. When a derived class is compared to its base class the comparison returns 0, otherwise a non-zero value. E.g.:

```
cout << typeid(ifstream).before(typeid(istream)) << '\n' << // not 0
        typeid(istream).before(typeid(ifstream)) << '\n';   // 0
```

With built-in types the implementor may implement that non-0 is returned when a ‘wider’ type is compared to a ‘smaller’ type and 0 otherwise:

```
cout << typeid(double).before(typeid(int)) << '\n' <<   // not 0
        typeid(int).before(typeid(double)) << '\n';     // 0
```

When two equal types are compared, 0 is returned:

```
cout << typeid(ifstream).before(typeid(ifstream)) << '\n';   // 0
```

When a `0`-pointer is passed to the `operator typeid` a `bad_typeid` exception is thrown.

14.7 Inheritance: when to use to achieve what?

Inheritance should not be applied automatically and thoughtlessly. Often composition can be used instead, improving on a class's design by reducing coupling. When inheritance is used *public* inheritance should not automatically be used but the type of inheritance that is selected should match the programmer's intent.

We've seen that polymorphic classes on the one hand offer interface members defining the functionality that can be requested of base classes and on the other hand offer virtual members that can be overridden. One of the signs of good class design is that member functions are designed according to the principle of 'one function, one task'. In the current context: a class member should either be a member of the class's public or protected interface or it should be available as a virtual member for reimplementation by derived classes. Often this boils down to virtual members that are defined in the base class's *private* section. Those functions shouldn't be called by code using the base class, but they exist to be overridden by derived classes using polymorphism to redefine the base class's behavior.

The underlying principle was mentioned before in the introductory paragraph of this chapter: according to the *Liskov Substitution Principle* (*LSP*) an *is-a* relationship between classes (indicating that a derived class object *is a* base class object) implies that a derived class object may be used in code expecting a base class object.

In this case inheritance is used *not* to let the derived class use the facilities already implemented by the base class but to reuse the base class polymorphically by reimplementing the base class's virtual members in the derived class.

In this section we'll discuss the reasons for using inheritance. Why should inheritance (not) be used? If it is used what do we try to accomplish by it?

Inheritance often competes with composition. Consider the following two alternative class designs:

```
class Derived: public Base
{ ... };

class Composed
{
    Base d_base;
    ...
};
```

Why and when prefer `Derived` over `Composed` and vice versa? What kind of inheritance should be used when designing the class `Derived`?

- Since `Composed` and `Derived` are offered as alternatives we are looking at the design of a class (`Derived` or `Composed`) that *is-implemented-in-terms-of* another class.
- Since `Composed` does itself not make `Base`'s interface available, `Derived` shouldn't do so either. The underlying principle is that *private inheritance* should be used when deriving a classs `Derived` from `Base` where `Derived` is-implemented-in-terms-of `Base`.
- Should we use inheritance or composition? Here are some arguments:
  - In general terms composition results in looser coupling and should therefore be preferred over inheritance.
  - Composition allows us to define classes having multiple members of the same type (think about a class having multiple `std::string` members) which can not be realized using inheritance.

  - Composition allows us to separate the class's interface from its implementation. This allows us to modify the class's data organization without the need to recompile code using our class. This is also known as the *bridge design pattern* or the *compiler firewall* or *pimpl* (pointer to the implementation) idiom.
  - If `Base` offers members in its *protected* interface that must be used when implementing `Derived` inheritance must also be used. Again: since we're implementing-in-terms-of the inheritance type should be `private`.
  - Protected inheritance may be considered when the derived class (`D`) itself is intended as a base class that should only make the members of its own base class (`B`) available to classes that are derived from it (i.e., `D`).

Private inheritance should also be used when a derived class is-a certain type of base class, but in order to initialize that base class an object of another class type must be available. Example: a new `istream` class-type (say: a stream `IRandStream` from which random numbers can be extracted) is derived from `std::istream`. Although an `istream` can be constructed empty (receiving its `streambuf` later using its `rdbuf` member), it is clearly preferable to initialize the `istream` base class right away.

Assuming that a `Randbuffer: public std::streambuf` has been created for generating random numbers then `IRandStream` can be derived from `Randbuffer` and `std::istream`. That way the `istream` base class can be initialized using the `Randbuffer` base class.

As a `RandStream` is definitely not a `Randbuffer` *public* inheritance is *not* appropriate. In this case `IRandStream` is-implemented-in-terms-of a `Randbuffer` and so *private* inheritance should be used.

`IRandStream`'s class interface should therefore start like this:

```
class IRandStream: private Randbuffer, public std::istream
{
    public:
        IRandStream(int lowest, int highest)    // defines the range
        :
            Randbuffer(lowest, highest),
            std::istream(this)                  // passes &Randbuffer
        {}
    ...
};
```

Public inheritance should be reserved for classes for which the LSP holds true. In those cases the derived classes can always be used instead of the base class from which they derive by code merely using base class references, pointers or members (I.e., conceptually the derived class *is-a* base class). This most often applies to classes derived from base classes offering virtual members. To separate the user interface from the redefinable interface the base class's public interface should *not* contain virtual members (except for the virtual destructor) and the virtual members should all be in the base class's private section. Such virtual members can still be overridden by derived classes (this should not come as a surprise, considering how polymorphism is implemented) and this design offers the base class full control over the context in which the redefined members are used. Often the public interface merely calls a virtual member, but those members can always be redefined to perform additional duties.

The prototypical form of a base class therefore looks like this:

```
class Base
{
    public:
            virtual ~Base();
            void process();             // calls virtual members (e.g.,
                                        // v_process)
        private:
            virtual void v_process();   // overridden by derived classes
    };
```

Alternatively a base class may offer a non-virtual destructor, which should then be protected. It shouldn't be public to prevent deleting objects through their base class pointers (in which case virtual destructors should be used). It should be protected to allow derived class destructors to call their base class destructors. Such base classes should, for the same reasons, have non-public constructors and overloaded assignment operators.

14.8 The 'streambuf' class

The class `std::streambuf` receives the character sequences processed by streams and defines the interface between stream objects and devices (like a file on disk). A `streambuf` object is usually not directly constructed, but usually it is used as base class of some derived class implementing the communication with some concrete device.

The primary reason for existence of the class `streambuf` is to decouple the `stream` classes from the devices they operate upon. The rationale here is to add an extra layer between the classes allowing us to communicate with devices and the devices themselves. This implements a *chain of command* which is seen regularly in software design.

The *chain of command* is considered a generic pattern when designing reusable software, encountered also in, e.g., the TCP/IP stack.

A `streambuf` can be considered yet another example of the chain of command pattern. Here the program talks to `stream` objects, which in turn forward their requests to `streambuf` objects, which in turn communicate with the devices. Thus, as we will see shortly, we are able to do in user-software what had to be done via (expensive) system calls before.

The class `streambuf` has no public constructor, but does make available several public member functions. In addition to these public member functions, several member functions are only available to classes derived from `streambuf`. In section 14.8.2 a predefined specialization of the class `streambuf` is introduced. All public members of `streambuf` discussed here are *also* available in `filebuf`.

The next section shows the `streambuf` members that may be overridden when deriving classes from `streambuf`. Chapter 25 offers concrete examples of classes derived from `streambuf`.

The class `streambuf` is used by streams performing input operations and by streams performing output operations and their member functions can be ordered likewise. The type `std::streamsize` used below may, for all practical purposes, be considered equal to the type `size_t`.

When inserting information into `ostream` objects the information is eventually passed on to the `ostream`'s `streambuf`. The `streambuf` may decide to throw an exception. However, this exception does not leave the `ostream` using the `streambuf`. Rather, the exception is caught by the `ostream`, which sets its `ios::bad_bit`. Exceptions thrown by manipulators which are inserted into `ostream` objects are *not* caught by the `ostream` objects.

Public members for input operations

- `std::streamsize in_avail()`:
  Returns a lower bound on the number of characters that can be read immediately.

- `int sbumpc()`:
  The next available character or `EOF` is returned. The returned character is removed from the `streambuf` object. If no input is available, `sbumpc` calls the (protected) member `uflow` (see section 14.8.1 below) to make new characters available. `EOF` is returned if no more characters are available.

- `int sgetc()`:
  The next available character or `EOF` is returned. The character is *not* removed from the `streambuf` object. To remove a character from the `streambuf` object, `sbumpc` (or `sgetn`) can be used.

- `int sgetn(char *buffer, std::streamsize n)`:
  At most `n` characters are retrieved from the input buffer, and stored in `buffer`. The actual number of characters read is returned. The (protected) member `xsgetn` (see section 14.8.1 below) is called to obtain the requested number of characters.

- `int snextc()`:
  The current character is obtained from the input buffer and returned as the next available character or `EOF` is returned. The character is *not* removed from the `streambuf` object.

- `int sputbackc(char c)`:
  Inserts `c` into the `streambuf`’s buffer to be returned as the next character to read from the `streambuf` object. Caution should be exercised when using this function: often there is a maximum of just one character that can be put back.

- `int sungetc()`:
  Returns the last character read to the input buffer, to be read again at the next input operation. Caution should be exercised when using this function: often there is a maximum of just one character that can be put back.

Public members for output operations

- `int pubsync()`:
  Synchronizes (i.e., flushes) the buffer by writing any information currently available in the `streambuf`’s buffer to the device. Normally only used by classes derived from `streambuf`.

- `int sputc(char c)`:
  Character `c` is inserted into the `streambuf` object. If, after writing the character, the buffer is full, the function calls the (protected) member function `overflow` to flush the buffer to the device (see section 14.8.1 below).

- `int sputn(char const *buffer, std::streamsize n)`:
  At most `n` characters from `buffer` are inserted into the `streambuf` object. The actual number of characters inserted is returned. This member function calls the (protected) member `xsputn` (see section 14.8.1 below) to insert the requested number of characters.

Public members for miscellaneous operations

The next three members are normally only used by classes derived from `streambuf`.

- `ios::pos_type pubseekoff(ios::off_type offset, ios::seekdir way, ios::openmode mode = ios::in | ios::out)`:
  Sets the offset of the next character to be read or written to `offset`, relative to the standard `ios::seekdir` values indicating the direction of the seeking operation.

- `ios::pos_type pubseekpos(ios::pos_type offset, ios::openmode mode = ios::in | ios::out)`:
  Sets the absolute position of the next character to be read or written to `pos`.

- `streambuf *pubsetbuf(char* buffer, std::streamsize n)`:
  The `streambuf` object is going to use `buffer`, which may contain at least `n` characters.

14.8.1 Protected 'streambuf' members

The *protected* members of the class `streambuf` are important for understanding and using `streambuf` objects. Although there are both protected data members and protected member functions defined in the `class streambuf` the protected *data* members are not mentioned here as using them would violate the principle of *data hiding*. As `streambuf`'s set of member functions is quite extensive, it is hardly ever necessary to use its data members directly. The following subsections do not even list all protected member functions but only those are covered that are useful for constructing specializations.

`Streambuf` objects control a buffer, used for input and/or output, for which begin-, actual- and end-pointers have been defined, as depicted in figure 14.4.

`Streambuf` offers two protected constructors:

- `streambuf::streambuf()`:
  Default (protected) constructor of the `class streambuf`.
- `streambuf::streambuf(streambuf const &rhs)`:
  (Protected) copy constructor of the `class streambuf`. Note that this copy constructor merely copies the values of the data members of `rhs`: after using the copy constructor both `streambuf` objects refer to the same data buffer and initially their pointers point at identical positions. Also note that these are *not* shared pointers, but only 'raw copies'.

14.8.1.1 Protected members for input operations

Several protected member functions are available for input operations. The member functions marked `virtual` may of course be redefined in derived classes:

- `char *eback()`:
  `Streambuf` maintains three pointers controlling its input buffer: `eback` points to the 'end of the putback' area: characters can safely be put back up to this position. See also figure 14.4. `Eback` points to the *beginning* of the input buffer.
- `char *egptr()`:
  `Egptr` points just beyond the last character that can be retrieved from the input buffer. See also figure 14.4. If `gptr` equals `egptr` the buffer must be refilled. This should be implemented by calling `underflow`, see below.
- `void gbump(int n)`:
  The object's `gptr` (see below) is advanced over `n` positions.
- `char *gptr()`:
  `Gptr` points to the next character to be retrieved from the object's input buffer. See also figure 14.4.
- `virtual int pbackfail(int c)`:
  This member function may be overridden by derived classes to do something intelligent when putting back character `c` fails. One might consider restoring the old read pointer when input buffer's begin has been reached. This member function is called when ungetting or putting back a character fails. In particular, it is called when
  - `gptr() == 0`: no buffering used,

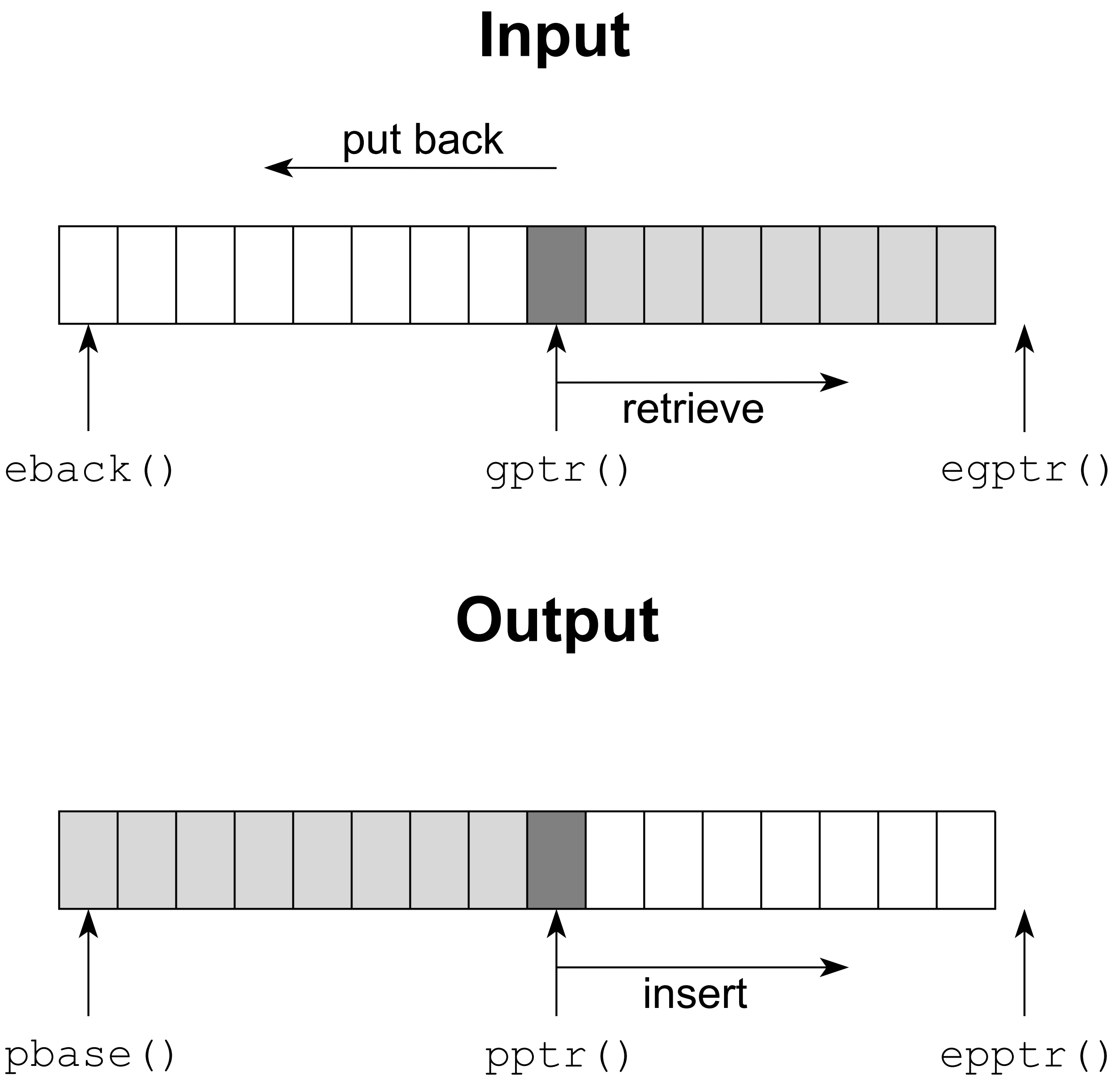
Input
put back
retrieve
eback()
gptr()
egptr()
Output
insert
pbase()
pptr()
epptr()

Figure 14.4: Input- and output buffer pointers of the class 'streambuf'

  - `gptr() == eback()`: no more room to push back,
  - `*gptr() != c`: a different character than the next character to be read must be pushed back.

  If `c == endOfFile()` then the input device must be reset by one character position. Otherwise `c` must be prepended to the characters to be read. The function should return `EOF` on failure. Otherwise 0 can be returned.

- `void setg(char *beg, char *next, char *beyond)`:
  Initializes an input buffer. `beg` points to the beginning of the input area, `next` points to the next character to be retrieved, and `beyond` points to the location just beyond the input buffer's last character. Usually `next` is at least `beg + 1`, to allow for a put back operation. No input buffering is used when this member is called as `setg(0, 0, 0)`. See also the member `uflow`, below.

- `virtual streamsize showmanyc()`:
  (Pronounce: s-how-many-c) This member function may be overridden by derived classes. It must return a guaranteed lower bound on the number of characters that can be read from the device before `uflow` or `underflow` returns `EOF`. By default 0 is returned (meaning no or some characters are returned before the latter two functions return `EOF`). When a positive value is returned then the next call of `u(nder)flow` does not return `EOF`.

- `virtual int uflow()`:
  This member function may be overridden by derived classes to reload an input buffer with fresh characters. Its default implementation is to call `underflow` (see below). If `underflow()` fails, `EOF` is returned. Otherwise, the next available character is returned as `static_cast<unsigned char>(*gptr())` following a `gbump(-1)`. `Uflow` also moves the pending character that is returned to the backup sequence. This is different from `underflow()`, which merely returns the next available character, but does not alter the input pointer positions.

  When *no* input buffering is required this function, rather than `underflow`, can be overridden to produce the next available character from the device to read from.

- `virtual int underflow()`:
  This member function may be overridden by derived classes to read another character from the device. The default implementation is to return `EOF`.

  It is called when

  - there is no input buffer (`eback() == 0`)
  - `gptr() >= egptr()`: the input buffer is exhausted.

  Often, when buffering is used, the complete buffer is not refreshed as this would make it impossible to put back characters immediately following a reload. Instead, buffers are often refreshed in halves. This system is called a *split buffer*.

  Classes derived from `streambuf` for reading normally at least override `underflow`. The prototypical example of an overridden `underflow` function looks like this:

```
int underflow()
{
    if (not refillTheBuffer())  // assume a member d_buffer is available
        return EOF;
                                // reset the input buffer pointers
    setg(d_buffer, d_buffer, d_buffer + d_nCharsRead);

                                // return the next available character
                                // (the cast is used to prevent
                                // misinterpretations of 0xff characters
                                // as EOF)
    return static_cast<unsigned char>(*gptr());
}
```

- `virtual streamsize xsgetn(char *buffer, streamsize n)`:
  This member function may be overridden by derived classes to retrieve at once `n` characters from the input device. The default implementation is to call `sbumpc` for every single character meaning that by default this member (eventually) calls `underflow` for every single character. The function returns the actual number of characters read or `EOF`. Once `EOF` is returned the `streambuf` stops reading the device.

14.8.1.2 Protected members for output operations

The following protected members are available for output operations. Again, some members may be overridden by derived classes:

- `virtual int overflow(int c)`:
  This member function may be overridden by derived classes to flush the characters currently stored in the output buffer to the output device, and then to reset the output buffer pointers so as to represent an empty buffer. Its parameter `c` is initialized to the next character to be processed. If no output buffering is used `overflow` is called for every single character that is written to the `streambuf` object. No output buffering is accomplished by setting the buffer pointers (using, `setp`, see below) to 0. The default implementation returns `EOF`, indicating that no characters can be written to the device.

  Classes derived from `streambuf` for writing normally at least override `overflow`. The prototypical example of an overridden `overflow` function looks like this:

```
int OFdStreambuf::overflow(int c)
{
    sync();                             // flush the buffer
    if (c != EOF)                       // write a character?
    {
        *pptr() = static_cast<char>(c); // put it into the buffer
        pbump(1);                       // advance the buffer's pointer
    }
    return c;
}
```

- `char *pbase()`:
  `Streambuf` maintains three pointers controlling its output buffer: `pbase` points to the beginning of the output buffer area. See also figure 14.4.

- `char *epptr()`:
  `Streambuf` maintains three pointers controlling its output buffer: `epptr` points just beyond the output buffer’s last available location. See also figure 14.4. If `pptr` (see below) equals `epptr` the buffer must be flushed. This is implemented by calling `overflow`, see before.

- `void pbump(int n)`:
  The location returned by `pptr` (see below) is advanced by `n`. The next character written to the stream will be entered at that location.

- `char *pptr()`:
  `Streambuf` maintains three pointers controlling its output buffer: `pptr` points to the location in the output buffer where the next available character should be written. See also figure 14.4.

- `void setp(char *beg, char *beyond)`:
  `Streambuf`'s output buffer is initialized to the locations passed to `setp`. `Beg` points to the beginning of the output buffer and `beyond` points just beyond the last available location of the output buffer. Use `setp(0, 0)` to indicate that no buffering should be used. In that case `overflow` is called for every single character to write to the device.

- `virtual streamsize xsputn(char const *buffer, streamsize n)`:
  This member function may be overridden by derived classes to write a series of at most `n` characters to the output buffer. The actual number of inserted characters is returned. If `EOF` is returned writing to the device stops. The default implementation calls `sputc` for each individual character. Redefine this member if, e.g., the `streambuf` should support the `ios::openmode ios::app`. Assuming the class `MyBuf`, derived from `streambuf`, features a data member `ios::openmode d_mode` (representing the requested `ios::openmode`), and a member `write(char const *buf, streamsize len)` (writing `len` bytes at `pptr()`), then the following code acknowledges the `ios::app` mode:

  ```
  std::streamsize MyStreambuf::xsputn(char const *buf, std::streamsize len)
  {
      if (d_openMode & ios::app)
          seekoff(0, ios::end);

      return write(buf, len);
  }
  ```

14.8.1.3 Protected members for buffer manipulation

Several protected members are related to buffer management and positioning:

- `virtual streambuf *setbuf(char *buffer, streamsize n)`:
  This member function may be overridden by derived classes to install a buffer. The default implementation performs no actions. It is called by `pubsetbuf`.

- `virtual ios::pos_type seekoff(ios::off_type offset, ios::seekdir way, ios::openmode mode = ios::in | ios::out)`:
  This member function may be overridden by derived classes to reset the next pointer for input or output to a new relative position (using `ios::beg`, `ios::cur` or `ios::end`). The default implementation indicates failure by returning -1. The function is called when `tellg` or `tellp` are called. When derived class supports seeking, then it should also define this function to handle repositioning requests. It is called by `pubseekoff`. The new position or an invalid position (i.e., -1) is returned.

- `virtual ios::pos_type seekpos(ios::pos_type offset, ios::openmode mode = ios::in | ios::out)`:
  This member function may be overridden by derived classes to reset the next pointer for input or output to a new absolute position (i.e, relative to `ios::beg`). The default implementation indicates failure by returning -1.

- `virtual int sync()`:
  This member function may be overridden by derived classes to flush the output buffer to the output device or to reset the input device just beyond the position of the character that was returned last. It returns 0 on success, -1 on failure. The default implementation (not using a buffer) is to return 0, indicating successful syncing. This member is used to ensure that any characters that are still buffered are written to the device or to put unconsumed characters back to the device when the `streambuf` object ceases to exist.

14.8.1.4 Deriving classes from 'streambuf'

When classes are derived from `streambuf` at least `underflow` should be overridden by classes intending to read information from devices, and `overflow` should be overridden by classes intending to write information to devices. Several examples of classes derived from `streambuf` are provided in chapter 25.

`Fstream` class type objects use a combined input/output buffer, resulting from `istream` and `ostream` being virtually derived from `ios`, which class defines a `streambuf`. To construct a class supporting both input and output using separate buffers, the `streambuf` itself may define two buffers. When `seekoff` is called for reading, a `mode` parameter can be set to `ios::in`, otherwise to `ios::out`. Thus the derived class knows whether it should access the `read` buffer or the `write` buffer. Of course, `underflow` and `overflow` do not have to inspect the mode flag as they by implication know on which buffer they should operate.

14.8.2 The class 'filebuf'

The `class filebuf` is a specialization of `streambuf` used by the file `stream` classes. Before using a `filebuf` the header file `<fstream>` must be included.

In addition to the (public) members that are available through the `class streambuf`, `filebuf` offers the following (public) members:

- `filebuf()`:
  `Filebuf` offers a public constructor. It initializes a plain `filebuf` object that is not yet connected to a stream.
- `bool is_open()`:
  `True` is returned if the `filebuf` is actually connected to an open file, `false` otherwise. See the `open` member, below.
- `filebuf *open(char const *name, ios::openmode mode)`:
  Associates the `filebuf` object with a file whose name is provided. The file is opened according to the provided `openmode`.
- `filebuf *close()`:
  Closes the association between the `filebuf` object and its file. The association is automatically closed when the `filebuf` object ceases to exist.

14.8.3 Safely interfacing streams to another std::streambuf

Consider classes derived from `std::istream` or `std::ostream`. Such a class could be designed as follows:

```
class XIstream: public std::istream
{
    public:
        ...
};
```

Assuming that the `streambuf` to which `XIstream` interfaces is not yet available construction time, `XIstream` only offers default constructors. The class could, however, offer a member `void switchStream(std::streambuf *sb)` to provide `XIstream` objects with a `streambuf` to interface to. How to implement `switchStream`? We could simply call `rdbuf`, passing it the pointer to the new streambuf may work, but the problem is that there may be an existing streambuf, which may have buffered some information that we don't want to lose.

Instead of using `rdbuf` the protected member `void init(std::streambuf *sb)` should be used for switching to another streambuf in an existing stream.

The `init` member expects a pointer to a streambuf which should be associated with the `istream` or `ostream` object. The `init` member properly ends any existing association before switching to the `streambuf` whose address is provided to `init`.

Assuming that the `streambuf` to which `switchStream`'s `sb` points persists, then `switchStream` could simply be implemented like this:

```
void switchStream(streambuf *sb)
{
    init(sb);
}
```

No further actions are required. The `init` member ends the current association, and only then switches to using `streambuf *sb`.

14.9 A polymorphic exception class

Earlier in the **C++** Annotations (section 10.3.1) we hinted at the possibility of designing a class `Exception` whose `process` member would behave differently, depending on the kind of exception that was thrown. Now that we've introduced polymorphism we can further develop this example.

It probably does not come as a surprise that our class `Exception` should be a polymorphic base class from which special exception handling classes can be derived. In section 10.3.1 a member `severity` was used offering functionality that may be replaced by members of the `Exception` base class.

The base class `Exception` may be designed as follows:

```
#ifndef INCLUDED_EXCEPTION_H_
#define INCLUDED_EXCEPTION_H_
#include <iostream>
#include <string>

class Exception
{
    std::string d_reason;

    public:
        Exception(std::string const &reason);
        virtual ~Exception();

        std::ostream &insertInto(std::ostream &out) const;
        void handle() const;

    private:
        virtual void action() const;
};

inline void Exception::action() const
```

```
{
    throw;
}
inline Exception::Exception(std::string const &reason)
:
    d_reason(reason)
{}
inline void Exception::handle() const
{
    action();
}
inline std::ostream &Exception::insertInto(std::ostream &out) const
{
    return out << d_reason;
}

inline std::ostream &operator<<(std::ostream &out, Exception const &e)
{
    return e.insertInto(out);
}

#endif
```

Objects of this class may be inserted into `ostream`s but the core element of this class is the virtual member function `action`, by default rethrowing an exception.

A derived class `Warning` simply prefixes the thrown warning text by the text `Warning:`, but a derived class `Fatal` overrides `Exception::action` by calling `std::terminate`, forcefully terminating the program.

Here are the classes `Warning` and `Fatal`

```
#ifndef WARNINGEXCEPTION_H_
#define WARNINGEXCEPTION_H_

#include "exception.h"

class Warning: public Exception
{
    public:
        Warning(std::string const &reason)
        :
            Exception("Warning: " + reason)
        {}
};
#endif


#ifndef FATAL_H_
#define FATAL_H_

#include "exception.h"

class Fatal: public Exception
{
    public:
        Fatal(std::string  const &reason);
    private:
        virtual void action() const;
};

inline Fatal::Fatal(std::string  const &reason)
:
    Exception(reason)
{}

inline void Fatal::action() const
{
    std::cout << "Fatal::action() terminates" << '\n';
    std::terminate();
}

#endif
```

When the example program is started without arguments it throws a `Fatal` exception, otherwise it throws a `Warning` exception. Of course, additional exception types could also easily be defined. To make the example compilable the `Exception` destructor is defined above `main`. The default destructor cannot be used, as it is a virtual destructor. In practice the destructor should be defined in its own little source file:

```
#include "warning.h"
#include "fatal.h"

Exception::~Exception()
{}

using namespace std;

int main(int argc, char **argv)
try
{
    try
    {
        if (argc == 1)
            throw Fatal("Missing Argument") ;
        else
            throw Warning("the argument is ignored");
    }
    catch (Exception const &e)
    {
        cout << e << '\n';
        e.handle();
    }
}
catch(...)
{
    cout << "caught rethrown exception\n";
}
```

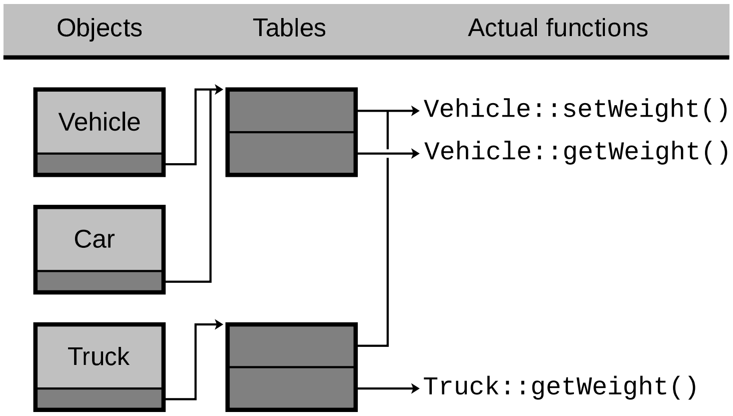

Figure 14.5: Internal organization objects when virtual functions are defined.

14.10 How polymorphism is implemented

This section briefly describes how polymorphism is implemented in **C++**. It is not necessary to understand how polymorphism is implemented if you just want to *use* polymorphism. However, we think it's nice to know how polymorphism is possible. Also, knowing how polymorphism is implemented clarifies why there is a (small) penalty to using polymorphism in terms of memory usage and efficiency.

The fundamental idea behind polymorphism is that the compiler does not know which function to call at compile-time. The appropriate function is selected at run-time. That means that the address of the function must be available somewhere, to be looked up prior to the actual call. This 'somewhere' place must be accessible to the object in question. So when a `Vehicle *vp` points to a `Truck` object, then `vp->mass()` calls `Truck`'s member function. The address of this function is obtained through the actual object to which `vp` points.

Polymorphism is commonly implemented as follows: an object containing virtual member functions also contains, usually as its first data member a hidden data member, pointing to an array containing the addresses of the class's virtual member functions. The hidden data member is usually called the *vpointer*, the array of virtual member function addresses the *vtable*.

The class's vtable is shared by all objects of that class. The overhead of polymorphism in terms of memory consumption is therefore:

- one vpointer data member per object pointing to:
- one vtable per class.

Consequently, a statement like `vp->mass` first inspects the hidden data member of the object pointed to by `vp`. In the case of the vehicle classification system, this data member points to a table containing two addresses: one pointer to the function `mass` and one pointer to the function `setMass` (three pointers if the class also defines (as it should) a virtual destructor). The actually called function is determined from this table.

The internal organization of the objects having virtual functions is illustrated in Figure 14.5 and Figure 14.6 (originals provided by `Guillaume Caumon`[3]).

As shown by Figure 14.5 and Figure 14.6, objects potentially using virtual member functions must have one (hidden) data member to address a table of function pointers. The objects of the classes

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[3] mailto:Guillaume.Caumon@ensg.inpl-nancy.fr

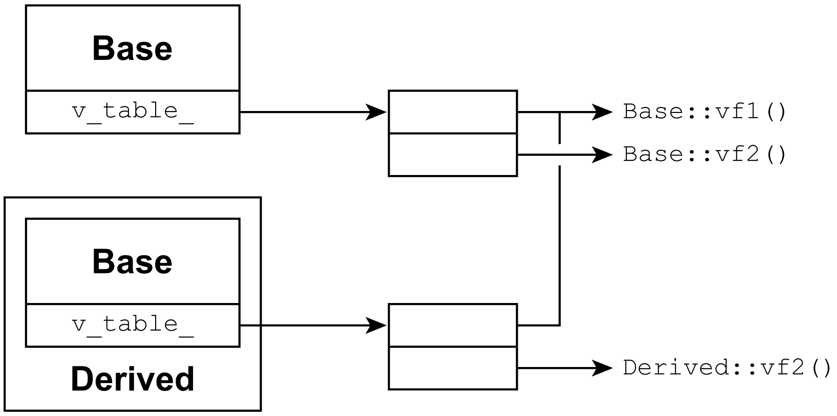

Figure 14.6: Complementary figure, provided by Guillaume Caumon

`Vehicle` and `Car` both address the same table. The class `Truck`, however, overrides `mass`. Consequently, `Truck` needs its own vtable.

A small complication arises when a class is derived from multiple base classes, each defining virtual functions. Consider the following example:

```
class Base1
{
    public:
        virtual ~Base1();
        void fun1();        // calls vOne and vTwo
    private:
        virtual void vOne();
        virtual void vTwo();
};
class Base2
{
    public:
        virtual ~Base2();
        void fun2();        // calls vThree
    private:
        virtual void vThree();
};
class Derived: public Base1, public Base2
{
    public:
        ~Derived() override;
    private:
        void vOne() override;
        void vThree() override;
};
```

In the example `Derived` is multiply derived from `Base1` and `Base2`, each supporting virtual functions. Because of this, `Derived` also has virtual functions, and so `Derived` has a `vtable` allowing a base class pointer or reference to access the proper virtual member.

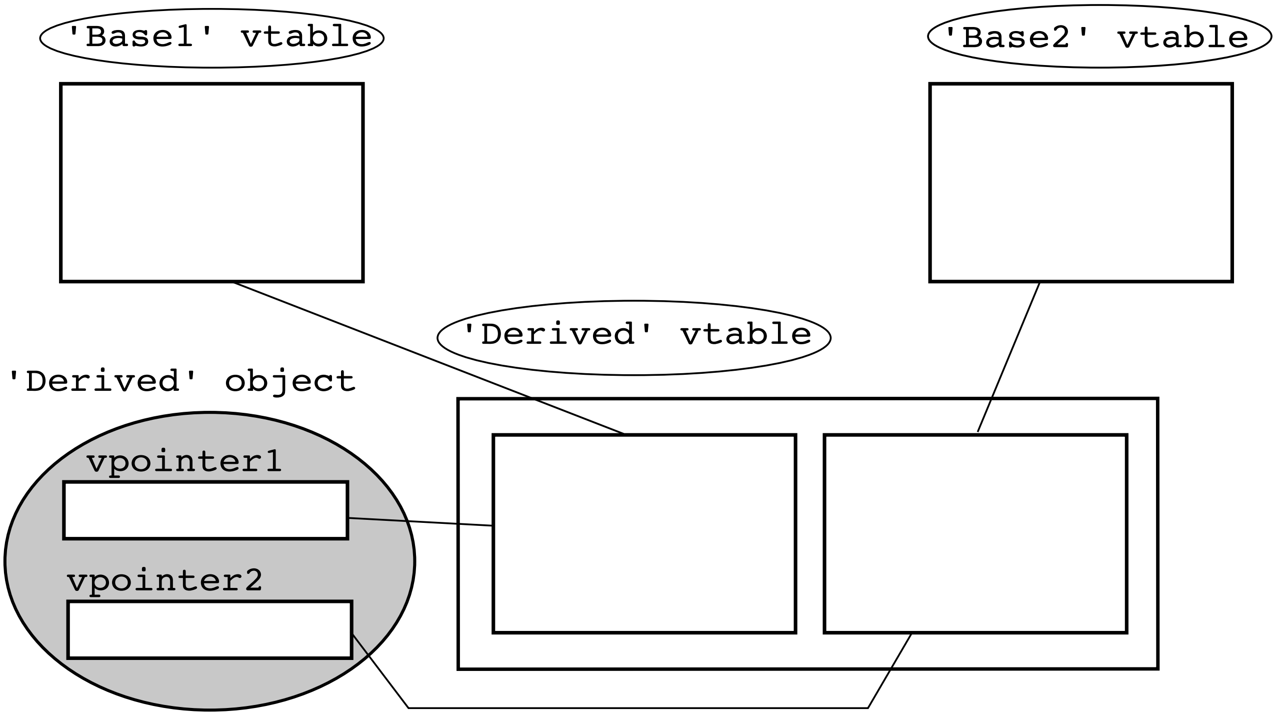

Figure 14.7: Vtables and vpointers with multiple base classes

When `Derived::fun1` is called (or a `Base1` pointer pointing to a `Derived` object calls `fun1`) then `fun1` calls `Derived::vOne` and `Base1::vTwo`. Likewise, when `Derived::fun2` is called `Derived::vThree` is called.

The complication occurs with `Derived`'s vtable. When `fun1` is called its class type determines the vtable to use and hence which virtual member to call. So when `vOne` is called from `fun1`, it is presumably the second entry in `Derived`'s vtable, as it must match the second entry in `Base1`'s vtable. However, when `fun2` calls `vThree` it apparently is also the second entry in `Derived`'s vtable as it must match the second entry in `Base2`'s vtable.

Of course this cannot be realized by a single vtable. Therefore, when multiple inheritance is used (each base class defining virtual members) another approach is followed to determine which virtual function to call. In this situation (cf. figure Figure 14.7) the class `Derived` receives *two* `vtable`s, one for each of its base classes and each `Derived` class object harbors *two* hidden vpointers, each one pointing to its corresponding vtable.

Since base class pointers, base class references, or base class interface members unambiguously refer to one of the base classes the compiler can determine which vpointer to use.

The following therefore holds true for classes multiply derived from base classes offering virtual member functions:

- the derived class defines a vtable for each of its base classes offering virtual members;
- Each derived class object contains as many hidden vpointers as it has vtables.
- Each of a derived class object's vpointers points to a unique vtable and the vpointer to use is determined by the class type of the base class pointer, the base class reference, or the base class interface function that is used.

14.11 Undefined reference to vtable ...

Occasionaly, the linker generates an error like the following:

```
In function `Derived::Derived()':
    : undefined reference to `vtable for Derived'
```

This error is generated when a virtual function's implementation is missing in a derived class, but the function is mentioned in the derived class's interface.

Such a situation is easily encountered:

- Construct a (complete) base class defining a virtual member function;
- Construct a Derived class mentioning the virtual function in its interface;
- The Derived class's virtual function is not implemented. Of course, the compiler doesn't know that the derived class's function is not implemented and will, when asked, generate code to create a derived class object;
- Eventually, the linker is unable to find the derived class's virtual member function. Therefore, it is unable to construct the derived class's vtable;
- The linker complains with the message:

  ```
  undefined reference to `vtable for Derived'
  ```

Here is an example producing the error:

```
class Base
{
    virtual void member();
};
inline void Base::member()
{}
class Derived: public Base
{
    virtual void member();      // only declared
};
int main()
{
    Derived d;  // Will compile, since all members were declared.
                // Linking will fail, since we don't have the
                // implementation of Derived::member()
}
```

It's of course easy to correct the error: implement the derived class's missing virtual member function.

Virtual functions should *never* be implemented inline. Since the vtable contains the addresses of the class's virtual functions, these functions must have addresses and so they must have been compiled as real (out-of-line) functions. By defining virtual functions inline you run the risk that the compiler simply overlooks those functions as they may very well never be explicitly called (but only polymorphically, from a base class pointer or reference). As a result their addresses may never enter their class's vtables (and even the vtable itself might remain undefined), causing linkage problems or resulting in programs showing unexpected behavior. All these kinds of problems are simply avoided: *never* define virtual members inline (see also section 7.8.2.1).

14.12 Virtual constructors

In section 14.2 we learned that **C++** supports *virtual destructors*. Like many other object oriented languages (e.g., **Java**), however, the notion of a *virtual constructor* is not supported. Not having virtual constructors becomes a liability when only base class references or pointers are available, and a copy of a derived class object is required. *Gamma et al.* (1995) discuss the *Prototype design pattern* to deal with this situation.

According to the *Prototype Design Pattern* each derived class is given the responsibility of implementing a member function returning a pointer to a copy of the object for which the member is called. The usual name for this function is `clone`. Separating the user interface from the reimplementation interface `clone` is made part of the interface and `newCopy` is defined in the reimplementation interface. A base class supporting 'cloning' defines a virtual destructor, `clone`, returning `newCopy`'s return value and the *virtual copy constructor*, a pure virtual function, having the prototype `virtual Base *newCopy() const = 0`. As `newCopy` is a pure virtual function all derived classes must now implement their own 'virtual constructor'.

This setup suffices in most situations where we have a pointer or reference to a base class, but it fails when used with abstract containers. We can't create a `vector<Base>`, with `Base` featuring the pure virtual `copy` member in its interface, as `Base` is called to initialize new elements of such a vector. This is impossible as `newCopy` is a pure virtual function, so a `Base` object can't be constructed.

The intuitive solution, providing `newCopy` with a default implementation, defining it as an ordinary virtual function, fails too as the container calls `Base(Base const &other)`, which would have to call `newCopy` to copy `other`. At this point it is unclear what to do with that copy, as the new `Base` object already exists, and contains no `Base` pointer or reference data member to assign `newCopy`'s return value to.

Alternatively (and preferred) the original `Base` class (defined as an abstract base class) is kept as-is and a wrapper class `Clonable` is used to manage the `Base` class pointers returned by `newCopy`. In chapter 17 ways to merge `Base` and `Clonable` into one class are discussed, but for now we'll define `Base` and `Clonable` as separate classes.

The class `Clonable` is a very standard class. It contains a pointer member so it needs a copy constructor, destructor, and overloaded assignment operator. It's given at least one non-standard member: `Base &base() const`, returning a reference to the derived object to which `Clonable`'s `Base *` data member refers. It is also provided with an additional constructor to initialize its `Base *` data member.

Any non-abstract class derived from `Base` must implement `Base *newCopy()`, returning a pointer to a newly created (allocated) copy of the object for which `newCopy` is called.

Once we have defined a derived class (e.g., `Derived1`), we can put our `Clonable` and `Base` facilities to good use. In the next example we see `main` defining a `vector<Clonable>`. An anonymous `Derived1` object is then inserted into the vector using the following steps:

- A new anonymous `Derived1` object is created;
- It initializes a `Clonable` using `Clonable(Base *bp)`;
- The just created `Clonable` object is inserted into the vector, using `Clonable`'s move constructor. There are only temporary `Derived` and `Clonable` objects at this point, so no copy construction is required.

In this sequence, only the `Clonable` object containing the `Derived1 *` is used. No additional copies need to be made (or destroyed).

Next, the `base` member is used in combination with `typeid` to show the actual type of the `Base &` object: a `Derived1` object.

`Main` then contains the interesting definition `vector<Clonable> v2(bv)`. Here a copy of `bv` is created. This copy construction observes the actual types of the `Base` references, making sure that the appropriate types appear in the vector's copy.

At the end of the program, we have created two `Derived1` objects, which are correctly deleted by the vector's destructors. Here is the full program, illustrating the 'virtual constructor' concept[4]:

```
    #include <iostream>
    #include <vector>
    #include <algorithm>
    #include <typeinfo>

// Base and its inline member:
    class Base
    {
        public:
            virtual ~Base();
            Base *clone() const;
        private:
            virtual Base *newCopy() const = 0;
    };
    inline Base *Base::clone() const
    {
        return newCopy();
    }

// Clonable and its inline members:
    class Clonable
    {
        Base *d_bp;

        public:
            Clonable();
            explicit Clonable(Base *base);
            ~Clonable();
            Clonable(Clonable const &other);
            Clonable(Clonable &&tmp);
            Clonable &operator=(Clonable const &other);
            Clonable &operator=(Clonable &&tmp);

            Base &base() const;
    };
    inline Clonable::Clonable()
    :
        d_bp(0)
    {}
    inline Clonable::Clonable(Base *bp)
    :
        d_bp(bp)
    {}
    inline Clonable::Clonable(Clonable const &other)
```

---

[4] Jesse van den Kieboom created an alternative implementation of a class `Clonable`, implemented as a class template. His implementation is found in the source archive under `contrib/classtemplates/`.

```
    :
        d_bp(other.d_bp->clone())
    {}
    inline Clonable::Clonable(Clonable &&tmp)
    :
        d_bp(tmp.d_bp)
    {
        tmp.d_bp = 0;
    }
    inline Clonable::~Clonable()
    {
        delete d_bp;
    }
    inline Base &Clonable::base() const
    {
        return *d_bp;
    }

// Derived and its inline member:
    class Derived1: public Base
    {
        public:
            ~Derived1();
        private:
            virtual Base *newCopy() const;
    };
    inline Base *Derived1::newCopy() const
    {
        return new Derived1(*this);
    }

// Members not implemented inline:
    Base::~Base()
    {}
    Clonable &Clonable::operator=(Clonable const &other)
    {
        Clonable tmp(other);
        std::swap(d_bp, tmp.d_bp);
        return *this;
    }
    Clonable &Clonable::operator=(Clonable &&tmp)
    {
        std::swap(d_bp, tmp.d_bp);
        return *this;
    }
    Derived1::~Derived1()
    {
        std::cout << "~Derived1() called\n";
    }

// The main function:
    using namespace std;

    int main()
    {
        vector<Clonable> bv;
    bv.push_back(Clonable(new Derived1()));
    cout << "bv[0].name: " << typeid(bv[0].base()).name() << '\n';

    vector<Clonable> v2(bv);
    cout << "v2[0].name: " << typeid(v2[0].base()).name() << '\n';
}
/*
    Output:
        bv[0].name: 8Derived1
        v2[0].name: 8Derived1
        ~Derived1() called
        ~Derived1() called
*/
```

Chapter 15

Friends

In all examples discussed up to now, we've seen that `private` members are only accessible by the members of their class. This is *good*, as it enforces encapsulation and data hiding. By encapsulating functionality within a class we prevent that a class exposes multiple responsibilities; by hiding data we promote a class's data integrity and we prevent that other parts of the software become implementation dependent on the data that belong to a class.

In this (very) short chapter we introduce the `friend` keyword and the principles that underly its use. The bottom line being that by using the `friend` keyword functions are granted access to a class's `private` members. Even so, this does not imply that the principle of data hiding is abandoned when the `friend` keyword is used.

In this chapter the topic of friendship among classes is not discussed. Situations in which it is natural to use friendship among classes are discussed in chapters 17 and 21 and such situations are natural extensions of the way friendship is handled for functions.

There should be a well-defined conceptual reason for declaring friendship (i.e., using the `friend` keyword). The traditionally offered definition of the class concept usually looks something like this:

> *A class is a set of data together with the functions that operate on that data.*

As we've seen in chapter 11 some functions have to be defined outside of a class interface. They are defined outside of the class interface to allow promotions for their operands or to extend the facilities of existing classes not directly under our control. According to the above traditional definition of the class concept those functions that cannot be defined in the class interface itself should nevertheless be considered functions belonging to the class. Stated otherwise: if permitted by the language's syntax they would certainly have been defined inside the class interface. There are two ways to implement such functions. One way consists of implementing those functions using available public member functions. This approach was used, e.g., in section 11.2. Another approach applies the definition of the class concept to those functions. By stating that those functions in fact belong to the class they should be given direct access to the data members of objects. This is accomplished by the `friend` keyword.

As a general principle we state that all functions operating on the data of objects of a class that are declared in the same file as the class interface itself belong to that class and may be granted direct access to the class's data members.

15.1 Friend functions

In section 11.2 the insertion operator of the class `Person` (cf. section 9.3) was implemented like this:

```
ostream &operator<<(ostream &out, Person const &person)
{
    return
        out <<
            "Name:    " << person.name() <<  ", "
            "Address: " << person.address() <<  ", "
            "Phone:   " << person.phone();
}
```

`Person` objects can now be inserted into streams.

However, this implementation required three member functions to be called, which may be considered a source of inefficiency. An improvement would be reached by defining a member `Person::insertInto` and let `operator<<` call that function. These two functions could be defined as follows:

```
std::ostream &operator<<(std::ostream &out, Person const &person)
{
    return person.insertInto(out);
}
std::ostream &Person::insertInto(std::ostream &out)
{
    return
        out << "Name:    " << d_name << ", "
               "Address: " << d_address << ", "
               "Phone:   " << d_phone;
}
```

As `insertInto` is a member function it has direct access to the object's data members so no additional member functions must be called when inserting `person` into `out`.

The next step consists of realizing that `insertInto` is only defined for the benefit of `operator<<`, and that `operator<<`, as it is declared in the header file containing `Person`'s class interface should be considered a function belonging to the class `Person`. The member `insertInto` can therefore be omitted when `operator<<` is declared as a friend.

Friend functions must be declared as friends in the class interface. These *friend declarations* are not *member* functions, and so they are independent of the class's `private`, `protected` and `public` sections. Friend declaration may be placed anywhere in the class interface. Convention dictates that friend declarations are listed directly at the top of the class interface. The class `Person`, using `friend` declaration for its extraction and insertion operators starts like this:

```
class Person
{
    friend std::ostream &operator<<(std::ostream &out, Person &pd);
    friend std::istream &operator>>(std::istream &in, Person &pd);

    // previously shown interface (data and functions)
};
```

The insertion operator may now directly access a `Person` object's data members:

```
std::ostream &operator<<(std::ostream &out, Person const &person)
{
    return
        cout << "Name:    " << person.d_name << ", "
                "Address: " << person.d_address << ", "
                "Phone:   " << person.d_phone;
}
```

Friend declarations are true declarations. Once a class contains friend declarations these friend functions do not have to be declared again below the class's interface. This also clearly indicates the class designer's intent: the friend functions are declared by the class, and can thus be considered functions belonging to the class.

15.2 Extended friend declarations

C++ has added *extended friend declarations* to the language. When a class is declared as a friend, then the `class` keyword no longer has to be provided. E.g.,

```
class Friend;                   // declare a class
typedef Friend FriendType;      // and a typedef for it
using FName = Friend;           // and a using declaration

class Class1
{
    friend Friend;              // FriendType and FName: also OK
};
```

In the pre-C++11 standards the friend declaration required an explicit `class`; e.g., `friend class Friend`.

The explicit use of `class` remains required if the compiler hasn't seen the friend's name yet. E.g.,

```
class Class1
{
    // friend Unseen;           // fails to compile: Unseen unknown.
    friend class Unseen;        // OK
};
```

Section 22.10 covers the use of extended friend declarations in class templates.

Chapter 16

Classes Having Pointers To Members

Classes having `pointer data members` have been discussed in detail in chapter 9. Classes defining pointer data-members deserve some special attention, as they usually require the definitions of copy constructors, overloaded assignment operators and destructors

Situations exist where we do not need a pointer to an object but rather a pointer to members of a class. Pointers to members can profitably be used to configure the behavior of objects of classes. Depending on which member a pointer to a member points to objects will show certain behavior.

Although pointers to members have their use, polymorphism can frequently be used to realize comparable behavior. Consider a class having a member `process` performing one of a series of alternate behaviors. Instead of selecting the behavior of choice at object construction time the class could use the interface of some (abstract) base class, passing an object of some derived class to its constructor and could thus configure its behavior. This allows for easy, extensible and flexible configuration, but access to the class's data members would be less flexible and would possibly require the use of 'friend' declarations. In such cases pointers to members may actually be preferred as this allows for (somewhat less flexible) configuration as well as direct access to a class's data members.

So the choice apparently is between on the one hand ease of configuration and on the other hand ease of access to a class's data members. In this chapter we'll concentrate on pointers to members, investigating what these pointers have to offer.

16.1 Pointers to members: an example

Knowing how pointers to variables and objects are used does not intuitively lead to the concept of *pointers to members* . Even if the return types and parameter types of member functions are taken into account, surprises can easily be encountered. For example, consider the following class:

```
class String
{
    char const *(*d_sp)() const;

    public:
        char const *get() const;
};
```

For this class, it is not possible to let `char const *(*d_sp)() const` point to the `String::get` member function as `d_sp` cannot be given the address of the member function `get`.

One of the reasons why this doesn't work is that the variable `d_sp` has global scope (it is a pointer to *a* function, not a pointer to a function within `String`), while the member function `get` is defined within the `String` class, and thus has `class scope`. The fact that `d_sp` is a data member of the class `String` is irrelevant here. According to `d_sp`'s definition, it points to a function living somewhere *outside* of the class.

Consequently, to define a pointer to a member (either data or function, but usually a function) of a class, the scope of the pointer must indicate class scope. Doing so, a pointer to the member `String::get` is defined like this:

```
    char const *(String::*d_sp)() const;
```

So, by prefixing the `*d_sp` pointer data member by `String::`, it is defined as a pointer in the context of the class `String`. According to its definition it is *a pointer to a function in the class `String`, not expecting arguments, not modifying its object's data, and returning a pointer to constant characters*.

16.2 Defining pointers to members

Pointers to members are defined by prefixing the normal pointer notation with the appropriate class plus scope resolution operator. Therefore, in the previous section, we used `char const * (String::*d_sp)() const` to indicate that `d_sp`

- is a pointer (`*d_sp`);
- points to something in the class `String` (`String::*d_sp`);
- is a pointer to a `const` function, returning a `char const *` (`char const * (String::*d_sp)() const`).

The prototype of a matching function is therefore:

```
    char const *String::somefun() const;
```

which is any `const` parameterless function in the class `String`, returning a `char const *`.

When defining pointers to members the standard procedure for constructing pointers to functions can still be applied:

- put parentheses around the fully qualified function name (i.e., the function's header, including the function's class name):

  ```
  char const * ( String::somefun ) () const
  ```

- Put a pointer (a star (*)) character immediately before the function name itself:

  ```
  char const * ( String:: * somefun ) () const
  ```

- Replace the function name with the name of the pointer variable:

  ```
  char const * (String::*d_sp)() const
  ```

Here is another example, defining a pointer to a data member. Assume the class `String` contains a `string d_text` member. How to construct a pointer to this member? Again we follow standard procedure:

- put parentheses around the fully qualified variable name:

  ```
  std::string (String::d_text)
  ```

- Put a pointer (a star (∗)) character immediately before the variable-name itself:

  ```
  std::string (String::*d_text)
  ```

- Replace the variable name with the name of the pointer variable:

  ```
  std::string (String::*tp)
  ```

  In this case, the parentheses are superfluous and may be omitted:

  ```
  string String::*tp
  ```

Alternatively, a very simple rule of thumb is

- Define a normal (i.e., global) pointer variable,
- Prefix the class name to the pointer character, once you point to something inside a class

For example, the following pointer to a global function

```
    char const * (*sp)() const;
```

becomes a pointer to a member function after prefixing the class-scope:

```
    char const * (String::*sp)() const;
```

Nothing forces us to define pointers to members in their target (`String`) classes. Pointers to members *may* be defined in their target classes (so they become data members), or in another class, or as a local variable or as a global variable. In all these cases the pointer to member variable can be given the address of the kind of member it points to. The important part is that a pointer to member can be initialized or assigned without requiring the existence of an object of the pointer's target class.

Initializing or assigning an address to such a pointer merely indicates to which member the pointer points. This can be considered some kind of *relative address*; relative to the object for which the function is called. No object is required when pointers to members are initialized or assigned. While it is allowed to initialize or assign a pointer to member, it is (of course) not possible to *call* those members without specifying an object of the correct type.

In the following example initialization of and assignment to pointers to members is illustrated (for illustration purposes all members of the class `PointerDemo` are defined `public`). In the example itself the `&`-operator is used to determine the addresses of the members. These operators as well as the class-scopes are required. Even when used inside member implementations:

```
    #include <cstddef>

    class PointerDemo
```

```
{
    public:
        size_t d_value;
        size_t get() const;
};

inline size_t PointerDemo::get() const
{
    return d_value;
}

int main()
{                                            // initialization
    size_t (PointerDemo::*getPtr)() const = &PointerDemo::get;
    size_t PointerDemo::*valuePtr         = &PointerDemo::d_value;

    getPtr   = &PointerDemo::get;            // assignment
    valuePtr = &PointerDemo::d_value;
}
```

This involves nothing special. The difference with pointers at global scope is that we're now restricting ourselves to the scope of the `PointerDemo` class. Because of this restriction, all *pointer* definitions and all variables whose addresses are used must be given the `PointerDemo` class scope.

Pointers to members can also be used with `virtual` member functions. No special syntax is required when pointing to virtual members. Pointer construction, initialization and assignment is done identically to the way it is done with non-virtual members.

16.3 Using pointers to members

Using pointers to members to call a member function requires the existence of an object of the class of the members to which the pointer to member refers to. With pointers operating at global scope, the dereferencing operator ∗ is used. With pointers to objects the field selector operator operating on pointers (->) or the field selector operating operating on objects (`.`) can be used to select appropriate members.

To use a pointer to member in combination with an object the pointer to member field selector (`.*`) must be specified. To use a pointer to a member via a pointer to an object the 'pointer to member field selector through a pointer to an object' (->∗) must be specified. These two operators combine the notions of a field selection (the `.` and -> parts) to reach the appropriate field in an object and of dereferencing: a dereference operation is used to reach the function or variable the pointer to member points to.

Using the example from the previous section, let's see how we can use pointers to member functions and pointers to data members:

```
#include <iostream>

class PointerDemo
{
    public:
        size_t d_value;
        size_t get() const;
};
```

```
    inline size_t PointerDemo::get() const
    {
        return d_value;
    }

    using namespace std;

    int main()
    {                                           // initialization
        size_t (PointerDemo::*getPtr)() const = &PointerDemo::get;
        size_t PointerDemo::*valuePtr   = &PointerDemo::d_value;

        PointerDemo object;                     // (1) (see text)
        PointerDemo *ptr = &object;

        object.*valuePtr = 12345;               // (2)
        cout << object.*valuePtr << '\n' <<
                object.d_value << '\n';

        ptr->*valuePtr = 54321;                 // (3)
        cout << object.d_value << '\n' <<
                (object.*getPtr)() << '\n' <<   // (4)
                (ptr->*getPtr)() << '\n';
    }
```

We note:

- At (1) a `PointerDemo` object and (in the next line) a pointer to such an object is defined.
- At (2) we specify an object (and hence the `.*` operator) to reach the member `valuePtr` points to. This member is given a value.
- At (3) the same member is assigned another value, but this time using the pointer to a `PointerDemo` object. Hence we use the `->*` operator.
- At (4) the `.*` and `->*` are used once again, this time to call a function through a pointer to member. As the function argument list has a higher priority than the pointer to member field selector operator, the latter *must* be protected by parentheses.

Pointers to members can be used profitably in situations where a class has a member that behaves differently depending on a configuration setting. Consider once again the class `Person` from section 9.3. `Person` defines data members holding a person's name, address and phone number. Assume we want to construct a `Person` database of employees. The employee database can be queried, but depending on the kind of person querying the database either the name, the name and phone number or all stored information about the person is made available. This implies that a member function like `address` must return something like '`<not available>`' in cases where the person querying the database is not allowed to see the person's address, and the actual address in other cases.

The employee database is opened specifying an argument reflecting the status of the employee who wants to make some queries. The status could reflect his or her position in the organization, like `BOARD`, `SUPERVISOR`, `SALESPERSON`, or `CLERK`. The first two categories are allowed to see all information about the employees, a `SALESPERSON` is allowed to see the employee's phone numbers, while the `CLERK` is only allowed to verify whether a person is actually a member of the organization.

We now construct a member `string personInfo(char const *name)` in the database class. A standard implementation of this class could be:

```
string PersonData::personInfo(char const *name)
{
    Person *p = lookup(name);   // see if `name' exists

    if (!p)
        return "not found";

    switch (d_category)
    {
        case BOARD:
        case SUPERVISOR:
            return allInfo(p);
        case SALESPERSON:
            return noPhone(p);
        case CLERK:
            return nameOnly(p);
    }
}
```

Although it doesn't take much time, the `switch` must nonetheless be evaluated every time `personInfo` is called. Instead of using a switch, we could define a member `d_infoPtr` as a pointer to a member function of the class `PersonData` returning a `string` and expecting a pointer to a `Person` as its argument.

Instead of evaluating the switch this pointer can be used to point to `allInfo`, `noPhone` or `nameOnly`. Furthermore, the member function the pointer points to will be known by the time the `PersonData` object is constructed and so its value needs to be determined only once (at the PersonData object's construction time).

Having initialized `d_infoPtr` the `personInfo` member function is now implemented simply as:

```
string PersonData::personInfo(char const *name)
{
    Person *p = lookup(name);       // see if `name' exists

    return p ? (this->*d_infoPtr)(p) :  "not found";
}
```

The member `d_infoPtr` is defined as follows (within the class `PersonData`, omitting other members):

```
class PersonData
{
    std::string (PersonData::*d_infoPtr)(Person *p);
};
```

Finally, the constructor initializes `d_infoPtr`. This could be realized using a simple switch:

```
PersonData::PersonData(PersonData::EmployeeCategory cat)
{
    switch (cat)
    {
        case BOARD:
        case SUPERVISOR:
            d_infoPtr = &PersonData::allInfo;
            break;
            case SALESPERSON:
                d_infoPtr = &PersonData::noPhone;
            break;
            case CLERK:
                d_infoPtr = &PersonData::nameOnly;
            break;
        }
    }
```

Note how addresses of member functions are determined. The class `PersonData` scope *must* be specified, even though we're already inside a member function of the class `PersonData`.

Since the `EmployeeCategory` values are known, the `switch` in the above constructor can also easily be avoided by defining a static array of pointers to functions. The class `PersonData` defines the static array:

```
    class PersonData
    {
        std::string (PersonData::*d_infoPtr)(Person *p);
        static std::string (PersonData::*s_infoPtr[])(Person *p);
    };
```

and `s_infoPtr[]` can be initialized compile-time:

```
    string (PersonData::*PersonData::s_infoPtr[])(Person *p) =
    {
        &PersonData::allInfo,       // BOARD
        &PersonData::allInfo,       // SUPERVISOR
        &PersonData::noPhone,       // SALESPERSON
        &PersonData::nameOnly       // CLERK
    };
```

The constructor, instead of using a `switch`, now directly calls the required member from the appropriate array element:

```
    PersonData::PersonData(PersonData::EmployeeCategory cat)
    :
        d_infoPtr(s_infoPtr[cat])
    {}
```

An example using pointers to data members is provided in section 19.1.61, in the context of the `stable_sort` generic algorithm.

16.4 Pointers to static members

Static members of a class can be used without having available an object of their class. Public static members can be called like free functions, albeit that their class names must be specified when they are called.

Assume a class `String` has a public static member function `count`, returning the number of string objects created so far. Then, without using any `String` object the function `String::count` may be called:

```
void fun()
{
    cout << String::count() << '\n';
}
```

Public static members can be called like free functions (but see also section 8.2.1). *Private* static members can only be called within the context of their class, by their class's member or friend functions.

Since static members have no associated objects their addresses can be stored in ordinary function pointer variables, operating at the global level. Pointers to members cannot be used to store addresses of static members. Example:

```
void fun()
{
    size_t (*pf)() = String::count;
            // initialize pf with the address of a static member function

    cout << (*pf)() << '\n';
            // displays the value returned by String::count()
}
```

16.5 Pointer sizes

An interesting characteristic of pointers to members is that their sizes differ from those of 'normal' pointers. Consider the following little program:

```
#include <string>
#include <iostream>

class X
{
    public:
        void fun();
        std::string d_str;
};
inline void X::fun()
{
    std::cout << "hello\n";
}

using namespace std;
int main()
{
    cout <<
       "size of pointer to data-member:     " << sizeof(&X::d_str) << "\n"
       "size of pointer to member function: " << sizeof(&X::fun) << "\n"
       "size of pointer to non-member data: " << sizeof(char *) << "\n"
       "size of pointer to free function:   " << sizeof(&printf) << '\n';
}

/*
    generated output (on 32-bit architectures):
        size of pointer to data-member:     4
        size of pointer to member function: 8
        size of pointer to non-member data: 4
        size of pointer to free function:   4
    */
```

On a 32-bit architecture a pointer to a member function requires eight bytes, whereas other kind of pointers require four bytes (Using GNU's g++ compiler).

Pointer sizes are hardly ever explicitly used, but their sizes may cause confusion in statements like:

```
    printf("%p", &X::fun);
```

Of course, `printf` is likely not the right tool for displaying the value of these **C++** specific pointers. The values of these pointers can be inserted into streams when a `union`, reinterpreting the 8-byte pointers as a series of size_t `char` values, is used:

```
    #include <string>
    #include <iostream>
    #include <iomanip>

    class X
    {
        public:
            void fun();
            std::string d_str;
    };
    inline void X::fun()
    {
        std::cout << "hello\n";
    }

    using namespace std;
    int main()
    {
        union
        {
            void (X::*f)();
            unsigned char *cp;
        }
            u = { &X::fun };

        cout.fill('0');
        cout << hex;
        for (unsigned idx = sizeof(void (X::*)()); idx-- > 0; )
            cout << setw(2) << static_cast<unsigned>(u.cp[idx]);
        cout << '\n';
    }
```

But why are their sizes different from the sizes of ordinary pointers? To answer this question let's first have a look at the familiar `std::fstream`. It is derived from `std::ifstream` and `std::ofstream`. An `fstream`, therefore, contains both an `ifstream` and an `ofstream`. An `fstream` will be organized as shown in figure 16.1.

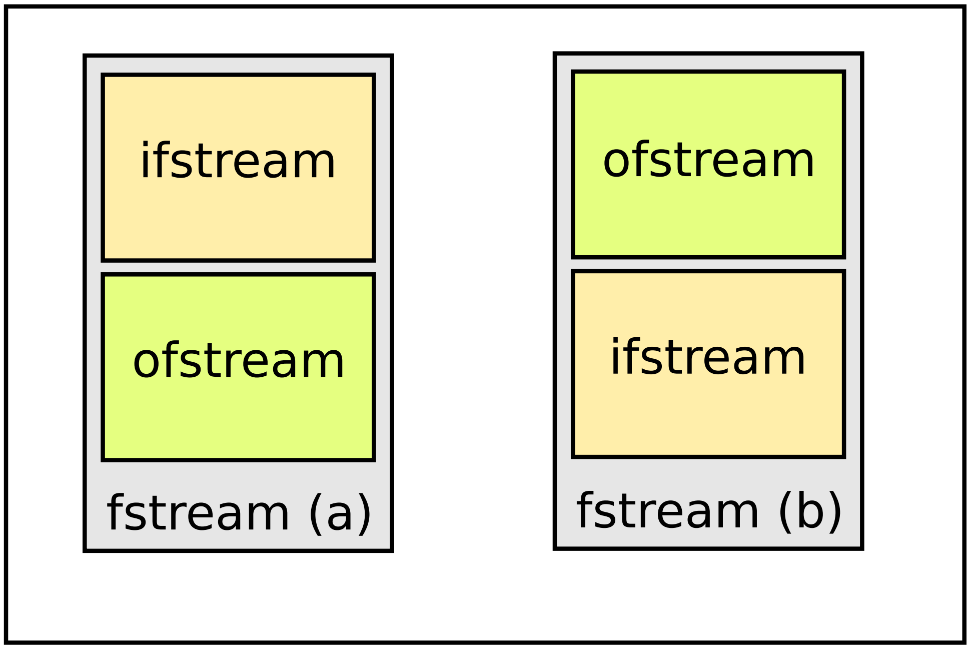

Figure 16.1: std::fstream object organization

In `fstream (a)` the first base class was `std::istream`, and the second baseclass was `std::ofstream`. But it could also very well be the other way around, as illustrated in `fstream (b)`: first the `std::ofstream`, then the `std::ifstream`. And that's the crux of the biscuit.

If we have an `fstream fstr{"myfile"}` object and do `fstr.seekg(0)`, then we call `ifstream's seekg` function. But if we do `fstr.seekp(0)`, then we call `ofstream's seekp` function. These functions have their own addresses, say &seekg and &seekp. But when we call a member function (like `fstr.seekp(0)`) then what we in fact are doing is `seekp(&fstr, 0)`.

But the problem here is that `&fstr` does not represent the correct object address: `seekp` operates on an `ofstream`, and that object does not start at `&fstr`, so (in `fstream (a)`), at `&(fstr + sizeof(ifstream))`.

So, the compiler, when calling a member function of a class using inheritance, must make a correction for the relative location of an object whose members we are calling.

However, when we're defining something like

```
    ostream &(fstream::*ptr)(ios::off_type step, ios::seekdir org) = &seekp;
```

and then do `(fstr->*)ptr(0)` the compiler doesn't know anymore which function is actually being called: it merely receives the function's address. To solve the compiler's problem the shift (for the location of the ofstream object) is now stored in the member pointer itself. That's one reason why the extra data field is needed when using function pointers.

Here is a concrete illustration: first we define 2 structs, each having a member function (all inline, using single line implementations to save some space):

```
    struct A
    {
        int a;
    };
```

```
struct B
{
    int b;
    void bfun() {}
};
```

Then we define C, which is derived from both A (first) and B (next) (comparable to `fstream`, which embeds `ifstream` and `ofstream`):

```
struct C: public A, public B
{};
```

Next, in `main` we define objects of two different unions and assign the address of `B::bfun` to their `ptr` fields, but `BPTR.ptr` looks at it as a member in the `struct B` world, while `CPTR.ptr` looks at it as a member in the `struct C` world.

Once the unions' pointer fields have been assigned their value[] arrays are used to display the content of the ptr fields (see below):

```
int main()
{
    union BPTR
    {
        void (B::*ptr)();
        unsigned long value[2];
    };
    BPTR bp;
    bp.ptr = &B::bfun;
    cout << hex << bp.value[0] << ' ' << bp.value[1] << dec << '\n';

    union CPTR
    {
        void (C::*ptr)();
        unsigned long value[2];
    };
    CPTR cp;
    cp.ptr = &C::bfun;
    cout << hex << cp.value[0] << ' ' << cp.value[1] << dec << '\n';
}
```

When this program is run, we see

```
400b0c 0
400b0c 4
```

(your address values (the first ones on the two lines) may differ). Note that the functions' addresses are the same, but since in the C world the B object lives beyond the A object, and the A object is 4 bytes large, we must add 4 to the value of the '`this`' pointer when calling the function from a C object. That's exactly what the shift value in the pointer's second field is telling the compiler.

Chapter 17

Nested Classes

Classes can be defined inside other classes. Classes defined inside other classes are called *nested classes*. Nested classes are used in situations where the nested class has a close conceptual relationship to its surrounding class. For example, with the class `string` a type `string::iterator` is available which provides all characters that are stored in the `string`. This `string::iterator` type could be defined as an object `iterator`, defined as nested class in the class `string`.

Since nested classes are defined inside other classes their members, when provided with references or pointers to objects of their surrounding classes, may access all members of those objects, even their private members.

A class can be nested in every part of the surrounding class: in the `public, protected` or `private` section. If a class is nested in the `public` section of a class, it is visible outside the surrounding class. If it is nested in the `protected` section it is visible in subclasses, derived from the surrounding class, if it is nested in the `private` section, it is only visible for the members of the surrounding class.

The surrounding class has no special privileges with respect to the nested class. For example, consider the following class definition:

```
    class Surround
    {
        public:
            class FirstWithin
            {
                int d_variable;

                public:
                    FirstWithin();
                    int var() const;
            };
        private:
            class SecondWithin
            {
                int d_variable;

                public:
                    SecondWithin();
                    int var() const;
            };
    };
```

```
inline int Surround::FirstWithin::var() const
{
    return d_variable;
}
inline int Surround::SecondWithin::var() const
{
    return d_variable;
}
```

In the Annotations(), in order to save space, nested class interfaces are usually declared inside their surrounding class, as shown above. Often this can be avoided, which is desirable as it more clearly separates the outer class's interface and the nested class's interface. Likewise, in-class member implementations should be avoided. Here is an illustration of how outer- and nested class interfaces can be separated:

```
class Surround
{
    class SecondWithin;

    public:
        class FirstWithin;
};

class Surround::FirstWithin
{
    int d_variable;

    public:
        FirstWithin();
        int var() const;
};

class Surround::SecondWithin
{
    int d_variable;

    public:
        SecondWithin();
        int var() const;
};
```

For these three classes access to members is defined as follows:

- The class `Surround::FirstWithin` is visible outside and inside `Surround`. The class `Surround::FirstWithin` thus has global visibility.
- `FirstWithin`'s constructor and its member function `var` are also globally visible.
- The data member `d_variable` is only visible to the members of the class `Surround::FirstWithin`. Neither the members of `Surround` nor the members of `Surround::SecondWithin` can directly access `Surround::FirstWithin::d_variable`.
- The class `Surround::SecondWithin` is only visible inside `Surround`. The public members of the class `Surround::SecondWithin` can also be used by the members of the class `Surround::FirstWithin`, as nested classes can be considered members of their surrounding class.

- `Surround::SecondWithin`'s constructor and its member function `var` also can only be reached by the members of `Surround` (and by the members of its nested classes).
- `Surround::SecondWithin::d_variable` is only visible to `Surround::SecondWithin`'s members. Neither the members of `Surround` nor the members of `Surround::FirstWithin` can access `d_variable` of the class `Surround::SecondWithin` directly.
- As always, an object of the class type is required before its members can be called. This also holds true for nested classes.

To grant the surrounding class access rights to the private members of a nested class the nested class may declare its surrounding class as a friend. Conversely, as nested classes can be considered members of their surrounding class their member functions have full access to the outer class members, if they are provided with an outer class object (see section 17.3).

Although nested classes can be considered members of the surrounding class, members of nested classes are *not* members of the surrounding class: members of the class `Surround` may not directly call `FirstWithin::var`. This is understandable considering that a `Surround` object is not also a `FirstWithin` or `SecondWithin` object. In fact, nested classes are just typenames. It is not implied that objects of such classes automatically exist in the surrounding class. If a member of the surrounding class should use a (non-static) member of a nested class then the surrounding class must define a nested class object, which can thereupon be used by the members of the surrounding class to use members of the nested class.

For example, in the following class definition there is a surrounding class `Outer` and a nested class `Inner`. The class `Outer` contains a member function `caller`. The member function `caller` uses the `d_inner` object that is composed within `Outer` to call `Inner::infunction`:

```
class Outer
{
    public:
        void caller();

    private:
        class Inner
        {
            public:
                void infunction();
        };
        Inner d_inner;      // class Inner must be known
};
void Outer::caller()
{
    d_inner.infunction();
}
```

17.1 Defining nested class members

Member functions of nested classes may be defined as inline functions. Inline member functions can be defined as if they were defined outside of the class definition. To define the member function `Outer::caller` outside of the class `Outer`, the function's fully qualified name (starting from the outermost class scope (`Outer`)) must be provided to the compiler. Inline and in-class functions can be defined accordingly. They can be defined and they can use any nested class. Even if the nested class's definition appears later in the outer class's interface.

When (nested) member functions are defined inline, their definitions should be put below their class interface. Static nested data members are also usually defined outside of their classes. If the class `FirstWithin` would have had a `static size_t` datamember `epoch`, it could have been initialized as follows:

```
    size_t Surround::FirstWithin::epoch = 1970;
```

Furthermore, multiple scope resolution operators are needed to refer to public static members in code outside of the surrounding class:

```
    void showEpoch()
    {
        cout << Surround::FirstWithin::epoch;
    }
```

Within the class `Surround` only the `FirstWithin::` scope must be used; within the class `FirstWithin` there is no need to refer explicitly to the scope.

What about the members of the class `SecondWithin`? The classes `FirstWithin` and `SecondWithin` are both nested within `Surround`, and can be considered members of the surrounding class. Since members of a class may directly refer to each other, members of the class `SecondWithin` can refer to (public) members of the class `FirstWithin`. Consequently, members of the class `SecondWithin` could refer to the `epoch` member of `FirstWithin` as `FirstWithin::epoch`.

17.2 Declaring nested classes

Nested classes may be declared before they are actually defined in a surrounding class. Such forward declarations are required if a class contains multiple nested classes, and the nested classes contain pointers, references, parameters or return values to objects of the other nested classes.

For example, the following class `Outer` contains two nested classes `Inner1` and `Inner2`. The class `Inner1` contains a pointer to `Inner2` objects, and `Inner2` contains a pointer to `Inner1` objects. Cross references require forward declarations. Forward declarations must be given an access specification that is identical to the access specification of their definitions. In the following example the `Inner2` forward declaration must be given in a `private` section, as its definition is also part of the class `Outer`'s private interface:

```
    class Outer
    {
        private:
            class Inner2;       // forward declaration

            class Inner1
            {
                Inner2 *pi2;    // points to Inner2 objects
            };
            class Inner2
            {
                Inner1 *pi1;    // points to Inner1 objects
            };
    };
```

17.3 Accessing private members in nested classes

To grant nested classes access rights to the private members of other nested classes, or to grant a surrounding class access to the private members of its nested classes the `friend` keyword must be used.

No friend declaration is required to grant a nested class access to the private members of its surrounding class. Static members of the surrounding class can directly be accessed, other members can be accessed if a surrounding class object is defined by or passed to members of the nested class. After all, a nested class is a type defined by its surrounding class and as such objects of the nested class are members of the outer class and thus can access all the outer class's members. Here is an example showing this principle. The example won't compile as members of the class `Extern` are denied access to `Outer`'s private members, but `Outer::Inner`'s members *can* access `Outer`'s private members:

```
class Outer
{
    int d_value;
    static int s_value;

    public:
        Outer()
        :
            d_value(12)
        {}
        class Inner
        {
            public:
                Inner()
                {
                    cout << "Outer's static value: " << s_value << '\n';
                }
                Inner(Outer &outer)
                {
                    cout << "Outer's value: " << outer.d_value << '\n';
                }
        };
};
class Extern            // won't compile!
{
    public:
        Extern(Outer &outer)
        {
            cout << "Outer's value: " << outer.d_value << '\n';
        }

        Extern()
        {
            cout << "Outer's static value: " << Outer::s_value << '\n';
        }
};

int Outer::s_value = 123;
int main()
{
        Outer outer;
        Outer::Inner in1;
        Outer::Inner in2{ outer };
    }
```

Now consider the situation where a class `Surround` has two nested classes `FirstWithin` and `SecondWithin`. Each of the three classes has a static data member `int s_variable`:

```
    class Surround
    {
        static int s_variable;
        public:
            class FirstWithin
            {
                static int s_variable;
                public:
                    int value();
            };
            int value();
        private:
            class SecondWithin
            {
                static int s_variable;
                public:
                    int value();
            };
    };
```

If the class `Surround` should be able to access `FirstWithin` and `SecondWithin`'s private members, these latter two classes must declare `Surround` to be their friend. The function `Surround::value` can thereupon access the private members of its nested classes. For example (note the `friend` declarations in the two nested classes):

```
    class Surround
    {
        static int s_variable;
        public:
            class FirstWithin
            {
                friend class Surround;
                static int s_variable;
                public:
                    int value();
            };
            int value();
        private:
            class SecondWithin
            {
                friend class Surround;
                static int s_variable;
                public:
                    int value();
            };
    };
    inline int Surround::FirstWithin::value()
```

```
{
    FirstWithin::s_variable = SecondWithin::s_variable;
    return (s_variable);
}
```

Friend declarations may be provided *beyond* the definition of the entity that is to be considered a friend. So a class can be declared a friend *beyond* its definition. In that situation in-class code may already use the fact that it is going to be declared a friend by the upcoming class. As an example, consider an in-class implementation of the function `Surround::FirstWithin::value`. The required `friend` declaration can also be inserted *after* the implementation of the function `value`:

```
class Surround
{
    public:
        class FirstWithin
        {
            static int s_variable;
            public:
                int value();
                {
                    FirstWithin::s_variable = SecondWithin::s_variable;
                    return s_variable;
                }
            friend class Surround;
        };
    private:
        class SecondWithin
        {
            friend class Surround;
            static int s_variable;
        };
};
```

Note that members named identically in outer and inner classes (e.g., '`s_variable`') may be accessed using the proper scope resolution expressions, as illustrated below:

```
class Surround
{
    static int s_variable;
    public:
        class FirstWithin
        {
            friend class Surround;
            static int s_variable;  // identically named
            public:
                int value();
        };
        int value();

    private:
        class SecondWithin
        {
            friend class Surround;
            static int s_variable;  // identically named
            public:
                int value();
        };
        static void classMember();
};
inline int Surround::value()
{                                   // scope resolution expression
    FirstWithin::s_variable = SecondWithin::s_variable;
    return s_variable;
}
inline int Surround::FirstWithin::value()
{
    Surround::s_variable = 4;       // scope resolution expressions
    Surround::classMember();
    return s_variable;
}
inline int Surround::SecondWithin::value()
{
    Surround::s_variable = 40;      // scope resolution expression
    return s_variable;
}
```

Nested classes aren't automatically each other's friends. Here `friend` declarations must be provided to grant one nested classes access to another nested class's private members.

To grant `FirstWithin` access to `SecondWithin`'s private members, `SecondWithin` must contain a `friend` declaration.

Likewise, the class `FirstWithin` simply uses `friend class SecondWithin` to grant `SecondWithin` access to `FirstWithin`'s private members. Even though the compiler hasn't seen `SecondWithin` yet, a friend declaration is also considered a forward declaration.

Note that `SecondWithin`'s forward declaration cannot be specified inside `FirstWithin` by using '`class Surround::SecondWithin;`', as this would generate an error message like:

> 'Surround' does not have a nested type named 'SecondWithin'

Now assume that in addition to the nested class `SecondWithin` there also exists an outer-level class `SecondWithin`. To declare that class a friend of `FirstWithin's` declare `friend ::SecondWithin` inside `class FirstWithin`. In that case, an outer level class declaration of `FirstWithin` must be provided before the compiler encounters the `friend ::SecondWithin` declaration.

Here is an example in which all classes have full access to all private members of all involved classes: , and a outer level `FirstWithin` has also been declared:

```
class SecondWithin;

class Surround
{
    // class SecondWithin;      not required (but no error either):
    //                          friend declarations (see below)
    //                          are also forward declarations

    static int s_variable;
    public:
        class FirstWithin
        {
            friend class Surround;
            friend class SecondWithin;
            friend class ::SecondWithin;

            static int s_variable;
            public:
                int value();
        };
        int value();            // implementation given above
    private:
        class SecondWithin
        {
            friend class Surround;
            friend class FirstWithin;

            static int s_variable;
            public:
                int value();
        };
};
inline int Surround::FirstWithin::value()
{
    Surround::s_variable = SecondWithin::s_variable;
    return s_variable;
}
inline int Surround::SecondWithin::value()
{
    Surround::s_variable = FirstWithin::s_variable;
    return s_variable;
}
```

17.4 Nesting enumerations

Enumerations may also be nested in classes. Nesting enumerations is a good way to show the close connection between the enumeration and its class. Nested enumerations have the same controlled visibility as other class members. They may be defined in the private, protected or public sections of classes and are inherited by derived classes. In the class `ios` we've seen values like `ios::beg` and `ios::cur`. In the current GNU **C++** implementation these values are defined as values of the `seek_dir` enumeration:

```
class ios: public _ios_fields
{
    public:
        enum seek_dir
        {
            beg,
            cur,
            end
        };
};
```

As an illustration assume that a class `DataStructure` represents a data structure that may be traversed in a forward or backward direction. Such a class can define an enumeration `Traversal` having the values `FORWARD` and `BACKWARD`. Furthermore, a member function `setTraversal` can be defined requiring a `Traversal` type of argument. The class can be defined as follows:

```
class DataStructure
{
    public:
        enum Traversal
        {
            FORWARD,
            BACKWARD
        };
        setTraversal(Traversal mode);
    private:
        Traversal
            d_mode;
};
```

Within the class `DataStructure` the values of the `Traversal` enumeration can be used directly. For example:

```
void DataStructure::setTraversal(Traversal mode)
{
    d_mode = mode;
    switch (d_mode)
    {
        FORWARD:
            // ... do something
        break;

        BACKWARD:
            // ... do something else
        break;
    }
}
```

Outside of the class `DataStructure` the name of the enumeration type is not used to refer to the values of the enumeration. Here the classname is sufficient. Only if a variable of the enumeration type is required the name of the enumeration type is needed, as illustrated by the following piece of code:

```
void fun()
{
    DataStructure::Traversal                // enum typename required
        localMode = DataStructure::FORWARD; // enum typename not required

    DataStructure ds;
                                            // enum typename not required
    ds.setTraversal(DataStructure::BACKWARD);
}
```

In the above example the constant `DataStructure;:FORWARD` was used to specify a value of an enum defined in the class `DataStructure`. Instead of `DataStructure::FORWARD` the construction `ds.FORWARD` is also accepted. In my opinion this syntactic liberty is ugly: `FORWARD` is a symbolic value that is defined at the class level; it's not a member of `ds`, which is suggested by the use of the member selector operator.

Only if `DataStructure` defines a nested class `Nested`, in turn defining the enumeration `Traversal`, the two class scopes are required. In that case the latter example should have been coded as follows:

```
void fun()
{
    DataStructure::Nested::Traversal
        localMode = DataStructure::Nested::FORWARD;

    DataStructure ds;

    ds.setTraversal(DataStructure::Nested::BACKWARD);
}
```

Here a construction like `DataStructure::Nested::Traversal localMode = ds.Nested::FORWARD` could also have been used, although I personally would avoid it, as `FORWARD` is not a member of `ds` but rather a symbol that is defined in `DataStructure`.

17.4.1 Empty enumerations

`Enum` types usually define symbolic values. However, this is not required. In section 14.6.1 the `std::bad_cast` type was introduced. A `bad_cast` is thrown by the `dynamic_cast<>` operator when a reference to a base class object cannot be cast to a derived class reference. The `bad_cast` could be caught as type, irrespective of any value it might represent.

Types may be defined without any associated values. An *empty enum* can be defined which is an `enum` not defining any values. The empty enum's type name may thereupon be used as a legitimate type in, e.g. a `catch` clause.

The example shows how an empty enum is defined (often, but not necessarily within a `class`) and how it may be thrown (and caught) as exceptions:

```
#include <iostream>

enum EmptyEnum
{};

int main()
try
{
    throw EmptyEnum();
}
catch (EmptyEnum)
{
    std::cout << "Caught empty enum\n";
}
```

17.5 Revisiting virtual constructors

In section 14.12 the notion of virtual constructors was introduced. In that section a class `Base` was defined as an abstract base class. A class `Clonable` was defined to manage `Base` class pointers in containers like vectors.

As the class `Base` is a minute class, hardly requiring any implementation, it can very well be defined as a nested class in `Clonable`. This emphasizes the close relationship between `Clonable` and `Base`. Nesting `Base` under `Clonable` changes

```
    class Derived: public Base
```

into:

```
    class Derived: public Clonable::Base
```

Apart from defining `Base` as a nested class and deriving from `Clonable::Base` rather than from `Base` (and providing `Base` members with the proper `Clonable::` prefix to complete their fully qualified names), no further modifications are required. Here are the modified parts of the program shown earlier (cf. section 14.12), now using `Base` nested under `Clonable`:

```
// Clonable and nested Base, including their inline members:
    class Clonable
    {
        public:
            class Base;
        private:
            Base *d_bp;
        public:
            class Base
            {
                public:
                    virtual ~Base();
                    Base *clone() const;
                private:
                    virtual Base *newCopy() const = 0;
            };
            Clonable();
            explicit Clonable(Base *base);
            ~Clonable();
            Clonable(Clonable const &other);
            Clonable(Clonable &&tmp);
            Clonable &operator=(Clonable const &other);
            Clonable &operator=(Clonable &&tmp);

            Base &base() const;
    };
    inline Clonable::Base *Clonable::Base::clone() const
    {
        return newCopy();
    }
    inline Clonable::Base &Clonable::base() const
    {
        return *d_bp;
    }

// Derived and its inline member:
    class Derived1: public Clonable::Base
    {
        public:
            ~Derived1();
        private:
            virtual Clonable::Base *newCopy() const;
    };
    inline Clonable::Base *Derived1::newCopy() const
    {
        return new Derived1(*this);
    }

// Members not implemented inline:
    Clonable::Base::~Base()
    {}
```

Chapter 18

The Standard Template Library

The `Standard Template Library` (STL) is a general purpose library consisting of containers, generic algorithms, iterators, function objects, allocators, adaptors and data structures. The data structures used by the algorithms are *abstract* in the sense that the algorithms can be used with (practically) any data type.

The algorithms can process these abstract data types because they are *template* based. This chapter does not cover template *construction* (see chapter 21 for that). Rather, it focuses on the *use* of the algorithms.

Several elements also used by the standard template library have already been discussed in the **C++** Annotations. In chapter 12 abstract containers were discussed, and in section 11.10 function objects were introduced. Also, *iterators* were mentioned at several places in this document.

The main components of the STL are covered in this and the next chapter. Iterators, adaptors, smart pointers, multi threading and other features of the STL are discussed in coming sections. Generic algorithms are covered in the next chapter (19).

Allocators take care of the memory allocation within the STL. The default allocator class suffices for most applications, and is not further discussed in the **C++** Annotations.

All elements of the STL are defined in the standard namespace. Therefore, a `using namespace std` or a comparable directive is required unless it is preferred to specify the required namespace explicitly. In header files the `std` namespace should explicitly be used (cf. section 7.11.1).

In this chapter the empty angle bracket notation is frequently used. In code a typename must be supplied between the angle brackets. E.g., `plus<>` is used in the **C++** Annotations, but in code `plus<string>` may be encountered.

18.1 Predefined function objects

Before using the predefined function objects presented in this section the `<functional>` header file must be included.

Function objects play important roles in generic algorithms. For example, there exists a generic algorithm `sort` expecting two iterators defining the range of objects that should be sorted, as well as a function object calling the appropriate comparison operator for two objects. Let's take a quick look at this situation. Assume strings are stored in a vector, and we want to sort the vector in descending order. In that case, sorting the vector `stringVec` is as simple as:

```
        sort(stringVec.begin(), stringVec.end(), greater<string>());
```

The last argument is recognized as a *constructor*: it is an *instantiation* of the `greater<>` class template, applied to `strings`. This object is called as a function object by the `sort` generic algorithm. The generic algorithm calls the function object's `operator()` member to compare two `string` objects. The function object's `operator()` will, in turn, call `operator>` of the `string` data type. Eventually, when `sort` returns, the first element of the vector will contain the string having the greatest `string` value of all.

The function object's `operator()` itself is *not* visible at this point. Don't confuse the parentheses in the '`greater<string>()`' argument with calling `operator()`. When `operator()` is actually used inside `sort`, it receives two arguments: two strings to compare for 'greaterness'. Since `greater<string>::operator()` is defined inline, the call itself is not actually present in the above `sort` call. Instead `sort` calls `string::operator>` through `greater<string>::operator()`.

Now that we know that a constructor is passed as argument to (many) generic algorithms, we can design our own function objects. Assume we want to sort our vector case-insensitively. How do we proceed? First we note that the default `string::operator<` (for an incremental sort) is not appropriate, as it does case sensitive comparisons. So, we provide our own `CaseInsensitive` class, which compares two strings case insensitively. Using the `POSIX` function `strcasecmp`, the following program performs the trick. It case-insensitively sorts its command-line arguments in ascending alphabetic order:

```
    #include <iostream>
    #include <string>
    #include <cstring>
    #include <algorithm>
    using namespace std;

    class CaseInsensitive
    {
        public:
            bool operator()(string const &left, string const &right) const
            {
                return strcasecmp(left.c_str(), right.c_str()) < 0;
            }
    };
    int main(int argc, char **argv)
    {
        sort(argv, argv + argc, CaseInsensitive{});
        for (int idx = 0; idx < argc; ++idx)
            cout << argv[idx] << " ";
        cout << '\n';
    }
```

The default constructor of the `class CaseInsensitive` is used to provide `sort` with its final argument. So the only member function that must be defined is `CaseInsensitive::operator()`. Since we know it's called with `string` arguments, we define it to expect two `string` arguments, which are used when calling `strcasecmp`. Furthermore, the function call operator `operator()` is defined inline, so that it does not produce overhead when called by the `sort` function. The `sort` function calls the function object with various combinations of `strings`. If the compiler grants our inline requests, it will in fact call `strcasecmp`, skipping two extra function calls.

The comparison function object is often a *predefined function object*. Predefined function object classes are available for many commonly used operations. In the following sections the available predefined function objects are presented, together with some examples showing their use. Near the end of the section about function objects *function adaptors* are introduced.

Predefined function objects are used predominantly with generic algorithms. Predefined function objects exists for arithmetic, relational, and logical operations.

18.1.1 Arithmetic function objects

The arithmetic function objects support the standard arithmetic operations: addition, subtraction, multiplication, division, modulo and negation. These function objects invoke the corresponding operators of the data types for which they are instantiated. For example, for addition the function object `plus<Type>` is available. If we replace `Type` by `size_t` then the addition operator for `size_t` values is used, if we replace `Type` by `string`, the addition operator for strings is used. For example:

```
#include <iostream>
#include <string>
#include <functional>
using namespace std;

int main(int argc, char **argv)
{
    plus<size_t> uAdd;              // function object to add size_ts

    cout << "3 + 5 = " << uAdd(3, 5) << '\n';

    plus<string> sAdd;              // function object to add strings

    cout << "argv[0] + argv[1] = " << sAdd(argv[0], argv[1]) << '\n';
}
/*
    Output when called as: a.out going

    3 + 5 = 8
    argv[0] + argv[1] = a.outgoing
*/
```

Why is this useful? Note that the function object can be used with all kinds of data types (not only with the predefined datatypes) supporting the operator called by the function object.

Suppose we want to perform an operation on a left hand side operand which is always the same variable and a right hand side argument for which, in turn, all elements of an array should be used. E.g., we want to compute the sum of all elements in an array; or we want to concatenate all the strings in a text-array. In situations like these function objects come in handy.

As stated, function objects are heavily used in the context of the generic algorithms, so let's take a quick look ahead at yet another one.

The generic algorithm `accumulate` visits all elements specified by an iterator-range, and performs a requested binary operation on a common element and each of the elements in the range, returning the accumulated result after visiting all elements specified by the iterator range. It's easy to use this algorithm. The next program accumulates all command line arguments and prints the final string:

```
#include <iostream>
#include <string>
#include <functional>
```

```
#include <numeric>
using namespace std;

int main(int argc, char **argv)
{
    string result =
            accumulate(argv, argv + argc, string{}, plus<string>());

    cout << "All concatenated arguments: " << result << '\n';
}
```

The first two arguments define the (iterator) range of elements to visit, the third argument is `string`. This anonymous string object provides an initial value. We could also have used

```
"All concatenated arguments: "s
```

in which case the `cout` statement could simply have been `cout << result << '\n'`. The string-addition operation is used, called from `plus<string>`. The final concatenated string is returned.

Now we define a class `Time`, overloading `operator+`. Again, we can apply the predefined function object `plus`, now tailored to our newly defined datatype, to add times:

```
#include <iostream>
#include <string>
#include <vector>
#include <functional>
#include <numeric>
using namespace std;

class Time
{
    friend ostream &operator<<(ostream &str, Time const &time);
    size_t d_days;
    size_t d_hours;
    size_t d_minutes;
    size_t d_seconds;
    public:
        Time(size_t hours, size_t minutes, size_t seconds);
        Time &operator+=(Time const &rhs);
};
Time &&operator+(Time const &lhs, Time const &rhs)
{
    Time ret(lhs);
    return std::move(ret += rhs);
}
Time::Time(size_t hours, size_t minutes, size_t seconds)
:
    d_days(0),
    d_hours(hours),
    d_minutes(minutes),
    d_seconds(seconds)
{}
Time &Time::operator+=(Time const &rhs)
{
    d_seconds   += rhs.d_seconds;
```

```
        d_minutes   += rhs.d_minutes   + d_seconds / 60;
        d_hours     += rhs.d_hours     + d_minutes / 60;
        d_days      += rhs.d_days      + d_hours   / 24;
        d_seconds   %= 60;
        d_minutes   %= 60;
        d_hours     %= 24;
        return *this;
    }
    ostream &operator<<(ostream &str, Time const &time)
    {
        return cout << time.d_days << " days, " << time.d_hours <<
                                                " hours, " <<
                        time.d_minutes << " minutes and " <<
                        time.d_seconds << " seconds.";
    }
    int main(int argc, char **argv)
    {
        vector<Time> tvector;

        tvector.push_back(Time( 1, 10, 20));
        tvector.push_back(Time(10, 30, 40));
        tvector.push_back(Time(20, 50,  0));
        tvector.push_back(Time(30, 20, 30));

        cout <<
            accumulate
            (
                tvector.begin(), tvector.end(), Time(0, 0, 0), plus<Time>()
            ) <<
            '\n';
    }
    //  Displays: 2 days, 14 hours, 51 minutes and 30 seconds.
```

The design of the above program is fairly straightforward. `Time` defines a constructor, it defines an insertion operator and it defines its own `operator+`, adding two time objects. In `main` four `Time` objects are stored in a `vector<Time>` object. Then, `accumulate` is used to compute the accumulated time. It returns a `Time` object, which is inserted into `cout`.

While this section's first example illustrated using a *named* function object, the last two examples illustrate how *anonymous* objects can be passed to the (`accumulate`) function.

The STL supports the following set of arithmetic function objects. The function call operator (`operator()`) of these function objects calls the matching arithmetic operator for the objects that are passed to the function call operator, returning that arithmetic operator's return value. The arithmetic operator that is actually called is mentioned below:

- `plus<>`: calls the binary `operator+`;
- `minus<>`: calls the binary `operator-`;
- `multiplies<>`: calls the binary `operator*`;
- `divides<>`: calls `operator/`;
- `modulus<>`: calls `operator%`;
- `negate<>`: calls the unary `operator-`. This arithmetic function object is a unary function object as it expects one argument.

In the next example the `transform` generic algorithm is used to toggle the signs of all elements of an array. `Transform` expects two iterators, defining the range of objects to be transformed; an iterator defining the begin of the destination range (which may be the same iterator as the first argument); and a function object defining a unary operation for the indicated data type.

```
#include <iostream>
#include <string>
#include <functional>
#include <algorithm>
using namespace std;

int main(int argc, char **argv)
{
    int iArr[] = { 1, -2, 3, -4, 5, -6 };

    transform(iArr, iArr + 6, iArr, negate<int>());

    for (int idx = 0; idx < 6; ++idx)
        cout << iArr[idx] << ", ";
    cout << '\n';
}
// Displays:  -1, 2, -3, 4, -5, 6,
```

18.1.2 Relational function objects

The relational operators are called by the relational function objects. All standard relational operators are supported: `==`, `!=`, `>`, `>=`, `<` and `<=`.

The STL supports the following set of relational function objects. The function call operator (`operator()`) of these function objects calls the matching relational operator for the objects that are passed to the function call operator, returning that relational operator's return value. The relational operator that is actually called is mentioned below:

- `equal_to<>`: calls `operator==`;
- `not_equal_to<>`: calls `operator!=`;
- `greater<>`: calls `operator>`;
- `greater_equal<>`: calls `operator>=`;
- `less<>`: this object's member `operator()` calls `operator<`;
- `less_equal<>`: calls `operator<=`.

An example using the relational function objects in combination with `sort` is:

```
#include <iostream>
#include <string>
#include <functional>
#include <algorithm>
using namespace std;

int main(int argc, char **argv)
{
        sort(argv, argv + argc, greater_equal<string>());

        for (int idx = 0; idx < argc; ++idx)
            cout << argv[idx] << " ";
        cout << '\n';

        sort(argv, argv + argc, less<string>());

        for (int idx = 0; idx < argc; ++idx)
            cout << argv[idx] << " ";
        cout << '\n';
    }
```

The example illustrates how strings may be sorted alphabetically and reversed alphabetically. By passing `greater_equal<string>` the strings are sorted in *decreasing* order (the first word will be the 'greatest'), by passing `less<string>` the strings are sorted in *increasing* order (the first word will be the 'smallest').

Note that `argv` contains `char *` values, and that the relational function object expects a `string`. The promotion from `char const *` to `string` is silently performed.

18.1.3 Logical function objects

The logical operators are called by the logical function objects. The standard logical operators are supported: `and`, `or`, and `not`.

The STL supports the following set of logical function objects. The function call operator (`operator()`) of these function objects calls the matching logical operator for the objects that are passed to the function call operator, returning that logical operator's return value. The logical operator that is actually called is mentioned below:

- `logical_and<>`: calls `operator&&`;
- `logical_or<>`: calls `operator||`;
- `logical_not<>`: calls `operator!`.

An example using `operator!` is provided in the following trivial program, using `transform` to transform the logical values stored in an array:

```
    #include <iostream>
    #include <string>
    #include <functional>
    #include <algorithm>
    using namespace std;

    int main(int argc, char **argv)
    {
        bool bArr[] = {true, true, true, false, false, false};
        size_t const bArrSize = sizeof(bArr) / sizeof(bool);

        for (size_t idx = 0; idx < bArrSize; ++idx)
            cout << bArr[idx] << " ";
        cout << '\n';
        transform(bArr, bArr + bArrSize, bArr, logical_not<bool>());

        for (size_t idx = 0; idx < bArrSize; ++idx)
            cout << bArr[idx] << " ";
        cout << '\n';
    }
    /*
      Displays:

        1 1 1 0 0 0
        0 0 0 1 1 1
    */
```

18.1.4 The 'std::not_fn' negator

A *negator* is a function object toggling the truth value of a function that's called from the negator: if the function returns `true` the negator returns `false` and vv.

The standard negator is `std::not_fn`, declared in the `<functional>` header file.

The function `not_fn` expects a (movable) object as its argument, returning the negated value of the return value of its argument's function call operator.

As an example consider a `main` function defining an array of `int` values:

```
    int main()
    {
        int arr[] = {1, 2, 3, 4, 5, 6, 7, 8, 9};
    }
```

To count the number of even values `count_if`, using a lambda function can be used:

```
        cout <<
            count_if(arr, arr + size(arr),
                [&](int value)
                {
                    return (value & 1) == 0;
                }
            ) << '\n';
```

To count the number of odd values, `not_fn` can be used in the above code like so:

```
        cout <<
            count_if(arr, arr + size(arr),
                not_fn(
                    [&](int value)
                    {
                        return (value & 1) == 0;
                    }
                )
            ) << '\n';
```

Of course, in this simple example the lambda function could also easily have been modified. But if instead of a lambda function an existing class implementing a function object had been used it would have been difficult or impossible to change the behavior of that class. If the class offers moving operations then `not_fn` can be used to negate the values returned by that class's function call operator.

18.2 Iterators

In addition to the conceptual iterator types presented in this section the STL defines several adaptors allowing objects to be passed as iterators. These adaptors are presented in the upcoming sections. Before those adaptors can be used the `<iterator>` header file must be included.

Although standard iterators are candidates for deprecation[1], this does not mean that they will (soon) be removed from the `std` library. It's probably a suboptimal strategy to 'reinvent' your own. Instead, it is advised to continue using the `std::iterator` classes until they have officially been replaced by alternatives.

Iterators are objects acting like pointers. Iterators have the following general characteristics:

- Two iterators may be compared for (in)equality using the `==` and `!=` operators. The *ordering* operators (e.g., >, <) can usually not be used.
- Given an iterator `iter`, `*iter` represents the object the iterator points to (alternatively, `iter->` can be used to reach the members of the object the iterator points to).
- Given an iterator `iter`, `iter.base()` returns the address of `*iter`. It returns the same type as `&*iter`. E.g.,

  ```
      vector<int> vi{ 1, 2, 3 };
      int *ip = vi.begin().base();
      cout << *ip << '\n';          // shows: 1
  ```

- `++iter` or `iter++` advances the iterator to the next element. The notion of advancing an iterator to the next element is consequently applied: several containers support *reverse_iterator* types, in which the `++iter` operation actually reaches a previous element in a sequence.
- *Pointer arithmetic* may be used with iterators of containers storing their elements consecutively in memory like `vector` and `deque`. For such containers `iter + 2` points to the second element beyond the one to which `iter` points. See also section 18.2.1, covering `std::distance`.
- Merely defining an iterator is comparable to having a 0-pointer. Example:

  ```
  #include <vector>
  #include <iostream>
  using namespace std;

  int main()
  {
      vector<int>::iterator vi;

      cout << &*vi;        // prints 0
  }
  ```

STL containers usually define members offering iterators (i.e., they define their own type `iterator`). These members are commonly called `begin` and `end` and (for reversed iterators (type `reverse_iterator`)) `rbegin` and `rend`.

---

[1] http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2016/p0174r1.html#2.1

Whereas reverse iterators can be constructed from ordinary (forward) iterators using `reverse_iterator` constructors as in:

```
string str;
auto revit = string::reverse_iterator{ str.begin() };
```

the opposite is not accomplished that way. To retrieve the forward iterator corresponding to a reverse iterator, the `reverse_iterator.base()` member can be used. E.g., to obtain the forward iterator corresponding to `revit` use

```
auto forward { revit.base() };
```

Standard practice requires iterator ranges to be *left inclusive*. The notation `[left, right)` indicates that `left` is an iterator pointing to the first element, while `right` is an iterator pointing just *beyond* the last element. The iterator range is *empty* when `left == right`.

The following example shows how all elements of a vector of strings can be inserted into `cout` using its iterator ranges `[begin(), end())`, and `[rbegin(), rend())`. Note that the `for-loops` for both ranges are identical. Furthermore it nicely illustrates how the `auto` keyword can be used to define the type of the loop control variable instead of using a much more verbose variable definition like `vector<string>::iterator` (see also section 3.3.7):

```
#include <iostream>
#include <vector>
#include <string>
using namespace std;

int main(int argc, char **argv)
{
    vector<string> args(argv, argv + argc);

    for (auto iter = args.begin(); iter != args.end(); ++iter)
        cout << *iter << " ";
    cout << '\n';

    for (auto iter = args.rbegin(); iter != args.rend(); ++iter)
        cout << *iter << " ";
    cout << '\n';
}
```

Furthermore, the STL defines *const_iterator* types that must be used when visiting a series of elements in a constant container. Whereas the elements of the vector in the previous example could have been altered, the elements of the vector in the next example are immutable, and `const_iterator`s are required:

```
#include <iostream>
#include <vector>
#include <string>
using namespace std;

int main(int argc, char **argv)
{
    vector<string> const args(argv, argv + argc);
```

```
        for
        (
            vector<string>::const_iterator iter = args.begin();
                iter != args.end();
                    ++iter
        )
            cout << *iter << " ";
        cout << '\n';

        for
        (
            vector<string>::const_reverse_iterator iter = args.rbegin();
                iter != args.rend();
                    ++iter
        )
            cout << *iter << " ";
        cout << '\n';
    }
```

The examples also illustrate that plain pointers can be used as iterators. The initialization `vector<string> args(argv, argv + argc)` provides the `args` vector with a pair of pointer-based iterators: `argv` points to the first element to initialize `args` with, `argv + argc` points just beyond the last element to be used, `++argv` reaches the next command line argument. This is a general pointer characteristic, which is why they too can be used in situations where `iterators` are expected.

The STL defines five types of iterators. These iterator types are expected by generic algorithms, and in order to create a particular type of iterator yourself it is important to know their characteristics. In general, iterators (see also section 22.14) must define:

- `operator==`, testing two iterators for equality,
- `operator!=`, testing two iterators for inequality,
- `operator++`, incrementing the iterator, as prefix operator,
- `operator*`, to access the element the iterator refers to,

The following types of iterators are used when describing generic algorithms in chapter 19:

- **InputIterators**:

  InputIterators are used to read from a container. The dereference operator is guaranteed to work as `rvalue` in expressions. Instead of an InputIterator it is also possible to use (see below) Forward-, Bidirectional- or RandomAccessIterators. Notations like `InputIterator1` and `InputIterator2` may be used as well. In these cases, numbers are used to indicate which iterators 'belong together'. E.g., the generic algorithm `inner_product` has the following prototype:

  ```
  Type inner_product(InputIterator1 first1, InputIterator1 last1,
                     InputIterator2 first2, Type init);
  ```

  `InputIterator1 first1` and `InputIterator1 last1` define a pair of input iterators on one range, while `InputIterator2 first2` defines the beginning of another range. Analogous notations may be used with other iterator types.

- **OutputIterators**:

  OutputIterators can be used to write to a container. The dereference operator is guaranteed to work as an `lvalue` in expressions, but not necessarily as `rvalue`. Instead of an OutputIterator it is also possible to use (see below) Forward-, Bidirectional- or RandomAccessIterators.

- **ForwardIterators**:

  ForwardIterators combine InputIterators and OutputIterators. They can be used to traverse containers in one direction, for reading and/or writing. Instead of a ForwardIterator it is also possible to use (see below) Bidirectional- or RandomAccessIterators.

- **BidirectionalIterators**:

  BidirectionalIterators can be used to traverse containers in both directions, for reading and writing. Instead of a BidirectionalIterator it is also possible to use (see below) a RandomAccessIterator.

- **RandomAccessIterators**:

  RandomAccessIterators provide random access to container elements. An algorithm like `sort` requires a RandomAccessIterator, and can therefore *not* be used to sort the elements of lists or maps, which only provide BidirectionalIterators.

The example given with the RandomAccessIterator illustrates how to relate iterators and generic algorithms: look for the iterator that's required by the (generic) algorithm, and then see whether the datastructure supports the required type of iterator. If not, the algorithm cannot be used with the particular datastructure.

18.2.1 std::distance and std::size

Earlier, in section 18.2 it was stated that iterators support pointer arithmetic for containers storing their elements consecutively in memory. This is not completely true: to determine the number of elements between the elements to which two iterators refer the iterator must support the subtraction operator.

Using pointer arithmetic to compute the number of elements between two iterators in, e.g., a `std::list` or `std::unordered_map` is not possible, as these containers do not store their elements consecutively in memory.

The function `std::distance` fills in that little gap: `std::distance` expects two InputIterators and returns the number of elements between them.

Before using `distance` the `<iterator>` header file must be included.

If the iterator specified as first argument exceeds the iterator specified as its second argument then the number of elements is non-positive, otherwise it is non-negative. If the number of elements cannot be determined (e.g., the iterators do not refer to elements in the same container), then `distance's` return value is undefined.

Example:

```
#include <iostream>
#include <unordered_map>

using namespace std;
```

```
int main()
{
    unordered_map<int, int> myMap = {{1, 2}, {3, 5}, {-8, 12}};

    cout << distance(++myMap.begin(), myMap.end()) << '\n'; // shows: 2
}
```

The `iterator` header file also defines the function `std::size`, returning the number of elements in a containers (as returned by the container's `size` member) or of an array whose dimension is known to the compiler at the point of `std::size's` call. E.g., if the size of an array `data` is known to the compiler, then to call a function `handler` (expecting the address of the first element of an array and the address of the location just beyond that array) the following statement can be used:

```
handler(data, data + std::size(data));
```

As noted, the `std::size` function is defined in the `iterator` header. However, it's also guaranteed available when including the header file of a container supporting iterators (including the `string` header file).

18.2.2 Insert iterators

Generic algorithms often require a target container into which the results of the algorithm are deposited. For example, the `copy` generic algorithm has three parameters. The first two define the range of visited elements, the third defines the first position where the results of the copy operation should be stored.

With the `copy` algorithm the number of elements to copy is usually available beforehand, since that number can usually be provided by pointer arithmetic. However, situations exist where pointer arithmetic cannot be used. Analogously, the number of resulting elements sometimes differs from the number of elements in the initial range. The generic algorithm `unique_copy` is a case in point. Here the number of elements that are copied to the destination container is normally not known beforehand.

In situations like these an *inserter* adaptor function can often be used to create elements in the destination container. There are three types of inserter adaptors:

- `back_inserter`: calls the container's `push_back` member to add new elements at the end of the container. E.g., to copy all elements of `source` in reversed order to the back of `destination`, using the `copy` generic algorithm:

  ```
  copy(source.rbegin(), source.rend(), back_inserter(destination));
  ```

- `front_inserter` calls the container's `push_front` member, adding new elements at the beginning of the container. E.g., to copy all elements of `source` to the front of the destination container (thereby also reversing the order of the elements):

  ```
  copy(source.begin(), source.end(), front_inserter(destination));
  ```

- `inserter` calls the container's `insert` member adding new elements starting at a specified starting point. E.g., to copy all elements of `source` to the destination container, starting at the beginning of `destination`, shifting up existing elements to beyond the newly inserted elements:

  ```
  copy(source.begin(), source.end(), inserter(destination,
      destination.begin()));
  ```

The inserter adaptors require the existence of two `typedef`s:

- `typedef Data value_type`, where `Data` is the data type stored in the class offering `push_back`, `push_front` or `insert` members (Example: `typedef std::string value_type`);
- `typedef value_type const &const_reference`

Concentrating on `back_inserter`, this iterator expects the name of a container supporting a member `push_back`. The inserter's `operator()` member calls the container's `push_back` member. Objects of any class supporting a `push_back` member can be passed as arguments to `back_inserter` provided the class adds

```
typedef DataType const &const_reference;
```

to its interface (where `DataType const &` is the type of the parameter of the class's member `push_back`). Example:

```
#include <iostream>
#include <algorithm>
#include <iterator>
using namespace std;

class Insertable
{
    public:
        typedef int value_type;
        typedef int const &const_reference;

        void push_back(int const &)
        {}
};

int main()
{
    int arr[] = {1};
    Insertable insertable;

    copy(arr, arr + 1, back_inserter(insertable));
}
```

18.2.3 Iterators for 'istream' objects

The `istream_iterator<Type>` can be used to define a set of iterators for `istream` objects. The general form of the `istream_iterator` iterator is:

```
istream_iterator<Type> identifier(istream &in)
```

Here, `Type` is the type of the data elements read from the `istream` stream. It is used as the 'begin' iterator in an iterator range. `Type` may be any type for which `operator>>` is defined in combination with `istream` objects.

The default constructor is used as the end-iterator and corresponds to the end-of-stream. For example,

```
istream_iterator<string> endOfStream;
```

The *stream* object that was specified when defining the begin-iterator is *not* mentioned with the default constructor.

Using `back_inserter` and `istream_iterator` adaptors, all strings from a stream can easily be stored in a container. Example (using anonymous `istream_iterator` adaptors):

```
#include <iostream>
#include <iterator>
#include <string>
#include <vector>
#include <algorithm>
using namespace std;

int main()
{
    vector<string> vs;

    copy(istream_iterator<string>(cin), istream_iterator<string>(),
         back_inserter(vs));

    for
    (
        vector<string>::const_iterator begin = vs.begin(), end = vs.end();
            begin != end; ++begin
    )
        cout << *begin << ' ';
    cout << '\n';
}
```

18.2.3.1 Iterators for 'istreambuf' objects

Input iterators are also available for `streambuf` objects.

To read from `streambuf` objects supporting input operations `istreambuf_iterators` can be used, supporting the operations that are also available for `istream_iterator`. Different from the latter iterator type `istreambuf_iterators` support three constructors:

- `istreambuf_iterator<Type>`:
  The end iterator of an iterator range is created using the default `istreambuf_iterator` constructor. It represents the end-of-stream condition when extracting values of type `Type` from the `streambuf`.
- `istreambuf_iterator<Type>(streambuf *)`:
  A pointer to a `streambuf` may be used when defining an `istreambuf_iterator`. It represents the begin iterator of an iterator range.
- `istreambuf_iterator<Type>(istream)`:
  An *istream* may be also used when defining an `istreambuf_iterator`. It accesses the `istream`'s `streambuf` and it also represents the begin iterator of an iterator range.

In section 18.2.4.1 an example is given using both `istreambuf_iterators` and `ostreambuf_iterators`.

18.2.4 Iterators for 'ostream' objects

An `ostream_iterator<Type>` adaptor can be used to pass an `ostream` to algorithms expecting an OutputIterator. Two constructors are available for defining `ostream_iterators`:

```
ostream_iterator<Type> identifier(ostream &outStream);
ostream_iterator<Type> identifier(ostream &outStream, char const *delim);
```

`Type` is the type of the data elements that should be inserted into an `ostream`. It may be any type for which `operator<<` is defined in combination with `ostream` objects. The latter constructor can be used to separate the individual `Type` data elements by `delimiter` strings. The former constructor does not use any delimiters.

The example shows how `istream_iterators` and an `ostream_iterator` may be used to copy information of a file to another file. A subtlety here is that you probably want to use `in.unsetf(ios::skipws)`. It is used to clear the `ios::skipws` flag. As a consequence whitespace characters are simply returned by the operator, and the file is copied character by character. Here is the program:

```
#include <iostream>
#include <algorithm>
#include <iterator>
using namespace std;

int main()
{
    cin.unsetf(ios::skipws);
    copy(istream_iterator<char>(cin), istream_iterator<char>(),
         ostream_iterator<char>(cout));
}
```

18.2.4.1 Iterators for 'ostreambuf' objects

Output iterators are also available for `streambuf` objects.

To write to `streambuf` objects supporting output operations `ostreambuf_iterators` can be used, supporting the operations that are also available for `ostream_iterator`. `Ostreambuf_iterators` support two constructors:

- `ostreambuf_iterator<Type>(streambuf *)`:
  A pointer to a `streambuf` may be used when defining an `ostreambuf_iterator`. It can be used as an OutputIterator.
- `ostreambuf_iterator<Type>(ostream)`:
  An *ostream* may be also used when defining an `ostreambuf_iterator`. It accesses the `ostream`'s `streambuf` and it can also be used as an OutputIterator.

The next example illustrates the use of both `istreambuf_iterators` and `ostreambuf_iterators` when copying a stream in yet another way. Since the stream's `streambuf`s are directly accessed the streams and stream flags are bypassed. Consequently there is no need to clear `ios::skipws` as in the previous section, while the next program's efficiency probably also exceeds the efficiency of the program shown in the previous section.

```
#include <iostream>
#include <algorithm>
#include <iterator>
using namespace std;

int main()
{
    istreambuf_iterator<char> in(cin.rdbuf());
    istreambuf_iterator<char> eof;
    ostreambuf_iterator<char> out(cout.rdbuf());

    copy(in, eof, out);
}
```

18.3 The class 'unique_ptr'

Before using the `unique_ptr` class presented in this section the `<memory>` header file must be included.

When pointers are used to access dynamically allocated memory strict bookkeeping is required to prevent memory leaks. When a pointer variable referring to dynamically allocated memory goes out of scope, the dynamically allocated memory becomes inaccessible and the program suffers from a memory leak. Consequently, the programmer has to make sure that the dynamically allocated memory is returned to the common pool just before the pointer variable goes out of scope.

When a pointer variable points to a dynamically allocated single value or object, bookkeeping requirements are greatly simplified when the pointer variable is defined as a `std::unique_ptr` object.

Unique_ptrs are *objects* masquerading as pointers. Since they are objects, their destructors are called when they go out of scope. Their destructors automatically delete the dynamically allocated memory to which they point. Unique_ptrs (and their cousins shared_ptrs (cf. section 18.4) are also called *smart pointers*).

`Unique_ptrs` have several special characteristics:

- when assigning a `unique_ptr` to another *move semantics* is used. If move semantics is not available compilation fails. On the other hand, if compilation succeeds then the used containers or generic algorithms support the use of `unique_ptr`s. Here is an example:

  ```
  std::unique_ptr<int> up1(new int);
  std::unique_ptr<int> up2(up1);        // compilation error
  ```

  The second definition fails to compile as `unique_ptr`'s copy constructor is private (the same holds true for the assignment operator). But the `unique_ptr` class *does* offer facilities to initialize and assign from *rvalue references*:

  ```
  class unique_ptr                        // interface partially shown
  {
      public:
  ```

```
        unique_ptr(unique_ptr &&tmp);   // rvalues bind here
    private:
        unique_ptr(const unique_ptr &other);
};
```

In the next example move semantics is used and so it compiles correctly:

```
unique_ptr<int> cp(unique_ptr<int>(new int));
```

- a `unique_ptr` object should only point to memory that was made available dynamically, as only dynamically allocated memory can be deleted.
- multiple `unique_ptr` objects should not be allowed to point to the same block of dynamically allocated memory. The `unique_ptr`'s interface was designed to prevent this from happening. Once a `unique_ptr` object goes out of scope, it deletes the memory it points to, immediately changing any other object also pointing to the allocated memory into a wild pointer.
- When a class `Derived` is derived from `Base`, then a newly allocated `Derived` class object can be assigned to a `unique_ptr<Base>`, without having to define a virtual destructor for `Base`. The `Base *` pointer that is returned by the `unique_ptr` object can simply be cast statically to `Derived`, and `Derived's` destructor is automatically called as well, if the `unique_ptr` definition is provided with a *deleter* function address. This is illustrated in the next example:

```
    class Base
    { ... };
    class Derived: public Base
    {
        ...
        public:
            // assume Derived has a member void process()

            static void deleter(Base *bp);
    };
    void Derived::deleter(Base *bp)
    {
        delete static_cast<Derived *>(bp);
    }
    int main()
    {
        unique_ptr<Base, void (*)(Base *)> bp(new Derived, &Derived::deleter);
        static_cast<Derived *>(bp.get())->process(); // OK!

    } // here ~Derived is called: no polymorphism required.
```

The class `unique_ptr` offers several member functions to access the pointer itself or to have a `unique_ptr` point to another block of memory. These member functions (and `unique_ptr` constructors) are introduced in the next few sections.

`Unique_ptr` can also be used with containers and (generic) algorithms. They can properly destruct any type of object, as their constructors accept customizable deleters. In addition, arrays can be handled by `unique_ptrs`.

18.3.1 Defining 'unique_ptr' objects

There are three ways to define `unique_ptr` objects. Each definition contains the usual `<type>` specifier between angle brackets:

- The default constructor simply creates a `unique_ptr` object that does not point to a particular block of memory. Its pointer is initialized to 0 (zero):

  ```
  unique_ptr<type> identifier;
  ```

  This form is discussed in section 18.3.2.
- The *move constructor* initializes an `unique_ptr` object. Following the use of the move constructor its `unique_ptr` argument no longer points to the dynamically allocated memory and its pointer data member is turned into a zero-pointer:

  ```
  unique_ptr<type> identifier(another unique_ptr for type);
  ```

  This form is discussed in section 18.3.3.
- The form that is used most often initializes a `unique_ptr` object to the block of dynamically allocated memory that is passed to the object's constructor. Optionally `deleter` can be provided. A (free) function (or function object) receiving the `unique_ptr`'s pointer as its argument can be passed as deleter. It is supposed to return the dynamically allocated memory to the common pool (doing nothing if the pointer equals zero).

  ```
  unique_ptr<type> identifier (new-expression [, deleter]);
  ```

  This form is discussed in section 18.3.4.

18.3.2 Creating a plain 'unique_ptr'

`Unique_ptr`'s default constructor defines a `unique_ptr` not pointing to a particular block of memory:

```
unique_ptr<type> identifier;
```

The pointer controlled by the `unique_ptr` object is initialized to `0` (zero). Although the `unique_ptr` object itself is not the pointer, its value *can* be compared to `0`. Example:

```
unique_ptr<int> ip;

if (!ip)
    cout << "0-pointer with a unique_ptr object\n";
```

Alternatively, the member `get` can be used (cf. section 18.3.5).

18.3.3 Moving another 'unique_ptr'

A `unique_ptr` may be initialized using an rvalue reference to a `unique_ptr` object for the same type:

```
unique_ptr<type> identifier(other unique_ptr object);
```

The move constructor is used, e.g., in the following example:

```
void mover(unique_ptr<string> &&param)
{
    unique_ptr<string> tmp(move(param));
}
```

Analogously, the assignment operator can be used. A `unique_ptr` object may be assigned to a temporary `unique_ptr` object of the same type (again move-semantics is used). For example:

```
#include <iostream>
#include <memory>
#include <string>

using namespace std;

int main()
{
    unique_ptr<string> hello1{ new string{ "Hello world" } };
    unique_ptr<string> hello2{ move(hello1) };
    unique_ptr<string> hello3;

    hello3 = move(hello2);
    cout << // *hello1 << '\n' <<   // would have segfaulted
            // *hello2 << '\n' <<   // same
            *hello3 << '\n';
}
// Displays:    Hello world
```

The example illustrates that

- `hello1` is initialized by a pointer to a dynamically allocated `string` (see the next section).
- The `unique_ptr hello2` grabs the pointer controlled by `hello1` using a move constructor. This effectively changes `hello1` into a 0-pointer.
- Then `hello3` is defined as a default `unique_ptr<string>`. But then it grabs its value using move-assignment from `hello2` (which, as a consequence, is changed into a 0-pointer).

If `hello1` or `hello2` had been inserted into `cout` a *segmentation fault* would have resulted. The reason for this should now be clear: it is caused by dereferencing 0-pointers. In the end, only `hello3` actually points to the originally allocated `string`.

18.3.4 Pointing to a newly allocated object

A `unique_ptr` is most often initialized using a pointer to dynamically allocated memory. The generic form is:

```
unique_ptr<type [, deleter_type]> identifier(new-expression
        [, deleter = deleter_type{}]);
```

The second (template) argument (`deleter(_type)`) is optional and may refer to a free function, a function object handling the destruction of the allocated memory, or a lambda function. A deleter is used, e.g., in situations where a double pointer is allocated and the destruction must visit each nested pointer to destroy the allocated memory (see below for an illustration).

Here is an example initializing a `unique_ptr` pointing to a `string` object:

```
unique_ptr<string> strPtr{ new string{ "Hello world" } };
```

The argument that is passed to the constructor is the pointer returned by `operator new`. Note that `type` does *not* mention the pointer. The type that is used in the `unique_ptr` construction is the same as the type that is used in `new` expressions.

Here is an example showing how an explicitly defined deleter may be used to delete a dynamically allocated array of pointers to strings:

```
#include <iostream>
#include <string>
#include <memory>
using namespace std;

struct Deleter
{
    size_t d_size;
    Deleter(size_t size = 0)
    :
        d_size(size)
    {}
    void operator()(string **ptr) const
    {
        for (size_t idx = 0; idx < d_size; ++idx)
            delete ptr[idx];
        delete[] ptr;
    }
};
int main()
{
    unique_ptr<string *, Deleter> sp2{ new string *[10], Deleter{ 10 } };

    Deleter &obj = sp2.get_deleter();
}
```

A `unique_ptr` can be used to reach the member functions that are available for objects allocated by the `new` expression. These members can be reached as if the `unique_ptr` was a plain pointer to the dynamically allocated object. For example, in the following program the text '`C++`' is inserted behind the word '`hello`':

```
#include <iostream>
#include <memory>
#include <cstring>
using namespace std;

int main()
{
    unique_ptr<string> sp{ new string{ "Hello world" } };

    cout << *sp << '\n';
    sp->insert(strlen("Hello "), "C++ ");
    cout << *sp << '\n';
}
/*
    Displays:
        Hello world
        Hello C++ world
*/
```

18.3.5 Operators and members

The class `unique_ptr` offers the following operators:

- `unique_ptr<Type> &operator=(unique_ptr<Type> &&tmp)`:
  This operator transfers the memory pointed to by the rvalue `unique_ptr` object to the lvalue `unique_ptr` object using *move semantics*. So, the rvalue object *loses* the memory it pointed at and turns into a 0-pointer. An existing `unique_ptr` may be assigned to another `unique_ptr` by converting it to an rvalue reference first using `std::move`. Example:

  ```
  unique_ptr<int> ip1(new int);
  unique_ptr<int> ip2;

  ip2 = std::move(ip1);
  ```

- `operator bool() const`:
  This operator returns `false` if the `unique_ptr` does not point to memory (i.e., its `get` member, see below, returns 0). Otherwise, `true` is returned.

- `Type &operator*()`:
  This operator returns a reference to the information accessible via a `unique_ptr` object . It acts like a normal pointer dereference operator.

- `Type *operator->()`:
  This operator returns a pointer to the information accessible via a `unique_ptr` object. This operator allows you to select members of an object accessible via a `unique_ptr` object. Example:

  ```
  unique_ptr<string> sp{ new string{ "hello" } };
  cout << sp->c_str();
  ```

The class `unique_ptr` supports the following member functions:

- `Type *get()`:
  A pointer to the information controlled by the `unique_ptr` object is returned. It acts like `operator->`. The returned pointer can be inspected. If it is zero the `unique_ptr` object does not point to any memory.

- `Deleter &unique_ptr<Type>::get_deleter()`:
  A reference to the deleter object used by the `unique_ptr` is returned.

- `Type *release()`:
  A pointer to the information accessible via a `unique_ptr` object is returned. At the same time the object itself becomes a 0-pointer (i.e., its pointer data member is turned into a 0-pointer). This member can be used to transfer the information accessible via a `unique_ptr` object to a plain `Type` pointer. After calling this member the proper destruction of the dynamically allocated memory is the responsibility of the programmer.

- `void reset(Type *)`:
  The dynamically allocated memory controlled by the `unique_ptr` object is returned to the common pool; the object thereupon controls the memory to which the argument that is passed to the function points. It can also be called without argument, turning the object into a 0-pointer. This member function can be used to assign a new block of dynamically allocated memory to a `unique_ptr` object.

- `void swap(unique_ptr<Type> &)`:
  Two identically typed `unique_ptrs` are swapped.

18.3.6 Using ‘unique_ptr’ objects for arrays

When a `unique_ptr` is used to store arrays the dereferencing operator makes little sense but with arrays `unique_ptr` objects benefit from index operators. The distinction between a single object `unique_ptr` and a `unique_ptr` referring to a dynamically allocated array of objects is realized through a template specialization.

With dynamically allocated arrays the following syntax is available:

- the index (`[]`) notation is used to specify that the smart pointer controls a dynamically allocated *array*. Example:

  ```
  unique_ptr<int[]> intArr(new int[3]);
  ```

- the index operator can be used to access the array’s elements. Example:

  ```
  intArr[2] = intArr[0];
  ```

In these cases the smart pointer’s destructors call `delete[]` rather than `delete`.

18.4 The class ‘shared_ptr’

In addition to the class `unique_ptr` the class `std::shared_ptr<Type>` is available, which is a reference counting smart pointer.

Before using `shared_ptrs` the `<memory>` header file must be included.

The shared pointer automatically destroys its content once its reference count has decayed to zero. As with `unique_ptr`, when defining a `shared_ptr<Base>` to store a newly allocated `Derived` class object, the returned `Base *` may be cast to a `Derived *` using a `static_cast`: polymorphism isn’t required, and when resetting the `shared_ptr` or when the `shared_ptr` goes out of scope, no slicing occurs, and `Derived`’s destructor (or, if configured: deleter) is called (cf. section 18.3).

`Shared_ptrs` support copy and move constructors as well as standard and move overloaded assignment operators.

Like `unique_ptrs, shared_ptrs` may refer to dynamically allocated arrays.

18.4.1 Defining ‘shared_ptr’ objects

There are four ways to define `shared_ptr` objects. Each definition contains the usual `<type>` specifier between angle brackets:

- The default constructor simply creates a `shared_ptr` object that does not point to a particular block of memory. Its pointer is initialized to 0 (zero):

  ```
  shared_ptr<type> identifier;
  ```

  This form is discussed in section 18.4.2.

- The copy constructor initializes a `shared_ptr` so that both objects share the memory pointed at by the existing object. The copy constructor also increments the `shared_ptr`’s reference count. Example:

  ```
  shared_ptr<string> org{ new string{ "hi there" } };
  shared_ptr<string> copy(org);   // reference count now 2
  ```

- The move constructor initializes a `shared_ptr` with the pointer and reference count of a temporary `shared_ptr`. The temporary `shared_ptr` is changed into a 0-pointer. An existing `shared_ptr` may have its data moved to a newly defined `shared_ptr` (turning the existing `shared_ptr` into a 0-pointer as well). In the next example a temporary, anonymous `shared_ptr` object is constructed, which is then used to construct `grabber`. Since `grabber`'s constructor receives an anonymous temporary object, the compiler uses `shared_ptr`'s move constructor:

  ```
  shared_ptr<string> grabber{ shared_ptr<string>{ new string{ "hi there" } } };
  ```

- The form that is used most often initializes a `shared_ptr` object to the block of dynamically allocated memory that is passed to the object's constructor. Optionally `deleter` can be provided. A (free) function (or function object) receiving the `shared_ptr`'s pointer as its argument can be passed as deleter. It is supposed to return the dynamically allocated memory to the common pool (doing nothing if the pointer equals zero).

  ```
  shared_ptr<type> identifier (new-expression [, deleter]);
  ```

  This form is discussed in section 18.4.3.

18.4.2 Creating a plain 'shared_ptr'

`Shared_ptr`'s default constructor defines a `shared_ptr` not pointing to a particular block of memory:

```
shared_ptr<type> identifier;
```

The pointer controlled by the `shared_ptr` object is initialized to `0` (zero). Although the `shared_ptr` object itself is not the pointer, its value *can* be compared to `0`. Example:

```
shared_ptr<int> ip;

if (!ip)
    cout << "0-pointer with a shared_ptr object\n";
```

Alternatively, the member `get` can be used (cf. section 18.4.4).

18.4.3 Pointing to a newly allocated object

Most often a `shared_ptr` is initialized by a dynamically allocated block of memory. The generic form is:

```
shared_ptr<type> identifier(new-expression [, deleter]);
```

The second argument (`deleter`) is optional and refers to a function object or free function handling the destruction of the allocated memory. A deleter is used, e.g., in situations where a double pointer is allocated and the destruction must visit each nested pointer to destroy the allocated memory (see below for an illustration). It is used in situations comparable to those encountered with `unique_ptr` (cf. section 18.3.4).

Here is an example initializing a `shared_ptr` pointing to a `string` object:

```
shared_ptr<string> strPtr{ new string{ "Hello world" } };
```

The argument that is passed to the constructor is the pointer returned by `operator new`. Note that `type` does *not* mention the pointer. The type that is used in the `shared_ptr` construction is the same as the type that is used in `new` expressions.

The next example illustrates that two `shared_ptrs` indeed share their information. After modifying the information controlled by one of the objects the information controlled by the other object is modified as well:

```
#include <iostream>
#include <memory>
#include <cstring>
using namespace std;

int main()
{
    shared_ptr<string> sp(new string{ "Hello world" });
    shared_ptr<string> sp2(sp);

    sp->insert(strlen("Hello "), "C++ ");
    cout << *sp << '\n' <<
            *sp2 << '\n';
}
/*
    Displays:
        Hello C++ world
        Hello C++ world
*/
```

18.4.4 Operators and members

The class `shared_ptr` offers the following operators:

- `shared_ptr &operator=(shared_ptr<Type> const &other)`:
  Copy assignment: the reference count of the operator's left hand side operand is reduced. If the reference count decays to zero the dynamically allocated memory controlled by the left hand side operand is deleted. Then it shares the information with the operator's right hand side operand, incrementing the information's reference count.
- `shared_ptr &operator=(shared_ptr<Type> &&tmp)`:
  Move assignment: the reference count of the operator's left hand side operand is reduced. If the reference count decays to zero the dynamically allocated memory controlled by the left hand side operand is deleted. Then it grabs the information controlled by the operator's right hand side operand which is turned into a 0-pointer.
- `operator bool() const`:
  If the `shared_ptr` actually points to memory `true` is returned, otherwise, `false` is returned.
- `Type &operator*()`:
  A reference to the information stored in the `shared_ptr` object is returned. It acts like a normal pointer.
- `Type *operator->()`:
  A pointer to the information controlled by the `shared_ptr` object is returned. Example:

  ```
  shared_ptr<string> sp{ new string{ "hello" } };
  cout << sp->c_str() << '\n';
  ```

The following member function member functions are supported:

- `Type *get()`:
  A pointer to the information controlled by the `shared_ptr` object is returned. It acts like `operator->`. The returned pointer can be inspected. If it is zero the `shared_ptr` object does not point to any memory.
- `Deleter &get_deleter()`:
  A reference to the `shared_ptr`'s deleter (function or function object) is returned.
- `void reset(Type *)`:
  The reference count of the information controlled by the `shared_ptr` object is reduced and if it decays to zero the memory it points to is deleted. Thereafter the object's information will refer to the argument that is passed to the function, setting its shared count to 1. It can also be called without argument, turning the object into a 0-pointer. This member function can be used to assign a new block of dynamically allocated memory to a `shared_ptr` object.
- `void reset(Type *, DeleterType &&)`:
  This variant of the previous member accepts a specific `Deleter` type: if `Type` is a base-class and derived class objects are used, these derived class objects may require specific actions at destruction time. When the previous member is used, then eventually the newly assigned object's destructor is called without using an explicit deleter function. The current member ensures that by the time the shared counter has decayed to zero the provided deleter is used.
- `void shared_ptr<Type>::swap(shared_ptr<Type> &&)`:
  Two identically typed `shared_ptrs` are swapped.
- `bool unique() const`:
  If the current object is the only object referring to the memory controlled by the object `true` is returned otherwise (including the situation where the object is a 0-pointer) `false` is returned.
- `size_t use_count() const`:
  The number of objects sharing the memory controlled by the object is returned.

18.4.5 Casting shared pointers

Be cautious when using standard **C++** style casts in combination with `shared_ptr` objects. Consider the following two classes:

```
struct Base
{};
struct Derived: public Base
{};
```

As with `unique_ptr`, when defining a `shared_ptr<Base>` to store a newly allocated `Derived` class object, the returned `Base *` may be cast to a `Derived *` using a `static_cast`: polymorphism isn't required, and when resetting the `shared_ptr` or when the `shared_ptr` goes out of scope, no slicing occurs, and `Derived`'s destructor is called (cf. section 18.3).

Of course, a `shared_ptr<Derived>` can easily be defined. Since a `Derived` object is also a `Base` object, a pointer to `Derived` can be considered a pointer to `Base` without using casts, but a `static_cast` could be used to force the interpretation of a `Derived *` to a `Base *`:

```
Derived d;
static_cast<Base *>(&d);
```

However, a plain `static_cast` cannot be used when initializing a shared pointer to a `Base` using the `get` member of a shared pointer to a `Derived` object. The following code snipped eventually results in an attempt to delete the dynamically allocated `Base` object twice:

```
shared_ptr<Derived> sd{ new Derived };
shared_ptr<Base> sb{ static_cast<Base *>(sd.get()) };
```

Since `sd` and `sb` point at the same object `~Base` will be called for the same object when `sb` goes out of scope and when `sd` goes out of scope, resulting in premature termination of the program due to a *double free* error.

These errors can be prevented using casts that were specifically designed for being used with `shared_ptrs`. These casts use specialized constructors that create a `shared_ptr` pointing to memory but shares ownership (i.e., a reference count) with an existing `shared_ptr`. These special casts are:

- `std::static_pointer_cast<Base>(std::shared_ptr<Derived> ptr)`:
  A `shared_ptr` to a `Base` class object is returned. The returned `shared_ptr` refers to the base class portion of the `Derived` class to which the `shared_ptr<Derived> ptr` refers. Example:

  ```
  shared_ptr<Derived> dp{ new Derived };
  shared_ptr<Base> bp = static_pointer_cast<Base>(dp);
  ```

- `std::const_pointer_cast<Class>(std::shared_ptr<Class const> ptr)`:
  A `shared_ptr` to a `Class` class object is returned. The returned `shared_ptr` refers to a non-const `Class` object whereas the `ptr` argument refers to a `Class const` object. Example:

  ```
  shared_ptr<Derived const> cp{ new Derived };
  shared_ptr<Derived> ncp = const_pointer_cast<Derived>(cp);
  ```

- `std::dynamic_pointer_cast<Derived>(std::shared_ptr<Base> ptr)`:
  A `shared_ptr` to a `Derived` class object is returned. The `Base` class must have at least one virtual member function, and the class `Derived`, inheriting from `Base` may have overridden `Base`’s virtual member(s). The returned `shared_ptr` refers to a `Derived` class object if the dynamic cast from `Base *` to `Derived *` succeeded. If the dynamic cast did not succeed the `shared_ptr`’s `get` member returns 0. Example (assume `Derived` and `Derived2` were derived from `Base`):

  ```
  shared_ptr<Base> bp(new Derived());
  cout << dynamic_pointer_cast<Derived>(bp).get() << ' ' <<
          dynamic_pointer_cast<Derived2>(bp).get() << '\n';
  ```

  The first `get` returns a non-0 pointer value, the second `get` returns 0.

18.4.6 Using ‘shared_ptr’ objects for arrays

Different from the `unique_ptr` class no specialization exists for the `shared_ptr` class to handle dynamically allocated arrays of objects.

But like `unique_ptrs`, with `shared_ptrs` referring to arrays the dereferencing operator makes little sense while in these circumstances `shared_ptr` objects would benefit from index operators.

It is not difficult to create a class `shared_array` offering such facilities. The class template `shared_array`, derived from `shared_ptr` merely should provide an appropriate *deleter* to make sure that the array and its elements are properly destroyed. In addition it should define the index operator and, when applicable should declare the derefencing operators using `delete`.

Here is an example showing how `shared_array` can be defined and used:

```
struct X
{
    ~X()
    {
        cout << "destr\n";  // show the object's destruction
    }
};
template <typename Type>
class shared_array: public shared_ptr<Type>
{
    struct Deleter          // Deleter receives the pointer
    {                       // and calls delete[]
       void operator()(Type* ptr)
       {
          delete[] ptr;
       }
    };
    public:
        shared_array(Type *p)            // other constructors
        :                                // not shown here
            shared_ptr<Type>(p, Deleter())
        {}
        Type &operator[](size_t idx)    // index operators
        {
            return shared_ptr<Type>::get()[idx];
        }
        Type const &operator[](size_t idx) const
        {
            return shared_ptr<Type>::get()[idx];
        }
        Type &operator*() = delete;     // delete pointless members
        Type const &operator*() const = delete;
        Type *operator->() = delete;
        Type const *operator->() const = delete;
};
int main()
{
    shared_array<X> sp{ new X[3] };
    sp[0] = sp[1];
}
```

18.5 Smart 'smart pointer' construction: 'make_shared' and 'make_unique'

Usually a `shared_ptr` is initialized at definition time with a pointer to a newly allocated object. Here is an example:

```
std::shared_ptr<string> sptr{ new std::string{ "hello world" } }
```

In such statements *two* memory allocation calls are used: one for the allocation of the `std::string` and one used interally by `std::shared_ptr`'s constructor itself.

The two allocations can be combined into one single allocation (which is also slightly more efficient than explicitly calling `shared_ptr`'s constructor) using the `make_shared` template. The function template `std::make_shared` has the following prototype:

```
template<typename Type, typename ...Args>
std::shared_ptr<Type> std::make_shared(Args ...args);
```

Before using `make_shared` the `<memory>` header file must be included.

This function template allocates an object of type `Type`, passing `args` to its constructor (using *perfect forwarding*, see section 22.5.2), and returns a `shared_ptr` initialized with the address of the newly allocated `Type` object.

Here is how the above `sptr` object can be initialized using `std::make_shared`. Notice the use of `auto` which frees us from having to specify `sptr`'s type explicitly:

```
auto sptr(std::make_shared<std::string>("hello world"));
```

After this initialization `std::shared_ptr<std::string> sptr` has been defined and initialized. It could be used as follows:

```
std::cout << *sptr << '\n';
```

In addition to `make_shared` the function `std::make_unique` can be used. It can be used `make_shared` but returns a `std::unique_ptr` rather than a `shared_ptr`.

18.6 Classes having pointer data members

Classes having pointer data members require special attention. In particular at construction time one must be careful to prevent wild pointers and/or memory leaks. Consider the following class defining two pointer data members:

```
class Filter
{
    istream *d_in;
    ostream *d_out;
    public:
        Filter(char const *in, char const *out);
};
```

Assume that `Filter` objects filter information read from `*d_in` and write the filtered information to `*d_out`. Using pointers to streams allows us to have them point at any kind of stream like `istreams, ifstreams, fstreams` or `istringstreams`. The shown constructor could be implemented like this:

```
Filter::Filter(char const *in, char const *out)
:
    d_in(new ifstream{ in }),
        d_out(new ofstream{ out })
    {
        if (!*d_in || !*d_out)
            throw "Input and/or output stream not available"s;
    }
```

Of course, the construction could fail. `new` could throw an exception; the stream constructors could throw exceptions; or the streams could not be opened in which case an exception is thrown from the constructor's body. Using a function try block helps. Note that if `d_in`'s initialization throws, there's nothing to be worried about. The `Filter` object hasn't been constructed, its destructor is not called and processing continues at the point where the thrown exception is caught. But `Filter`'s destructor is also not called when `d_out`'s initialization or the constructor's `if` statement throws: no object, and hence no destructor is called. This may result in memory leaks, as `delete` isn't called for `d_in` and/or `d_out`. To prevent this, `d_in` and `d_out` must first be initialized to 0 and only then the initialization can be performed:

```
    Filter::Filter(char const *in, char const *out)
    try
    :
        d_in(0),
        d_out(0)
    {
        d_in = new ifstream{ in };
        d_out = new ofstream{ out };

        if (!*d_in || !*d_out)
            throw "Input and/or output stream not available"s;
    }
    catch (...)
    {
        delete d_out;
        delete d_in;
    }
```

This quickly gets complicated, though. If `Filter` harbors yet another data member of a class whose constructor needs two streams then that data cannot be constructed or it must itself be converted into a pointer:

```
    Filter::Filter(char const *in, char const *out)
    try
    :
        d_in(0),
        d_out(0)
        d_filterImp(*d_in, *d_out)    // won't work
    { ... }

    // instead:

    Filter::Filter(char const *in, char const *out)
    try
    :
        d_in(0),
        d_out(0),
        d_filterImp(0)
    {
        d_in = new ifstream(in);
        d_out = new ofstream(out);
        d_filterImp = new FilterImp(*d_in, *d_out);
        ...
    }
    catch (...)
    {
        delete d_filterImp;
        delete d_out;
        delete d_in;
    }
```

Although the latter alternative works, it quickly gets hairy. In situations like these smart pointers should be used to prevent the hairiness. By defining the stream pointers as (smart pointer) objects they will, once constructed, properly be destroyed even if the rest of the constructor's code throws exceptions. Using a `FilterImp` and two `unique_ptr` data members `Filter`'s setup and its constructor becomes:

```
    class Filter
    {
        std::unique_ptr<std::ifstream> d_in;
        std::unique_ptr<std::ofstream> d_out;
        FilterImp d_filterImp;
        ...
    };

    Filter::Filter(char const *in, char const *out)
    try
    :
        d_in(new ifstream(in)),
        d_out(new ofstream(out)),
        d_filterImp(*d_in, *d_out)
    {
        if (!*d_in || !*d_out)
            throw "Input and/or output stream not available"s;
    }
```

We're back at the original implementation but this time without having to worry about wild pointers and memory leaks. If one of the member initializers throws the destructors of previously constructed data members (which are now objects) are always called.

As a rule of thumb: when classes need to define pointer data members they should define those pointer data members as smart pointers if there's any chance that their constructors throw exceptions.

18.7 Comparison classes

With the introduction of the *spaceship operator* (<=>, cf. section 11.6.2) several *comparison category classes* were added to the standard namespace.

Comparison classes are required when implementing the spaceship operator, and to use them (or when declaring and implementing the spachip operator) the `<compare>` header file must be included.

The weak class types do not support *substitutability*. Substitutability means that if two objects `one` and `two` are equal (so: `one == two` is `true`), then `fun(one) == fun(two)` is also `true`. Here `fun` is any function that only uses public const members of its argument that return *value types* (as compared to pointer types) which also support comparisons (also called *comparison-salient state*).

The operators of comparison classes expect at least one argument of their own class types. The other argument may either also be of their own class types or it can be the value 0 (or any value that can be considered 0, like `nullptr_t`).

There are five comparison classes, primarily used when implementing spaceship operators:

- `weak_equality`, used for classes that only support the `==` and `!=` operators, but not substitutability;
- `strong_equality`, used for classes that only support the `==` and `!=` operators, as well as substitutability;
- `partial_ordering` used for classes that support all comparison operators, do not support substitutability, and can be used when comparing incomparable arguments (i.e., all comparison operators return false);
- `weak_ordering` used for classes that support all comparison operators and that do not support substitutability;
- `strong_ordering` used for classes that support all comparison operators as well as substitutability;

18.7.1 The class ‘weak_equality’

The class `std::weak_equality` is used when implementing the spaceship operator for classes that only support (in)equality comparisons, but not substitutability. The class provides free functions `operator==` and `operator!=` expecting `weak_equality` arguments (one argument may be 0) and it defines two static objects:

- `weak_equality::equivalent`, indicating equality;
- `weak_equality::nonequivalent`, indicating non-equality;

Note: at the current release of the Gnu **C++** compiler (10.0.0) this class is not yet available in the `<compare>` header file.

18.7.2 The class ‘strong_equality’

The class `std::strong_equality` is used when implementing the spaceship operator for classes that only support (in)equality comparisons as well as substitutability. The class provides free functions `operator==` and `operator!=` expecting `strong_equality` arguments (one argument may be 0) and it defines four static objects:

- `strong_equality::equal`, indicating equality;
- `strong_equality::equivalent`, indicating equality;
- `strong_equality::nonequal`, indicating non-equality;
- `strong_equality::nonequivalent`, indicating non-equality;

Note: at the current release of the Gnu **C++** compiler (10.0.0) this class is not yet available in the `<compare>` header file.

18.7.3 The class 'partial_ordering'

The class `std::partial_ordering` is used when implementing the spaceship operator for classes that support all comparison operators (where one operand may be zero), that do not support substitutability, and whose objects, using the spaceship operator itself, can also be compared to any other type of object.

The class `partial_ordering` provides free functions for all comparison operations (`==, !=, <, <=, >,` and `>=`) expecting `partial_ordering` arguments (one argument may be 0). It also defines four static objects which can be returned by the spaceship operator:

- `partial_ordering::less`, returned when the lhs operand of the spaceship operator should be ordered before the rhs operand;
- `partial_ordering::equivalent`, indicating equality: there is no ordering preference between the two operands of the spaceship operator;
- `partial_ordering::greater`, returned when the lhs operand of the spaceship operator should be ordered after the rhs operand;
- `partial_ordering::unordered`, returned when all comparison operators of a class implementing the spaceship operator should return `false` (so `==, !=, <, <=, >,` and `>=` all return `false`).

As an example, consider road taxes. Trucks, cars, and motor cycles have to pay road taxes, but there's no road tax for bicycles. For ordering road taxes a class `RoadTax` may be used, defining the following spaceship operator (assuming that all types of vehicles are derived from a class `Vehicle`, and that `Vehicle` has a (virtual) member `double roadTax()` returning the amount of road tax that is due for the various types of vehicles; the amount is negative if no road tax is required):

```
partial_ordering RoadTax::operator<=>(Vehicle const &lhs,
                                      Vehicle const &rhs)
{
    return
      lhs.roadTax() < 0 or rhs.roadTax() < 0 ?
                                      partial_ordering::unordered :
      lhs.roadTax() < rhs.roadTax() ? partial_ordering::less      :
      lhs.roadTax() > rhs.roadTax() ? partial_ordering::greater   :
                                      partial_ordering::equivalent;
}
```

18.7.4 The class 'weak_ordering'

The class `std::weak_ordering` is used when implementing the spaceship operator for classes that support all comparison operators (where one operand may be zero), and that do not support substitutability.

The class `weak_ordering` differs from the `partial_ordering` class in that *unordered* cannot be used as a comparison result. Like the class `partial_ordering` it provides free functions for all comparison operations (`==, !=, <, <=, >,` and `>=`) expecting `partial_ordering` arguments (one argument may be 0). It also defines three static objects which can be returned by the spaceship operator:

- `weak_ordering::less`, returned when the lhs operand of the spaceship operator should be ordered before the rhs operand;
- `weak_ordering::equal`, indicating equality: there is no ordering preference between the two operands of the spaceship operator;
- `weak_ordering::greater`, returned when the lhs operand of the spaceship operator should be ordered after the rhs operand;

The example in the previous section can easily adapted to the `weak_ordering` comparison class: if the `roadTax` members of vehicles for which no road tax is due return zero then `RoadTax's` spaceship operator can be implemented this way:

```
weak_ordering RoadTax::operator<=>(Vehicle const &lhs,
                                   Vehicle const &rhs)
{
    return
      lhs.roadTax() < rhs.roadTax() ? weak_ordering::less      :
      lhs.roadTax() > rhs.roadTax() ? weak_ordering::greater   :
                                      weak_ordering::equal;
}
```

18.7.5 The class ‘strong_ordering’

The class `std::strong_ordering` is used when implementing the spaceship operator for classes that support all comparison operators (where one operand may be zero), as well as substitutability.

The class `strong_ordering` provides free functions for all comparison operations (`==, !=, <, <=, >`, and `>=`) expecting `partial_ordering` arguments (one argument may be 0). It also defines three static objects which can be returned by the spaceship operator:

- `strong_ordering::less`, returned when the lhs operand of the spaceship operator should be ordered before the rhs operand;
- `strong_ordering::equal`, indicating equality: there is no ordering preference between the two operands of the spaceship operator;
- `strong_ordering::greater`, returned when the lhs operand of the spaceship operator should be ordered after the rhs operand;

An example where the class `strong_ordering` was used has already been provided in section 11.6.2, where the spaceship operator itself was introduced.

18.8 Regular Expressions

C++ itself provides facilities for handling regular expressions. Regular expressions were already available in **C++** via its **C** heritage (as **C** has always offered functions like `regcomp` and `regexec`), but the dedicated regular expression facilities have a richer interface than the traditional **C** facilities, and can be used in code using templates.

Before using the specific **C++** implementations of regular expressions the header file `<regex>` must be included.

Regular expressions are extensively documented elsewhere (e.g., **regex**(7), Friedl, J.E.F `Mastering Regular Expressions`[2], O'Reilly). The reader is referred to these sources for a refresher on the topic of regular expressions. In essence, regular expressions define a small meta-language recognizing textual units (like 'numbers', 'identifiers', etc.). They are extensively used in the context of *lexical scanners* (cf. section 25.6.1) when defining the sequence of input characters associated with *tokens*. But they are also intensively used in other situations. Programs like **sed**(1) and **grep**(1) use regular expressions to find pieces of text in files having certain characteristics, and a program like **perl**(1) adds some 'sugar' to the regular expression language, simplifying the construction of regular expressions. However, though extremely useful, it is also well known that regular expressions tend to be very hard to read. Some even call the regular expression language a *write-only language*: while specifying a regular expression it's often clear why it's written in a particular way. But the opposite, understanding what a regular expression is supposed to represent if you lack the proper context, can be extremely difficult. That's why, from the onset and as a *rule of thumb*, it is stressed that an appropriate comment should be provided, with *each* regular expression, as to what it is supposed to match.

In the upcoming sections first a short overview of the regular expression language is provided, which is then followed by the facilities **C++** is currently offering for using regular expressions. These facilities mainly consist of classes helping you to specify regular expression, matching them to text, and determining which parts of the text (if any) match (parts of) the text being analyzed.

18.8.1 The regular expression mini language

Regular expressions are expressions consisting of elements resembling those of numeric expressions. Regular expressions consist of basic elements and operators, having various priorities and associations. Like numeric expressions, parentheses can be used to group elements together to form a unit on which operators operate. For an extensive discussion the reader is referred to, e.g., section 15.10 of the `ecma-international.org`[3] page, which describes the characteristics of the regular expressions used by default by **C++**'s `regex` classes.

C++'s default definition of regular expressions distinguishes the following *atoms*:

- `x`: the character 'x';
- `.`: any character except for the newline character;
- `[xyz]`: a character class; in this case, either an 'x', a 'y', or a 'z' matches the regular expression. See also the paragraph about character classes below;
- `[abj-oZ]`: a character class containing a range of characters; this regular expression matches an 'a', a 'b', any letter from 'j' through 'o', or a 'Z'. See also the paragraph about character classes below;
- `[^A-Z]`: a negated character class: this regular expression matches any character but those in the class beyond `^`. In this case, any character *except for* an uppercase letter. See also the paragraph about character classes below;
- `[:predef:]`: a *predefined* set of characters. See below for an overview. When used, it is interpreted as an element in a character class. It is therefore always embedded in a set of square brackets defining the character class (e.g., `[[:alnum:]]`);

---

[2] http://oreilly.com/catalog/

[3] http://ecma-international.org/ecma-262/5.1/#sec-15.10

- `\X`: if X is 'a', 'b', 'f', 'n', 'r', 't', or 'v', then the ANSI-C interpretation of '\x'. Otherwise, a literal 'X' (used to escape operators such as ∗);
- `(r)`: the regular expression `r`. It is used to override precedence (see below), but also to define `r` as a *marked sub-expression* whose matching characters may directly be retrieved from, e.g., a `std::smatch` object (cf. section 18.8.3);
- `(?:r)`: the regular expression `r`. It is used to override precedence (see below), but it is *not* regarded as a *marked sub-expression*;

In addition to these basic atoms, the following special atoms are available (which can also be used in character classes):

- `\s`: a whitespace character;
- `\S`: any character but a whitespace character;
- `\d`: a decimal digit character;
- `\D`: any character but a decimal digit character;
- `\w`: an alphanumeric character or an underscore (_) character;
- `\W`: any character but an alphanumeric character or an underscore (_) character.

Atoms may be concatenated. If `r` and `s` are atoms then the regular expression `rs` matches a target text if the target text matches `r` *and* `s`, in that order (without any intermediate characters inside the target text). E.g., the regular expression `[ab][cd]` matches the target text `ac`, but not the target text `a:c`.

Atoms may be combined using operators. Operators bind to the preceding atom. If an operator should operate on multiple atoms the atoms must be surrounded by parentheses (see the last element in the previous itemization). To use an operator character as an atom it can be escaped. Eg., ∗ represents an operator, `\*` the atom character star. Note that character classes do not recognize escape sequences: `[\*]` represents a character class consisting of two characters: a backslash and a star.

The following operators are supported (`r` and `s` represent regular expression atoms):

- `r*`: zero or more `r`s;
- `r+`: one or more `r`s;
- `r?`: zero or one `r`s (that is, an optional r);
- `r{m, n}`: where `1 <= m <= n`: matches 'r' at least m, but at most n times;
- `r{m,}`: where `1 <= m`: matches 'r' at least m times;
- `r{m}`: where `1 <= m`: matches 'r' exactly m times;
- `r|s`: matches either an 'r' or an 's'. This operator has a lower priority than any of the multiplication operators;
- `^r :` `^` is a pseudo operator. This expression matches 'r', if appearing at the beginning of the target text. If the `^`-character is not the first character of a regular expression it is interpreted as a literal `^`-character;
- `r$`: `$` is a pseudo operator. This expression matches 'r', if appearing at the end of the target text. If the `$`-character is not the last character of a regular expression it is interpreted as a literal `$`-character;

When a regular expression contains marked sub-expressions and multipliers, and the marked sub-expressions are multiply matched, then the target's final sub-string matching the marked sub-expression is reported as the text matching the marked sub-expression. E.g, when using `regex_search` (cf. section 18.8.4.3), marked sub-expression (`((a|b)+\s?)`), and target text `a a b`, then `a a b` is the fully matched text, while `b` is reported as the sub-string matching the first and second marked sub-expressions.

18.8.1.1 Character classes

Inside a character class all regular expression operators lose their special meanings, except for the special atoms `\s, \S, \d, \D, \w,` and `\W`; the character range operator `-`; the end of character class operator `]`; and, at the beginning of the character class, `^`. Except in combination with the special atoms the escape character is interpreted as a literal backslash character (to define a character class containing a backslash and a `d` simply use `[d\]`).

To add a closing bracket to a character class use `[]` immediately following the initial open-bracket, or start with `[^]` for a negated character class not containing the closing bracket. Minus characters are used to define character ranges (e.g., `[a-d]`, defining `[abcd]`) (be advised that the actual range may depend on the locale being used). To add a literal minus character to a character class put it at the very beginning (`[-`, or `[^-`) or at the very end (`-]`) of a character class.

Once a character class has started, all subsequent characters are added to the class's set of characters, until the final closing bracket (`]`) has been reached.

In addition to characters and ranges of characters, character classes may also contain *predefined sets of character*. They are:

```
[:alnum:] [:alpha:] [:blank:]
[:cntrl:] [:digit:] [:graph:]
[:lower:] [:print:] [:punct:]
[:space:] [:upper:] [:xdigit:]
```

These predefined sets designate sets of characters equivalent to the corresponding standard **C** `isXXX` function. For example, `[:alnum:]` defines all characters for which **isalnum**(3) returns true.

18.8.2 Defining regular expressions: std::regex

Before using the `(w)regex` class presented in this section the `<regex>` header file must be included.

The types `std::regex` and `std::wregex` define regular expression patterns. They define, respectively the types `basic_regex<char>` and `basic_regex<wchar_t>` types. Below, the class `regex` is used, but in the examples `wregex` could also have been used.

Regular expression facilities were, to a large extent, implemented through templates, using, e.g., the `basic_string<char>` type (which is equal to `std::string`). Likewise, generic types like *OutputIter* (output iterator) and *BidirConstIter* (bidirectional const iterator) are used with several functions. Such functions are function templates. Function templates determine the actual types from the arguments that are provided at *call-time*.

These are the steps that are commonly taken when using regular expressions:

- First, a regular expression is defined. This involves defining or modifying a `regex` object.
- Then the regular expression is provided with a *target text*, which may result in sections of the target text matching the regular expression.

- The sections of the target text matching (or not matching) the regular expression are retrieved to be processed elsewhere, or:
- The sections of the target text matching (or not matching) the regular expression are directly modified by existing regular expression facilities, after which the modified target text may be processed elsewhere.

The way `regex` objects handle regular expressions can be configured using a `bit_or` combined set of `std::regex_constants` values, defining a `regex::flag_type` value. These `regex_constants` are:

- `std::regex_constants::awk`:
  awk(1)'s (POSIX) regular expression grammar is used to specify regular exressions (e.g., regular expressions are delimited by `/`-characters, like `/\w+/`; for further details and for details of other regular expression grammars the reader should consult the man-pages of the respective programs);
- `std::regex_constants::basic`:
  the basic POSIX regular expression grammar is used to specify regular expressions;
- `std::regex_constants::collate`:
  the character range operator (`-`) used in character classes defines a locale sensitive range (e.g., `[a-k]`);
- `std::regex_constants::ECMAScript`:
  this `flag_type` is used by default by `regex` constructors. The regular expression uses the Modified ECMAScript regular expression grammar;
- `std::regex_constants::egrep`:
  egrep(1)'s (POSIX) regular expression grammar is used to specify regular expressions. This is the same grammar as used by `regex_constants::extended`, with the addition of the newline character (`'\n'`) as an alternative for the `'|'`-operator;
- `std::regex_constants::extended`:
  the extended POSIX regular expression grammar is used to specify regular expressions;
- `std::regex_constants::grep`:
  grep(1)'s (POSIX) regular expression grammar is used to specify regular expressions. This is the same grammar as used by `regex_constants::basic`, with the addition of the newline character (`'\n'`) as an alternative for the `'|'`-operator;
- `std::regex_constants::icase`:
  letter casing in the target string is ignored. E.g., the regular expression `A` matches `a` and `A`;
- `std::regex_constants::nosubs`:
  When performing matches, all sub-expressions (`(expr)`) are treated as non-marked (`?:expr`);
- `std::regex_constants::optimize`:
  optimizes the speed of matching regular expressions, at the cost of slowing down the construction of the regular expression somewhat. If the same regular expression object is frequently used then this flag may substantially improve the speed of matching target texts;

Constructors

The default, move and copy constructors are available. Actually, the default constructor defines one parameter of type `regex::flag_type`, for which the value `regex_constants::ECMAScript` is used by default.

- `regex()`:
  the default constructor defines a `regex` object not containing a regular expression;

- `explicit regex(char const *pattern)`:
  defines a `regex` object containing the regular expression found at `pattern`;
- `regex(char const *pattern, std::size_t count)`:
  defines a `regex` object containing the regular expression found at the first `count` characters of `pattern`;
- `explicit regex(std::string const &pattern)`:
  defines a `regex` object containing the regular expression found at `pattern`. This constructor is defined as a member template, accepting a `basic_string`-type argument which may also use non-standard character traits and allocators;
- `regex(ForwardIterator first, ForwardIterator last)`:
  defines a `regex` object containing the regular expression found at the (forward) iterator range `[first, last)`. This constructor is defined as a member template, accepting any forward iterator type (e.g., plain `char` pointers) which can be used to define the regular expression's pattern;
- `regex(std::initializer_list<Char> init)`:
  defines a `regex` object containing the regular expression from the characters in the initializer list `init`.

  Here are some examples:

```
std::regex re("\\w+");       // matches a sequence of alpha-numeric
                             // and/or underscore characters

std::regex re{'\\', 'w', '+'} ;     // idem

std::regex re(R"(\w+xxx")", 3);     // idem
```

Member functions

- `regex &operator=(RHS)`:
  The copy and move assignment operators are available. Otherwise, RHS may be:
  - an NTBS (of type `char const *`);
  - a `std::string const &` (or any compatible `std::basic_string`);
  - a `std::initializer_list<char>`;
- `regex &assign(RHS)`:
  This member accepts the same arguments as `regex's` constructors, including the (optional) `regex_constants` values;
- `regex::flag_type flag() const`:
  Returns the `regex_constants` flags that are active for the current `regex` object. E.g.,

```
int main()
{
    regex re;

    regex::flag_type flags = re.flags();

    cout <<                                 // displays: 16 0 0
        (re.flags() & regex_constants::ECMAScript) << ' '  <<
        (re.flags() & regex_constants::icase) << ' '  <<
        (re.flags() & regex_constants::awk) << ' '  << '\n';
}
```

Note that when a combination of `flag_type` values is specified at construction-time that only those flags that were specified are set. E.g., when `re(regex_constants::icase)` would have been specified the `cout` statement would have shown `0 1 0`. It's also possible to specify conflicting combinations of flag-values like `regex_constants::awk | regex_constants::grep`. The construction of such `regex` objects succeeds, but should be avoided.

- `locale_type get_loc() const`:
  Returns the locale that is associated with the current `regex` object;
- `locale_type imbue(locale_type locale)`:
  Replaces the `regex` object's current locale setting with `locale`, returning the replaced locale;
- `unsigned mark_count() const`:
  The number of *marked sub-expressions* in the `regex` object is returned. E.g.,

```
int main()
{
    regex re("(\\w+)([[:alpha:]]+)");
    cout << re.mark_count() << '\n';        // displays: 2
}
```

- `void swap(regex &other) noexcept`:
  Swaps the current `regex` object with `other`. Also available as a free function: `void swap(regex &lhs, regex &rhs)`, swapping `lhs` and `rhs`.

18.8.3 Retrieving matches: std::match_results

Once a `regex` object is available, it can be used to match some target text against the regular expression. To match a target text against a regular expression the following functions, described in the next section (18.8.4), are available:

- `regex_match` merely matches a target text against a regular expression, informing the caller whether a match was found or not;
- `regex_search` also matches a target text against a regular expression, but allows retrieval of matches of marked sub-expressions (i.e., parenthesized regular expressions);
- `regex_replace` matches a target text against a regular expression, and replaces pieces of matched sections of the target text by another text.

These functions must be provided with a target text and a `regex` object (which is not modified by these functions). Usually another argument, a `std::match_results` object is also passed to these functions, to contain the results of the regular expression matching procedure.

Before using the `match_results` class the `<regex>` header file must be included.

Examples of using `match_results` objects are provided in section 18.8.4. This and the next section are primarily for referential purposes.

Various specializations of the class `match_results` exist. The specialization that is used should match the specializations of the used `regex` class. E.g., if the regular expression was specified as a `char const *` the `match_results` specialization should also operate on `char const *` values. The various specializations of `match_results` have been given names that can easily be remembered, so selecting the appropriate specialization is simple.

The class `match_results` has the following specializations:

- `cmatch`:
  defines `match_results<char const *>`, using a `char const *` type of iterator. It should be used with a `regex(char const *)` regular expression specification;
- `wcmatch`:
  defines `match_results<wchar_ const *>`, using a `wchar_t const *` type of iterator. It should be used with a `regex(wchar_t const *)` regular expression specification;
- `smatch`:
  defines `match_results<std::string::const_iterator>`, using a `std::string::const_iterator` type of iterator. It should be used with a `regex(std::string const &)` regular expression specification;
- `wsmatch`:
  defines `match_results<std::wstring::const_iterator>`, using a `std::wstring::const_iterator` type of iterator. It should be used with a `regex(wstring const &)` regular expression specification.

Constructors

The default, copy, and move constructors are available. The default constructor defines an `Allocator const &` parameter, which by default is initialized to the default allocator. Normally, objects of the class `match_results` receive their match-related information by passing them to the above-mentioned functions, like `regex_match`. When returning from these functions members of the class `match_results` can be used to retrieve specific results of the matching process.

Member functions

- `match_results &operator=`:
  The copy and move assignment operators are available;
- `std::string const &operator[](size_t idx) const`:
  Returns a (const) reference to sub-match `idx`. With `idx` value 0 a reference to the full match is returned. If `idx >= size()` (see below) a reference to an empty sub-range of the target string is returned. The behavior of this member is undefined if the member `ready()` (see below) returns `false`;
- `Iterator begin() const`:
  Returns an iterator to the first sub-match. `Iterator` is a const-iterator for `const match_results` objects;
- `Iterator cbegin() const`:
  Returns an iterator to the first sub-match. `Iterator` is a const-iterator;
- `Iterator cend() const`:
  Returns an iterator pointing beyond the last sub-match. `Iterator` is a const-iterator;
- `Iterator end() const`:
  Returns an iterator pointing beyond the last sub-match. `Iterator` is a const-iterator for `const match_results` objects;
- `ReturnType format(Parameters) const`:
  As this member requires a fairly extensive description, it would break the flow of the current overview. This member is used in combination with the `regex_replace` function, and it is therefore covered in detail in that function's section (18.8.4.5);

- `allocator_type get_allocator() const`:
  Returns the object's allocator;

- `bool empty() const`:
  Returns `true` if the `match_results` object contains no matches (which is also returned after merely using the default constructor). Otherwise it returns `false`;

- `int length(size_t idx = 0) const`:
  Returns the length of sub-match `idx`. By default the length of the full match is returned. If `idx >= size()` (see below) 0 is returned;

- `size_type max_size() const`:
  Returns the maximum number of sub-matches that can be contained in a `match_results` object. This is an implementation dependent constant value;

- `int position(size_t idx = 0) const`:
  Returns the offset in the target text of the first character of sub-match `idx`. By default the position of the first character of the full match is returned. If `idx >= size()` (see below) -1 is returned;

- `std::string const &prefix() const`:
  Returns a (const) reference to a sub-string of the target text that ends at the first character of the full match;

- `bool ready() const`:
  No match results are available from a default constructed `match_results` object. It receives its match results from one of the mentioned matching functions. Returns `true` once match results are available, and `false` otherwise.

- `size_type size() const`:
  Returns the number of sub-matches. E.g., with a regular expression `(abc)|(def)` and target `defcon` three submatches are reported: the total match (def); the empty text for `(abc)`; and `def` for the `(def)` marked sub-expression.

  Note: when multipliers are used only the last match is counted and reported. E.g., for the pattern `(a|b)+` and target `aaab` *two* sub-matches are reported: the total match `aaab`, and the last match (`b`);

- `std::string str(size_t idx = 0) const`:
  Returns the characters defining sub-match `idx`. By default this is the full match. If `idx >= size()` (see below) an empty string returned;

- `std::string const &suffix() const`:
  Returns a (const) reference to a sub-string of the target text that starts beyond the last character of the full match;

- `void swap(match_results &other) noexcept`:
  Swaps the current `match_results` object with `other`. Also available as a free function: `void swap(match_results &lhs, match_results &rhs)`, swapping `lhs` and `rhs`.

18.8.4 Regular expression matching functions

Before using the functions presented in this section the `<regex>` header file must be included.

There are three major families of functions that can be used to match a target text against a regular expression. Each of these functions, as well as the `match_results::format` member, has a final `std::regex_constants::match_flag_type` parameter (see the next section), which is given the default value `regex_constants::match_default` which can be used to fine-tune the way the regular expression and the matching process is being used. This final parameter is not explicitly mentioned with the regular expression matching functions or with the `format` member. The three families of functions are:

- `bool std::regex_match(Parameters):`
  This family of functions is used to match a regular expression against a target text. Only if the regular expression matches the full target text `true` is returned; otherwise `false` is returned. Refer to section 18.8.4.2 for an overview of the available overloaded `regex_match` functions;

- `bool std::regex_search(Parameters):`
  This family of functions is also used to match a regular expression against a target text. This function returns true once the regular expression matches a sub-string of the target text; otherwise `false` is returned. See below for an overview of the available overloaded `regex_search` functions;

- `ReturnType std::regex_replace(Parameters):`
  This family of functions is used to produce modified texts, using the characters of a target string, a `regex` object and a format string. This member closely resembles the functionality of the `match_results::format` member discussed in section 18.8.4.4.

The `match_results::format` member can be used after `regex_replace` and is discussed after covering `regex_replace` (section 18.8.4.4).

18.8.4.1 The std::regex_constants::match_flag_type flags

All overloaded `format` members and all regular expression matching functions accept a final `regex_constants::match_flag_type` argument, which is a bit-masked type, for which the `bit_or` operator can be used. All `format` members by default specify the argument `match_default`.

The `match_flag_type` enumeration defines the following values (below, '`[first, last)`' refers to the character sequence being matched).

- `format_default` (not a bit-mask value, but a default value which is equal to 0). With just this specification ECMAScript rules are used to construct strings in `std::regex_replace`;
- `format_first_only`: `std::regex_replace` only replaces the first match;
- `format_no_copy`: non-matching strings are not passed to the output by `std::regex_replace`;
- `format_sed`: POSIX **sed**(1) rules are used to construct strings in `std::regex_replace`;
- `match_any`: if multiple matches are possible, then any match is an acceptable result;
- `match_continuous`: sub-sequences are only matching if they start at `first`;
- `match_not_bol`: the first character in `[first, last)` is treated as an ordinary character: `^` does not match `[first, first)`;
- `match_not_bow`: `\b` does not match `[first, first)`;
- `match_default` (not a bit-mask value, but equal to 0): the default value of the final argument that's passed to the regular expression matching functions and `match_results::format` member. ECMAScript rules are used to construct strings in `std::regex_replace`;
- `match_not_eol`: the last character in `[first, last)` is treated as an ordinary character: `$` does not match `[last,last)`;

- `match_not_eow`: `\b` does not match `[last, last)`;
- `match_not_null`: empty sequences are not considered matches;
- `match_prev_avail`: `+NOTRANS(-{}-{})first` refers to a valid character position. When specified `match_not_bol` and `match_not_bow` are ignored;

18.8.4.2 Matching full texts: std::regex_match

The regular expression matching function `std::regex_match` returns `true` if the regular expression defined in its provided `regex` argument *fully* matches the provided target text. This means that `match_results::prefix` and `match_results::suffix` must return empty strings. But defining sub-expressions is OK.

The following overloaded variants of this function are available:

- `bool regex_match(BidirConstIter first, BidirConstIter last, std::match_results &results, std::regex const &re)`:
  `BidirConstIter` is a bidirectional const iterator. The range `[first, last)` defines the target text. The match results are returned in `results`. The types of the iterators must match the type of the `match_results` that's used. E.g., a `cmatch` should be used if the iterators are of `char const *` types, and a `smatch` should be used if the iterators are of `string::const_iterator` types. Similar correspondence requirements hold true for the other overloaded versions of this function;
- `bool regex_match(BidirConstIter first, BidirConstIter last, std::regex const &re)`:
  this function behaves like the previous function, but does not return the results of the matching process in a `match_results` object;
- `bool regex_match(char const *target, std::match_results &results, std::regex const &re)`:
  this function behaves like the first overloaded variant, using the characters in `target` as its target text;
- `bool regex_match(char const *str, std::regex const &re)`:
  this function behaves like the previous function but does not return the match results;
- `bool regex_match(std::string const &target, std::match_results &results, std::regex const &re)`:
  this function behaves like the first overloaded variant, using the characters in `target` as its target text;
- `bool regex_match(std::string const &str, std::regex const &re)`:
  this function behaves like the previous function but does not return the match results;
- `bool regex_match(std::string const &&, std::match_results &, std::regex &) = delete` (the `regex_match` function does not accept temporary `string` objects as target strings, as this would result in invalid string iterators in the `match_result` argument.)

Here is a small example: the regular expression matches the matched text (provided by `argv[1]`) if it starts with 5 digits and then merely contains letters (`[[:alpha:]]`). The digits can be retrieved as sub-expression 1:

```
#include <iostream>
#include <regex>
```

```
using namespace std;

int main(int argc, char const **argv)
{
    regex re("(\\d{5})[[:alpha:]]+");

    cmatch results;

    if (not regex_match(argv[1], results, re))
        cout << "No match\n";
    else
        cout << "size: " << results.size() << ": " <<
                results.str(1) << " -- " << results.str() << '\n';
}
```

18.8.4.3 Partially matching text: std::regex_search

Different from `regex_match` the regular expression matching function `std::regex_search` returns `true` if the regular expression defined in its `regex` argument partially matches the target text.

The following overloaded variants of this function are available:

- `bool regex_search(BidirConstIter first, BidirConstIter last, std::match_results &results, std::regex const &re)`:
  `BidirConstIter` is a bidirectional const iterator. The range `[first, last)` defines the target text. The match results are returned in `results`. The types of the iterators must match the type of the `match_results` that's used. E.g., a `cmatch` should be used if the iterators are of `char const *` types, and a `smatch` should be used if the iterators are of `string::const_iterator` types. Similar correspondence requirements hold true for the other overloaded versions of this function;
- `bool regex_search(BidirConstIter first, BidirConstIter last, std::regex const &re)`:
  this function behaves like the previous function, but does not return the results of the matching process in a `match_results` object;
- `bool regex_search(char const *target, std::match_results &results, std::regex const &re)`:
  this function behaves like the first overloaded variant, using the characters in `target` as its target text;
- `bool regex_search(char const *str, std::regex const &re)`:
  this function behaves like the previous function but does not return the match results;
- `bool regex_search(std::string const &target, std::match_results &results, std::regex const &re)`:
  this function behaves like the first overloaded variant, using the characters in `target` as its target text;
- `bool regex_search(std::string const &str, std::regex const &re)`:
  this function behaves like the previous function but does not return the match results;
- `bool regex_search(std::string const &&, std::match_results &, std::regex &) = delete`:

the `regex_search` function does not accept temporary `string` objects as target strings, as this would result in invalid string iterators in the `match_result` argument.

The following example illustrates how `regex_search` could be used:

```
#include <iostream>
#include <string>
#include <regex>

using namespace std;

int main()
{
    while (true)
    {
        cout << "Enter a pattern or plain Enter to stop: ";

        string pattern;
        if (not getline(cin, pattern) or pattern.empty())
            break;

        regex re(pattern);
        while (true)
        {
            cout << "Enter a target text for `" << pattern << "'\n"
                    "(plain Enter for the next pattern): ";

            string text;
            if (not getline(cin, text) or text.empty())
                break;

            smatch results;
            if (not regex_search(text, results, re))
                cout << "No match\n";
            else
            {
                cout << "Prefix: "  << results.prefix() << "\n"
                        "Match:  "  << results.str()    << "\n"
                        "Suffix: "  << results.suffix() << "\n";
                for (size_t idx = 1; idx != results.size(); ++idx)
                    cout << "Match " << idx << " at offset " <<
                                results.position(idx) << ": " <<
                                results.str(idx) << '\n';
            }
        }
    }
}
```

18.8.4.4 The member std::match_results::format

The `match_results::format` member is a rather complex member function of the class `match_results`, which can be used to modify text which was previously matched against a regular expression, e.g., using the function `regex_search`. Because of its complexity and because the functionality of another regular expression processing function (`regex_replace`) offers similar functionality it is discussed at this point in the **C++** Annotations, just before discussing the `regex_replace` function.

The `format` member operates on (sub-)matches contained in a `match_results` object, using a *format string*, and producing text in which format specifiers (like `$&`) are replaced by matching sections of the originally provided target text. In addition, the `format` member recognizes all standard **C** escape sequences (like `\n`). The `format` member is used to create text that is modified with respect to the original target text.

As a preliminary illustration: if `results` is a `match_results` object and `match[0]` (the fully matched text) equals '`hello world`', then calling `format` with the format string `this is [$&]` produces the text `this is [hello world]`. Note the specification `$&` in this format string: this is an example of a format specifier. Here is an overview of all supported format specifiers:

- `` $` ``: corresponds to the text returned by the `prefix` member: all characters in the original target text up to the first character of the fully matched text;
- `$&`: corresponds to the fully matched text (i.e., the text returned by the `match_results::str` member);
- `$n`: (where `n` is an integral natural number): corresponds to the text returned bu `operator[](n)`;
- `$'`: corresponds to the text returned by the `suffix` member: all characters in the original target string beyond the last character of the fully matched text;
- `$$`: corresponds to the single `$` character.

Four overloaded versions of the `format` members are available. All overloaded versions define a final `regex_constants::match_flag_type` parameter, which is by default initialized to `match_default`. This final parameter is not explicitly mentioned in the following coverage of the `format` members.

To further illustrate the way the `format` members can be used it is assumed that the following code has been executed:

```
 1:     regex re("([[:alpha:]]+)\\s+(\\d+)");  // letters blanks digits
 2:
 3:     smatch results;
 4:     string target("this value 1024 is interesting");
 5:
 6:     if (not regex_search(target, results, re))
 7:         return 1;
```

After calling `regex_search` (line 6) the results of the regular expression matching process are available in the `match_results results` object that is defined in line 3.

The first two overloaded `format` functions expect an output-iterator to where the formatted text is written. These overloaded members return the final output iterator, pointing just beyond the character that was last written.

- `OutputIter format(OutputIter out, char const *first, char const *last) const`:
  the characters in the range `[first, last)` are applied to the sub-expressions stored in the `match_results` object, and the resulting string is inserted at `out`. An illustration is provided with the next overloaded version;

- `OutputIter format(OutputIter out, std::string const &fmt) const`:
  the content of `fmt` is applied to the sub-expressions stored in the `match_results` object, and the resulting string is inserted at `out`. The next line of code inserts the value 1024 into `cout` (note that `fmt` *must* be a `std::string`, hence the explicit use of the `string` constructor):

  ```
  results.format(ostream_iterator<char>(cout, ""), "$2"s);
  ```

The remaining two overloaded `format` members expect a `std::string` or an NTBS defining the format string. Both members return a `std::string` containing the formatted text:

- `std::string format(std::string const &fmt) const`
- `std::string format(char const *fmt) const`

The next example shows how a `string` can be obtained in which the order of the first and second marked sub-expressions contained in the previously obtained `match_results` object have been swapped:

```
string reverse(results.format("$2 and $1"));
```

18.8.4.5 Modifying target strings: std::regex_replace

The family of `std::regex_replace` functions uses regular expressions to perform substitution on sequences of characters. Their functionality closely resembles the functionality of the `match_results::format` member discussed in the previous section. The following overloaded variants are available:

- `OutputIt regex_replace(OutputIter out, BidirConstIter first, BidirConstIter last, std::regex const &re, std::string const &fmt)`:
  `OutputIter` is an output iterator; `BidirConstIter` a bidirectional const iterator.

  The function returns the possibly modified text in an iterator range `[out, retvalue)`, where `out` is the output iterator passed as the first argument to `regex_replace`, and `retvalue` is the output iterator returned by `regex_replace`.

  The function matches the text at the range `[first, last)` against the regular expression stored in `re`. If the regular expression does *not* match the target text in the range `[first, last)` then the target text is literally copied to `out`. If the regular expression *does* match the target text then

  - first, the match result's prefix is copied to `out`. The prefix equals the initial characters of the target text up to the very first character of the fully matched text.
  - next, the matched text is replaced by the content of the `fmt` format string, in which the format specifiers can be used that were described in the previous section (section 18.8.4.4), and the replaced text is copied to `out`;
  - finally, the match result's suffix is copied to `out`. The suffix equals all characters of the target text beyond the last character of the matched text.

  The workings of `regex_replace` is illustrated in the next example:

  ```
  regex re("([[:alpha:]]+)\\s+(\\d+)");  // letters blanks digits

  string target("this value 1024 is interesting");

  regex_replace(ostream_iterator<char>(cout, ""), target.begin(),
                  target.end(), re, "$2"s);
  ```

In line 5 `regex_replace` is called. Its format string merely contains `$2`, matching 1024 in the target text. The prefix ends at the word `value`, the suffix starts beyond 1024, so the statement in line 5 inserts the text

```
this 1024 is interesting
```

into the standard output stream.

- `OutputIt regex_replace( OutputIter out, BidirConstIter first, BidirConstIter last, std::regex const &re, char const *fmt)`:
  This variant behaves like the first variant. When using, in the above example, `"$2"` instead of `"$2"s`, then this variant would have been used;
- `std::string regex_replace(std::string const &str, std::regex const &re, std::string const &fmt)`:
  This variant returns a `std::string` containing the modified text, and expects a `std::string` containing the target text. Other than that, it behaves like the first variant. To use this overloaded variant in the above example the statement in line 5 could have been replaced by the following statement, initializing the `string result`:

  ```
  string result(regex_replace(target, re, "$2"s));
  ```

- `std::string regex_replace(std::string const &str, std::regex const &re, char const *fmt)`:
  After changing, in the above statement, `"$2"s` into `"$2"`, this variant is used, behaving exactly like the previous variant;
- `std::string regex_replace(char const *str, std::regex const &re, std::string const &fmt)`:
  This variant uses a `char const *` to point to the target text, and behaves exactly like the previous but one variant;
- `std::string regex_replace(char const *str, std::regex const &re, char const *fmt)`:
  This variant also uses a `char const *` to point to the target text, and also behaves exactly like the previous but one variant;

18.9 Randomization and Statistical Distributions

Before the statistical distributions and accompanying random number generators can be used the `<random>` header file must be included.

The STL offers several standard mathematical (statistical) distributions. These distributions allow programmers to obtain randomly selected values from a selected distribution.

These statistical distributions need to be provided with a random number generating object. Several of such random number generating objects are provided, extending the traditional `rand` function that is part of the **C** standard library.

These random number generating objects produce pseudo-random numbers, which are then processed by the statistical distribution to obtain values that are randomly selected from the specified distribution.

Although the STL offers various statistical distributions their functionality is fairly limited. The distributions allow us to obtain a random number from these distributions, but probability density functions or cumulative distribution functions are currently not provided by the STL. These functions (distributions as well as the density and the cumulative distribution functions) are, however, available in other libraries, like the `boost math library`[4] (specifically: `http://www.boost.org/doc/libs/1_44_0/libs/math/doc/sf_and_dist/html/index.html`).

It is beyond the scope of the **C++** Annotations to discuss the mathematical characteristics of the various statistical distributions. The interested reader is referred to the pertinent mathematical textbooks (like Stuart and Ord's (2009) *Kendall's Advanced Theory of Statistics*, Wiley) or to web-locations like `http://en.wikipedia.org/wiki/Bernoulli_distribution`.

18.9.1 Random Number Generators

The following generators are available:

Class template	Integral/Floating point	Quality	Speed	Size of state
`linear_congruential_engine`	Integral	Medium	Medium	1
`subtract_with_carry_engine`	Both	Medium	Fast	25
`mersenne_twister_engine`	Integral	Good	Fast	624

The `linear_congruential_engine` random number generator computes

$$\texttt{value}_{i+1} = (+\texttt{a} * \texttt{value}_{i} + \texttt{c}+) \ \% \ \texttt{m}$$

It expects template arguments for, respectively, the data type to contain the generated random values; the multiplier `a`; the additive constant `c`; and the modulo value `m`. Example:

```
linear_congruential_engine<int, 10, 3, 13> lincon;
```

The `linear_congruential` generator may be seeded by providing its constructor with a seeding-argument. E.g., `lincon(time(0))`.

The `subtract_with_carry_engine` random number generator computes

$$\texttt{value}_{i} = (\texttt{value}_{i-s} - \texttt{value}_{i-r} - \texttt{carry}_{i-1}) \ \% \ \texttt{m}$$

It expects template arguments for, respectively, the data type to contain the generated random values; the modulo value `m`; and the subtractive constants `s` and `r`. Example:

```
subtract_with_carry_engine<int, 13, 3, 13> subcar;
```

The `subtract_with_carry_engine` generator may be seeded by providing its constructor with a seeding-argument. E.g., `subcar(time(0))`.

The predefined `mersenne_twister_engine mt19937` (predefined using a `typedef` defined by the `<random>` header file) is used in the examples below. It can be constructed using '`mt19937 mt`' or it can be seeded by providing its constructor with an argument (e.g., `mt19937 mt(time(0))`). Its function call operator returns a random unsigned integral value.

Other ways to initialize the `mersenne_twister_engine` are beyond the scope of the **C++** Annotations (but see Lewis *et al.*[5] (1969)).

---

[4] http://www.boost.org/

[5] Lewis, P.A.W., Goodman, A.S., and Miller, J.M. (1969), A pseudorandom number generator for the System/360, IBM Systems Journal, 8, 136-146.

The random number generators may also be seeded by calling their members `seed` accepting `unsigned long` values or generator functions (as in `lc.seed(time(0)), lc.seed(mt)`).

The random number generators offer members `min` and `max` returning, respectively, their minimum and maximum values (inclusive). If a reduced range is required the generators can be nested in a function or class adapting the range.

Here's a small example showing how the `mersenne_twister_engine mt19937` can be used to generate random numbers:

```
#include <iostream>
#include <ctime>
#include <random>

using namespace std;

    // arguments: 1st: number of random numbers to generate
    //            2nd: lowest positve random number,
    //            3rd: highest positive random number

int main(int argc, char **argv)
{
    mt19937 mt( time(0) );      // seed with the current time in secs.

    for (
        size_t nGenerate = stoul(argv[1]), lowest = stoul(argv[2]),
                                           mod = stoul(argv[3]) + 1 - lowest;
            nGenerate--;
    )
        cout << (lowest + mt() % mod) << ' ';

    cout << '\n';
}
```

18.9.2 Statistical distributions

In the following sections the various statistical distributions that are supported by **C++** are covered. The notation `RNG` is used to indicate a *Random Number Generator* and `URNG` is used to indicate a *Uniform Random Number Generator*. With each distribution a `struct param_type` is defined containing the distribution's parameters. The organization of these `param_type` structs depends on (and is described at) the actual distribution.

All distributions offer the following members (*result_type* refers to the type name of the values returned by the distribution):

- `result_type max() const`
  returns the distribution's least upper bound;
- `result_type min() const`
  returns the distribution's greatest lower bound;
- `param_type param() const`
  returns the object's `param_type` struct;
- `void param(const param_type &param)` redefines the parameters of the distribution;

- `void reset()`: clears all of its cached values;

All distributions support the following operators (*distribution-name* should be replaced by the name of the intended distribution, e.g., `normal_distribution`):

- `template<typename URNG> result_type operator()(URNG &urng)` returns the next random value from the statistical distribution, with the function object `urng` returning the next random number selected from a uniform random distribution;
- `template<typename URNG> result_type operator() (URNG &urng, param_type &param)` returns the next random value from the statistical distribution initialized with the parameters provided by the `param` struct. The function object `urng` returns the next random number selected from a uniform random distribution;
- `std::istream &operator>>(std::istream &in, distribution-name &object)`: The parameters of the distribution are extracted from an `std::istream`;
- `std::ostream &operator<<(std::ostream &out, distribution-name const &bd)`: The parameters of the distribution are inserted into an `std::ostream`

The following example shows how the distributions can be used. Replacing the name of the distribution (`normal_distribution`) by another distribution's name is all that is required to switch distributions. All distributions have parameters, like the mean and standard deviation of the normal distribution, and all parameters have default values. The names of the parameters vary over distributions and are mentioned below at the individual distributions. Distributions offer members returning or setting their parameters.

Most distributions are defined as class templates, requiring the specification of a data type that is used for the function's return type. If so, an empty template parameter type specification (<>) will get you the default type. The default types are either `double` (for real valued return types) or `int` (for integral valued return types). The template parameter type specification must be omitted with distributions that are not defined as template classes.

Here is an example showing the use of the statistical distributions, applied to the normal distribution:

```
#include <iostream>
#include <ctime>
#include <random>
using namespace std;

int main()
{
    std::mt19937 engine(time(0));
    std::normal_distribution<> dist;

    for (size_t idx = 0; idx < 10; ++idx)
        std::cout << "a random value: " << dist(engine) << "\n";

    cout << '\n' <<
        dist.min() << " " << dist.max() << '\n';
}
```

18.9.2.1 Bernoulli distribution

The `bernoulli_distribution` is used to generate logical truth (boolean) values with a certain probability `p`. It is equal to a binomial distribution for one experiment (cf 18.9.2.2).

The bernoulli distribution is *not* defined as a class template.

Defined types:

```
typedef bool result_type;
struct param_type
{
  explicit param_type(double prob = 0.5);
  double p() const;                      // returns prob
};
```

Constructor and members:

- `bernoulli_distribution(double prob = 0.5)`
  constructs a bernoulli distribution with probability `prob` of returning `true`;
- `double p() const`
  returns `prob`;
- `result_type min() const`
  returns `false`;
- `result_type max() const`
  returns `true`;

18.9.2.2 Binomial distribution

The `binomial_distribution<IntType = int>` is used to determine the probability of the number of successes in a sequence of `n` independent success/failure experiments, each of which yields success with probability `p`.

The template type parameter `IntType` defines the type of the generated random value, which must be an integral type.

Defined types:

```
typedef IntType result_type;
struct param_type
{
  explicit param_type(IntType trials, double prob = 0.5);
  IntType t() const;                     // returns trials
  double p() const;                      // returns prob
};
```

Constructors and members and example:

- `binomial_distribution<>(IntType trials = 1, double prob = 0.5)` constructs a binomial distribution for `trials` experiments, each having probability `prob` of success.
- `binomial_distribution<>(param_type const &param)` constructs a binomial distribution according to the values stored in the `param` struct.

- `IntType t() const`
  returns `trials`;

- `double p() const`
  returns `prob`;

- `result_type min() const`
  returns 0;

- `result_type max() const`
  returns `trials`;

18.9.2.3 Cauchy distribution

The `cauchy_distribution<RealType = double>` looks similar to a normal distribution. But cauchy distributions have heavier tails. When studying hypothesis tests that assume normality, seeing how the tests perform on data from a Cauchy distribution is a good indicator of how sensitive the tests are to heavy-tail departures from normality.

The mean and standard deviation of the Cauchy distribution are undefined.

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType a = RealType(0),
                        RealType b = RealType(1));

    double a() const;
    double b() const;
};
```

Constructors and members:

- `cauchy_distribution<>(RealType a = RealType(0), RealType b = RealType(1))` constructs a cauchy distribution with specified `a` and `b` parameters.

- `cauchy_distribution<>(param_type const &param)` constructs a cauchy distribution according to the values stored in the `param` struct.

- `RealType a() const`
  returns the distribution's `a` parameter;

- `RealType b() const`
  returns the distribution's `b` parameter;

- `result_type min() const`
  returns the smallest positive `result_type` value;

- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.4 Chi-squared distribution

The `chi_squared_distribution<RealType = double>` with `n` degrees of freedom is the distribution of a sum of the squares of `n` independent standard normal random variables.

Note that even though the distribution's parameter `n` usually is an integral value, it doesn't have to be integral, as the chi_squared distribution is defined in terms of functions (`exp` and `Gamma`) that take real arguments (see, e.g., the formula shown in the `<bits/random.h>` header file, provided with the GNU `g++` compiler distribution).

The chi-squared distribution is used, e.g., when testing the goodness of fit of an observed distribution to a theoretical one.

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType n = RealType(1));

    RealType n() const;
};
```

Constructors and members:

- `chi_squared_distribution<>(RealType n = 1)` constructs a chi_squared distribution with specified number of degrees of freedom.
- `chi_squared_distribution<>(param_type const &param)` constructs a chi_squared distribution according to the value stored in the `param` struct;
- `IntType n() const`
  returns the distribution's degrees of freedom;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.5 Extreme value distribution

The `extreme_value_distribution<RealType = double>` is related to the Weibull distribution and is used in statistical models where the variable of interest is the minimum of many random factors, all of which can take positive or negative values.

It has two parameters: a location parameter `a` and scale parameter `b`. See also
`http://www.itl.nist.gov/div898/handbook/apr/section1/apr163.htm`

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType a = RealType(0),
                        RealType b = RealType(1));

    RealType a() const;     // the location parameter
    RealType b() const;     // the scale parameter
};
```

Constructors and members:

- `extreme_value_distribution<>(RealType a = 0, RealType b = 1)` constructs an extreme value distribution with specified `a` and `b` parameters;
- `extreme_value_distribution<>(param_type const &param)` constructs an extreme value distribution according to the values stored in the `param` struct.
- `RealType a() const`
  returns the distribution's location parameter;
- `RealType stddev() const`
  returns the distribution's scale parameter;
- `result_type min() const`
  returns the smallest positive value of `result_type`;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.6 Exponential distribution

The `exponential_distribution<RealType = double>` is used to describe the lengths between events that can be modeled with a homogeneous Poisson process. It can be interpreted as the continuous form of the geometric distribution.

Its parameter `prob` defines the distribution's *lambda* parameter, called its *rate* parameter. Its expected value and standard deviation are both `1 / lambda`.

Defined types:

```
    typedef RealType result_type;

    struct param_type
    {
        explicit param_type(RealType lambda = RealType(1));

        RealType lambda() const;
    };
```

Constructors and members:

- `exponential_distribution<>(RealType lambda = 1)` constructs an exponential distribution with specified `lambda` parameter.
- `exponential_distribution<>(param_type const &param)` constructs an exponential distribution according to the value stored in the `param` struct.
- `RealType lambda() const`
  returns the distribution's `lambda` parameter;

- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.7 Fisher F distribution

The `fisher_f_distribution<RealType = double>` is intensively used in statistical methods like the Analysis of Variance. It is the distribution resulting from dividing two *Chi-squared* distributions.

It is characterized by two parameters, being the degrees of freedom of the two chi-squared distributions.

Note that even though the distribution's parameter `n` usually is an integral value, it doesn't have to be integral, as the Fisher F distribution is constructed from Chi-squared distributions that accept a non-integral parameter value (see also section 18.9.2.4).

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType m = RealType(1),
                        RealType n = RealType(1));

    RealType m() const; // The degrees of freedom of the nominator
    RealType n() const; // The degrees of freedom of the denominator
};
```

Constructors and members:

- `fisher_f_distribution<>(RealType m = RealType(1), RealType n = RealType(1))` constructs a fisher_f distribution with specified degrees of freedom.
- `fisher_f_distribution<>(param_type const &param)` constructs a fisher_f distribution according to the values stored in the `param` struct.
- `RealType m() const`
  returns the degrees of freedom of the nominator;
- `RealType n() const`
  returns the degrees of freedom of the denominator;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.8 Gamma distribution

The `gamma_distribution<RealType = double>` is used when working with data that are not distributed according to the normal distribution. It is often used to model waiting times.

It has two parameters, `alpha` and `beta`. Its expected value is `alpha * beta` and its standard deviation is `alpha * beta`^{2}.

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType alpha = RealType(1),
                        RealType beta = RealType(1));

    RealType alpha() const;
    RealType beta() const;
};
```

Constructors and members:

- `gamma_distribution<>(RealType alpha = 1, RealType beta = 1)` constructs a gamma distribution with specified `alpha` and `beta` parameters.
- `gamma_distribution<>(param_type const &param)` constructs a gamma distribution according to the values stored in the `param` struct.
- `RealType alpha() const`
  returns the distribution's `alpha` parameter;
- `RealType beta() const`
  returns the distribution's `beta` parameter;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.9 Geometric distribution

The `geometric_distribution<IntType = int>` is used to model the number of bernoulli trials (cf. 18.9.2.1) needed until the first success.

It has one parameter, `prob`, representing the probability of success in an individual bernoulli trial.

Defined types:

```
typedef IntType result_type;

struct param_type
{
    explicit param_type(double prob = 0.5);
    double p() const;
};
```

Constructors, members and example:

- `geometric_distribution<>(double prob = 0.5)` constructs a geometric distribution for bernoulli trials each having probability `prob` of success.

- `geometric_distribution<>(param_type const &param)` constructs a geometric distribution according to the values stored in the `param` struct.
- `double p() const`
  returns the distribution's `prob` parameter;
- `param_type param() const`
  returns the object's `param_type` structure;
- `void param(const param_type &param)` redefines the parameters of the distribution;
- `result_type min() const`
  returns the distribution's lower bound (= `0`);
- `result_type max() const`
  returns the distribution's upper bound;
- `template<typename URNG> result_type operator()(URNG &urng)`
  returns the next random value from the geometric distribution
- `template<typename URNG> result_type operator()`
  `(URNG &urng, param_type &param)`
  returns the next random value from a geometric distribution initialized by the provided `param` struct.
- The random number generator that is passed to the generating functions must return integral values. Here is an example showing how the geometric distribution can be used:

```
#include <iostream>
#include <ctime>
#include <random>

int main()
{
    std::linear_congruential_engine<unsigned, 7, 3, 61> engine(0);

    std::geometric_distribution<> dist;

    for (size_t idx = 0; idx < 10; ++idx)
        std::cout << "a random value: " << dist(engine) << "\n";

    std::cout << '\n' <<
        dist.min() << " " << dist.max() << '\n';

}
```

18.9.2.10 Log-normal distribution

The `lognormal_distribution<RealType = double>` is a probability distribution of a random variable whose logarithm is normally distributed. If a random variable `X` has a normal distribution, then `Y = e`^{X} has a log-normal distribution.

It has two parameters, *m* and *s* representing, respectively, the mean and standard deviation of `ln(X)`.

Defined types:

```
typedef RealType result_type;
```

```
struct param_type
{
    explicit param_type(RealType m = RealType(0),
                        RealType s = RealType(1));

    RealType m() const;
    RealType s() const;
};
```

Constructor and members:

- `lognormal_distribution<>(RealType m = 0, RealType s = 1)` constructs a log-normal distribution for a random variable whose mean and standard deviation is, respectively, `m` and `s`.
- `lognormal_distribution<>(param_type const &param)` constructs a log-normal distribution according to the values stored in the `param` struct.
- `RealType m() const`
  returns the distribution's `m` parameter;
- `RealType stddev() const`
  returns the distribution's `s` parameter;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.11 Normal distribution

The `normal_distribution<RealType = double>` is commonly used in science to describe complex phenomena. When predicting or measuring variables, errors are commonly assumed to be normally distributed.

It has two parameters, *mean* and *standard deviation*.

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType mean = RealType(0),
                        RealType stddev = RealType(1));

    RealType mean() const;
    RealType stddev() const;
};
```

Constructors and members:

- `normal_distribution<>(RealType mean = 0, RealType stddev = 1)` constructs a normal distribution with specified `mean` and `stddev` parameters. The default parameter values define the *standard normal distribution*;

- `normal_distribution<>(param_type const &param)` constructs a normal distribution according to the values stored in the `param` struct.
- `RealType mean() const`
  returns the distribution's `mean` parameter;
- `RealType stddev() const`
  returns the distribution's `stddev` parameter;
- `result_type min() const`
  returns the lowest positive value of `result_type`;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.12 Negative binomial distribution

The `negative_binomial_distribution<IntType = int>` probability distribution describes the number of successes in a sequence of Bernoulli trials before a specified number of failures occurs. For example, if one throws a die repeatedly until the third time 1 appears, then the probability distribution of the number of other faces that have appeared is a negative binomial distribution.

It has two parameters: (`IntType`) k (> 0), being the number of failures until the experiment is stopped and (`double`) p the probability of success in each individual experiment.

Defined types:

```
typedef IntType result_type;

struct param_type
{
    explicit param_type(IntType k = IntType(1), double p = 0.5);

    IntType k() const;
    double p() const;
};
```

Constructors and members:

- `negative_binomial_distribution<>(IntType k = IntType(1), double p = 0.5)`
  constructs a negative_binomial distribution with specified `k` and `p` parameters;
- `negative_binomial_distribution<>(param_type const &param)` constructs a negative_binomial distribution according to the values stored in the `param` struct.
- `IntType k() const`
  returns the distribution's `k` parameter;
- `double p() const`
  returns the distribution's `p` parameter;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.13 Poisson distribution

The `poisson_distribution<IntType = int>` is used to model the probability of a number of events occurring in a fixed period of time if these events occur with a known probability and independently of the time since the last event.

It has one parameter, `mean`, specifying the expected number of events in the interval under consideration. E.g., if on average 2 events are observed in a one-minute interval and the duration of the interval under study is 10 minutes then `mean = 20`.

Defined types:

```
typedef IntType result_type;

struct param_type
{
    explicit param_type(double mean = 1.0);

    double mean() const;
};
```

Constructors and members:

- `poisson_distribution<>(double mean = 1)` constructs a poisson distribution with specified `mean` parameter.
- `poisson_distribution<>(param_type const &param)` constructs a poisson distribution according to the values stored in the `param` struct.
- `double mean() const`
  returns the distribution's `mean` parameter;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.14 Student t distribution

The `student_t_distribution<RealType = double>` is a probability distribution that is used when estimating the mean of a normally distributed population from small sample sizes.

It is characterized by one parameter: the degrees of freedom, which is equal to the sample size - 1.

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType n = RealType(1));

    RealType n() const;    // The degrees of freedom
};
```

Constructors and members:

- `student_t_distribution<>(RealType n = RealType(1))` constructs a student_t distribution with indicated degrees of freedom.
- `student_t_distribution<>(param_type const &param)` constructs a student_t distribution according to the values stored in the `param` struct.
- `RealType n() const`
  returns the degrees of freedom;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.9.2.15 Uniform int distribution

The `uniform_int_distribution<IntType = int>` can be used to select integral values randomly from a range of uniformly distributed integral values.

It has two parameters, `a` and `b`, specifying, respectively, the lowest value that can be returned and the highest value that can be returned.

Defined types:

```
typedef IntType result_type;

struct param_type
{
    explicit param_type(IntType a = 0, IntType b = max(IntType));

    IntType a() const;
    IntType b() const;
};
```

Constructors and members:

- `uniform_int_distribution<>(IntType a = 0, IntType b = max(IntType))` constructs a uniform_int distribution for the specified range of values.
- `uniform_int_distribution<>(param_type const &param)` constructs a uniform_int distribution according to the values stored in the `param` struct.
- `IntType a() const`
  returns the distribution's `a` parameter;
- `IntType b() const`
  returns the distribution's `b` parameter;
- `result_type min() const`
  returns the distribution's `a` parameter;
- `result_type max() const`
  returns the distribution's `b` parameter;

18.9.2.16 Uniform real distribution

The `uniform_real_distribution<RealType = double>` can be used to select `RealType` values randomly from a range of uniformly distributed `RealType` values.

It has two parameters, `a` and `b`, specifying, respectively, the half-open range of values (`[a, b)`) that can be returned by the distribution.

Defined types:

```
typedef RealType result_type;

struct param_type
{
    explicit param_type(RealType a = 0, RealType b = max(RealType));

    RealType a() const;
    RealType b() const;
};
```

Constructors and members:

- `uniform_real_distribution<>(RealType a = 0, RealType b = max(RealType))` constructs a uniform_real distribution for the specified range of values.
- `uniform_real_distribution<>(param_type const &param)` constructs a uniform_real distribution according to the values stored in the `param` struct.
- `RealType a() const`
  returns the distribution's `a` parameter;
- `RealType b() const`
  returns the distribution's `b` parameter;
- `result_type min() const`
  returns the distribution's `a` parameter;
- `result_type max() const`
  returns the distribution's `b` parameter;

18.9.2.17 Weibull distribution

The `weibull_distribution<RealType = double>` is commonly used in reliability engineering and in survival (life data) analysis.

It has two or three parameters and the two-parameter variant is offered by the STL. The three parameter variant has a shape (or slope) parameter, a scale parameter and a location parameter. The two parameter variant implicitly uses the location parameter value 0. In the two parameter variant the shape parameter (a) and the scale parameter (b) are provided. See `http://www.weibull.com/hotwire/issue14/relbasics14.htm` for an interesting coverage of the meaning of the Weibull distribution's parameters.

Defined types:

```
typedef RealType result_type;
```

```
struct param_type
{
    explicit param_type(RealType a = RealType{ 1 },
                        RealType b = RealType{ 1 });

    RealType a() const;      // the shape (slope) parameter
    RealType b() const;      // the scale parameter
};
```

Constructors and members:

- `weibull_distribution<>(RealType a = 1, RealType b = 1)` constructs a weibull distribution with specified `a` and `b` parameters;
- `weibull_distribution<>(param_type const &param)` constructs a weibull distribution according to the values stored in the `param` struct.
- `RealType a() const`
  returns the distribution's shape (or slope) parameter;
- `RealType stddev() const`
  returns the distribution's scale parameter;
- `result_type min() const`
  returns 0;
- `result_type max() const`
  returns the maximum value of `result_type`;

18.10 tie

We already encountered *structured bindings* in section 3.3.7.1. Structured bindings allow us to access the fields of structured types (like `structs, std::pair` or (cf. section 22.6) `tuples`) as local variables inside functions. A basic example using structured bindings is shown in the following code snippet:

```
pair<int, int> factory()
{
    return { 1, 2 };
}

void fun()
{
    auto [one, two] = factory();

    cout << one << ' ' << two << '\n';
}
```

Being able to use structured bindings is very useful in cases like these.

But what if we want to assign the fields of a struct to variables that have already been defined or that were passed to a function via its parameters? In those situations structured bindings offer no help. E.g., in the following code snippet a function `retrieve` is defined having an `int &` parameter and an `int` local variable and we want to assign the values returned by `factory` to those variables:

```
void retrieve(int &one)
{
    int two;
    // ...  = factory() ??
}
```

Structured bindings cannot be used here: the elements of structured bindings cannot be references. Although it *is* possible to define a `std::pair<int &, int &>` such an object cannot be initialized with the references of `one` and `two` which are directly referring to the fields returned by `factory`. These statements won't compile:

```
pair<int &, int &> p{one, two} = factory();
pair<int &, int &>{one, two} = factory();
```

While it is possible to first define a `pair<int &, int &>` object and then assign `factory's` return value to it, that approach clearly is less elegant than what's offered by structured bindings:

```
pair<int &, int &> p{one, two};
p = factory();
```

Fortunately, there is a better alternative. After including the `<tuple>` header file (see also section 22.6) `std::tie` is available allowing us to 'tie' references to fields of structured data types. Using `std::tie` it is very easy to associate the variables `one` and `two` of the function `retrieve` with the fields of the pair returned by `factory`:

```
void retrieve(int &one)
{
    int two;

    tie(one, two) = factory();

    cout << one << ' ' << two << '\n';
}
```

When Executing these statements:

```
int one = 0;
int two = 0;

cout << one << ' ' << two << '\n';

retrieve(one);

cout << one << ' ' << two << '\n';
```

the following output is obtained:

```
0 0
1 2
1 0
```

In addition to the above the `std::tie` function also supports ordering and (in)equality comparisons. The `struct Data` in the next example defines three fields: an `int`, a `std::string` and a `double`.

Each of these fields support ordering and (in)equality comparisons. In those cases, all comparison operators can easily be implemented through the spaceship operator (cf. section 11.6.2) using `std::tie`:

```
struct Data
{
    int d_int;
    string d_string;
    double d_double;
};


bool operator==(Data const &lhs, Data const &rhs)
{
    return tie(lhs.d_int, lhs.d_string, lhs.d_double) ==
           tie(rhs.d_int, rhs.d_string, rhs.d_double);
}

partial_ordering operator<=>(Data const &lhs, Data const &rhs)
{
    return tie(lhs.d_int, lhs.d_string, lhs.d_double) <=>
           tie(rhs.d_int, rhs.d_string, rhs.d_double);
}
```

Note that `struct Data's` spaceship operator returns `partial_ordering` values (cf. section 18.7.3). Although `int` and `std::string's` spaceship operators return `strong_ordering` values, `double's` spaceship operator doesn't. Instead it returns `partial_ordering` values. Consequently, `struct Data's` spaceship operator also returns `partial_ordering` values.

18.11 Optional return values

In order to use `std::optional` objects the `<optional>` header file must be included.

Consider a function returning subsequent lines from a stream. That function could be a member function reading from a stream which was opened by its object. A first implementation of such a member function could be

```
std::string Class::nextLine()
{
    string line;
    getline(d_stream, line);
    return line;
}
```

Of course, this implementation is sub-optimal as `getline` may fail.

Common ways to handle failures in these situations are

- the functions return pointers to strings, which are 0 when `getline` fails, and point to strings containing the lines if `getline` succeeds;
- the functions return bools and define string pointers or reference parameters: the functions' return values indicate whether or not `getline` succeeded;

- the functions return `std::pair` or `std::tuple` objects of which one field is a `bool` and the other field is a `std::string`.

The standard template library offers yet another way to handle situations like these: the template class

```
template <typename DataType>
class optional;
```

Here, `DataType` refers to the name of the data type that is handled by the `optional` class. Instead of returning a `std::string` the function `nextLine` may specify a `std::optional<std::string>` return type: `std::optional<std::string> Class::nextLine()`.

The interpretation of `std::optional` objects is simple: either it contains an object of its `DataType` or it doesn't. If it *does* contain a `DataType` object then that object is available as object instead of a pointer to an object (which might have been dynamically allocated) of the specified `DataType`. At the same type the `optional` object can be interpreted as a `bool`. If the `optional` object contains a `DataType` object the `optional's bool` value is `true`. If it doesn't contain a `DataType` value, then its `bool` value is `false`.

The class `std::optional` offers the following facilities:

- Constructors:
  The default constructor (e.g., `std::optional<std::string> opt;`) does not contain a value;
  Copy- and move constructors are available;
  Objects may be constructed from values that are convertible to the optional's `DataType` (e.g., an `optional<string>` can be initialized from a NTBS). If the initializing value is an rvalue reference then the `DataType` object is move-constructed from the initializing value;

- `operator=`
  The assignment operator can be used to reassign the `DataType` values of `optional` objects or to reassign the `optional` objects from another `optional` object using the same `DataType`. Copy- and move-assignment operators are available;

- Accessors:
  `explicit operator bool()` and the `has_value()` members return `true` if the `optional` object contains a `DataType` value;
  `value(), operator*(),` and `operator->()` return references to the optional's `DataType` value. The reference is a `const` reference if called from an `optional<DataType> const` object; it is an rvalue-reference if called from an rvalue reference to an `optional<DataType>` object. Notes:

  - the `operator*` and `operator->` members act like `value`, but do not imply that the `optional's DataType` member itself is stored as a pointer.
  - `value()` checks whether the `optional` object actually contains a `DataType` object, and throws a `std::bad_optional_access` exception if not.

  `value_or(Type &&defaultValue)` returns a copy of the `optional` object's `DataType` if the object contains a value or returns `DataType{ defaultValue }` if not. Note that `DataType` must be constructible from `Type`;

- Modifiers:
  `swap(optional<DataType> &other)`: swaps the current and other `optional` objects' content.
  `reset()`: erases the `optional's DataType` member. Following `reset() has_value()` returns `false`.

`emplace(Args &&...args)`, `emplace(initialize_list, Args &&...args)`: the first `emplace` forwards `args` to `DataType's` constructor; the second `emplace` forwards `args` to the initializer_list, and forwards that list to `DataType's` constructor;

- Comparison operators:
  All comparison operators (including `operator<=>`) are available (if defined for the `optional's DataType`) to compare the `DataType` objects of two `optional` objects;

- `std::optional<DataType> make_optional(...)`
  returns an `optional` object constructed from a `DataType` lvalue or rvalue reference, or constructed from the same arguments that are accepted by `emplace`.

Here is the implementation of a function `nextLine`, using `std::optional<std::string>` and a simple `main` function illustrating its workings:

```
#include <iostream>
#include <sstream>
#include <string>
#include <optional>

using namespace std;

optional<string> nextLine(istream &in)
{
    std::optional<std::string> opt;

    string line;
    if (getline(in, line))
        opt = move(line);

    cout << "internal: has value: " << opt.has_value() <<
                                ", value = " << *opt << '\n';
    return opt;
}

int main()
{
    istringstream in{ "hello world\n" };

    auto opt = nextLine(in);

    cout << "main:     has value: " << opt.has_value() <<
                                ", value = " << *opt << '\n';
    opt = nextLine(in);

    cout << "main:     has value: " << opt.has_value() <<
                                ", value = " << *opt << '\n';
}
```

The ouput of this program is:

```
internal: has value: 1, value = hello world
main:     has value: 1, value = hello world
internal: has value: 0, value =
main:     has value: 0, value = hello world
```

Note that after the 2nd call, when no value is returned, `opt` has kept the value it received at the first call: `optional's` assignment operator doesn't bother about values already present in their objects once it notices that `has_value` will return `false`. So be sure to inspect `has_value` or `operator bool` before calling `value`.

Chapter 19

The STL Generic Algorithms

19.1 The Generic Algorithms

Before using the generic algorithms presented in this chapter, except for those in the `Operators` category (defined below), the `<algorithm>` header file must be included. Before using a generic algorithm in the `Operators` category the `<numeric>` header file must be included.

In the previous chapter the Standard Template Library (STL) was introduced. An important element of the STL, the *generic algorithms*, was not covered in that chapter as they form a fairly extensive part of the STL. Over time the STL has grown considerably, mainly as a result of a growing importance and appreciation of *templates*. Covering generic algorithm in the STL chapter itself would turn that chapter into an unwieldy one and so the generic algorithms were moved to a chapter of their own.

Generic algorithms perform an amazing task. Due to the strength of templates, algorithms could be developed that can be applied to a wide range of different data types while maintaining type safety. The prototypical example of this is the `sort` generic algorithm. To contrast: while **C** requires programmers to write callback functions in which type-unsafe `void const *` parameters have to be used, internally forcing the programmer to resort to casts, STL's `sort` frequently allows the programmer merely to state something akin to

```
sort(first-element, last-element)
```

Generic algorithms should be used wherever possible. Avoid the urge to design your own code for commonly encountered algorithms. Make it a habit to *first* thoroughly search the generic algorithms for an available candidate. The generic algorithms should become your *weapon of choice* when writing code: acquire full familiarity with them and make their use your 'second nature'.

This chapter's sections cover the STL's generic algorithms in alphabetical order. For each algorithm the following information is provided:

- The required header file;
- The function prototype;
- A short description;
- A short example.

In the prototypes of the algorithms `Type` is used to specify a generic data type. Furthermore, the particular type of iterator (see section 18.2) that is required is mentioned as well as other generic types that might be required (e.g., performing `BinaryOperations`, like `plus<Type>`). Although iterators are commonly provided by abstract containers and comparable pre-defined data structures, at some point you may want to design your own iterators. Section 22.14 offers guidelines for constructing your own iterator classes and provides an overview of of operators that must be implemented for the various types of iterators.

Almost every generic algorithm expects an iterator range `[first, last)`, defining the series of elements on which the algorithm operates. The iterators point to objects or values. When an iterator points to a `Type` value or object, function objects used by the algorithms usually receive `Type const &` objects or values. Usually function objects cannot modify the objects they receive as their arguments. This does not hold true for *modifying generic algorithms*, which *are* of course able to modify the objects they operate upon.

Generic algorithms may be categorized. The **C++** Annotations distinguishes the following categories of generic algorithms:

- Comparators: comparing (ranges of) elements:

  equal; includes; lexicographical_compare; max; min; mismatch;

- Copiers: performing copy operations:

  copy; copy_backward; partial_sort_copy; remove_copy; remove_copy_if; replace_copy; replace_copy_if; reverse_copy; rotate_copy; unique_copy;

- Counters: performing count operations:

  count; count_if;

- Heap operators: manipulating a max-heap:

  make_heap; pop_heap; push_heap; sort_heap;

- Initializers: initializing data:

  fill; fill_n; generate; generate_n;

- Operators: performing arithmetic operations of some sort:

  accumulate; adjacent_difference; inner_product; partial_sum;

- Searchers: performing search (and find) operations:

  adjacent_find; binary_search; equal_range; find; find_end; find_first_of; find_if; lower_bound; max_element; min_element; search; search_n; set_difference; set_intersection;
  set_symmetric_difference; set_union; upper_bound;

- Shufflers: performing reordering operations (sorting, merging, permuting, swapping):

  inplace_merge; iter_swap; merge; next_permutation; nth_element; partial_sort; partial_sort_copy; partition; prev_permutation; remove; remove_copy; remove_copy_if; remove_if; reverse; reverse_copy; rotate; rotate_copy; sort; stable_partition; stable_sort; swap; unique;

- Visitors: visiting elements in a range:

  for_each; replace; replace_copy; replace_copy_if; replace_if; transform; unique_copy;

19.1.1 accumulate

- Header file: `<numeric>`
- Function prototypes:
  - `Type accumulate(InputIterator first, InputIterator last, Type init);`
  - `Type accumulate(InputIterator first, InputIterator last, Type init, BinaryOperation op);`
- Description:
  - The first prototype: `operator+` is applied to all elements implied by the iterator range and to the initial value `init`. The resulting value is returned.
  - The second prototype: the binary operator `op` is applied to all elements implied by the iterator range and to the initial value `init`, and the resulting value is returned.
- Example:

```
#include <numeric>
#include <vector>
#include <iostream>
using namespace std;

int main()
{
    int         ia[] = {1, 2, 3, 4};
    vector<int> iv(ia, ia + 4);

    cout <<
        "Sum of values: " << accumulate(iv.begin(), iv.end(), int()) <<
        "\n"
        "Product of values: " << accumulate(iv.begin(), iv.end(), int(1),
                                        multiplies<int>()) << '\n';
}
/*
    Displays:
        Sum of values: 10
        Product of values: 24
*/
```

19.1.2 adjacent_difference

- Header file: `<numeric>`
- Function prototypes:
  - `OutputIterator adjacent_difference(InputIterator first, InputIterator last, OutputIterator result);`
  - `OutputIterator adjacent_difference(InputIterator first, InputIterator last, OutputIterator result, BinaryOperation op);`
- Description: All operations are performed on the original values, all computed values are returned values.
  - The first prototype: the first returned element is equal to the first element of the input range. The remaining returned elements are equal to the difference of the corresponding element in the input range and its previous element.

  - The second prototype: the first returned element is equal to the first element of the input range. The remaining returned elements are equal to the result of the binary operator `op` applied to the corresponding element in the input range (left operand) and its previous element (right operand).

- Example:

```
#include <numeric>
#include <vector>
#include <iterator>
#include <iostream>
using namespace std;

int main()
{
    int             ia[] = {1, 2, 5, 10};
    vector<int>     iv(ia, ia + 4);
    vector<int>     ov(iv.size());

    adjacent_difference(iv.begin(), iv.end(), ov.begin());

    copy(ov.begin(), ov.end(), ostream_iterator<int>(cout, " "));
    cout << '\n';

    adjacent_difference(iv.begin(), iv.end(), ov.begin(), minus<int>());

    copy(ov.begin(), ov.end(), ostream_iterator<int>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        1 1 3 5
        1 1 3 5
*/
```

19.1.3 adjacent_find

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator adjacent_find(ForwardIterator first, ForwardIterator last);`
  - `OutputIterator adjacent_find(ForwardIterator first, ForwardIterator last, Predicate pred);`
- Description:
  - The first prototype: the iterator pointing to the first element of the first pair of two adjacent equal elements is returned. If no such element exists, `last` is returned.
  - The second prototype: the iterator pointing to the first element of the first pair of two adjacent elements for which the binary predicate `pred` returns `true` is returned. If no such element exists, `last` is returned.
- Example:

```
#include <algorithm>
```

```
#include <string>
#include <iostream>
using namespace std;

class SquaresDiff
{
    size_t d_minimum;
    public:
        SquaresDiff(size_t minimum)
        :
            d_minimum(minimum)
        {}
        bool operator()(size_t first, size_t second)
        {
            return second * second - first * first  >= d_minimum;
        }
};
int main()
{
    string sarr[] =
        {
            "Alpha", "bravo", "charley", "delta", "echo", "echo",
            "foxtrot", "golf"
        };
    string *last = sarr + sizeof(sarr) / sizeof(string);
    string *result = adjacent_find(sarr, last);

    cout << *result << '\n';
    result = adjacent_find(++result, last);

    cout << "Second time, starting from the next position:\n" <<
        (
            result == last ?
                "** No more adjacent equal elements **"
            :
                "*result"
        ) << '\n';

    size_t iv[] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
    size_t *ilast = iv + sizeof(iv) / sizeof(size_t);
    size_t *ires = adjacent_find(iv, ilast, SquaresDiff(10));

    cout <<
        "The first numbers for which the squares differ at least 10: "
        << *ires << " and " << *(ires + 1) << '\n';
}
/*
Displays:

echo
Second time, starting from the next position:
** No more adjacent equal elements **
The first numbers for which the squares differ at least 10: 5 and 6
*/
```

19.1.4 binary_search

- Header file: `<algorithm>`
- Function prototypes:
  - `bool binary_search(ForwardIterator first, ForwardIterator last, Type const &value);`
  - `bool binary_search(ForwardIterator first, ForwardIterator last, Type const &value, Comparator comp);`
- Description:
  - The first prototype: `value` is looked up using binary search in the series of elements implied by the iterator range `[first, last)`. The elements in the range must have been sorted by the `Type::operator<` function. `True` is returned if the element was found, `false` otherwise.
  - The second prototype: `value` is looked up using binary search in the series of elements implied by the iterator range `[first, last)`. The elements in the range must have been sorted by the `Comparator` function object. `True` is returned if the element was found, `false` otherwise. As illustrated by the following example, the function object function's first parameter refers to an element in the iterator range, while the function object's second parameter refers to `value`.
- Example:

```
#include <algorithm>
#include <string>
#include <iostream>
#include <functional>
using namespace std;

int main()
{
    string sarr[] =
        {
            "alpha", "bravo", "charley", "delta", "echo",
            "foxtrot", "golf", "hotel"
        };
    string *last = sarr + sizeof(sarr) / sizeof(string);
    bool result = binary_search(sarr, last, "foxtrot");
    cout << (result ? "found " : "didn't find ") << "foxtrot" << '\n';

    reverse(sarr, last);                // reverse the order of elements
                                        // binary search now fails:
    result = binary_search(sarr, last, "foxtrot");
    cout << (result ? "found " : "didn't find ") << "foxtrot" << '\n';
                                        // ok when using appropriate
                                        // comparator:
    result = binary_search(sarr, last, "foxtrot", greater<string>());
    cout << (result ? "found " : "didn't find ") << "foxtrot" << '\n';

    // alternatively, using a lambda expression showing the used 'sarr'
    // indices and the value of the second parameter:

    result = binary_search(sarr, last, "foxtrot",
        [&](string const &sarrEl, string const &value)
```

```
            {
                cout << "comparing element " << (&sarrEl - sarr) <<
                        " (" << sarrEl << ") to " << value << '\n';
                return sarrEl > value;
            }
        );
        cout << "found it: " << result << '\n';
    }
    //  Displays:
    //      found foxtrot
    //      didn't find foxtrot
    //      found foxtrot
    //      comparing element 4 (delta) to foxtrot
    //      comparing element 2 (foxtrot) to foxtrot
    //      comparing element 1 (golf) to foxtrot
    //      comparing element -3 (foxtrot) to foxtrot
    //      found it: 1
```

If `value` is in fact present in the range of values, then this generic algorithm doesn't answer the question where `value` is located. If that question must be answered the generic algorithms lower_bound and upper_bound can be used. Refer to section 19.1.67 for an extensive example illustrating the use of these latter two algorithms.

19.1.5 copy

- Header file: `<algorithm>`
- Function prototype:
  - `OutputIterator copy(InputIterator first, InputIterator last, OutputIterator destination);`
- Description:
  - The series of elements implied by the iterator range `[first, last)` is copied to an output range, starting at `destination` using the assignment operator of the underlying data type. The return value is the OutputIterator pointing just beyond the last element that was copied to the destination range (so, 'last' in the destination range is returned).
- Example:
  Note the second call to `copy`. It uses an `ostream_iterator` for `string` objects. This iterator writes the `string` values to the specified `ostream` (i.e., `cout`), separating the values by the specified separation string (i.e., `"  "`).

```
    #include <algorithm>
    #include <string>
    #include <iostream>
    #include <iterator>
    using namespace std;

    int main()
    {
        string sarr[] =
            {
                "alpha", "bravo", "charley", "delta", "echo",
                "foxtrot", "golf", "hotel"
        };
    string  *last = sarr + sizeof(sarr) / sizeof(string);

    copy(sarr + 2, last, sarr); // move all elements two positions left

                                // copy to cout using an ostream_iterator
                                // for strings,
    copy(sarr, last, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
//  Displays: charley delta echo foxtrot golf hotel golf hotel
```

- See also: `unique_copy`

19.1.6 copy_backward

- Header file: `<algorithm>`
- Function prototype:
  - `BidirectionalIterator copy_backward(InputIterator first, InputIterator last, BidirectionalIterator last2);`
- Description:
  - The series of elements implied by the iterator range `[first, last)` are copied from the element at position `last - 1` until (and including) the element at position `first` to the element range, *ending* at position `last2 - 1` using the assignment operator of the underlying data type. The destination range is therefore `[last2 - (last - first), last2)`.

    Note that this algorithm does *not* reverse the order of the elements when copying them to the destination range.

    The return value is the BidirectionalIterator pointing to the last element that was copied to the destination range (so, 'first' in the destination range, pointed to by `last2 - (last - first)`, is returned).
- Example:

```
#include <algorithm>
#include <string>
#include <iostream>
#include <iterator>
using namespace std;

int main()
{
    string sarr[] =
        {
            "alpha", "bravo", "charley", "delta", "echo",
            "foxtrot", "golf", "hotel"
        };
    string *last = sarr + sizeof(sarr) / sizeof(string);

    copy
    (
        copy_backward(sarr + 3, last, last - 3),
            last,
            ostream_iterator<string>(cout, " ")
        );
        cout << '\n';
    }
    // Displays:    golf hotel foxtrot golf hotel foxtrot golf hotel
```

19.1.7 count

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `size_t count(InputIterator first, InputIterator last, Type const &value);`
- **Description:**
  - The number of times `value` occurs in the iterator range `[first, last)` is returned. Uses `Type::operator==` to determine whether `value` is equal to an element in the iterator range.
- **Example:**

```
#include <algorithm>
#include <iostream>
using namespace std;

int main()
{
    int ia[] = {1, 2, 3, 4, 3, 4, 2, 1, 3};

    cout << "Number of times the value 3 is available: " <<
        count(ia, ia + sizeof(ia) / sizeof(int), 3) <<
        '\n';
}
// Displays:    Number of times the value 3 is available: 3
```

19.1.8 count_if

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `size_t count_if(InputIterator first, InputIterator last, Predicate predicate);`
- **Description:**
  - The number of times unary predicate ‘`predicate`’ returns `true` when applied to the elements implied by the iterator range `[first, last)` is returned.
- **Example:**

```
#include <algorithm>
#include <iostream>
```

```
using namespace std;

class Odd
{
    public:
        bool operator()(int value) const
        {
            return value & 1;
        }
};
int main()
{
    int     ia[] = {1, 2, 3, 4, 3, 4, 2, 1, 3};

    cout << "The number of odd values in the array is: " <<
        count_if(ia, ia + sizeof(ia) / sizeof(int), Odd{}) << '\n';
}
// Displays:    The number of odd values in the array is: 5
```

19.1.9 equal

- Header file: `<algorithm>`
- Function prototypes:
  - `bool equal(InputIterator first, InputIterator last, InputIterator otherFirst);`
  - `bool equal(InputIterator first, InputIterator last, InputIterator otherFirst, BinaryPredicate pred);`
- Description:
  - The first prototype: the elements in the range `[first, last)` are compared to a range of equal length starting at `otherFirst`. The function returns `true` if the visited elements in both ranges are equal pairwise. The ranges need not be of equal length, only the elements in the indicated range are considered (and must be available).
  - The second prototype: the elements in the range `[first, last)` are compared to a range of equal length starting at `otherFirst`. The function returns `true` if the binary predicate, applied to all corresponding elements in both ranges returns `true` for every pair of corresponding elements. The ranges need not be of equal length, only the elements in the indicated range are considered (and must be available).
- Example:

```
#include <algorithm>
#include <string>
#include <cstring>
#include <iostream>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first,
                        string const &second) const
        {
            return !strcasecmp(first.c_str(), second.c_str());
        }
};
int main()
{
    string first[] =
        {
            "Alpha", "bravo", "Charley", "delta", "Echo",
            "foxtrot", "Golf", "hotel"
        };
    string second[] =
        {
            "alpha", "bravo", "charley", "delta", "echo",
            "foxtrot", "golf", "hotel"
        };
    string *last = first + sizeof(first) / sizeof(string);

    cout << "The elements of `first' and `second' are pairwise " <<
        (equal(first, last, second) ? "equal" : "not equal") <<
        '\n' <<
        "compared case-insensitively, they are " <<
        (
            equal(first, last, second, CaseString{}) ?
                "equal" : "not equal"
        ) << '\n';
}
/*
    Displays:
        The elements of `first' and `second' are pairwise not equal
        compared case-insensitively, they are equal
*/
```

19.1.10 equal_range

- Header file: `<algorithm>`
- Function prototypes:
  - `pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first, ForwardIterator last, Type const &value);`
  - `pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first, ForwardIterator last, Type const &value, Compare comp);`
- Description (see also identically named member functions of, e.g., the `map` (section 12.4.7) and `multimap` (section 12.4.8)):
  - The first prototype: starting from a sorted sequence (where the `operator<` of the data type to which the iterators point was used to sort the elements in the provided range), a pair of iterators is returned representing the return value of, respectively, `lower_bound` (returning the first element that is not smaller than the provided reference value, see section 19.1.27) and `upper_bound` (returning the first element beyond the provided reference value, see section 19.1.67).
  - The second prototype: starting from a sorted sequence (where the `comp` function object was used to sort the elements in the provided range), a pair of iterators is returned representing the return values of, respectively, the functions `lower_bound` (section 19.1.27) and `upper_bound` (section 19.1.67).

- Example:

```
#include <algorithm>
#include <functional>
#include <iterator>
#include <iostream>
using namespace std;

int main()
{
    int                 range[] = {1, 3, 5, 7, 7, 9, 9, 9};
    size_t const      size = sizeof(range) / sizeof(int);

    pair<int *, int *>  pi;

    pi = equal_range(range, range + size, 6);

    cout << "Lower bound for 6: " << *pi.first << '\n';
    cout << "Upper bound for 6: " << *pi.second << '\n';

    pi = equal_range(range, range + size, 7);

    cout << "Lower bound for 7: ";
    copy(pi.first, range + size, ostream_iterator<int>(cout, " "));
    cout << '\n';

    cout << "Upper bound for 7: ";
    copy(pi.second, range + size, ostream_iterator<int>(cout, " "));
    cout << '\n';

    sort(range, range + size, greater<int>());

    cout << "Sorted in descending order\n";

    copy(range, range + size, ostream_iterator<int>(cout, " "));
    cout << '\n';

    pi = equal_range(range, range + size, 7, greater<int>());

    cout << "Lower bound for 7: ";
    copy(pi.first, range + size, ostream_iterator<int>(cout, " "));
    cout << '\n';

    cout << "Upper bound for 7: ";
    copy(pi.second, range + size, ostream_iterator<int>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        Lower bound for 6: 7
        Upper bound for 6: 7
        Lower bound for 7: 7 7 9 9 9
        Upper bound for 7: 9 9 9
        Sorted in descending order
        9 9 9 7 7 5 3 1
        Lower bound for 7: 7 7 5 3 1
```

```
            Upper bound for 7: 5 3 1
    */
```

19.1.11 exchange

- **Header file:** `<utility>`
- **Function prototype:**
  - `Type exchange(Type &object1, ValueType &&newValue);`
- **Description:**
  - `newValue` is assigned to `object1`, and `object1's` previous value is returned.
- **Example:**

```
#include <utility>
#include <iostream>
using namespace std;

int main(int argc, char **argv)
{
    bool more = argc > 5;

    cout << "more than 5: " << exchange(more, argc > 2) <<
            ", more than 2: " << more << '\n';
}
/*
    Using g++ at least version 7.0.0:
    With `a.out one two three' displays:

    more than 5: 0, more than 2: 1

*/
```

19.1.12 fill

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `void fill(ForwardIterator first, ForwardIterator last, Type const &value);`
- **Description:**
  - all the elements implied by the iterator range `[first, last)` are initialized to `value`, overwriting the previously stored values.
- **Example:**

```
#include <algorithm>
#include <vector>
#include <iterator>
#include <iostream>
```

```
using namespace std;

int main()
{
    vector<int>     iv(8);

    fill(iv.begin(), iv.end(), 8);

    copy(iv.begin(), iv.end(), ostream_iterator<int>(cout, " "));
    cout << '\n';
}
// Displays:    8 8 8 8 8 8 8 8
```

19.1.13 fill_n

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `void fill_n(ForwardIterator first, Size n, Type const &value);`
- **Description:**
  - `n` elements starting at the element pointed to by `first` are initialized to `value`, overwriting the previous stored values.
- **Example:**

```
#include <algorithm>
#include <vector>
#include <iterator>
#include <iostream>
using namespace std;

int main()
{
    vector<int>     iv(8);

    fill_n(iv.begin() + 2, 4, 8);

    copy(iv.begin(), iv.end(), ostream_iterator<int>(cout, " "));
    cout << '\n';
}
// Displays:    0 0 8 8 8 8 0 0
```

19.1.14 find

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `InputIterator find(InputIterator first, InputIterator last, Type const &value);`

- Description:
  - Element `value` is searched for in the range of the elements implied by the iterator range `[first, last)`. An iterator pointing to the first element found is returned. If the element was not found, `last` is returned. The `operator==` of the underlying data type is used to compare the elements.
- Example:

```
#include <algorithm>
#include <string>
#include <iterator>
#include <iostream>
using namespace std;

int main()
{
    string sarr[] =
        {
            "alpha", "bravo", "charley", "delta", "echo"
        };
    string  *last = sarr + sizeof(sarr) / sizeof(string);

    copy
    (
        find(sarr, last, "delta"), last,
                                   ostream_iterator<string>(cout, " ")
    );
    cout << '\n';

    if (find(sarr, last, "india") == last)
    {
        cout << "`india' was not found in the range\n";
        copy(sarr, last, ostream_iterator<string>(cout, " "));
        cout << '\n';
    }
}
/*
    Displays:
        delta echo
        `india' was not found in the range
        alpha bravo charley delta echo
*/
```

19.1.15 find_end

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator1 find_end(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2)`
  - `ForwardIterator1 find_end(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2, BinaryPredicate pred)`

- Description:
  - The first prototype: the sequence of elements implied by `[first1, last1)` is searched for the last occurrence of the sequence of elements implied by the range `[first2, last2)`. If the sequence `[first2, last2)` is not found, `last1` is returned, otherwise an iterator pointing to the first element of the matching sequence is returned. The `operator==` of the underlying data type is used to compare the elements in the two sequences.
  - The second prototype: the sequence of elements implied by `[first1, last1)` is searched for the last occurrence of the sequence of elements implied by `[first2, last2)`. If the sequence `[first2, last2)` is not found, `last1` is returned, otherwise an iterator pointing to the first element of the matching sequence is returned. The provided binary predicate is used to compare the elements in the two sequences.
- Example:

```
#include <algorithm>
#include <string>
#include <iterator>
#include <iostream>
using namespace std;

class Twice
{
    public:
        bool operator()(size_t first, size_t second) const
        {
            return first == (second << 1);
        }
};
int main()
{
    string sarr[] =
        {
            "alpha", "bravo", "charley", "delta", "echo",
            "foxtrot", "golf", "hotel",
            "foxtrot", "golf", "hotel",
            "india", "juliet", "kilo"
        };
    string search[] =
        {
            "foxtrot",
            "golf",
            "hotel"
        };
    string  *last = sarr + sizeof(sarr) / sizeof(string);

    copy
    (
        find_end(sarr, last, search, search + 3),   // sequence starting
        last, ostream_iterator<string>{ cout, " " } // at 2nd 'foxtrot'
    );
    cout << '\n';

    size_t range[] = {2, 4, 6, 8, 10, 4, 6, 8, 10};
    size_t nrs[]   = {2, 3, 4};
    copy                // sequence of values starting at last sequence
    (                   // of range[] that are twice the values in nrs[]
        find_end(range, range + 9, nrs, nrs + 3, Twice{}),
        range + 9, ostream_iterator<size_t>{ cout, " " }
    );
    cout << '\n';
}
/*
    Displays:
        foxtrot golf hotel india juliet kilo
        4 6 8 10
*/
```

19.1.16 find_first_of

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator1 find_first_of(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2)`
  - `ForwardIterator1 find_first_of(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2, BinaryPredicate pred)`
- Description:
  - The first prototype: the sequence of elements implied by `[first1, last1)` is searched for the first occurrence of an element in the sequence of elements implied by the range `[first2, last2)`. If no element in the sequence `[first2, last2)` is found, `last1` is returned, otherwise an iterator pointing to the first element in `[first1, last1)` that is equal to an element in `[first2, last2)` is returned. The `operator==` of the underlying data type is used to compare the elements in the two sequences.
  - The second prototype: the sequence of elements implied by `[first1, last1)` is searched for the first occurrence of an element in the sequence of elements implied by `[first2, last2)`. Each element in the range `[first1, last1)` is compared to each element in the range `[first2, last2)`, and an iterator to the first element in `[first1, last1)` for which the binary predicate `pred` (receiving an the element out of the range `[first1, last1)` and an element from the range `[first2, last2)`) returns `true` is returned. Otherwise, `last1` is returned.
- Example:

```
#include <algorithm>
#include <string>
#include <iterator>
#include <iostream>
using namespace std;

class Twice
{
    public:
        bool operator()(size_t first, size_t second) const
        {
            return first == (second << 1);
        }
};
int main()
{
    string sarr[] =
        {
            "alpha", "bravo", "charley", "delta", "echo",
            "foxtrot", "golf", "hotel",
            "foxtrot", "golf", "hotel",
            "india", "juliet", "kilo"
        };
    string search[] =
        {
            "foxtrot",
            "golf",
            "hotel"
        };
    string  *last = sarr + sizeof(sarr) / sizeof(string);

    copy
    (                                                  // sequence starting
        find_first_of(sarr, last, search, search + 3),// at 1st 'foxtrot'
        last, ostream_iterator<string>{ cout, " " }
    );
    cout << '\n';

    size_t range[] = {2, 4, 6, 8, 10, 4, 6, 8, 10};
    size_t nrs[]   = {2, 3, 4};

        // copy the sequence of values in 'range', starting at the
        // first element in 'range' that is equal to twice one of the
        // values in 'nrs', and ending at the last element of 'range'
    copy
    (
        find_first_of(range, range + 9, nrs, nrs + 3, Twice{}),
        range + 9, ostream_iterator<size_t>{ cout, " " }
    );
    cout << '\n';
}
/*
    Displays:
        foxtrot golf hotel foxtrot golf hotel india juliet kilo
        4 6 8 10 4 6 8 10
*/
```

19.1.17 find_if

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `InputIterator find_if(InputIterator first, InputIterator last, Predicate pred);`
- **Description:**

  - An iterator pointing to the first element in the range implied by the iterator range `[first, last)` for which the (unary) predicate `pred` returns `true` is returned. If the element was not found, `last` is returned.

- Example:

```
#include <algorithm>
#include <string>
#include <cstring>
#include <iterator>
#include <iostream>
using namespace std;

class CaseName
{
    std::string  d_string;

    public:
        CaseName(char const *str): d_string(str)
        {}
        bool operator()(std::string const &element) const
        {
            return strcasecmp(element.c_str(), d_string.c_str()) == 0;
        }
};
int main()
{
    string sarr[] =
        {
            "Alpha", "Bravo", "Charley", "Delta", "Echo"
        };
    string  *last = sarr + sizeof(sarr) / sizeof(string);

    copy
    (
        find_if(sarr, last, CaseName{ "charley" }),
        last, ostream_iterator<string>{ cout, " " }
    );
    cout << '\n';

    if (find_if(sarr, last, CaseName{ "india" }) == last)
    {
        cout << "`india' was not found in the range\n";
        copy(sarr, last, ostream_iterator<string>{ cout, " " });
        cout << '\n';
    }
}
/*
    Displays:
        Charley Delta Echo
        `india' was not found in the range
        Alpha Bravo Charley Delta Echo
*/
```

19.1.18 for_each

- Header file: `<algorithm>`
- Function prototype:
  - `Function for_each(ForwardIterator first, ForwardIterator last, Function func);`
- Description:
  - Each of the elements implied by the iterator range `[first, last)` is passed in turn as a reference to the function (or function object) `func`. The function may modify the elements it receives (as the used iterator is a forward iterator). Alternatively, if the elements should be transformed, `transform` (see section 19.1.64) can be used. The function itself or a copy of the provided function object is returned: see the example below, in which an extra argument list is added to the `for_each` call, which argument is eventually also passed to the function given to `for_each`. Within `for_each` the return value of the function that is passed to it is ignored. The `for_each` generic algorithm looks a lot like the range-based for loop, but different from the range-based for-loop the `for_each` algorithm can also be used with sub-ranges and with reverse-iterators.
- Example:

```
#include <algorithm>
#include <string>
#include <cstring>
#include <iostream>
#include <cctype>
using namespace std;

void lowerCase(char &c)                      // `c' *is* modified
{
    c = tolower(static_cast<unsigned char>(c));
}
void capitalizedOutput(string const &str)    // `str' is *not* modified
{
    char    *tmp = strcpy(new char[str.size() + 1], str.c_str());

    for_each(tmp + 1, tmp + str.size(), lowerCase);

    tmp[0] = toupper(*tmp);
    cout << tmp << " ";
    delete tmp;
};
int main()
{
    string sarr[] =
        {
            "alpha", "BRAVO", "charley", "DELTA",  "echo",
            "FOXTROT", "golf", "HOTEL"
        };
    string *last = sarr + sizeof(sarr) / sizeof(string);

    for_each(sarr, last, capitalizedOutput)("that's all, folks");
    cout << '\n';
}
```

```
/*
Displays:

Alpha Bravo Charley Delta Echo Foxtrot Golf Hotel That's all, folks
*/
```

- Here is another example using a function object:

```
#include <algorithm>
#include <string>
#include <iostream>
#include <cctype>
using namespace std;

void lowerCase(char &c)
{
    c = tolower(static_cast<unsigned char>(c));
}
class Show
{
    int d_count;

    public:
        Show()
        :
            d_count(0)
        {}
        void operator()(std::string &str)
        {
            std::for_each(str.begin(), str.end(), lowerCase);
            str[0] = toupper(str[0]);   // assuming str is not empty
            std::cout << ++d_count << " " << str << "; ";
        }
        int count() const
        {
            return d_count;
        }
};
int main()
{
    string sarr[] =
        {
            "alpha", "BRAVO", "charley", "DELTA", "echo",
            "FOXTROT", "golf", "HOTEL"
        };
    string *last = sarr + sizeof(sarr) / sizeof(string);

    cout << for_each(sarr, last, Show{}).count() << '\n';
}
/*
Displays (all on one line):

1 Alpha; 2 Bravo; 3 Charley; 4 Delta; 5 Echo; 6 Foxtrot;
                                          7 Golf; 8 Hotel; 8
*/
```

The example also shows that the `for_each` algorithm may be used with functions defining `const` and non-`const` parameters. Also, see section 19.1.64 for differences between the `for_each` and `transform` generic algorithms.

The `for_each` algorithm cannot directly be used (i.e., by passing `*this` as the function object argument) inside a member function to modify its own object as the `for_each` algorithm first creates its own copy of the passed function object. A *lambda function* or a *wrapper class* whose constructor accepts a pointer or reference to the current object and possibly to one of its member functions solves this problem.

19.1.19 generate

- Header file: `<algorithm>`
- Function prototype:
  - `void generate(ForwardIterator first, ForwardIterator last, Generator generator);`
- Description:
  - All elements implied by the iterator range `[first, last)` are initialized by the return value of `generator`, which can be a function or function object. `Generator::operator()` does not receive any arguments. The example uses a well-known fact from algebra: in order to obtain the square of `n + 1`, add `1 + 2 * n` to `n * n`.
- Example:

```
#include <algorithm>
#include <vector>
#include <iterator>
#include <iostream>
using namespace std;

class NaturalSquares
{
    size_t d_newsqr;
    size_t d_last;

    public:
        NaturalSquares(): d_newsqr(0), d_last(0)
        {}
        size_t operator()()
        {                   // using: (a + 1)^2 == a^2 + 2*a + 1
            return d_newsqr += (d_last++ << 1) + 1;
        }
};
int main()
{
    vector<size_t> uv(10);

    generate(uv.begin(), uv.end(), NaturalSquares{});

    copy(uv.begin(), uv.end(), ostream_iterator<int>{ cout, " " });
    cout << '\n';
}
// Displays:   1 4 9 16 25 36 49 64 81 100
```

19.1.20 generate_n

- Header file: `<algorithm>`
- Function prototypes:
  - `void generate_n(ForwardIterator first, Size n, Generator generator);`
- Description:
  - `n` elements starting at the element pointed to by iterator `first` are initialized by the return value of `generator`, which can be a function or function object.
- Example:

```
#include <algorithm>
#include <vector>
#include <iterator>
#include <iostream>
using namespace std;

class NaturalSquares
{
    size_t d_newsqr;
    size_t d_last;

    public:
        NaturalSquares(): d_newsqr(0), d_last(0)
        {}
        size_t operator()()
        {                           // using: (a + 1)^2 == a^2 + 2*a + 1
            return d_newsqr += (d_last++ << 1) + 1;
        }
};
int main()
{
    vector<size_t> uv(10);

    generate_n(uv.begin(), 5, NaturalSquares{});

    copy(uv.begin(), uv.end(), ostream_iterator<int>{ cout, " " });
    cout << '\n';
}
// Displays:    1 4 9 16 25 0 0 0 0 0
```

19.1.21 includes

- Header file: `<algorithm>`
- Function prototypes:
  - `bool includes(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2);`

  - `bool includes(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, Compare comp);`

- Description:
  - The first prototype: both sequences of elements implied by the ranges `[first1, last1)` and `[first2, last2)` should have been sorted using the `operator<` of the data type to which the iterators point. The function returns `true` if every element in the second sequence `[first2, last2)` is contained in the first sequence `[first1, last1)` (the second range is a subset of the first range).
  - The second prototype: both sequences of elements implied by the ranges `[first1, last1)` and `[first2, last2)` should have been sorted using the `comp` function object. The function returns `true` if every element in the second sequence `[first2, last2)` is contained in the first sequence `[first1, last1)` (the second range is a subset of the first range).

- Example:

```
#include <algorithm>
#include <string>
#include <cstring>
#include <iostream>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first,
                        string const &second) const
        {
            return !strcasecmp(first.c_str(), second.c_str());
        }
};
int main()
{
    string first1[] =
        {
            "alpha", "bravo", "charley", "delta",  "echo",
            "foxtrot", "golf", "hotel"
        };
    string first2[] =
        {
            "Alpha", "bravo", "Charley", "delta",  "Echo",
            "foxtrot", "Golf", "hotel"
        };
    string second[] =
        {
            "charley", "foxtrot", "hotel"
        };
    size_t n = sizeof(first1) / sizeof(string);

    cout << "The elements of `second' are " <<
        (includes(first1, first1 + n, second, second + 3) ? "" : "not")
        << " contained in the first sequence:\n"
           "second is a subset of first1\n";

    cout << "The elements of `first1' are " <<
```

```
        (includes(second, second + 3, first1, first1 + n) ? "" : "not")
        << " contained in the second sequence\n";

    cout << "The elements of `second' are " <<
        (includes(first2, first2 + n, second, second + 3) ? "" : "not")
        << " contained in the first2 sequence\n";

    cout << "Using case-insensitive comparison,\n"
        "the elements of `second' are "
        <<
        (includes(first2, first2 + n, second, second + 3, CaseString{}) ?
            "" : "not")
        << " contained in the first2 sequence\n";
}
/*
    Displays:
        The elements of `second' are  contained in the first sequence:
        second is a subset of first1
        The elements of `first1' are not contained in the second sequence
        The elements of `second' are not contained in the first2 sequence
        Using case-insensitive comparison,
        the elements of `second' are  contained in the first2 sequence
*/
```

19.1.22 inner_product

- Header file: `<numeric>`
- Function prototypes:
  - `Type inner_product(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, Type init);`
  - `Type inner_product(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, Type init, BinaryOperator1 op1, BinaryOperator2 op2);`
- Description:
  - The first prototype: the sum of all pairwise products of the elements implied by the range `[first1, last1)` and the same number of elements starting at the element pointed to by `first2` are added to `init`, and this sum is returned. The function uses the `operator+` and `operator*` of the data type to which the iterators point.
  - The second prototype: binary operator `op1` instead of the default addition operator, and binary operator `op2` instead of the default multiplication operator are applied to all pairwise elements implied by the range `[first1, last1)` and the same number of elements starting at the element pointed to by `first2`. The results of the binary operator calls are added to `init` and `init`'s final value is returned.
- Example:

```
#include <numeric>
#include <algorithm>
#include <iterator>
#include <iostream>
#include <string>
using namespace std;
```

```
class Cat
{
    std::string  d_sep;
    public:
        Cat(string const &sep)
        :
            d_sep(sep)
        {}
        string operator()
            (string const &s1, string const &s2) const
        {
            return s1 + d_sep + s2;
        }
};
int main()
{
    size_t ia1[] = {1, 2, 3, 4, 5, 6, 7};
    size_t ia2[] = {7, 6, 5, 4, 3, 2, 1};
    size_t init = 0;

    cout << "The sum of all squares in ";
    copy(ia1, ia1 + 7, ostream_iterator<size_t>{ cout, " " });
    cout << "is " <<
        inner_product(ia1, ia1 + 7, ia1, init) << '\n';

    cout << "The sum of all cross-products in ";
    copy(ia1, ia1 + 7, ostream_iterator<size_t>{ cout, " " });
    cout << "and ";
    copy(ia2, ia2 + 7, ostream_iterator<size_t>{ cout, " " });
    cout << "is " <<
        inner_product(ia1, ia1 + 7, ia2, init) << '\n';

    string names1[] = {"Frank", "Karel", "Piet"};
    string names2[] = {"Brokken", "Kubat", "Plomp"};

    cout << "A list of all combined names in ";
    copy(names1, names1 + 3, ostream_iterator<string>{ cout, " " });
    cout << "and\n";
    copy(names2, names2 + 3, ostream_iterator<string>{ cout, " " });
    cout << "is:" <<
        inner_product(names1, names1 + 3, names2, string{ "\t" },
            Cat{ "\n\t"}, Cat{ " " }) <<
        '\n';
}
/*
  Displays:
    The sum of all squares in 1 2 3 4 5 6 7 is 140
    The sum of all cross-products in 1 2 3 4 5 6 7 and 7 6 5 4 3 2 1 is 84
    A list of all combined names in Frank Karel Piet and
    Brokken Kubat Plomp is:
            Frank Brokken
            Karel Kubat
            Piet Plomp
*/
```

19.1.23 inplace_merge

- Header file: `<algorithm>`
- Function prototypes:
  - `void inplace_merge(BidirectionalIterator first, BidirectionalIterator middle, BidirectionalIterator last);`
  - `void inplace_merge(BidirectionalIterator first, BidirectionalIterator middle, BidirectionalIterator last, Compare comp);`
- Description:
  - The first prototype: the two (sorted) ranges `[first, middle)` and `[middle, last)` are merged, keeping a sorted list (using the `operator<` of the data type to which the iterators point). The final series is stored in the range `[first, last)`.
  - The second prototype: the two (sorted) ranges `[first, middle)` and `[middle, last)` are merged, keeping a sorted list (using the boolean result of the binary comparison operator `comp`). The final series is stored in the range `[first, last)`.
- Example:

```
#include <algorithm>
#include <string>
#include <cstring>
#include <iterator>
#include <iostream>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first, string const &second) const
        {
            return strcasecmp(first.c_str(), second.c_str()) < 0;
        }
};
int main()
{
    string range[] =
        {
            "alpha", "charley", "echo", "golf",
            "bravo", "delta", "foxtrot",
        };

    inplace_merge(range, range + 4, range + 7);
    copy(range, range + 7, ostream_iterator<string>{ cout, " " });
    cout << '\n';

    string range2[] =
        {
            "ALPHA", "CHARLEY", "DELTA", "foxtrot", "hotel",
            "bravo", "ECHO", "GOLF"
        };

    inplace_merge(range2, range2 + 5, range2 + 8, CaseString{});
    copy(range2, range2 + 8, ostream_iterator<string>{ cout, " " });
    cout << '\n';
}
/*
    Displays:
        alpha bravo charley delta echo foxtrot golf
        ALPHA bravo CHARLEY DELTA ECHO foxtrot GOLF hotel
*/
```

19.1.24 iota

- Header file: `<numeric>`
- Function prototype:
  - `void iota(ForwardIterator first, ForwardIterator last, Type value);`
- Description:
  - All elements implied by the iterator range `[first, last)` are assigned the values of the incremented sequence of values starting at `value`. `*first` receives `value`, `*(first + 1)` receives `++value`, etc.
- Example:

```
#include <numeric>
#include <algorithm>
#include <vector>
#include <iostream>
using namespace std;

int main()
{
    vector<size_t> uv(10);

    iota(uv.begin(), uv.end(), 0);

    copy(uv.begin(), uv.end(), ostream_iterator<int>{ cout, " " });
    cout << '\n';
}
// Displays:   0 1 2 3 4 5 6 7 8 9
```

19.1.25 iter_swap

- Header file: `<algorithm>`
- Function prototype:
  - `void iter_swap(ForwardIterator1 iter1, ForwardIterator2 iter2);`
- Description:
  - The elements pointed to by `iter1` and `iter2` are swapped.
- Example:

```
#include <algorithm>
```

```
#include <iterator>
#include <iostream>
#include <string>
using namespace std;

int main()
{
    string first[] = {"alpha", "bravo", "charley"};
    string second[] = {"echo", "foxtrot", "golf"};
    size_t const n = sizeof(first) / sizeof(string);

    cout << "Before:\n";
    copy(first, first + n, ostream_iterator<string>(cout, " "));
    cout << '\n';
    copy(second, second + n, ostream_iterator<string>(cout, " "));
    cout << '\n';

    for (size_t idx = 0; idx < n; ++idx)
        iter_swap(first + idx, second + idx);

    cout << "After:\n";
    copy(first, first + n, ostream_iterator<string>(cout, " "));
    cout << '\n';
    copy(second, second + n, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        Before:
        alpha bravo charley
        echo foxtrot golf
        After:
        echo foxtrot golf
        alpha bravo charley
*/
```

19.1.26 lexicographical_compare

- **Header file:** `<algorithm>`
- **Function prototypes:**
  - `bool lexicographical_compare(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2);`
  - `bool lexicographical_compare(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, Compare comp);`
- **Description:**
  - The first prototype: the corresponding pairs of elements in the ranges pointed to by the ranges `[first1, last1)` and `[first2, last2)` are compared. The function returns `true`
    - at the first element in the first range which is less than the corresponding element in the second range (using `operator<` of the underlying data type),
    - if `last1` is reached, but `last2` isn't reached yet.

False is returned in the other cases, which indicates that the first sequence is not lexicographically less than the second sequence. So, `false` is returned:

  - at the first element in the first range which is greater than the corresponding element in the second range (using `operator<` of the data type to which the iterators point, reversing the operands),
  - if `last2` is reached, but `last1` isn't reached yet,
  - if `last1` and `last2` are reached.

- The second prototype: with this function the binary comparison operation as defined by `comp` is used instead of `operator<` of the data type to which the iterators point.

- Example:

```
#include <algorithm>
#include <iterator>
#include <iostream>
#include <string>
#include <cstring>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first,
                        string const &second) const
        {
            return strcasecmp(first.c_str(), second.c_str()) < 0;
        }
};
int main()
{
    string word1 = "hello";
    string word2 = "help";

    cout << word1 << " is " <<
        (
            lexicographical_compare(word1.begin(), word1.end(),
                                    word2.begin(), word2.end()) ?
                "before "
            :
                "beyond or at "
        ) <<
        word2 << " in the alphabet\n";

    cout << word1 << " is " <<
        (
            lexicographical_compare(word1.begin(), word1.end(),
                                    word1.begin(), word1.end()) ?
                "before "
            :
                "beyond or at "
        ) <<
        word1 << " in the alphabet\n";

    cout << word2 << " is " <<
        (
                lexicographical_compare(word2.begin(), word2.end(),
                                        word1.begin(), word1.end()) ?
                    "before "
                :
                    "beyond or at "
            ) <<
            word1 << " in the alphabet\n";

        string one[] = {"alpha", "bravo", "charley"};
        string two[] = {"ALPHA", "BRAVO", "DELTA"};

        copy(one, one + 3, ostream_iterator<string>{ cout, " " });
        cout << " is ordered " <<
            (
                lexicographical_compare(one, one + 3,
                                        two, two + 3, CaseString{}) ?
                    "before "
                :
                    "beyond or at "
            );
        copy(two, two + 3, ostream_iterator<string>{ cout, " " });
        cout << "\n"
            "using case-insensitive comparisons.\n";
    }
    /*
        Displays:
            hello is before help in the alphabet
            hello is beyond or at hello in the alphabet
            help is beyond or at hello in the alphabet
            alpha bravo charley  is ordered before ALPHA BRAVO DELTA
            using case-insensitive comparisons.
    */
```

19.1.27 lower_bound

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator lower_bound(ForwardIterator first, ForwardIterator last, const Type &value);`
  - `ForwardIterator lower_bound(ForwardIterator first, ForwardIterator last, const Type &value, Compare comp);`
- Description:
  - The first prototype: the sorted elements indicated by the iterator range `[first, last)` are searched for the first element that is not less than (i.e., greater than or equal to) `value`. The returned iterator marks the location in the sequence where `value` can be inserted without breaking the sorted order of the elements. The `operator<` of the data type to which the iterators point is used. If no such element is found, `last` is returned.
  - The second prototype: the elements indicated by the iterator range `[first, last)` must have been sorted using the `comp` function (-object). Each element in the range is compared to `value` using the `comp` function. An iterator to the first element for which the

binary predicate `comp`, applied to the elements of the range and `value`, returns `false` is returned. If no such element is found, `last` is returned.

As illustrated by the following example, the function object function's first parameter refers to an element in the iterator range, while the function object's second parameter refers to `value`.

- Example:

```
#include <algorithm>
#include <iostream>
#include <iterator>
#include <vector>
#include <functional>
using namespace std;

int main()
{
    int     ia[] = { 10, 20, 30 };

    cout << "Sequence: ";
    copy(ia, ia + 3, ostream_iterator<int>(cout, " "));
    cout << "\n"
            "15 can be inserted before " <<
            *lower_bound(ia, ia + 3, 15) << "\n"
            "35 can be inserted after " <<
            (lower_bound(ia, ia + 3, 35) == ia + 3 ?
                                "the last element" : "???") << '\n';

    cout << "Sequence: ";
    copy(ia, ia + 3, ostream_iterator<int>(cout, " "));
    cout << "\n"
            "15 can be inserted before " <<
            *lower_bound(ia, ia + 3, 15, less<int>()) << "\n"
            "35 can be inserted before " <<
            (lower_bound(ia, ia + 3, 35, less<int>()) == ia ?
                                "the first element " : "???") << '\n';

    vector<int> array{ 5, 10, 20, 20, 20, 30 };
    auto iter = lower_bound(array.begin(), array.end(), 20,
                    [&](int &arrayEl, int value)
                    {
                        cout << "Comparing " << arrayEl <<
                            " (index: " << (&arrayEl - &array[0]) << ")"
                            " to " << value << '\n';
                        return arrayEl < value;
                    }
                );

    cout << "New 20 to insert at idx " << (iter - array.begin()) << '\n';
}
//  Displays:
//      Sequence: 10 20 30
//      15 can be inserted before 20
//      35 can be inserted after the last element
//      Sequence: 10 20 30
//      15 can be inserted before 20
//      35 can be inserted before ???
//      Comparing 20 (index: 3) to 20
//      Comparing 10 (index: 1) to 20
//      Comparing 20 (index: 2) to 20
//      New 20 to insert at idx 2
```

The `binary_search` generic algorithm (cf. section 19.1.4)can be used to determine whether or not `value` is present in the iterator range. The `upper_bound` algorithm can be used to find the last element of a series of values equal to `value`. The `upper_bound` section (19.1.67) also contains an extensive example illustrating the use of `lower_bound` and as `upper_bound`.

19.1.28 max

- Header file: `<algorithm>`
- Function prototypes:
  - `Type const &max(Type const &one, Type const &two);`
  - `Type const &max(Type const &one, Type const &two, Comparator comp);`
- Description:
  - The first prototype: the larger of the two elements `one` and `two` is returned, using the `operator>` of the data type to which the iterators point to determine which element is the larger one.
  - The second prototype: `one` is returned if the binary predicate `comp(one, two)` returns `true`, otherwise `two` is returned.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <cstring>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first, string const &second) const
        {
            return strcasecmp(second.c_str(), first.c_str()) > 0;
        }
};
int main()
{
    cout << "Word '" << max("first"s, "second"s) <<
                                "' is lexicographically last\n";

    cout << "Word '" << max("first"s, "SECOND"s) <<
                                "' is lexicographically last\n";

    cout << "Word '" << max("first"s, "SECOND"s,
                        CaseString{}) << "' is lexicographically last\n";
}
```

```
/*
    Displays:
        Word 'second' is lexicographically last
        Word 'first' is lexicographically last
        Word 'SECOND' is lexicographically last
*/
```

19.1.29 max_element

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator max_element(ForwardIterator first, ForwardIterator last);`
  - `ForwardIterator max_element(ForwardIterator first, ForwardIterator last, Comparator comp);`
- Description:
  - The first prototype: an iterator pointing to the largest element in the range implied by `[first, last)` is returned. The `operator<` of the data type to which the iterators point is used to decide which of the elements is the largest.
  - The second prototype: rather than using `operator<`, the binary predicate `comp` is used to make the comparisons between the elements implied by the iterator range `[first, last)`. The element for which `comp` returns most often `true`, compared with other elements, is returned.
- Example:

```
#include <algorithm>
#include <iostream>
using namespace std;

class AbsValue
{
    public:
        bool operator()(int first, int second) const
        {
            return abs(first) < abs(second);
        }
};
int main()
{
    int     ia[] = {-4, 7, -2, 10, -12};

    cout << "The max. int value is " << *max_element(ia, ia + 5) << '\n';
    cout << "The max. absolute int value is " <<
            *max_element(ia, ia + 5, AbsValue{}) << '\n';
}
/*
    Displays:
        The max. int value is 10
        The max. absolute int value is -12
*/
```

19.1.30 merge

- Header file: `<algorithm>`
- Function prototypes:
  - `OutputIterator merge(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result);`
  - `OutputIterator merge(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result, Compare comp);`
- Description:
  - The first prototype: the two (sorted) ranges `[first1, last1)` and `[first2, last2)` are merged, keeping a sorted list (using the `operator<` of the data type to which the iterators point). The final series is stored in the range starting at `result` and ending just before the `OutputIterator` returned by the function.
  - The second prototype: the two (sorted) ranges `[first1, last1)` and `[first2, last2)` are merged, keeping a sorted list (using the boolean result of the binary comparison operator `comp`). The final series is stored in the range starting at `result` and ending just before the `OutputIterator` returned by the function.
- Example:

```
#include <algorithm>
#include <string>
#include <cstring>
#include <iterator>
#include <iostream>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first, string const &second) const
        {
            return strcasecmp(first.c_str(), second.c_str()) < 0;
        }
};
int main()
{
    string range1[] =
        {                                       // 5 elements
            "alpha", "bravo", "foxtrot", "hotel", "zulu"
        };
    string range2[] =
        {                                       // 4 elements
            "delta", "echo", "golf", "romeo"
        };
    string result[5 + 4];

    copy(result,
        merge(range1, range1 + 5, range2, range2 + 4, result),
        ostream_iterator<string>{ cout, " " });
    cout << '\n';
    string range3[] =
        {
            "ALPHA", "bravo", "foxtrot", "HOTEL", "ZULU"
        };
    string range4[] =
        {
            "delta", "ECHO", "GOLF", "romeo"
        };

    copy(result,
        merge(range3, range3 + 5, range4, range4 + 4, result,
                                                  CaseString{}),
        ostream_iterator<string>{ cout, " " });
    cout << '\n';
}
/*
    Displays:
        alpha bravo delta echo foxtrot golf hotel romeo zulu
        ALPHA bravo delta ECHO foxtrot GOLF HOTEL romeo ZULU
*/
```

19.1.31 min

- Header file: `<algorithm>`
- Function prototypes:
  - `Type const &min(Type const &one, Type const &two);`
  - `Type const &min(Type const &one, Type const &two, Comparator comp);`
- Description:
  - The first prototype: the smaller of the two elements `one` and `two` is returned using the `operator<` of the data type to which the iterators point to decide which of the two elements is the smaller.
  - The second prototype: `one` is returned if the binary predicate `comp(one, two)` returns `false`, otherwise `two` is returned.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <cstring>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first, string const &second) const
        {
            return strcasecmp(second.c_str(), first.c_str()) > 0;
        }
};
int main()
{
        cout << "Word '" << min(string{ "first" }, string{ "second" }) <<
                                "' is lexicographically first\n";

        cout << "Word '" << min(string{ "first" }, string{ "SECOND" }) <<
                                "' is lexicographically first\n";

        cout << "Word '" << min(string{ "first" }, string{ "SECOND" },
                        CaseString{}) << "' is lexicographically first\n";
    }
    /*
        Displays:
            Word 'first' is lexicographically first
            Word 'SECOND' is lexicographically first
            Word 'first' is lexicographically first
    */
```

19.1.32 min_element

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator min_element(ForwardIterator first, ForwardIterator last);`
  - `ForwardIterator min_element(ForwardIterator first, ForwardIterator last, Comparator comp);`
- Description:
  - The first prototype: an iterator pointing to the smallest element in the range implied by the range `[first, last)` is returned using `operator<` of the data type to which the iterators point to decide which of the elements is the smallest.
  - The second prototype: rather than using `operator<`, the binary predicate `comp` is used to make the comparisons between the elements implied by the iterator range `[first, last)`. The element for which `comp` returns `false` most often is returned.
- Example:

```
    #include <algorithm>
    #include <iostream>
    using namespace std;

    class AbsValue
    {
        public:
            bool operator()(int first, int second) const
            {
                return abs(first) < abs(second);
            }
    };
    int main()
    {
        int     ia[] = {-4, 7, -2, 10, -12};

        cout << "The minimum int value is " << *min_element(ia, ia + 5) <<
                '\n';
    cout << "The minimum absolute int value is " <<
            *min_element(ia, ia + 5, AbsValue{}) << '\n';
}
/*
    Displays:
        The minimum int value is -12
        The minimum absolute int value is -2
*/
```

19.1.33 mismatch

- Header file: `<algorithm>`
- Function prototypes:
  - `pair<InputIterator1, InputIterator2> mismatch(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2);`
  - `pair<InputIterator1, InputIterator2> mismatch(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, Compare comp);`
- Description:
  - The first prototype: the two sequences of elements starting at `first1` and `first2` are compared using the equality operator of the data type to which the iterators point. Comparison stops if the compared elements differ (i.e., `operator==` returns false) or `last1` is reached. A `pair` containing iterators pointing to the final positions is returned. The second sequence may contain more elements than the first sequence. The behavior of the algorithm is undefined if the second sequence contains fewer elements than the first sequence.
  - The second prototype: the two sequences of elements starting at `first1` and `first2` are compared using the binary comparison operation as defined by `comp`, instead of `operator==`. Comparison stops if the `comp` function returns `false` or `last1` is reached. A `pair` containing iterators pointing to the final positions is returned. The second sequence may contain more elements than the first sequence. The behavior of the algorithm is undefined if the second sequence contains fewer elements than the first sequence.
- Example:

```
#include <algorithm>
#include <string>
#include <cstring>
#include <iostream>
#include <utility>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first, string const &second) const
        {
            return strcasecmp(first.c_str(), second.c_str()) == 0;
        }
};
int main()
{
    string range1[] =
        {
            "alpha", "bravo", "foxtrot", "hotel", "zulu"
        };
    string range2[] =
        {
            "alpha", "bravo", "foxtrot", "Hotel", "zulu"
        };
    pair<string *, string *> pss = mismatch(range1, range1 + 5, range2);

    cout << "The elements " << *pss.first << " and " << *pss.second <<
            " at offset " << (pss.first - range1) << " differ\n";
    if
    (
        mismatch(range1, range1 + 5, range2, CaseString{}).first
        ==
        range1 + 5
    )
        cout << "When compared case-insensitively they match\n";
}
/*
    Displays:
        The elements hotel and Hotel at offset 3 differ
        When compared case-insensitively they match
*/
```

19.1.34 next_permutation

- **Header file:** `<algorithm>`
- **Function prototypes:**
  - `bool next_permutation(BidirectionalIterator first, BidirectionalIterator last);`
  - `bool next_permutation(BidirectionalIterator first, BidirectionalIterator last, Comp comp);`
- **Description:**
  - The first prototype: the next permutation, given the sequence of elements in the range `[first, last)`, is determined. For example, if the elements `1, 2` and `3` are the range for which `next_permutation` is called, then subsequent calls of `next_permutation` reorders the following series:

    ```
    1 2 3
    1 3 2
    2 1 3
    2 3 1
    3 1 2
    3 2 1
    ```

    This example shows that the elements are reordered such that each new permutation represents the next bigger value (132 is bigger than 123, 213 is bigger than 132, etc.) using `operator<` of the data type to which the iterators point. The value `true` is returned if a reordering took place, the value `false` is returned if no reordering took place, which is the case if the sequence represents the last (biggest) value. In that case, the sequence is also sorted using `operator<`.

  - The second prototype: the next permutation given the sequence of elements in the range `[first, last)` is determined, using the binary predicate `comp` to compare elements. The elements in the range are reordered. The value `true` is returned if a reordering took place, the value `false` is returned if no reordering took place, which is the case if the resulting sequence would haven been ordered using the binary predicate `comp` to compare elements.

- Example:

```
#include <algorithm>
#include <iterator>
#include <iostream>
#include <string>
#include <cstring>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first, string const &second) const
        {
            return strcasecmp(first.c_str(), second.c_str()) < 0;
        }
};
int main()
{
    string saints[] = {"Oh", "when", "the", "saints"};

    cout << "All permutations of 'Oh when the saints':\n";
    cout << "Sequences:\n";
    do
    {
        copy(saints, saints + 4, ostream_iterator<string>{ cout, " " });
        cout << '\n';
    }
    while (next_permutation(saints, saints + 4, CaseString{}));

    cout << "After first sorting the sequence:\n";
    sort(saints, saints + 4, CaseString{});
    cout << "Sequences:\n";
    do
    {
        copy(saints, saints + 4, ostream_iterator<string>{ cout, " " });
        cout << '\n';
    }
    while (next_permutation(saints, saints + 4, CaseString{}));
}
/*
    Displays (partially):
        All permutations of 'Oh when the saints':
        Sequences:
        Oh when the saints
        saints Oh the when
        saints Oh when the
        saints the Oh when
        ...
```

```
            After first sorting the sequence:
            Sequences:
            Oh saints the when
            Oh saints when the
            Oh the saints when
            Oh the when saints
            ...
    */
```

19.1.35 nth_element

- Header file: `<algorithm>`
- Function prototypes:
  - `void nth_element(RandomAccessIterator first, RandomAccessIterator nth, RandomAccessIterator last);`
  - `void nth_element(RandomAccessIterator first, RandomAccessIterator nth, RandomAccessIterator last, Compare comp);`
- Description:
  - The first prototype: all elements in the range `[first, last)` are sorted relative to the element pointed to by `nth`: all elements in the range `[left, nth)` are smaller than the element pointed to by `nth`, and alle elements in the range `[nth + 1, last)` are greater than the element pointed to by `nth`. The two subsets themselves are not sorted. The `operator<` of the data type to which the iterators point is used to compare the elements.
  - The second prototype: all elements in the range `[first, last)` are sorted relative to the element pointed to by `nth`: all elements in the range `[left, nth)` are smaller than the element pointed to by `nth`, and alle elements in the range `[nth + 1, last)` are greater than the element pointed to by `nth`. The two subsets themselves are not sorted. The `comp` function object is used to compare the elements.
- Example:

```
#include <algorithm>
#include <iostream>
#include <iterator>
#include <functional>
using namespace std;

int main()
{
    int ia[] = {1, 3, 5, 7, 9, 2, 4, 6, 8, 10};

    nth_element(ia, ia + 3, ia + 10);

    cout << "sorting with respect to " << ia[3] << '\n';
    copy(ia, ia + 10, ostream_iterator<int>(cout, " "));
    cout << '\n';

    nth_element(ia, ia + 5, ia + 10, greater<int>());

    cout << "sorting with respect to " << ia[5] << '\n';
    copy(ia, ia + 10, ostream_iterator<int>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        sorting with respect to 4
        1 2 3 4 9 7 5 6 8 10
        sorting with respect to 5
        10 8 7 9 6 5 3 4 2 1
*/
```

19.1.36 partial_sort

- Header file: `<algorithm>`
- Function prototypes:
  - `void partial_sort(RandomAccessIterator first, RandomAccessIterator middle, RandomAccessIterator last);`
  - `void partial_sort(RandomAccessIterator first, RandomAccessIterator middle, RandomAccessIterator last, Compare comp);`
- Description:
  - The first prototype: the (`middle - first`) smallest elements are sorted and stored in the range `[first, middle)` using the `operator<` of the data type to which the iterators point to compare elements. The remaining elements of the series remain unsorted, and are stored in the range `[middle, last)`.
  - The second prototype: the (`middle - first`) smallest elements (according to the provided binary predicate `comp`) are sorted and stored in the range `[first, middle)`. The remaining elements of the series remain unsorted.
- Example:

```
#include <algorithm>
#include <iostream>
#include <functional>
#include <iterator>
using namespace std;

int main()
{
    int ia[] = {1, 3, 5, 7, 9, 2, 4, 6, 8, 10};

    partial_sort(ia, ia + 3, ia + 10);

    cout << "find the 3 smallest elements:\n";
    copy(ia, ia + 10, ostream_iterator<int>(cout, " "));
    cout << '\n';

    cout << "find the 5 biggest elements:\n";
    partial_sort(ia, ia + 5, ia + 10, greater<int>());
    copy(ia, ia + 10, ostream_iterator<int>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        find the 3 smallest elements:
```

```
        1 2 3 7 9 5 4 6 8 10
        find the 5 biggest elements:
        10 9 8 7 6 1 2 3 4 5
*/
```

19.1.37 partial_sort_copy

- Header file: `<algorithm>`
- Function prototypes:
  - `void partial_sort_copy(InputIterator first, InputIterator last, RandomAccessIterator dest_first, RandomAccessIterator dest_last);`
  - `void partial_sort_copy(InputIterator first, InputIterator last, RandomAccessIterator dest_first, RandomAccessIterator dest_last, Compare comp);`
- Description:
  - The first prototype: the (`dest_last - dest_first`) smallest elements in the range `[first, last)` are copied to the range `[dest_first, dest_last)`, using the `operator<` of the data type to which the iterators point to decide which of the elements to copy.
  - The second prototype: the (`dest_last - dest_first`) smallest elements in the range `[first, last)` (as decided by the binary predicate `comp` returning `true`). The elements for which the predicate `comp` returns `true` most often are copied to the range `[dest_first, dest_last)`.
- Example:

```
#include <algorithm>
#include <iostream>
#include <functional>
#include <iterator>
using namespace std;

int main()
{
    int ia[] = {1, 10, 3, 8, 5, 6, 7, 4, 9, 2};
    int ia2[6];

    partial_sort_copy(ia, ia + 10, ia2, ia2 + 6);

    copy(ia, ia + 10, ostream_iterator<int>(cout, " "));
    cout << '\n';
    cout << "the 6 smallest elements: ";
    copy(ia2, ia2 + 6, ostream_iterator<int>(cout, " "));
    cout << '\n';

    cout << "the 4 smallest elements to a larger range:\n";
    partial_sort_copy(ia, ia + 4, ia2, ia2 + 6);
    copy(ia2, ia2 + 6, ostream_iterator<int>(cout, " "));
    cout << '\n';

    cout << "the 4 biggest elements to a larger range:\n";
    partial_sort_copy(ia, ia + 4, ia2, ia2 + 6, greater<int>());
```

```
        copy(ia2, ia2 + 6, ostream_iterator<int>(cout, " "));
        cout << '\n';
    }
    /*
        Displays:
            1 10 3 8 5 6 7 4 9 2
            the 6 smallest elements: 1 2 3 4 5 6
            the 4 smallest elements to a larger range:
            1 3 8 10 5 6
            the 4 biggest elements to a larger range:
            10 8 3 1 5 6
    */
```

19.1.38 partial_sum

- Header file: `<numeric>`
- Function prototypes:
  - `OutputIterator partial_sum(InputIterator first, InputIterator last, OutputIterator result);`
  - `OutputIterator partial_sum(InputIterator first, InputIterator last, OutputIterator result, BinaryOperation op);`
- Description:
  - The first prototype: each element in the range `[result, <returned OutputIterator>)` receives a value which is obtained by adding the elements in the corresponding range of the range `[first, last)`. The first element in the resulting range will be equal to the element pointed to by `first`.
  - The second prototype: the value of each element in the range `[result, <returned OutputIterator>)` is obtained by applying the binary operator `op` to the previous element in the resulting range and the corresponding element in the range `[first, last)`. The first element in the resulting range will be equal to the element pointed to by `first`.
- Example:

```
    #include <numeric>
    #include <algorithm>
    #include <iostream>
    #include <functional>
    #include <iterator>
    using namespace std;

    int main()
    {
        int ia[] = {1, 2, 3, 4, 5};
        int ia2[5];

        copy(ia2,
            partial_sum(ia, ia + 5, ia2),
            ostream_iterator<int>(cout, " "));
        cout << '\n';

        copy(ia2,
            partial_sum(ia, ia + 5, ia2, multiplies<int>()),
            ostream_iterator<int>(cout, " "));
        cout << '\n';
    }
    /*
        Displays:
            1 3 6 10 15
            1 2 6 24 120
    */
```

19.1.39 partition

- Header file: `<algorithm>`
- Function prototype:
  - `BidirectionalIterator partition(BidirectionalIterator first, BidirectionalIterator last, UnaryPredicate pred);`
- Description:
  - All elements in the range `[first, last)` for which the unary predicate `pred` evaluates as `true` are placed before the elements which evaluate as `false`. The return value points just beyond the last element in the partitioned range for which `pred` evaluates as `true`.
- Example:

```
    #include <algorithm>
    #include <iostream>
    #include <string>
    #include <iterator>
    using namespace std;

    class LessThan
    {
        int d_x;
        public:
            LessThan(int x)
            :
                d_x(x)
            {}
            bool operator()(int value) const
            {
                return value <= d_x;
            }
    };
    int main()
    {
        int ia[] = {1, 3, 5, 7, 9, 10, 2, 8, 6, 4};
        int *split;

        split = partition(ia, ia + 10, LessThan{ ia[9] });
        cout << "Last element <= 4 is ia[" << split - ia - 1 << "]\n";

        copy(ia, ia + 10, ostream_iterator<int>{ cout, " " });
        cout << '\n';
    }
```

```
/*
    Displays:
        Last element <= 4 is ia[3]
        1 3 4 2 9 10 7 8 6 5
*/
```

19.1.40 prev_permutation

- Header file: `<algorithm>`
- Function prototypes:
  - `bool prev_permutation(BidirectionalIterator first, BidirectionalIterator last);`
  - `bool prev_permutation(BidirectionalIterator first, BidirectionalIterator last, Comp comp);`
- Description:
  - The first prototype: the previous permutation given the sequence of elements in the range `[first, last)` is determined. The elements in the range are reordered such that the first ordering is obtained representing a 'smaller' value (see `next_permutation` (section 19.1.34) for an example involving the opposite ordering). The value `true` is returned if a reordering took place, the value `false` is returned if no reordering took place, which is the case if the provided sequence was already ordered, according to the `operator<` of the data type to which the iterators point.
  - The second prototype: the previous permutation given the sequence of elements in the range `[first, last)` is determined , using the binary predicate `comp` to compare elements. The elements in the range are reordered. The value `true` is returned if a reordering took place, the value `false` is returned if no reordering took place, which is the case if the original sequence was already ordered, using the binary predicate `comp` to compare two elements.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <cstring>
#include <iterator>
using namespace std;

class CaseString
{
    public:
        bool operator()(string const &first, string const &second) const
        {
            return strcasecmp(first.c_str(), second.c_str()) < 0;
        }
};
int main()
{
    string  saints[] = {"Oh", "when", "the", "saints"};

    cout << "All previous permutations of 'Oh when the saints':\n";
    cout << "Sequences:\n";
    do
    {
        copy(saints, saints + 4, ostream_iterator<string>{ cout, " " });
        cout << '\n';
    }
    while (prev_permutation(saints, saints + 4, CaseString{}));

    cout << "After first sorting the sequence:\n";
    sort(saints, saints + 4, CaseString{});
    cout << "Sequences:\n";
    while (prev_permutation(saints, saints + 4, CaseString{}))
    {
        copy(saints, saints + 4, ostream_iterator<string>{ cout, " " });
        cout << '\n';
    }
    cout << "No (more) previous permutations\n";
}
/*
    Displays:
        All previous permutations of 'Oh when the saints':
        Sequences:
        Oh when the saints
        Oh when saints the
        Oh the when saints
        Oh the saints when
        Oh saints when the
        Oh saints the when
        After first sorting the sequence:
        Sequences:
        No (more) previous permutations
*/
```

19.1.41 remove

- Header file: `<algorithm>`
- Function prototype:
  - `ForwardIterator remove(ForwardIterator first, ForwardIterator last, Type const &value);`
- Description:
  - The elements in the range pointed to by `[first, last)` are reordered such that all values unequal to `value` are placed at the beginning of the range. The returned forward iterator points to the first element that can be removed after reordering. The range `[returnvalue, last)` is called the *leftover* of the algorithm. Note that the leftover may contain elements different from `value`, but these elements can be removed safely, as such elements are also present in the range `[first, returnvalue)`. Such duplication is the result of the fact that the algorithm *copies*, rather than *moves* elements into new locations. The function uses `operator==` of the data type to which the iterators point to determine which elements to remove.
- Example:

```
#include <algorithm>
```

```
#include <iostream>
#include <string>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november", "alpha",
            "alpha", "alpha", "papa", "quebec" };
    string *removed;
    size_t const size = sizeof(words) / sizeof(string);

    cout << "Removing all \"alpha\"s:\n";
    removed = remove(words, words + size, "alpha");
    copy(words, removed, ostream_iterator<string>(cout, " "));
    cout << '\n'
         << "Leftover elements are:\n";
    copy(removed, words + size, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
                    Removing all "alpha"s:
                    kilo lima mike november papa quebec
                    Leftover elements are:
                    alpha alpha alpha papa quebec
*/
```

19.1.42 remove_copy

- **Header file:** `<algorithm>`
- **Function prototypes:**
  - `OutputIterator remove_copy(InputIterator first, InputIterator last, OutputIterator result, Type const &value);`
- **Description:**
  - The elements in the range pointed to by `[first, last)` not matching `value` are copied to the range `[result, returnvalue)`, where `returnvalue` is the value returned by the function. The range `[first, last)` is not modified. The function uses `operator==` of the data type to which the iterators point to determine which elements not to copy.
- **Example:**

```
#include <algorithm>
#include <iostream>
#include <string>
#include <functional>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november", "alpha",
            "oscar", "alpha", "alpha", "papa", "quebec" };
    size_t const size = sizeof(words) / sizeof(string);
    string remaining
            [
                size -
                count_if
                (
                    words, words + size,
                    bind2nd(equal_to<string>(), "alpha"s)
                )
            ];
    string *returnvalue =
            remove_copy(words, words + size, remaining, "alpha");

    cout << "Removing all \"alpha\"s:\n";
    copy(remaining, returnvalue, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        Removing all "alpha"s:
        kilo lima mike november oscar papa quebec
*/
```

19.1.43 remove_copy_if

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `OutputIterator remove_copy_if(InputIterator first, InputIterator last, OutputIterator result, UnaryPredicate pred);`
- **Description:**
  - The elements in the range pointed to by `[first, last)` for which the unary predicate `pred` returns `true` are removed from the resulting copy. All other elements are copied to the range `[result, returnvalue)`, where `returnvalue` is the value returned by the function. The range `[first, last)` is not modified.
- **Example:**

```
#include <algorithm>
#include <iostream>
#include <string>
#include <functional>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november", "alpha",
            "oscar", "alpha", "alpha", "papa", "quebec" };
        size_t const size = sizeof(words) / sizeof(string);
        string remaining[
                          size -
                          count_if
                          (
                              words, words + size,
                              bind2nd(equal_to<string>(), "alpha")
                          )
                      ];
        string *returnvalue =
                    remove_copy_if
                    (
                        words, words + size, remaining,
                        bind2nd(equal_to<string>(), "alpha")
                    );

        cout << "Removing all \"alpha\"s:\n";
        copy(remaining, returnvalue, ostream_iterator<string>(cout, " "));
        cout << '\n';
    }
    /*
        Displays:
            Removing all "alpha"s:
            kilo lima mike november oscar papa quebec
    */
```

19.1.44 remove_if

- Header file: `<algorithm>`
- Function prototype:
  - `ForwardIterator remove_if(ForwardIterator first, ForwardIterator last, UnaryPredicate pred);`
- Description:
  - The elements in the range pointed to by `[first, last)` are reordered such that all values for which the unary predicate `pred` evaluates as `false` are placed at the beginning of the range, while their relative order is kept. The returned forward iterator points to the first element, after reordering, for which `pred` returns `true`. The range `[returnvalue, last)` is called the *leftover* of the algorithm. The leftover may contain elements for which the predicate `pred` returns `false`, but these can safely be removed, as such elements are also present in the range `[first, returnvalue)`. Such duplication is the result of the fact that the algorithm *copies*, rather than *moves* elements into new locations.
- Example:

```
    #include <functional>
    #include <algorithm>
    #include <iostream>
    #include <string>
    #include <iterator>
    using namespace std;

    int main()
```

```
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november", "alpha",
            "oscar", "alpha", "alpha", "papa", "quebec" };
    size_t const size = sizeof(words) / sizeof(string);

    cout << "Removing all \"alpha\"s:\n";

    string *removed = remove_if(words, words + size,
                bind2nd(equal_to<string>(), "alpha"s));

    copy(words, removed, ostream_iterator<string>(cout, " "));
    cout << '\n'
         << "Trailing elements are:\n";
    copy(removed, words + size, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        Removing all "alpha"s:
        kilo lima mike november oscar papa quebec
        Trailing elements are:
        oscar alpha alpha papa quebec
*/
```

19.1.45 replace

- Header file: `<algorithm>`
- Function prototype:
  - `ForwardIterator replace(ForwardIterator first, ForwardIterator last, Type const &oldvalue, Type const &newvalue);`
- Description:
  - All elements equal to `oldvalue` in the range pointed to by `[first, last)` are replaced by a copy of `newvalue`. The algorithm uses `operator==` of the data type to which the iterators point.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november", "alpha",
            "oscar", "alpha", "alpha", "papa" };
    size_t const size = sizeof(words) / sizeof(string);

    replace(words, words + size, "alpha"s, "ALPHA"s);
    copy(words, words + size, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays
        kilo ALPHA lima mike ALPHA november ALPHA oscar ALPHA ALPHA papa
*/
```

19.1.46 replace_copy

- Header file: `<algorithm>`
- Function prototype:
  - `OutputIterator replace_copy(InputIterator first, InputIterator last, OutputIterator result, Type const &oldvalue, Type const &newvalue);`
- Description:
  - All elements equal to `oldvalue` in the range pointed to by `[first, last)` are replaced by a copy of `newvalue` in a new range `[result, returnvalue)`, where `returnvalue` is the return value of the function. The algorithm uses `operator==` of the data type to which the iterators point.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november", "alpha",
            "oscar", "alpha", "alpha", "papa"};
    size_t const size = sizeof(words) / sizeof(string);
    string remaining[size];

    copy
    (
        remaining,
        replace_copy(words, words + size, remaining, "alpha"s, "ALPHA"s),
        ostream_iterator<string>(cout, " ")
    );
    cout << '\n';
}
/*
    Displays:
        kilo ALPHA lima mike ALPHA november ALPHA oscar ALPHA ALPHA papa
*/
```

19.1.47 replace_copy_if

- Header file: `<algorithm>`

- Function prototypes:
  - `OutputIterator replace_copy_if(ForwardIterator first, ForwardIterator last, OutputIterator result, UnaryPredicate pred, Type const &value);`
- Description:
  - The elements in the range pointed to by `[first, last)` are copied to the range `[result, returnvalue)`, where `returnvalue` is the value returned by the function. The elements for which the unary predicate `pred` returns `true` are replaced by `value`. The range `[first, last)` is not modified.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <functional>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november",
          "alpha", "oscar", "alpha", "alpha", "papa"};
    size_t const size = sizeof(words) / sizeof(string);
    string result[size];

    // Note: the comparisons are: "mike" > word[i]
    replace_copy_if(words, words + size, result,
                    bind1st(greater<string>(), "mike"s), "ALPHA"s);
    copy (result, result + size, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays (all strings in words[] which are exceeded by 'mike' are
              replaced by ALPHA):
        ALPHA ALPHA ALPHA mike ALPHA november ALPHA oscar ALPHA ALPHA papa
*/
```

19.1.48 replace_if

- Header file: `<algorithm>`
- Function prototype:
  - `ForwardIterator replace_if(ForwardIterator first, ForwardIterator last, UnaryPredicate pred, Type const &value);`
- Description:
  - The elements in the range pointed to by `[first, last)` for which the unary predicate `pred` evaluates as `true` are replaced by `value`.

Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <functional>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "alpha", "lima", "mike", "alpha", "november", "alpha",
            "oscar", "alpha", "alpha", "papa"};
    size_t const size = sizeof(words) / sizeof(string);

    replace_if(words, words + size,
               bind1st(equal_to<string>(), "alpha"s), "ALPHA"s);
    copy(words, words + size, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        kilo ALPHA lima mike ALPHA november ALPHA oscar ALPHA ALPHA papa
*/
```

19.1.49 reverse

- **Header file:** `<algorithm>`
- **Function prototype:**
  - `void reverse(BidirectionalIterator first, BidirectionalIterator last);`
- **Description:**
  - **The elements in the range pointed to by `[first, last)` are reversed.**
- **Example:**

```
#include <algorithm>
#include <iostream>
#include <string>
using namespace std;

int main()
{
    string line;

    while (getline(cin, line))
    {
        reverse(line.begin(), line.end());
        cout << line << '\n';
    }
}
```

19.1.50 reverse_copy

- Header file: `<algorithm>`
- Function prototype:
  - `OutputIterator reverse_copy(BidirectionalIterator first, BidirectionalIterator last, OutputIterator result);`
- Description:
  - The elements in the range pointed to by `[first, last)` are copied to the range `[result, returnvalue)` in reversed order. The value `returnvalue` is the value that is returned by the function.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
using namespace std;

int main()
{
    string line;

    while (getline(cin, line))
    {
        size_t    size = line.size();
        char        copy[size + 1];

        cout << "line: " << line << '\n' <<
                "reversed: ";
        reverse_copy(line.begin(), line.end(), copy);
        copy[size] = 0;     // 0 is not part of the reversed
                            // line !
        cout << copy << '\n';
    }
}
```

19.1.51 rotate

- Header file: `<algorithm>`
- Function prototype:
  - `void rotate(ForwardIterator first, ForwardIterator middle, ForwardIterator last);`
- Description:
  - The elements implied by the range `[first, middle)` are moved to the end of the container, the elements implied by the range `[middle, last)` are moved to the beginning of the container, keeping the order of the elements in the two subsets intact.
- Example:

```
#include <algorithm>
```

```
#include <iostream>
#include <string>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
        { "kilo", "lima", "mike", "november", "oscar",
          "foxtrot", "golf", "hotel", "india", "juliet" };
    size_t const size = sizeof(words) / sizeof(string);
    size_t const midsize = size / 2;

    rotate(words, words + midsize, words + size);

    copy(words, words + size, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        foxtrot golf hotel india juliet kilo lima mike november oscar
*/
```

19.1.52 rotate_copy

- Header file: `<algorithm>`
- Function prototypes:
  - `OutputIterator rotate_copy(ForwardIterator first, ForwardIterator middle, ForwardIterator last, OutputIterator result);`
- Description:
  - The elements implied by the range `[middle, last)` and then the elements implied by `[first, middle)` are copied to the destination container having range `[result, returnvalue)`, where `returnvalue` is the iterator returned by the function. The original order of the elements in the two subsets is not altered.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <iterator>
using namespace std;

int main()
{
    string words[] =
       { "kilo", "lima", "mike", "november", "oscar",
          "foxtrot", "golf", "hotel", "india", "juliet" };
    size_t const size = sizeof(words) / sizeof(string);
    size_t const midsize = size / 2;
    string out[size];
    copy(out,
        rotate_copy(words, words + midsize, words + size, out),
        ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        foxtrot golf hotel india juliet kilo lima mike november oscar
*/
```

19.1.53 search

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator1 search(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2);`
  - `ForwardIterator1 search(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2, BinaryPredicate pred);`
- Description:
  - The first prototype: an iterator into the first range `[first1, last1)` is returned where the elements in the range `[first2, last2)` are found using `operator==` of the data type to which the iterators point. If no such location exists, `last1` is returned.
  - The second prototype: an iterator into the first range `[first1, last1)` is returned where the elements in the range `[first2, last2)` are found using the provided binary predicate `pred` to compare the elements in the two ranges. If no such location exists, `last1` is returned.
- Example:

```
#include <algorithm>
#include <iostream>
#include <iterator>
using namespace std;

class absInt
{
    public:
        bool operator()(int i1, int i2) const
        {
            return abs(i1) == abs(i2);
        }
};
int main()
{
    int range1[] =  {-2, -4, -6, -8, 2, 4, 6, 8};
    int range2[] =  {6, 8};

    copy
    (
        search(range1, range1 + 8, range2, range2 + 2),
        range1 + 8,
            ostream_iterator<int>(cout, " ")
        );
        cout << '\n';

        copy
        (
            search(range1, range1 + 8, range2, range2 + 2, absInt()),
            range1 + 8,
            ostream_iterator<int>(cout, " ")
        );
        cout << '\n';
    }
    /*
        Displays:
            6 8
            -6 -8 2 4 6 8
    */
```

19.1.54 search_n

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator1 search_n(ForwardIterator1 first1, ForwardIterator1 last1, Size count, Type const &value);`
  - `ForwardIterator1 search_n(ForwardIterator1 first1, ForwardIterator1 last1, Size count, Type const &value, BinaryPredicate pred);`
- Description:
  - The first prototype: an iterator into the first range `[first1, last1)` is returned where `n` consecutive elements having value `value` are found using `operator==` of the data type to which the iterators point to compare the elements. If no such location exists, `last1` is returned.
  - The second prototype: an iterator into the first range `[first1, last1)` is returned where `n` consecutive elements having value `value` are found using the provided binary predicate `pred` to compare the elements. If no such location exists, `last1` is returned.
- Example:

```
    #include <algorithm>
    #include <iostream>
    #include <iterator>
    using namespace std;

    bool eqInt(int i1, int i2)
    {
        return abs(i1) == abs(i2);
    }
    int main()
    {
        int range1[] =  {-2, -4, -4, -6, -8, 2, 4, 4, 6, 8};

        copy
        (
            search_n(range1, range1 + 8, 2, 4),
            range1 + 8,
            ostream_iterator<int>(cout, " ")
        );
        cout << '\n';

        copy
        (
            search_n(range1, range1 + 8, 2, 4, eqInt),
            range1 + 8,
            ostream_iterator<int>(cout, " ")
        );
        cout << '\n';
    }
    /*
        Displays:
            4 4
            -4 -4 -6 -8 2 4 4
    */
```

19.1.55 set_difference

- Header file: `<algorithm>`
- Function prototypes:
  - `OutputIterator set_difference(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result);`
  - `OutputIterator set_difference(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result, Compare comp);`
- Description:
  - The first prototype: a sorted sequence of the elements pointed to by the range `[first1, last1)` that are not present in the range `[first2, last2)` is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using `operator<` of the data type to which the iterators point.
  - The second prototype: a sorted sequence of the elements pointed to by the range `[first1, last1)` that are not present in the range `[first2, last2)` is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using the `comp` function object.
- Example:

```
    #include <algorithm>
    #include <iostream>
    #include <string>
    #include <cstring>
    #include <iterator>
    using namespace std;

    bool caseless(string const &left, string const &right)
    {
```

```
    return strcasecmp(left.c_str(), right.c_str()) < 0;
}
int main()
{
    string set1[] = { "kilo", "lima", "mike", "november",
                      "oscar", "papa", "quebec" };
    string set2[] = { "papa", "quebec", "romeo"};
    string result[7];
    string *returned;

    copy(result,
        set_difference(set1, set1 + 7, set2, set2 + 3, result),
        ostream_iterator<string>(cout, " "));
    cout << '\n';

    string set3[] = { "PAPA", "QUEBEC", "ROMEO"};

    copy(result,
        set_difference(set1, set1 + 7, set3, set3 + 3, result,
        caseless),
        ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        kilo lima mike november oscar
        kilo lima mike november oscar
*/
```

19.1.56 set_intersection

- Header file: `<algorithm>`
- Function prototypes:
  - `OutputIterator set_intersection(InputIterator1 first1, InputIterator1) linebreak() tt(last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result);`
  - `OutputIterator set_intersection(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result, Compare comp);`
- Description:
  - The first prototype: a sorted sequence of the elements pointed to by the range `[first1, last1)` that are also present in the range `[first2, last2)` is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using `operator<` of the data type to which the iterators point.
  - The second prototype: a sorted sequence of the elements pointed to by the range `[first1, last1)` that are also present in the range `[first2, last2)` is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using the `comp` function object.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <cstring>
#include <iterator>
using namespace std;

bool caseless(string const &left, string const &right)
{
    return strcasecmp(left.c_str(), right.c_str()) < 0;
}
int main()
{
    string set1[] = { "kilo", "lima", "mike", "november",
                      "oscar", "papa", "quebec" };
    string set2[] = { "papa", "quebec", "romeo"};
    string result[7];
    string *returned;

    copy(result,
        set_intersection(set1, set1 + 7, set2, set2 + 3, result),
        ostream_iterator<string>(cout, " "));
    cout << '\n';

    string set3[] = { "PAPA", "QUEBEC", "ROMEO"};

    copy(result,
        set_intersection(set1, set1 + 7, set3, set3 + 3, result,
                                                        caseless),
        ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        papa quebec
        papa quebec
*/
```

19.1.57 set_symmetric_difference

- **Header file:** `<algorithm>`
- **Function prototypes:**
  - `OutputIterator set_symmetric_difference(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result);`
  - `OutputIterator set_symmetric_difference(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result, Compare comp);`
- **Description:**
  - The first prototype: a sorted sequence of the elements pointed to by the range `[first1, last1)` that are not present in the range `[first2, last2)` and those in the range

  `[first2, last2)` that are not present in the range `[first1, last1)` is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using `operator<` of the data type to which the iterators point.
  - The second prototype: a sorted sequence of the elements pointed to by the range `[first1, last1)` that are not present in the range `[first2, last2)` and those in the range `[first2, last2)` that are not present in the range `[first1, last1)` is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using the `comp` function object.

- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <cstring>
#include <iterator>
using namespace std;

bool caseless(string const &left, string const &right)
{
    return strcasecmp(left.c_str(), right.c_str()) < 0;
}
int main()
{
    string set1[] = { "kilo", "lima", "mike", "november",
                      "oscar", "papa", "quebec" };
    string set2[] = { "papa", "quebec", "romeo"};
    string result[7];

    copy(result,
        set_symmetric_difference(set1, set1 + 7, set2, set2 + 3,
                                                       result),
        ostream_iterator<string>(cout, " "));
    cout << '\n';

    string set3[] = { "PAPA", "QUEBEC", "ROMEO"};

    copy(result,
        set_symmetric_difference(set1, set1 + 7, set3, set3 + 3,
                                               result, caseless),
        ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        kilo lima mike november oscar romeo
        kilo lima mike november oscar ROMEO
*/
```

19.1.58 set_union

- Header file: `<algorithm>`
- Function prototypes:

  - `OutputIterator set_union(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result);`
  - `OutputIterator set_union(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2, OutputIterator result, Compare comp);`

- Description:
  - The first prototype: a sorted sequence of the elements that are present in either the range `[first1, last1)` or the range `[first2, last2)` or in both ranges is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using `operator<` of the data type to which the iterators point;
  - The second prototype: a sorted sequence of the elements that are present in either the range `[first1, last1)` or the range `[first2, last2)` or in both ranges is returned, starting at `result`, and ending at the `OutputIterator` returned by the function. The elements in the two ranges must have been sorted using `comp` function object.

  Note that in the final range each element appears only once, unless there are already duplicate elements in the sources, in which case they will also appear multiple times in the result;

- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <cstring>
#include <iterator>
#include <vector>
using namespace std;

bool caseless(string const &left, string const &right)
{
    return strcasecmp(left.c_str(), right.c_str()) < 0;
}
int main()
{
    string set1[] = { "kilo", "lima", "mike", "november",
                      "oscar", "papa", "quebec" };
    string set2[] = { "papa", "quebec", "romeo"};
    string result[8];

    copy(result,
        set_union(set1, set1 + 7, set2, set2 + 3, result),
        ostream_iterator<string>(cout, " "));
    cout << '\n';

    string set3[] = { "PAPA", "QUEBEC", "ROMEO"};

    copy(result,
        set_union(set1, set1 + 7, set3, set3 + 3, result, caseless),
        ostream_iterator<string>(cout, " "));
    cout << '\n';

    std::vector<int> v1 = {1, 2, 3,       4, 5, 5, 5};
    std::vector<int> v2 = {      3, 3, 3,  4, 5,       6, 7};
    set_union(v1.begin(), v1.end(), v2.begin(), v2.end(),
              ostream_iterator<int>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        kilo lima mike november oscar papa quebec romeo
        kilo lima mike november oscar papa quebec ROMEO
        1 2 3 3 3 4 5 5 5 6 7
*/
```

19.1.59 sort

- Header file: `<algorithm>`
- Function prototypes:
  - `void sort(RandomAccessIterator first, RandomAccessIterator last);`
  - `void sort(RandomAccessIterator first, RandomAccessIterator last, Compare comp);`
- Description:
  - The first prototype: the elements in the range `[first, last)` are sorted in ascending order using `operator<` of the data type to which the iterators point.
  - The second prototype: the elements in the range `[first, last)` are sorted in ascending order using the `comp` function object to compare the elements. The binary predicate `comp` should return `true` if its first argument should be placed earlier in the sorted sequence than its second argument.
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <functional>
#include <iterator>
using namespace std;

int main()
{
    string words[] = {"november", "kilo", "mike", "lima",
                      "oscar", "quebec", "papa"};

    sort(words, words + 7);
    copy(words, words + 7, ostream_iterator<string>(cout, " "));
    cout << '\n';

    sort(words, words + 7, greater<string>());
    copy(words, words + 7, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        kilo lima mike november oscar papa quebec
```

```
            quebec papa oscar november mike lima kilo
    */
```

19.1.60 stable_partition

- Header file: `<algorithm>`
- Function prototype:
  - `BidirectionalIterator stable_partition(BidirectionalIterator first, BidirectionalIterator last, UnaryPredicate pred);`
- Description:
  - All elements in the range `[first, last)` for which the unary predicate `pred` evaluates as `true` are placed before the elements which evaluate as `false`. Apart from this reordering, the relative order of all elements for which the predicate evaluates to `false` and the relative order of all elements for which the predicate evaluates to `true` is kept. The return value points just beyond the last element in the partitioned range for which `pred` evaluates as `true`.
- Example:

```
    #include <algorithm>
    #include <iostream>
    #include <string>
    #include <functional>
    #include <iterator>
    using namespace std;

    int main()
    {
        int org[] = {1, 3, 5, 7, 9, 10, 2, 8, 6, 4};
        int ia[10];
        int *split;

        copy(org, org + 10, ia);
        split = partition(ia, ia + 10, bind2nd(less_equal<int>(), ia[9]));
        cout << "Last element <= 4 is ia[" << split - ia - 1 << "]\n";

        copy(ia, ia + 10, ostream_iterator<int>(cout, " "));
        cout << '\n';

        copy(org, org + 10, ia);
        split = stable_partition(ia, ia + 10,
                                    bind2nd(less_equal<int>(), ia[9]));
        cout << "Last element <= 4 is ia[" << split - ia - 1 << "]\n";

        copy(ia, ia + 10, ostream_iterator<int>(cout, " "));
        cout << '\n';
    }
    /*
        Displays:
            Last element <= 4 is ia[3]
            1 3 4 2 9 10 7 8 6 5
            Last element <= 4 is ia[3]
            1 3 2 4 5 7 9 10 8 6
    */
```

19.1.61 stable_sort

- Header file: `<algorithm>`
- Function prototypes:
  - `void stable_sort(RandomAccessIterator first, RandomAccessIterator last);`
  - `void stable_sort(RandomAccessIterator first, RandomAccessIterator last, Compare comp);`
- Description:
  - The first prototype: the elements in the range `[first, last)` are stable-sorted in ascending order using `operator<` of the data type to which the iterators point: the relative order of equal elements is kept.
  - The second prototype: the elements in the range `[first, last)` are stable-sorted in ascending order using the `comp` binary predicate to compare the elements. This predicate should return `true` if its first argument should be placed before its second argument in the sorted set of element.
- Example (annotated below):

```
#include <algorithm>
#include <iostream>
#include <string>
#include <vector>
#include <iterator>
using namespace std;

struct Pss: public pair<string, string>                         // 1
{
    Pss(string const &s1, string const &s2)
    :
        pair<string, string>(s1, s2)
    {}
};
ostream &operator<<(ostream &out, Pss const &p)                 // 2
{
    return out << "    " << p.first << " " << p.second << '\n';
}
class Sortby
{
    string Pss::*d_field;
    public:
        Sortby(string Pss::*field)                              // 3
        :
            d_field(field)
        {}
        bool operator()(Pss const &p1, Pss const &p2) const     // 4
        {
            return p1.*d_field < p2.*d_field;
        }
    };
    int main()
    {
        vector<Pss> namecity {                                      // 5
                Pss("Hampson",   "Godalming"),
                Pss("Moran",     "Eugene"),
                Pss("Goldberg",  "Eugene"),
                Pss("Moran",     "Godalming"),
                Pss("Goldberg",  "Chicago"),
                Pss("Hampson",   "Eugene")
        };

        sort(namecity.begin(), namecity.end(), Sortby{ &Pss::first });// 6

        cout << "sorted by names:\n";
        copy(namecity.begin(), namecity.end(),
                                    ostream_iterator<Pss>{ cout });

                                                                    // 7
        stable_sort(namecity.begin(), namecity.end(),
                                    Sortby{ &Pss::second });

        cout << "sorted by names within sorted cities:\n";
        copy(namecity.begin(), namecity.end(),
                                    ostream_iterator<Pss>{ cout });
    }
    /*
        Displays:
            sorted by names:
                Goldberg Eugene
                Goldberg Chicago
                Hampson Godalming
                Hampson Eugene
                Moran Eugene
                Moran Godalming
            sorted by names within sorted cities:
                Goldberg Chicago
                Goldberg Eugene
                Hampson Eugene
                Moran Eugene
                Hampson Godalming
                Moran Godalming
    */
```

Note that the example implements a solution to an often occurring problem: how to sort using multiple hierarchal criteria. The example deserves some additional attention:

- First, at `// 1` a wrapper struct `Pss` is created around `std::pair<std::string, std::string>`. The intent here is to define a type that is a wrapper around a class that is defined in the `std` namespace for which no insertion operation has been defined. This struct design conflicts with the principles outlined in section 14.7. However, inheritance is defensible here as the intention is not to add 'missing features' and as `pair` itself is in essence just Plain Old Data.
- Next (`// 2`), `operator<<` is overloaded for `Pss` objects. Although the compiler wouldn't have complained if this operator had been defined in the `std` namespace for the `pair<string,`

`string>` type, this would also have been bad style as the `std` namespace is *off limits* to ordinary programs. By defining a wrapper type around `pair<string, string>` bad style can be prevented.

- Then (`// 3`), a class `Sortby` is defined, allowing us to construct an anonymous object receiving a pointer to one of the `Pss` data members that are used for sorting. In this case, as both members are `string` objects, its constructor can easily be defined. It expects a pointer to a `string` member of the class `Pss`.
- `Sortby`'s `operator()` member (`// 4`) receives two references to `Pss` objects and uses its pointer to member to compare the appropriate fields of the `Pss` objects.
- In `main` some data is stored in a `vector` (`// 5`).
- Then (`// 6`) the first sort takes place. The least important criterion must be sorted first and for this a simple `sort` suffices. Since we want the names to be sorted within cities, the names represent the least important criterion, so we sort by names: `Sortby(&Pss::first)`.
- The next important criterion, the cities, are sorted next (`// 7`). Since the relative ordering of the *names* are not altered anymore by `stable_sort`, the ties that are observed when cities are sorted are solved in such a way that the existing relative ordering is not broken. So, we end up getting Goldberg in Eugene before Hampson in Eugene, before Moran in Eugene. To sort by cities, we use another anonymous `Sortby` object: `Sortby(&Pss::second)`.

19.1.62 swap

- Header file: `<algorithm>`
- Function prototype:
  - `void swap(Type &object1, Type &object2);`
- Description:
  - The elements `object1` and `object2` exchange their values. They do so by either cyclic copy assignment or cyclic move assignment (if available).
- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <iterator>
using namespace std;

int main()
{
    string first[] = {"alpha", "bravo", "charley"};
    string second[] = {"echo", "foxtrot", "golf"};
    size_t const n = sizeof(first) / sizeof(string);

    cout << "Before:\n";
    copy(first, first + n, ostream_iterator<string>(cout, " "));
    cout << '\n';
    copy(second, second + n, ostream_iterator<string>(cout, " "));
    cout << '\n';

    for (size_t idx = 0; idx < n; ++idx)
```

```
            swap(first[idx], second[idx]);

        cout << "After:\n";
        copy(first, first + n, ostream_iterator<string>(cout, " "));
        cout << '\n';
        copy(second, second + n, ostream_iterator<string>(cout, " "));
        cout << '\n';
    }
    /*
        Displays:
            Before:
            alpha bravo charley
            echo foxtrot golf
            After:
            echo foxtrot golf
            alpha bravo charley
    */
```

19.1.63 swap_ranges

- Header file: `<algorithm>`
- Function prototype:
  - `ForwardIterator2 swap_ranges(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 result);`
- Description:
  - The elements in the range pointed to by `[first1, last1)` are swapped with the elements in the range `[result, returnvalue)`, where `returnvalue` is the value returned by the function. The two ranges must be disjoint.
- Example:

```
    #include <algorithm>
    #include <iostream>
    #include <string>
    #include <iterator>
    using namespace std;

    int main()
    {
        string first[] = {"alpha", "bravo", "charley"};
        string second[] = {"echo", "foxtrot", "golf"};
        size_t const n = sizeof(first) / sizeof(string);

        cout << "Before:\n";
        copy(first, first + n, ostream_iterator<string>(cout, " "));
        cout << '\n';
        copy(second, second + n, ostream_iterator<string>(cout, " "));
        cout << '\n';

        swap_ranges(first, first + n, second);

        cout << "After:\n";
    copy(first, first + n, ostream_iterator<string>(cout, " "));
    cout << '\n';
    copy(second, second + n, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        Before:
        alpha bravo charley
        echo foxtrot golf
        After:
        echo foxtrot golf
        alpha bravo charley
*/
```

19.1.64 transform

- Header file: `<algorithm>`
- Function prototypes:
  - `OutputIterator transform(InputIterator first, InputIterator last, OutputIterator result, UnaryOperator op);`
  - `OutputIterator transform(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, OutputIterator result, BinaryOperator op);`
- Description:
  - The first prototype: the unary operator `op` is applied to each of the elements in the range `[first, last)`, and the resulting values are stored in the range starting at `result`. The return value points just beyond the last generated element.
  - The second prototype: the binary operator `op` is applied to each of the elements in the range `[first1, last1)` and the corresponding element in the second range starting at `first2`. The resulting values are stored in the range starting at `result`. The return value points just beyond the last generated element.
- Example:

```
#include <functional>
#include <vector>
#include <algorithm>
#include <iostream>
#include <string>
#include <cctype>
#include <iterator>
using namespace std;

string caps(string const &src)
{
    string tmp;
    tmp.resize(src.length());

    transform(src.begin(), src.end(), tmp.begin(), ::toupper);
    return tmp;
}
```

```
int main()
{
    string words[] = {"alpha", "bravo", "charley"};

    copy(words, transform(words, words + 3, words, caps),
                            ostream_iterator<string>(cout, " "));
    cout << '\n';

    int         values[] = {1, 2, 3, 4, 5};
    vector<int> squares;

    transform(values, values + 5, values,
                            back_inserter(squares), multiplies<int>());

    copy(squares.begin(), squares.end(),
                            ostream_iterator<int>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        ALPHA BRAVO CHARLEY
        1 4 9 16 25
*/
```

the following differences between the `for_each` (section 19.1.18) and `transform` generic algorithms should be noted:

- With `transform` the *return value* of the function object's `operator()` member is used; the argument that is passed to the `operator()` member itself is not changed.
- With `for_each` the function object's `operator()` receives a reference to an argument, which itself may be changed by the function object's `operator()`.

Also note that the range-based for loop can often be used instead of the `transform` generic algorithm. However, but different from the range-based for-loop the `transform` algorithm can also be used width sub-ranges and with reverse-iterators.

19.1.65 unique

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator unique(ForwardIterator first, ForwardIterator last);`
  - `ForwardIterator unique(ForwardIterator first, ForwardIterator last, BinaryPredicate pred);`
- Description:
  The `std::unique` generic algorithm assumes that the elements in the range have previously been sorted (cf. section 19.1.59).
  - The first prototype: using `operator==` of the data type to which the iterators point, all but the first of consecutively equal elements in the range pointed to by `[first, last)` are relocated to the end of the range. The returned forward iterator marks the beginning of the *leftover*. All elements in the range `[first, return-value)` are unique, all elements in the range `[return-value, last)` have undetermined (but valid) values.

  - The second prototype: all but the first of consecutive elements in the range pointed to by `[first, last)` for which the binary predicate `pred` returns `true` are relocated to the end of the range. The predicate `pred` expects two arguments of the data type to which the iterators point. The returned forward iterator marks the beginning of the *leftover*. For all pairs of elements in the range `[first, return-value)` `pred` returns `false` (i.e., they are *unique*). All elements in the *leftover* (i.e., the range `[return-value, last)`) have undetermined (but valid) values.

- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <cstring>
#include <iterator>
using namespace std;

bool casestring(string const &first, string const &second)
{
    return strcasecmp(first.c_str(), second.c_str()) == 0;
}
int main()
{
    string words[] = {"alpha", "alpha", "Alpha", "papa", "quebec" };
    size_t const size = sizeof(words) / sizeof(string);

    string *removed = unique(words, words + size);
    copy(words, removed, ostream_iterator<string>(cout, " "));
    cout << '\n'
         << "Trailing elements are:\n";
    copy(removed, words + size, ostream_iterator<string>(cout, " "));
    cout << '\n';

    removed = unique(words, words + size, casestring);
    copy(words, removed, ostream_iterator<string>(cout, " "));
    cout << '\n'
         << "Trailing elements are:\n";
    copy(removed, words + size, ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        alpha Alpha papa quebec
        Trailing elements are:
        quebec
        alpha papa quebec
        Trailing elements are:
        quebec quebec
*/
```

19.1.66 unique_copy

- Header file: `<algorithm>`

- Function prototypes:

- `OutputIterator unique_copy(InputIterator first, InputIterator last, OutputIterator result);`
- `OutputIterator unique_copy(InputIterator first, InputIterator last, OutputIterator result, BinaryPredicate pred);`

- Description:
  - The first prototype: the elements in the range `[first, last)` are copied to the resulting container, starting at `result`. Consecutively equal elements (using `operator==` of the data type to which the iterators point) are copied only once (keeping the first of a series of equal elements). The returned output iterator points just beyond the last copied element.
  - The second prototype: the elements in the range `[first, last)` are copied to the resulting container, starting at `result`. Consecutive elements in the range pointed to by `[first, last)` for which the binary predicate `pred` returns `true` are copied only once (keeping the first of a series of equal elements). The returned output iterator points just beyond the last copied element.

- Example:

```
#include <algorithm>
#include <iostream>
#include <string>
#include <vector>
#include <iterator>
#include <cstring>
using namespace std;

bool casestring(string const &first, string const &second)
{
    return strcasecmp(first.c_str(), second.c_str()) == 0;
}
int main()
{
    string words[] = {"oscar", "Alpha", "alpha", "alpha",
                                                "papa", "quebec" };
    size_t const size = sizeof(words) / sizeof(string);
    vector<string> remaining;

    unique_copy(words, words + size, back_inserter(remaining));

    copy(remaining.begin(), remaining.end(),
            ostream_iterator<string>(cout, " "));
    cout << '\n';

    vector<string> remaining2;

    unique_copy(words, words + size,
                            back_inserter(remaining2), casestring);

    copy(remaining2.begin(), remaining2.end(),
            ostream_iterator<string>(cout, " "));
    cout << '\n';
}
/*
    Displays:
        oscar Alpha alpha papa quebec
```

```
            oscar Alpha papa quebec
    */
```

19.1.67 upper_bound

- Header file: `<algorithm>`
- Function prototypes:
  - `ForwardIterator upper_bound(ForwardIterator first, ForwardIterator last, Type const &value);`
  - `ForwardIterator upper_bound(ForwardIterator first, ForwardIterator last, Type const &value, Compare comp);`
- Description:
  - The first prototype: the sorted elements (using ascending sort) stored in the iterator range `[first, last)` are searched for the first element that is greater than `value`. The returned iterator marks the first location in the sequence where `value` can be inserted without breaking the sorted order of the elements using `operator<` of the data type to which the iterators point. If no such element is found, `last` is returned.
  - The second prototype: the elements implied by the iterator range `[first, last)` must have been sorted using the `comp` function or function object. Each element in the range is compared to `value` using the `comp` function. An iterator is returned pointing to the first element for which the binary predicate `comp`, applied to the elements of the range and `value`, returns `true`. The `comp` function object function's first parameter refers to `value` and the function object's second parameter refers to an element in the iterator range.

    Caveat: note that the `comp` object's parameters when using `upper_bound` are swapped compared to the parameters expected by `lower_bound`.
  - When the values in the iterator range were sorted in ascending order (i.e., using `operator<`) then `upper_bound` returns an iterator pointing beyond the last of a series of values equal to `value`, while `lower_bound` returns an iterator pointing to the first of such a series of equal values.

    When the iterator range contains a series of values which are, according to `comp`, equal to `value` then `upper_bound` returns an iterator to the first element beyond that series, while `lower_bound` returns an iterator to the first element of that series.

    The following program illustrates the various possibilities. Th program illustrates both `lower_bound` and `upper_bound` and also illustrates the situation where `value' Type` is unequal to the types of the values in the iterator range. Specific comment is provided below the program's code.
- Example:

```
#include <algorithm>
#include <iostream>
using namespace std;

int main()
{
    typedef pair<int, char> pic;

    pic picArr[] =
        { {1, 'f'}, {5, 'r'}, {5, 'a'}, {7, 'n'}, {8, 'k'} };
    pic *picArrEnd = picArr + size(picArr);

    cout << "Sequence: ";
    for (auto &pair: picArr)
        cout << '{' << pair.first << ',' << pair.second << "}, ";
    cout << '\n';

    auto iter = lower_bound(picArr, picArrEnd, 5,
                    [&](pic const &range, int value)
                    {
                        return range.first < value;
                    }
                );
    cout << "  lower bound, <,  {5,?} can be inserted before {" <<
                iter->first << ',' << iter->second << "}\n";

    iter = upper_bound(picArr, picArrEnd, 5,
                    [&](int value, pic const &range)
                    {
                        return value < range.first;
                    }
                );
    cout << "  upper_bound, <,  {5,?} can be inserted before {" <<
                iter->first << ',' << iter->second << "}\n";

    iter = upper_bound(picArr, picArrEnd, 9,
                    [&](int value, pic const &range)
                    {
                        return value < range.first;
                    }
                );
    cout << "  upper_bound, <,  {9,?} can be inserted " <<
                ( &*iter == picArrEnd ? "at the end" : "???") << '\n';

    sort(picArr, picArrEnd,
        [](pic const &lhs, pic const &rhs)
        {
            return lhs.first > rhs.first;
        }
    );

    cout << "\nSequence: ";
    for (auto &pair: picArr)
        cout << '{' << pair.first << ',' << pair.second << "}, ";
    cout << '\n';

    iter = lower_bound(picArr, picArrEnd, 5,
                    [&](pic const &range, int value)
                    {
                        return range.first > value;
                    }
                );
    cout << "  lower_bound, >,  {5,?} can be inserted before {" <<
                iter->first << ',' << iter->second << "}\n";

    iter = upper_bound(picArr, picArrEnd, 5,
                    [&](int value, pic const &range)
                    {
```

```
69:                         return value > range.first;
70:                     }
71:                 );
72:     cout << "  upper_bound, >,  {5,?} can be inserted before {" <<
73:                 iter->first << ',' << iter->second << "}\n";
74:
75:     iter = upper_bound(picArr, picArrEnd, 0,
76:                     [&](int value, pic const &range)
77:                     {
78:                         return value > range.first;
79:                     }
80:                 );
81:     cout << "  upper_bound, >,  {0,?} can be inserted " <<
82:                 ( &*iter == picArrEnd ? "at the end" : "???") << '\n';
83: }
84: // Displays:
85: // Sequence: {1,f}, {5,r}, {5,a}, {7,n}, {8,k},
86: //   lower bound, <,  {5,?} can be inserted before {5,r}
87: //   upper_bound, <,  {5,?} can be inserted before {7,n}
88: //   upper_bound, <,  {9,?} can be inserted at the end
89: //
90: // Sequence: {8,k}, {7,n}, {5,r}, {5,a}, {1,f},
91: //   lower_bound, >,  {5,?} can be inserted before {5,r}
92: //   upper_bound, >,  {5,?} can be inserted before {1,f}
93: //   upper_bound, >,  {0,?} can be inserted at the end
```

- Lines 7 thru 12: the iterator range consists of a series of `pairs`, sorted by their `first` members.
- Lines 18 thru 23: `lower_bound` is called using a lambda expression to define the `Compare` function object. Note (line 19) that a reference to a value in the iterator range is the lambda expression's first parameter, while the target value is its second parameter.
- Lines 27 thru 32: here `upper_bound` is called, also using a lambda expression. With `upper_bound` the target value is the lambda expression's first parameter, while a reference to a value in the iterator range is its second parameter.
- Lines 57 thru 62, 66 thru 71, and 75 thru 80: after sorting the values in the `picArr` array in descending order `lower_bound` and `upper_bound` are again used. This time instead of using the $<$ operator the $>$ operator should be used.

The binary_search generic algorithm can be used to simply determine whether or nog `value` is present in the iterator range. The lower_bound generic algorithm can be used to find the first element of a series of values equal to `value`.

19.1.68 Heap algorithms

A heap is a kind of binary tree which can be represented by an array. In the standard heap, the key of an element is not smaller than the key of its children. This kind of heap is called a *max heap*. A tree in which numbers are keys could be organized as shown in figure 19.1. Such a tree may also be organized in an array:

```
12, 11, 10, 8, 9, 7, 6, 1, 2, 4, 3, 5
```

In the following description, keep two pointers into this array in mind: a pointer `node` indicates the location of the next node of the tree, a pointer `child` points to the next element which is a child of the `node` pointer. Initially, `node` points to the first element, and `child` points to the second element.

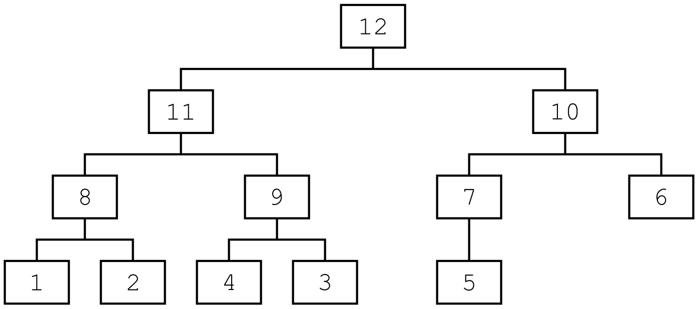

Figure 19.1: A binary tree representation of a heap

- `*node++ (== 12)`. 12 is the top node. its children are `*child++` (11) and `*child++` (10), both less than 12.
- The next node (`*node++ (== 11)`), in turn, has `*child++` (8) and `*child++` (9) as its children.
- The next node (`*node++ (== 10)`) has `*child++` (7) and `*child++` (6) as its children.
- The next node (`*node++ (== 8)`) has `*child++` (1) and `*child++` (2) as its children.
- Then, node (`*node++ (== 9)`) has children `*child++` (4) and `*child++` (3).
- Finally (as far as children are concerned) (`*node++ (== 7)`) has one child `*child++` (5)

Since `child` now points beyond the array, the remaining nodes have no children. So, nodes 6, 1, 2, 4, 3 and 5 don't have children.

Note that the left and right branches are not ordered: 8 is less than 9, but 7 is larger than 6.

A heap is created by traversing a binary tree level-wise, starting from the top node. The top node is 12, at the zeroth level. At the first level we find 11 and 10. At the second level 8, 9, 7 and 6 are found, etc.

Heaps can be constructed in containers supporting random access. So, a list is not an appropriate data structure for a heap. Heaps can be constructed from an (unsorted) array (using `make_heap`). The top-element can be pruned from a heap, followed by reordering the heap (using `pop_heap`), a new element can be added to the heap, followed by reordering the heap (using `push_heap`), and the elements in a heap can be sorted (using `sort_heap`, which, of course, invalidates the heap).

19.1.68.1 The 'make_heap' function

- Header file: `<algorithm>`
- Function prototypes:
  - `void make_heap(RandomAccessIterator first, RandomAccessIterator last);`
  - `void make_heap(RandomAccessIterator first, RandomAccessIterator last, Compare comp);`

- Description:
  - The first prototype: the elements in the range `[first, last)` are reordered to form a max-heap using `operator<` of the data type to which the iterators point.
  - The second prototype: the elements in the range `[first, last)` are reordered to form a max-heap using the binary comparison function object `comp` to compare elements.

19.1.68.2 The 'pop_heap' function

- Header file: `<algorithm>`
- Function prototypes:
  - `void pop_heap(RandomAccessIterator first, RandomAccessIterator last);`
  - `void pop_heap(RandomAccessIterator first, RandomAccessIterator last, Compare comp);`
- Description:
  - The first prototype: the first element in the range `[first, last)` is moved to `last - 1`. Then, the elements in the range `[first, last - 1)` are reordered to form a max-heap using the `operator<` of the data type to which the iterators point.
  - The second prototype: the first element in the range `[first, last)` is moved to `last - 1`. Then, the elements in the range `[first, last - 1)` are reordered to form a max-heap using the binary comparison function object `comp` to compare elements.

19.1.68.3 The 'push_heap' function

- Header file: `<algorithm>`
- Function prototypes:
  - `void push_heap(RandomAccessIterator first, RandomAccessIterator last);`
  - `void push_heap(RandomAccessIterator first, RandomAccessIterator last, Compare comp);`
- Description:
  - The first prototype: assuming that the range `[first, last - 1)` contains a valid heap, and the element at `last - 1` contains an element to be added to the heap, the elements in the range `[first, last - 1)` are reordered to form a max-heap using the `operator<` of the data type to which the iterators point.
  - The second prototype: assuming that the range `[first, last - 1)` contains a valid heap, and the element at `last - 1` contains an element to be added to the heap, the elements in the range `[first, last - 1)` are reordered to form a max-heap using the binary comparison function object `comp` to compare elements.

19.1.68.4 The 'sort_heap' function

- Header file: `<algorithm>`

- Function prototypes:
  - `void sort_heap(RandomAccessIterator first, RandomAccessIterator last);`
  - `void sort_heap(RandomAccessIterator first, RandomAccessIterator last, Compare comp);`
- Description:
  - The first prototype: assuming the elements in the range `[first, last)` form a valid max-heap, the elements in the range `[first, last)` are sorted using `operator<` of the data type to which the iterators point.
  - The second prototype: assuming the elements in the range `[first, last)` form a valid heap, the elements in the range `[first, last)` are sorted using the binary comparison function object `comp` to compare elements.

19.1.68.5 An example using the heap functions

Here is an example showing the various generic algorithms manipulating heaps:

```
#include <algorithm>
#include <iostream>
#include <functional>
#include <iterator>
using namespace std;

void show(int *ia, char const *header)
{
    cout << header << ":\n";
    copy(ia, ia + 20, ostream_iterator<int>(cout, " "));
    cout << '\n';
}
int main()
{
    int ia[] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
                11, 12, 13, 14, 15, 16, 17, 18, 19, 20};

    make_heap(ia, ia + 20);
    show(ia, "The values 1-20 in a max-heap");

    pop_heap(ia, ia + 20);
    show(ia, "Removing the first element (now at the end)");

    push_heap(ia, ia + 20);
    show(ia, "Adding 20 (at the end) to the heap again");

    sort_heap(ia, ia + 20);
    show(ia, "Sorting the elements in the heap");


    make_heap(ia, ia + 20, greater<int>());
    show(ia, "The values 1-20 in a heap, using > (and beyond too)");

    pop_heap(ia, ia + 20, greater<int>());
    show(ia, "Removing the first element (now at the end)");
```

```
        push_heap(ia, ia + 20, greater<int>());
        show(ia, "Re-adding the removed element");

        sort_heap(ia, ia + 20, greater<int>());
        show(ia, "Sorting the elements in the heap");
    }
    /*
        Displays:
            The values 1-20 in a max-heap:
            20 19 15 18 11 13 14 17 9 10 2 12 6 3 7 16 8 4 1 5
            Removing the first element (now at the end):
            19 18 15 17 11 13 14 16 9 10 2 12 6 3 7 5 8 4 1 20
            Adding 20 (at the end) to the heap again:
            20 19 15 17 18 13 14 16 9 11 2 12 6 3 7 5 8 4 1 10
            Sorting the elements in the heap:
            1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
            The values 1-20 in a heap, using > (and beyond too):
            1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
            Removing the first element (now at the end):
            2 4 3 8 5 6 7 16 9 10 11 12 13 14 15 20 17 18 19 1
            Re-adding the removed element:
            1 2 3 8 4 6 7 16 9 5 11 12 13 14 15 20 17 18 19 10
            Sorting the elements in the heap:
            20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
    */
```

Chapter 20

Multi Threading

The 98 **C++** standard did not acknowledge the existence of multi-threading. Between then and the release of the current **C++** standard computers have evolved to multi-core machines, and using multi-threading by now is a real option to consider when developing software.

Multi-threading is an extensive and complex subject, and many good reference texts on the subject exist. The **C++** multi-threading is built upon the facilities offered by the *pthreads* library (cf. Nichols, B, *et al.*'s `Pthreads Programming`[1], O'Reilly). However, in line with **C++**'s current-day philosophy the multi-threading implementation offered by the language offers a high level interface to multi-threading, and using the raw pthread building blocks is hardly ever necessary (cf. Williams, A. (2012): **C++ Concurrency in action**).

This chapter covers the facilities for multi-threading as supported by **C++**. Although the coverage aims at providing the tools and examples allowing you to create your own multi-threaded programs, coverage necessarily is far from complete. The topic of multi threading is too extensive for that. The mentioned reference texts provide a good starting point for any further study of multi threading.

A *thread of execution* (commonly abbreviated to a *thread*) is a single flow of control within a program. It differs from a separately executed program, as created by the **fork**(1) system call in the sense that threads all run inside one program, while **fork**(1) creates independent copies of a running program. Multi-threading means that multiple tasks are being executed in parallel inside one program, and no assumptions can be made as to which thread is running first or last, or at what moment in time. Especially when the number of threads does not exceed the number of cores, each thread may be active at the same time. If the number of threads exceed the number of cores, the operating system will resort to *task switching*, offering each thread time slices in which it can perform its tasks. Task switching takes time, and the law of diminishing returns applies here as well: if the number of threads greatly exceeds the number of available cores (also called *overpopulation*), then the overhead incurred may exceed the benefit of being able to run multiple tasks in parallel.

Since all threads are running inside one single program, all threads share the program's data and code. When the same data are accessed by multiple threads, and at least one of the threads is modifying these data, access must be synchronized to avoid that threads read data while these data are being modified by other threads, and to avoid that multiple threads modify the same data at the same time.

So how do we run a multi-threaded program in **C++**? Let's look at *hello world*, the multi-threaded way:

```
#include <iostream>
#include <thread>
```

---

[1] http://oreilly.com/catalog/

```
 3:
 4: void hello()
 5: {
 6:     std::cout << "hello world!\n";
 7: }
 8:
 9: int main()
10: {
11:     std::thread hi(hello);
12:     hi.join();
13: }
```

- At line 2 the header `thread` is included, informing the compiler about the existence of the class `std::thread` (cf. section 20.1.2);
- At line 11 the `std::thread hi` object is created. It is provided with the name of a function (hello) which will be called in a separate thread. Actually, the second thread, running `hello`, is immediately started when a `std::thread` is defined this way;
- The `main` function itself also represents a thread: the program's first thread. It should wait until the second thread has finished. This is realized in line 12, where `hi.join()` waits until the thread `hi` has finished its job. Since there are no further statements in `main`, the program itself ends immediately thereafter.
- The function `hello` itself, defined in lines 4 through 7, is trivial: it simply inserts the text '`hello world`' into `cout`, and terminates, thus ending the second thread.

When compiling multi-threaded programs using the GNU `g++` compiler the `-pthread` option must be specified.

To create a multi-threaded program defined in a source file `multi.cc` the `g++` compiler can be called like this:

```
g++ --std=c++14 -pthread -Wall multi.cc
```

20.1 Multi Threading

In **C++** multi threading may be implemented at various levels of abstraction. In general the highest level of abstraction which is available to implement a multi-threaded problem should be used. Not so much because it's often simpler than using lower levels of abstraction, but because higher levels of abstraction are usually semantically closer to the original problem description, resulting in code which is easier to understand and therefore easier to maintain. Also, high-abstraction classes also provide exception safety and prevent the occurrence of memory leaks.

C++'s main tool for creating multi-threaded programs is the class `std::thread`, and some examples of its use have already been shown at the beginning of this chapter.

Characteristics of individual threads can be queried from the `std::this_thread` namespace. Also, `std::this_thread` offers some control over the behavior of an individual thread.

To synchronize access to shared data **C++** offers *mutexes* (implemented by the class `std::mutex`) and *condition variables* (implemented by the class `std::condition_variable`).

Members of these classes may throw `system_error` objects (cf. section 10.9) when encountering a low-level error condition.

20.1.1 The namespace std::this_thread

The `namespace std::this_thread` contains functions that are uniquely associated with the currently running thread.

Before using the namespace `this_thread` the `<thread>` header file must be included.

Inside the `std::this_thread` namespace several free functions are defined, providing information about the current thread or that can be used to control its behavior:

- `thread::id this_thread::get_id() noexcept`:
  returns an object of type `thread::id` that identifies the currently active thread of execution. For an active thread the returned `id` is unique in the sense that it maps 1:1 to the currently active thread, and is not returned by any other thread. If a thread is currently not running `thread::id()` is returned by the `std::thread` object's `get_id` member.
- `void yield() noexcept`:
  when a thread calls `this_thread::yield()` the current thread is briefly suspended, allowing other (waiting) threads to start.
- `void sleep_for(chrono::duration<Rep, Period> const &relTime) noexcept`:
  when a thread calls `this_thread::sleep_for(...)` it is suspended for the amount of time that's specified in its argument. E.g.,

  ```
  std::this_thread::sleep_for(std::chrono::seconds(5));
  ```
- `void sleep_until(chrono::time_point<Clock, Duration> const &absTime) noexcept`:
  when a thread calls this member it is suspended until the specified `absTime` is in the past. The next example has the same effect as the previous example:

  ```
  // assume using namespace std
  this_thread::sleep_until(chrono::system_clock().now() + chrono::seconds(5));
  ```

  Conversely, the `sleep_until` call in the next example immediately returns:

  ```
  this_thread::sleep_until(chrono::system_clock().now() - chrono::seconds(5));
  ```

20.1.2 The class std::thread

Multi threading in **C++** starts off with objects of the class `std::thread`. Each object of this class handles a separate thread.

Before using `Thread` objects the `<thread>` header file must be included.

Thread objects can be constructed in various ways:

- `thread() noexcept`:
  The default constructor creates a `thread` object. As it receives no function to execute, it does not start a separate thread of execution. It is used, e.g., as a data member of a class, allowing class objects to start a separate thread at some later point in time;
- `thread(thread &&tmp) noexcept`:
  The move constructor takes ownership of the thread controlled by `tmp`, while `tmp`, if it runs a thread, loses control over its thread. Following this, `tmp` is in its default state, and the newly created thread is responsible for calling, e.g., `join`.

- `explicit thread(Fun &&fun, Args &&...args)`:
  This *member template* (cf. section 22.1.3) expects a function (or functor) as its first argument. The function is immediately started as a separate thread. If the function (or functor) expects arguments, then these arguments can be passed to the `thread's` constructor immediately following its first (function) argument. Additional arguments are passed with their proper types and values to `fun`. Following the `thread` object's construction, a separately running thread of execution is started.

  The notation `Arg &&...args` indicates that any additional arguments are passed as is to the function. The types of the arguments that are passed to the `thread` constructor and that are expected by the called function must match: values must be values, references must be reference, r-value references must be r-value references (or move construction must be supported). The following example illustrates this requirement:

```
#include <iostream>
#include <thread>

using namespace std;

struct NoMove
{
    NoMove() = default;
    NoMove(NoMove &&tmp) = delete;
};

struct MoveOK
{
    int d_value = 10;

    MoveOK() = default;
    MoveOK(MoveOK const &) = default;

    MoveOK(MoveOK &&tmp)
    {
        d_value = 0;
        cout << "MoveOK move cons.\n";
    }
};

void valueArg(int value)
{}
void refArg(int &ref)
{}
void r_refArg(int &&tmp)
{
    tmp = 100;
}
void r_refNoMove(NoMove &&tmp)
{}
void r_refMoveOK(MoveOK &&tmp)
{}

int main()
{
    int value = 0;

    std::thread(valueArg,   value).join();
44:     std::thread(refArg,     ref(value)).join();
45:     std::thread(r_refArg,   move(value)).join();
46:
47: //  std::thread(refArg,     value);
48:
49:     std::thread(r_refArg,   value).join();
50:     cout << "value after r_refArg: " << value << '\n';
51:
52: //  std::thread(r_refNoMove, NoMove());
53:
54:     NoMove noMove;
55: //  std::thread(r_refNoMove, noMove).join();
56:
57:     MoveOK moveOK;
58:     std::thread(r_refMoveOK, moveOK).join();
59:     cout << moveOK.d_value << '\n';
60: }
```

- At lines 43 through 45 we see a value, reference, and and r-value reference being passed to a `std::thread`: with the functions running the threads expecting matching argument types.
- Line 47 fails to compile, as a value argument doesn't match the reference expected by `refArg`. Note that this problem was solved in line 43 by using the `std::ref` function.
- On the other hand lines 49 and 58 compile OK, as `int` values and class-types supporting move operations can be passed as values to functions expecting r-value references. In this case notice that the functions expecting the r-value references do not access the provided arguments (except for the actions performed by their move constructors), but use move construction to create temporary values or objects on which the functions operate.
- Lines 52 and 55 won't compile as the `NoMove` struct doesn't offer a move constructor.
- Member functions of classes can also be used as thread functions. In those cases the constructor's first argument must be the address of the member function, the second argument must be a pointer (or reference, or object) for which the member function is called as thread function, while subsequent arguments are passed as arguments to the member function. Here is a simple example illustrating these options:

```
struct Demo
{
    int d_value = 0;

    void fun(int value)
    {
        d_value = value;
        cout << "fun sets value to " << value << "\n";
    }
};

int main()
{
    Demo demo;

    thread thr{&Demo::fun, ref(demo), 12 };
    thr.join();
    cout << "demo's value: " << demo.d_value << '\n';   // 12

    thr = thread{&Demo::fun, &demo, 42 };
```

```
        thr.join();
        cout << "demo's value: " << demo.d_value << '\n';   // 42

        thr = thread{&Demo::fun, demo, 77 };
        thr.join();
        cout << "demo's value: " << demo.d_value << '\n';   // 42: the thread
                                                            // copied demo
    }
```

Be careful when passing local variables as arguments to thread objects: if the thread continues to run when the function whose local variables are used terminates, then the thread suddenly uses wild pointers or wild references, as the local variables no longer exist. To prevent this from happening (illustrated by the next example) do as follows:

- pass an anonymous copy of the local variable as argument to the `thread` constructor, or
- call `join` on the thread object to ensure that the thread has finished within the local variable's lifetime.

```
 1: #include <iostream>
 2: #include <thread>
 3: #include <string>
 4: #include <chrono>
 5:
 6: void threadFun(std::string const &text)
 7: {
 8:     for (size_t iter = 1; iter != 6; ++iter)
 9:     {
10:         std::cout << text << '\n';
11:         std::this_thread::sleep_for(std::chrono::seconds(1));
12:     }
13: }
14:
15: std::thread safeLocal()
16: {
17:     std::string text = "hello world";
18:     return std::thread(threadFun, std::string{ text });
19: }
20:
21: int main()
22: {
23:     std::thread local(safeLocal());
24:     local.join();
25:     std::cout << "safeLocal has ended\n";
26: }
```

In line 18 be sure not to call `std::ref(text)` instead of `std::string{ text }`.

If the thread cannot be created a `std::system_error` exception is thrown.

Since this constructor not only accepts functions but also function objects as its first argument, a *local context* may be passed to the function object's constructor. Here is an example of a thread receiving a function object using a local context:

```
#include <iostream>
#include <thread>
#include <array>
```

```
using namespace std;

class Functor
{
    array<int, 30> &d_data;
    int d_value;

    public:
        Functor(array<int, 30> &data, int value)
        :
            d_data(data),
            d_value(value)
        {}
        void operator()(ostream &out)
        {
            for (auto &value: d_data)
            {
                value = d_value++;
                out << value << ' ';
            }
            out << '\n';
        }
};

int main()
{
    array<int, 30> data;
    Functor functor{ data, 5 };
    thread funThread{ functor, ref(cout) };
    funThread.join();
};
```

The class `std::thread` does not provide a copy constructor.

The following members are available:

- `thread &operator=(thread &&tmp) noexcept:`

  If the operator's left-hand side operand (lhs) is a joinable thread, then `terminate` is called. Otherwise, `tmp` is assigned to the operator's lhs and `tmp's` state is changed to the thread's default state (i.e., `thread()`).

- `void detach():`
  Requires `joinable` (see below) to return `true`. The thread for which `detach` is called continues to run. The (e.g., parent) thread calling `detach` continues immediately beyond the `detach`-call. After calling `object.detach()`, '`object`' no longer represents the (possibly still continuing but now detached) thread of execution. It is the detached thread's implementation's responsibility to release its resources when its execution ends.

  Since `detach` disconnects a thread from the running program, e.g., `main` no longer can wait for the thread's completion. As a program ends when `main` ends, its still running detached threads also stop, and a program may not properly finish all its threads, as demonstrated by the following example:

  ```
  #include <thread>
  #include <iostream>
  #include <chrono>
  ```

```
    void fun(size_t count, char const *txt)
    {
        for (; count--; )
        {
            std::this_thread::sleep_for(std::chrono::milliseconds(100));
            std::cout << count << ": " << txt << std::endl;
        }
    }

    int main()
    {
        std::thread first(fun, 5, "hello world");
        first.detach();

        std::thread second(fun, 5, "a second thread");
        second.detach();

        std::this_thread::sleep_for(std::chrono::milliseconds(400));
        std::cout << "leaving" << std::endl;
    }
```

A detached thread may very well continue to run after the function that launched it has finished. Here, too, you should be very careful not to pass local variables to the detached thread, as their references or pointers will be undefined once the function defining the local variables terminates:

```
#include <iostream>
#include <thread>
#include <chrono>

using namespace std;
using namespace chrono;

void add(int const &p1, int const &p2)
{
    this_thread::sleep_for(milliseconds(200));
    cerr << p1 << " + " << p2 << " = " << (p1 + p2) << '\n';
}

void run()
{
    int v1 = 10;
    int v2 = 20;

//  thread(add, ref(v1), ref(v2)).detach();     // DON'T DO THIS
    thread(add, int(v1), int(v2)).detach();     // this is OK: own copies
}

void oops()
{
    int v1 = 0;
    int v2 = 0;
}

int main()
```

```
{
    run();
    oops();
    this_thread::sleep_for(seconds(1));
}
```

- `id get_id() const noexcept`:
  If the current object does not represent a running thread `thread::id()` is returned. Otherwise, the thread's unique ID (also obtainable from within the thread via `this_thread::get_id()`) is returned.

- `unsigned thread::hardware_concurrency() noexecpt`:
  This static member returns the number of threads that can run at the same time on the current computer. On a stand-alone multi-core computer it (probably) returns the number of cores.

- `void join()`:
  Requires `joinable` to return `true`. If the thread for which `join` is called hasn't finished yet then the thread calling `join` will be suspended (also called *blocked*) until the thread for which `join` is called has completed. Following its completion the object whose `join` member was called no longer represents a running thread, and its `get_id` member will return `std::thread::id()`.

  This member was used in several examples shown so far. As noted: when `main` ends while a joinable thread is still running, `terminate` is called, aborting the program.

- `bool joinable() const noexcept`:
  returns `object.get_id() != id()`, where `object` is the `thread` object for which `joinable` was called.

- `native_handle_type native_handle()`:
  returns the thread's *handle* (implementation defined). This handle can be passed to functions like `pthread_getschedparam` and `pthread_setschedparam` to get/set the thread's scheduling policy and parameters.

- `void swap(thread &other) noexcept`:
  The states of the `thread` object for which `swap` was called and `other` are swapped. Note that threads may always be swapped, even when their thread functions are currently being executed.

Things to note:

- When intending to define an anonymous thread it may appear not to start, unless you immediately also call `join`. E.g.,

  ```
  void doSomething();
  int main()
  {
      thread(doSomething);         // nothing happens??
      thread(doSomething).join()   // doSomething is executed??
  }
  ```

  This similar to the situation we encountered in section 7.5: the first statement doesn't define an anonymous `thread` object at all. It simply defines the `thread` object `doSomething`. Consequently, compilation of the second statement fails, as there is no `thread(thread &)` constructor. When the first statement is omitted, the `doSomething` function is executed by the second statement. If the second statement is omitted, a default constructed `thread` object by the name of `doSomething` is defined.

- A thread only starts after its construction has completed. This includes move constructions or move assignments. E.g., in a statement like

  ```
  thread object(thread(doSomething));
  ```

  the move constructor is used to transfer control from an anonymous thread executing `doSomething` to the thread `object`. Only after `object`'s construction has completed `doSomething` is started in the separate thread.

- Exceptions thrown from the thread (e.g., by the function defining the thread's actions) are local to the executed thread. Either they must be caught by the executing thread (as each running thread has its own execution stack), or they can be passed to the starting thread using a `packaged_task` and a `future` (cf., respectively, sections 20.11 and 20.8).

A thread ends when the function executing a thread finishes. When a `thread` object is destroyed while its thread function is still running, `terminate` is called, aborting the program's end. Bad news: the destructors of existing objects aren't called and exceptions that are thrown are left uncaught. This happens in the following program as the thread is still active when `main` ends:

```
#include <iostream>
#include <thread>

void hello()
{
    while (true)
        std::cout << "hello world!\n";
}

int main()
{
    std::thread hi(hello);
}
```

There are several ways to solve this problem. One of them is discussed in the next section.

20.1.2.1 Static data and threads: thread_local

With multi-threaded programs the well-known distinction between global and local data is somewhat too coarse. For single- and multi-threaded programs alike, global data are available to all of the program's code, and local data are available to the function (or compound statement) in which the local data are defined. But multi-threaded programs may feel the need for an intermediate type of data, uniquely available to the different threads.

The `thread_local` keyword provides this intermediate data level. Global variables declared as `thread_local` are global within each individual thread. Each thread owns a copy of the `thread_local` variables, and may modify them at will. A `thread_local` variable in one thread is completely separated from that variable in another thread. Here is an example:

```
#include <iostream>
#include <thread>

using namespace std;

thread_local int t_value = 100;
```

```
 7:
 8: void modify(char const *label, int newValue)
 9: {
10:     cout << label << " before: " << t_value << ". Address: " <<
11:                                                      &t_value << endl;
12:     t_value = newValue;
13:     cout << label << " after: " << t_value << endl;
14: }
15:
16: int main()
17: {
18:     thread(modify, "first", 50).join();
19:     thread(modify, "second", 20).join();
20:     modify("main", 0);
21: }
```

- At line 6 the `thread_local` variable `t_value` is defined. It is initialized to 100, and that becomes the initial value for each separately running thread;
- In lines 8 through 14 the function `modify` is defined. It assigns a new value to `t_value`;
- At lines 18 and 19 two threads are started, which are immediately joining the main thread again.
- The main thread itself is also a thread, and it directly calls `modify`.

Running this program shows that each separate thread starts with `t_value` being 100, and then modifies it without affecting the values of `t_value` used by other threads.

Note that, although the `t_value` variables are unique to each thread, identical addresses may be shown for them. Since each thread uses its own stack, these variables may occupy the same relative locations within their respective stacks, giving the illusion that their physical addresses are identical.

20.1.2.2 Exceptions and join()

Once a thread starts and it isn't detached it must eventually join its starting (parent) thread, or the program aborts. Usually, once a thread has started the parent thread continues to do some work by itself:

```
void childActions();
void doSomeWork();

void parent()
{
    thread child(childActions);
    doSomeWork();
    child.join();
}
```

However, maybe `doSomeWork` can't complete its work, and throws an exception, to be caught outside of `parent`. This, unfortunately, ends `parent`, and `child.join()` is missed. Consequently, the program aborts because of a thread that hasn't been joined.

Clearly, all exceptions must be caught, `join` must be called, and the exception must be rethrown. But `parent` cannot use a function try-block, as the thread object is already out of scope once execution reaches the matching `catch`-clause. So we get:

```
void childActions();
void doSomeWork();

void parent()
{
    thread child(childActions);
    try
    {
        doSomeWork();
        child.join();
    }
    catch (...)
    {
        child.join();
        throw;
    }
}
```

This is ugly: suddenly the function's code is clobbered with a `try-catch` clause, as well as some unwelcome code-duplication.

This situation can be avoided using object based programming. Like, e.g., unique pointers, which use their destructors to encapsulate the destruction of dynamically allocated memory, we can use a comparable technique to encapsulate thread joining in an object's destructor.

By defining the `thread` object inside a class we're sure that by the time the our object goes out of scope, even if the `childActions` function throws an exception, the thread's `join` member is called. Here are the bare essentials of our `JoinGuard` class, providing the join-guarantee (using in-line member implementations for brevity):

```
 1: #include <thread>
 2:
 3: class JoinGuard
 4: {
 5:     std::thread d_thread;
 6:
 7:     public:
 8:         JoinGuard(std::thread &&threadObj)
 9:         :
10:             d_thread(std::move(threadObj))
11:         {}
12:         ~JoinGuard()
13:         {
14:             if (d_thread.joinable())
15:                 d_thread.join();
16:         }
17: };
```

- At line 8 its only constructor starts: it receives a temporary `thread` object, which is moved, in line 10, to `JoinGuard's d_thread` data member.

- When the `JoinGuard` object ceases to exist, its destructor (line 12) makes sure the thread is joined if it's still joinable (lines 14 and 15).

Here is an example how `JoinGuard` could be used:

```
 1: #include <iostream>
 2: #include "joinguard.h"
 3:
 4: void childActions();
 5:
 6: void doSomeWork()
 7: {
 8:     throw std::runtime_error("doSomeWork throws");
 9: }
10:
11: void parent()
12: {
13:     JoinGuard{std::thread{childActions}};
14:     doSomeWork();
15: }
16:
17: int main()
18: try
19: {
20:     parent();
21: }
22: catch (std::exception const &exc)
23: {
24:     std::cout << exc.what() << '\n';
25: }
```

- At line 4 `childActions` is declared. Its implementation (not provided here) defines the child thread's actions.
- The `main` function (lines 17 through 25) provides the function try-block to catch the exception thrown by `parent`;
- The `parent` function defines (line 13) an anonymous `JoinGuard`, receiving an anonymous `thread` object. Anonymous objects are used, as the parent function doesn't need to access them anymore.
- In line 14 `doSomeWork` is called, which throws an exception. This ends `parent`, but just before that `JoinGuard’s` destructor makes sure that the child-thread has been joined.

20.1.3 The class std::jthread

In addition to `std::thread` the class `std::jthread` can be used.

Before using `jthread` objects the `<thread>` header file must be included.

Objects of the class `jthread` act like `thread` objects, but a `jthread` thread automatically joins the thread that activated `jthread`. Moreover, in some situations `jthread` threads can directly be ended.

Once a `jthread` object receiving a function defining the thread's actions has been constructed that function immediately starts as a separate thread. If that function ends by returning a value then that value is ignored. If the function throws an exception the program ends by calling `std::terminate`. Alternatively, if the function should communicate a return value or an exception to, e.g., the function starting the `jthread` a `std::promise` (cf. section (20.12)) can be used or it can modify variables which are shared with other threads (see also sections 20.2 and 20.5).

The class `jthread` offers theses constructors:

- `jthread() noexcept:`
  The default constructor creates a `jthread` object that doesn't start a thread. It could be used as a data member of a class, allowing class objects to start the `jthread` at some later point in time;
- `explicit jthread(Function &&function, Args &&...args):`
  This constructor (which is a *member template*, cf. section 22.1.3) expects a function (or functor) as its first argument, starting the thread defined by `function`. The function receives as its first argument the return value of `jthread's` member `get_stop_token` (see below), followed by the `args` parameters (if present). If `function's` first argument is not a `std::stop_token` then `function`, merely receiving the `args` parameter values as its arguments. Arguments are passed to `function` with their proper types and values (see the example shown below at the description of the `jthread` member `request_stop`;)
- The class `jthread` supports move construction and move assignment, but does not offer copy construction and copy assignment, but it does

The following members are available and operate like the identically named `std::thread` members. Refer to section 20.1.2 for their descriptions:

- `void detach();`
- `id get_id() const noexcept;`
- `unsigned thread::hardware_concurrency() noexecpt`
- `void join();`
- `bool joinable() const noexcept;`
- `native_handle_type native_handle();`
- `void swap(thread &other) noexcept.`

The following members are specific to `jthread`, allowing other threads to end the thread started by `jthread`:

- `std::stop_source get_stop_source() noexcept:`
  returns the `jthread's std::stop_source`.
- `std::get_stop_token get_stop_token() const noexcept:`
  returns the `jthread's std::stop_token`.
- `bool request_stop() noexcept:`
  attempts to end the thread started by the `jthread` object. The function operates atomically: it can be called from multiple threads without causing race conditions. It returns `true` if the stop request was successfully issued. It returns `false` if a stop request has already been issued, which may also happen if `request_stop` was issued by different threads, and another thread is still in the process of ending `jthread's` thread.
  When issuing `request_stop` then `std::stop_callback` functions (see the next section) that were registered for the thread's stop state are synchroneously called. If those callback functions throw exceptions then `std::terminate` is called. Also, any waiting condition variables that are associated with the `jthread's` stop state end their waiting states.

Here is a short program illustrating `request_stop`:

```
 1: #include <iostream>     // don't forget the -pthread compiler option
 2: #include <thread>
 3: #include <chrono>
 4: using namespace std;
 5:
 6: void fun(std::stop_token stop)
 7: {
 8:     while (not stop.stop_requested())
 9:     {
10:         cout << "next\n";
11:         this_thread::sleep_for(1s);
12:     }
13: }
14:
15: int main()
16: {
17:     jthread thr(fun);
18:
19:     this_thread::sleep_for(3s);
20:
21:     thr.request_stop();
22:     thr.join();
23: }
```

- at line 17 the `jthread` thread starts, receiving function `fun` as its argument;
- as `fun` defines a `std::stop_token` parameter, `jthread` will start that function. It performs (line 8) a `while` loop that continues until `stop's stop_requested` returns `true`. The loop itself shows a brief output line (line 10) followed by a one-second sleep (line 11);
- the `main` function, having started the thread, sleeps for three seconds (line 19), and then (line 21) issues a stop-request, ending the thread.

When running the program three lines containing `next` are displayed.

20.1.3.1 std::stop_callback

Before using `std::stop_callback` objects the `<stop_token>` header file must be included.

In addition to merely ending thread functions via `jthread's request_stop` member function it's also possible to associate *callback functions* with `request_stop`, which are executed when `request_stop` is called. In situations where callback functions are registered when the thread function has already been stopped the callback functions are immediately called when they are being registered (registering callback functions is covered below).

Note that multiple callback functions can be registered. However, the order in which these callback functions are run once the thread is stopped is not defined. Moreover, exceptions may not leave callback functions or the program ends by calling `std::terminate`.

Callback functions are registered by objects of the class `std::stop_callback`. The class `stop_callback` offers the following constructors:

- `explicit stop_callback(std::stop_token const &st, Function &&cb) noexcept;`

- `explicit stop_callback(std::stop_token &&st, Function &&cb) noexcept;`

Notes:

- `Function` can be the name of a (void) function without parameters or it can be an (anonymous or existing) object offering a parameter-less (void) function call operator. The functions do not necessarily have to be void functions, but their return values are ignored;

- The `noexcept` is only used if `Function` is also declared as `noexcept` (if `Function` is the name of a functor-class then `noexcept` is used if its constructor is declared with `noexcept`);

- The class `stop_callback` does not offer copy/move construction and assignment.

Here is the example used in the previous section, this time defining a callback function. When running this program its output is

```
next
next
next
stopFun called via stop_callback
```

```
 1: void fun(std::stop_token stop)
 2: {
 3:     while (not stop.stop_requested())
 4:     {
 5:         cout << "next\n";
 6:         this_thread::sleep_for(1s);
 7:     }
 8: }
 9:
10: void stopFun()
11: {
12:     cout << "stopFun called via stop_callback\n";
13: }
14:
15: int main()
16: {
17:     jthread thr(fun);
18:
19:     stop_callback sc{ thr.get_stop_token(), stopFun };
20:
21:     this_thread::sleep_for(3s);
22:
23:     thr.request_stop();
24:     thr.join();
25: }
```

The function `fun` is identical to the one shown in the previous section, but `main` defines (line 19) the `stop_callback` object `sc`, passing it `thr’s get_stop_token’s` return value and the address of the function `stopFun`, defined in lines 10 thru 13. In this case once `request_stop` is called (line 23) the callback function `stopFun` is called as well.

20.2 Synchronization (mutexes)

Objects of mutex classes are used to protect shared data.

Before using mutexes the `<mutex>` header file must be included.

One of the key characteristics of multi-threaded programs is that threads may share data. Functions running as separate threads have access to all global data, and may also share the local data of their parent threads. However, unless proper measures are taken, this may easily result in data corruption, as illustrated by the following simulation of some steps that could be encountered in a multi-threaded program:

```
---------------------------------------------------------------------------
Time step:    Thread 1:     var        Thread 2:       description
---------------------------------------------------------------------------
    0                        5
    1           starts                                  T1 active
    2           writes var                              T1 commences writing
    3           stopped                                 Context switch
    4                                   starts          T2 active
    5                                   writes var      T2 commences writing
    6                       10          assigns 10      T2 writes 10
    7                                   stopped         Context switch
    8           assigns 12                              T1 writes 12
    9                       12
----------------------------------------------------------------------------
```

In this example, threads 1 and 2 share variable `var`, initially having the value 5. At step 1 thread 1 starts, and starts to write a value into `var`. However, it is interrupted by a context switch, and thread 2 is started (step 4). Thread 2 *also* wants to write a value into `var`, and succeeds until time step 7, when another context switch takes place. By now `var` is 10. However, thread 1 was also in the process of writing a value into `var`, and it is given a chance to complete its work: it assigns 12 to `var` in time step 8. Once time step 9 is reached, thread 2 proceeds on the (erroneous) assumption that `var` must be equal to 10. Clearly, from the point of view of thread 2 its data have been corrupted.

In this case data corruption was caused by multiple threads accessing the same data in an uncontrolled way. To prevent this from happening, access to shared data should be protected in such a way that only one thread at a time may access the shared data.

Mutexes are used to prevent the abovementioned kinds of problems by offering a guarantee that data are only accessed by the thread that could lock the mutex that is used to synchronize access to those data.

Exclusive data access completely depends on cooperation between the threads. If thread 1 uses mutexes, but thread 2 doesn't, then thread 2 may freely access the common data. Of course that's bad practice, which should be avoided.

It is stressed that although *using* mutexes is the programmer's responsibility, their *implementation* isn't: mutexes offer the necessary atomic calls. When requesting a mutex-lock the thread is blocked (i.e., the mutex statement does not return) until the lock has been obtained by the requesting thread.

Apart from the class `std::mutex` the class `std::recursive_mutex` is available. When a `recursive_mutex` is called multiple times by the same thread it increases its lock-count. Before other threads may access the protected data the recursive mutex must be unlocked again that number of times. Moreover, the classes `std::timed_mutex` and `std::recursive_timed_mutex` are available. Their locks expire when released, but also after a certain amount of time.

The members of the mutex classes perform *atomic actions*: no context switch occurs while they are active. So when two threads are trying to *lock* a mutex only one can succeed. In the above example: if both threads would use a mutex to control access to `var` thread 2 would not have been able to assign 12 to `var`, with thread 1 assuming that its value was 10. We could even have two threads running purely parallel (e.g., on two separate cores). E.g.:

```
-------------------------------------------------------------------------
Time step:    Thread 1:        Thread 2:        escription
-------------------------------------------------------------------------
    1         starts           starts           T1 and T2 active
    2         locks            locks            Both threads try to
                                                lock the mutex
    3         blocks...        obtains lock     T2 obtains the lock,
                                                and T1 must wait
    4         (blocked)        processes var    T2 processes var,
                                                T1 still blocked
    5         obtains lock     releases lock    T2 releases the lock,
                                                and T1 immediately
                                                obtains the lock
    6         processes var                     now T1 processes var
    7         releases lock                     T1 also releases the lock
-------------------------------------------------------------------------
```

Although mutexes can directly be used in programs, this rarely happens. It is more common to embed mutex handling in locking classes that make sure that the mutex is automatically unlocked again when the mutex lock is no longer needed. Therefore, this section merely offers an overview of the interfaces of the mutex classes. Examples of their use will be given in the upcoming sections (e.g., section 20.3).

All mutex classes offer the following constructors and members:

- `mutex() constexpr`:
  The default `constexpr` constructor is the only available constructor;
- `~mutex()`:
  The destructor does *not* unlock a locked mutex. If locked it must explicitly be unlocked using the mutex's `unlock` member;
- `void lock()`:
  The calling thread blocks until it owns the mutex. Unless `lock` is called for a recursive mutex a *system_error* is thrown if the thread already owns the lock. Recursive mutexes increment their internal *lock count*;
- `bool try_lock() noexcept`:
  The calling thread tries to obtain ownership of the mutex. If ownership is obtained, `true` is returned, otherwise `false`. If the calling thread already owns the lock `true` is also returned, and in this case a recursive mutex also increments its internal *lock count*;
- `void unlock() noexcept`:
  The calling thread releases ownership of the mutex. A `system_error` is thrown if the thread does not own the lock. A recursive mutex decrements its interal lock count, releasing ownership of the mutex once the lock count has decayed to zero;

The timed-mutex classes (`timed_mutex, recursive_timed_mutex`) also offer these members:

- `bool try_lock_for(chrono::duration<Rep, Period> const &relTime) noexcept`:
  The calling thread tries to obtain ownership of the mutex within the specified time interval. If ownership is obtained, `true` is returned, otherwise `false`. If the calling thread already owns the lock `true` is also returned, and in this case a recursive timed mutex also increments its internal *lock count*. The `Rep` and `Duration` types are inferred from the actual `relTime` argument. E.g.,

  ```
  std::timed_mutex timedMutex;
  timedMutex.try_lock_for(chrono::seconds(5));
  ```

- `bool try_lock_until(chrono::time_point<Clock, Duration> const &absTime) noexcept`:
  The calling thread tries to obtain ownership of the mutex until `absTime` has passed. If ownership is obtained, `true` is returned, otherwise `false`. If the calling thread already owns the lock `true` is also returned, and in this case a recursive timed mutex also increments its internal *lock count*. The `Clock` and `Duration` types are inferred from the actual `absTime` argument. E.g.,

  ```
  std::timed_mutex timedMutex;
  timedMutex.try_lock_until(chrono::system_clock::now() + chrono::seconds(5));
  ```

20.2.1 Initialization in multi-threaded programs

Before using the `std::once_flag` and the `std::call_once` function, introduced in this section, the `<mutex>` header file must be included.

In single threaded programs the initialization of global data does not necessarily occur at one point in code. An example is the initialization of the object of a singleton class (cf. *Gamma et al.* (1995), Design Patterns, Addison-Wesley). Singleton classes may define a single static pointer data member `Singleton *s_object`, pointing to the singleton's object, and may offer a static member `instance`, implemented something like this:

```
Singleton &Singleton::instance()
{
    return s_object ?
                s_object
            :
                (s_object = new Singleton);
}
```

With multi-threaded programs this approach immediately gets complex. For example, if two threads call `instance` at the same time, while `s_object` still equals 0, then both may call `new Singleton`, resulting in one dynamically allocated `Singleton` object becoming unreachable. Other threads, called after `s_object` was initialized for the first time, may either return a reference to that object, or may return a reference to the object initialized by the second thread. Not exactly the expected behavior of a singleton.

Mutexes (cf. section 20.2) can be used to solve these kinds of problems, but they result in some overhead and inefficiency, as the mutex must be inspected at each call of `Singleton::instance`.

When variables must dynamically be initialized, and the initialization should take place only once the `std::once_flag` type and the `std::call_once` function should be used.

The `call_once` function expects two or three arguments:

- The first argument is a `once_flag` variable, keeping track of the actual initialization status. The `call_once` function simply returns if the `once_flag` indicates that initialization already took place;
- The second argument is the address of a function which must be called only once. This function may be a free function or it may be the address of a class member function;
- If the second argument is the address of a class member function, then the object for which the member function should be called must be provided as `call_once's` third argument.

A thread-safe implementation of the singleton's `instance` function can now easily be designed (using in-class implementations for brevity):

```
class Singleton
{
    static std::once_flag s_once;
    static Singleton *s_singleton;
    ...
    public:
        static Singleton *instance()
        {
            std::call_once(s_once, []{s_singleton = new Singleton;} );
            return s_singleton;
        }
    ...
};
```

However, there are additional ways to initialize data, even for multi-threaded programs:

- First, suppose a constructor is declared with the `constexpr` keyword (cf. section 8.1.4.1), satisfying the requirements for constant initialization. In this case, a static object, initialized using that constructor, is guaranteed to be initialized before any code is run as part of the static initialization phase. This is used by `std::mutex`, as it eliminates the possibility of race conditions when global mutexes are initialized.
- Second, a static variable defined within a compound statement may be used (e.g., a static local variable within a function body). Static variables defined within a compound statement are initialized the first time the function is called at the point in the code where the static variable is defined. Here is an example:

```
#include <iostream>

struct Cons
{
    Cons()
    {
        std::cout << "Cons called\n";
    }
};
void called(char const *time)
{
    std::cout << time << "time called() activated\n";
    static Cons cons;
}
int main()
{
```

```
            std::cout << "Pre-1\n";
            called("first");
            called("second");
            std::cout << "Pre-2\n";
            Cons cons;
        }
    /*
        Displays:
            Pre-1
            firsttime called() activated
            Cons called
            secondtime called() activated
            Pre-2
            Cons called
    */
```

This feature causes a thread to wait automatically if another thread is still initializing the static data (note that *non-static* data never cause problems, as non-static local variables only exist within their own thread of execution).

20.2.2 Shared mutexes

Shared mutexes (via the type `std::shared_mutex`) are available after including the `<shared_mutex>` header file. Shared mutex types behave like `timed_mutex` types and optionally have the characteristics described below.

The class `shared_mutex` provides a non-recursive mutex with shared ownership semantics, comparable to, e.g., the `shared_ptr` type. A program using `shared_mutexes` is undefined if:

- it destroys a shared_mutex object owned by any thread;
- a thread recursively attempts to gain ownership of a `shared_mutex`;
- a thread terminates while owning a `shared_mutex`.

Shared mutex types provide a shared lock ownership mode. Multiple threads can simultaneously hold a shared lock ownership of a `shared_mutex` type of object. But no thread can hold a shared lock while another thread holds an exclusive lock on the same `shared_mutex` object, and vice-versa.

The type `shared_mutex` offers the following members:

- `void lock_shared()`:
  Blocks the calling thread until shared ownership of the mutex can be obtained by the calling thread. An exception is thrown if the current thread already owns the lock, if it is not allowed to lock the mutex, or if the mutex is already locked and blocking is not possible;
- `void unlock_shared()`:
  Releases a shared lock on the mutex held by the calling thread. Nothing happens if the current thread does not already own the lock;
- `bool try_lock_shared()`:
  The current thread attempts to obtain shared ownership of the mutex without blocking. If shared ownership is not obtained, there is no effect and `try_lock_shared` immediately returns. Returns `true` if the shared ownership lock was acquired, `false` otherwise. An implementation may fail to obtain the lock even if it is not held by any other thread. Initially the calling thread may not yet own the mutex;

- `bool try_lock_shared_for(rel_time)`:
  Attempts to obtain shared lock ownership for the calling thread within the relative time period specified by `rel_time`. If the time specified by `rel_time` is less than or equal to `rel_time.zero()`, the member attempts to obtain ownership without blocking (as if by calling `try_lock_shared()`). The member shall return within the time interval specified by `rel_time` only if it has obtained shared ownership of the mutex object. Returns `true` if the shared ownership lock was acquired, `false` otherwise. Initially the calling thread may not yet own the mutex;

- `bool try_lock_shared_until(abs_time)`:
  Attempts to obtain shared lock ownership for the calling thread until the time specified by `abs_time` has passed. If the time specified by `abs_time` has already passed then the member attempts to obtain ownership without blocking (as if by calling `try_lock_shared()`). Returns `true` if the shared ownership lock was acquired, `false` otherwise. Initially the calling thread may not yet own the mutex;

20.3 Locks and lock handling

Locks are used to simplify the use of mutexes. Before locks can be used the `<mutex>` header file must be included.

Whenever threads share data, and at least one of the threads may change common data, mutexes should be used to prevent threads from using the same data synchronously.

Usually locks are released at the end of action blocks. This requires explicit calls to the mutexes' `unlock` function, which introduces comparable problems as we've seen with the thread's `join` member.

To simplify locking and unlocking two mutex wrapper classes are available:

- `std::lock_guard`:
  objects of this class offer the basic unlock-guarantee: their destructors call the member `unlock` of the mutexes they control;

- `std::unique_lock`:
  objects of this class offer a more extensive interface, allowing explicit unlocking and locking of the mutexes they control, while their destructors preserve the unlock-guarantee also offered by `lock_guard`;

The class `lock_guard` offers a limited, but useful interface:

- `lock_guard<Mutex>(Mutex &mutex)`:
  when defining a `lock_guard` object the mutex type (e.g., `std::mutex, std::timed_mutex, std::shared_mutex`) is specified, and a mutex of the indicated type is provided as its argument. The construction blocks until the `lock_guard` object owns the lock. The `lock_guard's` destructor automatically releases the mutex lock.

- `lock_guard<Mutex>(Mutex &mutex, std::adopt_lock_t)`:
  this constructor is used to transfer control over the mutex from the calling thread to the `lock_guard`. The mutex lock is released again by the `lock_guard's` destructor. At construction time the mutex must already be owned by the calling thread. Here is an illustration of how it can be used:

  ```
  void threadAction(std::mutex &mut, int &sharedInt)
  {
  ```

```
 3:     std::lock_guard<std::mutex> lg{mut, std::adopt_lock_t()};
 4:     // do something with sharedInt
 5: }
```

  - At line 1 `threadAction` receives a reference to a mutex. Assume the mutex owns the lock;
  - At line 3 control is transferred to the `lock_guard`. Even though we don't explicitly use the `lock_guard` object, an object should be defined to prevent the compiler from destroying an anonymous object before the function ends;
  - When the function ends, at line 5, the mutex's lock is released by the `lock_guard's` destructor.

- `mutex_type`:
  in addition to the constructors and destructor, `lock_guard<Mutex>` types also define the type `mutex_type`: it is a synonym of the `Mutex` type that is passed to the `lock_guard`'s constructor.

Here is a simple example of a multi-threaded program using `lock_guards` to prevent information inserted into `cout` from getting mixed.

```
bool oneLine(istream &in, mutex &mut, int nr)
{
   lock_guard<mutex> lg(mut);

    string line;
    if (not getline(in, line))
        return false;

    cout << nr << ": " << line << endl;

    return true;
}

void io(istream &in, mutex &mut, int nr)
{
    while (oneLine(in, mut, nr))
        this_thread::yield();
}

int main(int argc, char **argv)
{
    ifstream in(argv[1]);
    mutex ioMutex;

    thread t1(io, ref(in), ref(ioMutex), 1);
    thread t2(io, ref(in), ref(ioMutex), 2);
    thread t3(io, ref(in), ref(ioMutex), 3);

    t1.join();
    t2.join();
    t3.join();
}
```

As with `lock_guard`, a mutex-type must be specified when defining objects of the class `std::unique_lock`. The class `unique_lock` is much more elaborate than the basic `lock_guard` class template. Its interface does not define a copy constructor or overloaded assignment operator, but it *does* define a move constructor and a move assignment operator. In the following overview of `unique_lock`'s inteface `Mutex` refers to the mutex-type that is specified when defining a `unique_lock`:

- `unique_lock() noexcept`:
  the default constructor is not yet associated with a `mutex` object. It must be assigned a `mutex` (e.g., using move-assignment) before it can do anything useful;
- `explicit unique_lock(Mutex &mutex)`:
  initializes a `unique_lock` with an existing `Mutex` object, and calls `mutex.lock()`;
- `unique_lock(Mutex &mutex, defer_lock_t) noexcept`:
  initializes a `unique_lock` with an existing `Mutex` object, but does not call `mutex.lock()`. Call it by passing a `defer_lock_t` object as the constructor's second argument, e.g.,

  ```
  unique_lock<mutex> ul(mutexObj, defer_lock_t())
  ```
- `unique_lock(Mutex &mutex, try_to_lock_t) noexcept`:
  initializes a `unique_lock` with an existing `Mutex` object, and calls `mutex.try_lock()`: the constructor won't block if the mutex cannot be locked;
- `unique_lock(Mutex &mutex, adopt_lock_t) noexcept`:
  initializes a `unique_lock` with an existing `Mutex` object, and assumes that the current thread has already locked the mutex;
- `unique_lock(Mutex &mutex, chrono::duration<Rep, Period> const &relTime) noexcept`:
  this constructor tries to obtain ownership of the `Mutex` object by calling `mutex.try_lock_for(relTime)`. The specified mutex type must therefore support this member (e.g., it is a `std::timed_mutex`). It could be called like this:

  ```
  std::unique_lock<std::timed_mutex> ulock(timedMutex,
                                           std::chrono::seconds(5));
  ```
- `unique_lock(Mutex &mutex, chrono::time_point<Clock, Duration> const &absTime) noexcept`:
  this constructor tries to obtain ownership of the `Mutex` object by calling `mutex.try_lock_until(absTime)`. The specified mutex type must therefore support this member (e.g., it is a `std::timed_mutex`). This constructor could be called like this:

  ```
  std::unique_lock<std::timed_mutex> ulock(
                  timedMutex,
                  std::chrono::system_clock::now() + std::chrono::seconds(5)
              );
  ```
- `void lock()`:
  blocks the current thread until ownership of the mutex that is managed by the `unique_lock` is obtained. If no mutex is currently managed, then a `system_error` exception is thrown.
- `Mutex *mutex() const noexcept`:
  returns a pointer to the mutex object stored inside the `unique_lock` (a `nullptr` is returned if no mutex object is currently associated with the `unique_lock` object.)
- `explicit operator bool() const noexcept`:
  returns `true` if the `unique_lock` owns a locked mutex, otherwise `false` is returned;

- `unique_lock& operator=(unique_lock &&tmp) noexcept`:
  if the left-hand operand owns a lock, it will call its mutex's `unlock` member, whereafter `tmp's` state is transferred to the left-hand operand;

- `bool owns_lock() const noexcept`:
  returns `true` if the `unique_lock` owns the mutex, otherwise `false` is returned;

- `Mutex *release() noexcept`:
  returns a pointer to the mutex object that is associated with the `unique_lock` object, discarding that association;

- `void swap(unique_lock& other) noexcept`:
  swaps the states of the current `unique_lock` and `other`;

- `bool try_lock()`:
  tries to obtain ownership of the mutex that is associated witg the `unique_lock`, returning `true` if this succeeds, and `false` otherwise. If no mutex is currently associated with the `unique_lock` object, then a `system_error` exception is thrown;

- `bool try_lock_for(chrono::duration<Rep, Period> const &relTime)`:
  this member function tries to obtain ownership of the `Mutex` object managed by the `unique_lock` object by calling the mutex's `try_lock_for(relTime)` member. The specified mutex type must therefore support this member (e.g., it is a `std::timed_mutex`);

- `bool try_lock_until(chrono::time_point<Clock, Duration> const &absTime)`:
  this member function tries to obtain ownership of the `Mutex` object managed by the `unique_lock` object by calling the mutex's `mutex.try_lock_until(absTime)` member. The specified mutex type must therefore support this member (e.g., it is a `std::timed_mutex`);

- `void unlock()`:
  releases ownership of the mutex (or reduces the mutex's lock count). A `system_error` exception is thrown if the `unique_lock` object does not own the mutex.

In addition to the members of the classes `std::lock_guard` and `std::unique_lock` the functions `std::lock` and `std::try_lock` are available. These functions can be used to prevent *deadlocks*, the topic of the next section.

20.3.1 Deadlocks

A deadlock occurs when two locks are required to process data, but one thread obtains the first lock and another thread obtains the second lock. **C++** defines the generic `std::lock` and `std::try_lock` functions that can be used to help preventing such situations.

Before these functions can be used the `<mutex>` header file must be included

In the following overview `L1 &l1, ...` represents one or more references to objects of lockable types:

- `void std::lock(L1 &l1, ...)`:
  When the function returns locks were obtained on all `li` objects. If a lock could not be obtained for at least one of the objects, then all locks obtained so far are relased, even if the object for which no lock could be obtained threw an exception;

- `int std::try_lock(L1 &l1, ...)`:
  This function calls the lockable objects' `try_lock` members. If all locks could be obtained, then -1 is returned. Otherwise the (0-based) index of the first argument which could not be locked is returned, releasing all previously obtained locks.

As an example consider the following little multi-threaded program: The threads use mutexes to obtain unique access to `cout` and to an `int value`. However, `fun1` first locks `cout` (line 7), and then `value` (line 10); `fun2` first locks `value` (line 16) and then `cout` (line 19). Clearly, if `fun1` has locked `cout` `fun2` can't obtain the lock until `fun1` has released it. Unfortunately, `fun2` has locked `value`, and the functions only release their locks when returning. But in order to access the information in `value` `fun1` it must have obtained a lock on `value`, which it can't, as `fun2` has already locked `value`: the threads are waiting for each other, and neither thread gives in.

```
 1:
 2: int value;
 3: mutex valueMutex;
 4: mutex coutMutex;
 5:
 6: void fun1()
 7: {
 8:     lock_guard<mutex> lg1(coutMutex);
 9:     cout << "fun 1 locks cout\n";
10:
11:     lock_guard<mutex> lg2(valueMutex);
12:     cout << "fun 1 locks value\n";
13: }
14:
15: void fun2()
16: {
17:     lock_guard<mutex> lg1(valueMutex);
18:     cerr << "fun 2 locks value\n";
19:
20:     lock_guard<mutex> lg2(coutMutex);
21:     cout << "fun 2 locks cout\n";
22: }
23:
24: int main()
25: {
26:     thread t1(fun1);
27:     fun2();
28:     t1.join();
29: }
30:
```

A good recipe for avoiding deadlocks is to prevent nested (or multiple) mutex lock calls. But if multiple mutexes must be used, always obtain the locks in the same order. Rather than doing this yourself, `std::lock` and `std::try_lock` should be used whenever possible to obtain multiple mutex locks. These functions accept multiple arguments, which must be lockable types like `lock_guard`, `unique_lock`, or even a plain `mutex`. The previous deadlocking program, can be modified to call `std::lock` to lock both mutexes. In this example using one single mutex would also work, but the modified program now looks as similar as possible to the previous program. Note how in lines 10 and 21 a different ordering of the `unique_locks` arguments was used: it is not necessary to use an identical argument order when calling `std::lock` or `std::try_lock`.

```
 1:
 2: int value;
 3: mutex valueMutex;
 4: mutex coutMutex;
 5:
 6: void fun1()
```

```
{
    unique_lock<mutex> lg1(coutMutex, defer_lock);
    unique_lock<mutex> lg2(valueMutex, defer_lock);

    lock(lg1, lg2);

    cout << "fun 1 locks cout\n";
    cout << "fun 1 locks value\n";
}

void fun2()
{
    unique_lock<mutex> lg1(coutMutex, defer_lock);
    unique_lock<mutex> lg2(valueMutex, defer_lock);

    lock(lg2, lg1);

    cout << "fun 2 locks cout\n";
    cout << "fun 2 locks value\n";
}

int main()
{
    thread t1(fun1);
    thread t2(fun2);
    t1.join();
    t2.join();
}

```

20.3.2 Shared locks

Shared locks are available through the type `std::shared_lock`, after including the `<shared_mutex>` header file.

An object of the type `std::shared_lock` controls the shared ownership of a lockable object within a scope. Shared ownership of the lockable object may be acquired at construction time or thereafter, and once acquired, it may be transferred to another `shared_lock` object. Objects of type `shared_lock` cannot be copied, but move construction and assignment is supported.

The behavior of a program is undefined if the contained pointer to a mutex (`pm`) has a non-zero value and the lockable object pointed to by `pm` does not exist for the entire remaining lifetime of the `shared_lock` object. The supplied mutex type must be a `shared_mutex` or a type having the same characteristics.

The type `shared_lock` offers the following constructors, destructor and operators:

- `shared_lock() noexcept`:
  The default constructor creates a `shared_lock` which is not owned by a thread and for which `pm == 0`;
- `explicit shared_lock(mutex_type &mut)`:
  This constructor locks the mutex, calling `mut.lock_shared()`. The calling thread may not already own the lock. Following the construction `pm == &mut`, and the lock is owned by the current thread;

- `shared_lock(mutex_type &mut, defer_lock_t) noexcept`:
  This constructor assigns `pm` to `&mut`, but the calling thread does not own the lock;

- `shared_lock(mutex_type &mut, try_to_lock_t)`:
  This constructor tries to locks the mutex, calling `mut.try_lock_shared()`. The calling thread may not already own the lock. Following the construction `pm == &mut`, and the lock may or may not be owned by current thread, depending on the return value of `try_lock_shared`;

- `shared_lock(mutex_type &mut, adopt_lock_t)`:
  This constructor can be called if the calling thread has shared ownership of the mutex. Following the construction `pm == &mut`, and the lock is owned by the current thread;

- `shared_lock(mutex_type &mut, chrono::time_point<Clock, Duration> const &abs_time)`:
  This constructor is a member template, where `Clock` and `Duration` are types specifying a clock and absolute time (cf. section 4.2). It can be called if the calling thread does not already own the mutex. It calls `mut.try_lock_shared_until(abs_time)`. Following the construction `pm == &mut`, and the lock may or may not be owned by current thread, depending on the return value of `try_lock_shared_until`;

- `shared_lock(mutex_type &mut, chrono::duration<Rep, Period> const &rel_time)`:
  This constructor is a member template, where `Clock` and `Period` are types specifying a clock and relative time (cf. section 4.2). It can be called if the calling thread does not already own the mutex. It calls `mut.try_lock_shared_for(abs_time)`. Following the construction `pm == &mut`, and the lock may or may not be owned by current thread, depending on the return value of `try_lock_shared_for`;

- `shared_lock(shared_lock &&tmp) noexcept`:
  The move constructor transfers the information in `tmp` to the newly constructed `shared_lock`. Following the construction `tmp.pm == 0` and `tmp` no longer owns the lock;

- `~shared_lock()`:
  If the lock is owned by the current thread, `pm->unlock_shared()` is called;

- `shared_lock &operator=(shared_lock &&tmp) noexcept` (The move assignment operator calls `pm->unlock_shared` and then transfers the information in `tmp` to the current `shared_lock` object. Following this `tmp.pm == 0` and `tmp` no longer owns the lock;)

- `explicit operator bool () const noexcept`:
  Returns whether or not the `shared_lock` object owns the lock.

The following members are provided:

- `void lock()`:
  Calls `pm->lock_shared()`, after which the current tread owns the shared lock. Exceptions may be thrown from `lock_shared`, and otherwise if `pm == 0` or if the current thread already owns the lock;

- `mutex_type *mutex() const noexcept`:
  Returns `pm`;

- `mutex_type *release() noexcept`:
  Returns the previous value of `pm`, which is equal to zero after calling this member. Also, the current object no longer owns the lock;

- `void swap(shared_lock &other) noexcept`:
  Swaps the data members of the current and the `other` `shared_lock` objects. There is also a free member `swap`, a function template, swapping two `shared_lock<Mutex>` objects, where `Mutex` represents the mutex type for which the shared lock objects were instantiated: `void swap(shared_lock<Mutex> &one, shared_lock<Mutex> &two) noexcept;`
- `bool try_lock()`:
  Calls `pm->try_lock_shared()`, returning this call's return value. Exceptions may be thrown from `try_lock_shared`, and otherwise if `pm == 0` or if the current thread already owns the lock;
- `bool try_lock_for(const chrono::duration<Rep, Period>& rel_time)`:
  A member template, where `Clock` and `Period` are types specifying a clock and relative time (cf. section 4.2). It calls `mut.try_lock_shared_for(abs_time)`. Following the call the lock may or may not be owned by current thread, depending on the return value of `try_lock_shared_until`. Exceptions may be thrown from `try_lock_shared_for`, and otherwise if `pm == 0` or if the current thread already owns the lock;
- `bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time)`:
  A member template, where `Clock` and `Duration` are types specifying a clock and absolute time (cf. section 4.2). It calls `mut.try_lock_shared_until(abs_time)`, returning its return value. Following the call the lock may or may not be owned by current thread, depending on the return value of `try_lock_shared_until`. Exceptions may be thrown from `try_lock_shared_until`, and otherwise if `pm == 0` or if the current thread already owns the lock;
- `void unlock()`:
  Unlocks the shared mutex lock, releasing its ownership. Throws an exception if the shared mutex was not owned by the current thread.

20.4 Event handling (condition variables)

This section introduces *condition variables*. Condition variables allow programs to synchronize threads using the *states* of data, rather than simply locking the *access* to data (which is realized using mutexes).

Before condition variables can be used the `<condition_variable>` header file must be included.

To start our discussion, consider a classic producer-consumer scenario: the producer generates items which are consumed by a consumer. The producer can only produce a certain number of items before its storage capacity has filled up and the client cannot consume more items than the producer has produced.

At some point the producer's storage capacity has filled to the brim, and the producer has to wait until the client has at least consumed some items, thereby creating space in the producer's storage. Similarly, the consumer cannot start consuming until the producer has at least produced some items.

Implementing this scenario only using mutexes (data locking) is not an attractive option, as merely using mutexes forces a program to implement the scenario using *polling*: processes must continuously (re)acquire the mutex's lock, determine whether they can perform some action, followed by the release of the lock. Often there's no action to perform, and the process is busy acquiring and releasing the mutex's lock. Polling forces threads to wait until they can lock the mutex, even though continuation might already be possible. The polling interval could be reduced, but that too isn't an attractive option, as that increases the overhead associated with handling the mutexes (also called 'busy waiting').

Condition variables can be used to prevent polling. Threads can use condition variables to *notify* waiting threads that there is something for them to do. This way threads can synchronize on data values (*states*).

As data values may be modified by multiple threads, threads still need to use mutexes, but only for controlling access to the data. In addition, condition variables allow threads to *release* ownership of mutexes until a certain value has been obtained, until a preset amount of time has been passed, or until a preset point in time has been reached.

The prototypical setup of threads using condition variables looks like this:

- consumer thread(s) act like this:

```
lock the mutex
while the required condition has not yet been attained (i.e., is false):
    wait until being notified
     (this automatically releasing the mutex's lock).
once the mutex's lock has been reacquired, and the required condition
has been attained:
    process the data
release the mutex's lock.
```

- producer thread(s) act similarly:

```
lock the mutex
while the required condition has not yet been attained:
    do something to attain the required condition
notify waiting threads (that the required condition has been attained)
release the mutex's lock.
```

No matter which thread starts, the thread holding the mutex's lock will at some point release the lock, allowing the other process to (re)acquire it. If the consumer starts it immediately releases the lock once it enters its waiting state; if the producer starts it releases the lock once the condition is true.

This protocol hides a subtle initial synchronization requirement. The consumer will miss the producer's notification if it (i.e., the consumer) hasn't yet entered its waiting state. So *waiting (consumer) threads should start before notifying (producer) threads*. Once threads have started, no assumptions can be made anymore about the order in which any of the condition variable's members (`notify_one, notify_all, wait, wait_for`, and `wait_until`) are called.

Condition variables come in two flavors: objects of the class `std::condition_variable` are used in combination with objects of type `unique_lock<mutex>`. Because of optimizations which are available for this specific combination using `condition_variables` is somewhat more efficient than using the more generally applicable class `std::condition_variable_any`, which may be used with any (e.g., user supplied) lock type.

Condition variable classes (covered in detail in the next two sections) offer members like `wait, wait_for, wait_until, notify_one` and `notify_all` that may concurrently be called. The notifying members are always atomically executed. Execution of the `wait` members consists of three atomic parts:

- the mutex is released, and the thread is suspended until its notification;
- Once the notification has been received, the lock is reacquired
- The wait state ends (and processing continues beyond the `wait` call).

So, returning from `wait`-members the previously waiting thread has reacquired the mutex's lock.

In addition to the condition variable classes the following free function and `enum` type is provided:

- `void std::notify_all_at_thread_exit(condition_variable &cond, unique_lock<mutex> lockObject)`:
  once the current thread has ended, all other threads waiting on `cond` are notified. It is good practice to exit the thread as soon as possible after calling `notify_all_at_thread_exit`.

  Waiting threads must verify that the thread they were waiting for has indeed ended. This is usually realized by first obtaining the lock on `lockObject`, followed by verifying that the condition they were waiting for is true and that the lock was not reacquired before `notify_all_at_thread_exit` was called.

- `std::cv_status`:
  the `cv_status` enum is used by several member functions of the condition variable classes (cf. sections 20.4.1 and 20.4.2):

```
namespace std
{
    enum class cv_status
    {
        no_timeout,
        timeout
    };
}
```

20.4.1 The class std::condition_variable

The class `std::condition_variable` merely offers a default constructor. No copy constructor or overloaded assignment operator is provided.

Before using the class `condition_variable` the `<condition_variable>` header file must be included.

The class's destructor requires that no thread is blocked by the thread destroying the `condition_variable`. So all threads waiting on a `condition_variable` must be notified before a `condition_variable` object's lifetime ends. Calling `notify_all` (see below) before a `condition_variable's` lifetime ends takes care of that, as the `condition_variable's` thread releases its lock of the `mutex` variable, allowing one of the notified threads to lock the mutex.

In the following member-descriptions a type `Predicate` indicates that a provided `Predicate` argument can be called as a function without arguments, returning a `bool`. Also, other member functions are frequently referred to. It is tacitly assumed that all member referred to below were called using the same condition variable object.

The class `condition_variable` supports several `wait` members, which block the thread until notified by another thread (or after a configurable waiting time). However, `wait` members may also spuriously unblock, without having reacquired the lock. Therefore, returning from `wait` members threads should verify that the required condition is actually true. If not, again calling `wait` may be appropriate. The next piece of pseudo code illustrates this scheme:

```
while (conditionNotTrue())
    condVariable.wait(&uniqueLock);
```

The class `condition_variable`'s members are:

- `void notify_one() noexcept`:
  one `wait` member called by other threads returns. Which one actually returns cannot be predicted.

- `void notify_all() noexcept`:
  all `wait` members called by other threads unblock their wait states. Of course, only one of them will subsequently succeed in reacquiring the condition variable's lock object.

- `void wait(unique_lock<mutex>& uniqueLock)`:
  before calling `wait` the current thread must have acquired the lock of `uniqueLock`. Calling `wait` releases the lock, and the current thread is blocked until it has received a notification from another thread, and has reacquired the lock.

- `void wait(unique_lock<mutex>& uniqueLock, Predicate pred)`:
  this is a member template, using the template header `template <typename Predicate>`. The template's type is automatically derived from the function's argument type and does not have to be specified explicitly.

  Before calling `wait` the current thread must have acquired the lock of `uniqueLock`. As long as '`pred`' returns `false` `wait(lock)` is called.

- `cv_status wait_for(unique_lock<mutex> &uniqueLock, std::chrono::duration<Rep, Period> const &relTime)`:
  this member is defined as a member template, using the template header `template <typename Rep, typename Period>`. The template's types are automatically derived from the types of the function's arguments and do not have to be specified explicitly. E.g., to wait for at most 5 seconds `wait_for` can be called like this:

  ```
  cond.wait_for(&unique_lock, std::chrono::seconds(5));
  ```

  This member returns when being notified or when the time interval specified by `relTime` has passed.

  When returning due to a timeout, `std::cv_status::timeout` is returned, otherwise `std::cv_status::no_timeout` is returned.

  Threads should verify that the required data condition has been met after `wait_for` has returned.

- `bool wait_for(unique_lock<mutex> &uniqueLock, chrono::duration<Rep, Period> const &relTime, Predicate pred)`:
  this member is defined as a member template, using the template header `template <typename Rep, typename Period, typename Predicate>`. The template's types are automatically derived from the types of the function's arguments and do not have to be specified explicitly.

  As long as `pred` returns false, the previous `wait_for` member is called. If the previous member returns `cv_status::timeout`, then `pred` is returned, otherwise `true`.

- `cv_status wait_until(unique_lock<mutex>& uniqueLock, chrono::time_point<Clock, Duration> const &absTime)`:
  this member is defined as a member template, using the template header `template <typename Clock, typename Duration>`. The template's types are automatically derived from the types of the function's arguments and do not have to be specified explicitly. E.g., to wait until 5 minutes after the current time `wait_until` can be called like this:

  ```
  cond.wait_until(&unique_lock, chrono::system_clock::now() +
                                std::chrono::minutes(5));
  ```

This function acts identically to the `wait_for(unique_lock<mutex> &uniqueLock, chrono::duration<Rep, Period> const &relTime)` member described earlier, but uses an absolute point in time, rather than a relative time specification.

This member returns when being notified or when the time interval specified by `relTime` has passed.
When returning due to a timeout, `std::cv_status::timeout` is returned, otherwise `std::cv_status::no_timeout` is returned.

- `bool wait_until(unique_lock<mutex> &lock, chrono::time_point<Clock, Duration> const &absTime, Predicate pred)`:
  this member is defined as a member template, using the template header `template <typename Clock, typename Duration, typename Predicate>`. The template's types are automatically derived from the types of the function's arguments and do not have to be specified explicitly.

  As long as `pred` returns false, the previous `wait_until` member is called. If the previous member returns `cv_status::timeout`, then `pred` is returned, otherwise `true`.

Threads should verify that the required condition is `true` when wait-members of condition variables return.

20.4.2 The class std::condition_variable_any

Different from the class `condition_variable` the class `std::condition_variable_any` can be used with any (e.g., user supplied) lock type, and not just with the stl-provided `unique_lock<mutex>`.

Before using the class `condition_variable_any` the `<condition_variable>` header file must be included.

The functionality that is offered by `condition_variable_any` is identical to the functionality offered by the class `condition_variable`, albeit that the lock-type that is used by `condition_variable_any` is not predefined. The class `condition_variable_any` therefore requires the specification of the lock-type that must be used by its objects.

In the interface shown below this lock-type is referred to as `Lock`. Most of `condition_variable_any's` members are defined as member templates, defining a `Lock` type as one of its parameters. The requirements of these lock-types are identical to those of the stl-provided `unique_lock`, and user-defined lock-type implementations should provide at least the interface and semantics that is also provided by `unique_lock`.

This section merely presents the interface of the class `condition_variable_any`. As its interface offers the same members as `condition_variable` (allowing, where applicable, passing any lock-type instead of just `unique_lock` to corresponding members), the reader is referred to the previous section for a description of the semantics of the class members.

Like `condition_variable`, the class `condition_variable_any` only offers a default constructor. No copy constructor or overloaded assignment operator is provided.

Also, like `condition_variable`, the class's destructor requires that no thread is blocked by the current thread. This implies that all other (waiting) threads must have been notified; those threads may, however, subsequently block on the lock specified in their `wait` calls.

Note that, in addition to `Lock`, the types `Clock, Duration, Period, Predicate`, and `Rep` are template types, defined just like the identically named types mentioned in the previous section.

Assuming that `MyMutex` is a user defined mutex type, and that `MyLock` is a user defined lock-type (cf.

section 20.3 for details about lock-types), then a `condition_variable_any` object can be defined and used like this:

```
MyMutex mut;
MyLock<MyMutex> ul(mut);
condition_variable_any cva;

cva.wait(ul);
```

These are the class `condition_variable_any's` members:

- `void notify_one() noexcept;`
- `void notify_all() noexcept;`
- `void wait(Lock& lock);`
- `void wait(Lock& lock, Predicate pred);`
- `cv_status wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& absTime);`
- `bool wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& absTime, Predicate pred);`
- `cv_status wait_for(Lock& lock, const chrono::duration<Rep, Period>& relTime);`
- `bool wait_for(Lock& lock, const chrono::duration<Rep, Period>& relTime,) Predicate pred;`

20.4.3 An example using condition variables

Condition variables are used to synchronize threads on the values of data, rather than on the mere access to data (for which plain mutex-objects can be used). Using condition variables, a thread simply sleeps until it is notified by another thread. In a producer-consumer type of program this is usually accomplished like this:

```
consumer loop:
    - wait until there's an item in store,
      then reduce the number of stored items
    - remove the item from the store
    - increment the number of available storage locations
    - do something with the retrieved item

producer loop:
    - produce the next item
    - wait until there's room to store the item,
      then reduce the number of available storage locations
    - store the item
    - increment the number of stored items
```

It is important that the two storage administrative tasks (registering the number of available items and available storage locations) are either performed by the client or by the producer. For the consumer 'waiting' means:

- Get a lock on the variable containing the actual count

- As long as the count is zero: wait, releasing the lock until another thread has increased the count, then re-acquire the lock.
- Reduce the count
- Release the lock.

This scheme is implemented in a class `Semaphore`, offering members `wait` and `notify_all`. For a more extensive discussion of semaphores see *Tanenbaum, A.S. and Austin, T.* (2013) Structured Computer Organization, Pearson Prentice-Hall.

The data member containing the actual count is called `d_available`. It is protected by `mutex d_mutex`. In addition a `condition_variable d_condition` is defined:

```
std::mutex d_mutex;
std::condition_variable d_condition;
size_t d_available;
```

The waiting process is implemented through its member function `wait`:

```
1: void Semaphore::wait()
2: {
3:     std::unique_lock<std::mutex> lk(d_mutex);   // get the lock
4:     while (d_available == 0)
5:         d_condition.wait(lk);   // internally releases the lock
6:                                 // and waits, on exit
7:                                 // acquires the lock again
8:     --d_available;              // dec. available
9: }   // the lock is released
```

In line 5 `d_condition.wait` releases the lock. It waits until receiving a notification, and re-acquires the lock just before returning. Consequently, `wait's` code always has complete and unique control over `d_available`.

What about notifying the a waiting thread? This is handled in lines 4 and 5 of the member function `notify_all`:

```
1: void Semaphore::notify_all()
2: {
3:     std::lock_guard<std::mutex> lk(d_mutex);    // get the lock
4:     if (d_available++ == 0)
5:         d_condition.notify_all();   // use notify_one to notify one other
6:                                     // thread
7: }   // the lock is released
```

At line 4 `d_available` is always incremented; by using a postfix increment it can simultaneously be tested for being zero. If it was initially zero then `d_available` is now one. A thread waiting until `d_available` exceeds zero may now continue. A waiting thread is notified by calling `d_condition.notify_one`. In situations where multiple threads are waiting '`notify_all`' can also be used.

Using the facilities of the class `Semaphore` whose constructor expects an initial value of its `semaphore` data member, the classic consumer-producer paradigm can now be implemented using multi-threading[2]:

---

[2] A more elaborate example of the producer-consumer program is found in the `yo/threading/examples/events.cc` file in the **C++** Annotations's source archive

```
Semaphore available(10);
Semaphore filled(0);
std::queue itemQueue;

void consumer()
{
    while (true)
    {
        filled.wait();
            // mutex lock the queue with multiple consumers
        size_t item = itemQueue.front();
        itemQueue.pop();
        available.notify_all();
        process(item);      // not implemented here
    }
}

void producer()
{
    size_t item = 0;
    while (true)
    {
        ++item;
        available.wait();
            // mutex lock the queue with multiple consumers
        itemQueue.push(item);
        filled.notify_all();
    }
}
int main()
{
    thread consume(consumer);
    thread produce(producer);

    consume.join();
    produce.join();
}
```

20.5 Atomic actions: mutexes not required

Before using the facilities introduced in this section the `<atomic>` header file must be included.

When data are shared among multiple threads, data corruption is usually prevented using mutexes. To increment a simple `int` using this strategy code as shown below is commonly used:

```
{
    lock_guard<mutex> lk{ intVarMutex };
    ++intVar;
}
```

The compound statement is used to limit the `lock_guard's` lifetime, so that `intVar` is only locked for a short little while.

This scheme is not complex, but at the end of the day having to define a `lock_guard` for every single use of a simple variable, and having to define a matching mutex for each simple variable is a bit annoying and cumbersome.

C++ offers a way out through the use of *atomic data types*. Atomic data types are available for all basic types, and also for (trivial) user defined types. Trivial types are (see also section 23.6.2) all scalar types, arrays of elements of a trivial type, and classes whose constructors, copy constructors, and destructors all have default implementations, and their non-static data members are themselves of trivial types.

The class template `std::atomic<Type>` is available for all built-in types, including pointer types. E.g., `std::atomic<bool>` defines an atomic `bool` type. For many types alternative somewhat shorter type names are available. E.g, instead of `std::atomic<unsigned short>` the type `std::atomic_ushort` can be used. Refer to the `atomic` header file for a complete list of alternate names.

If `Trivial` is a user-defined trivial type then `std::atomic<Trivial>` defines an atomic variant of `Trivial`: such a type does not require a separate `mutex` to synchronize access by multiple threads.

Objects of the class template `std::atomic<Type>` cannot directly be copied or assigned to each other. However, they can be initialized by values of type `Type`, and values of type `Type` can also directly be assigned to `std::atomic<Type>` objects. Moreover, since `atomic<Type>` types offer conversion operators returning their `Type` values, an `atomic<Type>` objects can also be assigned to or initialized by another `atomic<Type>` object using a `static_cast`:

```
    atomic<int> a1 = 5;
    atomic<int> a2{ static_cast<int>(a1) };
```

The class `std::atomic<Type>` provides several public members, shown below. Non-member (free) functions operating on `atomic<Type>` objects are also available.

The `std::memory_order` enumeration defines the following symbolic constants, which are used to specify ordering constraints of atomic operations:

- `memory_order_acq_rel`: the operation must be a read-modify-write operation, combining `memory_order_acquire` and `memory_order_release`;
- `memory_order_acquire`: the operation is an acquire operation. It synchronizes with a release operation that wrote the same memory location;
- `memory_order_consume`: the operation is a consume operation on the involved memory location;
- `memory_order_relaxed`: no ordering constraints are provided by the operation;
- `memory_order_release`: the operation is a release operation. It synchronizes with acquire operations on the same location;
- `memory_order_sec_cst`: the default memory order specification for all operations. Memory storing operations use `memory_order_release`, memory load operations use `memory_order_acquire`, and read-modify-write operations use `memory_order_acq_rel`.

The memory order cannot be specified for the overloaded operators provided by `atomic<Type>`. Otherwise, most `atomic` member functions may also be given a final `memory_order` argument. Where this is not available it is explictly mentioned at the function's description.

Here are the standard available `std::atomic<Type>` member functions:

- `bool compare_exchange_strong(Type &currentValue, Type newValue) noexcept`:
  The value in the atomic object is compared to `newValue` using byte-wise comparisons. If equal (and `true` is returned) then `newValue` is stored in the atomic object; if unequal (and `false` is returned) the object's current value is stored in `currentValue`;

- `bool compare_exchange_weak(Type &oldValue, Type newValue) noexcept`:
  The value in the atomic object is compared to `newValue` using byte-wise comparisons. If equal (and `true` is returned), then `newValue` is stored in the atomic object; if unequal, or `newValue` cannot be atomically assigned to the current object `false` is returned and the object's current value is stored in `currentValue`;

- `Type exchange(Type newValue) noexcept`:
  The object's current value is returned, and `newValue` is assigned to the current object;

- `bool is_lock_free() const noexept`:
  If the operations on the current object can be performed lock-free `true` is returned, otherwise `false`. This member has no `memory_order` parameter;

- `Type load() const noexcept`:
  The object's value is returned;

- `operator Type() const noexcept`:
  The object's value is returned;

- `void store(Type newValue) noexcept`:
  `NewValue` is assigned to the current object. Note that the standard assignment operator can also be used.

In addition to the above members, integral atomic types '`Integral`' (essentially the atomic variants of all built-in integral types) also offer the following member functions:

- `Integral fetch_add(Integral value) noexcept`:
  `Value` is added to the object's value, and the object's value at the time of the call is returned;

- `Integral fetch_sub(Integral value) noexcept`:
  `Value` is subtracted from the object's value, and the object's value at the time of the call is returned;

- `Integral fetch_and(Integral mask) noexcept`:
  The `bit-and` operator is applied to the object's value and `mask`, assigning the resulting value to the current object. The object's value at the time of the call is returned;

- `Integral fetch_|=(Integral mask) noexcept`:
  The `bit-or` operator is applied to the object's value and `mask`, assigning the resulting value to the current object. The object's value at the time of the call is returned;

- `Integral fetch_^=(Integral mask) noexcept`:
  The `bit-xor` operator is applied to the object's value and `mask`, assigning the resulting value to the current object. The object's value at the time of the call is returned;

- `Integral operator++() noexcept`:
  The prefix increment operator, returning object's new value;

- `Integral operator++(int) noexcept`:
  The postfix increment operator, returning the object's value before it was incremented;

- `Integral operator--() noexcept`

  The prefix decrement operator, returning object's new value;

- `Integral operator--(int) noexcept`

  The postfix decrement operator, returning the object's value before it was decremented;

- `Integral operator+=(Integral value) noexcept:`
  `Value` is added to the object's current value and the object's new value is returned;

- `Integral operator-=(Integral value) noexcept:`
  `Value` is subtracted from the object's current value and the object's new value is returned;

- `Integral operator&=(Integral mask) noexcept:`
  The `bit-and` operator is applied to the object's current value and `mask`, assigning the resulting value to the current object. The object's new value is returned;

- `Integral operator|=(Integral mask) noexcept:`
  The `bit-or` operator is applied to the object's current value and `mask`, assigning the resulting value to the current object. The object's new value is returned;

- `Integral operator^=(Integral mask) noexcept:`
  The `bit-xor` operator is applied to the object's current value and `mask`, assigning the resulting value to the current object. The object's new value is returned;

Some of the free member functions have names ending in `_explicit`. The `_explicit` functions define an additional parameter '`memory_order order`', which is not available for the non-`_explicit` functions (e.g., `atomic_load(atomic<Type> *ptr)` and `atomic_load_explicit(atomic<Type> *ptr, memory_order order)`)

Here are the free functions that are available for all atomic types:

- `bool std::atomic_compare_exchange_strong(_explicit)(std::atomic<Type> *ptr, Type *oldValue, Type newValue) noexept:`
  returns `ptr->compare_exchange_strong(*oldValue, newValue);`

- `bool std::atomic_compare_exchange_weak(_explicit)(std::atomic<Type> *ptr, Type *oldValue, Type newValue) noexept:`
  returns `ptr->compare_exchange_weak(*oldValue, newValue);`

- `Type std::atomic_exchange(_explicit)(std::atomic<Type> *ptr, Type newValue) noexept:`
  returns `ptr->exchange(newValue);`

- `void std::atomic_init(std::atomic<Type> *ptr, Type init) noexept:`
  Stores `init` *non*-atomically in `*ptr`. The object pointed to by `ptr` must have been default constructed, and as yet no member functions must have been called for it. This function has no `memory_order` parameter;

- `bool std::atomic_is_lock_free(std::atomic<Type> const *ptr) noexept:`
  returns `ptr->is_lock_free()`. This function has no `memory_order` parameter;

- `Type std::atomic_load(_explicit)(std::atomic<Type> *ptr) noexept:`
  returns `ptr->load();`

- `void std::atomic_store(_explicit)(std::atomic<Type> *ptr, Type value) noexept:`
  calls `ptr->store(value).`

In addition to the abovementioned free functions `atomic<Integral>` types also offer the following free member functions:

- `Integral std::atomic_fetch_add(_explicit)(std::atomic<Integral> *ptr, Integral value) noexcept`:
  returns `ptr->fetch_add(value);`
- `Integral std::atomic_fetch_sub(_explicit)(std::atomic<Integral> *ptr, Integral value) noexcept`:
  returns `ptr->fetch_sub(value);`
- `Integral std::atomic_fetch_and(_explicit)(std::atomic<Integral> *ptr, Integral mask) noexcept`:
  returns `ptr->fetch_and(value);`
- `Integral std::atomic_fetch_or(_explicit)(std::atomic<Integral> *ptr, Integral mask) noexcept`:
  returns `ptr->fetch_or(value);`
- `Integral std::atomic_fetch_xor(_explicit)(std::atomic<Integral> *ptr, Integral mask) noexcept`:
  returns `ptr->fetch_xor(mask).`

20.6 An example: threaded quicksort

The quicksort sorting algorithm (Hoare, 1962) is a well-known sorting algorithm. Given an array of `n` elements, it works like this:

- Pick an element from the array, and partition the array with respect to this element (call it the *pivot element*) (in the example below, assume a function `partition` performing the partition is available). This leaves us with two (possibly empty) sub-arrays: one to the left of the pivot element, and one to the right of the pivot element;
- Recursively perform quicksort on the left-hand sub-array;
- Recursively perform quicksort on the right-hand sub-array.

To convert this algorithm to a multi-threaded algorithm appears to be be a simple task:

```
void quicksort(Iterator begin, Iterator end)
{
    if (end - begin < 2)            // less than 2 elements are left
        return;                     // and we're done

    Iter pivot = partition(begin, end); // determine an iterator pointing
                                        // to the pivot element

    thread lhs(quicksort, begin, pivot);// start threads on the left-hand
                                        // side sub-arrays
    thread rhs(quicksort, pivot + 1, end);  // and on the right-hand side
                                            // sub-arrays
    lhs.join();
    rhs.join();                         // and we're done
}
```

Unfortunately, this translation to a multi-threaded approach won't work for reasonably large arrays because of a phenomenon called *overpopulation*: more threads are started than the operating system

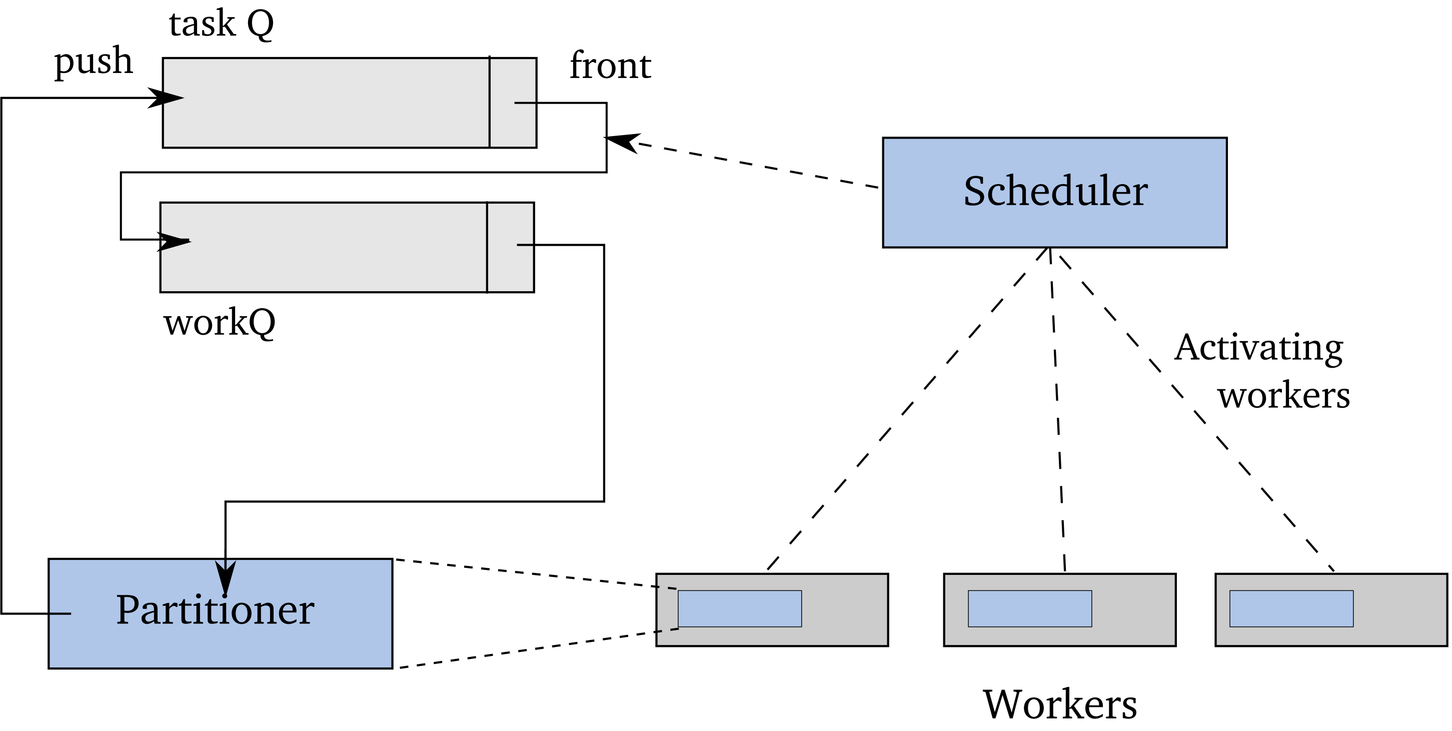

Figure 20.1: Data structure used for multi-threading quicksort

is prepared to give us. In those cases a *Resource temporarily unavailable* exception is thrown, and the program ends.

Overpopulation can be avoided by using a *pool of workers*, where each 'worker' is a thread, which in this case is responsible for handling one (sub) array, but not for the nested calls. The pool of workers is controlled by a scheduler, receiving the requests to sort sub-arrays, and passing these requests on to the next available worker.

The main data structure of the example program developed in this section is a queue of `std::pairs` containing iterators of the array to be sorted (cf. Figure 20.1, the sources of the program are found in the **C++** Annotations's `yo/threading/examples/multisort` directory). Two queues are being used: one queue is a task-queue, receiving the iterators of sub-arrays to be partitioned. Instead of immediately launching new threads (the `lhs` and `rhs` threads in the above example), the ranges to be sorted are pushed on the task-queue. The other queue is the work-queue: elements are moved from the task-queue to the work-queue, where they will be processed by one of the worker threads.

The program's `main` function starts the workforce, reads the data, pushes the arrays `begin` and `end` iterators on the task queue and then starts the scheduler. Once the scheduler ends the sorted array is displayed:

```
int main()
{
    workForce();            // start the worker threads
    readData();             // read the data into vector<int> g_data
    g_taskQ.push(           // prepare the main task
                Pair(g_data.begin(), g_data.end())
            );
    scheduler();            // sort g_data
    display();              // show the sorted elements
}
```

The workforce consists of a bunch of detached threads. Each thread represents a worker, implemented in the function `void worker`. Since the number of worker threads is fixed, overpopulation doesn't occur. Once the array has been sorted and the program stops these detached threads simply end:

```
for (size_t idx = 0; idx != g_sizeofWorkforce; ++idx)
    thread(worker).detach();
```

The scheduler continues for as long as there are sub-arrays to sort. When this is the case the task queue's front element is moved to the work queue. This reduces the work queue's size, and prepares an assignment for the next available worker. The scheduler now waits until a worker is available. Once workers are available one of them is informed of the waiting assignment, and the scheduler waits for the next task:

```
void scheduler()
{
    while (newTask())
    {
        g_workQ.rawPushFront(g_taskQ);

        g_workforce.wait();            // wait for a worker to be available
        g_worker.notify_all();            // activate a worker
    }
}
```

The function `newTask` simply checks whether the task queue is empty. If so, and none of the workers is currently busy sorting a sub-array then the array has been sorted, and `newTask` can return `false`. When the task queue is empty but a worker is still busy, it may be that new sub-array dimensions are going to be placed on the task queue by an active worker. Whenever a worker is active the `Semaphore g_workforce's` size is less than the size of the work force:

```
bool wip()
{
    return g_workforce.size() != g_sizeofWorkforce;
}

bool newTask()
{
    bool done;

    unique_lock<mutex> lk(g_taskMutex);
    while ((done = g_taskQ.empty()) && wip())
        g_taskCondition.wait(lk);

    return not done;
}
```

Each detached worker thread performs a continuous loop. In the loop it waits for a notification by the scheduler. Once it receives a notification it retrieves its assignment from the work queue, and partitions the sub-array specified in its assignment. Partitioning may result in new tasks. Once this has been completed the worker has completed its assignment: it increments the available workforce and notifies the scheduler that it should check whether all tasks have been performed:

```
void worker()
```

```
{
    while (true)
    {
        g_worker.wait();      // wait for action

        partition(g_workQ.popFront());
        g_workforce.notify_all();

        lock_guard<mutex> lk(g_taskMutex);
        g_taskCondition.notify_one();
    }
}
```

Sub-arrays smaller than two elements need no partitioning. All larger sub-arrays are partitioned relative to their first element. The `std::partition` generic algorithm does this well, but if the pivot is itself an element of the array to partition then the pivot's eventual location is undetermined: it may be found anywhere in the series of elements which are at least equal to the pivot. The two required sub-arrays, however, can easily be constructed:

- First call `std::partition` relative to an array's first element, partitioning the array's remaining elements, returning `mid`, pointing to the first element of the series of elements that are at least as large as the array's first element;
- Then swap the array's first element with element to which `mid - 1` points;
- The two sub-arrays range from, respectively, `array.begin()` to `mid - 1` (elements all smaller than the pivot), and from `mid` to `array.end()` (elements all at least as large as the pivot).

The two iterator pairs defining these two sub-arrays are thereupon added to the task queue, creating two new tasks to be dealt with by the scheduler:

```
void partition(Pair const &range)
{
    if (range.second - range.first < 2)
        return;

    auto rhsBegin = partition(range.first + 1, range.second,
                        bind2nd(less<int>(), *range.first));
    auto lhsEnd = rhsBegin - 1;

    swap(*range.first, *lhsEnd);

    pushTask(range.first, lhsEnd);
    pushTask(rhsBegin, range.second);
}
```

20.7 Shared States

Just before a thread ends it may have produced some results. These results may have to to be communicated to other threads. In multi threaded programs several classes and functions can be used that produce *shared states*, making it easy to communicate results to other threads. Results could be values, objects or exceptions.

Objects that contain such shared states are called *asynchronous return objects*. However, due to the nature of multi threading, a thread may request the results of an asynchronous return object before these result are actually available. In those cases the requesting thread blocks, waiting for the results to become available. Asynchronous return objects offer `wait` and `get` members which, respectively, *wait* until the results have become available, and *produce* the asynchronous results once they are available. The phrase that is used to indicate that the results are available is 'the shared state has been made ready'.

Shared states are made ready by *asynchronous providers*. Asynchronous providers are simply objects or functions providing results to shared states. Making a shared state ready means that an asynchronous provider

- marks its shared state as being ready, and
- unblocks any waiting threads (e.g., by allowing blocking members, like `wait`, to return).

Once a shared state has been made ready it contains a value, object, or exception which can be retrieved by objects having access to the shared state. While code is waiting for a shared state to become ready the value or exception that is going to be stored in the shared state may be computed. When multiple threads try to access the same shared state they must use synchronizing mechanisms (like mutexes, cf. section 20.2) to prevent access-conflicts.

Shared states use reference counting to keep track of the number of asynchronous return objects or asynchronous providers that hold references to them. These return objects and providers may release their references to these shared states (which is called 'releasing the shared state). This happens when a return object or provider holds the last reference to the shared state, and the shared state is destroyed.

On the other hand, an asynchronous provider may also *abandon* its shared state. In that case the provider, in sequence,

- stores an exception object of type `std::future_error`, holding the error condition `std::broken_promise` in its shared state;
- makes its shared data ready; and
- releases its shared data.

Objects of the class `std::future` (see the next section) are asynchronous return objects. They can be produced by the `std::async` (section 20.10) family of functions, and by objects of the classes `std::packaged_task` (section 20.11), and `std::promise` (section 20.12).

20.8 Asynchronous return objects: std::future

Condition variables allow threads to wait until data have obtained certain values. A thread may also have to wait until a sub-thread has finished when calling a sub-thread's `join` member.

Waiting may be unwelcome: instead of just waiting our thread might also be doing something useful. It might as well pick up the results produced by a sub-thread at some point in the future.

In fact, exchanging data among threads always poses some difficulties, as it requires shared variables, and the use of locks and mutexes to prevent data corruption. Rather than waiting and using locks it would be nice if some asynchronous task could be started, allowing the initiating thread (or even other threads) to pick up the result at some point in the future, when the results are needed, without having to worry about data locks or waiting times. For situations like these **C++** provides the class `std::future`.

Before using the class `std::future` the `<future>` header file must be included.

Objects of the class template `std::future` harbor the results produced by asynchronously executed tasks. The class `std::future` is a class template. Its template type parameter specifies the type of the result returned by the asynchronously executed task. This type may be `void`.

On the other hand, the asynchronously executed task may throw an exception (ending the task). In that case the `future` object catches the exception, and rethrows it once its return value (i.e., the value returned by the asynchronously executed task) is requested.

In this section the members of the class template `future` are described. `Future` objects are commonly initialized through anonymous `future` objects returned by the factory function `std::async` or by the `get_future` members of the classes `std::promise`, and `std::packaged_task` (introduced in upcoming sections). Examples of the use of `std::future` objects are provided in those sections.

Some of `future`'s members return a value of the strongly typed enumeration `std::future_status`. This enumeration defines three symbolic constants: `future_status::ready`, `future_status::timeout`, and `future_status::deferred`.

Error conditions are returned through `std::future_error` exceptions. These error conditions are represented by the values of the strongly typed enumeration `std::future_errc` (covered in the next section).

The class `future` itself provides the following constructors:

- `future()`:
  The default constructor constructs an `future` object that does not refer to shared results. Its `valid` member returns `false`.
- `future(future &&tmp) noexcept`:
  The move constructor is available. Its `valid` member returns what `tmp.valid()` would haved returned prior to the constructor invocation. After calling the move constructor `tmp.valid()` returns `false`.

The class `future` does not offer a copy constructor or an overloaded assignment operator.

Here are the members of the class `std::future`:

- `future &operator=(future &&tmp)`:
  The move assignment operator grabs the information from the `tmp` object; following this, `tmp.valid()` returns `false`.
- `std::shared_future<ResultType> share() &&`:
  Returns a `std::shared_future<ResultType>` (see section 20.9). After calling this function, the `future's valid` member returns `false`.
- `ResultType get()`:
  First `wait` (see below) is called. Once `wait` has returned the results produced by the associated asynchronous task are returned. With `future<Type>` specifications the returned value is the moved shared value if `Type` supports move assignment, otherwise a copy is returned. With `future<Type &>` specifications a `Type &` is returned, with `future<void>` specifications nothing is returned. If the shared value is an exception, it is thrown instead of returned. After calling this member the `future` object's `valid` member returns `false`.

- `bool valid() const`:
  Returns `true` if the (`future`) object for which `valid` is called refers to an object returned by an asynchronous task. If `valid` returns `false`, the `future` object exists, but in addition to `valid` only its destructor and move constructor can safely be called. When other members are called while `valid` returns `false` a `std::future_error` exception is thrown (having the value `future_errc::no_state`).

- `void wait() const`:
  The thread is blocked until the results produced by the associated asynchronous task are available.

- `std::future_status wait_for(chrono::duration<Rep, Period> const &rel_time) const`:
  This member template derives the template types `Rep` and `Period` from the actually specified duration (cf. section 4.2.2). If the results contain a deferred function nothing happens. Otherwise `wait_for` blocks

  until the results are available or until the amount of time specified by `rel_time` has expired. Possible return values are:

  - `future_status::deferred` if the results contains a deferred function;
  - `future_status::ready` if the results are avaiable;
  - `future_status::timeout` if the function is returning because the amount of time specified by `rel_time` has expired.

- `future_status wait_until(chrono::time_point<Clock, Duration> const &abs_time) const`:
  This member template derives the template types `Clock` and `Duration` from the actually specified `abs_time` (cf. section 4.2.4). If the results contain a deferred function nothing happens. Otherwise `wait_until` blocks until the results are available or until the point in time specified by `abs_time` has expired. Possible return values are:

  - `future_status::deferred` if the results contain a deferred function;
  - `future_status::ready` if the results are available;
  - `future_status::timeout` if the function is returning because the point in time specified by `abs_time` has expired.

The class `std::future<ResultType>` declares the following friends:

```
std::promise<ResultType>
```

(sf. section 20.12), and

```
template<typename Function, typename... Args>
    std::future<typename result_of<Function(Args...)>::type>
    std::async(std::launch, Function &&fun, Args &&...args);
```

(cf. section 20.10).

20.8.1 The std::future_error exception and the std::future_errc enum

Members of the class `std::future` may return errors by throwing `std::future_error` exceptions. These error conditions are represented by the values of the strongly typed enumeration `std::future_errc` which defines the following symbolic constants:

- `broken_promise`

  `Broken_promise` is thrown when a `future` object was received whose value was never assigned by a `promise` or `packaged_task`. For example, an object of the class `promise<int>` should set the value of the `future<int>` object returned by its `get_future` member (cf. section 20.12), but if it doesn't do so, then a `broken_promise` exception is thrown, as illustrated by the following program:

  ```
   1: std::future<int> fun()
   2: {
   3:     return std::promise<int>().get_future();
   4: }
   5:
   6: int main()
   7: try
   8: {
   9:     fun().get();
  10: }
  11: catch (std::exception const &exc)
  12: {
  13:     std::cerr << exc.what() << '\n';
  14: }
  ```

  At line 3 a `promise` object is created, but its value is never set. Consequently, it 'breaks its promise' to produce a value: when `main` tries to retrieve its value (in line 9) a `std::futue_error` exception is thrown containing the `future_errc::broken_promise` value

- `future_already_retrieved`

  `Future_already_retrieved` is thrown when multiple attempts are made to retrieve the `future` object from, e.g., a `promise` or `packaged_task` object that (eventually) should be ready. For example:

  ```
   1: int main()
   2: {
   3:     std::promise<int> promise;
   4:     promise.get_future();
   5:     promise.get_future();
   6: }
  ```

  Note that after defining the `std::promise` object in line 3 it has merely been defined: no value is ever assigned to its `future`. Even though no value is assigned to the `future` object, it *is* a valid object. I.e., after some time the future *should* be ready, and the future's `get` member should produce a value. Hence, line 4 succeeds, but then, in line 5, the exception is thrown as 'the future has already been retrieved'.

- `promise_already_satisfied`

  `Promise_already_satisfied` is thrown when multiple attempts are made to assign a value to a `promise` object. Assigning a value or `exception_ptr` to the `future` of a `promise` object may happen only once. For example:

  ```
   1: int main()
   2: {
   3:     std::promise<int> promise;
   4:     promise.set_value(15);
   5:     promise.set_value(155);
   6: }
  ```

- `no_state`

  `No_state` is thrown when a member function (other than `valid`, see below) of a `future` object is called when its `valid` member returns `false`. This happens, e.g., when calling members of a default constructed `future` object. `No_state` is not thrown for `future` objects returned by the `async` factory function or returned by the `get_future` members of `promise` or `packaged_task` type of objects. Here is an example:

  ```
  int main()
  {
      std::future<int> fut;
      fut.get();
  }
  ```

The class `std::future_error` is derived from the class `std::exception`, and offers, in addition to the `char const *what() const` member also the member `std::error_code const &code() const`, returning an `std::error_code` object associated with the thrown exception.

20.9 Shared asynchronous return objects: std::shared_future

When a thread activates an asynchronous provider (e.g., a `std::async`) then the return value of the asynchronously called function becomes available in its activating thread through a `std::future` object. The `future` object cannot be used by another thread. If this is required (e.g., see this chapter's final section) the `future` object must be converted to a `std::shared_future` object.

Before using the class `std::shared_future` the `<future>` header file must be included.

Once a `shared_future` object is available, its `get` member (see below) can repeatedly be called to retrieve the results of the original `future` object. This is illustrated by the next small example:

```
 1: int main()
 2: {
 3:     std::promise<int> promise;
 4:     promise.set_value(15);
 5:
 6:     auto fut = promise.get_future();
 7:     auto shared1 = fut.share();
 8:
 9:     std::cerr << "Result: " << shared1.get() << '\n';
10:               << "Result: " << shared1.get() << '\n';
11:               << "Valid: " << fut.valid() << '\n';
12:
13:     auto shared2 = fut.share();
14:
15:     std::cerr << "Result: " << shared2.get() << '\n';
16:               << "Result: " << shared2.get() << '\n';
17: }
```

In lines 9 and 10 the `promise's` results are retrieved multiple times, but having obtained the `shared_future` in line 7, the original `future` object no longer has an associated shared state. Therefore, when another attempt is made (in line 13) to obtain the `shared_future`, a *no associated state* exception is thrown and the program aborts.

However, multiple copies of `shared_future` objects may co-exist. When multiple copies of `shared_future` objects exist (e.g. in different threads), the results of the associated asynchronous task are made ready (become available) at exactly the same moment in time.

The relationship between the classes `future` and `shared_future` resembles the relationship between the classes `unique_ptr` and `shared_ptr`: there can only be one instance of a `unique_pointer`, pointing to data, whereas there can be many instances of a `shared_pointer`, each pointing to the same data.

The effect of calling any member of a `shared_future` object for which `valid() == false` other than the destructor, the move-assignment operator, or `valid` is undefined.

The class `shared_future` supports the following constructors:

- `shared_future() noexcept`

  an empty `shared_future` object is constructed that does not refer to shared results. After using this constructor the object's `valid` member returns `false`.

- `shared_future(shared_future const &other)`

  a `shared_future` object is constructed that refers to the same results as `other` (if any). After using this constructor the object's `valid` member returns the same value as `other.valid()`.

- `shared_future(shared_future<Result> &&tmp) noexcept`

  Effects: move constructs a shared_future object that refers to the results that were originally referred to by `tmp` (if any). After using this constructor the object's `valid` member returns the same value as `tmp.valid()` returned prior to the constructor invocation, and `tmp.valid()` returns `false`.

- `shared_future(future<Result> &&tmp) noexcept`

  Effects: move constructs a shared_future object that refers to the results that were originally referred to by `tmp` (if any). After using this constructor the object's `valid` member returns the same value as `tmp.valid()` returned prior to the constructor invocation, and `tmp.valid()` returns `false`.

The class's destructor destroys the `shared_future` object for which it is called. If the object for which the destructor is called is the last `shared_future` object, and no `std::promise` or `std::packaged_task` is associated with the results associated with the current object, then the results are also destroyed.

Here are the members of the class `std::shared_future`:

- `shared_future& operator=(shared_future &&tmp)`:
  The move assignment operator releases the current object's shared results, and move assigns `tmp's` results to the current object. After calling the move assignment operator the current object's `valid` member returns the same value as `tmp.valid()` returned prior to the invocation of the move assignment operator, and `tmp.valid()` returns `false`;

- `shared_future& operator=(shared_future const &rhs)`:
  The assignment operator releases the current object's shared results, and `rhs`'s results are shared with the current object. After calling the assignment operator the current object's `valid` member returns the same value as `tmp.valid()`;

- `Result const &shared_future::get() const`:
  (Specializations for `shared_future<Result &>` and `shared_future<void>` are also

available). This member waits until the shared results are available, and subsequently returns `Result const &`. Note that access to the data stored in `Results`, accessed through `get` is not synchronized. It is the responsibility of the programmer to avoid race conditions when accessing `Result's` data. If `Result` holds an exception, it is thrown when `get` is called;

- `bool valid() const`:
  Returns `true` if the current object refers to shared results;
- `void wait() const`:
  Blocks until shared results are available (i.e., the associated asynchronous task has produced results);
- `future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const`:
  (The template types `Rep` and `Period` normally are derived by the compiler from the actual `rel_time` specification.) If the shared results contain a deferred function (cf. section 20.10) nothing happens. Otherwise `wait_for` blocks until the results of the associated asynchronous task has produced results, or until the relative time specified by `rel_time` has expired. The member returns
  - `future_status::deferred` if the shared results contain a deferred function;
  - `future_status::ready` if the shared results are available;
  - `future_status::timeout` if the function is returning because the amount of time specified by `rel_time` has expired;
- `future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const`:
  (The template types `Clock` and `Duration` normally are derived by the compiler from the actual `abs_time` specification.) If the shared results contain a deferred function nothing happens. Otherwise `wait_until` blocks until the shared results are available or until the point in time specified by `abs_time` has expired. Possible return values are:
  - `future_status::deferred` if the shared results contain a deferred function;
  - `future_status::ready` if the shared results are available;
  - `future_status::timeout` if the function is returning because the point in time specified by `abs_time` has expired.

20.10 Starting a new thread: std::async

In this section the function template `std::async` is covered. `Async` is used to start asynchronous tasks, returning values (or `void`) to the calling thread, which is hard to realize merely using the `std::thread` class.

Before using the function `async` the `<future>` header file must be included.

When starting a thread using the facilities of the class `std::thread` the initiating thread at some point commonly calls the thread's `join` method. At that point the thread must have finished or execution blocks until `join` returns. While this often is a sensible course of action, it may not always be: maybe the function implementing the thread has a return value, or it could throw an exception.

In those cases `join` cannot be used: if an exception leaves a thread, then your program ends. Here is an example:

```
void thrower()
{
 3:     throw std::exception();
 4: }
 5:
 6: int main()
 7: try
 8: {
 9:    std::thread subThread(thrower);
10: }
11: catch (...)
12: {
13:     std::cerr << "Caught exception\n";
14: }
```

In line 3 `thrower` throws an exception, leaving the thread. This exception is not caught by `main`'s try-block (as it is defined in another thread). As a consequence, the program terminates.

This scenario doesn't occur when `std::async` is used. `Async` may start a new asynchronous task, and the activating thread may retrieve the return value of the function implementing the asynchronous task or any exception leaving that function from a `std::future` object returned by the `async` function. Basically, `async` is called similarly to the way a thread is started using `std::thread`: it is passed a function and optionally arguments which are forwarded to the function.

Although the function implementing the asynchronous task may be passed as first argument, `async's` first argument may also be a value of the strongly typed enumeration `std::launch`:

```
enum class launch
{
    async,
    deferred
};
```

When passing `launch::async` the asynchronous task immediately starts; when passing `launch::deferred` the asynchronous task is deferred. When `std::launch` is not specified the default value `launch::async | launch::deferred` is used, giving the implementation freedom of choice, usually resulting in deferring execution of the asynchronous task.

So, here is the first example again, this time using `async` to start the sub-thread:

```
bool fun()
{
    return std::cerr << "    hello from fun\n";
}
int exceptionalFun()
{
    throw std::exception();
}

int main()
try
{
    auto fut1 = std::async(std::launch::async, fun);
    auto fut2 = std::async(std::launch::async, exceptionalFun);

    std::cerr << "fun returned " << std::boolalpha << fut1.get() << '\n';
    std::cerr << "exceptionalFun did not return " << fut2.get() << '\n';
18: }
19: catch (...)
20: {
21:     std::cerr << "caught exception thrown by exceptionalFun\n";
22: }
```

Now the threads immediately start, but although the results are available around line 13, the thrown exception isn't terminating the program. The first thread's return value is made available in line 16, the exception thrown by the second thread is simply caught by main's try-block (line 19).

The function template `async` has several overloaded versions:

- The basic form expects a function or functor as its first argument, returning a `std::future` holding the function's return value or exception thrown by the function:

```
template <typename Function, class ...Args>
std::future<
    typename std::result_of< Function(Args ...) >::type
> std::async(Function &&fun, Args &&...args);
```

- Alternatively, the first argument may be the address of a member function. In that case the (required) second argument is an object (or a pointer to an object) of that member function's class. Any remaining arguments are passed to the member function (see also the remarks below).
- The first argument may also be a combination (using the `bit_or` operator) of the enumeration values of the `std::launch` enumeration:

```
template <class Function, class ...Args>
std::future<typename std::result_of<Function(Args ...)>::type>
    std::async(std::launch policy, Function &&fun, Args &&...args);
```

- If the first argument specifies `std::launch` values, the second argument may also be the address of a member function. In that case the (required) third argument is an object (or a pointer to an object) of that member function's class. Any remaining arguments are passed to the member function (see also the remarks below).

When calling `async` all arguments except for the `std::launch` argument must be references, pointers or move-constructible objects:

- When a member function is specified, then the object for which the member function is called must be a named object, an anonymous object, or a pointer to a named object.
- When a named object is passed to the `async` function template then copy construction is used to construct a copy of the argument which is then forwarded to the thread-launcher.
- When an anonymous object is passed to the `async` function template then move construction is used to forward the anonymous object to the thread launcher.

Once the thread itself starts another move construction is used to construct an object for the duration of the thread. When a pointer to an object is passed, the sub-thread uses the object referred to by the pointer, and neither copy- nor move-construction is required. However, when using a pointer to an object the programmer should make sure that the object's lifetime exceeds the duration of the thread (note that this is not automatically guaranteed, as the asynchronous task may not actually start before the future's `get` member is called).

Because of the default `std::launch::deferred | std::launch::async` argument used by the basic `async` call it is likely that the function which is passed to `async` doesn't immediately start. The `launch::deferred` policy allows the implementor to defer its execution until the program explicitly asks for the function's results. Consider the following program:

```
 1: void fun()
 2: {
 3:     std::cerr << "    hello from fun\n";
 4: }
 5:
 6: std::future<void> asyncCall(char const *label)
 7: {
 8:     std::cerr << label << " async call starts\n";
 9:     auto ret = std::async(fun);
10:     std::cerr << label << " async call ends\n";
11:     return ret;
12: }
13:
14: int main()
15: {
16:     asyncCall("First");
17:     asyncCall("Second");
18: }
```

Although `async` is called in line 9, the program's output may not show `fun's` output line when it is run. This is a result of the (default) use of `lauch::deferred`: the system simply defers `fun's` execution until requested, which doesn't happen. But the `future` object that's returned by `async` has a member `wait`. Once `wait` returns the shred state must be available. In other words: `fun` must have finished. Here is what happens when after line 9 the line `ret.wait()` is inserted:

```
First async call starts
    hello from fun
First async call ends
Second async call starts
    hello from fun
Second async call ends
```

Actually, evaluation of `fun` can be requested at the point where we need its results, maybe even after calling `asyncCall`, as shown in the next example:

```
1: int main()
2: {
3:     auto ret1 = asyncCall("First");
4:     auto ret2 = asyncCall("Second");
5:
6:     ret1.get();
7:     ret2.get();
8: }
```

Here the `ret1` and `ret2 std::future` objects are created, but their `fun` functions aren't evaluated yet. Evaluation occurs at lines 6 and 7, resulting in the following output:

```
First async call starts
First async call ends
```

```
Second async call starts
Second async call ends
    hello from fun
    hello from fun
```

The `std::async` function template is used to start a thread, making its results available to the calling thread. On the other hand, we may only be able to *prepare* (package) a task (a thread), but may have to leave the completion of the task to another thread. Scenarios like this are realized through objects of the class `std::packaged_task`, which is the topic of the next section.

20.11 Preparing a task for execution: std::packaged_task

The class template `std::packaged_task` allows a program to 'package' a function or functor and pass the package to a thread for further processing. The processing thread then calls the packaged function, passing it its arguments (if any). After completing the function the `packaged_task's` future is ready, allowing the program to retrieve the results produced by the function. Thus, functions and the results of function calls can be transferred between threads.

Before using the class template `packaged_task` the `<future>` header file must be included.

Before describing the class's interface, let's first look at an example to get an idea about how a `packaged_task` can be used. Remember that the essence of `packaged_task` is that part of your program prepares (packages) a task for another thread to complete, and that the program at some point needs the result of the completed task.

To clarify what's happening here, let's first look at a real-life analogon. Every now and then I make an appointment with my garage to have my car serviced. The 'package' in this case are the details about my car: its make and type determine the kind of actions my garage performs when servicing it. My neighbor also has a car, which also needs to be serviced every now and then. This also results in a 'package' for the garage. At the appropriate time me and my neighbor take our cars to the garage (i.e., the packages are passed to another thread). The garage services the cars (i.e., calls the functions stored in the `packaged_tasks` [note that the tasks differ, depending on the types of the cars]), and performs some actions that are associated with it (e.g., registering that my or my neighbor's car has been serviced, or order replacement parts). In the meantime my neighbor and I perform our own businesses (the program continues while a separate thread runs as well). But by the end of the day we'd like to use our cars again (i.e., get the results associated with the `packaged_task`). A common result in this example is the garage's bill, which we have to pay (the program obtains the `packaged_task's` results).

Here is a little **C++** program illustrating the use of a `packaged_task` (assuming the required headers and `using namespace std` have been specified):

```
mutex carDetailsMutex;
condition_variable condition;
string carDetails;
packaged_task<size_t (std::string const &)> serviceTask;

size_t volkswagen(string const &type)
{
    cout << "performing maintenance by the book for a " << type << '\n';
    return type.size() * 75;            // the size of the bill
}

size_t peugeot(string const &type)
```

```
13: {
14:     cout << "performing quick and dirty maintenance for a " << type << '\n';
15:     return type.size() * 50;             // the size of the bill
16: }
17:
18: void garage()
19: {
20:     while (true)
21:     {
22:         unique_lock<mutex> lk(carDetailsMutex);
23:         while (carDetails.empty())
24:             condition.wait(lk);
25:
26:         cout << "servicing a " << carDetails << '\n';
27:         serviceTask(carDetails);
28:         carDetails.clear();
29:     }
30: }
31:
32: int main()
33: {
34:     thread(garage).detach();
35:
36:     while (true)
37:     {
38:         string car;
39:         if (not getline(cin, car) || car.empty())
40:             break;
41:         {
42:             lock_guard<mutex> lk(carDetailsMutex);
43:             carDetails = car;
44:         }
45:         serviceTask =  packaged_task<size_t (string const &)>(
46:                         car[0] == 'v' ? volkswagen : peugeot
47:                     );
48:         auto bill = serviceTask.get_future();
49:         condition.notify_one();
50:         cout << "Bill for servicing a " << car <<
51:                                 ": EUR " << bill.get() << '\n';
52:     }
53: }
```

- Lines 1-3 define the variables used for synchronization;

- Line 4 defines a `packaged_task`: `serviceTask` is initialized with a function (or functor) expecting a `string`, returning a `size_t`;

- Lines 6-10 and 12-16 define such functions: `volkswagen` and `peugeot` represent the tasks to perform when cars of the provided types come in for service; presumably they return the bill.

- Lines 18-30 define the function `void garage`, defining the actions performed by the garage when cars come in for service. These actions are performed by a separate detached thread, starting in line 34. In a continuous loop it waits until it obtains a lock on the `carDetailsMutex` and `carDetails` is no longer empty. Then, at line 27, it passes `carDetails` to the `packaged_task ‘serviceTask’`. By itself this is not identical to calling the `packaged_task’s` function, but eventually its function will be called. At this point the `packaged_task` receives its function's arguments, which it eventually will forward to its configured function. Finally, at line 28 it clears `carDetails`, thus preparing itself for the next request.

- Lines 32-53 define `main`:
  - First, at line 34 the anonymous detached thread running `garage` is started.

  Then the program's main loop starts (lines 36-52):
  - The main thread reads commands from the standard input until an empty or no line is received (lines 38-40).
  - By convention the line's first letter starts the car's brand (`volkswagen` or `peugeot`), and the `packaged_task`, provided with the right servicing function, is constructed next (line 45).
  - Then, at line 48 the results, stored in a `future`, are retrieved. Although at this point the `future` might not be ready, the `future` object itself *is*, and it is simply returned as the bill.
  - Now we're ready to inform the garage that it can service a car: the garage is notified in line 49.

  Anything may happen next: the program may perform any actions, but eventually it requests the results produced by the garage.
  - The main thread obtains the results by calling `bill.get()` in line 51. If, by this time, the car is still being serviced, the bill isn't ready yet, and `bill.get()` blocks until it is, and the bill for servicing a car is shown.

Now that we've seen an example of a program using a `packaged_task`, let's have a look at its interface. Note that the class `packaged_task` is a class template: its template type parameter specifies the prototype of a function or function object implementing the task performed by the `packaged_task` object.

Constructors and destructor:

- `packaged_task() noexcept`:
  The default constructor constructs a `packaged_task` object which is not associated with a function or shared state;
- `explicit packaged_task(ReturnType(Args...) &&function)`:
  A `packaged_task` is constructed for a function or functor expecting arguments of types `Args...`, and returning a value of type `ReturnType`. The `packaged_task` class template specifies `ReturnType (Args...)` as its template type parameter. The constructed object contains a shared state, and a (move constructed) copy of `function`.

  Optionally an `Allocator` may be specified as second template type parameter, in which case the first two arguments are `std::allocator_arg_t, Allocator const &alloc`. The type `std::allocator_arg_t` is a type introduced to disambiguate constructor selections, and can simply be specified as `std::allocator_arg_t()`.

  This constructor may throw a `std::bad_alloc` exception or exceptions thrown by `function's` copy or move constructors
- `packaged_task(packaged_task &&tmp) noexcept`:
  The move constructor moves any existing shared state from `tmp` to the newly constructed object, removing the shared state from `tmp`.
- `~packaged_task()`:
  The object's shared state (if any) is abandoned

Member functions:

- `future<ReturnType> get_future()`:
  A `std::future` object is returned holding the results of the separately executed thread. When `get_future` is incorrectly called a `future_error` exception is thrown, containing one of the following values:
  - `future_already_retrieved` if `get_future` was already called on a `packaged_task` object containing the same shared state as the current object;
  - `no_state` if the current object has no shared state.

  Note: Any `futures` that share the object's shared state may access the result returned by the object's task.
- `void make_ready_at_thread_exit(Args... args)`:
  Calls `void operator()(Args... args)` (see below) when the current thread exits, once all objects of thread storage duration associated with the current thread have been destroyed.
- `packaged_task &operator=(packaged_task &&tmp)`:
  The move assignment operator first releases the current object's shared state (if available), after which the current object and `tmp` are swapped;
- `void operator()(Args... args)`:
  The `args` arguments are forwarded to the current object's stored task. When the stored task returns its return value is stored in the current object's shared state. Otherwise any exception thrown by the task is stored in the object's shared state. Following this the object's shared state is made ready, and any threads blocked in a function waiting for the object's shared state to become ready are unblocked. A `future_error` exception is thrown upon error, containing
  - `promise_already_satisfied` if the shared state has already been made ready;
  - `no_state` if the current object does not have any shared state.

  Calling this member synchronizes with calling any member function of a `(shared_)future` object that provides access to the `packaged_task's` results.
- `void reset()`:
  Abandons any available shared state, initializing the current object to `packaged_task(std::move(funct))`, where `funct` is the object's stored task. This member may throw the following exceptions:
  - `bad_alloc` if memory for the new shared state could not be allocated;
  - any exception thrown by the move constructor of the task stored in the shared state;
  - `future_error` with a `no_state` error condition if the current object contains no shared state.
- `void swap(packaged_task &other) noexcept`:
  The shared states and stored tasks of the current object and other are swapped.
- `bool valid() const noexcept`:
  Returns `true` if the current object contains a shared state, otherwise `false` is returned;

The following non-member (free) function operating on `packaged_task` objects is available:

- `void swap+(packaged_task<ReturnType(Args...)> &lhs, packaged_task<ReturnType(Args...)> &rhs+) noexcept`

  Calls `lhs.swap(rhs)`

20.12 The class ‘std::promise’

In addition to `std::packaged_task` and `std::async` the class template `std::promise` can be used to obtain the results from a separate thread.

Before using the class template `promise` the `<future>` header file must be included.

A `promise` is used to obtain the results from another thread without further synchronization requirements. Consider the following program:

```
void compute(int *ret)
{
    *ret = 9;
}

int main()
{
    int ret = 0;
    std::thread(compute, &ret).detach();
    cout << ret << '\n';
}
```

Chances are that this program shows the value 0: the `cout` statement has already been executed before the detached thread has had a chance to complete its work. In this example that problem can easily be solved by using a non-detached thread, and using the thread’s `join` member, but when multiple threads are used that requires named threads and as many `join` calls. Instead, using a `promise` might be preferred:

```
void compute(promise<int> &ref)
{
    ref.set_value(9);
}

int main()
{
    std::promise<int> prom;
    std::thread(compute, ref(prom)).detach();

    cout << prom.get_future().get() << '\n';
}
```

This example also uses a detached thread, but its results are kept for future reference in a `promise` object, instead of directly being assigned to a final destination variable. The `promise` object contains a `future` object holding the computed value. The `future’s get` member blocks until the future has been made ready, at which point the result becomes available. By then the detached thread may or may not yet have been completed. If it already completed its work then `get` immediately returns, otherwise there will be a slight delay.

Promises are useful when implementing a multi threaded version of some algorithm without having to use additional synchronization statements. As an example consider matrix multiplications. Each element of the resulting product matrix is computed as the inner product of two vectors: the inner product of a row of the left-hand matrix operand and a column of the right-hand matrix operand becomes element `[row][column]` of the resulting matrix. Since each element of the resulting matrix can independently be computed from the other elements, a multi threaded implementation is well possible. In the following example the function `innerProduct` (lines 4..11) leaves its result in a `promise` object:

```
 1: int m1[2][2] = {{1, 2}, {3, 4}};
 2: int m2[2][2] = {{3, 4}, {5, 6}};
 3:
 4: void innerProduct(promise<int> &ref, int row, int col)
 5: {
 6:     int sum = 0;
 7:     for (int idx = 0; idx != 2; ++idx)
 8:         sum += m1[row][idx] * m2[idx][col];
 9:
10:     ref.set_value(sum);
11: }
12:
13: int main()
14: {
15:     promise<int> result[2][2];
16:
17:     for (int row = 0; row != 2; ++row)
18:     {
19:         for (int col = 0; col != 2; ++col)
20:             thread(innerProduct, ref(result[row][col]), row, col).detach();
21:     }
22:
23:     for (int row = 0; row != 2; ++row)
24:     {
25:         for (int col = 0; col != 2; ++col)
26:             cout << setw(3) << result[row][col].get_future().get();
27:         cout << '\n';
28:     }
29: }
```

Each inner product is computed by a separate (anonymous and detached) thread (lines 17..21), which starts as soon as the run-time system allows it to start. By the time the threads have finished the resulting inner products can be retrieved from the promises’ futures. Since futures’ `get` members block until their results are actually available, the resulting matrix can simply be displayed by calling those members in sequence (lines 23..28).

So, a `promise` allows us to use a thread to compute a value (or exception, see below), which value may then be collected by another thread at some future point in time. The promise remains available, and as a consequence further synchronization of the threads and the program starting the threads is not necessary. When the promise object contains an exception, rather than a value, its future’s `get` member rethrows the stored exception.

Here is the class `promise's` interface. Note that the class `promise` is a class template: its template type parameter `ReturnType` specifies the template type parameter of the `std::future` that can be retrieved from it.

Constructors and destructor:

- `promise()`:
  The default constructor constructs a `promise` object containing a shared state. The shared state may be returned by the member `get_future` (see below), but that future has not yet been made ready;
- `promise(promise &&tmp) noexcept`:

The move constructor constructs a `promise` object, transferring the ownership of `tmp's` shared state to the newly constructed object. After the object has been constructed, `tmp` no longer contains a shared state;

- `~promise()`:
  The object's shared state (if any) is abandoned;

Member functions:

- `std::future<ReturnType> get_future()`:
  A `std::future` object sharing the current object's shared state is returned. A `future_error` exception is thrown upon error, containing
  - `future_already_retrieved` if `get_future` was already called on a `packaged_task` object containing the same shared state as the current object;
  - `no_state` if the current object has no shared state.

  Note: Any `futures` that share the object's shared state may access the result returned by the object's task;
- `promise &operator=(promise &&rhs) noexcept`:
  The move assignment operator first releases the current object's shared state (if available), after which the current object and `tmp` are swapped;
- `void promise<void>::set_value()`:
  See below, at the last `set_value` member's description;
- `void set_value(ReturnType &&value)`:
  See below, at the last `set_value` member's description;
- `void set_value(ReturnType const &value)`:
  See the next member function's description;
- `void set_value(ReturnType &value)`:
  The argument (`value`) is atomically stored in the shared state, which is then also made ready. A `future_error` exception is thrown upon error, containing
  - `promise_already_satisfied` if the shared state has already been made ready;
  - `no_state` if the current object does not have any shared state.

  Alternatively, any exception thrown by `value`'s move or copy constructor may be thrown;
- `void set_exception(std::exception_ptr obj)`:
  `Exception_ptr obj` (cf. section 20.12.1) is atomically stored in the shared state, making that state ready. A `future_error` exception is thrown upon error, containing
  - `promise_already_satisfied` if the shared state has already been made ready;
  - `no_state` if the current object does not have any shared state;
- `void set_exception_at_thread_exit(exception_ptr ptr)`:
  The exception pointer `ptr` is stored in the shared state without immediately making that state ready. The state becomes ready when the current thread exits, once all objects of thread storage duration which are associated with the ending thread have been destroyed. A `future_error` exception is thrown upon error, containing
  - `promise_already_satisfied` if the shared state has already been made ready;
  - `no_state` if the current object does not have any shared state;
- `void set_value_at_thread_exit()`:
  See below, at the last `set_value_at_thread_exit` member's description;

- `void set_value_at_thread_exit(ReturnType &&value)`:
  See below, at the last `set_value_at_thread_exit` member's description;
- `void set_value_at_thread_exit(ReturnType const &value)`:
  See the next `set_value_at_thread_exit` member's description;
- `void set_value_at_thread_exit(ReturnType &value)`:
  Stores `value` in the shared state without immediately making that state ready. The state becomes ready when the current thread exits, once all objects of thread storage duration which are associated with the ending thread have been destroyed. A `future_error` exception is thrown upon error, containing
  - `promise_already_satisfied` if the shared state has already been made ready;
  - `no_state` if the current object does not have any shared state;
- `void swap(promise& other) noexcept`:
  The shared states (if any) of the current object and `other` are exchanged.

The following non-member (free) function operating on `promise` objects is available:

- `void swap(promise<ReturnType> &lhs, promise<ReturnType> &rhs) noexcept`:
  Calls `lhs.swap(rhs)`

20.12.1 Exception propagation: std::exception_ptr

`Std::promise's` member `set_exception` does not expect a `std::exception` argument, but an object of the class `std::exception_ptr`. In this section we take a closer look at the class `exception_ptr`.

Before using the class `exception_ptr` the `<future>` header file must be included.

The class `exception_ptr's` default constructor initializes it to a null-pointer. In the following code snippet the variable `isNull` is set to true:

```
std::exception_ptr obj;
bool isNull =  obj == nullptr && obj == 0;
```

The class `exception_ptr` provides copy and move constructors as well as copy and move assignment operators.

Two `exception_ptr` objects can be compared for equality. They are equal if they refer to the same exception. Move assignment transfers the exception referred to by the right-hand side operand to the left-hand side operand, and turns the right-hand side operand into a null pointer.

There is no published method directly retrieving the exception to which an `exception_ptr` object refers. However, there are some free functions constructing or handling `exception_ptr` objects:

- `std::exception_ptr std::current_exception() noexcept`:
  An `exception_ptr` object is returned referring to the currently handled exception (or a copy of the currently handled exception, or a default constructed `exception_ptr` object if no current exception is available). This function can also be called when a default exception catcher is used. E.g., assuming that `obj` refers to an available `std::promise` object, then the following code snippet assigns the exception caught by default catch clause to `obj`:

  ```
  ...
  ```

```
catch (...)
{
    obj.set_exception(std::current_exception());
}
```

The exception referred to by `current_exception` does not have to be an object of the class `std::exception`. Any type of object or value thrown as an exception is retrieved as an `exception_ptr` by `current_exception`. The exception referred to by an `exception_ptr` object remains valid for at least as long as there exists an `exception_ptr` object that refers to it. Calling `current_exception` twice in a row then the two returned `exception_ptr` objects may or may not refer to the same exception object.

- `std::exception_ptr make_exception_ptr(Type value) noexcept`:
  This function template constructs an `exception_ptr` from a value of any type which is passed as its argument. `Type` does not necessarily have to be a `std::exception`. The constructed `exception_ptr` could, e.g., be assigned to a `std::promise`. When the promise's future's `get` member is subsequently called (possibly from within another thread) the exception will be thrown. Here are some examples, showing how values of different types can be passed as arguments to `make_exception_ptr`, and showing how the eventually constructed `exception_ptr` is assigned to the `obj`, which is assumed to be of a `std::promise` type:

```
auto ptr = make_exception_ptr(exception());
ptr = make_exception("hello world"s);
ptr = make_exception(12);

obj.set_exception(make_exception_ptr(ptr));
```

- `void std::rethrow_exception(exception_ptr obj)`:
  The exception to which `obj` refers is thrown. Note: `obj` cannot be a `nullptr`.

20.13 An example: multi-threaded compilations

In this section another program is developed. This section's example program illustrates the use of `packaged_tasks`.

Like the multi-threaded quicksort example a worker pool is used. However, in this example the workers in fact do not know what their task is. In the current example the tasks happens to be identical, but different tasks might as well have been used, without having to update the workers.

The program uses a `class Task` containing a command-specification (`d_command`), and a task specification (`d_task`) (cf. Figure 20.2), the sources of the program are found in the `yo/threading/examples/multicompile` directory of the **C++** Annotations.

Like before `main` first starts its workforce as detached threads. Following this, the compilation jobs are performed by yet another detached thread. Eventually, the results of the compilation jobs are handled by `results`:

```
int main()
{
    workforce();                        // start the worker threads
    thread(jobs).detach();              // start working on the jobs
    results();                          // handle the results.
}
```

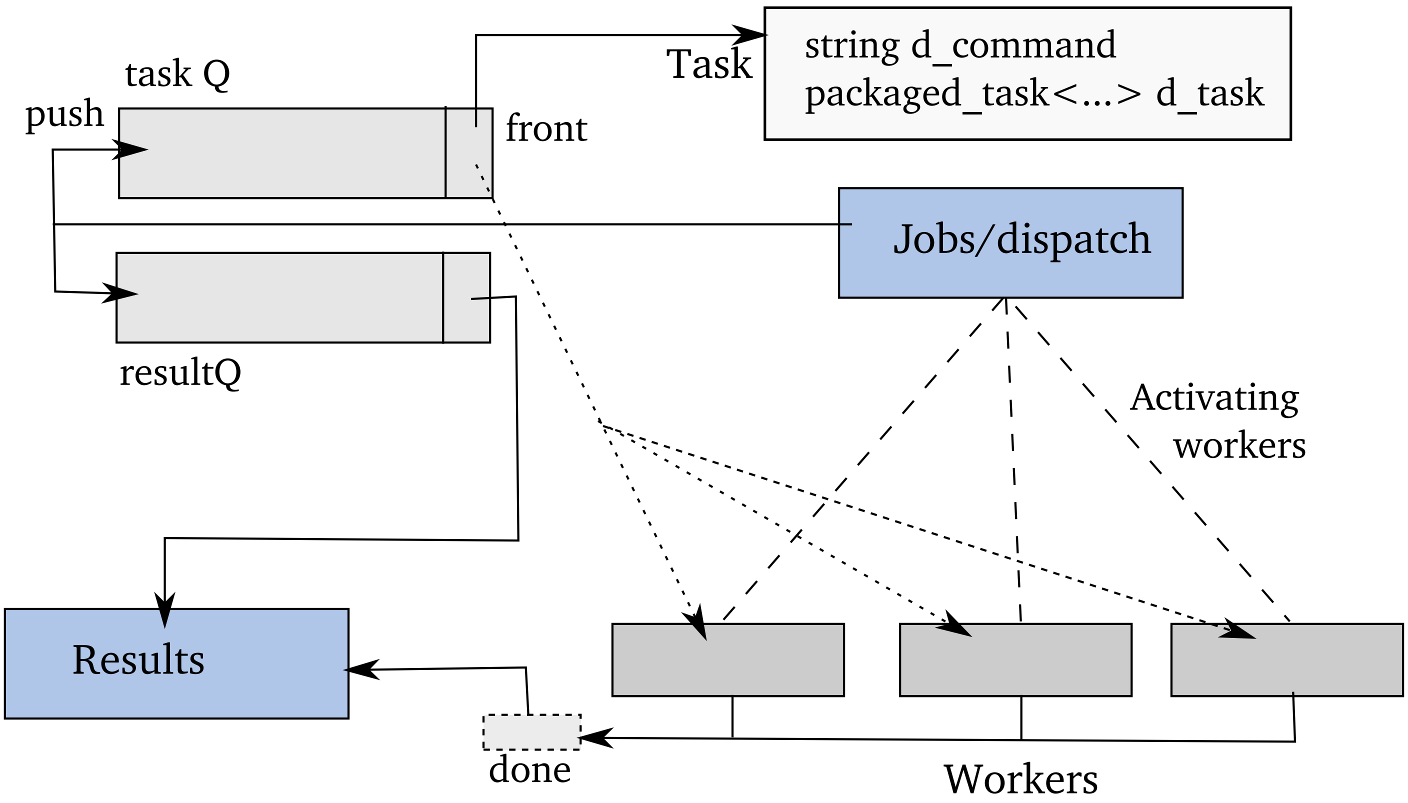
task Q
push
front
Task
string d_command
packaged_task<...> d_task
Jobs/dispatch
resultQ
Activating workers
Results
done
Workers

Figure 20.2: Data structure used for the multi-threading compilation

The `jobs`-thread reads the names of the files to compile from the standard input stream, and passes them on to `dispatch` for further handling by the workers. Lines 7 and 8 are executed at the end, and are a safeguard against empty input. The safeguard is discussed below, at `newResult's` description.

```
1: void jobs()
2: {
3:     string line;
4:     while (getline(cin, line) && dispatch(line))
5:         ;
6:
7:     g_ready = true;
8:     g_resultCond.notify_one();
9: }
```

Next the dispatcher. It ignores empty lines. Also, if a compilation has failed by the time the dispatcher is called, processing stops (lines 6-7). Otherwise, the dispatcher waits for an available worker, prepares a new task, and notifies a worker to handle it:

```
1: bool dispatch(string const &line)
2: {
3:     if (line.empty())
4:         return true;
5:
6:     if (g_done.load())
7:         return false;
8:
9:     g_workforce.wait();
```

```
    newTask(line);
    g_worker.notify_all();
    return true;
}
```

The function `newTask` prepares the program for the next task. First a `Task` object is created. `Task` contains the name of the file to compile, and a `packaged_task`. It encapsulates all activities that are associated with a `packaged_task`. Here is its (in-class) definition:

```
 1: typedef packaged_task<Result (string const &fname)> PackagedTask;
 2: 
 3: class Task
 4: {
 5:     string d_command;
 6:     PackagedTask d_task;
 7: 
 8:     public:
 9:         Task()  = default;
10: 
11:         Task(string const &command, PackagedTask &&tmp)
12:         :
13:             d_command(command),
14:             d_task(move(tmp))
15:         {}
16: 
17:         void operator()()
18:         {
19:             d_task(d_command);
20:         }
21: 
22:         shared_future<Result> result()
23:         {
24:             return d_task.get_future().share();
25:         }
26: };
```

Note (lines 22-25) that `result` returns a `shared_future`. Since the dispatcher runs in a different thread than the one processing the results, the `futures` created by the dispatcher must be shared with the `futures` required by the function processing the results. Hence the `shared_futures` returned by `Task::result`.

Once a `Task` object has been constructed its `shared_future` is pushed on the result queue. Although the actual results aren't available by this time, the `result` function (see below) is notified that something has been pushed on its queue. Additionally, the `Task` itself is pushed on the task queue, where a worker may retrieve it:

```
class Task
{
    string d_command;
    PackagedTask d_task;

    public:
        Task()  = default;

        Task(string const &command, PackagedTask &&tmp);
        void operator()();
        shared_future<Result> result();
};

void pushResultQ(shared_future<Result> const &sharedResult)
{
    lock_guard<mutex> lk(g_resultQMutex);
    g_resultQ.push(sharedResult);
    g_ready = true;
    g_resultCond.notify_one();
}
```

The workers have a simple task: retrieve the next task from the task queue's front, then perform that task. Whatever happens inside the tasks themselves is of no concern: the worker thread eventually ends when the program ends:

```
void worker()
{
    Task task;

    while (true)
    {
        g_worker.wait();

        g_taskQ.popFront(task);
        task();

        g_workforce.notify_all();
    }
}
```

This completes the description of how tasks are handled. The task itself remains to be described. In the current example program source files are being compiled. The compilation command is passed to the constructor of a `CmdFork` object, which starts the compiler as a child process. The result of the compilation is retrieved via its `childExit` (returning the compiler's exit code) and `childOutput` (returning any textual output produced by the compiler) members. If compilation fails, the exit value won't be zero. In this case no further compilation tasks will be initiated (lines 11 and 12; the implementation of the `class CmdFork` is available from the **C++** Annotations' `yo/threading/examples/cmdfork` directory). Here is the function `compile`:

```
 1: Result compile(string const &line)
 2: {
 3:     string command("/usr/bin/g++ -Wall --std=c++11 -c " + line);
 4:
 5:     CmdFork cmdFork(command);
 6:     cmdFork.fork();
 7:
 8:     Result ret {cmdFork.childExit() == 0,
 9:                 line + "\n" + cmdFork.childOutput()};
10:
11:     if (not ret.ok)
12:         g_done = true;
13:
14:     return ret;
15: }
```

The `results` function continues for as long as there are results. Once results are available they are displayed. Whenever a compilation has failed the `Result's d_ok` member is `false` and `results` ends:

```
    void results()
    {
        while (newResult())
        {
            Result const &result = g_resultQ.front().get();

            cerr << result.display;
            if (not result.ok)
                return;

            g_resultQ.pop();
        }
    }
```

The function `newResult` controls `results' while`-loop. It returns `true` when there are some results available in the result queue. When no filenames are presented at the standard input stream or when no result has as yet been pushed on the result queue `newResult` waits. It also waits when there are no results available in the results queue, but at least one worker thread is busy. Whenever a result is pushed on the result queue, and also once the input stream has been processed `newResult` is notified. Following the notification `newResult` returns, and `results` either ends or shows the results appearing at te result queue's front:

```
    bool newResult()
    {
        unique_lock<mutex> lk(g_resultQMutex);

        while
        (
            (
                g_resultQ.empty()
                &&
                g_workforce.size() != g_sizeofWorkforce
            )
            ||
            not g_ready.load()
        )
            g_resultCond.wait(lk);

        return not g_resultQ.empty();
    }
```

20.14 Transactional Memory

Transactional memory is used to simplify shared data access in multithreaded programs. The benefits of transactional memory is best illustrated by a small program. Consider a situation where threads need to write information to a file. A plain example of such a program would be:

```
    void fun(int value)
```

```
{
    for (size_t rept = 0; rept != 10; ++rept)
    {
        this_thread::sleep_for(chrono::seconds(1));
        cout << "fun " << value << '\n';
    }
};

int main()
{
    thread thr{ fun, 1 };
    fun(2);
    thr.join();
}
```

When this program is run the `fun 1` and `fun 2` messages are intermixed. To prevent this we traditionally define a `mutex`, lock it, write the message, and release the lock:

```
void fun(int value)
{
    static mutex guard;

    for (size_t rept = 0; rept != 10; ++rept)
    {
        this_thread::sleep_for(chrono::seconds(1));
        guard.lock();
        cout << "fun " << value << '\n';
        guard.unlock();
    }
};
```

Transactional memory handles the locking for us. Transactional memory is used when statements are embedded in a `synchronized` block. The function `fun`, using transactional memory, looks like this:

```
void fun(int value)
{
    for (size_t rept = 0; rept != 10; ++rept)
    {
        this_thread::sleep_for(chrono::seconds(1));
        synchronized
        {
            cout << "fun " << value << '\n';
        }
    }
};
```

To compile source files using transactional memory the `g++` compiler option `-fgnu-tm` must be specified.

The code inside a synchronized block is executed as a single, as if the block was protected by a mutex. Different from using mutexes transactional memory is implemented in software instead of using hardware-facilities.

Considering how easy it is to use transactional memory compared to using the `mutex`-based locking mechanism using transactional memory appears too good to be true. And in a sense it is. When encountering a synchronized block the thread unconditionally executes the block's statements. At the same time it keeps a detailed log of all its actions. Once the statements have been completed the thread checks whether another thread didn't start executing the block just before it. If so, it reverses its actions, using the synchronized block's log. The implication of this should be clear: there's at least the overhead of maintaining the log, and *if* another thread started executing the synchronized block before the current thread then there's the additional overhead of reverting its actions and to try again.

The advantages of transactional memory should also be clear: the programmers no longer is responsible for correctly controlling access to shared memory; risks of encountering deadlocks have disappeared as has all adminstrative overhead of defining mutexes, locking and unlocking. Especially for inherently slow operations like writing to files transactional memory can greatly simplify parts of your code. Consider a `std::stack`. Its top-element can be inspected but its `pop` member does not return the topmost element. To retrieve the top element and then maybe remove it traditionally requires a mutex lock surrounding determining the stack's size, and if empty, release the lock and wait. If not empty then retrieve its topmost element, followed by removing it from the stack. Using a transactional memory we get something as simple as:

```
bool retrieve(stack<Item> &itemStack, Item &item)
{
    synchronized
    {
        if (itemStack.empty())
            return false;
        item = std::move(itemStack.top());
        itemStack.pop();
        return true;
    }
}
```

Variants of `synchronized` are:

- `atomic_noexcept`: the statements inside its compound statement may not throw exceptions. If they do, `std::abort` is called. If the earlier `fun` function specifies `atomic_noexcept` instead of `synchronized` the compiler generates and error about the use of the insertion operator, from which an exception may be thrown.
- `atomic_cancel`: not yet supported by `g++` (version 8.2.0). If an exception other than (`std::`) `bad_alloc, bad_array_new_length, bad_cast, bad_typeid, bad_exception, exception, tx_exception<Type>` is thrown `std::abort` is called. If an acceptable exception is thrown, then the statements executed so far are undone.
- `atomic_commit`: if an exception is thrown from its compound statement all thus far executed statements are kept (i.e., not undone).

Chapter 21

Function and Variable Templates

C++ supports syntactic constructs allowing programmers to define and use completely general (or abstract) functions or classes, based on generic types and/or (possibly inferred) constant values. In the chapters on abstract containers (chapter 12) and the `STL` (chapter 18) we've already used these constructs, commonly known as the *template mechanism*.

The template mechanism allows us to specify classes and algorithms, fairly independently of the actual types for which the templates are eventually going to be used. Whenever the template is used, the compiler generates code that is tailored to the particular data type(s) used with the template. This code is generated at compile-time from the template's definition. The piece of generated code is called an *instantiation* of the template.

In this chapter the syntactic peculiarities of templates are covered. The notions of *template type parameter*, *template non-type parameter*, and *function template* are introduced and several examples of templates are provided (both in this chapter and in chapter 25). Template *classes* are covered in chapter 22. For good reasons variadic functions are deprecated in **C++**. However, *variadic templates* tell us a completely different story, and variadic templates are perfectly acceptable. Both function- and class-templates can be defined as variadic templates. Both forms are covered in section 22.5.

Templates already offered by the language include the abstract containers (cf. chapter 12); the `string` (cf. chapter 5); streams (cf. chapter 6); and the generic algorithms (cf. chapter 19). So, templates play a central role in present-day **C++**, and should not be considered an esoteric feature of the language.

Templates should be approached somewhat similarly as generic algorithms: they're a *way of life*; a **C++** software engineer should actively look for opportunities to use them. Initially, templates may appear to be rather complex and you might be tempted to turn your back on them. However, over time their strengths and benefits are more and more appreciated. Eventually you'll be able to recognize opportunities for using templates. That's the time where your efforts should no longer focus on constructing ordinary functions and classes (i.e., functions or classes that are not templates), but on constructing templates.

This chapter starts by introducing *function templates*. The emphasis is on the required syntax. This chapter lays the foundation upon which the other chapters about templates are built.

21.1 Defining function templates

A function template's definition is very similar to the definition of a normal function. A function template has a function head, a function body, a return type, possibly overloaded definitions, etc..

However, different from ordinary functions, function templates always use one or more *formal types*: types for which almost any existing (class or primitive) type could be used. Let's have a look at a simple example. The following function `add` expects two `Type` arguments and returns their sum:

```
Type add(Type const &lhs, Type const &rhs)
{
    return lhs + rhs;
}
```

Note how closely the above function's definition follows its description. It receives two arguments, and returns its sum. Now consider what would happen if we defined this function for, e.g., `int` values. We would write:

```
int add(int const &lhs, int const &rhs)
{
    return lhs + rhs;
}
```

So far, so good. However, were we to add two doubles, we would overload this function:

```
double add(double const &lhs, double const &rhs)
{
    return lhs + rhs;
}
```

There is no end to the number of overloaded versions we might be forced to construct: an overloaded version for `string`, for `size_t`, for .... In general, we would need an overloaded version for every type supporting `operator+` and a copy constructor. All these overloaded versions of basically the same function are required because of the strongly typed nature of **C++**. Because of this, a truly generic function cannot be constructed without resorting to the template mechanism.

Fortunately, we've already seen an important part of a template function. Our initial function `add` actually is an implementation of such a function although it isn't a full template definition yet. If we gave the first `add` function to the compiler, it would produce an error message like:

```
error: `Type' was not declared in this scope
error: parse error before `const'
```

And rightly so, as we failed to define `Type`. The error is prevented when we change `add` into a full template definition. To do this, we look at the function's implementation and decide that `Type` is actually a *formal* typename. Comparing it to the alternate implementations, it is clear that we could have changed `Type` into `int` to get the first implementation, and into `double` to get the second.

The full template definition allows for this formal nature of the `Type` typename. Using the keyword `template`, we prefix one line to our initial definition, obtaining the following function template definition:

```
template <typename Type>
Type add(Type const &lhs, Type const &rhs)
{
    return lhs + rhs;
}
```

In this definition we distinguish:

- The keyword `template`, starting a template definition or declaration.
- The angle bracket enclosed list following `template`. This is a list containing one or more comma-separated elements. This angle bracket enclosed list is called the *template parameter list*. Template parameter lists using multiple elements could look like this:

  ```
  typename Type1, typename Type2
  ```

- Inside the template parameter list we find the *formal type* name `Type`. It is a formal type name, comparable to a formal parameter name in a function's definition. Up to now we've only encountered formal variable names with functions. The *types* of the parameters were always known by the time the function was defined. Templates escalate the notion of formal names one step further up the ladder. Templates allow type names to be formalized, rather than just the variable names themselves. The fact that `Type` is a formal type name is indicated by the keyword `typename`, prefixed to `Type` in the template parameter list. A formal type name like `Type` is also called a *template type parameter*. Template non-type parameters also exist, and are shortly introduced.

  Other texts on **C++** sometimes use the keyword `class` where we use `typename`. So, in other texts template definitions might start with a line like:

  ```
  template <class Type>
  ```

  In the **C++** Annotations the use of `typename` over `class` is preferred, reasoning that a template type parameter is, after all, a type name (some authors prefer `class` over `typename`; in the end it's a matter of taste).

- The `template` keyword and the template parameter list is called the template header.
- The function head: it is like a normal function head, albeit that the template's type parameters must be used in its parameter list. When the function is eventually called using actual arguments having actual types, these actual types are used by the compiler to infer which version (i.e., overload to fit the actual argument types) of the function template must be used. At the point where the function is called the compiler creates the function that is called, a process called *instantiation*. The function head may also use a formal type to specify its return value. This feature was actually used in the `add` template definition.
- The function parameters are specified as `Type const &` parameters. This has the usual meaning: the parameters are references to `Type` objects or values that will not be modified by the function.
- The function body is like a normal function body. In the body the formal type names may be used to define or declare variables, which may then be used as any other local variable. But some restrictions apply. Looking at `add`'s body, it is clear that `operator+` is used, as well as a copy constructor, as the function returns a value. This allows us to formulate the following restrictions for the formal type `Type` as used by our `add` function template:
  - `Type` should support `operator+`
  - `Type` should support a copy constructor

  Consequently, while `Type` could be a `string`, it could never be an `ostream`, as neither `operator+` nor the copy constructor are available for streams.

Normal scope rules and identifier visibility rules apply to templates. Within the template definition's scope formal type names overrule identically named identifiers of broader scopes.

21.1.1 Considerations regarding template parameters

We've managed to design our first function template:

```
template <typename Type>
Type add(Type const &lhs, Type const &rhs)
{
    return lhs + rhs;
}
```

Look again at `add`'s parameters. By specifying `Type const &` rather than `Type` superfluous copying is prevented, at the same time allowing values of primitive types to be passed as arguments to the function. So, when `add(3, 4)` is called, `int{4}` is assigned to `Type const &rhs`. In general, function parameters should be defined as `Type const &` to prevent unnecessary copying. The compiler is smart enough to handle 'references to references' in this case, which is something the language normally does not support. For example, consider the following `main` function (here and in the following simple examples it is assumed that the template and the required headers and namespace declarations have been provided):

```
int main()
{
    size_t const &var = size_t{ 4 };
    cout << add(var, var) << '\n';
}
```

Here `var` is a reference to a constant `size_t`. It is passed as argument to `add`, thereby initializing `lhs` and `rhs` as `Type const &` to `size_t const &` values. The compiler interprets `Type` as `size_t`. Alternatively, the parameters might have been specified using `Type &`, rather than `Type const &`. The disadvantage of this (non-const) specification being that temporary values cannot be passed to the function anymore. The following therefore fails to compile:

```
int main()
{
    cout << add(string{ "a" }, string{ "b" }) << '\n';
}
```

Here, a `string const &` cannot be used to initialize a `string &`. Had `add` defined `Type &&` parameters then the above program would have compiled just fine. In addition the following example correctly compiles as the compiler decides that `Type` apparently is a `string const`:

```
int main()
{
    string const &s = string{ "a" };
    cout << add(s, s) << '\n';
}
```

What can we deduce from these examples?

- In general, function parameters should be specified as `Type const &` parameters to prevent unnecessary copying.
- The template mechanism is fairly flexible. Formal types are interpreted as plain types, const types, pointer types, etc., depending on the actually provided types. The rule of thumb is that

the formal type is used as a generic mask for the actual type, with the formal type name covering whatever part of the actual type must be covered. Some examples, assuming the parameter is defined as `Type const &`:

Provided argument:	**Actually used Type:**
`size_t const`	`size_t`
`size_t`	`size_t`
`size_t *`	`size_t *`
`size_t const *`	`size_t const *`

As a second example of a function template, consider the following function template:

```
template <typename Type, size_t Size>
Type sum(Type const (&array)[Size])
{
    Type tp{};  // note: the default constructor must exist.

    for (size_t idx = 0; idx < Size; idx++)
        tp += array[idx];

    return tp;
}
```

This template definition introduces the following new concepts and features:

- The *template parameter list*. This template parameter list has two elements. The first element is a well-known template type parameter, but the second element has a very specific type: a `size_t`. Template parameters of specific (i.e., non-formal) types used in template parameter lists are called *template non-type parameters*. A template non-type parameter defines the type of a constant expression, which must be known by the time the template is instantiated and which is specified in terms of existing types, such as a `size_t`.
- Looking at the function's head, we see one parameter:

  ```
  Type const (&array)[Size]
  ```

  This parameter defines `array` as a reference to an array having `Size` elements of type `Type` that may not be modified.
- In the parameter definition, both `Type` and `Size` are used. `Type` is of course the template's type parameter `Type`, but `Size` is also a template parameter. It is a `size_t`, whose value must be inferable by the compiler when it compiles an actual call of the `sum` function template. Consequently, `Size` must be a `const` value. Such a constant expression is called a *template non-type parameter*, and its type is named in the template's parameter list.
- When the function template is called, the compiler must be able to infer not only `Type`'s concrete value, but also `Size`'s value. Since the function `sum` only has one parameter, the compiler is only able to infer `Size`'s value from the function's actual argument. It can do so if the provided argument is an array (of known and fixed size) rather than a pointer to `Type` elements. So, in the following `main` function the first statement will compile correctly but the second statement will not:

  ```
  int main()
  {
      int values[5];
  ```

```
    int *ip = values;

    cout << sum(values) << '\n';     // compiles OK
    cout << sum(ip) << '\n';         // won't compile
}
```

- Inside the function's body the definition `Type tp{}` is used to define and initialize `tp` to a default value. Note here that no fixed value (like 0) is used. Also, be careful not to use `Type tp()`, as this is a *declaration* of a function `tp`, expecting no arguments, and returning a `Type`. Generally, when it is required to explicitly initialize a value the empty curly braces should be used. The advantage of explicitly calling the type's constructor is primarily encountered when `Type` is a basic type. E.g., if `Type` is an `int` then `Type tp{}` initializes `tp` to zero, whereas `Type tp` results in `tp` having an undefined value. But all types, even the primitive types, support default constructors (some classes may choose not to implement a default constructor, or to make it inaccessible; but most do offer default constructors). The default constructor of primitive types initializes their variables to 0 (or `false`). Furthermore, the statement `Type tp = Type()` is a true initialization: `tp` is initialized by `Type`'s default constructor, rather than using `Type`'s copy constructor to assign `Type`'s copy to `tp`.

  It's interesting to note (although not directly related to the current topic) that the syntactic construction `Type tp(Type())` *cannot* be used, even though it also looks like a proper initialization. Usually an initializing argument can be provided to an object's definition, like `string s("hello")`. Why, then, is `Type tp = Type()` accepted, whereas `Type tp(Type())` isn't? When `Type tp(Type())` is used it won't result in an error message. So we don't immediately detect that it's *not* a `Type` object's default initialization. Instead, the compiler starts generating error messages once `tp` is used. This is caused by the fact that in **C++** (and in **C** alike) the compiler does its best to recognize a function or function pointer whenever possible: the *function prevalence rule*. According to this rule `Type()` is (because of the pair of parentheses) interpreted as a *pointer to a function* expecting no arguments; returning a `Type`. The compiler will do so unless it clearly isn't possible to do so. In the initialization `Type tp = Type()` it *can't* see a pointer to a function as a `Type` object cannot be given the value of a function pointer (remember: `Type()` is interpreted as `Type (*)()` whenever possible). But in `Type tp(Type())` it *can* use the pointer interpretation: `tp` is now *declared* as a *function* expecting a pointer to a function returning a `Type`, with `tp` itself also returning a `Type`. E.g., `tp` could have been defined as:

  ```
  Type tp(Type (*funPtr)())
  {
      return (*funPtr)();
  }
  ```

- Comparable to the first function template, `sum` also assumes the existence of certain public members in `Type`'s class. This time `operator+=` and `Type`'s copy constructor.

Like class definitions, template definitions should not contain `using` directives or declarations: the template might be used in a situation where such a directive overrides the programmer's intentions: ambiguities or other conflicts may result from the template's author and the programmer using different `using` directives (E.g, a `cout` variable defined in the `std` namespace and in the programmer's own namespace). Instead, within template definitions only fully qualified names, including all required namespace specifications should be used.

21.1.2 Auto and decltype

In section 3.3.7 the `auto` keyword was introduced. The keyword `decltype`, related to `auto`, shows somewhat different behavior. This section concentrates on `decltype`. Different from `auto`, which requires no further specifications, `decltype` is always followed by an expression between parentheses (e.g., `decltype(variable)`).

As an initial illustration, assume we have a function defining a parameter `std::string const &text`. Inside the function we may encounter the following two definitions:

```
    auto scratch1{text};
    decltype(text) scratch2 = text;
```

With `auto` the compiler deduces a plain type, so `scratch1` is a `string`, and copy construction is used to initialize it from '`text`'.

Now consider `decltype`: `decltype` determines `text's` type: `string const &`, which is thereupon used as `scratch2's` type: `string const &scratch2`, referring to whatever string `text` refers to. This is `decltype's` standard behavior: when provided with a variable's name, it is replaced by that variable's type.

Alternatively, an expression can be specified when using `decltype`. Of course, a variable is an expression by itself, but in the context of `decltype` we define an 'expression' as any expression that is more complex than just a plain variable specification. But it may be as simple as `(variable)`: the name of a variable between parentheses.

When an expression is used, the compiler determines whether a reference could be appended to the expression's type. If so, `decltype(expression)` is replaced by the type of such an lvalue reference (so you get `expression-type &`). If not, `decltype(expression)` is replaced by the expression's plain type.

Here are some examples:

```
    int *ptr;
    decltype(ptr) ref = ptr;
        // decltype's argument is a plain variable, and so
        // ptr's type is used: int *ref = ptr.
        // decltype(ptr) is replaced by int *.
        // (resulting in two warnings about not-initialized/used variables).

    int *ptr;
    decltype( (ptr) ) ref = ptr;
        // decltype's argument is an expression, and so
        // int *&ref = ptr is used.
        // decltype( (ptr) )  is replaced by int *&.

    int value;
    decltype(value + value) var = value + value;
        // decltype's argument is an expression, and so the compiler tries
        // to replace decltype(...) by int & (int &var = value + value)
        // since value + value is a temporary, var's type cannot be int &
        // and so decltype(...) is replaced by int
        // (i.e., value + value's type)

    string lines[20];
    decltype(lines[0]) ref = lines[6];
        // decltype's argument is an expression, so
        // string &ref = lines[6] is used.
        // decltype(...) is replaced by string &
```

```
string &&strRef = string{};
decltype(strRef) ref = std::move(strRef);
    // decltype's argument is a plain variable so the variable's
    // type is used: string &&ref = std::move(strRef).
    // decltype(...) is replaced by string &&

string &&strRef2 = string{}
decltype((strRef2)) ref2 = strRef2;
    // decltype's argument is an expression, so
    // string && &ref = strRef is used. This automatically becomes
    // string &ref = strRef which is OK
    // decltype is replaced by string &.
```

In addition to this, `decltype(auto)` specifications can be used, in which case `decltype’s` rules are applied to `auto`. So, `auto` is used to determine the type of the initializing expression. Then, if the initializing expression is a mere variable, then the expression’s type is used. Otherwise, if a reference can be added to the expression’s type then `decltype(auto)` is replaced by a reference to the expression’s type. Here are some examples:

```
int *ptr;
decltype(auto) ptr2 = ptr;
    // auto produces ptr's type: int *, ptr is a plain variable, so
    // decltype(auto) is replaced by int *

int value;
decltype(auto) ret = value + value;
    // auto produces int, value + value is an expression, so int & is
    // attempted. However, value + value cannot be assigned to a
    // reference so the expression's type is used:
    // decltype(auto) is replaced by int

string lines[20];
decltype(auto) line = lines[0];
    // auto produces string, lines[0] is an expression, so string & is
    // attempted. string &line = lines[0] is OK, so
    // decltype(auto) is replaced by string &

decltype(auto) ref = string{}
    // auto produces string, string{} is an expression, so string & is
    // attempted. However, string &ref = string{} is not a valid
    // initialization, so string itself is used:
    // decltype(auto) is replaced by string
```

In practice, the `decltype(auto)` form is most often encountered with function templates to define return types. Have a look at the following struct definition (not using function templates, but illustrating the workings of `decltype(auto)`):

```
struct Data
{
    vector<string> d_vs;
    string *d_val = new string[10];

    Data()
    :
        d_vs(1)
        {}

        auto autoFun() const
        {
            return d_val[0];
        }

        decltype(auto) declArr() const
        {
            return d_val[0];
        }

        decltype(auto) declVect() const
        {
            return d_vs[0];
        }
    };
```

- The member `autoFun` returns `auto`. Since `d_val[0]` is passed to `auto`, `auto` is deducing as `string`, and the function's return type is `string`;
- The member `declArr` returns `decltype(auto)`. Since `d_val[0]` is an expression, representing a `string`, `decltype(auto)` is deduced as `string &`, which becomes the function's return type.
- The member `declVect` returns `decltype(auto)`. Since `d_vs[0]` is an expression, representing `string`, `decltype(auto)` is deduced as `string &`. However, since `declVect` is also a const member, this reference should be a `string const &`. This is recognized by `decltype(auto)`, and so the function's return type becomes `string const &`.

If you're wondering why there's no `const` in `declArr's` return type while there is one in `declVect's` return type then have a look at `d_vs` and `d_val`: both are constant in the context of their functions, but `d_val`, so a `const *`, points to non-const `string` objects. So, `declArr` does *not* have to return a `string const &`, whereas `declVect` *should* return a `string const &`.

21.1.2.1 declval

The keyword `decltype` is a tool for determining the type of an expression. To use it an expression to which `decltype` is applied must be available. But what if a function template defines a `typename Class` template parameter and the function template should use the return type of the function `Class::fun()`? Since two classes may define members `fun` having different return types, the return type to use is not immediately available.

These kinds of problems are solved by using the function template `std::declval`, defined in the `<utility>` header file. This function template defines one template type parameter, and returns an rvalue reference to an object of the template type parameter's class, without actually creating a temporary object. But since an rvalue reference is available, its `fun` function can be called, and the return type of *that* function can then be produced by `decltype`. There are no specific requirements for the constructors of the class type that's passed to `declval`. Specifically: it doesn't have to have a default or public constructor (but access rights *are* used). Consider this function template:

```
    template <typename Type>
    decltype(std::declval<Type>().fun()) value()
    {
        return 12.5;
    }
```

The function `value's` return type is defined as the as yet unknown `Type::fun's` return type.

By defining two structs, both having `fun` member functions `value's` actual return type can now be returned. This is used in `main` where respectively an `int` and a `double` is returned, resulting in the output `12 12.5`:

```
    struct Integral
    {
        int fun() const;            // implementation not required
    };

    struct Real
    {
        double fun() const;         // same.
    };

    int main()
    {
        std::cout << value<Integral>() << ' ' << value<Real>() << '\n';
    }
```

21.1.3 Late-specified return type

Traditional **C++** requires function templates to specify their return type or to specify the return type as a template type parameter. Consider the following function:

```
    int add(int lhs, int rhs)
    {
        return lhs + rhs;
    }
```

The above function may be converted to a function template:

```
    template <typename Lhs, typename Rhs>
    Lhs add(Lhs lhs, Rhs rhs)
    {
        return lhs + rhs;
    }
```

Unfortunately, when the function template is called as

```
    add(3, 3.4)
```

the intended return type is probably a `double` rather than an `int`. This can be solved by adding an additional template type parameter specifying the return type but then that type must explicitly be specified:

```
    add<double>(3, 3.4);
```

Using `decltype` (cf. section 3.3.7) to define the return type won't work as `lhs` and `rhs` aren't known to the compiler by the time `decltype` is used. Thus the next attempt to get rid of the additional template type parameter fails to compile:

```
template <typename Lhs, typename Rhs>
decltype(lhs + rhs) add(Lhs lhs, Rhs rhs)
{
    return lhs + rhs;
}
```

The `decltype`-based definition of a function's return type may become fairly complex. This complexity can be reduced by using the *late-specified return type* syntax that *does* allow the use of `decltype` to define a function's return type. It is primarily used with function templates but it may also be used for ordinary (non-template) functions:

```
template <typename Lhs, typename Rhs>
auto add(Lhs lhs, Rhs rhs) -> decltype(lhs + rhs)
{
    return lhs + rhs;
}
```

When this function is used in a statement like `cout << add(3, 3.4)` the resulting value will be 6.4, which is most likely the intended result, rather than 6. As an example how a late-specified return type may reduce the complexity of a function's return type definition consider the following:

```
template <typename T, typename U>
decltype((*(T*)0)+(*(U*)0)) add(T t, U u);
```

Kind of hard to read? A term like `(*(T*)0)` defines 0, using a **C** cast, as a pointer to type `T` and then dereferences the pointer, producing a value of type `T` (even though that value itself doesn't exist as a variable). Likewise for the second term that's used in the `decltype` expression. The resulting type is thereupon used as `add's` return type. Using a late-specified return type we get the equivalent:

```
template <typename T, typename U>
auto add(T t, U u) -> decltype(t+u);
```

which most people consider easier to understand.

The expression specified with `decltype` does not necessarily use the parameters `lhs` and `rhs` themselves. In the next function definition `lhs.length` is used instead of `lhs` itself:

```
template <typename Class, typename Rhs>
auto  add(Class lhs, Rhs rhs) -> decltype(lhs.length() + rhs)
{
    return lhs.length() + rhs;
}
```

Any variable visible at the time `decltype` is compiled can be used in the `decltype` expression. It is also possible to handle member selection through pointers to members. The following code aims at specifying the address of a member function as `add`'s first argument and then use its return value type to determine the function template's return type. Here is an example:

```
std::string global{"hello world"};
```

```
template <typename MEMBER, typename RHS>
auto  add(MEMBER mem, RHS rhs) -> decltype((global.*mem)() + rhs)
{
    return (global.*mem)() + rhs;
}

int main()
{
    std::cout << add(&std::string::length, 3.4) << '\n'; // shows: 14.4
}
```

21.2 Passing arguments by reference (reference wrappers)

Before using the reference wrappers discussed in this section the `<functional>` header file must be included.

Situations exist where the compiler is unable to infer that a reference rather than a value is passed to a function template. In the following example the function template `outer` receives `int x` as its argument and the compiler dutifully infers that `Type` is `int`:

```
template <typename Type>
void outer(Type t)
{
    t.x();
}
void useInt()
{
    int arg;
    outer(arg);
}
```

Compilation will of course fail (as `int` values don't have `x` members) and the compiler nicely reports the inferred type, e.g.:

```
In function 'void outer(Type) [with Type = int]': ...
```

Another type of error results from using `call` in the next example. Here, `call` is a function template expecting a function-type argument. The function that's passed to `call` is `sqrtArg`, defining a reference to a `double`: the variable that's passed to `sqrtArg` is modified by `sqrtArg`.

```
void sqrtArg(double &arg)
{
    arg = sqrt(arg);
}
template<typename Fun, typename Arg>
void call(Fun fun, Arg arg)
{
    fun(arg);
    cout << "In call: arg = " << arg << '\n';
}
```

The first time `call` is used, `call(sqrtArg, value)` will not modify `value`: the compiler infers `Arg` to be a `double` value, and hence passes `value` by value to `call`, thus preventing `sqrtArg` to modify `main's` variable.

To change `main's` variable `value` the compiler must be informed that `value` must be passed by reference. Note that we do not want to define `call`'s template parameter as a reference parameter, as passing arguments by value might be appropriate in other situations.

In these situations the `ref(arg)` and `cref(arg)` *reference wrappers* should be used. They accept an argument and return their argument as a (const) reference-typed argument. To actually change `value` it can be passed to `call` using `ref(value)` as shown in the following `main` function:

```
int main()
{
    double value = 3;
    call(sqrtArg, value);
    cout << "Passed value, returns: " << value << '\n';

    call(sqrtArg, ref(value));
    cout << "Passed ref(value), returns: " << value << '\n';
}
/*
    Displays:
        In call: arg = 1.73205
        Passed value, returns: 3
        In call: arg = 1.73205
        Passed ref(value), returns: 1.73205
*/
```

21.3 Using local and unnamed types as template arguments

Usually, types have names. But an *anonymous type* may also be defined:

```
enum
{
    V1,
    V2,
    V3
};
```

Here, the `enum` defines an *unnamed* or *anonymous type*.

When defining a function template, the compiler normally deduces the types of its template type parameters from its arguments:

```
template <typename T>
void fun(T &&t);

fun(3);     // T is int
fun('c');   // T is char
```

The following, however, can also be used:

```
fun(V1);    // T is a value of the above enum type
```

Within `fun` a `T` variable may be defined, even if it's an anonymous type:

```
template <typename T>
void fun(T &&t)
{
    T var(t);
}
```

Values or objects of locally defined types may also be passed as arguments to function templates. E.g.,

```
void definer()
{
    struct Local
    {
        double  dVar;
        int     iVar;
    };
    Local local;            // using a local type

    fun(local);             // OK: T is 'Local'
}
```

21.4 Template parameter deduction

In this section we concentrate on the process by which the compiler deduces the actual types of the template type parameters. These types are deduced when a function template is called using a process called *template parameter deduction*. As we've already seen, the compiler is able to substitute a wide range of actual types for a single formal template type parameter. Even so, not every thinkable conversion is possible. In particular when a function has multiple parameters of the same template type parameter, the compiler is very restrictive when determining what argument types are actually accepted.

When the compiler deduces the actual types for template type parameters it *only* considers the types of the arguments that are actually used. Neither local variables nor the function's return value is considered in this process. This is understandable. When a function is called the compiler is only certain about the types of the function template's arguments. At the point of the call it definitely does not see the types of the function's local variables. Also, the function's return value might not actually be used or may be assigned to a variable of a subrange (or super-range) type of a deduced template type parameter. So, in the following example, the compiler won't ever be able to call `fun()`, as it won't be able to deduce the actual type for the `Type` template type parameter.

```
template <typename Type>
Type fun()              // can never be called as `fun()'
{
    return Type{};
}
```

Although the compiler won't be able to handle a call to '`fun()`', it *is* possible to call `fun()` using an explicit type specification. E.g., `fun<int>()` calls `fun`, instantiated for `int`. This is of course *not* the same as *compiler* argument deduction.

In general, when a function has multiple parameters of identical template type parameters, the actual types must be exactly the same. So, whereas

```
void binarg(double x, double y);
```

may be called using an `int` and a `double`, with the `int` argument silently being converted to a `double`, a similar function template cannot be called using an `int` and `double` argument: the compiler won't by itself promote `int` to `double` deciding that `Type` should be `double`:

```
template <typename Type>
void binarg(Type const &p1, Type const &p2)
{}

int main()
{
    binarg(4, 4.5); // ?? won't compile: different actual types
}
```

What, then, are the transformations the compiler applies when deducing the actual types of template type parameters? It performs but three types of parameter type transformations and a fourth one to function template non-type parameters. If it cannot deduce the actual types using these transformations, the function template will not be considered. The transformations performed by the compiler are:

- *lvalue transformations*, creating an *rvalue* from an *lvalue*;
- *qualification transformations*, inserting a `const` modifier to a non-constant argument type;
- *transformation to a base class instantiated from a class template*, using a template base class when an argument of a template derived class type was provided in the call.
- Standard transformations for function template non-type parameters. This isn't a template type parameter transformation, but it refers to any remaining template non-type parameter of function templates. For these function parameters the compiler performs any standard conversion it has available (e.g., `int` to `size_t`, `int` to `double`, etc.).

The purpose of the various template parameter type deduction transformations is *not* to match function arguments to function parameters, but rather, having matched arguments to parameters, to determine the *actual types* of the various template type parameters.

21.4.1 Lvalue transformations

There are three types of *lvalue transformations*:

- **lvalue-to-rvalue transformations.**

    An lvalue-to-rvalue transformation is applied when an `rvalue` is required, but an `lvalue` is provided. This happens when a variable is used as argument to a function specifying a *value parameter*. For example,

    ```
    template<typename Type>
    Type negate(Type value)
    {
        return -value;
    ```

```
}
int main()
{
    int x = 5;
    x = negate(x);  // lvalue (x) to rvalue (copies x)
}
```

- **array-to-pointer transformations.**

  An array-to-pointer transformation is applied when the name of an array is assigned to a pointer variable. This is frequently used with functions defining pointer parameters. Such functions frequently receive arrays as their arguments. The array's address is then assigned to the pointer-parameter and its type is used to deduce the corresponding template parameter's type. For example:

  ```
  template<typename Type>
  Type sum(Type *tp, size_t n)
  {
      return accumulate(tp, tp + n, Type());
  }
  int main()
  {
      int x[10];
      sum(x, 10);
  }
  ```

  In this example, the location of the array `x` is passed to `sum`, expecting a pointer to some type. Using the array-to-pointer transformation, `x`'s address is considered a pointer value which is assigned to `tp`, deducing that `Type` is `int` in the process.

- **function-to-pointer transformations.**

  This transformation is most frequently used with function templates defining a parameter which is a pointer to a function. When calling such a function the name of a function may be specified as its argument. The address of the function is then assigned to the pointer-parameter, deducing the template type parameter in the process. This is called a function-to-pointer transformation. For example:

  ```
  #include <cmath>

  template<typename Type>
  void call(Type (*fp)(Type), Type const &value)
  {
      (*fp)(value);
  }
  int main()
  {
      call(sqrt, 2.0);
  }
  ```

  In this example, the address of the `sqrt` function is passed to `call`, expecting a pointer to a function returning a `Type` and expecting a `Type` for its argument. Using the function-to-pointer transformation, `sqrt`'s address is assigned to `fp`, deducing that `Type` is `double` in the process (note that `sqrt` is the *address* of a function, not a variable that is a pointer to a function, hence the lvalue transformation).

  The argument `2.0` could not have been specified as `2` as there is no `int sqrt(int)` prototype. Furthermore, the function's first parameter specifies `Type (*fp)(Type)`, rather than `Type (*fp)(Type const &)` as might have been expected from our previous discussion about how to specify the types of function template's parameters, preferring references over values. However, `fp`'s argument `Type` is not a function template parameter, but a parameter of the function `fp` points to. Since `sqrt` has prototype `double sqrt(double)`, rather than `double sqrt(double const &)`, `call`'s parameter `fp` *must* be specified as `Type (*fp)(Type)`. It's that strict.

21.4.2 Qualification transformations

A *qualification transformation* adds `const` or `volatile` qualifications to *pointers*. This transformation is applied when the function template's type parameter explicitly specifies `const` (or `volatile`) but the function's argument isn't a `const` or `volatile` entity. In that case `const` or `volatile` is provided by the compiler. Subsequently the compiler deduces the template's type parameter. For example:

```
template<typename Type>
Type negate(Type const &value)
{
    return -value;
}
int main()
{
    int x = 5;
    x = negate(x);
}
```

Here we see the function template's `Type const &value` parameter: a reference to a `const Type`. However, the argument isn't a `const int`, but an `int` that can be modified. Applying a qualification transformation, the compiler adds `const` to `x`'s type, and so it matches `int const x`. This is then matched against `Type const &value` allowing the compiler to deduce that `Type` must be `int`.

21.4.3 Transformation to a base class

Although the *construction* of class templates is the topic of chapter 22, we've already extensively *used* class templates before. For example, abstract containers (cf. chapter 12) are defined as class templates. Class templates can, like ordinary classes, participate in the construction of class hierarchies.

In section 22.11 it is shown how a class template can be derived from another class template.

As class template derivation remains to be covered, the following discussion is necessarily somewhat premature. The reader may of course skip briefly to section 22.11 returning back to this section thereafter.

In this section it should be assumed, for the sake of argument, that a class template `Vector` has somehow been derived from a `std::vector`. Furthermore, assume that the following function template has been constructed to sort a vector using some function object `obj`:

```
template <typename Type, typename Object>
void sortVector(std::vector<Type> vect, Object const &obj)
{
    sort(vect.begin(), vect.end(), obj);
}
```

To sort `std::vector<string>` objects case-insensitively, a `class Caseless` could be constructed as follows:

```
class CaseLess
{
    public:
        bool operator()(std::string const &before,
                        std::string const &after) const
        {
            return strcasecmp(before.c_str(), after.c_str()) < 0;
        }
};
```

Now various vectors may be sorted using `sortVector()`:

```
int main()
{
    std::vector<string> vs;
    std::vector<int> vi;

    sortVector(vs, CaseLess());
    sortVector(vi, less<int>());
}
```

Applying the transformation *transformation to a base class instantiated from a class template*, the function template `sortVector` may now also be used to sort `Vector` objects. For example:

```
int main()
{
    Vector<string> vs;      // `Vector' instead of `std::vector'
    Vector<int> vi;

    sortVector(vs, CaseLess());
    sortVector(vi, less<int>());
}
```

In this example, `Vector`s were passed as argument to `sortVector`. Applying the transformation to a base class instantiated from a class template, the compiler considers `Vector` to be a `std::vector` enabling it to deduce the template's type parameter. A `std::string` for the `Vector vs`, an `int` for `Vector vi`.

21.4.4 The template parameter deduction algorithm

The compiler uses the following algorithm to deduce the actual types of its template type parameters:

- In turn, the function template's parameters are identified using the arguments of the called function.

- For each template parameter used in the function template's parameter list, the template type parameter is associated with the corresponding argument's type (e.g., `Type` is `int` if the argument is `int x`, and the function's parameter is `Type &value`).

- While matching the argument types to the template type parameters, the three allowed transformations (see section 21.4) for template type parameters are applied where necessary.

- If identical template type parameters are used with multiple function parameters, the deduced template types must exactly match. So, the next function template cannot be called with an `int` and a `double` argument:

  ```
  template <typename Type>
  Type add(Type const &lhs, Type const &rhs)
  {
      return lhs + rhs;
  }
  ```

  When calling this function template, two identical types must be used (albeit that the three standard transformations are of course allowed). If the template deduction mechanism does not come up with identical actual types for identical template types, then the function template is not going to be instantiated.

21.4.5 Template type contractions

With function templates the combination of the types of template arguments and template parameters shows some interesting contractions. What happens, for example if a template type parameter is specified as an rvalue reference but an lvalue reference argument type is provided?

In such cases the compiler performs type contractions. Doubling identical reference types results in a simple contraction: the type is deduced to be a single reference type. Example: if the template parameter type is specified as a `Type &&` and the actual parameter is an `int &&` then `Type` is deduced to be an `int`, rather than an `int &&`.

This is fairly intuitive. But what happens if the actual type is `int &`? There is no such thing as an `int & &&param` and so the compiler contracts the double reference by removing the rvalue reference, keeping the lvalue reference. Here the following rules are applied:

1. A function template parameter defined as an lvalue reference to a template's type parameter (e.g., `Type &`) receiving an lvalue reference argument results in a single lvalue reference.
2. A function template parameter defined as an rvalue reference to a template's type parameter (e.g., `Type &&`) receiving any kind of reference argument uses the reference type of the argument.

Examples:

- When providing an `Actual &` argument then `Type &` becomes an `Actual &` and `Type` is inferred as `Actual`;
- When providing an `Actual &` then `Type &&` becomes an `Actual &` and `Type` is inferred as `Actual`;
- When providing an `Actual &&` then `Type &` also becomes `Actual &` and `Type` is inferred as `Actual`;
- When providing an `Actual &&` then `Type &&` becomes `Actual &&` and `Type` is inferred as `Actual`;

Let's look at a concrete exampe where contraction occurs. Consider the following function template where a function parameter is defined as an rvalue references to some template type parameter:

```
template <typename Type>
```

```
void function(Type &&param)
{
    callee(static_cast<Type &&>(param));
}
```

In this situation, when `function` is called with an (lvalue) argument of type `TP &` the template type parameter `Type` is deduced to be `Tp &`. Therefore, `Type &&param` is instantiated as `Tp &param`, `Type` becomes `Tp` and the rvalue reference is replaced by an lvalue reference.

Likewise, when `callee` is called using the `static_cast` the same contraction occurs, so `Type &&param` operates on `Tp &param`. Therefore (using contraction) the static cast *also* uses type `Tp &param`. If `param` happened to be of type `Tp &&` then the static cast uses type `Tp &&param`.

This characteristic allows us to pass a function argument to a nested function *without* changing its type: lvalues remain lvalues, rvalues remain rvalues. This characteristic is therefore also known as *perfect forwarding* which is discussed in greater detail in section 22.5.2. Perfect forwarding prevents the template author from having to define multiply overloaded versions of a function template.

21.5 Declaring function templates

Up to now, we've only defined function templates. There are various consequences of including function template definitions in multiple source files, none of them serious, but worth knowing.

- Like class interfaces, template definitions are usually included in header files. Every time a header file containing a template definition is read by the compiler it must process the full definition. It must do so even if it does not actually use the template. This somewhat slows-down the compilation. For example, compiling a template header file like `algorithm` on my old laptop takes about four times the amount of time it takes to compile a plain header file like `cmath`. The header file `iostream` is even harder to process, requiring almost 15 times the amount of time it takes to process `cmath`. Clearly, processing templates is serious business for the compiler. On the other hand this drawback shouldn't be taken too seriously. Compilers are continuously improving their template processing capacity and computers keep getting faster and faster. What was a nuisance a few years ago is hardly noticeable today.

- Every time a function template is instantiated, its code appears in the resulting object module. However, if multiple instantiations of a template using the same actual types for its template parameters exist in multiple object files the *one definition rule* is lifted. The linker weeds out superfluous instantiations (i.e., identical definitions of instantiated templates). In the final program only one instantiation for a particular set of actual template type parameters remain available (see section 21.6 for an illustration). Therefore, the linker has an additional task to perform (*viz.* weeding out multiple instantiations), which somewhat slows down the linking process.

- Sometimes the definitions themselves are *not* required, but references or pointers to the templates *are*. Requiring the compiler to process the full template definitions in those cases needlessly slows down the compilation process.

- In the context of *template meta programming* (see chapter 23) it is sometimes not even required to provide a template implementation. Instead, only *specializations* (cf. section 21.9) are created which are based upon the mere *declaration*.

So in some contexts template *definitions* may not be required. Instead the software engineer may opt to *declare* a template rather than to include the template's definition time and again in various source files.

When templates are declared, the compiler does not have to process the template's definitions again and again; and no instantiations are created on the basis of template declarations alone. Any actually required instantiation must then be available elsewhere (of course, this holds true for declarations in general). Unlike the situation we encounter with ordinary functions, which are usually stored in libraries, it is currently not possible to store templates in libraries (although the compiler may construct *precompiled header files*). Consequently, using template declarations puts a burden on the shoulders of the software engineer, who has to make sure that the required instantiations exist. Below a simple way to accomplish that is introduced.

To create a function template declaration simply replace the function's body by a semicolon. Note that this is exactly identical to the way ordinary function declarations are constructed. So, the previously defined function template `add` can simply be declared as

```
template <typename Type>
Type add(Type const &lhs, Type const &rhs);
```

We've already encountered template declarations. The header file `iosfwd` may be included in sources not requiring instantiations of elements from the class `ios` and its derived classes. For example, to compile the *declaration*

```
std::string getCsvLine(std::istream &in, char const *delim);
```

it is not necessary to include the `string` and `istream` header files. Rather, a single

```
#include <iosfwd>
```

is sufficient. Processing `iosfwd` requires only a fraction of the time it takes to process the `string` and `istream` header files.

21.5.1 Instantiation declarations

If declaring function templates speeds up the compilation and the linking phases of a program, how can we make sure that the required instantiations of the function templates are available when the program is eventually linked together?

For this a variant of a template declaration is available, a so-called *explicit instantiation declaration*. An explicit instantiation declaration consists of the following elements:

- It starts with the keyword `template`, omitting the template parameter list.
- Next the function template's return type and name are specified.
- The function template's name is followed by a *type specification list*. A type specification list is an angle brackets enclosed list of type names. Each type specifies the actual type of the corresponding template type parameter in the template's parameter list.
- Finally the function template's parameter list is specified, terminated by a semicolon.

Although this is a declaration, it is understood by the compiler as a request to instantiate that particular variant of the function template.

Using explicit instantiation declarations all instantiations of template functions required by a program can be collected in one file. This file, which should be a normal *source* file, should include the template definition header file and should subsequently specify the required explicit instantiation declarations. Since it's a source file, it is not included by other sources. So namespace `using` directives and declarations may safely be used once the required headers have been included. Here is an example showing the required instantiations for our earlier `add` function template, instantiated for `double`, `int`, and `std::string` types:

```
#include "add.h"
#include <string>
using namespace std;

template int add<int>(int const &lhs, int const &rhs);
template double add<double>(double const &lhs, double const &rhs);
template string add<string>(string const &lhs, string const &rhs);
```

If we're sloppy and forget to mention an instantiation required by our program then the repair is easily made by adding the missing instantiation declaration to the above list. After recompiling the file and relinking the program we're done.

21.6 Instantiating function templates

Different from an ordinary function that results in code once the compiler reads its definition a template is not instantiated when its definition is read. A template is merely a *recipe* telling the compiler how to create particular code once it's time to do so. It's indeed very much like a recipe in a cooking book. You reading how to bake a cake doesn't mean you have actually baked that cake by the time you've read the recipe.

So, when is a function template actually instantiated? There are two situations where the compiler decides to instantiate templates:

- They are instantiated when they are used (e.g., the function `add` is called with a pair of `size_t` values);
- When addresses of function templates are taken they are instantiated. Example:

  ```
  char (*addptr)(char const &, char const &) = add;
  ```

The location of statements causing the compiler to instantiate a template is called the template's *point of instantiation*. The point of instantiation has serious implications for the function template's code. These implications are discussed in section 21.13.

The compiler is not always able to deduce the template's type parameters unambiguously. When the compiler reports an ambiguity it must be solved by the software engineer. Consider the following code:

```
#include <iostream>
#include "add.h"

size_t fun(int (*f)(int *p, size_t n));
double fun(double (*f)(double *p, size_t n));

int main()
{
    std::cout << fun(add);
}
```

When this little program is compiled, the compiler reports an ambiguity it cannot resolve. It has two candidate functions as for each overloaded version of `fun` an `add` function can be instantiated:

```
error: call of overloaded 'fun(<unknown type>)' is ambiguous
note: candidates are: int fun(size_t (*)(int*, size_t))
note:                 double fun(double (*)(double*, size_t))
```

Such situations should of course be avoided. Function templates can only be instantiated if there's no ambiguity. Ambiguities arise when multiple functions emerge from the compiler's function selection mechanism (see section 21.14). It is up to us to resolve the ambiguities. They *could* be resolved using a blunt `static_cast` (by which we select among alternatives, all of them possible and available):

```
#include <iostream>
#include "add.h"

int fun(int (*f)(int const &lhs, int const &rhs));
double fun(double (*f)(double const &lhs, double const &rhs));

int main()
{
    std::cout << fun(
                    static_cast<int (*)(int const &, int const &)>(add)
                );
}
```

But it's good practice to avoid type casts wherever possible. How to do this is explained in the next section (21.7).

21.6.1 Instantiations: no 'code bloat'

As mentioned in section 21.5, the linker removes identical instantiations of a template from the final program, leaving only one instantiation for each unique set of actual template type parameters. To illustrate the linker's behavior we do as follows:

- First we construct several source files:
  - `source1.cc` defines a function `fun`, instantiating `add` for `int`-type arguments, including `add`'s template definition. It displays `add`'s address using `union PointerUnion`:

    ```
    union PointerUnion
    {
        int (*fp)(int const &, int const &);
        void *vp;
    };
    ```

    Here is a program using `PointerUnion`:

    ```
    #include <iostream>
    #include "add.h"
    #include "pointerunion.h"

    void fun()
    {
        PointerUnion pu = { add };
    ```

```
        std::cout << pu.vp << '\n';
    }
```

- `source2.cc` defines the same function, but merely declares the proper `add` template using a template declaration (*not* an instantiation declaration). Here is `source2.cc`:

```
    #include <iostream>
    #include "pointerunion.h"

    template<typename Type>
    Type add(Type const &, Type const &);

    void fun()
    {
        PointerUnion pu = { add };

        std::cout << pu.vp << '\n';
    }
```

- `main.cc` again includes `add`'s template definition, declares the function `fun` and defines `main`, defining `add` for `int`-type arguments as well and displaying `add`'s function address. It also calls the function `fun`. Here is `main.cc`:

```
    #include <iostream>
    #include "add.h"
    #include "pointerunion.h"

    void fun();

    int main()
    {
        PointerUnion pu = { add };

        fun();
        std::cout << pu.vp << '\n';
    }
```

- All sources are compiled to object modules. Note the different sizes of `source1.o` (1912 bytes using `g++` version 4.3.4 (sizes of object modules reported in this section may differ for different compilers and/or run-time libraries)) and `source2.o` (1740 bytes). Since `source1.o` contains the instantiation of `add`, it is somewhat larger than `source2.o`, containing only the template's declaration. Now we're ready to start our little experiment.

- Linking `main.o` and `source1.o`, we obviously link together two object modules, each containing its own instantiation of the same template function. The resulting program produces the following output:

```
    0x80486d8
    0x80486d8
```

  Furthermore, the size of the resulting program is 6352 bytes.

- Linking `main.o` and `source2.o`, we now link together an object module containing the instantiation of the `add` template, and another object module containing the mere declaration of the same template function. So, the resulting program cannot but contain a single instantiation of the required function template. This program has exactly the same size, and produces exactly the same output as the first program.

From our little experiment we conclude that the linker indeed removes identical template instantiations from a final program. Furthermore we conclude that using mere template declarations does not result in template instantiations.

21.7 Using explicit template types

In the previous section we saw that the compiler may encounter ambiguities when attempting to instantiate a template. In an example overloaded versions of a function (`fun`) existed, expecting different types of arguments. The ambiguity resulted from the fact that both arguments could have been provided by an instantiation of a function template. The intuitive way to solve such an ambiguity is to use a `static_cast`. But casts should be avoided wherever possible.

With function templates static casts may indeed be avoided using *explicit template type arguments*. Explicit template type arguments can be used to inform the compiler about the actual types it should use when instantiating a template. To use explicit type arguments the function's name is followed by an *actual template type argument list* which may again be followed by the function's argument list. The actual types mentioned in the actual template argument list are used by the compiler to 'deduce' what types to use when instantiating the template. Here is the example from the previous section, now using explicit template type arguments:

```
#include <iostream>
#include "add.h"

int fun(int (*f)(int const &lhs, int const &rhs));
double fun(double (*f)(double const &lhs, double const &rhs));

int main()
{
    std::cout << fun(add<int>) << '\n';
}
```

Explicit template type arguments can be used in situations where the compiler has no way to detect which types should actually be used. E.g., in section 21.4 the function template `Type fun()` was defined. To instantiate this function for the `double` type, we can call `fun<double>()`.

21.8 Overloading function templates

Let's once again look at our `add` template. That template was designed to return the sum of two entities. If we would want to compute the sum of three entities, we could write:

```
int main()
{
    add(add(2, 3), 4);
}
```

This is an acceptable solution for the occasional situation. However, if we would have to add three entities regularly, an *overloaded* version of the `add` function expecting three arguments might be a useful function to have. There's a simple solution to this problem: function templates may be overloaded.

To define an overloaded function template, merely put multiple definitions of the template in its header file. For the `add` function this would boil down to:

```
template <typename Type>
Type add(Type const &lhs, Type const &rhs)
{
    return lhs + rhs;
}
template <typename Type>
Type add(Type const &lhs, Type const &mid, Type const &rhs)
{
    return lhs + mid + rhs;
}
```

The overloaded function does not have to be defined in terms of simple values. Like all overloaded functions, a unique set of function parameters is enough to define an overloaded function template. For example, here's an overloaded version that can be used to compute the sum of the elements of a vector:

```
template <typename Type>
Type add(std::vector<Type> const &vect)
{
    return accumulate(vect.begin(), vect.end(), Type());
}
```

When overloading function templates we do not have to restrict ourselves to the function's parameter list. The template's type parameter list itself may also be overloaded. The last definition of the `add` template allows us to specify a `vector` as its first argument, but no `deque` or `map`. Overloaded versions for those types of containers could of course be constructed, but how far should we go? A better approach seems to be to look for common characteristics of these containers. If found we may be able to define an overloaded function template based on these common characteristics. One common characteristic of the mentioned containers is that they all support `begin` and `end` members, returning iterators. Using this, we could define a template type parameter representing containers that must support these members. But mentioning a plain 'container type' doesn't tell us for what type of data it was instantiated. So we need a second template type parameter representing the container's data type, thus overloading the template's type parameter list. Here is the resulting overloaded version of the `add` template:

```
template <typename Container, typename Type>
Type add(Container const &cont, Type const &init)
{
    return std::accumulate(cont.begin(), cont.end(), init);
}
```

One may wonder whether the `init` parameter could not be left out of the parameter list as `init` often has a default initialization value. The answer is 'yes', but there are complications. It *is* possible to define the `add` function as follows:

```
template <typename Type, typename Container>
Type add(Container const &cont)
{
    return std::accumulate(cont.begin(), cont.end(), Type());
}
```

Note, however, that the template's type parameters were reordered, which is necessary because the compiler won't be able to determine `Type` in a call like:

```
int x = add(vectorOfInts);
```

After reordering the template type parameters, putting `Type` first, an explicit template type argument can be provided for the first template type parameter:

```
int x = add<int>(vectorOfInts);
```

In this example we provided a `vector<int>` argument. One might wonder why we have to specify `int` explicitly to allow the compiler to determine the template type parameter `Type`. In fact, we don't. A third kind of template parameter exists, a *template template parameter*, allowing the compiler to determine `Type` directly from the actual container argument. Template template parameters are discussed in section 23.4.

21.8.1 An example using overloaded function templates

With all these overloaded versions in place, we may now start the compiler to compile the following function:

```
using namespace std;

int main()
{
    vector<int> v;

    add(3, 4);          // 1 (see text)
    add(v);             // 2
    add(v, 0);          // 3
}
```

- In statement 1 the compiler recognizes two identical types, both `int`. It therefore instantiates `add<int>`, our very first definition of the `add` template.
- In statement 2 a single argument is used. Consequently, the compiler looks for an overloaded version of `add` requiring but one argument. It finds the overloaded function template expecting a `std::vector`, deducing that the template's type parameter must be `int`. It instantiates

  ```
  add<int>(std::vector<int> const &)
  ```

- In statement 3 the compiler again encounters an argument list having two arguments. However, this time the types of the arguments aren't equal, so `add` template's first definition can't be used. But it *can* use the last definition, expecting entities having different types. As a `std::vector` supports `begin` and `end`, the compiler is now able to instantiate the function template

```
add<std::vector<int>, int>(std::vector<int> const &, int const &)
```

Having defined the `add` function template for two equal and two different template type parameters we've exhausted the possibilities for using an `add` function template having two template type parameters.

21.8.2 Ambiguities when overloading function templates

Although it *is* possible to define another function template `add` this introduces an ambiguity as the compiler won't be able to choose which of the two overloaded versions defining two differently typed function parameters should be used. For example when defining:

```
#include "add.h"

template <typename T1, typename T2>
T1 add(T1 const &lhs, T2 const &rhs)
{
    return lhs + rhs;
}
int main()
{
    add(3, 4.5);
}
```

the compiler reports an ambiguity like the following:

```
    error: call of overloaded `add(int, double)' is ambiguous
    error: candidates are: Type add(const Container&, const Type&)
                                [with Container = int, Type = double]
    error:                 T1 add(const T1&, const T2&)
                                [with T1 = int, T2 = double]
```

Now recall the overloaded function template accepting three arguments:

```
template <typename Type>
Type add(Type const &lhs, Type const &mvalue, Type const &rhs)
{
    return lhs + mvalue + rhs;
}
```

It may be considered as a disadvantage that only equally typed arguments are accepted by this function (three `int`s, three `double`s, etc.). To remedy this we define yet another overloaded function template, this time accepting arguments of any type. This function template can only be used if `operator+` is defined between the function's actually used types, but apart from that there appears to be no problem. Here is the overloaded version accepting arguments of any type:

```
template <typename Type1, typename Type2, typename Type3>
Type1 add(Type1 const &lhs, Type2 const &mid, Type3 const &rhs)
{
    return lhs + mid + rhs;
}
```

Now that we've defined the above two overloaded function templates expecting three arguments let's call `add` as follows:

```
add(1, 2, 3);
```

Should we expect an ambiguity here? After all, the compiler might select the former function, deducing that `Type == int`, but it might also select the latter function, deducing that `Type1 == int`, `Type2 == int` and `Type3 == int`. Remarkably, the compiler reports no ambiguity.

No ambiguity is reported because of the following. If overloaded template functions are defined using *less* and *more* specialized template type parameters (e.g., less specialized: all types different vs. more specialized: all types equal) then the compiler selects the more specialized function whenever possible.

As a rule of thumb: overloaded function templates must allow a unique combination of template type arguments to be specified to prevent ambiguities when selecting which overloaded function template to instantiate. The *ordering* of template type parameters in the function template's type parameter list is not important. E.g., trying to instantiate one of the following function templates results in an ambiguity:

```
template <typename T1, typename T2>
void binarg(T1 const &first, T2 const &second)
{}
template <typename T1, typename T2>
void binarg(T2 const &first, T1 const &second)
{}
```

This should not come as a surprise. After all, template type parameters are just formal names. Their names (`T1`, `T2` or `Whatever`) have no concrete meanings.

21.8.3 Declaring overloaded function templates

Like any function, overloaded functions may be declared, either using plain declarations or instantiation declarations. Explicit template argument types may also be used. Example:

- To declare a function template `add` accepting certain containers:

  ```
  template <typename Container, typename Type>
  Type add(Container const &container, Type const &init);
  ```

- to use an instantiation declaration (in which case the compiler must already have seen the template's definition):

  ```
  template int add<std::vector<int>, int>
                  (std::vector<int> const &vect, int const &init);
  ```

- to use explicit template type arguments:

  ```
  std::vector<int> vi;
  int sum = add<std::vector<int>, int>(vi, 0);
  ```

21.9 Specializing templates for deviating types

The initial `add` template, defining two identically typed parameters works fine for all types supporting `operator+` and a copy constructor. However, these assumptions are not always met. For example, with `char *`s, using `operator+` or a 'copy constructor' does not make sense. The compiler tries to instantiate the function template, but compilation fails as `operator+` is not defined for pointers.

In such situations the compiler may be able to resolve the template type parameters but it (or we ...) may then detect that the standard implementation is pointless or produces errors.

To solve this problem a *template explicit specialization* may be defined. A template explicit specialization defines the function template for which a generic definition already exists using specific actual template type parameters. As we saw in the previous section the compiler always prefers a more specialized function over a less specialized one. So the template explicit specialization is selected whenever possible.

A template explicit specialization offers a specialization for its template type parameter(s). The special type is consistently substituted for the template type parameter in the function template's code. For example if the explicitly specialized type is `char const *` then in the template definition

```
template <typename Type>
Type add(Type const &lhs, Type const &rhs)
{
    return lhs + rhs;
}
```

`Type` must be replaced by `char const *`, resulting in a function having prototype

```
char const *add(char const *const &lhs, char const *const &rhs);
```

Now we try to use this function:

```
int main(int argc, char **argv)
{
    add(argv[0], argv[1]);
}
```

However, the compiler ignores our specialization and tries to instantiate the initial function template. This fails, leaving us wondering why it didn't select the explicit specialization....

To see what happened here we replay, step by step, the compiler's actions:

- `add` is called with `char *` arguments.
- Both types are equal, so the compiler deduces that `Type` equals `char *`.
- Now it inspects the specialization. Can a `char *` template type argument match a `char const *const &` template parameter? Here opportunities for the allowable transformations from section 21.4 may arise. A qualification transformation seems to be the only viable one, allowing the compiler to bind a const-parameter to a non-const argument.
- So, in terms of `Type` the compiler can match an argument of some `Type` or an argument of some `Type const` to a `Type const &`.
- `Type` itself is not modified, and so `Type` is a `char *`.
- Next the compiler inspects the available explicit specializations. It finds one, specializing for `char const *`.
- Since a `char const *` is not a `char *` it rejects the explicit specialization and uses the generic form, resulting in a compilation error.

If our `add` function template should also be able to handle `char *` template type arguments another explicit specialization for `char *` may be required, resulting in the prototype

```
char *add(char *const &lhs, char *const &rhs);
```

Instead of defining another explicit specialization an *overloaded* function template could be designed expecting pointers. The following function template definition expects two pointers to constant `Type` values and returns a pointer to a non-constant `Type`:

```
template <typename Type>
Type *add(Type const *t1, Type const *t2)
{
    std::cout << "Pointers\n";
    return new Type;
}
```

What actual types may be bound to the above function parameters? In this case only a `Type const *`, allowing `char const *`'s to be passed as arguments. There's no opportunity for a qualification transformation here. The qualification transformation allows the compiler to add a `const` to a non-const argument if the parameter itself (and *not* `Type`) is specified in terms of a `const` or `const &`. Looking at, e.g., `t1` we see that it's defined as a `Type const *`. There's nothing `const` here that's referring to the parameter (in which case it would have been `Type const *const t1` or `Type const *const &t1`). Consequently a qualification transformation cannot be applied here.

As the above overloaded function template only accepts `char const *` arguments, it will not accept (without a reinterpret cast) `char *` arguments. So `main`'s `argv` elements cannot be passed to our overloaded function template.

21.9.1 Avoiding too many specializations

So do we have to define yet another overloaded function template, this time expecting `Type *` arguments? It is possible, but at some point it should become clear that our approach doesn't scale. Like ordinary functions and classes, function templates should have one conceptually clear purpose. Trying to add overloaded function templates to overloaded function templates quickly turns the template into a kludge. Don't use this approach. A better approach is to construct the template so that it fits its original purpose, to make allowances for the occasional specific case and to describe its purpose clearly in its documentation.

In some situations constructing template explicit specializations may of course be defensible. Two specializations for `const` and non-`const` pointers to characters might be appropriate for our `add` function template. Here's how they are constructed:

- Start with the keyword `template`.
- Next, an empty set of angle brackets is written. This indicates to the compiler that there must be an *existing* template whose prototype matches the one we're about to define. If we err and there is no such template then the compiler reports an error like:

  ```
  error: template-id `add<char*>' for `char* add(char* const&, char*
         const&)' does not match any template declaration
  ```

- Now the function's head is defined. It must match the prototype of the initial function template or the form of a template explicit instantiation declaration (see section 21.5.1) if its specialized type cannot be determined from the function's arguments. It must specify the correct returntype, function name, maybe explicit template type arguments, as well as the function's parameter list.
- Finally the function's body is defined, providing the special implementation that is required for the specialization.

Here are two explicit specializations for the function template `add`, expecting `char *` and `char const *` arguments:

```
template <> char *add<char *>(char *const &p1,
                                    char *const &p2)
{
    std::string str(p1);
    str += p2;
    return strcpy(new char[str.length() + 1], str.c_str());
}

template <> char const *add<char const *>(char const *const &p1,
                                    char const *const &p2)
{
    static std::string str;
    str = p1;
    str += p2;
    return str.c_str();
}
```

Template explicit specializations are normally included in the file containing the other function template's implementations.

21.9.2 Declaring specializations

Template explicit specializations can be declared in the usual way. I.e., by replacing its body with a semicolon.

When *declaring* a template explicit specialization the pair of angle brackets following the `template` keyword are essential. If omitted, we would have constructed a template instantiation declaration. The compiler would silently process it, at the expense of a somewhat longer compilation time.

When declaring a template explicit specialization (or when using an instantiation declaration) the explicit specification of the template type parameters can be omitted if the compiler is able to deduce these types from the function's arguments. As this is the case with the `char (const) *` specializations, they could also be declared as follows:

```
template <> char *add(char *const &p1, char *const &p2)
template <> char const *add(char const *const &p1,
                            char const *const &p2);
```

If in addition `template <>` could be omitted the template character would be removed from the declaration. The resulting declaration is now a mere function declaration. This is not an error: function templates and ordinary (non-template) functions may mutually overload each other. Ordinary functions are not as restrictive as function templates with respect to allowed type conversions. This could be a reason to overload a template with an ordinary function every once in a while.

A function template explicit specialization is not just another overloaded version of the function template. Whereas an overloaded version may define a completely different set of template parameters, a specialization must use the same set of template parameters as its non-specialized variant. The compiler uses the specialization in situations where the actual template arguments match the types defined by the specialization (following the rule that the most specialized set of parameters matching a set of arguments will be used). For different sets of parameters overloaded versions of functions (or function templates) must be used.

21.9.3 Complications when using the insertion operator

Now that we've covered explicit specializations and overloading let's consider what happens when a class defines a `std::string` conversion operator (cf. section 11.3).

A conversion operator is guaranteed to be used as an rvalue. This means that objects of a class defining a `string` conversion operator can be assigned to, e.g., `string` objects. But when trying to insert objects defining `string` conversion operators into streams then the compiler complains that we're attempting to insert an inappropriate type into an `ostream`.

On the other hand, when this class defines an `int` conversion operator insertion is performed flawlessly.

The reason for this distinction is that `operator<<` is defined as a plain (free) function when inserting a basic type (like `int`) but it is defined as a function template when inserting a `string`. Hence, when trying to insert an object of our class defining a `string` conversion operator the compiler visits all overloaded versions of insertion operators inserting into `ostream` objects.

Since no basic type conversion is available the basic type insertion operators can't be used. Since the available conversions for template arguments do not allow the compiler to look for conversion operators our class defining the `string` conversion operator cannot be inserted into an `ostream`.

If it should be possible to insert objects of such a class into `ostream` objects the class must define its own overloaded insertion operator (in addition to the `string` conversion operator that was required to use the class's objects as rvalue in `string` assignments).

21.10 Static assertions

The

```
static_assert(constant expression, error message)
```

utility is available to allow assertions to be made from inside template definitions. Here are two examples of its use:

```
static_assert(BUFSIZE1 == BUFSIZE2,
                            "BUFSIZE1 and BUFSIZE2 must be equal");

template <typename Type1, typename Type2>
void rawswap(Type1 &type1, Type2 &type2)
{
    static_assert(sizeof(Type1) == sizeof(Type2),
                    "rawswap: Type1 and Type2 must have equal sizes");
    // ...
}
```

The first example shows how to avoid yet another preprocessor directive (in this case the `#error` directive).

The second example shows how `static_assert` can be used to ensure that a template operates under the right condition(s).

The string defined in `static_assert`'s second argument is displayed and compilation stops if the condition specified in `static_assert`'s first argument is `false`.

Like the `#error` preprocessor directive `static_assert` is a compile-time matter that doesn't have any effect on the run-time efficiency of the code in which it is used.

21.11 Numeric limits

The header file `<climits>` defines constants for various types, e.g., `INT_MAX` defines the maximum value that can be stored in an `int`.

The disadvantage of the limits defined in `climits` is that they are fixed limits. Let's assume you write a function template that receives an argument of a certain type. E.g,

```
template<typename Type>
Type operation(Type &&type);
```

Assume this function should return the largest negative value for `Type` if `type` is a negative value and the largest positive value if `type` is a positive value. However, 0 should be returned if the type is not an integral value.

How to proceed?

Since the constants in `climits` can only be used if the type to use is already known, the only approach seems to be to create function template specializations for the various integral types, like:

```
template<>
int operation<int>(int &&type)
{
    return type < 0 ? INT_MIN : INT_MAX;
}
```

The facilities provided by numeric_limits provide an alternative. To use these facilities the header file `<limits>` header file must be included.

The class template `numeric_limits` offers various members answering all kinds of questions that could be asked of numeric types. Before introducing these members, let's have a look at how we could implement the `operation` function template as just one single function template:

```
template<typename Type>
Type operation(Type &&type)
{
    return
        not numeric_limits<Type>::is_integer ? 0 :
        type < 0 ? numeric_limits<Type>::min() :
                   numeric_limits<Type>::max();
}
```

Now `operation` can be used for all the language's primitive types.

Here is an overview of the facilities offered by `numeric_limits`. Note that the member functions defined by `numeric_limits` return `constexpr` values. A member '`member`' defined by `numeric_limits` for type `Type` can be used as follows:

```
numeric_limits<Type>::member    // data members
numeric_limits<Type>::member()  // member functions
```

- `Type denorm_min()`:
  if available for `Type`: its minimum positive denormalized value; otherwise it returns `numeric_limits<Type>::min()`.
- `int digits`:
  the number of non-sign bits used by `Type` values, or (floating point types) the number of digits in the mantissa are returned.
- `int digits10`:
  the number of digits that are required to represent a `Type` value without changing it.
- `Type constexpr epsilon()`:
  The difference for `Type` between the smallest value exceeding 1 and 1 itself.
- `float_denorm_style has_denorm`:
  denormalized floating point value representations use a variable number of exponent bits. The `has_denorm` member returns information about denormalized values for type `Type`:
  - `denorm_absent`: `Type` does not allow denormalized values;
  - `denorm_indeterminate`: `Type` may or may not use denormalized values; the compiler cannot determine this at compile-time;
  - `denorm_present`: `Type` uses denormalized values;
- `bool has_denorm_loss`:
  `true` if a loss of accuracy was detected as a result of using denormalization (rather than being an inexact result).
- `bool has_infinity`:
  `true` if `Type` has a representation for positive infinity.
- `bool has_quiet_NaN`:
  `true` if `Type` has a representation for a non-signaling 'Not-a-Number' value.
- `bool has_signaling_NaN`:
  `true` if `Type` has a representation for a signaling 'Not-a-Number' value.
- `Type constexpr infinity()`:
  if available for `Type`: its positive infinity value.
- `bool is_bounded`:
  `true` if `Type` contains a finite set of values.
- `bool is_exact`:
  `true` if `Type` uses an exact representation.
- `bool is_iec559`:
  `true` if `Type` uses the IEC-559 (IEEE-754) standard. Such types always return `true` for `has_infinity`, `has_quiet_NaN` and `has_signaling_NaN`, while `infinity()`, `quiet_NaN()` and `signaling_NaN()` return non-zero values.
- `bool is_integer`:
  `true` if `Type` is an integral type.
- `bool is_modulo`:
  `true` if `Type` is a 'modulo' type. Values of modulo types can always be added, but the addition may 'wrap around' producing a smaller `Type` result than either of the addition's two operands.
- `bool is_signed`:
  `true` if `Type` is signed.
- `bool is_specialized`:
  `true` for specializations of `Type`.

- `Type constexpr lowest()`:
  `Type`'s lowest finite value representable by `Type`: no other finite value smaller than the value returned by `lowest` exists. This value equals the value returned by `min` except for floating-point types.

- `T constexpr max()`:
  `Type`'s maximum value.

- `T constexpr min()`:
  `Type`'s minimum value. For denormalized floating point types the minimum positive normalized value.

- `int max_exponent`:
  maximum positive integral value for the exponent of a floating point type `Type` producing a valid `Type` value.

- `int max_exponent10`:
  maximum integral value for the exponent that can be used for base 10, producing a valid `Type` value.

- `int min_exponent`:
  minimum negative integral value for the exponent of a floating point type `Type` producing a valid `Type` value.

- `int min_exponent10`:
  minimum negative integral value for the exponent that can be used for base 10, producing a valid `Type` value.

- `Type constexpr quiet_NaN()`:
  if available for `Type`: its a non-signaling 'Not-a-Number' value.

- `int radix`:
  if `Type` is an integral type: base of the representation; if `Type` is a floating point type: the base of the exponent of the representation.

- `Type constexpr round_error()`:
  the maximum rounding error for `Type`.

- `float_round_style round_syle`:
  the rounding style used by `Type`. It has one of the following `enum float_round_style` values:

  - `round_toward_zero`: values are rounded towards zero;
  - `round_to_nearest`: values are rounded to the nearest representable value;
  - `round_toward_infinity`:values are rounded towards infinity;
  - `round_toward_neg_infinity`: if it rounds towards negative infinity;
  - `round_indeterminate`: if the rounding style is indeterminable at compile-time.

- `Type constexpr signaling_NaN()`:
  if available for `Type`: its a signaling 'Not-a-Number' value.

- `bool tinyness_before`:
  `true` if `Type` allows tinyness to be detected before rounding.

- `bool traps`:
  `true` if `Type` implements trapping.

21.12 Polymorphous wrappers for function objects

In **C++** pointers to (member) functions have fairly strict rvalues. They can only point to functions matching their types. This becomes a problem when defining templates where the type of a function pointer may depend on the template's parameters.

To solve this problem *polymorphous (function object) wrappers* can be used. Polymorphous wrappers refer to function pointers, member functions or function objects, as long as their parameters match in type and number.

Before using polymorphic function wrappers the `<functional>` header file must be included.

Polymorphic function wrappers are made available through the `std::function` class template. Its template argument is the prototype of the function to create a wrapper for. Here is an example of the definition of a polymorphic function wrapper that can be used to point to a function expecting two `int` values and returning an `int`:

```
std::function<int (int, int)> ptr2fun;
```

Here, the template's parameter is `int (int, int)`, indicating a function expecting two `int` arguments, and returning and `int`. Other prototypes return other, matching, function wrappers.

Such a function wrapper can now be used to point to any function the wrapper was created for. E.g., '`plus<int> add`' creates a functor defining an `int operator()(int, int)` function call member. As this qualifies as a function having prototype `int (int, int)`, our `ptr2fun` may point to `add`:

```
ptr2fun = add;
```

If `ptr2fun` does not yet point to a function (e.g., it is merely defined) and an attempt is made to call a function through it a '`std::bad_function_call`' exception is thrown. Also, a polymorphic function wrapper that hasn't been assigned to a function's address represents the value `false` in logical expressions (as if it had been a pointer having value zero):

```
std::function<int(int)> ptr2int;

if (not ptr2int)
    cout << "ptr2int is not yet pointing to a function\n";
```

Polymorphous function wrappers can also be used to refer to functions, functors or other polymorphous function wrappers having prototypes for which standard conversions exist for either parameters or return values. E.g.,

```
bool predicate(long long value);

void demo()
{
    std::function<int(int)> ptr2int;

    ptr2int = predicate;    // OK, convertible param. and return type

    struct Local
    {
        short operator()(char ch);
        };

        Local object;

        std::function<short(char)> ptr2char(object);

        ptr2int = object;       // OK, object is a functor whose function
                                //  operator has a convertible param. and
                                // return type.
        ptr2int = ptr2char;     // OK, now using a polym. funct. wrapper
    }
```

21.13 Compiling template definitions and instantiations

Consider this definition of the `add` function template:

```
    template <typename Container, typename Type>
    Type add(Container const &container, Type init)
    {
        return std::accumulate(container.begin(), container.end(), init);
    }
```

Here `std::accumulate` is called using `container`'s `begin` and `end` members.

The calls `container.begin()` and `container.end()` are said to *depend on template type parameters*. The compiler, not having seen `container`'s interface, cannot check whether `container` actually has members `begin` and `end` returning input iterators.

On the other hand, `std::accumulate` itself is independent of any template type parameter. Its *arguments* depend on template parameters, but the function call itself isn't. Statements in a template's body that are independent of template type parameters are said *not to depend on template type parameters*.

When the compiler encounters a template definition, it verifies the syntactic correctness of all statements not depending on template parameters. I.e., it must have seen all class definitions, all type definitions, all function declarations etc. that are used in those statements. If the compiler hasn't seen the required definitions and declarations then it will reject the template's definition. Therefore, when submitting the above template to the compiler the `numeric` header file must first have been included as this header file declares `std::accumulate`.

With statements depending on template parameters the compiler cannot perform those extensive syntactic checks. It has no way to verify the existence of a member `begin` for the as yet unspecified type `Container`. In these cases the compiler performs superficial checks, assuming that the required members, operators and types eventually become available.

The location in the program's source where the template is instantiated is called its *point of instantiation*. At the point of instantiation the compiler deduces the actual types of the template's parameters. At that point it checks the syntactic correctness of the template's statements that depend on template type parameters. This implies that the compiler must have seen the required declarations *only at the point of instantiation*. As a rule of thumb, you should make sure that all required declarations (usually: header files) have been read by the compiler at every point of instantiation of the template. For the template's definition itself a more relaxed requirement can be formulated. When the definition is read only the declarations required for statements *not* depending on the template's type parameters must have been provided.

21.14 The function selection mechanism

When the compiler encounters a function call, it must decide which function to call when overloaded functions are available. Earlier we've encountered principles like 'the most specific function is selected'. This is a fairly intuitive description of the compiler's function selection mechanism. In this section we'll have a closer look at this mechanism.

Assume we ask the compiler to compile the following `main` function:

```
int main()
{
    process(3, 3);
}
```

Furthermore assume that the compiler has encountered the following function declarations when it's about to compile `main`:

```
template <typename T>
void process(T &t1, int i);                 // 1

template <typename T1, typename T2>
void process(T1 const &t1, T2 const &t2);   // 2

template <typename T>
void process(T const &t, double d);         // 3

template <typename T>
void process(T const &t, int i);            // 4

template <>
void process<int, int>(int i1, int i2);     // 5

void process(int i1, int i2);               // 6

void process(int i, double d);              // 7

void process(double d, int i);              // 8

void process(double d1, double d2);         // 9

void process(std::string s, int i)          // 10

int add(int, int);                          // 11
```

The compiler, having read `main`'s statement, must now decide which function must actually be called. It proceeds as follows:

- First, a set of *candidate functions* is constructed. This set contains all functions that:
  - are visible at the point of the call;
  - have the same names as the called function.

  As function 11 has a different name, it is removed from the set. The compiler is left with a set of 10 candidate functions.

- Second, the set of *viable functions* is constructed. Viable functions are functions for which type conversions exist that can be applied so as to match the types of the function's parameters to the types of the actual arguments.

  This implies that at least the number of arguments must match the number of parameters of the viable functions. Function 10's first argument is a `string`. As a `string` cannot be initialized by an `int` value no appropriate conversion exists and function 10 is removed from the list of candidate functions. `double` parameters can be retained. Standard conversions *do* exists for `int`s to `double`s, so all functions having ordinary `double` parameters can be retained. Therefore, the set of viable functions consists of functions 1 through 9.

At this point the compiler tries to determine the types of the template type parameters. This step is outlined in the following subsection.

21.14.1 Determining the template type parameters

Having determined the set of candidate functions and from that set the set of viable functions the compiler must now determine the actual types of the template type parameters.

It may use any of the three standard template parameter transformation procedures (cf. section 21.4) when trying to match actual types to template type parameters. In this process it concludes that no type can be determined for the `T` in function 1's `T &t1` parameter as the argument `3` is a constant `int` value. Thus function 1 is removed from the list of viable functions. The compiler is now confronted with the following set of potentially instantiated function templates and ordinary functions:

```
void process(T1 [= int] const &t1, T2 [= int] const &t2);   // 2
void process(T [= int] const &t, double d);                 // 3
void process(T [= int] const &t, int i);                    // 4
void process<int, int>(int i1, int i2);                     // 5
void process(int i1, int i2);                               // 6
void process(int i, double d);                              // 7
void process(double d, int i);                              // 8
void process(double d1, double d2);                         // 9
```

The compiler associates a *direct match count* value to each of the viable functions. The direct match count counts the number of arguments that can be matched to function parameters without an (automatic) type conversion. E.g., for function 2 this count equals 2, for function 7 it is 1 and for function 9 it is 0. The functions are now (decrementally) sorted by their direct match count values:

```
                                                           match
                                                           count
void process(T1 [= int] const &t1, T2 [= int] const &t2);    2 // 2
void process(T [= int] const &t, int i);                     2 // 4
void process<int, int>(int i1, int i2);                      2 // 5
void process(int i1, int i2);                                2 // 6
void process(T [= int] const &t, double d);                  1 // 3
void process(int i, double d);                               1 // 7
void process(double d, int i);                               1 // 8
void process(double d1, double d2);                          0 // 9
```

If there is no draw for the top value the corresponding function is selected and the function selection process is completed.

When multiple functions appear at the top the compiler verifies that no ambiguity has been encountered. An ambiguity is encountered if the *sequences* of parameters for which type conversions were (not) required differ. As an example consider functions 3 and 8. Using D for 'direct match' and C for 'conversion' the arguments match function 3 as D,C and function 8 as C,D. Assuming that 2, 4, 5 and 6 were not available, then the compiler would have reported an ambiguity as the sequences of argument/parameter matching procedures differ for functions 3 and 8. The same difference is encountered comparing functions 7 and 8, but no such difference is encountered comparing functions 3 and 7.

At this point there is a draw for the top value and the compiler proceeds with the subset of associated functions (functions 2, 4, 5 and 6). With each of these functions an 'ordinary parameter count' is associated counting the number of non-template parameters of the functions. The functions are decrementally sorted by this count, resulting in:

```
                                                      ordin. param.
                                                          count
    void process(int i1, int i2);                           2 // 6
    void process(T [= int] const &t, int i);                1 // 4
    void process(T1 [= int] const &t1, T2 [= int] const &t2);  0 // 2
    void process<int, int>(int i1, int i2);                 0 // 5
```

Now there is no draw for the top value. The corresponding function (`process(int, int)`, function 6) is selected and the function selection process is completed. Function 6 is used in `main`'s function call statement.

Had function 6 not been defined, function 4 would have been used. Assuming that neither function 4 nor function 6 had been defined, the selection process would continue with functions 2 and 5:

```
                                                      ordin. param.
                                                          count
    void process(T1 [= int] const &t1, T2 [= int] const &t2);  0 // 2
    void process<int, int>(int i1, int i2);                 0 // 5
```

In this situation a draw is encountered once again and the selection process continues. A 'type of function' value is associated with each of the functions having the highest ordinary parameter count and these functions are decrementally sorted by their type of function values. Value 2 is associated to ordinary functions, value 1 to template explicit specializations and value 0 to plain function templates.

If there is no draw for the top value the corresponding function is selected and the function selection process is completed. If there is a draw the compiler reports an ambiguity and cannot determine which function to call. Assuming only functions 2 and 5 existed then this selection step would have resulted in the following ordering:

```
                                                        function
                                                          type
    void process<int, int>(int i1, int i2);                 1 // 5
    void process(T1 [= int] const &t1, T2 [= int] const &t2);  0 // 2
```

Function 5, the template explicit specialization, would have been selected. Here is a summary of the function template selection mechanism (cf. figure Figure 21.1):

- The set of candidate functions is constructed: identical names;
- The set of viable functions is constructed: correct number of parameters and available type conversions;

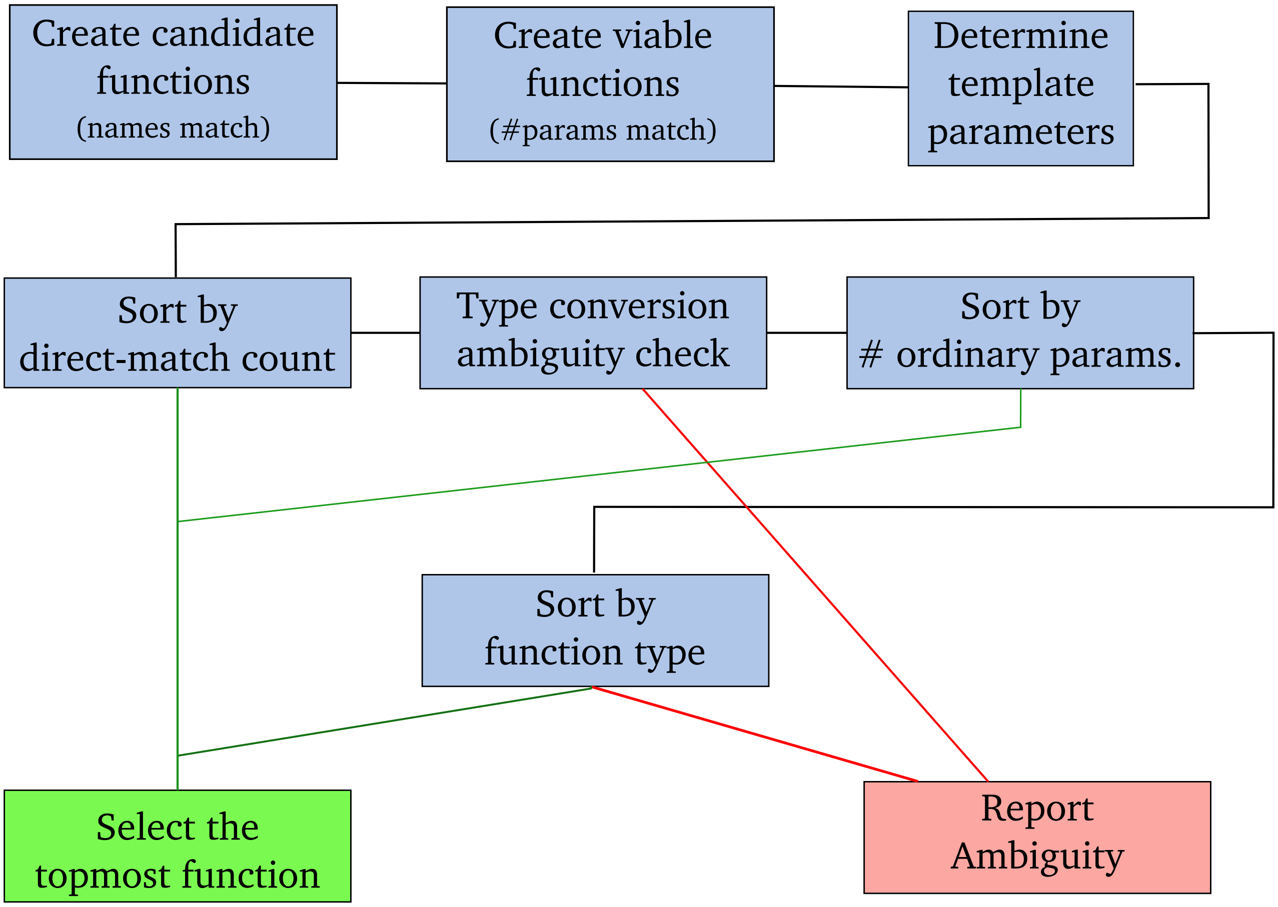
Create candidate functions
(names match)
Create viable functions
(#params match)
Determine template parameters
Sort by direct-match count
Type conversion ambiguity check
Sort by # ordinary params.
Sort by function type
Select the topmost function
Report Ambiguity

Figure 21.1: The function template selection mechanism

- Template type determination, dropping templates whose type parameters cannot be determined;
- Decrementally sort the functions by their direct match count values. If there is no draw for the top value the associated function is selected, completing the selection process.
- Inspect the functions associated with the top value for ambiguities in automatic type conversion sequences. If different sequences are encountered report an ambiguity and terminate the selection process.
- Decrementally sort the functions associated with the top value by their ordinary parameter count values. If there is no draw for the top value the associated function is selected, completing the selection process.
- Decrementally sort the functions associated with the top value by their function type values using 2 for ordinary functions, 1 for template explicit specializations and 0 for plain function templates. If there is no draw for the top value the associated function is selected, completing the selection process.
- Report an ambiguity and terminate the selection process.

21.15 SFINAE: Substitution Failure Is Not An Error

Consider the following struct definition:

```
struct Int
{
    typedef int type;
};
```

Although at this point it may seem strange to embed a typedef in a struct, in chapter 23 we will encounter situations where this is actually very useful. It allows us to define a variable of a type that is required by the template. E.g., (ignore the use of `typename` in the following function parameter list, but see section 22.2.1 for details):

```
template <typename Type>
void func(typename Type::type value)
{
}
```

When calling `func(10)` `Int` has to be specified explicitly since there may be many structs that define `type`: the compiler needs some assistance. The correct call is `func<Int>(10)`. Now that it's clear that `Int` is meant, and the compiler correctly deduces that `value` is an `int`.

But templates may be overloaded and our next definition is:

```
template <typename Type>
void func(Type value)
{}
```

Now, to call this function we specify `func<int>(10)` and again this flawlessly compiles.

But as we've seen in the previous section when the compiler determines which template to instantiate it creates a list of viable functions and selects the function to instantiate by matching the parameter types of viable functions with the provided actual argument types. To do so it has to *determine* the types of the parameters and herein lies a problem.

When evaluating `Type = int` the compiler encounters the prototypes `func(int::type)` (first template definition) and `func(int)` (second template definition). But there is no `int::type`, and so in a way this generates an error. The error results from matching the provided template type argument with the types used in the various template definitions.

A type-problem caused by substituting a type in a template definition is, however, *not* considered an error, but merely an indication that that particular type cannot be used in that particular template. The template is therefore removed from the list of candidate functions.

This principle is known as *substitution failure is not an error* (SFINAE) and it is often used by the compiler to select not only a simple overloaded function (as shown here) but also to choose among available template specializations (see also sections 23.6.1 and 23.9.3).

21.16 Conditional function definitions using ‘if constexpr’

In addition to the common `if (cond)` selection statement the `if constexpr (cond)` syntax is supported by the language. Although it can be used in all situations where a standard `if` selection statement are used, its specific use is encountered inside function templates: `if constexpr` allows the compiler to (conditionally) instantiate elements of a template function, depending on the compile-time evaluation of the `if constexpr’s (cond)` clause.

Here is an example:

```
 1: void positive();
 2: void negative();
 3:
 4: template <int value>
 5: void fun()
 6: {
 7:     if constexpr (value > 0)
 8:         positive();
 9:     else if constexpr (value < 0)
10:         negative();
11: }
12:
13: int main()
14: {
15:     fun<4>();
16: }
```

- At lines 7 and 9 `if constexpr` statements start. Since `value` is a template non-type parameter its value is compile-time available, and so are the values of the condition sections.
- In line 15 `fun<4>()` is called: the condition in line 7 is therefore `true`, and the condition in line 9 is `false`.
- The compiler therefore instantiates `fun<4>()` this way:

  ```
  void fun<4>()
  {
      positive();
  }
  ```

Note that the `if constexpr` statements themselves do not result in executable code: it is used by the compiler to *select* which part (or parts) it should instantiate. In this case only `positive`, which must be available before the program's linking phase can properly complete.

21.17 Summary of the template declaration syntax

In this section the basic syntactic constructions for declaring templates are summarized. When *defining* templates, the terminating semicolon should be replaced by a function body.

Not every template declaration may be converted into a template definition. If a definition may be provided it is explicitly mentioned.

- A plain template declaration (a definition may be provided):

  ```
  template <typename Type1, typename Type2>
  void function(Type1 const &t1, Type2 const &t2);
  ```

- A template instantiation declaration (no definition may be provided):

  ```
  template
  void function<int, double>(int const &t1, double const &t2);
  ```

- A template using explicit types (no definition may be provided):

  ```
  void (*fp)(double, double) = function<double, double>;
  void (*fp)(int, int) = function<int, int>;
  ```

- A template explicit specialization (a definition may be provided):

  ```
  template <>
  void function<char *, char *>(char *const &t1, char *const &t2);
  ```

- A template declaration declaring friend function templates within class templates (covered in section 22.10, no definition may be provided):

  ```
  friend void function<Type1, Type2>(parameters);
  ```

21.18 Variables as templates (template variables)

In addition to function templates and class templates (cf. chapter 22) **C++** supports *variable templates*. Variable templates might come in handy when defining (function or class) templates defining variables of types specified by template type parameters.

A variable template starts with a familiar `template` header, followed by the definition of the variable itself. The template header specifies a type, for which a default type may also be specified. E.g.,

```
template<typename T = long double>
constexpr T pi = T(3.1415926535897932385);
```

To use this variable a type must be specified, and as long as the initialized value can be converted to the specified type the conversion is silently performed by the compiler:

```
cout << pi<> << ' ' << pi<int>;
```

At the second insertion the `long double` initialization value is converted to `int`, and 3 is displayed.

Specializations are also supported. E.g., to show the text 'pi' a specialization for a `char const *` type can be defined:

```
template<>
constexpr char const *pi<char const *> = "pi";
```

With this specialization we can do `cout << pi<char const *>` to show `pi`.

Chapter 22

Class Templates

Templates can not only be constructed for functions but also for complete classes. Consider constructing a class template when a class should be able to handle different types of data. Class templates are frequently used in **C++**: chapter 12 discusses data structures like `vector, stack` and `queue`, that are implemented as *class templates*. With class templates, the algorithms and the data on which the algorithms operate are completely separated from each other. To use a particular data structure in combination with a particular data type only the data type needs to be specified when defining or declaring a class template object (as in `stack<int> iStack`).

In this chapter constructing and using class templates is discussed. In a sense, class templates compete with object oriented programming (cf. chapter 14), that uses a mechanism resembling that of templates. Polymorphism allows the programmer to postpone the implementation of algorithms by deriving classes from base classes in which algorithms are only partially implemented. The actual definition and processing of the data upon which the algorithms operate may be postponed until derived classes are defined. Likewise, templates allow the programmer to postpone the specification of the data upon which the algorithms operate. This is most clearly seen with abstract containers, which completely specify the algorithms and at the same time leave the data type on which the algorithms operate completely unspecified.

There exists an intriguing correspondence between the kind of polymorphism we've encountered in chapter 14 and certain uses of class templates. In their book **C++ Coding Standards** (Addison-Wesley, 2005) Sutter and Alexandrescu refer to *static polymorphism* and *dynamic polymorphism*. *Dynamic* polymorphism is what we use when overriding virtual members. Using *vtable*s the function that is actually called depends on the type of object a (base) class pointer points at. *Static* polymorphism is encountered in the context of templates, and is discussed and compared to dynamic polymorphism in section 22.12.

Generally, class templates are easier to use than polymorphism. It is certainly easier to write `stack<int> istack` to create a stack of `ints` than to derive a new class `Istack: public stack` and to implement all necessary member functions defining a similar stack of `ints` using object oriented programming. On the other hand, for each different type for which an object of a class template is defined another, possibly complete class must be reinstantiated. This is not required in the context of object oriented programming where derived classes *use*, rather than *copy*, the functions that are already available in their base classes (but see also section 22.11).

Previously we've already used class templates. Objects like `vector<int> vi` and `vector<string> vs` are commonly used. The data types for which these templates are defined and instantiated are an inherent part of such container types. It is stressed that it is the *combination* of a class template type and its template parameter(s), rather than the mere class template's type that defines or generates a type. So `vector<int>` is a type as is `vector<string>`. Such types could very well be represented by typedefs:

```
typedef std::vector<int>         IntVector;
typedef std::vector<std::string> StringVector;

IntVector vi;
StringVector vs;
```

22.0.1 Template Argument Deduction

One important difference between function templates and class templates is that the template arguments of function templates can normally be deduced by the compiler, whereas template arguments of class templates may have to be specified by the user. That's not always required, but since the template types of class templates are an inherent part of the class template's type it must be completely clear to the compiler what the class template's types are.

So, in case we have a

```
template <typename T>
void fun(T const &param);
```

we can do

```
vector<int> vi;
fun(vi)
```

and the compiler deduces `T == vector<int>`.

On the other hand, if we have

```
template <typename T>
struct Fun
{
    T d_data;
    Fun();
};
```

we can**not** do

```
Fun fun;
```

since `Fun` is not a type, and the compiler cannot deduce what the intended type is.

Sometimes the compiler *can* deduce the intended types. Consider this:

```
vector vi{ 1, 2, 3, 4 };
```

In this case the compiler deduces `int` from the provided values. The compiler is smart enought to select the most general type, as in this example, where `double` is deduced:

```
vector vi{ 1, 2.5 };
```

The compiler is doing its utmost to deduce types when they're not explicitly specified, and it will stay on the safe side. So the vector is a `vector<int>` in the first example and a `vector<double>` in the second.

Although it's nice that the compiler is willing and able to deduce types in many situations it's at the same time a potential source of confusion. In the first example only non-negative values are used, so why not define a `vector<unsigned>` or a `vector<size_t>`? In the second example the compiler deduces `vector<double>`, but `vector<float>` could very well also have been used.

To avoid confusion, as a rule of thumb, it might be a good idea to specify the types of class templates when defining class type objects. It requires hardly any effort and it completely clarifies what you want and mean. So prefer

```
    vector<int>     vi{ 1, 2, 3 };
    vector<double>  vd{ 1, 2.5 };
```

over the definitions implicitly using types.

22.0.1.1 Simple Definitions

Here are some examples of how simple definitions where the compiler deduces template arguments can (and cannot) be specified.

Starting point:

```
    template <class ...Types>           // any set of types
    class Deduce
    {
        public:
            Deduce(Types ...params);    // constructors
            void fun();                 // a member function
    };
```

Some definitions:

```
                                    // deduce:     full definition:
                                    // --------------------------------
    Deduce first{1};                // 1: int   -> Deduce<int> first{1}
    Deduce second;                  // no Types -> Deduce<> second;
    Deduce &&ref = Deduce<int>{ 1 };// int      -> Deduce<int> &&ref

    template <class Type>
    Deduce third{ static_cast<Type *>(0) };
```

The template `third` is a recipe for constructing `Deduce` objects from a type that's specified for `third`. The pointer's type simply is a pointer to the specified type (so, specifying `third<int>` implies an `int *`). Now that the type of `third`'s argument is available (i.e., an `int *`) the compiler deduces that `third{0}` is a `Deduce<int *>`.

This `Deduce<int *>` object could, e.g., be used to initialize a named `Deduce<int *>` object:

```
    auto x = third<int>;        // x's full definition: Deduce<int *> x{0}
```

`Deduce's` member functions can be used by anonymous and named objects:

```
    x.fun();                    // OK: fun called by named object
    third<int>.fun();           // OK: fun called by anonymous object
```

Here are some examples that won't compile:

```
extern Deduce object;       // not an object definition
Deduce *pointer = 0;        // any set of types could be intended
Deduce function();          // same.
```

When defining objects, either using function-type or curly-brace definitions template argument deduction is realized as follows:

- First, a list of available constructors is formed. The list contains all available ordinary constructors and constructor templates (i.e, constructors defined as member templates);
- For each element of that list a parallel imaginary function is formed by the compiler (forming function templates for constructor templates, and ordinary functions for ordinary constructors);
- The return types of these imaginary functions are the class types of the constructors, using the template parameters of the original class template. For example, for the `Deduce::Deduce` constructor the imaginary function

  ```
  template <class ...Types>
  Deduce<Types ...> imaginary(Types ...params);
  ```

  is formed.
- Next, ordinary argument deduction and overload resolution is applied to the set of imaginary functions. If this results in a best match for one of these imaginary functions then that function's class type (or specialization) will be used. Otherwise the program is ill-formed.

Let's apply this process to the class `Deduce`. The set of imaginary functions matching `Deduce` looks like this:

```
                                    // already encountered: matching
template <class ...Types>           // Deduce(Types ...params)
Deduce<Types ...> imaginary(Types ...params);

                                    // the copy constructor: matching
template <class ...Types>           // Deduce(Deduce<Types ...> const &)
Deduce<Types ...> imaginary(Deduce<Types ...> const &other);

                                    // the move constructor, matching
template <class ...Types>           // Deduce(Deduce<Types ...> &&)
Deduce<Types ...> imaginary(Deduce<Types ...> &&tmp);
```

For the construction `Deduce first{1}` the first imaginary function wins the overload contest, resulting in the template argument deduction `int` for `class ...Types`, and hence `Deduce<int> first{1}` is defined.

Note that when a class template is nested under a class template, the nested class template's name depends on the outer class type. The outer class then provides the name qualifier for the inner class template. In such cases template argument deduction is used for the nested class, but (as it is not used for name qualifiers) is not used for the outer class. Here is an example: adding a nested class template to `Deduce`:

```
template <class OuterType>
class Outer
```

```
{
    public:
        template <class InnerType>
        struct Inner
        {
            Inner(OuterType);
            Inner(OuterType, InnerType);
            template <typename ExtraType>
            Inner(ExtraType, InnerType);
        };
};
// defining:
Outer<int>::Inner inner{2.0, 1};
```

In this case, the compiler uses these imaginary functions:

```
template <typename InnerType>
Outer<int>::Inner<InnerType>            // copy constructor
    imaginary(Outer<int>::Inner<InnerType> const &);

template <typename InnerType>
Outer<int>::Inner<InnerType>            // move constructor
    imaginary(Outer<int>::Inner<InnerType> &&);

template <typename InnerType>           // first declared constructor
Outer<int>::Inner<InnerType> imaginary(int);

template <typename InnerType>           // second declared constructor
Outer<int>::Inner<InnerType> imaginary(int, InnerType);

template <typename InnerType>           // third declared constructor
template <typename ExtraType>
Outer<int>::Inner<InnerType> imaginary(ExtraType, InnerType);
```

Template argument deduction for calling `imaginary(2.0, 1)` results in `double` for its first argument and `int` for its second. Overload resolution then favors the last imaginary function, and so `ExtraType: double` and `InnerType: int`. Consequently,

```
Outer<int>::Inner inner{ 2.0, 1 };
```

is defined as:

```
Outer<int>::Inner<int> Inner{ 2.0, 1 };
```

22.0.1.2 Explicit Conversions

Have a look at the following class interface:

```
template <class T>
struct Class
{
    std::vector<T> d_data;
```

```
        struct Iterator
        {
            typedef T type;
            bool operator!=(Iterator const &rhs);
            Iterator operator++(int);
            type const &operator*() const;
            // ...
        };

        Class();

        Class(T t);

        Class(Iterator begin, Iterator end);

        template <class Tp>
        Class(Tp first, Tp second)
        {}

        Iterator begin();
        Iterator end();
    };
```

The implementation of the `Class` constructor expecting two `Class::Iterator` arguments would probably be somewhat similar to the following:

```
    template <class T>
    Class<T>::Class(Iterator begin, Iterator end)
    {
        while (begin != end)
            d_data.push_back(*begin++);
    }
```

where `d_data` is some container storing `T` values. A `Class` object can now constructed from a pair of `Class::Iterators`:

```
    Class<int> source;
    ...
    Class<int> dest{source.begin(), source.end()};
```

Here, the simple template argument deduction procedure fails to deduce the `int` template argument. This fails:

```
    Class dest{source.begin(), source.end()};
```

When attempting to instantiate a `Class` object by passing it `Class::Iterators` the compiler cannot directly deduce from the provided arguments that a `Class<Class::Iterator::type>` is to be used: `type` isn't directly available. Compare this to `Class's` third constructor, where

```
    Class intObject{12};
```

allows the compiler to create an imaginary function

```
template <class Type>
Class <Type> imaginary(Type param)
```

in which case `Type` clearly is an `int`, and so a `Class<int>` object is constructed.

When we try to do this for `Class(Iterator, Iterator)` we get

```
template <class Iterator>
Class<???> imaginary(Iterator, Iterator);
```

and here `Class's` template argument isn't directly related to `Iterator`: the compiler cannot deduce its type and consequently compilation fails.

A similar argument applies to the fourth constructor, which receives two `Tp` arguments, which are both independent from `Class's` template type.

In cases like these simple type template argument deduction procedure fails. Still, not everything is lost: *explicit conversions*, defined as *explicitly specified deduction rules* which are added (below) to the class's interface can be used.

An explicitly specified deduction rule connects a class template constructor signature to a class template type. It specifies the template arguments for the class template object that is constructed using the constructor whose signature is specified. The generic syntactical form of an explicitly specified deduction rule looks like this:

```
class template constructor signature -> resulting class type ;
```

Let's apply this to `Class(Iterator begin, Iterator end)`. Its signature is

```
template <class Iterator>
Class(Iterator begin, Iterator end)
```

Requiring that `Iterator` defines a typename `type`, we can now formulate a resulting class type:

```
Class<typename Iterator::type>
```

Now we can combine both in an explicitly specified deduction rule (which is added as a separate line below `Class's` interface):

```
template <class Iterator>
Class(Iterator begin, Iterator end) -> Class<typename Iterator::type>;
```

After adding this deduction rule to `Class's` interface the following constructor calls successfully compile:

```
Class src{12};      // already OK

Class dest1{src.begin(), src.end()};
                    // begin() and end() return Class<int>::Iterator
                    // objects. Typename Class<int>::Iterator::type
                    // is defined as int, so Class<int> dest1 is
                    // defined.
```

```
struct Double       // used at the next construction
{
    typedef double type;
    // ... members ...
};

Class dest2{Double{}, Double{}};
                    // Here the struct Double defines
                    // typename double type, so
                    // Class<double> dest2 is defined.
```

Within classes the compiler uses (as before) the class itself when merely referring to the class name: when referring to `Class` in the class `Class`, the compiler considers `Class` to be `Class<T>`. So the headers of the declaration and definition of `Class's` copy constructor look like this:

```
Class(Class const &other);      // declaration

template <class T>              // definition
Class<T>::Class(Class const &other)
{
    // ...
}
```

Sometimes the default type is not what you want, in which case the required type must explicitly be specified. Consider what happens if add a member `dup` to `Class`:

```
template <typename T>
template <typename Tp>
auto Class<T>::dup(Tp first, Tp second)
{
    return Class{ first, second };  // probably not what you want
}                                   // (see the following text)
```

Here, because we're inside `Class` the compiler deduces that `Class<T>` must be returned. But in the previous section we decided that, when initializing `Class` from iterators, `Class<typename Tp::type>` should be constructed and returned. To accomplish that, the required type is explicitly specified:

```
template <typename T>
template <typename Tp>
auto Class<T>::dup(Tp first, Tp second)
{                               // OK: explicitly specified Class tyoe.
    return Class<typename Tp::type>{ first, second };
}
```

As shown in this example, simple (implicit) or explicit deduction rules do not *have* to be used: they *can* be used in many standard situations where explicitly specifying the class's template arguments appears to be superfluous. Template argument deduction was added to the language to simplify object construction when using class templates. But in the end you don't *have* to use these deduction rules: it's always still possible to explicitly specify template arguments.

22.1 Defining class templates

Having covered the construction of function templates, we're now ready for the next step: constructing class templates. Many useful class templates already exist. Rather than illustrating the construction of a class template by looking at an already existing class template the construction of another potentially useful new class template will be undertaken.

The new class implements a *circular queue*. A circular queue has a fixed number of `max_size` elements. New elements are inserted at its back and only its head and tail elements can be accessed. Only the head element can be removed from a circular queue. Once `n` elements have been appended the next element is inserted again at the queue's (physical) first position. The circular queue allows insertions until it holds `max_size` elements. As long as a circular queue contains at least one element elements may be removed from it. Trying to remove an element from an empty circular queue or to add another element to a full circular queue results in exceptions being thrown. In addition to other constructors a circular queue must offer a constructor initializing its objects for `max_size` elements. This constructor must make available the memory for the `max_size` elements but must not call those elements default constructors (hinting at the use of the placement `new` operator). A circular queue should offer value semantics as well as a move constructor.

Please note that in the above description the actual data type that is used for the circular queue is nowhere mentioned. This is a clear indication that our class could very well be defined as a *class template*. Alternatively, the class could be defined for some concrete data type which is then abstracted when converting the class to a class template.

The actual construction of a class template is provided in the next section, where the class template `CirQue` (circular queue) is developed.

22.1.1 Constructing the circular queue: CirQue

The construction of a class template is illustrated in this section. Here, we'll develop the class template `CirQue` (circular queue). This class template has one template type parameter, `Data`, representing the data type that is stored in the circular queue. The outline of the interface of this class template looks like this:

```
template<typename Data>
class CirQue
{
    // member declarations
};
```

A class template's definition starts like a function template's definition:

- The keyword `template`, starting a template definition or declaration.
- The angle bracket enclosed list following `template`: a list containing one or more comma-separated elements is called the *template parameter list*. Template parameter lists may have multiple elements, like this:

  ```
  typename Type1, typename Type2, typename Type3
  ```

  When a class template defines multiple template type parameters they are matched in sequence with the list of template type arguments provided when defining objects of such a class template. Example:

  ```
  template <typename Type1, typename Type2, typename Type3>
  ```

```
class MultiTypes
{
    ...
};

MultiTypes<int, double, std::string> multiType;
    // Type1 is int, Type2 is double, Type3 is std::string
```

- Inside the template parameter list we find the *formal type* name (`Data` for `CirQue`). It is a formal (type) name, like the formal types used in function template parameter lists.

- Following the template header the class interface is defined. It may use the formal type names defined in the template header as type names.

Once the `CirQue` class template has been defined it can be used to create all kinds of circular queues. As one of its constructors expects a `size_t` argument defining the maximum number of elements that can be stored in the circular queue, circular queues could be defined like this:

```
CirQue<int> cqi(10);            // max 10 ints
CirQue<std::string> cqstr(30);  // max 30 strings
```

As noted in the introductory section of this chapter the combination of name of the class template and the data type for which it is instantiated defines a data type. Also note the similarity between defining a `std::vector` (of some data type) and a `CirQue` (of some data type).

Like `std::map` containers class templates may be defined with multiple template type parameters.

Back to `CirQue`. A `CirQue` must be capable of storing `max_size` `Data` elements. These elements are eventually stored in memory pointed at by a pointer `Data *d_data`, initially pointing to raw memory. New elements are added at the backside of the `CirQue`. A pointer `Data *d_back` is used to point to the location where the next element is going to be stored. Likewise, `Data *d_front` points to the location of the `CirQue`'s first element. Two `size_t` data members are used to monitor the filling state of the `CirQue`: `d_size` represents the number of elements currently stored in the `CirQue`, `d_maxSize` represents the maximum number of elements that the `CirQue` can contain. Thus, the `CirQue`'s data members are:

```
size_t d_size;
size_t d_maxSize;
Data *d_data;
Data *d_front;
Data *d_back;
```

22.1.2 Non-type parameters

Function template parameters are either template type parameters or template non-type parameters (actually, a third type of template parameter exists, the *template template parameter*, which is discussed in chapter 23 (section 23.4)).

Class templates may also define non-type parameters. Like the function template non-type parameters they must be (integral) constants whose values must be known at object instantiation time.

Different from function template non-type parameters the values of class template non-type parameters are *not* deduced by the compiler using arguments passed to class template members.

Assume we extend our design of the class template `CirQue` so that it defines a second (non-type) parameter `size_t Size`. Our intent is to use this `Size` parameter in the constructor defining an array parameter of `Size` elements of type `Data`.

The `CirQue` class template now becomes (only showing the relevant constructor):

```
template <typename Data, size_t Size>
class CirQue
{
    // ... data members
    public:
        CirQue(Data const (&arr)[Size]);
        ...
};

template <typename Data, size_t Size>
CirQue<Data, Size>::CirQue(Data const (&arr)[Size])
:
    d_maxSize(Size),
    d_size(0),
    d_data(operator new(Size * sizeof(Data))),
    d_front(d_data),
    d_back(d_data),
{
    std::copy(arr, arr + Size, back_inserter(*this));
}
```

Unfortunately, this setup doesn't satisfy our needs as the values of template non-type parameters are not deduced by the compiler. When the compiler is asked to compile the following `main` function it reports a mismatch between the required and actual number of template parameters:

```
int main()
{
    int arr[30];

    CirQue<int> ap{ arr };
}
/*
    Error reported by the compiler:

    In function `int main()':
        error: wrong number of template arguments (1, should be 2)
        error: provided for `template<class Data, size_t Size>
               class CirQue'
*/
```

Defining `Size` as a non-type parameter having a default value doesn't work either. The compiler always uses the default unless its value is explicitly specified. Reasoning that `Size` can be 0 unless we need another value, we might be tempted to specify `size_t Size = 0` in the template's parameter type list. Doing so we create a mismatch between the default value 0 and the actual size of the array `arr` as defined in the above `main` function. The compiler, using the default value, reports:

```
In instantiation of `CirQue<int, 0>':
...
error: creating array with size zero (`0')
```

So, although class templates may use non-type parameters they must always be specified like type parameters when an object of that class is defined. Default values can be specified for those non-type parameters causing the compiler to use the default when the non-type parameter is left unspecified.

Default template parameter values (either type or non-type template parameters) may *not* be specified when defining template member functions. In general: function template definitions (and thus: class template member functions) may not be given default template (non) type arguments. If default template arguments are to be used for class template members, they *have* to be specified by the class interface.

Similar to non-type parameters of function templates default argument values for non-type class template parameters may only be specified as constants:

- Global variables have constant addresses, which can be used as arguments for non-type parameters.
- Local and dynamically allocated variables have addresses that are *not* known by the compiler when the source file is compiled. These addresses can therefore *not* be used as arguments for non-type parameters.
- Lvalue transformations are allowed: if a pointer is defined as a non-type parameter, an array name may be specified.
- Qualification conversions are allowed: a pointer to a non-const object may be used with a non-type parameter defined as a `const` pointer.
- Promotions are allowed: a constant of a 'narrower' data type may be used when specifying a default argument for a non-type parameter of a 'wider' type (e.g., a `short` can be used when an `int` is called for, a `long` when a `double` is called for).
- Integral conversions are allowed: if a `size_t` parameter is specified, an `int` may be used as well.
- Variables cannot be used to specify template non-type parameters as their values are not constant expressions. Variables defined using the `const` modifier, however, may be used as their values never change.

Although our attempts to define a constructor of the class `CirQue` accepting an array as its argument has failed so far, we're not yet out of options. In the next section a method is described that *does* allow us to reach our goal.

22.1.3 Member templates

Our previous attempt to define a template non-type parameter that is initialized by the compiler to the number of elements of an array failed because the template's parameters are not implicitly deduced when a constructor is called. Instead, they must explicitly be specified when an object of the class template is defined. As the template arguments are specified just before the template's constructor is called the compiler doesn't have to deduce anything and it can simply use the explicitly specified template arguments.

In contrast, when *function* templates are used, the actual template parameters are deduced from the arguments used when calling the function. This opens up an alley leading to the solution of our problem. If the constructor itself is turned into a function template (having its own template header), then the compiler *will* be able to deduce the non-type parameter's value and there is no need anymore to specify it explicitly using a class template non-type parameter.

Members (functions or nested classes) of class templates that are themselves templates are called *member templates*.

Member templates are defined as any other template, including its own template header.

When converting our earlier `CirQue(Data const (&array)[Size])` constructor into a member template the class template's `Data` type parameter can still be used, but we must provide the member template with a non-type parameter of its own. Its declaration in the (partially shown) class interface looks like this:

```
template <typename Data>
class CirQue
{
    public:
        template <size_t Size>
        explicit CirQue(Data const (&arr)[Size]);
};
```

Its implementation becomes:

```
template <typename Data>
template <size_t Size>
CirQue<Data>::CirQue(Data const (&arr)[Size])
:
    d_size(0),
    d_maxSize(Size),
    d_data(static_cast<Data *>(operator new(sizeof(arr)))),
    d_front(d_data),
    d_back(d_data)
{
    std::copy(arr, arr + Size, std::back_inserter(*this));
}
```

The implementation uses the STL's `copy` algorithm and a `back_inserter` adapter to insert the array's elements into the `CirQue`. To use the `back_inserter` `CirQue` must define two (public) `typedef`s (cf. section 18.2.2):

```
typedef Data value_type;
typedef value_type const &const_reference;
```

Member templates have the following characteristics:

- Two `template` headers must be used: the class template's `template` header is specified first followed by the member template's template header;
- Normal access rules apply: the member template can be used by programs to construct an `CirQue` object of a given data type. As usual for class templates, the data type must be specified when the object is constructed. To construct a `CirQue` object from the array `int array[30]` we define:

  ```
  CirQue<int> object(array);
  ```
- Any member can be defined as a member template, not just a constructor;
- When a template member is implemented below its class interface, the template class header must precede the function template header of the member template;

- The implementation of the member template must specify its proper scope. The member template is defined as a member of the class `CirQue`, instantiated for the formal template parameter type `Data`;
- The template parameter names in the declaration and implementation must be identical;
- The member template should be defined inside its proper namespace environment. The organization of files defining class templates within a namespace should therefore be:

```
namespace SomeName
{
    template <typename Type, ...>   // class template definition
    class ClassName
    {
        ...
    };

    template <typename Type, ...>   // non-inline member definition(s)
    ClassName<Type, ...>::member(...)
    {
        ...
    }
}                                   // namespace closes
```

A potentially occurring problem remains. Assume that in addition to the above member template a `CirQue<Data>::CirQue(Data const *data)` has been defined. Some (here not further elaborated) protocol could be defined allowing the constructor to determine the number of elements that should be stored in the `CirQue` object. When we now define

```
CirQue<int> object{ array };
```

it is this latter constructor, rather than the member template, that the compiler will use.

The compiler selects this latter constructor as it is a more specialized version of a constructor of the class `CirQue` than the member template (cf. section 21.14). Problems like these can be solved by defining the constructor `CirQue(Data const *data)` into a member template as well or by defining a constructor using two parameters, the second parameter defining the number of elements to copy.

When using the former constructor (i.e., the member template) it must define a template type parameter `Data2`. Here '`Data`' cannot be used as template parameters of a member template may not shadow template parameters of its class. Using `Data2` instead of `Data` takes care of this subtlety. The following declaration of the constructor `CirQue(Data2 const *)` could appear in `CirQue`'s header file:

```
template <typename Data>
class CirQue
{
    template <typename Data2>
    explicit CirQue(Data2 const *data);
}
```

Here is how the two constructors are selected in code defining two `CirQue` objects:

```
int main()
```

```
{
    int array[30];
    int *iPtr = array;

    CirQue<int> ac{ array };     // calls CirQue(Data const (&arr)[Size])
    CirQue<int> acPtr{ iPtr };  // calls CirQue(Data2 const *)
}
```

22.1.4 CirQue's constructors and member functions

It's time to return to `Cirque`'s design and construction again.

The class `CirQue` offers various member functions. Normal design principles should be adhered to when constructing class template members. Class template type parameters should preferably be defined as `Type const &`, rather than `Type`, to prevent unnecessary copying of large data structures. Template class constructors should use member initializers rather than member assignment within the body of the constructors. Member function definitions should preferably not be provided in-class but below the class interface. Since class template member functions are function templates their definitions should be provided in the header file offering the class interface. They *may* be given the `inline` attribute.

`CirQue` declares several constructors and (public) members (their definitions are provided as well; all definitions are provided below the class interface).

Here are the constructors and the destructor:

- `explicit CirQue(size_t maxSize = 0)`:
  Constructor initializing a `CirQue` capable of storing `max_size Data` elements. As the constructor's parameter is given a default argument value this constructor can also be used as a default constructor, allowing us to define, e.g., vectors of `CirQue`s. The constructor initializes the `Cirque` object's `d_data` member to a block of raw memory and `d_front` and `d_back` are initialized to `d_data`. As class template member functions are themselves function templates their implementations outside of the class template's interface must start with the class template's template header. Here is the implementation of the `CirQue(size_t)` constructor:

```
template<typename Data>
CirQue<Data>::CirQue(size_t maxSize)
:
    d_size(0),
    d_maxSize(maxSize),
    d_data(
        maxSize == 0 ?
            0
        :
            static_cast<Data *>(
                        operator new(maxSize * sizeof(Data)))
    ),
    d_front(d_data),
    d_back(d_data)
{}
```

- `CirQue(CirQue<Data> const &other)`:
  The copy constructor has no special features. It uses a private support member `inc` to increment `d_back` (see below) and placement new to copy the other's `Data` elements to the current object. The implementation of the copy constructor is straightforward:

```
template<typename Data>
CirQue<Data>::CirQue(CirQue<Data> const &other)
:
    d_size(other.d_size),
    d_maxSize(other.d_maxSize),
    d_data(
        d_maxSize == 0 ?
            0
        :
            static_cast<Data *>(
                operator new(d_maxSize * sizeof(Data)))
    ),
    d_front(d_data + (other.d_front - other.d_data))
{
    Data const *src = other.d_front;
    d_back = d_front;
    for (size_t count = 0; count != d_size; ++count)
    {
        new(d_back) Data(*src);
        d_back = inc(d_back);
        if (++src == other.d_data + d_maxSize)
            src = other.d_data;
    }
}
```

- `CirQue(CirQue<Data> &&tmp)`:
  The move constructor merely initializes the current object's `d_data` pointer to 0 and swaps (see the member `swap`, below) the temporary object with the current object. `CirQue`'s destructor inspects `d_data` and immediately returns when it's zero. Implementation:

```
template<typename Data>
CirQue<Data>::CirQue(CirQue<Data> &&tmp)
:
    d_data(0)
{
    swap(tmp);
}
```

- `CirQue(Data const (&arr)[Size])`:
  This constructor is declared as a member template, providing the `Size` non-type parameter. It allocates room for `Size` data elements and copies `arr`'s content to the newly allocated memory.Implementation:

```
template <typename Data>
template <size_t Size>
CirQue<Data>::CirQue(Data const (&arr)[Size])
:
    d_size(0),
    d_maxSize(Size),
    d_data(static_cast<Data *>(operator new(sizeof(arr)))),
    d_front(d_data),
    d_back(d_data)
{
    std::copy(arr, arr + Size, std::back_inserter(*this));
}
```

- `CirQue(Data const *data, size_t size)`:
  This constructor acts very much like the previous one, but is provided with a pointer to the first `Data` element and with a `size_t` providing the number of elements to copy. In our current design the member template variant of this constructor is left out of the design. As the implementation of this constructor is very similar to that of the previous constructor, it is left as an exercise to the reader.

- `~CirQue()`:
  The destructor inspects the `d_data` member. If it is zero then nothing has been allocated and the destructor immediately returns. This may occur in two situations: the circular queue contains no elements or the information was grabbed from a temporary object by some move operation, setting the temporary's `d_data` member to zero. Otherwise `d_size` elements are destroyed by explicitly calling their destructors followed by returning the element's raw memory to the common pool. Implementation:

  ```
  template<typename Data>
  CirQue<Data>::~CirQue()
  {
      if (d_data == 0)
          return;
      for (; d_size--; )
      {
          d_front->~Data();
          d_front = inc(d_front);
      }
      operator delete(d_data);
  }
  ```

Here are `Cirque`'s members:

- `CirQue &operator=(CirQue<Data> const &other)`:
  The copy assignment operator has a standard implementation:

  ```
  template<typename Data>
  CirQue<Data> &CirQue<Data>::operator=(CirQue<Data> const &rhs)
  {
      CirQue<Data> tmp(rhs);
      swap(tmp);
      return *this;
  }
  ```

- `CirQue &operator=(CirQue<Data> &&tmp)`:
  The move assignment operator also has a standard implementation. As its implementation merely calls `swap` it is defined as an inline function template:

  ```
  template<typename Data>
  inline CirQue<Data> &CirQue<Data>::operator=(CirQue<Data> &&tmp)
  {
      swap(tmp);
      return *this;
  }
  ```

- `void pop_front()`:
  removes the element pointed at by `d_front` from the `CirQue`. Throws an exception if the `CirQue` is empty. The exception is thrown as a `CirQue<Data>::EMPTY` value, defined by

the `enum CirQue<Data>::Exception` (see `push_back`). The implementation is straightforward (explicitly calling the destructor of the element that is removed):

```
template<typename Data>
void CirQue<Data>::pop_front()
{
    if (d_size == 0)
        throw EMPTY;

    d_front->~Data();
    d_front = inc(d_front);
    --d_size;
}
```

- `void push_back(Data const &object)`:
  adds another element to the `CirQue`. Throws a `CirQue<Data>::FULL` exception if the `CirQue` is full. The exceptions that can be thrown by a `CirQue` are defined in its `Exception` enum:

  ```
  enum Exception
  {
      EMPTY,
      FULL
  };
  ```

  A copy of `object` is installed in the `CirQue`'s raw memory using placement `new` and its `d_size` is incremented.

  ```
  template<typename Data>
  void CirQue<Data>::push_back(Data const &object)
  {
      if (d_size == d_maxSize)
          throw FULL;

      new (d_back) Data(object);
      d_back = inc(d_back);
      ++d_size;
  }
  ```

- `void swap(CirQue<Data> &other)`:
  swaps the current `CirQue` object with another `CirQue<Data>` object;

  ```
  template<typename Data>
  void CirQue<Data>::swap(CirQue<Data> &other)
  {
      static size_t const size = sizeof(CirQue<Data>);

      char tmp[size];
      memcpy(tmp, &other, size);
      memcpy(reinterpret_cast<char *>(&other), this, size);
      memcpy(reinterpret_cast<char *>(this), tmp, size);
  }
  ```

The remaining public members all consist of one-liners and were implemented as inline function templates:

- `Data &back()`:
  returns a reference to the element pointed at by `d_back` (undefined result if the `CirQue` is empty):

  ```
  template<typename Data>
  inline Data &CirQue<Data>::back()
  {
      return d_back == d_data ? d_data[d_maxSize - 1] : d_back[-1];
  }
  ```

- `Data &front()`:
  returns reference to the element pointed at by `d_front` (undefined result if the `CirQue` is empty);

  ```
  template<typename Data>
  inline Data &CirQue<Data>::front()
  {
      return *d_front;
  }
  ```

- `bool empty() const`:
  returns `true` if the `CirQue` is empty;

  ```
  template<typename Data>
  inline bool CirQue<Data>::empty() const
  {
      return d_size == 0;
  }
  ```

- `bool full() const`:
  returns `true` if the `CirQue` is full;

  ```
  template<typename Data>
  inline bool CirQue<Data>::full() const
  {
      return d_size == d_maxSize;
  }
  ```

- `size_t size() const`:
  returns the number of elements currently stored in the `CirQue`;

  ```
  template<typename Data>
  inline size_t CirQue<Data>::size() const
  {
      return d_size;
  }
  ```

- `size_t maxSize() const`:
  returns the maximum number of elements that can be stored in the `CirQue`;

  ```
  template<typename Data>
  inline size_t CirQue<Data>::maxSize() const
  {
      return d_maxSize;
  }
  ```

Finally, the class has one private member, `inc`, returning a cyclically incremented pointer into `CirQue`'s raw memory:

```
    template<typename Data>
    Data *CirQue<Data>::inc(Data *ptr)
    {
        ++ptr;
        return ptr == d_data + d_maxSize ? d_data : ptr;
    }
```

22.1.5 Using CirQue objects

When objects of a class template are instantiated, *only* the definitions of all the template's member functions that are actually used must have been seen by the compiler.

That characteristic of templates could be refined to the point where each definition is stored in a separate function template definition file. In that case only the definitions of the function templates that are actually needed would have to be included. However, it is hardly ever done that way. Instead, the usual way to define class templates is to define the interface and to define the remaining function templates immediately below the class template's interface (defining some functions inline).

Now that the class `CirQue` has been defined, it can be used. To use the class its object must be instantiated for a particular data type. In the following example it is initialized for data type `std::string`:

```
#include "cirque.h"
#include <iostream>
#include <string>
using namespace std;

int main()
{
    CirQue<string> ci(4);
    ci.push_back("1");
    ci.push_back("2");
    cout << ci.size() << ' ' << ci.front() << ' ' << ci.back() << '\n';

    ci.push_back("3");
    ci.pop_front();
    ci.push_back("4");
    ci.pop_front();
    ci.push_back("5");
    cout << ci.size() << ' ' << ci.front() << ' ' << ci.back() << '\n';

    CirQue<string> copy(ci);
    copy.pop_front();
    cout << copy.size() << ' ' << copy.front() << ' ' << copy.back() << '\n';

    int arr[] = {1, 3, 5, 7, 9};
    CirQue<int> ca(arr);
    cout << ca.size() << ' ' << ca.front() << ' ' << ca.back() << '\n';

//    int *ap = arr;
//    CirQue<int> cap(ap);
}
```

This program produces the following output:

```
2 1 2
3 3 5
2 4 5
5 1 9
```

22.1.6 Default class template parameters

Different from function templates, template parameters of template classes may be given default argument values. This holds true for both template type- and template non-type parameters. If default template arguments were defined and if a class template object is instantiated without specifying arguments for its template parameters then the template parameter's defaults are used.

When defining defaults keep in mind that they should be suitable for the majority of instantiations of the class. E.g., for the class template `CirQue` the template's type parameter list could have been altered by specifying `int` as its default type:

```
template <typename Data = int>
```

Even though default arguments can be specified, the compiler must still be informed that object definitions refer to templates. When instantiating class template objects using default template arguments the type specifications may be omitted but the angle brackets must be retained. Assuming a default type for the `CirQue` class, an object of that class may be defined as:

```
CirQue<> intCirQue(10);
```

Default template arguments cannot be specified when defining template members. So, the definition of, e.g., the `push_back` member must always begin with the same `template` specification:

```
template <typename Data>
```

When a class template uses multiple template parameters, all may be given default values. Like default function arguments, once a default value is used all remaining template parameters must also use their default values. A template type specification list may not start with a comma, nor may it contain multiple consecutive commas.

22.1.7 Declaring class templates

Class templates may also be *declared*. This may be useful in situations where forward class declarations are required. To declare a class template, simply remove its interface (the part between the curly braces):

```
template <typename Data>
class CirQue;
```

Default template arguments may also be specified when declaring class templates. However, default template arguments cannot be specified for both the declaration and the definition of a class template. As a rule of thumb default template arguments should be omitted from *declarations*, as class template declarations are never used when instantiating objects but are only occasionally used as forward references. Note that this differs from default parameter value specifications for member functions in ordinary classes. Such defaults are always specified when declaring the member functions in the class interface.

22.1.8 Preventing template instantiations

In **C++** templates are instantiated when the address of a function template or class template object is taken or when a function template or class template is used. As described in section 22.1.7 it is possible to (forward) declare a class template to allow the definition of a pointer or reference to that template class or to allow it being used as a return type.

In other situations templates are instantiated when they are being used. If this happens many times (i.e., in many different source files) then this may slow down the compilation process considerably. Fortunately, **C++** allows programmers to *prevent* templates from being instantiated, using the `extern template` syntax. Example:

```
    extern template class std::vector<int>;
```

Having declared the class template it can be used in its translation unit. E.g., the following function properly compiles:

```
#include <vector>
#include <iostream>
using namespace std;

extern template class vector<int>;

void vectorUser()
{
    vector<int> vi;
    cout << vi.size() << '\n';
}
```

But be careful:

- The declaration by itself does *not* make the class definition available. The `vector` header file *still* needs to be included to make the features of the class vector known to the compiler. But due to the `extern template` declaration none of the used members will be instantiated for the current compilation unit;
- The compiler *assumes* (as it always does) that what is declared has been implemented elsewhere. In this case the compiler encounters an *implicit declaration*: the features of the vector class that are actually used by the above program are not individually declared but they are declared as a group, using the `extern template` declaration. This not only holds true for explicitly used members but hidden members (copy constructors, move constructors, conversion operators, constructors called during promotions, to name a few): all are assumed by the compiler to have been instantiated elsewhere;
- Although the above source file *compiles*, the *instantiations* of the templates must be available before the linker can build the final program. To accomplish this one or more source files may be constructed in which all required instantiations are made available.

  In a stand-alone program one might postpone defining the required members and wait for the linker to complain about unresolved external references. These may then be used to create a series of instantiation declarations which are then linked to the program to satisfy the linker. Not a very simple task, though, as the declarations must strictly match the way the members are declared in the class interface. An easier approach is to define an *instantiation source file* in which all facilities that are used by the program are actually instantiated in a function that is never called by the program. By adding this instantiation function to the source file containing `main` we can be sure that all required members are instantiated as well. Here is an example of how this can be done:

```
#include <vector>
#include <iostream>

extern void vectorUser();

int main()
{
    vectorUser();
}

// this part is never called. It is added to make sure all required
// features of declared templates will also be instantiated.

namespace
{
    void instantiator()
    {
        std::vector<int> vi;
        vi.size();
    }
}
```

- Last, but certainly not least: a fully matching instantiation declaration of a class template (e.g., for `std::vector<int>`) looks like this:

  ```
  template class std::vector<int>;
  ```

  Adding this to a source file, however, will instantiate the *full class*, i.e., all its members are now instantiated. This may not what you want, as it might needlessly inflate your final executable.

- On the other hand, if it is known that the required template members have already been instantiated elsewhere, then an *extern template* declaration can be used to prevent member instantiations in the current compilation unit, which may speed up compilation. E.g.,

  ```
          // the compiler assumes that required members of
          // vector<int> have already been instantiated elsewhere
  extern template class std::vector<int>;

  int main()
  {
      std::vector<int> vi(5);      // constructor and operator[]
      ++vi[0];                     // are NOT instantiated
  }
  ```

22.1.9 Generic lambda expressions

Generic lambda expressions may use `auto` to define their parameters. When used, a lambda expression is instantiated by looking at the actual types of arguments. Since `auto` is generic, different parameters defined using `auto` can be instantiated to different types. Here is an example (assuming all required headers and namespace declaration were specified):

```
int main()
```

```
 2: {
 3:     auto lambda = [](auto lhs, auto rhs)
 4:                 {
 5:                     return lhs + rhs;
 6:                 };
 7:
 8:     vector<int> values {1, 2, 3, 4, 5};
 9:     vector<string> text {"a", "b", "c", "d", "e"};
10:
11:     cout <<
12:         accumulate(values.begin(), values.end(), 0, lambda) << '\n' <<
13:         accumulate(text.begin(), text.end(), string{}, lambda) << '\n';
14: }
```

The generic lambda function is defined in lines 3 through 6, and is assigned to the `lambda` identifier. Then, `lambda` is passed to `accumulate` in lines 12 and 13. In line 12 it is instantiated to add `int` values, in line 13 to add `std::string` values: the same `lambda` is instantiated to two completely different functors, which are only locally available in `main`.

Generic lambda expressions are in fact class templates. To illustrate: the above example of a generic lambda expression could also have been implemented using the following class template:

```
struct Lambda
{
    template <typename LHS, typename RHS>
    auto operator()(LHS const &lhs, RHS const &rhs) const
    {
        return lhs + rhs;
    }
};
auto lambda = Lambda{};
```

This identity implies that using `auto` in the lambda expression's parameter list obeys the rules of template argument deduction (cf. section 21.4), which are somewhat different from the way `auto` normally operates.

Another extension is the way generic lambda expressions capture outer scope variables. Previously variables could only be captured by value or by reference. As a consequence an outer scope variable of a type that only supports move construction could not be passed by value to a lambda function. This restriction was dropped, allowing variables to be initialized from arbitrary expressions. This not only allows move-initialization of variables in the lambda introducer, but with generic lambdas variables may also be initialized if they do not have a correspondingly named variable in the lambda expression's outer scope. In this case initializer expressions can be used as follows:

```
auto fun = [value = 1]
           {
               return value;
           };
```

This lambda function (of course) returns 1: the declared capture deduces the type from the initializer expression as if `auto` had been used.

To use move-initialization `std::move` should be used. E.g., a *unique_ptr* only supports move-assignment. Here it is used to return one of its values via a lambda function:

```
std::unique_ptr<int> ptr(new int(10));
```

```
auto fun = [value = std::move(ptr)]
           {
               return *value;
           };
```

In generic lambda expressions the keyword `auto` indicates that the compiler determines which types to use when the lambda function is instantiated. A generic lambda expression therefore *is* a class template, even though it doesn't look like one. As an example, the following lambda expression defines a generic class template, which can be used as shown:

```
char const *target = "hello";

 auto lambda =
    [target](auto const &str)
    {
        return str == target;
    };

    vector<string> vs{stringVectorFactory()};

    find_if(vs.begin(), vs.end(), lambda);
```

This works fine, but if you define `lambda` this way then you should be prepared for complex error messages if the types of the derefenced iterators and lambda's (silently assumed) `str` type don't match.

Here is a little program illustrating how generic lambda expressions can be used in other generic lambda expressions: class templates could also have been used. In lines 1 through 9 a generic lambda expression `accumulate` is defined, defining a second paramater which is used as a function: its argument therefore should be usable as a function. A functor definitely is, an the second generic lambda expression `lambda`, defined in lines 11 through 14 provides it. In line 21 `accumulate` and `lambda` are instantiated so that they operate on (a vector of) `int`s, in line 22 they are instantiated for processing (a vector of) `string`s:

```
 1: auto accumulate(auto const &container, auto function)
 2: {
 3:     auto accu = decltype(container[0]){};
 4:
 5:     for (auto &value: container)
 6:         accu = function(accu, value);
 7:
 8:     return accu;
 9: }
10:
11: auto lambda = [](auto lhs, auto rhs)
12:             {
13:                 return lhs + rhs;
14:             };
15:
16: int main()
17: {
18:     vector<int> values  = {1, 2, 3, 4, 5};
19:     vector<string> text = {"a", "b", "c", "d", "e"};
20:
21:     cout << accumulate(values,  lambda) << '\n' <<
```

```
                accumulate(text,    lambda) << '\n';
}
```

In some situations generic lambdas are a bit too generic, resulting in verbose implementations which are not required by templates in general. Consider a generic lambda that specifies an `auto &it` parameter, but in addition it should specify a parameter `value` of type `ValueType` that should be defined by `it's` class. Such a parameter requires the use of a `decltype` (and maybe also the use of `std::decay_t`) to retrieve `it's` actual type. Inside the lambda's body a `using` declaration can be specified to make the type available, but that again requires a verbose specification using `std::decay_t` and `decltype`. Here is an example:

```
auto generic =
    [](auto &it,
       typename std::decay_t<decltype(it)>::ValueType value)
    {
        using Type = std::decay_t<decltype(it)>;
        typename Type::ValueType val2{ value };
        Type::staticMember();
    };
```

To avoid this kind of verbosity generic lambda functions can also be defined like ordinary tempates, in which case the template header immediately follows the lambda-introducer. Using this alternative form the definition of the `generic` generic lambda simply and straightforwardly becomes:

```
auto generic =
    []<typename Type>(Type &it, typename Type::ValueType value)
    {
        typename Type::ValueType val2{ value };
        Type::staticMember();
    };
```

22.2 Static data members

When static members are defined in class templates, they are defined for every new type for which the class template is instantiated. As they are static members, there will only be one member per type for which the class template is instantiated. For example, in a class like:

```
template <typename Type>
class TheClass
{
    static int s_objectCounter;
};
```

There will be *one* `TheClass<Type>::objectCounter` for each different `Type` specification. The following object definitions result in the instantiation of just one single static variable, shared among the two objects:

```
TheClass<int> theClassOne;
TheClass<int> theClassTwo;
```

Mentioning static members in interfaces does not mean these members are actually defined. They are only *declared* and must be *defined* separately. With static members of class templates this is no different. The definitions of static members are usually provided immediately following (i.e., below) the template class interface. For example, the static member `s_objectCounter`'s definition, positioned just below its class interface, looks like this:

```
template <typename Type>                    // definition, following
int TheClass<Type>::s_objectCounter = 0;    // the interface
```

Here `s_objectCounter` is an `int` and is thus independent of the template type parameter `Type`. Multiple instantiations of `s_objectCounter` for identical `Type`s cause no problem, as the linker will remove all but one instantiation from the final executable (cf. section 21.5).

In list-like constructions, where a pointer to objects of the class itself is required, the template type parameter `Type` must be used when defining the static variable. Example:

```
template <typename Type>
class TheClass
{
    static TheClass *s_objectPtr;
};

template <typename Type>
TheClass<Type> *TheClass<Type>::s_objectPtr = 0;
```

As usual, the definition can be read from the variable name back to the beginning of the definition: `s_objectPtr` of the class `TheClass<Type>` is a pointer to an object of `TheClass<Type>`.

When a static variable of a template's type parameter's type is defined, it should of course not be given the initial value 0. The default constructor (e.g., `Type()`) is usually more appropriate. Example:

```
template <typename Type>                    // s_type's definition
Type TheClass<Type>::s_type = Type();
```

22.2.1 Extended use of the keyword 'typename'

Until now the keyword `typename` has been used to indicate a template type parameter. However, it is also used to disambiguate code inside templates. Consider the following function template:

```
template <typename Type>
Type function(Type t)
{
    Type::Ambiguous *ptr;

    return t + *ptr;
}
```

When this code is processed by the compiler, it complains with an -at first sight puzzling- error message like:

```
4: error: 'ptr' was not declared in this scope
```

The error message is puzzling as it was the programmer's intention to declare a pointer to a type `Ambiguous` defined within the class template `Type`. But the compiler, confronted with

`Type::Ambiguous` may interpret the statement in various ways. Clearly it cannot inspect `Type` itself trying to uncover `Type`'s true nature as `Type` is a template type. Because of this `Type`'s actual definition isn't available yet.

The compiler is confronted with two possibilities: either `Type::Ambiguous` is a *static member* of the as yet mysterious template `Type`, or it is a *subtype* of `Type`. As the standard specifies that the compiler must assume the former, the statement

```
Type::Ambiguous *ptr;
```

is interpreted as a *multiplication* of the static member `Type::Ambiguous` and the (now undeclared) entity `ptr`. The reason for the error message should now be clear: in this context `ptr` is unknown.

To disambiguate code in which an identifier refers to a subtype of a template type parameter the keyword `typename` must be used. Accordingly, the above code is altered into:

```
template <typename Type>
Type function(Type t)
{
    typename Type::Ambiguous *ptr;

    return t + *ptr;
}
```

Classes fairly often define subtypes. When such subtypes appear inside template definitions as subtypes of template type parameters the `typename` keyword *must* be used to identify them as subtypes. Example: a class template `Handler` defines a `typename Container` as its template type parameter. It also defines a data member storing the iterator returned by the container's `begin` member. In addition `Handler` offers a constructor accepting any container supporting a `begin` member. `Handler`'s class interface could then look like this:

```
template <typename Container>
class Handler
{
    Container::const_iterator d_it;

    public:
        Handler(Container const &container)
        :
            d_it(container.begin())
        {}
};
```

What did we have in mind when designing this class?

- The typename `Container` represents any container supporting iterators.
- The container presumably supports a member `begin`. The initialization `d_it(container.begin())` clearly depends on the template's type parameter, so it's only checked for basic syntactic correctness.
- Likewise, the container presumably supports a *subtype* `const_iterator`, defined in the class `Container`.

The final consideration is an indication that `typename` is required. If this is omitted and a `Handler` is instantiated the compiler produces a peculiar compilation error:

```
#include "handler.h"
#include <vector>
using namespace std;

int main()
{
    vector<int> vi;
    Handler<vector<int> > ph{ vi };
}
/*
    Reported error:

handler.h:4: error: syntax error before `;' token
*/
```

Clearly the line

```
Container::const_iterator d_it;
```

in the class `Handler` causes a problem. It is interpreted by the compiler as a *static member* instead of a subtype. The problem is solved using `typename`:

```
template <typename Container>
class Handler
{
    typename Container::const_iterator d_it;
    ...
};
```

An interesting illustration that the compiler indeed assumes `X::a` to be a member `a` of the class `X` is provided by the error message we get when we try to compile `main` using the following implementation of `Handler`'s constructor:

```
Handler(Container const &container)
:
    d_it(container.begin())
{
    size_t x = Container::ios_end;
}
/*
    Reported error:

    error: `ios_end' is not a member of type `std::vector<int,
            std::allocator<int> >'
*/
```

Now consider what happens if the function template introduced at the beginning of this section doesn't return a `Type` value, but a `Type::Ambiguous` value. Again, a subtype of a template type is referred to, and `typename` must be used:

```
template <typename Type>
```

```
typename Type::Ambiguous function(Type t)
{
    return t.ambiguous();
}
```

Using `typename` in the specification of a return type is further discussed in section 23.1.1.

`Typename`s can be embedded in `typedef`s. As is often the case, this reduces the complexities of declarations and definitions appearing elsewhere. In the next example the type `Iterator` is defined as a subtype of the template type `Container`. `Iterator` may now be used without requiring the use of the keyword `typename`:

```
template <typename Container>
class Handler
{
    typedef typename Container::const_iterator Iterator;

    Iterator d_it;
    ...
};
```

22.3 Specializing class templates for deviating types

The class `CirQue` can be used for many different types. Their common characteristic is that they can simply be pointed at by the class's `d_data` member. But this is not always as simple as it looks. What if `Data` turns out to be a `vector<int>`? For such data types the vanilla `CirQue` implementation cannot be used and a specialization could be considered. When considering a specialization one should also consider inheritance. Often a class derived from the class template accepting the incompatible data structure as its argument but otherwise equal to the original class template can easily be designed. The developmental advantage of inheritance over specialization is clear: the inherited class inherits the members of its base class while the specialization inherits nothing. All members defined by the original class template must be implemented again by the class template's specialization.

The specialization considered here is a true specialization in that the data members and representation used by the specialization greatly differ from the original `CirQue` class template. Therefore all members defined by the orginal class template must be modified to fit the specialization's data organization.

Like function template specializations class template specializations start with a template header that may or may not have an empty template parameter list. If the template parameters are directly specialized by the specialization it remains empty (e.g., `CirQue`'s template type parameter `Data` is specialized for `char *` data). But the template parameter list may show `typename Data` when specializing for a `vector<Data>`, i.e., a vector storing any type of data. This leads to the following principle:

> A template specialization is recognized by the template argument list following a function or class template's *name* and *not* by an empty template parameter list. Class template specializations may have non-empty template parameter lists. If so, a *partial class template specialization* is defined.

A completely specialized class has the following characteristics:

- The class template specialization must be provided after the generic class template definition. As it is a specialization the compiler must first have seen the original class template;
- The completely specialized class template's template parameter list is empty;
- All of the class's template parameters are given explicit type names or (for the non-type parameters) explicit values. These explicitations are provided in a template parameter specification list (surrounded by angle brackets) that is inserted immediately after the specialized template's class *name*;
- All members of the specialized class template use specialized types and values where original template parameters are used in the original template definition;
- All original template's members (maybe with the exception of some constructors) *should* be redefined by the specialization. If a member is left out of the specialization, it cannot be used for a specialized class template object;
- The specialization may define additional members (but maybe shouldn't as it breaks the one-to-one correspondence between the original and specialized class template);
- Member functions of specialized class templates may be declared by the specializing class and implemented below their class interface. If their implementations follow the class interface they may *not* begin with a `template <>` header, but must immediately start with the member function's header.

22.3.1 Example of a class specialization

Here is an example of a completely specialized `CirQue` class, specialized for a `vector<int>`. All members of the specialized class are declared, but only non-trivial implementations of its members are provided. The specialized class uses a copy of the `vector` passed to the constructor and implements a circular queue using its `vector` data member:

```
#ifndef INCLUDED_CIRQUEVECTOR_H_
#define INCLUDED_CIRQUEVECTOR_H_

#include <vector>
#include "cirque.h"

template<>
class CirQue<std::vector<int>>
{
    typedef std::vector<int> IntVect;

    IntVect d_data;
    size_t d_size;

    typedef IntVect::iterator iterator;
    iterator d_front;
    iterator d_back;

    public:
        typedef int value_type;
        typedef value_type const &const_reference;

        enum Exception
        {
            EMPTY,
            FULL
        };

        CirQue();
        CirQue(IntVect const &iv);
        CirQue(CirQue<IntVect> const &other);

        CirQue &operator=(CirQue<IntVect> const &other);

        int &back();
        int &front();
        bool empty() const;
        bool full() const;
        size_t maxSize() const;
        size_t size() const;
        void pop_front();
        void push_back(int const &object);
        void swap(CirQue<IntVect> &other);

    private:
        iterator inc(iterator const &iter);
};

CirQue<std::vector<int>>::CirQue()
:
    d_size(0)
{}
CirQue<std::vector<int>>::CirQue(IntVect const &iv)
:
    d_data(iv),
    d_size(iv.size()),
    d_front(d_data.begin()),
    d_back(d_data.begin())
{}
CirQue<std::vector<int>>::CirQue(CirQue<IntVect> const &other)
:
    d_data(other.d_data),
    d_size(other.d_size),
    d_front(d_data.begin() + (other.d_front - other.d_data.begin())),
    d_back(d_data.begin() + (other.d_back - other.d_data.begin()))
{}
CirQue<std::vector<int>> &CirQue<std::vector<int>>::operator=(
                                        CirQue<IntVect> const &rhs)
{
    CirQue<IntVect> tmp(rhs);
    swap(tmp);
}
void CirQue<std::vector<int>>::swap(CirQue<IntVect> &other)
{
    char tmp[sizeof(CirQue<IntVect>)];
    memcpy(tmp, &other, sizeof(CirQue<IntVect>));
    memcpy(reinterpret_cast<char *>(&other), this, sizeof(CirQue<IntVect>));
    memcpy(reinterpret_cast<char *>(this), tmp, sizeof(CirQue<IntVect>));
}
void CirQue<std::vector<int>>::pop_front()
```

```
{
    if (d_size == 0)
        throw EMPTY;

    d_front = inc(d_front);
    --d_size;
}
void CirQue<std::vector<int>>::push_back(int const &object)
{
    if (d_size == d_data.size())
        throw FULL;

    *d_back = object;
    d_back = inc(d_back);
    ++d_size;
}
inline int &CirQue<std::vector<int>>::back()
{
    return d_back == d_data.begin() ? d_data.back() : d_back[-1];
}
inline int &CirQue<std::vector<int>>::front()
{
    return *d_front;
}
CirQue<std::vector<int>>::iterator CirQue<std::vector<int>>::inc(
    CirQue<std::vector<int>>::iterator const &iter)
{
    iterator tmp(iter + 1);
    tmp =  tmp == d_data.end() ? d_data.begin() : tmp;
    return tmp;
}

#endif
```

The next example shows how to use the specialized `CirQue` class:

```
static int iv[] = {1, 2, 3, 4, 5};

int main()
{
    vector<int> vi(iv, iv + 5);
    CirQue<vector<int>> ci(vi);

    cout << ci.size() << ' ' << ci.front() << ' ' << ci.back() << '\n';
    ci.pop_front();
    ci.pop_front();

    CirQue<vector<int>> cp;

    cp = ci;
    cout << cp.size() << ' ' << cp.front() << ' ' << cp.back() << '\n';
    cp.push_back(6);
    cout << cp.size() << ' ' << cp.front() << ' ' << cp.back() << '\n';
}
```

```
/*
    Displays:
        5 1 5
        3 3 5
        4 3 6
*/
```

22.4 Partial specializations

In the previous section class template specializations were introduced. In this section we'll introduce a variant of this specialization, both in number and type of template parameters that are specialized. *Partial specializations* may be defined for class templates having multiple template parameters.

Function templates cannot be partially specialized: there is no need for that, as a 'partially specialized function template' merely is a function template that is tailored to particular types of some of its parameters. Since function templates can be overloaded, 'partially specializing' a function template simply means that overloads have to be defined for those specialized parameter types.

With partial specializations a subset (any subset) of template type parameters are given specific values. It is also possible to use a class template partial specialization when the intent is to specialize the class template, but to parameterize the data type that is processed by the specialization.

To start our discussion with an example of the latter use of a partial class template specialization consider the class `CirQue<vector<int>>` developed in the previous section. When designing `CirQue<vector<int>>` you may have asked yourself how many specializations you'd have to implement. One for `vector<int>`, one for `vector<string>`, one for `vector<double>`? As long as the data types handled by the `vector` used by the class `CirQue<vector<...>>` behaves like an `int` (i.e., is a value-type of class) the answer is: zero. Instead of defining full specializations for each new data type the data type itself can be parameterized, resulting in a partial specialization:

```
    template <typename Data>
    class CirQue<std::vector<Data>>
    {
        ...
    };
```

The above class is a specialization as a template argument list is appended to the `CirQue` class name. But as the class template itself has a non-empty template parameter list it is in fact recognized as a partial specialization. There is one characteristic that distinguishes the implementation (subsequent to the class template's interface) of a class template member function of a partial specialization from the implementation of a member function of a full specialization. Implementations of partially specialized class template member functions receive a template header. No template headers are used when implementing fully specialized class template members.

Implementing the partial specialization for `CirQue` is not difficult and is left as an exercise for the reader (hints: simply change `int` into `Data` in the `CirQue<vector<int>>` specialization of the previous section). Remember to prefix the type `iterator` by `typename` (as in `typedef typename DataVect::iterator iterator`) (as discussed in section 22.2.1).

In the next subsections we'll concentrate on specializing class template non-type template parameters. These partial specializations are now illustrated using some simple concepts defined in matrix algebra, a branch of linear algebra.

22.4.1 Intermezzo: some simple matrix algebraic concepts

In this section some simple matrix algebraic terms are introduced. These terms are used in the next sections to illustrate and discuss partial specializations of class templates. Readers proficient in matrix algebra may skip this section without loss of continuity.

A matrix is commonly thought of as a table of some rows and columns, filled with numbers. Immediately we recognize an opening for using templates: the numbers might be plain `double` values, but they could also be complex numbers, for which our complex container (cf. section 12.5) might prove useful. Our class template is therefore provided with a `DataType` template type parameter. It is specified when a matrix is constructed. Some simple matrices using `double` values, are:

```
1   0   0           An identity matrix,
0   1   0           (a 3 x 3 matrix).
0   0   1

1.2  0    0    0    A rectangular matrix,
0.5  3.5  18   23   (a 2 x 4 matrix).

1   2   4   8       A matrix of one row
                    (a 1 x 4 matrix), also known as a
                    `row vector' of 4 elements.
                    (column vectors are analogously defined)
```

Various operations are defined on matrices. They may, for example be added, subtracted or multiplied. Here we will not focus on these operations. Rather, we concentrate on some simple operations: computing marginals and sums.

Marginals are the sums of row elements or the sums of column elements of a matrix. These two kinds of marginals are also known as, respectively, *row marginals* and *column marginals*.

- *Row marginals* are obtained by adding, for each row, all the row's elements and putting these (`Rows`) sums in corresponding elements of a (column) vector of `Rows` elements.
- Column marginals are obtained by adding, for each column, all the column's elements and putting these (`Columns`) sums in corresponding elements of a (row) vector of `Columns` elements.
- The sum of all elements of a matrix can of course be computed as the sum of the elements of one of its marginals.

The following example shows a matrix, its marginals, and the sum of its values:

```
-------------------------------------
                            row
            matrix          marginals
            ---------
            1   2   3        6
            4   5   6       15
            ---------
column      5   7   9       21   (sum)
marginals
-------------------------------------
```

22.4.2 The Matrix class template

We'll start out by introducing a class template defining a matrix. Having defined this class template we'll continue with defining several specializations.

Since matrices consist of well defined numbers of rows and columns (the *dimensions* of the matrix), that normally do not change when matrices are used, we might consider specifying their values as template non-type parameters. The `DataType = double` will be used in the majority of cases. Therefore, `double` can be selected as the template's default type argument. Since it's a sensible default, the `DataType` template type parameter is used last in the template type parameter list.

Our template class `Matrix` begins its life as:

```
template <size_t Rows, size_t Columns, typename DataType = double>
class Matrix
...
```

What do we want our class template to offer?

- It needs a place to store its matrix elements. This can be defined as an array of '`Rows`' rows each containing '`Columns`' elements of type `DataType`. It can be an array, rather than a pointer, since the matrix' dimensions are known *a priori*. Since a vector of `Columns` elements (a *row* of the matrix), as well as a vector of `Row` elements (a *column* of the matrix) is often used, the class could use *typedefs* to represent them. The class interface's initial section thus contains:

```
    typedef Matrix<1, Columns, DataType>    MatrixRow;
    typedef Matrix<Rows, 1, DataType>       MatrixColumn;

    MatrixRow d_matrix[Rows];
```

- It should offer constructors: a default constructor and (e.g.,) a constructor initializing the matrix from a stream. A copy or move constructor is not required as the class does not use pointers. Likewise, no overloaded assignment operator or destructor is required. Implementations:

```
template <size_t Rows, size_t Columns, typename DataType>
Matrix<Rows, Columns, DataType>::Matrix()
{
    std::fill(d_matrix, d_matrix + Rows, MatrixRow());
}
template <size_t Rows, size_t Columns, typename DataType>
Matrix<Rows, Columns, DataType>::Matrix(std::istream &str)
{
    for (size_t row = 0; row < Rows; row++)
        for (size_t col = 0; col < Columns; col++)
            str >> d_matrix[row][col];
}
```

- The class's `operator[]` member (and its `const` variant) only handles the first index, returning a reference to a complete `MatrixRow`. How elements in a `MatrixRow` can be retrieved is shortly covered. To keep the example simple, no array bound check has been implemented:

```
template <size_t Rows, size_t Columns, typename DataType>
Matrix<1, Columns, DataType>
&Matrix<Rows, Columns, DataType>::operator[](size_t idx)
{
    return d_matrix[idx];
}
```

- Now we get to the interesting parts: computing marginals and the sum of all elements in a `Matrix`. We'll define the type `MatrixColumn` as the type containing the row marginals of a matrix, and the type `MatrixRow` as the type containing the column marginals of a matrix.

  There is also the sum of all the elements of a matrix. This sum of all the elements of a matrix is a number that itself can be thought of as a `1 x 1` matrix.

  Marginals can be considered as special forms of matrices. To represent these marginals we can construct *partial specializations* defining the class templates `MatrixRow` and `MatrixColumn` objects; and we construct a partial specialization handling `1 x 1` matrices. These partial specializations are used to compute marginals and the sum of all the elements of a matrix.

  Before concentrating on these partial specializations themselves we'll use them here to implement the members computing the marginals and the sum of all elements of a matrix:

  ```
  template <size_t Rows, size_t Columns, typename DataType>
  Matrix<1, Columns, DataType>
  Matrix<Rows, Columns, DataType>::columnMarginals() const
  {
      return MatrixRow(*this);
  }

  template <size_t Rows, size_t Columns, typename DataType>
  Matrix<Rows, 1, DataType>
  Matrix<Rows, Columns, DataType>::rowMarginals() const
  {
      return MatrixColumn(*this);
  }

  template <size_t Rows, size_t Columns, typename DataType>
  DataType Matrix<Rows, Columns, DataType>::sum()  const
  {
      return rowMarginals().sum();
  }
  ```

22.4.3 The MatrixRow partial specialization

Class template *partial specializations* can be defined for any (subset) of template parameters. They can be defined for template type parameters and for template non-type parameters alike. Our first partial specialization defines a row of a generic `Matrix`, mainly (but not only) used for the construction of column marginals. Here is how such a partial specialization is designed:

- The partial specialization starts with a template header defining all template parameters that are *not* specialized in the partial specialization. This template header cannot specify any defaults (like `DataType = double`) since defaults were already specified by the generic class template definition. The specialization *must* follow the definition of the generic class template's definition, or the compiler complains that it doesn't know what class is being specialized. Following the template header, the class's interface starts. It's a class template (partial) specialization so the class name must be followed by a template argument list specifying the template arguments used by the partial specialization. The arguments specify explicit types or values for some of the template's parameters. Remaining types are simply copied from the class template partial specialization's template parameter list. E.g., the `MatrixRow` specialization specifies 1 for the generic class template's `Rows` non-type parameter (as we're talking here about a single row). Both `Columns` and `DataType` remain to be specified. The `MatrixRow` partial specialization therefore starts as follows:

  ```
  template <size_t Columns, typename DataType>  // no default allowed
  ```

```
class Matrix<1, Columns, DataType>
```

- A `MatrixRow` holds the data of a single row. So it needs a data member storing `Columns` values of type `DataType`. Since `Columns` is a constant value, the `d_row` data member can be defined as an array:

```
    DataType d_column[Columns];
```

- The class template partial specialization's constructors require some attention. The default constructor is simple. It merely initializes the `MatrixRow`'s data elements using `DataType`'s default constructor:

```
template <size_t Columns, typename DataType>
Matrix<1, Columns, DataType>::Matrix()
{
    std::fill(d_column, d_column + Columns, DataType());
}
```

  Another constructor is needed initializing a `MatrixRow` object with the column marginals of a generic `Matrix` object. This requires us to provide the constructor with a non-specialized `Matrix` parameter.

  The rule of thumb here is to define a member template that allows us to keep the general nature of the parameter. The generic `Matrix` template requires three template parameters. Two of these were already provided by the template specialization. The third parameter is mentioned in the member template's template header. Since this parameter refers to the number of rows of the generic matrix it is simply called `Rows`.

  Here then is the implementation of the second constructor, initializing the `MatrixRow`'s data with the column marginals of a generic `Matrix` object:

```
template <size_t Columns, typename DataType>
template <size_t Rows>
Matrix<1, Columns, DataType>::Matrix(
                        Matrix<Rows, Columns, DataType> const &matrix)
{
    std::fill(d_column, d_column + Columns, DataType());

    for (size_t col = 0; col < Columns; col++)
        for (size_t row = 0; row < Rows; row++)
            d_column[col] += matrix[row][col];
}
```

  The constructor's parameter is a reference to a `Matrix` template using the additional `Row` template parameter as well as the template parameters of the partial specialization.

- We don't really require additional members to satisfy our current needs. To access the data elements of the `MatrixRow` an overloaded `operator[]()` is of course useful. Again, the `const` variant can be implemented like the non-`const` variant. Here is its implementation:

```
template <size_t Columns, typename DataType>
DataType &Matrix<1, Columns, DataType>::operator[](size_t idx)
{
    return d_column[idx];
}
```

Now that we have defined the generic `Matrix` class and the partial specialization defining a single row the compiler selects the row's specialization whenever a `Matrix` is defined using `Row = 1`. For example:

```
Matrix<4, 6> matrix;          // generic Matrix template is used
Matrix<1, 6> row;             // partial specialization is used
```

22.4.4 The MatrixColumn partial specialization

The partial specialization for a `MatrixColumn` is constructed similarly. Let's present its highlights (the full `Matrix` class template definition as well as all its specializations are provided in the `cplusplus.yo.zip` archive (that can be obtained from the **C++** Annotations' `Gitlab`[1] website) in the file `yo/classtemplates/examples/matrix.h`):

- The class template partial specialization once again starts with a template header. Now the class interface specifies a fixed value for the second template parameter of the generic class template. This illustrates that we can construct partial specializations for every single template parameter; not just for the first or the last:

```
template <size_t Rows, typename DataType>
class Matrix<Rows, 1, DataType>
```

- Its constructors are implemented completely analogously to the way the `MatrixRow` constructors were implemented. Their implementations are left as an exercise to the reader (and they can be found in `matrix.h`).
- An additional member `sum` is defined to compute the sum of the elements of a `MatrixColumn` vector. It's simply implemented using the `accumulate` generic algorithm:

```
template <size_t Rows, typename DataType>
DataType Matrix<Rows, 1, DataType>::sum()
{
    return std::accumulate(d_row, d_row + Rows, DataType());
}
```

22.4.5 The 1x1 matrix: avoid ambiguity

The reader might wonder what happens if we define the following matrix:

```
Matrix<1, 1> cell;
```

Is this a `MatrixRow` or a `MatrixColumn` specialization? The answer is: neither.

It's ambiguous, precisely because *both* the columns *and* the rows could be used with a (different) template partial specialization. If such a `Matrix` is actually required, yet another specialized template must be designed.

Since this template specialization can be useful to obtain the sum of the elements of a `Matrix`, it's covered here as well.

---

[1] https://fbb-git.gitlab.io/cppannotations/

- This class template partial specialization also needs a template header, this time only specifying `DataType`. The class definition specifies two fixed values: 1 for the number of rows and 1 for the number of columns:

  ```
  template <typename DataType>
  class Matrix<1, 1, DataType>
  ```

- The specialization defines the usual batch of constructors. Constructors expecting a more generic `Matrix` type are again implemented as member templates. For example:

  ```
  template <typename DataType>
  template <size_t Rows, size_t Columns>
  Matrix<1, 1, DataType>::Matrix(
                          Matrix<Rows, Columns, DataType> const &matrix)
  :
      d_cell(matrix.rowMarginals().sum())
  {}

  template <typename DataType>
  template <size_t Rows>
  Matrix<1, 1, DataType>::Matrix(Matrix<Rows, 1, DataType> const &matrix)
  :
      d_cell(matrix.sum())
  {}
  ```

- Since `Matrix<1, 1>` is basically a wrapper around a `DataType` value, we need members to access that latter value. A type conversion operator might be useful, but we also defined a `get` member to obtain the value if the conversion operator isn't used by the compiler (which happens when the compiler is given a choice, see section 11.3). Here are the accessors (leaving out their `const` variants):

  ```
  template <typename DataType>
  Matrix<1, 1, DataType>::operator DataType &()
  {
      return d_cell;
  }

  template <typename DataType>
  DataType &Matrix<1, 1, DataType>::get()
  {
      return d_cell;
  }
  ```

Finally, the `main` function shown below illustrates how the `Matrix` class template and its partial specializations can be used:

```
#include <iostream>
#include "matrix.h"
using namespace std;

int main(int argc, char **argv)
{
    Matrix<3, 2> matrix(cin);

    Matrix<1, 2> colMargins(matrix);
```

```
        cout << "Column marginals:\n";
        cout << colMargins[0] << " " << colMargins[1] << '\n';

        Matrix<3, 1> rowMargins(matrix);
        cout << "Row marginals:\n";
        for (size_t idx = 0; idx < 3; idx++)
            cout << rowMargins[idx] << '\n';

        cout << "Sum total: " << Matrix<1, 1>(matrix) << '\n';
    }
    /*
        Generated output from input: 1 2 3 4 5 6

        Column marginals:
        9 12
        Row marginals:
        3
        7
        11
        Sum total: 21
    */
```

22.5 Variadic templates

Up to this point we've encountered templates defining a fixed number of template parameters. However, templates may also defined as *variadic templates*, allowing any number of arguments to be passed to their instantiations.

Variadic templates are defined for function templates and for class templates. Variadic templates allow us to specify an arbitrary number of template arguments of any type.

Variadic templates were added to the language to prevent us from having to define many overloaded templates and to be able to create *type safe* variadic functions.

Although **C** (and **C++**) support variadic functions, their use has always been deprecated in **C++** as those functions are notoriously type-*un*safe. Variadic function templates can be used to process objects that until now couldn't be processed properly by **C**-style variadic functions.

Template headers of variadic templates use the phrase `typename ...Params` (`Params` being a formal name). A variadic class template `Variadic` could be declared as follows:

```
    template<typename ...Params> class Variadic;
```

Assuming the class template's definition is available then this template can be instantiated using any number of template arguments. Example:

```
    class Variadic<
            int,
            std::vector<int>,
            std::map<std::string, std::vector<int>>
    > v1;
```

The template argument list of a variadic template can also be empty. Example:

```
class Variadic<> empty;
```

If this is considered undesirable using an empty template argument list can be prevented by providing one or more fixed parameters. Example:

```
template<typename First, typename ...Rest>
class tuple;
```

C's function `printf` is a well-known example of a type-unsafe function. It is turned into a type-safe function when it is implemented as a variadic function template. Not only does this turn the function into a type-safe function but it is also automatically extended to accept any type that can be defined by **C++**. Here is a possible declaration of a variadic function template `printcpp`:

```
template<typename ...Params>
void printcpp(std::string const &strFormat, Params ...parameters);
```

The ellipsis (...) used in the declaration serves two purposes:

- In the template header it is written to the *left* of a template parameter name where it declares a *parameter pack*. A parameter pack allows us to specify any number of template arguments when instantiating the template. Parameter packs can be used to bind type and non-type template arguments to template parameters.
- In a template implementation it appears to the *right* of the template pack's parameter name. In that case it represents a series of template arguments that are subsequently matched with a function parameter that in turn is provided to the right of the ellipsis. Here the ellipsis is known as the *unpack operator* as it 'unpacks' a series of arguments in a function's argument list thereby implicitly defining its parameters.

C++ offers no syntax to access the individual template arguments directly. However, the arguments can be visited recursively. An example is provided in the next section. The *number* of arguments is determined using a new invocation of the `sizeof` operator:

```
template<typename ...Params>
struct StructName
{
    enum: size_t { s_size = sizeof ...(Params) };
};

// StructName<int, char>::s_size          -- initialized to 2
```

22.5.1 Defining and using variadic templates

The arguments associated with a variadic template parameter are not directly available to the implementation of a function or class template. We have to resort to other means to obtain them.

By defining a partial specialization of a variadic template, explicitly defining an additional template type parameter, we can associate the first template argument of a parameter pack with this additional (first) type parameter. The setup of such a variadic function template (e.g., `printcpp`, see the previous section) is as follows:

- The `printcpp` function receives at least a format string. Following the format string any number of additional arguments may be specified.

- If there are no arguments trailing the format string then there is no need to use a function template. An overloaded (non-template) function is defined to handle this situation.
- A variadic function template handles all remaining situations. In this case there is always at least one argument trailing the format string. That argument's type is matched with the variadic template function's first (ordinary) template type parameter `First`. The types of any remaining arguments are bound to the template function's second template parameter, which is a parameter pack.
- The variadic function template processes the argument trailing the format string. Then it recursively calls itself passing the format string and the parameter pack to the recursive call
- If the recursive call merely receives the format string the overloaded (non-template) function is called (cf. section 21.14) ending the recursion. Otherwise the parameter pack's first argument is matched with the recursive call's `First` parameter. As this reduces the size of the recursive call's parameter pack the recursion eventually stops.

The overloaded non-template function prints the remainder of the format string, *en passant* checking for any left-over format specifications:

```
void printcpp(string const &format)
{
    size_t left = 0;
    size_t right = 0;

    while (true)
    {
        if ((right = format.find('%', right)) == string::npos)
            break;
        if (format.find("%%", right) != right)
            throw std::runtime_error(
                            "printcpp: missing arguments");
        ++right;
        cout << format.substr(left, right - left);
        left = ++right;
    }
    cout << format.substr(left);
}
```

Here is the variadic function template's implementation:

```
template<typename First, typename ...Params>
void printcpp(std::string const &format, First value, Params ...params)
{
    size_t left = 0;
    size_t right = 0;
    while (true)
    {
        if ((right = format.find('%', right)) == string::npos)      // 1
            throw std::runtime_error("printcpp: too many arguments");

        if (format.find("%%", right) != right)                      // 2
            break;

        ++right;
        cout << format.substr(left, right - left);
        left = ++right;
    }
    cout << format.substr(left, right - left) << value;
    printcpp(format.substr(right + 1), params...);
}
```

- At 1 the format string is searched for a parameter specification `%`. If none is found then the function is called with too many arguments and it throws an exception;
- At 2 it verifies that it has not encountered `%%`. If only a single `%` has been seen the `while`-loop ends, the format string is inserted into `cout` up to the `%` followed by `value`, and the recursive call receives the remaing part of the format string as well as the remaining parameter pack;
- If `%%` was seen the format string is inserted up to the second `%`, which is ignored, and processing of the format string continues beyond the `%%`.

Make sure that the overloaded function is at least declared before the compiler processes the function template's definition or it won't call the overloaded function `printcpp` when compiling the function template.

Different from **C**'s `printf` function `printcpp` only recognizes `%` and `%%` as format specifiers. The above implementation does not recognize, e.g., field widths. Type specifiers like `%c` and `%x` are of course not needed as `ostream`'s insertion operator is aware of the types of the arguments that are inserted into the `ostream`. Extending the format specifiers so that field widths etc. are recognized by this `printcpp` implementation is left as an exercise to the reader. Here is an example showing how `printcpp` can be called:

```
printcpp("Hello % with %%main%% called with % args"
                                        " and a string showing %\n",
    "world", argc, "A String"s);
```

22.5.2 Perfect forwarding

Consider `string`'s member `insert`. `String::insert` has several overloaded implementations. It can be used to insert text (completely or partially) provided by a `string` or by a `char const *` argument; to insert single characters a specified number of times; iterators can be used to specify the range of characters to be inserted; etc., etc.. All in all, `string` offers as many as five overloaded `insert` members.

Assume the existence of a class `Inserter` that is used to insert information into all kinds of objects. Such a class could have a `string` data member into which information can be inserted. `Inserter`'s interface only partially has to copy `string`'s interface to realize this: only `string::insert`'s interfaces must be duplicated. The members duplicating interfaces often contain one statement (calling the appropriate member function of the object's data member) and are for this reason often implemented in-line. Such *wrapper functions* merely *forward* their parameters to the matching member functions of the object's data member.

Another example is found in *factory functions* that also frequently forward their parameters to the constructors of objects that they return.

C++ simplifies and generalizes forwarding of parameters by offering *perfect forwarding*, implemented through rvalue references and variadic templates. With perfect forwarding the arguments passed to functions are 'perfectly forwarded' to nested functions. Forwarding is called *perfect* as the arguments are forwarded in a type-safe way. To use perfect forwarding nested functions must define parameter lists matching the forwarding parameters both in types and number.

Perfect forwarding is easily implemented:

- The forwarding function is defined as a template
(usually a *variadic* template, but single argument forwarding is also possible. To define and forward a single argument omit the ellipsis from the following code);
- The forwarding function's parameter list is an *rvalue reference parameter pack* (e.g., `Params &&...params`);
- `std::forward` is used to forward the forwarding function's arguments to the nested function, keeping track of their types and number. Before `forward` can be used the `<utility>` header file must be included.
- The nested function is called using this stanza to specify its arguments:
`std::forward<Params>(params)...`.

In the next example perfect forwarding is used to implement *one* member `Inserter::insert` that can be used to call any of the five overloaded `string::insert` members. The `insert` function that's actually called now simply depends on the types and number of arguments that are passed to `Inserter::insert`:

```
class Inserter
{
    std::string d_str;  // somehow initialized
    public:
                        // constructors not implemented,
                        // but see below
        Inserter();
        Inserter(std::string const &str);
        Inserter(Inserter const &other);
        Inserter(Inserter &&other);

        template<typename ...Params>
        void insert(Params &&...params)
        {
            d_str.insert(std::forward<Params>(params)...);
        }
};
```

A factory function returning an `Inserter` can also easily be implemented using perfect forwarding. Rather than defining four overloaded factory functions a single one now suffices. By providing the factory function with an additional template type parameter specifying the class of the object to construct the factory function is turned into a completely general factory function:

```
template <typename Class, typename ...Params>
Class factory(Params &&...params)
{
    return Class(std::forward<Params>(params)...);
}
```

Here are some examples showing its use:

```
Inserter inserter(factory<Inserter>("hello"));
string delimiter(factory<string>(10, '='));
Inserter copy(factory<Inserter>(inserter));
```

The function `std::forward` is provided by the standard library. It performs no magic, but merely returns `params` as a nameless object. That way it acts like `std::move` that also removes the name from an object, returning it as a nameless object. The unpack operator has nothing to do with the use of `forward` but merely tells the compiler to apply `forward` to each of the arguments in turn. Thus it behaves similarly to **C**'s ellipsis operator used by variadic functions.

Perfect forwarding was introduced in section 21.4.5: a template function defining a `Type &&param`, with `Type` being a template type parameter converts `Type &&` to `Tp &` if the function is called with an argument of type `Tp &`. Otherwise it binds `Type` to `Tp`, with `param` being defined as `Tp &&param`. As a result an *lvalue* argument binds to an lvalue-type (`Tp &`), while an *rvalue* argument binds to an rvalue-type (`Tp &&`).

The function `std::forward` merely passes the argument (and its type) on to the called function or object. Here is its simplified implementation:

```
typedef <type T>
T &&forward(T &&a)
{
    return a;
}
```

Since `T &&` turns into an lvalue reference when `forward` is called with an lvalue (or lvalue reference) and remains an rvalue reference if `forward` is called with an rvalue reference, and since `forward` (like `std::move`) anonymizes the variable passed as argument to `forward`, the argument value is forwarded while passing its type from the function's parameter to the called function's argument.

This is called *perfect forwarding* as the nested function can only be called if the types of the arguments that were used when calling the 'outer' function (e.g., `factory`) exactly match the types of the parameters of the nested function (e.g., `Class`'s constructor). Perfect forwarding therefore is a tool to realize type safety.

A cosmetic improvement to `forward` requires users of `forward` to specify the type to use rather than to have the compiler deduce the type as a result of the function template parameter type deduction's process. This is realized by a small support struct template:

```
template <typename T>
struct identity
{
    typedef T type;
};
```

This struct merely defines `identity::type` as `T`, but as it is a struct it must be specified explicitly. It cannot be determined from the function's argument itself. The subtle modification to the above implementation of `forward` thus becomes (cf. section 22.2.1 for an explanation of the use of `typename`):

```
typedef <type T>
T &&forward(typename identity<T>::type &&arg)
{
    return arg;
}
```

Now `forward` must explicitly state `arg`'s type, as in:

```
std::forward<Params>(params)
```

Using the `std::forward` function and the rvalue reference specification is not restricted to the context of parameter packs. Because of the special way rvalue references to template type parameters are treated (cf. section 21.4.5) they can profitably be used to forward individual function parameters as well. Here is an example showing how an argument to a function can be forwarded from a template to a function that is itself passed to the template as a pointer to an (unspecified) function:

```
template<typename Fun, typename ArgType>
void caller(Fun fun, ArgType &&arg)
{
    fun(std::forward<ArgType>(arg));
}
```

A function `display(ostream &out)` and `increment(int &x)` may now both be called through `caller`. Example:

```
caller(display, cout);
int x = 0;
caller(increment, x);
```

22.5.3 The unpack operator

The *unpack operator* is used to obtain template arguments in many situations. No mechanism other than recursion (as shown in section 22.5.1) is available to obtain the individual types and values of a variadic template.

The unpack operator can also be used to define template classes that are derived from any number of base classes. Here is how it's done:

```
template <typename ...BaseClasses>
class Combi: public BaseClasses...          // derive from base classes
{
    public:
                                            // specify base class objects
                                            // to its constructor using
                                            // perfect forwarding
        Combi(BaseClasses &&...baseClasses)
        :
            BaseClasses(baseClasses)...     // use base class initializers
        {}                                  // for each of the base
};                                          // classes
```

This allows us to define classes that combine the features of any number of other classes. If the class `Combi` is derived of classes `A, B`, and `C` then `Combi` is-an `A, B`, and `C`. It should of course be given a virtual destructor. A `Combi` object can be passed to functions expecting pointers or references to any of its base class type objects. Here is an example defining `Combi` as a class derived from a vector of complex numbers, a string and a pair of ints and doubles (using uniform intializers in a sequence matching the sequence of the types specified for the used `Combi` type):

```
typedef Combi<
    vector<complex<double>>, string, pair<int, double>
> MultiTypes;

MultiTypes mt = { {3.5, 4}, "mt", {1950, 1.72} };
```

The same construction can also be used to define template data members supporting variadic type lists such as `tuples` (cf. section 22.6). Such a class could be designed along these lines:

```
template <typename ...Types>
struct Multi
{
    std::tuple<Types...> d_tup;        // define tuple for Types types

    Multi(Types ...types)
    :                                   // initialize d_tup from Multi's
        d_tup(std::forward<Types>(types)...)   //             arguments
    {}
};
```

The ellipses that are used when forwarding parameter packs are essential. The compiler considers their omission an error. In the following `struct` definition it was the intent of the programmer to pass a parameter pack on to a nested object construction but ellipses were omitted while specifying the template parameters, resulting in a *parameter packs not expanded with '...'* error message:

```
template <int size, typename ...List>
struct Call
{
    Call(List &&...list)
    {
        Call<size - 1, List &&> call(std::forward<List>(list)...);
    }
};
```

Instead of the above definition of the `call` object the programmer should have used:

```
Call<size - 1, List &&...> call(std::forward<List>(list)...);
```

22.5.4 Non-type variadic templates

Variadic templates not necessarily define template types. Non-types can also be used with variadic templates. The following function template accepts any series of `int` values, forwarding these values to a class template. The class template defines an `enum` value `result` which is returned by the function, unless no int values were specified, in which case 0 is returned.

```
template <int ... Ints>
int forwarder()
{
    return computer<Ints ...>::result;  // forwarding the Ints
}

template <>     // specialization if no ints are provided
int forwarder<>()
{
    return 0;
}

// use as:
cout << forwarder<1, 2, 3>() << ' ' << forwarder<>() << '\n';
```

The `sizeof` operator can be used for variadic non-type parameters as well: `sizeof...(Ints)` would return 3 when used in the first function template for `forwarder<1, 2, 3>()`.

Variadic non-type parameters are used to define variadic literal operators, introduced in section 23.3.

22.5.5 Folding expressions

Functions accepting variable numbers of arguments (of possibly varying types) are commonly handled using variadic templates. Implementations usually process the first argument, passing the remaining arguments to an overloaded function, which is defined by the compiler for these remaining argument types. One of the overloaded versions, accepting zero or one argument, ends the compiler's recursive implementations.

Sometimes the arguments must be combined using binary operators (like `arg1 + arg2 + ...`). In those cases a *folding expression* can be used instead of combining the arguments using a traditional variadic template.

All binary operators (including the assignment, compound assignment and comma operators) can be used in folding expressions.

- A *unary left fold* is a fold expression that looks like this:

  ```
  (... op expr)
  ```

  where *op* is the binary operator that is used in the fold expression, and *expr* is an expression formulated in terms of the function parameter representing the variadic arguments. Here is an example:

  ```
  template <typename ReturnType, typename ...Params>
  ReturnType sum(Params ...params)
  {
      return (... + params);
  }
  ```

  If a more elaborate expression than just the designator of the variadic arguments is used then the expression must be clearly demarcated, e.g., by surrounding in with parentheses:

  ```
  return (... + (2 * params));
  ```

  In a unary fold expression all the function's arguments matching the types of the parameter pack are combined using specified operator. E.g.,

  ```
  sum<int>(1, 2, 3);
  ```

  returns 6.

There are no special restrictions that apply to function templates using fold expressions. Directly returning the result of the fold expression is OK, but the result could also be used in another expression (maybe inserting its value into an `ostream`), or when initializing a variable or object. Also, the types of the arguments do not have to be identical: the only requirement is that the fully expanded expression (in the example: `1 + 2 + 3` is a valid expression).

- A *unary right fold* is a fold expression that results in the same expression as its unary left fold alternative, but swaps the ellipses and the `params` identifier:

  ```
  (expr op ...)
  ```

Together, unary left folds and unary right folds are called *unary folds*.

- A *binary fold* is a fold expression of the following form:

  ```
  (expr1 op ... op expr2)
  ```

  Here, either `expr1` is the identifier representing the variable arguments or `expr2` must be that identifier. The other one can be any other valid expression (as with unary folds, both expressions must be clearly demarcated). In addition, both operators must be identical.

If a binary operator has been overloaded, it will be used where applicable. A well-known example is of course `operator<<` as defined for `std::ostream` objects. A binary fold defined for `operator<<` will not only do shifts, but can also be used to insert a series of arguments into `cout`:

```
template <class ...Pack>
ostream &out2(ostream &out, Pack &&...args)
{
    return (out << ... << args);
};
```

Here is another interesting example: a fold expression for the comma operator:

```
template <class ...Pack>
void call(Pack &&...args)
{
    ... , args();
};
```

This unary fold calls each of its arguments in sequence. Arguments could be function addresses, function object or lambda functions. Note the use of the rvalue reference when defining the variadic parameter list which prevents copying of function objects that might be passed to `call`. Assuming that `struct Functor` defines a functor, and that `void function()` has been defined, then `call` could be called this way:

```
Functor functor;
call(functor, function, functor,
    []()
    {
        // ...
    }
);
```

Finally: don't forget the parentheses surrounding fold expressions: they are required!

22.6 Tuples

C++ offers a *generalized pair* container: the *tuple*, covered in this section. Before tuples can be used the header file `<tuple>` must be included.

Whereas `std::pair` containers have limited functionality and only support two members, tuples have slightly more functionality and may contain an unlimited number of different data types. In that respect a tuple can be considered the 'template's answer to **C**'s struct'.

A tuple's generic declaration (and definition) uses the variadic template notation:

```
template <class ...Types>
class tuple;
```

Here is an example of its use:

```
typedef std::tuple<int, double &, std::string, char const *> tuple_idsc;

double pi = 3.14;
tuple_idsc idsc(59, pi, "hello", "fixed");

// access a field:
std::get<2>(idsc) = "hello world";
```

The `std::get<idx>(tupleObject)` function template returns a reference to the `idx`th (zero based) field of the tuple `tupleObject`. The index is specified as the function template's non-type template argument.

Type-based tuple addressing () can be used for tuple types used once in a tuple definition (if the same type is used repeatedly referring to that type introduces an ambiguity). The next example shows how to refer to the elements in the above example by type:

```
get<int>(idsc)              // 59
get<double &>(idsc)         // 3.14
get<string>(idsc)           // "hello"s
get<char const *>(idsc)     // "fixed"
```

Tuples may be constructed without specifying initial values. Primitive types are initialized to zeroes; class type fields are initialized by their default constructors. Be aware that in some situations the construction of a tuple may succeed but its use may fail. Consider:

```
tuple<int &> empty;
cout << get<0>(empty);
```

Here the tuple `empty` cannot be used as its `int &` field is an undefined reference. However, `empty`'s construction succeeds.

Tuples may be assigned to each other if their type lists are identical; if supported by their constituent types copy constructors are available as well. Copy construction and assignment is also available if a right-hand type can be converted to its matching left-hand type or if the left-hand type can be constructed from the matching right-hand type. Tuples (matching in number and (convertible) types) can be compared using relational operators as long as their constituent types support comparisons. In this respect tuples are like pairs.

Tuples offer the following static elements (using compile-time initialization):

- `std::tuple_size<Tuple>::value` returns the number of types defined for the tuple type `Tuple`. Example:

  ```
  cout << tuple_size<tuple_idsc>::value << '\n';  // displays: 4
  ```

- `std::tuple_element<idx, Tuple>::type` returns the type of element `idx` of `Tuple`. Example:

  ```
  tuple_element<2, tuple_idsc>::type text;  // defines std::string text
  ```

The unpack operator can also be used to forward the arguments of a constructor to a tuple data member. Consider a class `Wrapper` that is defined as a variadic template:

```
template <typename ...Params>
class Wrapper
{
    ...
    public:
        Wrapper(Params &&...params);
};
```

This class may be given a tuple data member which should be initialized by the types and values that are used when initializing an object of the class `Wrapper` using perfect forwarding. Comparable to the way a class may inherit from its template types (cf. section 22.5.3) it may forward its types and constructor arguments to its tuple data member:

```
template <typename ...Params>
class Wrapper
{
    std::tuple<Params...> d_tuple;     // same types as used for
                                        // Wrapper itself
    public:
        Wrapper(Params &&...params)
        :                               // initialize d_tuple with
                                        // Wrapper's arguments
            d_tuple(std::forward<Params>(params)...)
        {}
};
```

22.6.1 Tuples and structured bindings

Structured bindings were introduced in section 3.3.7.1. That section concentrated on associating structured binding declarations with data members of structs, returned as POD values.

Structured bindings, however, can also be used in a much more generic way, by associating them with tuples. By doing so structured bindings don't have to be associated with data members, but they may hold values returned by class members.

The association between structured binding declarations and tuples is very strong. In fact it is so strong that the standard explicitly allows users to define tuple specializations, even though tuple specializations live in the standard namespace, which otherwise is off-limits to programmers (except, of course, when using its features).

In order to allow structured bindings to be associated with class members the following steps must be performed:

- The class must be provided with overloaded `get` member templates, using `int` (or another integral type) specializations, where each specialization returns a class element (e.g., a member function).

  The availability of `if constexpr` clauses makes it easy to combine all these specializations into a single member template.

  Alternatively, a function template defined outside of the class can be defined, which allows associating structured bindings with class members even if you're not the class's author. In this case the function defines a `ClassType [cv] &object` parameter.

- A specialization of `std::tuple_size<Type>` is provided, defining `static size_t const value` as the number of index values that can be specified with the `get<idx>` function. Although defining entities in the standard namespace is normally *off limits* to ordinary programs, in this special case such specializations are allowed by the **C++** standard.
- A specialization of `std::tuple_element<idx, Type>` is provided, defining `type` as the type matching the return type of `get<idx>`.

The flexibility that is achieved by being able to use structured bindings this way is enormous. As long as a class offers members returning values those members can be associated with structured binding variables. The member functions don't even have to return values that are immediately available (e.g, as data members accessors) but their return values could also be computed on the spot, by simply referring to the corresponding structured binding variable.

To illustrate the abovementioned steps for associating structured bindings with class members we use these classes:

```
class Euclid
{
    size_t d_x;
    size_t d_y;

    public:
        Euclid(size_t x = 0, size_t y = 0);
        double distance() const;        // sqrt(d_x * d_x + d_y * d_y)
};
class Data
{
    std::string d_text{ "hello from Data" };
    Euclid d_euclid;

    public:
        void setXY(size_t x, size_t y);

        Euclid factory() const;
        double distance() const;
        std::string const &text() const;
};
```

The first step towards allowing structured bindings for `Data` consists of defining a (member) termplate `get`. If `Data` is our own class we can add a member template `get`. Alternatively, if we're only interested in accessing `Data's` public members we could derive a class `DataGet` from `Data`, and provide that class with the `get` member template. Yet another possibility is to define a free `get` function template. The `get` function must return whatever we're interested in. To make the appropriate selection we use an integral type (`int, size_t, ...`) selector value, and the function template thus only has a non-type template parameter. Rather than defining several specializations using the `if constexpr` clause is advised, as it greatly simplifies the function's definition.

Our `get` function defines selector 0 for `factory`, selector 1 for `distance` and selector 2 for `text`. The `distance` member simply returns `d_euclid.distance()`, and `Euclid::distance` is run-time evaluated using its `d_x` and `d_y` values. Thus, `distance` is an example of a function that will be run-time evaluated when we're referring, later on, to the third structured bindings variable.

Here's the definition of the member template `get`:

```
template <size_t Nr>
```

```
    auto get() const
    {
        if constexpr (Nr == 0)
            return factory();

        if constexpr (Nr == 1)
            return distance();

        if constexpr (Nr == 2)
            return text();

        static_assert(Nr >= 0 and Nr < 3);
    }
```

This function is still suboptimal. Consider its specialization for value 2: it returns `Data::text()`. As `auto` merely inspects the returned data type, `get<2>()` returns a `std::string`, rather than (text's) return type, which is a `std::string const &`. To use the return types that are actually returned by `Data's` member functions, `get's` return type should be defined as `decltype(auto)` rather than just `auto`:

```
    template <size_t Nr>
    decltype(auto) get() const
    ...
```

When defining `get` as a free function template it must be provided with a parameter `Data const &data` (or `Data &data` if members are used that may modify `data's` data members), returning the parameter's member functions. E.g.,

```
        // get as a free function template:
    template <size_t Nr>
    decltype(auto) get(Data const &data)
    {
        if constexpr (Nr == 0)
            return data.factory();

        if constexpr (Nr == 1)
            return data.distance();

        ... // (etc)
    }
```

Now that step 1 has been completed, we turn our attention to the `std::tuple` specializations. These specializations are defined inside the `std` namespace (using `namespace std { ... }` or `std::tuple...`).

The specialization of `std::tuple_size` for `Data` defines `static size_t const value` as the number of index values that can be specified with the `get<idx>` function:

```
    template<>
    struct std::tuple_size<Data>
    {
        static size_t const value = 3;
    };
```

The specialization of `std::tuple_element` for `Data` returns the types matching the various return types of the `get` member template. Its implementation also provides a nice example where `declval` is used: the return type of the `get<Nr>` specialization must be determined. But to obtain that return type a `Data` object is required, which isn't available by just mentioning `Data` in `tupe_element's` specialization. However, `declval<Data>()` defines an rvalue reference, which *can* be passed to `get<Nr>`. But the function's return *value* isn't required, so the object doesn't have to be constructed. Only its return type is needed. Hence, by surrounding the `get<Nr>` call by `decltype` no object is constructed, and merely its return type is used:

```
template<size_t Nr>
struct std::tuple_element<Nr, Data>
{
    using type = decltype( declval<Data>().get<Nr>() );
    // if get<Nr> is a free function use:
    //           decltype( get<Nr>( declval<Data>() ) );

};
```

As `tuple_size` and `tuple_element` are directly associated with the class `Data` their definitions should be provided in `Data's` header file, below `Data's` class interface.

Here's how this could be used in a `main` function, showing single object access and access using a range-based for-loop:

```
int main()
{
    Data data;
    auto &[ ef, dist, txt ] = data;
    // or maybe:
    // auto &&[ ef, dist, txt ] = Data{};

    cout << dist << ' ' << txt << '\n';

    Data array[5];
    for (auto &[ ef, dist, txt]: array)
        cout << "for: " << dist << ' ' << txt << '\n';
}
```

22.7 Computing the return type of function objects

As amply illustrated in chapter 19 function objects play an important role with generic algorithms. Like generic algorithms themselves, function objects can be generically defined as members of class templates. If the function call operators (`operator()`) of such classes define parameters then the types of those parameters may also be abstracted by defining the function call operators themselves as member templates. Example:

```
template <typename Class>
class Filter
{
    Class obj;
    public:
        template <typename Param>
        Param operator()(Param const &param) const
```

```
            {
                return obj(param);
            }
    };
```

The template class `Filter` is a wrapper around `Class`, filtering `Class`'s function call operator through its own function call operator. In the above example the return value of `Class`'s function call operator is simply passed on, but any other manipulation is of course also possible.

A type that is specified as `Filter`'s template type argument may of course have multiple function call operators:

```
    struct Math
    {
        int operator()(int x);
        double operator()(double x);
    };
```

`Math` objects can now be filtered using `Filter<Math> fm` using `Math`'s first or second function call operator, depending on the actual argument type. With `fm(5)` the `int`-version is used, with `fm(12.5)` the `double`-version is used.

However, this scheme doesn't work if the function call operators have different return and argument types. Because of this the following class `Convert` cannot be used with `Filter`:

```
    struct Convert
    {
        double operator()(int x);            // int-to-double
        std::string operator()(double x);    // double-to-string
    };
```

This problem can be tackled successfully by the class template `std::result_of<Functor(Typelist)>`. Before using `std::result_of` the header file `<functional>` must be included.

The `result_of` class template offers a `typedef` (`type`), representing the type that is returned by `Functor<TypeList>`. It can be used as follows to improve the implementation of `Filter`:

```
    template <typename Class>
    class Filter
    {
        Class obj;
        public:
            template <typename Arg>
                typename std::result_of<Class(Arg)>::type
                operator()(Arg const &arg) const
                {
                    return obj(arg);
                }
    };
```

Using this definition, `Filter<Convert> fc` can be constructed. Now `fc(5)` returns a `double`, while `fc(4.5)` returns a `std::string`.

The class `Convert` must define the relationships between its function call operators and their return types. Predefined function objects (like those in the standard template library) already do so, but self-defined function objects must do this explicitly.

If a function object class defines only one function call operator it can define its return type by a `typedef`. If the above class `Convert` would only define the first of its two function call operators then the `typedef` (in the class's `public` section) should be:

```
typedef double type;
```

If multiple function call operators are defined, each with its own signature and return type, then the association between signature and return type is set up as follows (all in the class's `public` section):

- define a generic `struct result` like this:

  ```
  template <typename Signature>
  struct result;
  ```

- For each function call signature define a *specialization* of `struct result`. `Convert`'s first function call operator gives rise to:

  ```
  template <typename Class>
  struct result<Class(int)>
  {
      typedef double type;
  };
  ```

  and `Convert`'s second function call operator to:

  ```
  template <typename Class>
  struct result<Class(double)>
  {
      typedef std::string type;
  };
  ```

- In cases where function call operators have multiple arguments the specifications should again provide for the correct signatures. A function call operator called with an `int` and a `double`, returning a `size_t` gets:

  ```
  template <typename Class>
  struct result<Class(int, double)>
  {
      typedef size_t type;
  };
  ```

22.8 Instantiating class templates

Class templates are instantiated when an object of a class template is defined. When a class template object is defined or declared its template parameters must explicitly be specified.

Template parameters are *also* specified when default template parameter values are specified albeit that in that case the compiler provides the defaults (cf. section 22.4 where `double` is used as the default type to use for the template's `DataType` parameter). The actual values or types of template parameters are *never* deduced from arguments as is done with function template parameters. So to define a `Matrix` of complex-valued elements, the following syntax is used:

```
    Matrix<3, 5, std::complex> complexMatrix;
```

Since the class template `Matrix` uses a default data type a matrix of `double`-valued elements can be defined like this:

```
    Matrix<3, 5> doubleMatrix;
```

A class template object may be *declared* using the keyword `extern`. For example, to *declare* the matrix `complexMatrix` use:

```
    extern Matrix<3, 5, std::complex> complexMatrix;
```

A class template declaration suffices to compile return values or parameters that are of class template types. Example: the following source file may be compiled, although the compiler hasn't seen the definition of the `Matrix` class template. Generic classes and (partial) specializations may all be declared. A function expecting or returning a class template object, reference, or parameter automatically becomes a function template itself. This is necessary to allow the compiler to tailor the function to the types of various actual arguments that may be passed to the function:

```
    #include <cstddef>

    template <size_t Rows, size_t Columns, typename DataType = double>
    class Matrix;

    template <size_t Columns, typename DataType>
    class Matrix<1, Columns, DataType>;

    Matrix<1, 12> *function(Matrix<2, 18, size_t> &mat);
```

When class templates are *used* the compiler must first have seen their implementations. So, template member functions must be known to the compiler when the template is instantiated. This does not mean that *all* members of a template class are instantiated or must have been seen when a class template object is defined. The compiler only instantiates those members that are actually used. This is illustrated by the following simple class `Demo` that has two constructors and two members. When we use one constructor and call one member in `main` note the sizes of the resulting object file and executable program. Next the class definition is modified in that the unused constructor and member are commented out. Again we compile and link the program. Now observe that these latter sizes are identical to the former sizes. There are other ways to illustrate that only used members are instantiated. The `nm` program could be used. It shows the symbolic content of object files. Using `nm` we'll reach the same conclusion: *only template member functions that are actually used are instantiated*. Here is the class template `Demo` that was used for our little experiment. In `main` only the first constructor and the first member function are called and thus only these members were instantiated:

```
    #include <iostream>

    template <typename Type>
    class Demo
    {
        Type d_data;
        public:
            Demo();
            Demo(Type const &value);
            void member1();
            void member2(Type const &value);
    };
    template <typename Type>
    Demo<Type>::Demo()
    :
        d_data(Type())
    {}
    template <typename Type>
    void Demo<Type>::member1()
    {
        d_data += d_data;
    }

    // the following members should be commented out before
    // compiling for the 2nd time:

    template <typename Type>
    Demo<Type>::Demo(Type const &value)
    :
        d_data(value)
    {}
    template <typename Type>
    void Demo<Type>::member2(Type const &value)
    {
        d_data += value;
    }

    int main()
    {
        Demo<int> demo;
        demo.member1();
    }
```

22.9 Processing class templates and instantiations

In section 21.13 the distinction between code depending on template parameters and code not depending on template parameters was introduced. The same distinction also holds true when class templates are defined and used.

Code not depending on template parameters is verified by the compiler when the template is defined. If a member function in a class template uses a `qsort` function, then `qsort` does not depend on a template parameter. Consequently, `qsort` must be known to the compiler when it encounters `qsort`'s function call. In practice this implies that the `<cstdlib>` header file must have been read by the compiler before it is able to compile the class template definition.

On the other hand, if a template defines a `<typename Ret>` template type parameter to parameterize the return type of some template member function as in:

```
    Ret member();
```

then the compiler may encounter `member` or the class to which `member` belongs in the following locations:

- the location where a class template object is defined. This is called the *point of instantiation* of the class template object. The compiler must have read the class template's implementation and has performed a basic check for syntactic correctness of member functions like `member`. It won't accept a definition or declaration like `Ret && *member`, because **C++** does not support functions returning pointers to rvalue references. Furthermore, it checks whether the actual type name that is used for instantiating the object is valid. This type name must be known to the compiler at the object's point of instantiation.
- the location where the template member function is used. This is called the template member function's point of instantiation. Here the `Ret` parameter must have been specified (or deduced) and at this point `member`'s statements that depend on the `Ret` template parameter are checked for syntactic correctness. For example, if `member` contains a statement like

  ```
  Ret tmp(Ret(), 15);
  ```

  then this is in principle a syntactically valid statement. However, when `Ret = int` the statement fails to compile as `int` does not have a constructor expecting two `int` arguments. Note that this is *not* a problem when the compiler instantiates an object of `member`'s class. At the point of instantiation of the object its member function '`member`' is not instantiated and so the invalid `int` construction remains undetected.

22.10 Declaring friends

Friend functions are normally constructed as *support* (free) functions of a class that cannot be implemented and declared as class members. The insertion operator for output streams is a well known example. Friend classes are most often seen in the context of nested classes. Here the inner class declares the outer class as its friend (or the other way around). Again we see a support mechanism: the inner class is constructed to support the outer class.

Like ordinary classes, class templates may declare other functions and classes as their friends. Conversely, ordinary classes may declare template classes as their friends. Here too, the friend is constructed as a special function or class augmenting or supporting the functionality of the declaring class. Although the `friend` keyword can be used by any type of class (ordinary or template) when using class templates the following cases should be distinguished:

- A class template may declare an ordinary function or class as its friend. This is a common friend declaration, such as the insertion operator for `ostream` objects.
- A class template may declare another function template or class template as its friend. In this case, the friend's template parameters may have to be specified.

  If the actual values of the friend's template parameters *must* be equal to the template parameters of the class declaring the friend, the friend is said to be a *bound friend* class or function template. In this case the template parameters of the template specifying the `friend` declaration determine (*bind*) the values of the template parameters of the friend class or function. Bound friends result in a one-to-one correspondence between the template's parameters and the friend's template parameters.
- In the most general case a class template may declare another function template or class template to be its friend, irrespective of the friend's actual template arguments.

  In this case an *unbound friend* class or function template is declared. The template parameters of the friend class or function template remain to be specified and are not related in some predefined way to the template parameters of the class declaring the friend. If a class template has data members of various types, specified by its template parameters and another class should be allowed direct access to these data members we want to specify any of the current template arguments when specifying such a friend. Rather than specifying multiple bound friends, a single generic (unbound) friend may be declared, specifying the friend's actual template parameters only when this is required.

- The above cases, in which a template is declared as a friend, may also be encountered when ordinary classes are used:
  - The ordinary class declaring ordinary friends has already been covered (chapter 15).
  - The equivalent of bound friends occurs if an ordinary class specifies specific actual template parameters when declaring its friend.
  - The equivalent of unbound friends occurs if an ordinary class declares a generic template as its friend.

22.10.1 Non-templates used as friends in templates

A class template may declare an ordinary function, ordinary member function or ordinary class as its friend. Such a friend may access the class template's private members.

Concrete classes and ordinary functions can be declared as friends, but before a single member function of a class can be declared as a friend, the compiler must have seen the class interface declaring that member. Let's consider the various possibilities:

- A class template may declare an ordinary function to be its friend. It is not completely clear *why* we would like to declare an ordinary function as a friend. Usually we pass an object of the class declaring the friend to such a function. With class templates this requires us to provide the (friend) function with a template parameter without specifying its types. As the language does not support constructions like

  ```
  void function(std::vector<Type> &vector)
  ```

  unless `function` itself is a template, it is not immediately clear how and why such a friend should be constructed. One reason could be to allow the function access to the class's private static members. In addition such friends could instantiate objects of classes that declare them as their friends. This would allow the friend functions direct access to such object's private members. For example:

  ```
      template <typename Type>
      class Storage
      {
          friend void basic();
          static size_t s_time;
          std::vector<Type> d_data;
          public:
              Storage();
      };
      template <typename Type>
      size_t Storage<Type>::s_time = 0;
      template <typename Type>
      Storage<Type>::Storage()
      {}

      void basic()
      {
  ```

```
        Storage<int>::s_time = time(0);
        Storage<double> storage;
        std::sort(storage.d_data.begin(), storage.d_data.end());
    }
```

- Declaring an ordinary class to be a class template's friend probably finds more applications. Here the ordinary (friend) class may instantiate any kind of object of the class template. The friend class may then access all private members of the instantiated class template:

```
    template <typename Type>
    class Composer
    {
        friend class Friend;
        std::vector<Type> d_data;
        public:
            Composer();
    };

    class Friend
    {
        Composer<int> d_ints;
        public:
            Friend(std::istream &input);
    };

    inline::Friend::Friend(std::istream &input)
    {
        std::copy(std::istream_iterator<int>(input),
                  std::istream_iterator<int>(),
                  back_inserter(d_ints.d_data));
    }
```

- Alternatively, just a single member function of an ordinary class may be declared as a friend. This requires that the compiler has read the friend class's interface before declaring the friend. Omitting the required destructor and overloaded assignment operators, the following shows an example of a class whose member `sorter` is declared as a friend of the class `Composer`:

```
    template <typename Type>
    class Composer;

    class Friend
    {
        Composer<int> *d_ints;
        public:
            Friend(std::istream &input);
            void sorter();
    };

    template <typename Type>
    class Composer
    {
        friend void Friend::sorter();
        std::vector<Type> d_data;
        public:
            Composer(std::istream &input)
            {
                std::copy(std::istream_iterator<int>(input),
                          std::istream_iterator<int>(),
                          back_inserter(d_data));
            }
    };

    inline Friend::Friend(std::istream &input)
    :
        d_ints(new Composer<int>{ input })
    {}

    inline void Friend::sorter()
    {
        std::sort(d_ints->d_data.begin(), d_ints->d_data.end());
    }
```

In this example `Friend::d_ints` is a pointer member. It cannot be a `Composer<int>` object as the `Composer` class interface hasn't yet been seen by the compiler when it reads `Friend`'s class interface. Disregarding this and defining a data member `Composer<int> d_ints` results in the compiler generating the error

```
error: field `d_ints' has incomplete type
```

'Incomplete type', as the compiler at this points knows of the existence of the class `Composer`, but as it hasn't seen `Composer`'s interface it doesn't know what size the `d_ints` data member has.

22.10.2 Templates instantiated for specific types as friends

With *bound friend* class or function templates there is a one-to-one mapping between the template arguments of the friend templates and the template arguments of the class templates declaring them as friends. In this case, the friends themselves are templates too. Here are the various possibilities:

- A function template is a friend of a class template. In this case we don't experience the problems we encountered with ordinary functions declared as friends of class templates. Since the friend function template itself is a template it may be provided with the required template arguments allowing it to become the declaring class's friend. The various declarations are organized like this:
  - The class template declaring the bound template friend function is defined;
  - The (friend) function template is defined, now having access to all the class template's (private) members.

  The bound template friend declaration specifies the required template arguments immediately following the template's function name. Without the template argument list affixed to the function name it would remain an ordinary friend function. Here is an example showing a bound friend to create a subset of the entries of a dictionary. For real life examples, a dedicated function object returning `!key1.find(key2)` is probably more useful. For the current example, `operator==` is acceptable:

```
    template <typename Key, typename Value>
    class Dictionary
    {
        friend Dictionary<Key, Value>
            subset<Key, Value>(Key const &key,
                            Dictionary<Key, Value> const &dict);

    std::map<Key, Value> d_dict;
    public:
        Dictionary();
};

template <typename Key, typename Value>
Dictionary<Key, Value>
           subset(Key const &key, Dictionary<Key, Value> const &dict)
{
    Dictionary<Key, Value> ret;

    std::remove_copy_if(dict.d_dict.begin(), dict.d_dict.end(),
                        std::inserter(ret.d_dict, ret.d_dict.begin()),
                        std::bind2nd(std::equal_to<Key>(), key));
    return ret;
}
```

- By declaring a full class template as a class template's friend, all members of the friend class may access all private members of the class declaring the friend. As the friend class only needs to be declared, the organization of the declaration is much easier than when function templates are declared as friends. In the following example a class `Iterator` is declared as a friend of a class `Dictionary`. Thus, the `Iterator` is able to access `Dictionary`'s private data. There are some interesting points to note here:
  - To declare a class template as a friend, that class only needs to be declared as a class template before it is declared as a friend:

    ```
    template <typename Key, typename Value>
    class Iterator;

    template <typename Key, typename Value>
    class Dictionary
    {
        friend class Iterator<Key, Value>;
    ```

  - However, members of the friend class may already be used, even though the compiler hasn't seen the friend class's interface yet:

    ```
    template <typename Key, typename Value>
    template <typename Key2, typename Value2>
    Iterator<Key2, Value2> Dictionary<Key, Value>::begin()
    {
        return Iterator<Key, Value>(*this);
    }
    template <typename Key, typename Value>
    template <typename Key2, typename Value2>
    Iterator<Key2, Value2> Dictionary<Key, Value>::subset(Key const &key)
    {
        return Iterator<Key, Value>(*this).subset(key);
    }
    ```

  - Of course, the friend class's interface must eventually be seen by the compiler. Since it's a support class for `Dictionary` it can safely define a `std::map` data member that is initialized by the friend class's constructor. The constructor may then access the `Dictionary`'s private data member `d_dict`:

    ```
    template <typename Key, typename Value>
    ```

```
class Iterator
{
    std::map<Key, Value> &d_dict;

    public:
        Iterator(Dictionary<Key, Value> &dict)
        :
            d_dict(dict.d_dict)
        {}
```

  - The `Iterator` member `begin` may return a `map` iterator. Since the compiler does not know what the instantiation of the map looks like, a `map<Key, Value>::iterator` is a template subtype. So it cannot be used as-is, but it must be prefixed by `typename` (see the function `begin`'s return type in the next example):

```
template <typename Key, typename Value>
typename std::map<Key, Value>::iterator Iterator<Key, Value>::begin()
{
    return d_dict.begin();
}
```

- In the previous example we might decide that only a `Dictionary` should be able to construct an `Iterator` (maybe because we conceptually consider `Iterator` to be a sub-type of `Dictionary`). This is easily accomplished by defining `Iterator`'s constructor in its private section, and by declaring `Dictionary` to be a friend of `Iterator`. Consequently, only a `Dictionary` can create an `Iterator`. By declaring the constructor of a *specific* `Dictionary` type as a friend of `Iterator`'s we declare a *bound* friend. This ensures that only that particular type of `Dictionary` can create `Iterator`s using template parameters identical to its own. Here is how it's done:

```
template <typename Key, typename Value>
class Iterator
{
    friend Dictionary<Key, Value>::Dictionary();
    std::map<Key, Value> &d_dict;
    Iterator(Dictionary<Key, Value> &dict);
    public:
```

  In this example, `Dictionary`'s constructor is `Iterator`'s friend. The friend is a template member. Other members can be declared as a class's friend as well. In those cases their prototypes must be used, also specifying the types of their return values. Assuming that

```
std::vector<Value> sortValues()
```

  is a member of `Dictionary` then the matching bound friend declaration is:

```
friend std::vector<Value> Dictionary<Key, Value>::sortValues();
```

- A class template may define free members, which should have access to the data of instantiations of the class template, but only for matching types. An example is a class template for which the free member `operator==` must be available. If this is required for a template `ClassTemplate`, requiring a `typename Type` template type argument, then a free member

```
template<typename Type>
bool operator==(ClassTemplate<Type> const &lhs,
                ClassTemplate<Type> const &rhs);
```

must have been declared prior to `ClassTemplate`'s interface itself. Within the class interface `operator==` may then be declared as a friend, specifying `operator==` as a specialized function template (note the <> following the function name) like this:

```
template <typename Type>
class ClassTemplate
{
    friend  bool operator==<>(ClassTemplate<Type> const &lhs,
                              ClassTemplate<Type> const &rhs);
    ...
};
```

Now that the class has been declared, `operator==`'s implementation may follow.

Finally, the following example can be used as a prototype for situations where bound friends are useful:

```
template <typename T>   // a function template
void fun(T *t)
{
    t->not_public();
};
template<typename X>    // a free member function template
bool operator==(A<X> const &lhs, A<X> const &rhs);
template <typename X>   // a class template
class A
{                       // fun() is used as friend bound to A,
                        // instantiated for X, whatever X may be
    friend void fun<A<X>>(A<X> *);
                        // operator== is a friend for A<X> only
    friend  bool operator==<>(A<X> const &lhs, A<X> const &rhs);

    int d_data = 10;

    public:
        A();

    private:
        void not_public();
};
template <typename X>
A<X>::A()
{
    fun(this);
}
template <typename X>
void A<X>::not_public()
{}
template<typename X>    // may access lhs/rhs's private data
bool operator==(A<X> const &lhs, A<X> const &rhs)
{
    return lhs.d_data == rhs.d_data;
}

int main()
```

```
{
    A<int> a;

    fun(&a);            // fun instantiated for A<int>.
}
```

22.10.3 Unbound templates as friends

When a friend is declared as an *unbound* friend it merely declares an existing template to be its friend (no matter how it is instantiated). This may be useful in situations where the friend should be able to instantiate objects of class templates declaring the friend, allowing the friend to access the instantiated object's private members. Functions, classes, and member functions may all be declared as unbound friends.

Here are the syntactic conventions declaring unbound friends:

- Declaring a function template as an unbound friend: any instantiation of the function template may instantiate objects of the template class and may access its private members. Assume the following function template has been defined

  ```
  template <typename Iterator, typename Class, typename Data>
  Class &ForEach(Iterator begin, Iterator end, Class &object,
                      void (Class::*member)(Data &));
  ```

  This function template can be declared as an unbound friend in the following class template `Vector2`:

  ```
  template <typename Type>
  class Vector2: public std::vector<std::vector<Type> >
  {
      template <typename Iterator, typename Class, typename Data>
      friend Class &ForEach(Iterator begin, Iterator end, Class &object,
                  void (Class::*member)(Data &));
      ...
  };
  ```

  If the function template is defined inside some namespace this namespace must be mentioned as well. Assuming that `ForEach` is defined in the namespace `FBB` its friend declaration becomes:

  ```
  template <typename Iterator, typename Class, typename Data>
  friend Class &FBB::ForEach(Iterator begin, Iterator end, Class &object,
                  void (Class::*member)(Data &));
  ```

  The following example illustrates the use of an unbound friend. The class `Vector2` stores vectors of elements of template type parameter `Type`. Its `process` member allows `ForEach` to call its private `rows` member. The `rows` member, in turn, uses another `ForEach` to call its private `columns` member. Consequently, `Vector2` uses two instantiations of `ForEach` which is a clear hint for using an unbound friend. It is assumed that `Type` class objects can be inserted into `ostream` objects (the definition of the `ForEach` function template can be found in the `cplusplus.yo.zip` archive that can be retrieved from `https://fbb-git.gitlab.io/cppannotations/`). Here is the program:

  ```
      template <typename Type>
      class Vector2: public std::vector<std::vector<Type> >
  ```

```
{
    typedef typename Vector2<Type>::iterator iterator;

    template <typename Iterator, typename Class, typename Data>
    friend Class &ForEach(Iterator begin, Iterator end, Class &object,
                void (Class::*member)(Data &));
    public:
        void process();

    private:
        void rows(std::vector<Type> &row);
        void columns(Type &str);
};

template <typename Type>
void Vector2<Type>::process()
{
    ForEach<iterator, Vector2<Type>, std::vector<Type> >
            (this->begin(), this->end(), *this, &Vector2<Type>::rows);
}

template <typename Type>
void Vector2<Type>::rows(std::vector<Type> &row)
{
    ForEach(row.begin(), row.end(), *this,
                                    &Vector2<Type>::columns);
    std::cout << '\n';
}

template <typename Type>
void Vector2<Type>::columns(Type &str)
{
    std::cout << str << " ";
}

using namespace std;

int main()
{
    Vector2<string> c;
    c.push_back(vector<string>(3, "Hello"));
    c.push_back(vector<string>(2, "World"));

    c.process();
}
/*
    Generated output:

    Hello Hello Hello
    World World
*/
```

- Analogously, a full class template may be declared as friend. This allows all instantiations of the friend's member functions to instantiate objects of the class template declaring the friend class. In this case, the class declaring the friend should offer functionality that is useful to different instantiations of its friend class (i.e., instantiations using different template arguments). The syntactic convention is comparable to the convention used when declaring an unbound friend function template:

```
template <typename Type>
class PtrVector
{
    template <typename Iterator, typename Class>
    friend class Wrapper;      // unbound friend class
};
```

All members of the class template `Wrapper` may now instantiate `PtrVector`s using any actual type for its `Type` parameter. This allows the `Wrapper` instantiation to access all of `PtrVector`'s private members.

- When only some members of a class template need access to private members of another class template (e.g., the other class template has private constructors and only some members of the first class template need to instantiate objects of the second class template), then the latter class template may declare only those members of the former class template requiring access to its private members as its friends. Again, the friend class's interface may be left unspecified. However, the compiler must be informed that the friend member's class is indeed a class. A forward declaration of that class must therefore be provided. In the next example `PtrVector` declares `Wrapper::begin` as its friend. Note the forward declaration of the class `Wrapper`:

```
template <typename Iterator>
class Wrapper;

template <typename Type>
class PtrVector
{
    template <typename Iterator> friend
        PtrVector<Type> Wrapper<Iterator>::begin(Iterator const &t1);
    ...
};
```

22.10.4 Extended friend declarations

Through *extended friend declarations*, which are also available for class templates, template type parameters can be declared as friends. A template type argument, however, does not necessarily have to be a type for which the keyword `friend` makes sense, like `int`. In those cases the friend declaration is simply ignored.

Consider the following class template, declaring `Friend` as a friend:

```
template <typename Friend>
class Class
{
    friend Friend;
    void msg();             // private, displays some message
};
```

Now, an actual `Friend` class may access all of `Class`'s members

```
class Concrete
{
        Class<Concrete> d_class;
        Class<std::string> d_string;

       public:
            void msg()
            {
                d_class.msg();    // OK: calls private Class<Concrete>::msg()
                //d_string.msg(); // fails to compile: msg() is private
            }
    };
```

A declaration like `Class<int> intClass` is also OK, but here the friend declaration is simply ignored. After all, there are no 'int members' to access `Class<int>`'s private members.

22.11 Class template derivation

Class templates can be used for inheritance purposes as well. When a class template is used in class derivation, the following situations should be distinguished:

- An existing class template is used as base class when deriving a ordinary class. The derived class itself will partially be a class template, but this is somewhat hidden from view when an object of the derived class is defined.
- An existing class template is used as the base class when deriving another class template. Here the class template characteristics remain clearly visible.
- An ordinary class is used as the base class when deriving a template class. This interesting hybrid allows us to construct class templates that are *partially compiled*.

These three variants of class template derivation are elaborated in this and the upcoming sections.

Consider the following base class:

```
    template<typename T>
    class Base
    {
        T const &t;

        public:
            Base(T const &t);
    };
```

The above class is a class template that can be used as a base class for the following derived class template `Derived`:

```
    template<typename T>
    class Derived: public Base<T>
    {
        public:
            Derived(T const &t);
    };
    template<typename T>
    Derived<T>::Derived(T const &t)
```

```
:
    Base(t)
{}
```

Other combinations are also possible. The base class may be instantiated by specifying template arguments, turning the derived class into an ordinary class (showing a class object's definition as well):

```
class Ordinary: public Base<int>
{
    public:
        Ordinary(int x);
};
inline Ordinary::Ordinary(int x)
:
    Base(x)
{}

Ordinary ordinary{ 5 };
```

This approach allows us to add functionality to a class template, without the need for constructing a derived class template.

Class template derivation pretty much follows the same rules as ordinary class derivation, not involving class templates. Some subtleties that are specific for class template derivation may easily cause confusion like the use of `this` when members of a template base class are called from a derived class. The reasons for using `this` are discussed in section 23.1. In the upcoming sections the focus will be on the class derivation proper.

22.11.1 Deriving ordinary classes from class templates

When an existing class template is used as a base class for deriving an ordinary class, the class template parameters are specified when defining the derived class's interface. If in a certain context an existing class template lacks a particular functionality, then it may be useful to derive an ordinary class from a class template. For example, although the class `map` can easily be used in combination with the `find_if()` generic algorithm (section 19.1.17), it requires the construction of a class and at least two additional function objects of that class. If this is considered too much overhead then extending a class template with tailor-made functionality might be considered.

Example: a program executing commands entered at the keyboard might accept all unique initial abbreviations of the commands it defines. E.g., the command `list` might be entered as `l, li, lis` or `list`. By deriving a class `Handler` from

```
map<string, void (Handler::*)(string const &cmd)>
```

and by defining a member function `process(string const &cmd)` to do the actual command processing a program might simply execute the following `main()` function:

```
int main()
{
    string line;
    Handler cmd;
```

```
        while (getline(cin, line))
            cmd.process(line);
    }
```

The class `Handler` itself is derived from a `std::map`, in which the map's values are pointers to `Handler`'s member functions, expecting the command line entered by the user. Here are `Handler`'s characteristics:

- The class is derived from a `std::map`, expecting the command associated with each command-processing member as its keys. Since `Handler` uses the map merely to define associations between the commands and the processing member functions and to make available `map`'s `typedef`s, private derivation is used:

```
class Handler: private std::map<std::string,
                        void (Handler::*)(std::string const &cmd)>
```

- The actual association can be defined using static private data members: `s_cmds` is an array of `Handler::value_type` values, and `s_cmds_end` is a constant pointer pointing beyond the array's last element:

```
    static value_type s_cmds[];
    static value_type *const s_cmds_end;
```

- The constructor simply initializes the map from these two static data members. It could be implemented inline:

```
inline Handler::Handler()
:
    std::map<std::string,
                void (Handler::*)(std::string const &cmd)>
    (s_cmds, s_cmds_end)
{}
```

- The member `process` iterates along the map's elements. Once the first word on the command line matches the initial characters of the command, the corresponding command is executed. If no such command is found, an error message is issued:

```
void Handler::process(std::string const &line)
{
    istringstream istr(line);
    string cmd;
    istr >> cmd;
    for (iterator it = begin(); it != end(); it++)
    {
        if (it->first.find(cmd) == 0)
        {
            (this->*it->second)(line);
            return;
        }
    }
    cout << "Unknown command: " << line << '\n';
}
```

22.11.2 Deriving class templates from class templates

Although it's perfectly acceptable to derive an ordinary class from a class template, the resulting class of course has limited generality compared to its template base class. If generality is important, it's probably a better idea to derive a class template from a class template. This allows us to extend an existing class template with new functionality or to override the functionality of the existing class template.

The class template `SortVector` presented below is derived from the existing class template `std::vector`. It allows us to perform a *hierarchic sort* of its elements using any ordering of any data members its data elements may contain. To accomplish this there is but one requirement. `SortVector`'s data type must offer dedicated member functions comparing its members.

For example, if `SortVector`'s data type is an object of class `MultiData`, then `MultiData` should implement member functions having the following prototypes for each of its data members which can be compared:

```
    bool (MultiData::*)(MultiData const &rhv)
```

So, if `MultiData` has two data members, `int d_value` and `std::string d_text` and both may be used by a hierarchic sort, then `MultiData` should offer the following two members:

```
    bool intCmp(MultiData const &rhv);  // returns d_value < rhv.d_value
    bool textCmp(MultiData const &rhv); // returns d_text  < rhv.d_text
```

Furthermore, as a convenience it is assumed that `operator<<` and `operator>>` have been defined for `MultiData` objects.

The class template `SortVector` is directly derived from the template class `std::vector`. Our implementation inherits all members from that base class. It also offers two simple constructors:

```
    template <typename Type>
    class SortVector: public std::vector<Type>
    {
        public:
            SortVector()
            {}
            SortVector(Type const *begin, Type const *end)
            :
                std::vector<Type>(begin, end)
            {}
```

Its member `hierarchicSort` is the true *raison d'être* for the class. It defines the hierarchic sort criteria. It expects a pointer to a series of pointers to member functions of the class `Type` as well as a `size_t` representing the size of the array.

The array's first element indicates `Type`'s most significant sort criterion, the array's last element indicates the class's least significant sort criterion. Since the `stable_sort` generic algorithm was designed explicitly to support hierarchic sorting, the member uses this generic algorithm to sort `SortVector`'s elements. With hierarchic sorting, the least significant criterion should be sorted first. `hierarchicSort`'s implementation is therefore easy. It requires a support class `SortWith` whose objects are initialized by the addresses of the member functions passed to the `hierarchicSort()` member:

```
    template <typename Type>
```

```
void SortVector<Type>::hierarchicSort(
            bool (Type::**arr)(Type const &rhv) const,
            size_t n)
{
    while (n--)
        stable_sort(this->begin(), this->end(), SortWith<Type>(arr[n]));
}
```

The class `SortWith` is a simple wrapper class around a pointer to a predicate function. Since it depends on `SortVector`'s actual data type the class `SortWith` must also be a class template:

```
template <typename Type>
class SortWith
{
   bool (Type::*d_ptr)(Type const &rhv) const;
```

`SortWith`'s constructor receives a pointer to a predicate function and initializes the class's `d_ptr` data member:

```
template <typename Type>
SortWith<Type>::SortWith(bool (Type::*ptr)(Type const &rhv) const)
:
    d_ptr(ptr)
{}
```

Its binary predicate member (`operator()`) must return `true` if its first argument should eventually be placed ahead of its second argument:

```
template <typename Type>
bool SortWith<Type>::operator()(Type const &lhv, Type const &rhv) const
{
    return (lhv.*d_ptr)(rhv);
}
```

The following examples, which can be embedded in a `main` function, provides an illustration:

- First, A `SortVector` object is created for `MultiData` objects. It uses the `copy` generic algorithm to fill the `SortVector` object from information appearing at the program's standard input stream. Having initialized the object its elements are displayed to the standard output stream:

  ```
  SortVector<MultiData> sv;

  copy(istream_iterator<MultiData>(cin),
          istream_iterator<MultiData>(),
          back_inserter(sv));
  ```

- An array of pointers to members is initialized with the addresses of two member functions. The text comparison is the most significant sort criterion:

  ```
  bool (MultiData::*arr[])(MultiData const &rhv) const =
  {
      &MultiData::textCmp,
      &MultiData::intCmp,
  };
  ```

- Next, the array's elements are sorted and displayed to the standard output stream:

  ```
          sv.hierarchicSort(arr, 2);
  ```

- Then the two elements of the array of pointers to `MultiData`'s member functions are swapped, and the previous step is repeated:

  ```
          swap(arr[0], arr[1]);
          sv.hierarchicSort(arr, 2);
  ```

After compiling the program the following command can be given:

```
echo a 1 b 2 a 2 b 1 | a.out
```

This results in the following output:

```
a 1 b 2 a 2 b 1
====
a 1 a 2 b 1 b 2
====
a 1 b 1 a 2 b 2
====
```

22.11.3 Deriving class templates from ordinary classes

An ordinary class may be used as the base class for deriving a template class. The advantage of such an inheritance tree is that the base class's members may all be compiled beforehand. When objects of the class template are now instantiated only the actually used members of the derived class template must be instantiated.

This approach may be used for all class templates having member functions whose implementations do not depend on template parameters. These members may be defined in a separate class which is then used as a base class of the class template derived from it.

As an illustration of this approach we'll develop such a class template below. We'll develop a class `Table` derived from an ordinary class `TableType`. The class `Table` displays elements of some type in a table having a configurable number of columns. The elements are either displayed horizontally (the first *k* elements occupy the first row) or vertically (the first *r* elements occupy a first column).

When displaying the table's elements they are inserted into a stream. The table is handled by a separate class (`TableType`), implementing the table's presentation. Since the table's elements are inserted into a stream, the conversion to text (or `string`) is implemented in `Table`, but the handling of the strings themselves is left to `TableType`. We'll cover some characteristics of `TableType` shortly, concentrating on `Table`'s interface first:

- The class `Table` is a class template, requiring only one template type parameter: `Iterator` referring to an iterator to some data type:

  ```
  template <typename Iterator>
  class Table: public TableType
  {
  ```

- `Table` doesn't need any data members. All data manipulations are performed by `TableType`.

- `Table` has two constructors. The constructor's first two parameters are `Iterator`s used to iterate over the elements that must be entered into the table. The constructors require us to specify the number of columns we would like our table to have as well as a *FillDirection*. `FillDirection` is an `enum`, defined by `TableType`, having values `HORIZONTAL` and `VERTICAL`. To allow `Table`'s users to exercise control over headers, footers, captions, horizontal and vertical separators, one constructor has a `TableSupport` reference parameter. The class `TableSupport` is developed at a later stage as a virtual class allowing clients to exercise this control. Here are the class's constructors:

```
        Table(Iterator const &begin, Iterator const &end,
                size_t nColumns, FillDirection direction);
        Table(Iterator const &begin, Iterator const &end,
                TableSupport &tableSupport,
                size_t nColumns, FillDirection direction);
```

- The constructors are `Table`'s only two public members. Both constructors use a base class initializer to initialize their `TableType` base class and then call the class's private member `fill` to insert data into the `TableType` base class object. Here are the constructor's implementations:

```
template <typename Iterator>
Table<Iterator>::Table(Iterator const &begin, Iterator const &end,
                TableSupport &tableSupport,
                size_t nColumns, FillDirection direction)
:
    TableType(tableSupport, nColumns, direction)
{
    fill(begin, end);
}

template <typename Iterator>
Table<Iterator>::Table(Iterator const &begin, Iterator const &end,
                size_t nColumns, FillDirection direction)
:
    TableType(nColumns, direction)
{
    fill(begin, end);
}
```

- The class's `fill` member iterates over the range of elements `[begin, end)`, as defined by the constructor's first two parameters. As we will see shortly, `TableType` defines a protected data member `std::vector<std::string> d_string`. One of the requirements of the data type to which the iterators point is that this data type can be inserted into streams. So, `fill` uses an `ostringstream` object to obtain the textual representation of the data, which is then appended to `d_string`:

```
template <typename Iterator>
void Table<Iterator>::fill(Iterator it, Iterator const &end)
{
    while (it != end)
    {
        std::ostringstream str;
        str << *it++;
        d_string.push_back(str.str());
    }
    init();
}
```

This completes the implementation of the class `Table`. Note that this class template only has three members, two of them being constructors. Therefore, in most cases only two function templates must be instantiated: a constructor and the class's `fill` member. For example, the following defines a table having four columns, vertically filled by `string`s extracted from the standard input stream:

```
Table<istream_iterator<string> >
    table(istream_iterator<string>(cin), istream_iterator<string>(),
          4, TableType::VERTICAL);
```

The fill-direction is specified as `TableType::VERTICAL`. It could also have been specified using `Table`, but since `Table` is a class template its specification would have been slightly more complex: `Table<istream_iterator<string> >::VERTICAL`.

Now that the `Table` derived class has been designed, let's turn our attention to the class `TableType`. Here are its essential characteristics:

- It is an ordinary class, designed to operate as `Table`'s base class.
- It uses various private data members, among which `d_colWidth`, a vector storing the width of the widest element per column and `d_indexFun`, pointing to the class's member function returning the element in `table[row][column]`, conditional to the table's fill direction. `TableType` also uses a `TableSupport` pointer and a reference. The constructor not requiring a `TableSupport` object uses the `TableSupport *` to allocate a (default) `TableSupport` object and then uses the `TableSupport &` as the object's alias. The other constructor initializes the pointer to 0 and uses the reference data member to refer to the `TableSupport` object provided by its parameter. Alternatively, a static `TableSupport` object could have been used to initialize the reference data member in the former constructor. The remaining private data members are probably self-explanatory:

```
        TableSupport           *d_tableSupportPtr;
        TableSupport           &d_tableSupport;
        size_t                 d_maxWidth;
        size_t                 d_nRows;
        size_t                 d_nColumns;
        WidthType                d_widthType;
        std::vector<size_t>    d_colWidth;
        size_t                (TableType::*d_widthFun)
                                         (size_t col) const;
        std::string const     &(TableType::*d_indexFun)
                                         (size_t row, size_t col) const;
```

- The actual `string` objects populating the table are stored in a protected data member:

```
        std::vector<std::string> d_string;
```

- The (protected) constructors perform basic tasks: they initialize the object's data members. Here is the constructor expecting a reference to a `TableSupport` object:

```
#include "tabletype.ih"

TableType::TableType(TableSupport &tableSupport, size_t nColumns,
                        FillDirection direction)
:
    d_tableSupportPtr(0),
    d_tableSupport(tableSupport),
    d_maxWidth(0),
    d_nRows(0),
    d_nColumns(nColumns),
    d_widthType(COLUMNWIDTH),
    d_colWidth(nColumns),
    d_widthFun(&TableType::columnWidth),
    d_indexFun(direction == HORIZONTAL ?
                    &TableType::hIndex
                :
                    &TableType::vIndex)
{}
```

- Once `d_string` has been filled, the table is initialized by `Table::fill`. The `init` protected member resizes `d_string` so that its size is exactly `rows x columns`, and it determines the maximum width of the elements per column. Its implementation is straightforward:

```
#include "tabletype.ih"

void TableType::init()
{
    if (!d_string.size())                     // no elements
        return;                               // then do nothing

    d_nRows = (d_string.size() + d_nColumns - 1) / d_nColumns;
    d_string.resize(d_nRows * d_nColumns);    // enforce complete table

                                              // determine max width per column,
                                              // and max column width
    for (size_t col = 0; col < d_nColumns; col++)
    {
        size_t width = 0;
        for (size_t row = 0; row < d_nRows; row++)
        {
            size_t len = stringAt(row, col).length();
            if (width < len)
                width = len;
        }
        d_colWidth[col] = width;

        if (d_maxWidth < width)               // max. width so far.
            d_maxWidth = width;
    }
}
```

- The public member `insert` is used by the insertion operator (`operator<<`) to insert a `Table` into a stream. First it informs the `TableSupport` object about the table's dimensions. Next it displays the table, allowing the `TableSupport` object to write headers, footers and separators:

```
#include "tabletype.ih"

ostream &TableType::insert(ostream &ostr) const
{
    if (!d_nRows)
        return ostr;

    d_tableSupport.setParam(ostr, d_nRows, d_colWidth,
                            d_widthType == EQUALWIDTH ? d_maxWidth : 0);
        for (size_t row = 0; row < d_nRows; row++)
        {
            d_tableSupport.hline(row);

            for (size_t col = 0; col < d_nColumns; col++)
            {
                size_t colwidth = width(col);

                d_tableSupport.vline(col);
                ostr << setw(colwidth) << stringAt(row, col);
            }

            d_tableSupport.vline();
        }
        d_tableSupport.hline();

        return ostr;
    }
```

- The `cplusplus.yo.zip` archive contains `TableSupport`'s full implementation. This implementation is found in the directory `yo/classtemplates/examples/table`. Most of its remaining members are private. Among those, these two members return table element `[row][column]` for, respectively, a horizontally filled table and a vertically filled table:

```
        inline std::string const &TableType::hIndex(size_t row, size_t col) const
        {
            return d_string[row * d_nColumns + col];
        }
        inline std::string const &TableType::vIndex(size_t row, size_t col) const
        {
            return d_string[col * d_nRows + row];
        }
```

The support class `TableSupport` is used to display headers, footers, captions and separators. It has four virtual members to perform those tasks (and, of course, a virtual constructor):

- `hline(size_t rowIndex)`: called just before displaying the elements in row `rowIndex`.
- `hline()`: called immediately after displaying the final row.
- `vline(size_t colIndex)`: called just before displaying the element in column `colIndex`.
- `vline()`: called immediately after displaying all elements in a row.

The reader is referrred to the `cplusplus.yo.zip` archive for the full implementation of the classes `Table`, `TableType` and `TableSupport`. Here is a little program showing their use:

```
    /*
                                  table.cc
    */

    #include <fstream>
    #include <iostream>
    #include <string>
    #include <iterator>
```

```
#include <sstream>

#include "tablesupport/tablesupport.h"
#include "table/table.h"

using namespace std;
using namespace FBB;

int main(int argc, char **argv)
{
    size_t nCols = 5;
    if (argc > 1)
    {
        istringstream iss(argv[1]);
        iss >> nCols;
    }

    istream_iterator<string>   iter(cin);   // first iterator isn't const

    Table<istream_iterator<string> >
        table(iter, istream_iterator<string>(), nCols,
              argc == 2 ? TableType::VERTICAL : TableType::HORIZONTAL);

    cout << table << '\n';
}
/*
    Example of generated output:
    After: echo a b c d e f g h i j | demo 3
        a e i
        b f j
        c g
        d h
    After: echo a b c d e f g h i j | demo 3 h
        a b c
        d e f
        g h i
        j
*/
```

22.12 Static Polymorphism

Chapter 14 introduced polymorphism. Polymorphism allows us to use a base class's interface to call implementations which are defined in derived classes. Traditionally this involves defining *Vtables* for polymorphic classes, containing pointers to functions that can be overridden in derived classes. Objects of polymorphic classes harbor hidden pointers, pointing to their class's Vtables. This type of polymorphism is called *dynamic polymorphism*, and it uses *late binding* as the function to call is determined run-time, rather than compile-time.

In many cases, however, dynamic polymorphism isn't really required. Usually the derived class objects that are passed to functions expecting base class references are invariants: at fixed locations in programs fixed class types are used to create objects. The polymorphic nature of these objects is used inside the functions that receive these objects, expecting references to their base classes. As an example consider reading information from a network socket. A class `SocketBuffer` is derived from `std::streambuf`, and the `std::stream` receiving a pointer to the `SocketBuffer` merely uses `std::streambuf's` interface. However, the implementation, by using polymorphism, in fact communicates with functions defined in `SocketBuffer`.

The disadvantages of this scheme are that, firstly, inside the functions expecting references to polymorphic base classes execution is somewhat slowed down precisely because of late-binding. Member functions aren't directly called, but are called indirectly via the object's *vpointer* and their derived class's *Vtable*. Secondly, programs using dynamic polymorphism tend to become somewhat bloated compared to programs using static binding. The code bloat is caused by the requirement to satisfy at link-time all the references that are mentioned in all the object files comprising the final program. This requirement forces the linker to link all the functions whose addresses are stored in the *Vtables* of all polymorphic classes, even if these functions are never actually called.

Static polymorphism allows us to avoid these disadvantages. It can be used instead of dynamic polymorphism in cases where the abovementioned invariant holds. Static polymorphism, also called the *curiously recurring template pattern* (*CRTP*), is an example of *template meta programming* (see also chapter 23 for additional examples of template meta programming).

Whereas dynamic polymorphism is based on the concepts of *vpointers, Vtables*, and *function overriding*, static polymorphism capitalizes on the fact that function templates (c.q., member templates) are only compiled into executable code when they are actually called. This allows us to write code in which functions are called which are completely non-existent at the time we write our code. This, however, shouldn't worry us too much. After all, we use a comparable approach when calling a purely virtual function of an abstract base class. The function is really called, but which function is eventually called is determined later in time. With dynamic polymorphism it is determined run-time, with static polymorphism it is determined compile-time.

There's no need to consider static and dynamic polymorphism as mutually exclusive variants of polymorphism. Rather, both can be used together, combining their strengths.

This section contains several subsections.

- First, the syntax used with static polymorphism is introduced and illustrated;
- Next, it is shown how classes that use dynamic polymorphism can be converted to classes that use static polymorphism;
- Finally it is illustrated how static polymorphism can be used to reduce implementation effort. Static polymorphism allows us to implement only once what would have to be implemented repeatedly when only dynamic polymorphism is used.

22.12.1 An example of static polymorphism

With static polymorphism a class template takes the role of a base class in dynamic polymorphism. This class template declares several members, which are comparable to members of a polymorphic base class: they are either support members or they call members that are overridden in derived classes.

In the context of dynamic polymorphism these overridable members are the base class's virtual members. In the context of static polymorphism there are no virtual members. Instead, the statically polymorphic base class (referred to as the 'base class' below) declares a *template type parameter* (referred to as the 'derived class type' below). Next, the base class's interfacing members call members of the derived class type.

Here is a simple example: a class template acting as a base class. Its public interface consists of one member. But different from dynamic polymorphism there's no reference in the class's interface to any member showing polymorphic behavior (i.e, no 'virtual' members are declared):

```
template <class Derived>
struct Base
{
    void interface();
}
```

Let's have a closer look at the member '`interface`'. This member is called by functions receiving a reference or pointer to the base class, but it may call members that must be available in the derived class type at the point where `interface` is called. Before we can call members of the derived class type an object of the derived class type must be available. This object is obtained through inheritance. The derived class type is going to be derived from the base class. Thus `Base's this` pointer is also `Derived's this` pointer.

Forget about polymorphism for a second: when we have a `class Derived: public Base` then (because of inheritance) a `static_cast<Derived *>` can be used to cast a `Base *` to a `Derived` object. A `dynamic_cast` of course doesn't apply, as we don't use dynamic polymorphism. But a `static_cast` is appropriate since our `Base *` *does* in fact point to a `Derived` class object.

So, to call a `Derived` class member from inside `interface` we can use the following implementation (remember that `Base` is a base class of `Derived`):

```
template<class Derived>
void Base<Derived>::interface()
{
    static_cast<Derived *>(this)->polymorphic();
}
```

It's remarkable that, when the compiler is given this implementation it cannot determine whether `Derived` is *really* derived from `Base`. Neither can it determine whether the class `Derived` indeed offers a member `polymorphic`. The compiler simply *assumes* this to be true. If so, then the provided implementation is syntactically correct. One of the key characteristics of using templates is that the implementation's viability is eventually determined at the function's point of instantiation (cf. section 21.6). At that point the compiler will verify that, e.g., the function `polymorphic` really is available.

Thus, in order to use the above scheme we must ensure that

- derived class type is actually derived from the base class and
- that the derived class type defines a member '`polymorphic`'.

The first requirement is satisfied by using the *curiously recurring template pattern*:

```
class First: public Base<First>
```

In this curious pattern the class `First` is derived from `Base`, which itself is instantiated for `First`. This is acceptable, as the compiler already has determined that the type `First` exists. At this point that is all it needs.

The second requirement is simply satisfied by defining the member `polymorphic`. In chapter 14 we saw that virtual and overriding members belong to the class's private interface. We can apply the same philosophy here, by placing `polymorphic` in `First's` private interface, allowing it to be accessed from the base class by declaring

```
friend void Base<First>::interface();
```

`First's` complete class interface can now be designed, followed by `polymorphic's` implementation:

```
class First: public Base<First>
{
    friend void Base<First>::interface();

    private:
        void polymorphic();
};
void First::polymorphic()
{
    std::cout << "polymorphic from First\n";
}
```

Note that the class `First` itself is not a class template: its members can be separately compiled and stored in, e.g., a library. Also, as is the case with dynamic polymorphism, the member `polymorphic` has full access to all of `First`'s data members and member functions.

Multiple classes can now be designed like `First`, each offering their own implementation of `polymorphic`. E.g., the member `Second::polymorphic` of the class `Second`, designed like `First`, could be implemented like this:

```
void Second::polymorphic()
{
    std::cout << "polymorphic from Second\n";
}
```

The polymorphic nature of `Base` becomes apparent once a function template is defined in which `Base::interface` is called. Again, the compiler simply assumes a member `interface` exists when it reads the definition of the following function template:

```
template <class Class>
void fun(Class &object)
{
    object.interface();
}
```

Only where this function is actually called will the compiler verify the viability of the generated code. In the following `main` function a `First` object is passed to `fun`: `First` declares `interface` through its base class, and `First::polymorphic` is called by `interface`. The compiler will at this point (i.e., where `fun` is called) check whether `first` indeed has a member `polymorphic`. Next a `Second` object is passed to `fun`, and here again the compiler checks whether `Second` has a member `Second::polymorphic`:

```
int main()
{
    First first;
    fun(first);

    Second second;
    fun(second);
}
```

There are also downsides to using static polymorphism:

- First, the sentence 'a `Second` object is passed to `fun`' formally isn't correct, since `fun` is a function template the functions `fun` called as `fun(first)` and `fun(second)` are *different* functions, not just calls of one function with different arguments. With static polymorphism every instantiation using its own template parameters results in completely new code which is generated when the template (e.g., `fun`) is instantiated. This is something to consider when creating statically polymorphic base classes. If the base class defines data members and member functions, and if these additional members are used by derived class types, then each member has its own instantiation for each derived class type. This also results in code bloat, albeit of a different kind than observed with dynamic polymorphism. This kind of code bloat can often be somewhat reduced by deriving the base class from its own (ordinary, non-template) base class, encapsulating all elements of the statically polymorphic base class that do not depend on its template type parameters.
- Second, if different types of statically polymorphic objects are dynamically created (using the `new` operator) then the types of the returned pointers are all different. In addition, the types of the pointers to their statically polymorphic base classes differ from each other. These latter pointers are different because they are pointers to `Base<Derived>`, representing different types for different `Derived` types. Consequently, and different from dynamic polymorphism, these pointers cannot be collected in, e.g., a vector of shared pointers to base class pointers. There simply isn't one base class pointer type. Thus, because of the different base class types, there's no direct statically polymorphic equivalent to virtual destructors.
- Third, as illustrated in the next section, designing static polymorphic classes using multiple levels of inheritance is not a trivial task.

Summarizing, static polymorphism is best used in situations where a small number of different derived class types are used, where a fixed number of derived class objects are used, and where the statically polymorphic base classes themselves are lean (possibly encapsulating some of their code in ordinary base classes of their own).

22.12.2 Converting dynamic polymorphic classes to static polymorphic classes

So you've decided that you want to convert some of your dynamically polymorphic classes into statically polymorphic classes. Now what?

In chapter 14 the base class `Vehicle` and some derived classes were introduced. `Vehicle`, `Car` and `Truck`'s interfaces look like this (regarding the members that are involved in their polymorphic behaviors):

```
class Vehicle
{
    public:
        int mass() const;

    private:
        virtual int vmass() const;
};

class Car: public Vehicle
{
    private:
        int vmass() const override;
};

class Truck: public Car
{
    private:
        int vmass() const override;
};
```

When converting dynamically polymorphic classes to statically polymorphic classes we must realize that polymorphic classes show two important characteristics:

- they define facilities (data members, member functions) that are inherited by derived classes (e.g., `Vecicle::mass`) (i.e., the inheritable interface), and
- derived classes implement the redefinable interface in a way that suits their purpose (e.g., `Truck::vmass`).

With statically polymorphic classes these two characteristics should completely be separated. As we've seen in the previous section, a statically polymorphic derived class derives from its base class by using its own class type as argument to the base class's type parameter. This works fine if there's only one level of inheritance (i.e., one base class, and one or more classes that are directly derived from that base class).

With multiple levels of inheritance (e.g., `Truck -> Car -> Vehicle`) `Truck`'s inheritance specification becomes a problem. Here's an intial attempt to use atatic polymorphism and multiple levels of inheritance:

```
template <class Derived>
class Vehicle
{
    public:
        void mass()
        {
            static_cast<Derived *>(this)->vmass();
        }
};

class Car: public Vehicle<Car>
{
    friend void Vehicle<Car>::mass();
    void vmass();
};

class Truck: public Car
{
    void vmass();
};
```

- If `Truck` inherits from `Car`, then `Truck` implicitly derives from `Vehicle<Car>`, as `Car` derives from `Vehicle<Car>`. Consequently, when `Truck{}.mass()` is called it is not `Truck::vmass` that's activated, but *Car's* `vmass` function. But `Truck` *must* derive from `Car` in order to use `Car's` protected features and to add `Car's` public features to its own public interface.
- Multiple inheritance also doesn't solve the issue: when inheriting `Truck` from `Vehicle<Truck>` *and* from `Car` results in a class `Truck` that *also* inherits from

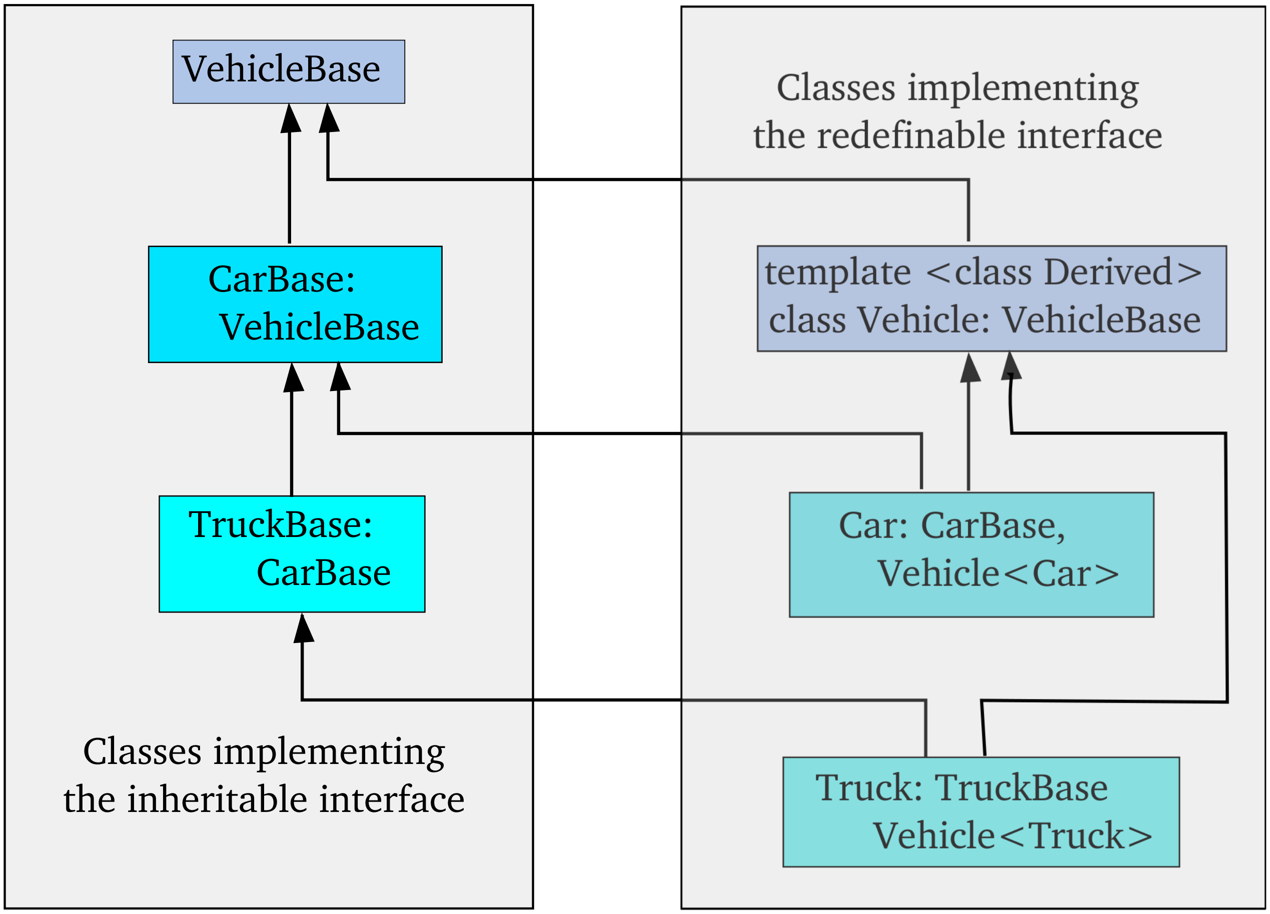
VehicleBase
CarBase:
VehicleBase
TruckBase:
CarBase
Classes implementing
the inheritable interface
Classes implementing
the redefinable interface
template <class Derived>
class Vehicle: VehicleBase
Car: CarBase,
Vehicle<Car>
Truck: TruckBase
Vehicle<Truck>

Figure 22.1: Vehicle Static Polymorphic Class Design

> `Vehicle<Car>` (through `Truck's Car` base class), and compilation fails as the compiler encounters an ambiguity when instantiating `Vehicle::mass`: should it call `Class::vmass` or should it call `Truck::vmass`?

To solve this problem (i.e., to ensure that `Truck{}.mass()` calls `Truck::vmass`) the redefinable interface must be separated from the inheritable interface.

In derived classes the protected and public interfaces of (direct or indirect) base classes are made available using standard inheritance. This is shown in the left-hand side of figure 22.1.

The left-hand side classes are used as base classes for the next level of inheritance (except for `TruckBase`, but `TruckBase` could be used as base class for yet another level of class inheritance). This line of inheritance declares the inheritable interface of the classes.

Each of the classes to the left is a base class of a single class to the right: `VehicleBase` is a base class for `Vehicle`, `TruckBase` for `Truck`. The classes to the left contain all members that are completely independent of the elements that are involved in realizing the static polymorphism. As that's a mere design principle to realize multiple levels of static polymorphism the common data hiding principles are relaxed, and the left-hand side classes declare their matching right-hand side derived class templates as friend, to allow full access to all members of a left-hand side class, including the private members, from the matching derived class template to the right. E.g., `VehicleBase` declares `Vechicle` as its friend:

```
class VehicleBase
```

```
{
    template <class Derived>
    friend class Vehicle;

    // all members originally in Vehicle, but not involved
    // in realizing static polymorphism are declared here. E.g.,
    size_t d_massFactor = 1;
};
```

The top level class to the left (`VehicleBase`) lays the foundation of static polymorphism, by defining that part of the interface that uses the statically redefinable functions. E.g, using the curiously recurring template pattern it defines a class member `mass` that calls the function `vmass` of its derived class (in addition it can use all members of its non-class template base class). E.g,:

```
template <class Derived>
class Vehicle: public VehicleBase
{
    public:
        int mass() const
        {
            return d_massFactor *
                    static_cast<Derived const *>(this)->vmass();
        }
};
```

Which function actually is called when `vmass` is called depends on the implementation in the class `Derived`, which is handled by the remaining classes, shown below `Vehicle`, which are all derived from `Vehicle` (as well as from their own `...Base` class). These classes use the curiously recurring template pattern. E.g.,

```
class Car: public CarBase, public Vehicle<Car>
```

So, if `Car` now implements its own `vmass` function, which can use any of its own (i.e., `CarBase's` members), then *that* function is called when calling a `Vehicle's mass` function. E.g.,

```
template <class Vehicle>
void fun(Vehicle &vehicle)
{
    cout << vehicle.mass() << '\n';
}

int main()
{
    Car car;
    fun(car);       // Car's vmass is called

    Truck truck;
    fun(truck);     // Truck's vmass is called
}
```

Now that we've analyzed the design of statically polymorphic classes using multiple levels of inheritance let's summarize the steps that took to implement static polymorphism

- First, starting at the base class, the class `Vehicle`. `Vehicle's` non-redefinable interface is moved to a class `VehicleBase`, and `Vehicle` itself is turned into a statically polymorphic base class. In general all members of the original polymorphic base class that do not use or implement virtual members should be moved to the `XBase` class.

- `VehicleBase` declares `Vehicle` to be a `friend`, to allow `Vehicle` full access to its former members, that are now in `VehicleBase`.
- `Vehicle's` members refer to the redefinable interface. I.e., its members call members of its `Derived` template type parameter. In this implementation `Vehicle` does not implement its own `vmass` member. We cannot define `Vehicle<Vehicle>`, and with static polymorphism the base class is essentially comparable to an abstract base class. If this is inconvenient then a default class can be specified for `Vehicle's Derived` class, implementing the redefinable interface of the original polymorphic base class (allowing for definitions like `Vehicle<> vehicle`).
- Likewise the remaining classes have their members not involved in static polymorphism moved to a base class. E.g., class `Car` moves these members to `CarBase` and `Truck` moves those members to `TruckBase`.
- A standard linear line of inheritance is used from `VehicleBase` to `CarBase` and from there to `TruckBase`.
- Each of the remaining classes (here: `Car` and `Truck`) is a class template that derives from its base classes, and also, using the curiously recurrent template pattern, from `Vehicle`.
- Each of these remaining classes can now implement its own version of the redefinable interface, as used by the members of `Vehicle`.

This design pattern can be extended to any level of inheritance: for each new level a base class is constructed, deriving from the most deeply nested `XXXBase` class so far, and deriving from `Vehicle<XXX>`, implementing its own ideas about the redefinable interface.

Functions that are used in combination with statically polymorphic classes themselves must be function templates. E.g.,

```
template <class Vehicle>
void fun(Vehicle &vehicle)
{
    cout << vehicle.mass() << '\n';
}
```

Here, `Vehicle` is just a formal name. When an object is passed to `fun` it must offer a member `mass`, or compilation will fail. If the object is in fact a `Car` or `Truck`, then their `Vehicle<Type>` static base class member `mass` is called, which in turn uses static polymorphism to call the member `vmass` as implemented by the actually passed class type. The following `main` function displays, respectively, 1000 and 15000:

```
int main()
{
    Car car;
    fun(car);

    Truck truck;
    fun(truck);
}
```

Note that this program implements `fun` twice, rather than once in the case of dynamic polymorphism. The same holds true for the `Vehicle` class template: two implementations, one for the `Car` type, and one for the `Truck` type. The statically polymorphic program will be slightly faster, though.

(A compilable example using static polymorphism is found in the **C++** Annotations's source distribution's file `yo/classtemplates/examples/staticpolymorphism/polymorph.cc`.)

22.12.3 Using static polymorphism to avoid reimplementations

Static polymorphism may profitably be used to avoid reimplementing code in an otherwise dynamic polymorphic environment.

Consider the situation where we have a class containing a container of pointers to some polymorphic base class type (like the class `Vehicle` from chapter 14). How to copy such a container to another container? We're not hinting at using shared pointers here, but would like to make a full copy. Clearly, we'll need to duplicate the objects the pointers point at, and assign these new pointers to the copied object's container.

The prototype design patttern is commonly used to create copies of objects of polymorphic classes, given pointers to their base classes.

To apply the prototype design pattern we have to implement `newCopy` in all derived classes. Not by itself a big deal, but static polymorphism can nicely be used here to avoid having to reimplement this function for each derived class.

We start off with an abstract base class `VehicleBase` declaring a pure virtual member `newCopy`:

```
struct VehicleBase
{
    virtual ~VehicleBase();
    VehicleBase *clone() const; // calls newCopy

    // declare any additional members defining the
    // public user interface here

    private:
        VehicleBase *newCopy() const = 0;
};
```

Next we define a static polymorphic class `CloningVehicle` which is derived from `VehicleBase` (note that we thus combine dynamic and static polymorphism). This class provides the generic implementation of `newCopy`. This is possible because all derived classes can use this implementation. Also, `CloningVehicle` will be re-implemented for each concrete type of vehicle that is eventually used: a `Car`, a `Truck`, an `AmphibiousVehicle`, etc, etc. `CloningVehicle` thus isn't shared (like `VehicleBase`), but instantiated for each new type of vehicle.

The core characteristic of a statically polymorphic class is that it can use its class template type parameter via a `static_cast` of its own type. A member function like `newCopy` is implemented always the same way, viz., by using the derived class's copy constructor. Here is the class `CloningVehicle`:

```
template <class Derived>
class CloningVehicle: public VehicleBase
{
    VehicleBase *newCopy() const
    {
        return new Derived(*static_cast<Derived const *>(this));
    }
};
```

And we're done. All types of vehicles should now be derived from `CloningVehicle`, which automatically provides them with their own implementation of `newCopy`. E.g., a class `Car` looks like this:

```
class Car: public CloningVehicle<Car>
{
    // Car's interface, no need to either
    // declare or implement newCopy,
    // but a copy constructor is required.
};
```

Having defined a `std::vector<VehicleBase *> original` we could create a copy of `original` like this:

```
for(auto pointer: original)
    duplicate.push_back(pointer->clone());
```

Irrespective of the actual type of vehicle to which the pointers point, their `clone` members will return pointers to newly allocated copies of objects of their own types.

22.13 Class templates and nesting

When a class is nested within a class template, it automatically becomes a class template itself. The nested class may use the template parameters of the surrounding class, as shown by the following skeleton program. Within a class `PtrVector`, a class `iterator` is defined. The nested class receives its information from its surrounding class, a `PtrVector<Type>` class. Since this surrounding class should be the only class constructing its iterators, `iterator`'s constructor is made private and the surrounding class is given access to the private members of `iterator` using a *bound friend* declaration. Here is the initial section of `PtrVector`'s class interface:

```
template <typename Type>
class PtrVector: public std::vector<Type *>
```

This shows that the `std::vector` base class stores pointers to `Type` values, rather than the values themselves. Of course, a destructor is now required as the (externally allocated) memory for the `Type` objects must eventually be freed. Alternatively, the allocation might be part of `PtrVector`'s tasks, when it stores new elements. Here it is assumed that `PtrVector`'s clients do the required allocations and that the destructor is implemented later on.

The nested class defines its constructor as a private member, and allows `PtrVector<Type>` objects access to its private members. Therefore only objects of the surrounding `PtrVector<Type>` class type are allowed to construct their `iterator` objects. However, `PtrVector<Type>`'s clients may construct *copies* of the `PtrVector<Type>::iterator` objects they use.

Here is the nested class `iterator`, using a (required) `friend` declaration. Note the use of the `typename` keyword: since `std::vector<Type *>::iterator` depends on a template parameter, it is not yet an instantiated class. Therefore `iterator` becomes an implicit typename. The compiler issues a warning if `typename` has been omitted. Here is the class interface:

```
        class iterator
        {
            friend class PtrVector<Type>;
```

```
                typename std::vector<Type *>::iterator d_begin;

                iterator(PtrVector<Type> &vector);

                public:
                    Type &operator*();
            };
```

The implementation of the members shows that the base class's `begin` member is called to initialize `d_begin`. `PtrVector<Type>::begin`'s return type must again be preceded by `typename`:

```
    template <typename Type>
    PtrVector<Type>::iterator::iterator(PtrVector<Type> &vector)
    :
        d_begin(vector.std::vector<Type *>::begin())
    {}

    template <typename Type>
    Type &PtrVector<Type>::iterator::operator*()
    {
        return **d_begin;
    }
```

The remainder of the class is simple. Omitting all other functions that might be implemented, the function `begin` returns a newly constructed `PtrVector<Type>::iterator` object. It may call the constructor since the class `iterator` declared its surrounding class as its friend:

```
    template <typename Type>
    typename PtrVector<Type>::iterator PtrVector<Type>::begin()
    {
        return iterator(*this);
    }
```

Here is a simple skeleton program, showing how the nested class `iterator` might be used:

```
    int main()
    {
        PtrVector<int> vi;

        vi.push_back(new int(1234));

        PtrVector<int>::iterator begin = vi.begin();

        std::cout << *begin << '\n';
    }
```

Nested enumerations and nested typedefs can also be defined by class templates. The class `Table`, mentioned before (section 22.11.3) inherited the enumeration `TableType::FillDirection`. Had `Table` been implemented as a full class template, then this enumeration would have been defined in `Table` itself as:

```
    template <typename Iterator>
    class Table: public TableType
```

```
{
    public:
        enum FillDirection
        {
            HORIZONTAL,
            VERTICAL
        };
    ...
};
```

In this case, the actual value of the template type parameter must be specified when referring to a `FillDirection` value or to its type. For example (assuming `iter` and `nCols` are defined as in section 22.11.3):

```
Table<istream_iterator<string> >::FillDirection direction =
            argc == 2 ?
                Table<istream_iterator<string> >::VERTICAL
            :
                Table<istream_iterator<string> >::HORIZONTAL;

Table<istream_iterator<string> >
    table(iter, istream_iterator<string>(), nCols, direction);
```

22.14 Constructing iterators

In section 18.2 the iterators used with generic algorithms were introduced. We've seen that several types of iterators were distinguished: InputIterators, ForwardIterators, OutputIterators, BidirectionalIterators and RandomAccessIterators.

To ensure that an object of a class is interpreted as a particular type of iterator, the class must be derived from the class `std::iterator`. Before a class can be derived from this class the `<iterator>` header file must be included.

In section 18.2 the characteristics of iterators were discussed. All iterators should support (using `Iterator` as the generic name of the designed iterator class and `Type` to represent the (possibly `const`, in which case the associated operator should be a `const` member as well) data type to which `Iterator` objects refer):

- a prefix increment operator (`Iterator &operator++()`);
- a dereference operator (`Type &operator*()`);
- a 'pointer to' operator (`Type *operator->()`);
- comparison operators testing the (in)equality of two iterator objects (`bool operator==(Iterator const &other)`, `bool operator!=(Iterator const &other)`).

When iterators are to be used in the context of generic algorithms they must meet additional requirements. This is caused by the fact that generic algorithms perform checks on the types of the iterators they receive. Simple pointers are usually accepted, but if an iterator-object is used it must be able to specify the kind of iterator it represents.

When deriving a class from the class `iterator` the type of iterator is defined by the class template's *first* parameter, and the data type to which the iterator refers is defined by the class template's *second* parameter.

The type of iterator that is implemented by the derived class is specified using a so-called *iterator_tag*, provided as the first template argument of the class `iterator`. For the five basic iterator types, these tags are:

- `std::input_iterator_tag`. This tag defines an InputIterator. Iterators of this type allow reading operations, iterating from the first to the last element of the series to which the iterator refers.

  The InputIterator dereference operator should be declared as follows:

  ```
  Type const &operator*() const;
  ```

  Except for the standard operators there are no further requirements for InputIterators.

- `std::output_iterator_tag`. This tag defines an OutputIterator. Iterators of this type allow for assignment operations, iterating from the first to the last element of the series to which the iterator refers.

  The OutputIterator dereference operator should allow assignment to the data its dereference operator refers to. Therefore, the OutputIterator dereference operator should be declared as follows:

  ```
  Type &operator*();
  ```

  Except for the standard operators there are no further requirements for OutputIterators.

- `std::forward_iterator_tag`. This tag defines a ForwardIterator. Iterators of this type allow reading *and* assignment operations, iterating from the first to the last element of the series to which the iterator refers.

  The ForwardIterator dereference operator should allow assignment to the data its dereference operator refers to. Therefore, the ForwardIterator dereference operator should be declared as follows:

  ```
  Type &operator*();
  ```

  Except for the standard operators there are no further requirements for ForwardIterators.

- `std::bidirectional_iterator_tag`. This tag defines a BidirectionalIterator. Iterators of this type allow reading *and* assignment operations, iterating step by step, possibly in alternating directions, over all elements of the series to which the iterator refers.

  The Bidirectional dereference operator should allow assignment to the data its dereference operator refers to and it should allow stepping backward. BidirectionalIterator should therefore, in addition to the standard operators required for iterators, offer the following operators:

  ```
  Type &operator*();
  Iterator &operator--();
  ```

- `std::random_access_iterator_tag`. This tag defines a RandomAccessIterator. Iterators of this type allow reading *and* assignment operations, iterating, possibly in alternating directions, over all elements of the series to which the iterator refers using any available (random) stepsize.

  RandomIterator class dereference operators should allow assignment to the data they refer to, and, in addition to the standard operators required for iterators, offer the following operators:

  - `Type &operator*()`, allowing assignment to the data the dereference operator refers to;

- `Iterator &operator--()`, allowing single steps backward;
- `Type operator-(Iterator const &rhs) const`, returning the number of data elements between the current and `rhs` iterator (returning a negative value if `rhs` refers to a data element beyond the data element `this` iterator refers to);
- `Iterator operator+(int step) const`, returning an iterator referring to a data element `step` data elements beyond the data element `this` iterator refers to;
- `Iterator operator-(int step) const`, returning an iterator referring to a data element `step` data elements before the data element `this` iterator refers to;
- `bool operator<(Iterator const &rhs) const`, returning `true` if the data element `this` iterator refers to is located before the data element the `rhs` iterator refers to.

Each iterator tag assumes that a certain set of operators is available. The *RandomAccessIterator* is the most complex of iterators, as it implies all other iterators.

Note that iterators are always defined over a certain range (`[begin, end)`). Increment and decrement operations may result in undefined behavior of the iterator if the resulting iterator value would refer to a location outside of this range.

Often, iterators only access the elements of the series to which they refer. Internally, an iterator may use an ordinary pointer but it is hardly ever necessary for the iterator to allocate its own memory. Therefore, as the assignment operator and the copy constructor do not have to allocate any memory, their *default implementations* usually suffice. For the same reason iterators usually don't require destructors.

Most classes offering members returning iterators do so by having members construct the required iterators that are thereupon returned as objects by those member functions. As the *caller* of these member functions only has to *use* or sometimes *copy* the returned iterator objects, there is usually no need to provide any publicly available constructor, except for the copy constructor. Therefore these constructors are usually defined as *private* or *protected* members. To allow an outer class to create iterator objects, the iterator class usually declares the outer class as its *friend*.

In the following sections the construction of a *RandomAccessIterator*, the most complex of all iterators, and the construction of a *reverse RandomAccessIterator* is discussed. The container class for which a random access iterator must be developed may actually store its data elements in many different ways (e.g., using containers or pointers to pointers). Therefore it is difficult to construct a template iterator class which is suitable for a large variety of container classes.

In the following sections the available `std::iterator` class is used to construct an inner class representing a random access iterator. The reader may follow the approach illustrated there to construct iterator classes for other contexts. An example of such a template iterator class is provided in section 25.5.

The random access iterator developed in the next sections reaches data elements that are only accessible through pointers. The iterator class is designed as an inner class of a class derived from a vector of string pointers.

22.14.1 Implementing a 'RandomAccessIterator'

In the chapter about containers (chapter 12) it was noted that containers own the information they contain. If they contain objects, then those objects are destroyed once the containers are destroyed. As pointers are not objects their use in containers is discouraged (STL's `unique_ptr` and `shared_ptr` type objects may be used, though). Although discouraged, we might be able to use pointer data types in specific contexts. In the following class `StringPtr`, an ordinary class is derived from the `std::vector` container that uses `std::string *` as its data type:

```
#ifndef INCLUDED_STRINGPTR_H_
#define INCLUDED_STRINGPTR_H_

#include <string>
#include <vector>

class StringPtr: public std::vector<std::string *>
{
    public:
        StringPtr(StringPtr const &other);
        ~StringPtr();

        StringPtr &operator=(StringPtr const &other);
};

#endif
```

This class needs a destructor: as the object stores string pointers, a destructor is required to destroy the strings once the `StringPtr` object itself is destroyed. Similarly, a copy constructor and an overloaded assignment operator are required. Other members (in particular: constructors) are not explicitly declared here as they are not relevant to this section's topic.

Assume that we want to be able to use the `sort` generic algorithm with `StringPtr` objects. This algorithm (see section 19.1.59) requires two *RandomAccessIterators*. Although these iterators are available (via `std::vector`'s `begin` and `end` members), they return iterators to `std::string *`s, which cannot sensibly be compared.

To remedy this, we may define an internal type `StringPtr::iterator`, not returning iterators to pointers, but iterators to the *objects* these pointers point to. Once this `iterator` type is available, we can add the following members to our `StringPtr` class interface, hiding the identically named, but useless members of its base class:

```
StringPtr::iterator begin();    // returns iterator to the first element
StringPtr::iterator end();      // returns iterator beyond the last
                                // element
```

Since these two members return the (proper) iterators, the elements in a `StringPtr` object can easily be sorted:

```
int main()
{
    StringPtr sp;               // assume sp is somehow filled

    sort(sp.begin(), sp.end()); // sp is now sorted
}
```

To make this all work, the type `StringPtr::iterator` must be defined. As suggested by its type name, `iterator` is a nested type of `StringPtr`. To use a `StringPtr::iterator` in combination with the `sort` generic algorithm it must also be a `RandomAccessIterator`. Therefore, `StringPtr::iterator` itself must be derived from the existing class `std::iterator`.

To derive a class from `std::iterator`, both the iterator type and the data type the iterator points to must be specified. Caveat: our iterator takes care of the `string *` dereferencing; so the required data type is `std::string`, and *not* `std::string *`. The class `iterator` therefore starts its interface as:

```
    class iterator:
        public std::iterator<std::random_access_iterator_tag, std::string>
```

Since its base class specification is quite complex, we could consider associating this type with a shorter name using the following `typedef`:

```
    typedef std::iterator<std::random_access_iterator_tag, std::string>
            Iterator;
```

In practical situations, if the type (`Iterator`) is used only once or twice, the type definition only adds clutter to the interface, and is better not used.

Now we're ready to redesign `StringPtr`'s class interface. It offers members returning (reverse) iterators, and a nested `iterator` class. Here is its interface:

```
class StringPtr: public std::vector<std::string *>
{
    public:
        class iterator;
        typedef std::reverse_iterator<iterator> reverse_iterator;

    iterator begin();
    iterator end();
    reverse_iterator rbegin();
    reverse_iterator rend();
};

class StringPtr::iterator: public
        std::iterator<std::random_access_iterator_tag, std::string>
{
    friend class StringPtr;

    friend bool operator==(iterator const &lhs, iterator const &rhs);
    friend int operator-(iterator const &lhs, iterator const &rhs);
    friend bool operator<(iterator const &lhs, iterator const &rhs);
    friend iterator operator+(iterator const &lhs, int step);
    friend iterator operator-(iterator const &lhs, int step);

    std::vector<std::string *>::iterator d_current;

    iterator(std::vector<std::string *>::iterator const &current);

    public:
        iterator &operator--();
        iterator operator--(int);
        iterator &operator++();
        iterator operator++(int);

        iterator &operator+=(int step); // increment over `n' steps
        iterator &operator-=(int step); // decrement over `n' steps

        std::string &operator*() const;
        std::string *operator->() const;// access the fields of the
                                        // struct an iterator points
                                        // to. E.g., it->length()
};
```

As usual, the interface offers hooks for a more detailed study of the class.

First we have a look at `StringPtr::iterator`'s characteristics:

- `iterator` defines `StringPtr` as its friend, so `iterator`'s constructor may remain private. Only the `StringPtr` class itself is now able to construct `iterators`, which seems like a sensible thing to do. Under the current implementation, *copy-construction* should of course also be possible. Furthermore, since an iterator is already provided by `StringPtr`'s base class, we can use that iterator to access the information stored in the `StringPtr` object.
- `StringPtr::begin` and `StringPtr::end` may simply return `iterator` objects. They are implemented like this:

  ```
  inline StringPtr::iterator StringPtr::begin()
  {
      return iterator(this->std::vector<std::string *>::begin());
  }
  inline StringPtr::iterator StringPtr::end()
  {
      return iterator(this->std::vector<std::string *>::end());
  }
  ```

- All of `iterator`'s remaining members are public. It's very easy to implement them, mainly manipulating and dereferencing the available iterator `d_current`. A `RandomAccessIterator` (which is the most complex of iterators) requires a series of operators. They usually have very simple implementations, making them good candidates for inline-members:
  - `iterator &operator++()`; the pre-increment operator:

    ```
    inline StringPtr::iterator &StringPtr::iterator::operator++()
    {
        ++d_current;
        return *this;
    }
    ```

  - `iterator operator++(int)`; the post-increment operator:

    ```
    inline StringPtr::iterator StringPtr::iterator::operator++(int)
    {
        return iterator(d_current++);
    }
    ```

  - `iterator &operator--()`; the pre-decrement operator:

    ```
    inline StringPtr::iterator &StringPtr::iterator::operator--()
    {
        --d_current;
        return *this;
    }
    ```

  - `iterator operator--(int)`; the post-decrement operator:

    ```
    inline StringPtr::iterator StringPtr::iterator::operator--(int)
    {
        return iterator(d_current--);
    }
    ```

- `iterator &operator=(iterator const &other);` the overloaded assignment operator. Since `iterator` objects do not allocate any memory themselves, the default assignment operator can be used.
- `bool operator==(iterator const &rhv) const;` testing the equality of two `iterator` objects:

  ```
  inline bool operator==(StringPtr::iterator const &lhs,
                         StringPtr::iterator const &rhs)
  {
      return lhs.d_current == rhs.d_current;
  }
  ```
- `bool operator!=(iterator const &rhv) const;` testing the inequality of two `iterator` objects:

  ```
  inline bool operator!=(StringPtr::iterator const &lhs,
                         StringPtr::iterator const &rhs)
  {
      return not (lhs == rhs);
  }
  ```
- `bool operator<(iterator const &rhv) const;` testing whether the left-hand side iterator points to an element of the series located *before* the element pointed to by the right-hand side iterator:

  ```
  inline bool operator<(StringPtr::iterator const &lhs,
                        StringPtr::iterator const &rhs)
  {
      return lhs.d_current < rhs.d_current;
  }
  ```
- `int operator-(iterator const &rhv) const;` returning the number of elements between the element pointed to by the left-hand side iterator and the right-hand side iterator (i.e., the value to add to the left-hand side iterator to make it equal to the value of the right-hand side iterator):

  ```
  inline int operator-(StringPtr::iterator const &lhs,
                       StringPtr::iterator const &rhs)
  {
      return lhs.d_current - rhs.d_current;
  }
  ```
- `Type &operator*() const;` returning a reference to the object to which the current iterator points. With an `InputIterator` and with all `const_iterators`, the return type of this overloaded operator should be `Type const &`. This operator returns a reference to a string. This string is obtained by dereferencing the dereferenced `d_current` value. As `d_current` is an iterator to `string *` elements, two dereference operations are required to reach the string itself:

  ```
  inline std::string &StringPtr::iterator::operator*() const
  {
      return **d_current;
  }
  ```
- `iterator operator+(int stepsize) const;` this operator advances the current iterator by `stepsize`:

  ```
  inline StringPtr::iterator operator+(StringPtr::iterator const &lhs,
                                                                int step)
  {
      StringPtr::iterator ret{ lhs };
  ```

```
    ret.d_current += step;          // avoids ambiguity
    return ret;
}
```

- `iterator operator-(int stepsize) const`; this operator decreases the current iterator by `stepsize`:

  ```
  inline StringPtr::iterator operator-(StringPtr::iterator const &lhs,
                                                                 int step)
  {
      StringPtr::iterator ret{ lhs };
      ret.d_current -= step;          // avoids ambiguity
      return ret;
  }
  ```

- `iterator(iterator const &other)`; iterators may be constructed from existing iterators. This constructor doesn't have to be implemented, as the default copy constructor can be used.
- `std::string *operator->() const` is an additionally added operator. Here only one dereference operation is required, returning a pointer to the string, allowing us to access the members of a string via its pointer.

  ```
  inline std::string *StringPtr::iterator::operator->() const
  {
      return *d_current;
  }
  ```

- Two more additionally added operators are `operator+=` and `operator-=`. They are not formally required by `RandomAccessIterators`, but they come in handy anyway:

  ```
  inline StringPtr::iterator &StringPtr::iterator::operator+=(int step)
  {
      d_current += step;
      return *this;
  }
  inline StringPtr::iterator &StringPtr::iterator::operator-=(int step)
  {
      d_current -= step;
      return *this;
  }
  ```

The interfaces required for other iterator types are simpler, requiring only a subset of the interface required by a random access iterator. E.g., the forward iterator is never decremented and never incremented over arbitrary step sizes. Consequently, in that case all decrement operators and `operator+(int step)` can be omitted from the interface. Of course, the tag to use would then be `std::forward_iterator_tag`. The tags (and the set of required operators) vary accordingly for the other iterator types.

22.14.2 Implementing a 'reverse_iterator'

Once we've implemented an iterator, the matching *reverse iterator* can be implemented in a jiffy. Comparable to the `std::iterator` a `std::reverse_iterator` exists, that nicely implements the reverse iterator for us once we have defined an iterator class. Its constructor merely requires an object of the iterator type for which we want to construct a reverse iterator.

To implement a reverse iterator for `StringPtr` we only need to define the `reverse_iterator` type in its interface. This requires us to specify only one line of code, which must be inserted after the interface of the class `iterator`:

```
    typedef std::reverse_iterator<iterator> reverse_iterator;
```

Also, the well known members `rbegin` and `rend` are added to `StringPtr`'s interface. Again, they can easily be implemented inline:

```
inline StringPtr::reverse_iterator StringPtr::rbegin()
{
    return reverse_iterator(end());
}
inline StringPtr::reverse_iterator StringPtr::rend()
{
    return reverse_iterator(begin());
}
```

Note the arguments the `reverse_iterator` constructors receive: the *begin point* of the reversed iterator is obtained by providing `reverse_iterator`'s constructor with the value returned by the member `end`: the *endpoint* of the normal iterator range; the *endpoint* of the reversed iterator is obtained by providing `reverse_iterator`'s constructor with the value returned by the member `begin`: the *begin point* of the normal iterator range.

The following small program illustrates the use of `StringPtr`'s `RandomAccessIterator`:

```
    #include <iostream>
    #include <algorithm>
    #include "stringptr.h"
    using namespace std;

    int main(int argc, char **argv)
    {
        StringPtr sp;

        while (*argv)
            sp.push_back(new string{ *argv++ });

        sort(sp.begin(), sp.end());
        copy(sp.begin(), sp.end(), ostream_iterator<string>(cout, " "));

        cout << "\n======\n";

        sort(sp.rbegin(), sp.rend());
        copy(sp.begin(), sp.end(), ostream_iterator<string>(cout, " "));

        cout << '\n';
    }
    /*
            when called as:
        a.out bravo mike charlie zulu quebec

            generated output:
        a.out bravo charlie mike quebec zulu
        ======
        zulu quebec mike charlie bravo a.out
    */
```

Although it is thus possible to construct a reverse iterator from a normal iterator, the opposite does not hold true: it is not possible to initialize a normal iterator from a reverse iterator.

Assume we would like to process all lines stored in `vector<string> lines` up to any trailing empty lines (or lines only containing blanks) it might contain. How should we proceed? One approach is to start the processing from the first line in the vector, continuing until the first of the trailing empty lines. However, once we encounter an empty line it does of course not have to be the first line of the set of trailing empty lines. In that case, we'd better use the following algorithm:

- First, use

  ```
  rit = find_if(lines.rbegin(), lines.rend(), NonEmpty());
  ```

  to obtain a `reverse_iterator rit` pointing to the last non-empty line.

- Next, use

  ```
  for_each(lines.begin(), --rit, Process());
  ```

  to process all lines up to the first empty line.

However, we can't mix iterators and reverse iterators when using generic algorithms. So how can we initialize the second iterator using the available `reverse_iterator`? The solution is not very difficult, as an iterator may be initialized from a pointer. Although the reverse iterator `rit` is not a pointer, `&*(rit - 1)` or `&*+NOTRANS(-{}-{})rit` *is*. So we use

```
for_each(lines.begin(), &*--rit, Process());
```

to process all the lines up to the first of the set of trailing empty lines. In general, if `rit` is a `reverse_iterator` pointing to some element and we need an `iterator` to point to that element, we may use `&*rit` to initialize the iterator. Here, the dereference operator is applied to reach the element the reverse iterator refers to. Then the address operator is applied to obtain its address with which we can initialize the iterator.

When defining a `const_reverse_iterator` (e.g., matching a `const_iterator` class), then the `const_iterator's operator*` member should be a member returning a non-modifiable value or object. Since a `const_reverse_iterator` uses the iterator's `operator--` member, we're running against a small conceptual conflict. On the one hand, a `std::input_iterator_tag` is inappropriate, since we must allow decrementing the iterator. On the other hand, a `std::bidirectional_iterator` is inappropriate, since we don't allow modification of the data.

Iterator tags are primarily conceptual. If `const_iterators` and `const_reverse_iterators` only allow increment operations, then an `input_iterator_tag` most closely matches the iterator's intended use. Hence this tag is used below.

Furthermore, in line with the nature of a `input_iterator_tag` our `const_iterator` should not offer an `operator--`. This, of course, causes problems: a reverse iterator must be able to use the iterator's `operator--` member. This can easily be solved by stashing the iterator's `operator--` in the iterator's private section, and declaring `std::reverse_iterator<(const_)iterator>` its friend (note that declaring a `(const_)reverse_iterator` that is derived from `std::reverse_iterator` doesn't solve the issue: it is `std::reverse_iterator` that calls the iterator's `operator--`, not a class that is derived from it).

There is, however, another issue. After deriving a `const_reverse_iterator` from `const_iterator`, and subsequently dereferencing a `const_reverse_iterator`, the compiler generates an error message like the following (using `Type = int`):

```
error: invalid initialization of non-const reference of type
```

```
'std::reverse_iterator<const_iterator>::reference {aka int&}' from an rvalue
of type 'int'
  return *--__tmp;
```

This message is caused by `std::reverse_iterator` by default expecting that the iterator's `operator*` returns a reference to a modifiable `Type`.

To control such default expectancies, iterators can use `typedefs` to fine-tune these expectancies. The following `typedefs` are interpreted by `std::reverse_iterator`:

```
    pointer          -   the type of the pointer to the data
                         (e.g., Type *)
    const_pointer    -   the type of a pointer to immutable data
                         (e.g., Type const *)
    reference        -   the type of a reference to the data
                         (e.g., Type &)
    const_reference -    the type of a reference to immmutable data
                         (e.g., Type const &)
    difference_type -    the type representing differences between
                         pointers (by default `ptrdiff_t')
```

The mentioned error can simply be prevented by declaring '`typedef int const &reference`' in the `iterator` class. Alternatively, `int const` may be specified as the data type for the `std::iterator`'s base class.

To define a `iterator, const_iterator, reverse_iterator` and `const_reverse_iterator` for a class `Data` the following framework can be used:

```
#include <string>
#include <iterator>

class Data
{
    std::string *d_data;
    size_t d_n;

    public:
        class iterator;
        class const_iterator;

        typedef std::reverse_iterator<iterator> reverse_iterator;
        typedef std::reverse_iterator<const_iterator> const_reverse_iterator;
};

class Data::iterator: public std::iterator<std::input_iterator_tag,
                                            std::string>
{
    public:
        iterator() = default;

        iterator &operator++();
        std::string &operator*();

    private:
        friend class Data;
        iterator(std::string *data, size_t idx);

        friend class std::reverse_iterator<iterator>;
        iterator &operator--();
};

bool operator==(Data::iterator const &lhs, Data::iterator const &rhs);



class Data::const_iterator: public std::iterator<std::input_iterator_tag,
                                                 std::string const>
{
    public:
        const_iterator() = default;

        const_iterator &operator++();
        std::string const &operator*() const;

    private:
        friend class Data;
        const_iterator(std::string const *data, size_t idx);

        friend class std::reverse_iterator<const_iterator>;
        const_iterator &operator--();
};

bool operator==(Data::const_iterator const &lhs,
                Data::const_iterator const &rhs);


int main()
{
    Data::iterator iter;
    Data::reverse_iterator riter(iter);

    *riter;

    Data::const_iterator citer;
    Data::const_reverse_iterator criter(citer);

    *criter;

};
```

Chapter 23

Advanced Template Use

The main purpose of templates is to provide a generic definition of classes and functions that may then be tailored to specific types.

But templates allow us to do more than that. If not for compiler implementation limitations, templates could be used to program, at compile-time, just about anything we use computers for. This remarkable feat, offered by no other current-day computer language, stems from the fact that templates allow us to do three things at compile-time:

- Templates allow us to do integer arithmetic (and to save computed values symbolically);
- Templates allow us to make compile-time decisions;
- Templates allow us to do things repeatedly.

Of course, asking the compiler to compute, e.g., prime numbers, is one thing. But it's a completely different thing to do so in an award winning way. Don't expect speed records to be broken when the compiler performs complex calculations for us. But that's all beside the point. In the end we *can* ask the compiler to compute virtually anything using **C++**'s template language, including prime numbers....

In this chapter these remarkable features of templates are discussed. Following a short overview of subtleties related to templates the main characteristics of template meta programming are introduced.

In addition to template type and template non-type parameters there is a third kind of template parameter, the *template template parameter*. This kind of template parameter is introduced shortly, laying the groundwork for the discussion of *trait classes* and *policy classes*.

This chapter ends with the discussion of several additional and interesting applications of templates: adapting compiler error messages, conversions to class types and an elaborate example discussing compile-time list processing.

Much of the inspiration for this chapter came from two highly recommended books: Andrei Alexandrescu's 2001 book **Modern C++ design** (Addison-Wesley) and Nicolai Josutis and David Vandevoorde's 2003 book **Templates** (Addison-Wesley).

23.1 Subtleties

In section 22.2.1 a special application of the keyword `typename` was discussed. There we learned that it is not only used to define a name for a (complex) type, but also to distinguish types defined by class templates from members defined by class templates. In this section two more applications of `typename` are introduced:

- In section 23.1.1 we apply `typename` to situations where types nested in templates are returned from member functions of class templates;
- in section 23.1.2 we cover the problem of how to refer to base class templates from derived class templates.

In addition to the special applications of `typename` section 23.1.3 introduces some new syntax that is related to the extended use of the keyword `typename`: `::template, .template` and `->template` are used to inform the compiler that a name used inside a template is itself a class template.

23.1.1 Returning types nested under class templates

In the following example a nested class, not depending on a template parameter, is defined inside a class template. The class template member `nested` returns an object of this nested class. The example uses a (deprecated) in-class member implementation. The reason for this shortly becomes clear.

```
template <typename T>
class Outer
{
    public:
        class Nested
        {};
        Nested nested() const
        {
            return Nested{};
        }
};
```

The above example compiles flawlessly. Inside the class `Outer` there is no ambiguity with respect to the meaning of `nested`'s return type.

However, following good practices inline and template members should be implemented below their class interfaces (see section 7.8.1). So we remove the implementation from the interface and put it below the interface:

```
template <typename T>
class Outer
{
    public:
        class Nested
        {};

        Nested nested() const;
};
```

```
template <typename T>
Outer<T>::Nested Outer<T>::nested() const
{
    return Nested{};
}
```

Suddenly the compiler refuses to compile the `nested` member. Fortunately, it also suggests a solution in its error message:

```
error: need `typename' before `Outer<T>::Nested' because
       `Outer<T>' is a dependent scope
 Outer<T>::Nested Outer<T>::nested() const
 ~~~~~~~~
```

Now that the implementation has been moved out of the interface the return type (i.e., `Outer<T>::Nested`) refers to a type defined by `Outer<T>` rather than to a member of `Outer<T>`, and so `typename` must once again be used.

A general rule for using `typename` can be formulated: the keyword `typename` must be used whenever a type is referred to that is a *subtype* of a type that itself depends on a template type parameter.

When using the inline implementation no such dependency is used as the function's return type is simply `Nested`. When implementing the function outside of the class interface (which should be considered 'good practice') then a specification of the class defining `Nested` must be provided for the function's return type. So it becomes `Outer<T>::Nested` which clearly is a type depending on a template type parameter.

Like before, writing `typename` in front of `Outer<T>::Nested` removes the compilation error. Thus, the correct implementation of the function `nested` becomes:

```
template <typename T>
typename Outer<T>::Nested Outer<T>::nested() const
{
    return Nested();
}
```

23.1.2 Type resolution for base class members

Below we see two class templates. `Base` and `Derived`, `Base` being `Derived`'s base class:

```
#include <iostream>

template <typename T>
class Base
{
    public:
        void member();
};
template <typename T>
void Base<T>::member()
{
    std::cout << "This is Base<T>::member()\n";
}
template <typename T>
```

```
class Derived: public Base<T>
{
    public:
        Derived();
};
template <typename T>
Derived<T>::Derived()
{
    member();
}
```

This example won't compile, and the compiler tells us something like:

```
error: there are no arguments to 'member' that depend on a template
       parameter, so a declaration of 'member' must be available
```

This error causes some confusion as ordinary (non-template) base classes readily make their public and protected members available to classes that are derived from them. This is no different for class templates, but only if the compiler can figure out what we mean. In the above example the compiler *can't* as it doesn't know for what type `T` the member function `member` must be initialized when called from `Derived<T>::Derived`.

To appreciate why this is true, consider the situation where we have defined a specialization:

```
template <>
Base<int>::member()
{
    std::cout << "This is the int-specialization\n";
}
```

Since the compiler, when `Derived<SomeType>::Derived` is called, does not know whether a specialization of `member` is in effect, it can't decide (when compiling `Derived<T>::Derived`) for what type to instantiate `member`. It can't decide this when compiling `Derived<T>::Derived` as `member`'s call in `Derived::Derived` doesn't require a template type parameter.

In cases like these, where no template type parameter is available to determine which type to use, the compiler must be told that it should postpone its decision about the template type parameter to use (and therefore about the particular (here: `member`) function to call) until instantiation time.

This may be implemented in two ways: either by using `this` or by explicitly mentioning the base class, instantiated for the derived class's template type(s). When `this` is used the compiler is informed that we're referring to the type `T` for which the template was instantiated. Any confusion about which member function to use (the derived class or base class member) is resolved in favor of the derived class member. Alternatively, the base or derived class can explicitly be mentioned (using `Base<T>` or `Derived<T>`) as shown in the next example. Note that with the `int` template type the `int` specialization is used.

```
#include <iostream>

template <typename T>
class Base
{
    public:
        void member();
};
```

```
template <typename T>
void Base<T>::member()
{
    std::cout << "This is Base<T>::member()\n";
}
template <>
void Base<int>::member()
{
    std::cout << "This is the int-specialization\n";
}
template <typename T>
class Derived: public Base<T>
{
    public:
        Derived();
        virtual void member();
};
template <typename T>
void Derived<T>::member()
{
    std::cout << "This is Derived<T>::member()\n";
}
template <typename T>
Derived<T>::Derived()
{
    this->member();          // Using `this' implies using the
                             // type for which T was instantiated
    Derived<T>::member();    // Same: calls the Derived member
    Base<T>::member();       // Same: calls the Base member
    std::cout << "Derived<T>::Derived() completed\n";
}

int main()
{
    Derived<double> d;
    Derived<int> i;
}

/*
    Generated output:
This is Derived<T>::member()
This is Derived<T>::member()
This is Base<T>::member()
Derived<T>::Derived() completed
This is Derived<T>::member()
This is Derived<T>::member()
This is the int-specialization
Derived<T>::Derived() completed
*/
```

The above example also illustrates the use of virtual member templates (although virtual member templates aren't often used). In the example `Base` declares a `virtual void member` and `Derived` defines its overriding function `member`. In that case `this->member()` in `Derived::Derived` calls, due to `member`'s virtual nature, `Derived::member`. The statement `Base<T>::member()`, however, always calls `Base`'s `member` function and can be used to bypass dynamic polymorphism.

23.1.3 ::template, .template and ->template

In general, the compiler is able to determine the true nature of a name. As discussed, this is not always the case and sometimes we have to advise the compiler. The `typename` keyword may often be used for that purpose.

But `typename` cannot always come to the rescue. While parsing a source the compiler receives a series of *tokens*, representing meaningful units of text encountered in the program's source. A token could represent, e.g., an identifier or a number. Other tokens represent operators, like `=`, `+` or <. It is precisely the last token that may cause problems as it may have very different meanings. The correct meaning cannot always be determined from the context in which the compiler encounters <. In some situations the compiler *does* know that < does not represent the *less than* operator, as when a template parameter list follows the keyword `template`, e.g.,

```
template <typename T, int N>
```

Clearly, in this case < does not represent a 'less than' operator.

The special meaning of < when it is preceded by `template` forms the basis for the syntactic constructs discussed in this section.

Assume the following class has been defined:

```
template <typename Type>
class Outer
{
    public:
        template <typename InType>
        class Inner
        {
            public:
                template <typename X>
                void nested();
        };
};
```

The class template `Outer` defines a nested class template `Inner`. `Inner` in turn defines a template member function.

Next a class template `Usage` is defined, offering a member function `caller` expecting an object of the above `Inner` type. An initial setup for `Usage` looks like this:

```
template <typename T1, typename T2>
class Usage
{
    public:
        void caller(Outer<T1>::Inner<T2> &obj);
   ...
};
```

The compiler won't accept this as it interprets `Outer<T1>::Inner` as a class type. But there is no class `Outer<T1>::Inner`. Here the compiler generates an error like:

```
error: 'class Outer<T1>::Inner' is not a type
```

To inform the compiler that `Inner` itself is a template, using the template type parameter <`T2`>, the `::template` construction is required. It tells the compiler that the next < should not be interpreted as a 'less than' token, but rather as a template type argument. So, the declaration is modified to:

```
void caller(Outer<T1>::template Inner<T2> &obj);
```

This still doesn't get us where we want to be: after all `Inner<T2>` is a type, nested under a class template, depending on a template type parameter. In fact, the original `Outer<T1>::Inner<T2> &obj` declaration results in a series of error messages, one of them looking like this:

```
error: expected type-name before '&' token
```

As is often the case this error message nicely indicates what should be done to get it right: add `typename`:

```
void caller(typename Outer<T1>::template Inner<T2> &obj);
```

Of course, `caller` itself is not only just declared, it must also be implemented. Assume that its implementation should call `Inner`'s member `nested`, instantiated for yet another type `X`. The class template `Usage` should therefore receive a third template type parameter, called `T3`. Assume it has been defined. To implement `caller`, we write:

```
void caller(typename Outer<T1>::template Inner<T2> &obj)
{
    obj.nested<T3>();
}
```

Once again we run into a problem. In the function's body the compiler once again interprets < as 'less than', seeing a logical expression having as its right-hand side a primary expression instead of a function call specifying a template type `T3`.

To tell the compiler that is should interpret <`T3`> as a type to instantiate, the `template` keyword must once again be used. This time it is used in the context of the member selection operator. We write `.template` to inform the compiler that what follows is not a 'less than' operator, but rather a type specification. The function's final implementation becomes:

```
void caller(typename Outer<T1>::template Inner<T2> &obj)
{
    obj.template nested<T3>();
}
```

Instead of defining value or reference parameters functions may also define pointer parameters. Had `obj` been defined as a pointer parameter the implementation would have had to use the `->template` construction, rather than the `.template` construction. E.g.,

```
void caller(typename Outer<T1>::template Inner<T2> *ptr)
{
    ptr->template nested<T3>();
}
```

As we've seen class templates can be derived from base class templates. The base class template can declare a static member template, which is available to a class that is derived from this base class. Such a base class might look like this:

```
template <typename Type>
struct Base
{
    template <typename Tp>
    static void fun();
};
```

Normally, when a base class defines a static member we can just call that member by prefixing its name by its class name. E.g.,

```
int main()
{
    Base<int>::fun<double>();
}
```

This also works fine if a class `Derived` is derived from `Base`, instantiated for a specific type:

```
struct Der: public Base<int>
{
    static void call()
    {
        Base<int>::fun<int>();       // OK
        fun<int>();                  // also OK
    };
};
```

However, when the derived class itself is a class template this way to call `fun` does not compile anymore, as it interprets `Base<Type>::fun` in `Base<Type>::fun<int>` as a type, to be instantiated for `int`. This interpretation can be overruled by us by indicating that `fun` itself is a template. For this the `::template` prefix is used:

```
template <typename Type>
struct Der: public Base<Type>
{
    //template <typename Tp>    // 'call' may be a member template
    //static                    // 'call' may be a static member
    void call()
    {
        // fun<int>();                      // won't compile
        // Base<Type>::fun<int>();          // won't compile
        Base<Type>::template fun<int>();    // OK
        Base<Type>::template fun<Tp>();     // OK if call is a
                                            //    member template
    };
};
```

23.2 Template Meta Programming

23.2.1 Values according to templates

In template programming values are preferably represented by `enum` values. Enums are preferred over, e.g., `int const` values since enums never require any linkage. They are pure symbolic values with no memory representation whatsoever.

Consider the situation where a programmer must use a cast, say a `reinterpret_cast`. A problem with a `reinterpret_cast` is that it is the ultimate way to turn off all compiler checks. All bets are off, and we can write extreme but absolutely pointless `reinterpret_cast` statements, like

```
int intVar = 12;
ostream &ostr = reinterpret_cast<ostream &>(intVar);
```

Wouldn't it be nice if the compiler would warn us against such oddities by generating an error message?

If that's what we'd like the compiler to do, there must be some way to distinguish madness from weirdness. Let's assume we agree on the following distinction: reinterpret casts are never acceptable if the target type represents a larger type than the expression (source) type, since that would immediately result in exceeding the amount of memory that's actually available to the target type. For this reason it's clearly silly to `reinterpret_cast<double *>(&intVar)`, but `reinterpret_cast<char *>(&intVar)` could be defensible.

The intent is now to create a new kind of cast, let's call it `reinterpret_to_smaller_cast`. It should only be allowed to perform a `reinterpret_to_smaller_cast` if the target type occupies less memory than the source type (note that this exactly the opposite reasoning as used by Alexandrescu (2001), section 2.1).

To start, we construct the following template:

```
template<typename Target, typename Source>
Target &reinterpret_to_smaller_cast(Source &source)
{
    // determine whether Target is smaller than source
    return reinterpret_cast<Target &>(source);
}
```

At the comment an enum-definition is inserted defining a symbol having a suggestive name. A compile-time error results if the required condition is not met and the error message displays the name of the symbol. A division by zero is clearly not allowed, and noting that a `false` value represents a zero value, the condition could be:

```
1 / (sizeof(Target) <= sizeof(Source));
```

The interesting part is that this condition doesn't result in any code at all. The enum's value is a plain value that's computed by the compiler while evaluating the expression:

```
template<typename Target, typename Source>
Target &reinterpret_to_smaller_cast(Source &source)
{
    enum
    {
        the_Target_size_exceeds_the_Source_size =
            1 / (sizeof(Target) <= sizeof(Source))
    };
    return reinterpret_cast<Target &>(source);
}
```

When `reinterpret_to_smaller_cast` is used to cast from `int` to `double` an error is produced by the compiler, like this:

```
error: enumerator value for 'the_Target_size_exceeds_the_Source_size'
    is not an integer constant
```

whereas no error is reported if, e.g., `reinterpret_to_smaller_cast<int>(doubleVar)` is requested with `doubleVar` defined as a `double`.

In the above example an `enum` was used to compute (at compile-time) a value that is illegal if an assumption is not met. The creative part is finding an appropriate expression.

Enum values are well suited for these situations as they do not consume any memory and their evaluation does not produce any executable code. They can be used to accumulate values too: the resulting enum value then contains a final value, computed by the compiler rather than by executable code as the next sections illustrate. In general, programs shouldn't do run-time what they can do at compile-time and performing complex calculations resulting in constant values is a clear example of this principle.

23.2.1.1 Converting integral types to types

Another use of values buried inside templates is to 'templatize' simple scalar `int` values. This is useful in situations where a scalar value (often a `bool` value) is available to select a specialization but a type is required to base the selection on. This situation is shortly encountered (section 23.2.2).

Templatizing integral values is based on the fact that a class template together with its template arguments defines a type. E.g., `vector<int>` and `vector<double>` are different types.

Turning integral values into templates is easily done. Define a template (it does not have to have any content at all) and store the integral value in an `enum`:

```
template <int x>
struct IntType
{
    enum { value = x };
};
```

As `IntType` does not have any members the '`class IntType`' can be defined as '`struct IntType`', saving us from having to type `public:`.

Defining the `enum` value '`value`' allows us to retrieve the value used at the instantiation at no cost in storage. Enum values are neither variables nor data members and thus have no address. They are mere values.

It's easy to use the `struct IntType`. An anonymous or named object can be defined by specifying a value for its `int` non-type parameter. Example:

```
int main()
{
    IntType<1> it;
    cout << "IntType<1> objects have value: " << it.value << "\n" <<
            "IntType<2> objects are of a different type "
                    "and have values " << IntType<2>().value << '\n';
}
```

Actually, neither the named object nor the anonymous object is required. As the `enum` is defined as a plain value, associated with the `struct IntType` we merely have to specify the specific `int` for which the `struct IntType` is defined to retrieve its '`value`', like this:

```
int main()
{
    cout << "IntType<100>, no object, defines `value': " <<
            IntType<100>::value << "\n";
}
```

23.2.2 Selecting alternatives using templates

An essential characteristic of programming languages is that they allow the conditional execution of code. For this **C++** offers the `if` and `switch` statements. If we want to be able to 'program the compiler' this feature must also be offered by templates.

Like templates storing values templates making choices do not require any code to be executed at run-time. The selection is purely made by the compiler, at compile-time. The essence of template meta programming is that we are *not* using or relying on any executable code. The result of a template meta program often is executable code, but that code is a function of decisions merely made by the compiler.

Template (member) functions are only instantiated when they are actually used. Consequently we can define specializations of functions that are mutually exclusive. Thus it is possible to define a specialization that can be compiled in situation one, but not in situation two and to define another specialization that can be compiled in situation two, but not in situation one. Using specializations code can be generated that is tailored to the demands of a particular situation.

A feature like this cannot be implemented in run-time executable code. For example, when designing a generic storage class the software engineer may intend to store *value class* type objects as well as objects of *polymorphic class* types in the final storage class. Thus the software engineer may conclude that the storage class should contain pointers to objects, rather than the objects themselves. The initial implementation attempt could look like this:

```
template <typename Type>
void Storage::add(Type const &obj)
{
    d_data.push_back(
        d_ispolymorphic ?
            obj.clone()
        :
            new Type{obj}
    );
}
```

The intent is to use the `clone` member function of the class `Type` if `Type` is a polymorphic class and the standard copy constructor if `Type` is a value class.

Unfortunately, this scheme usually fails as value classes do not define `clone` member functions and polymorphic base classes should *delete* their copy constructors (cf. section 7.6). It doesn't matter to the compiler that `clone` is never called for value classes and that the copy constructor is only available in value classes and not in polymorphic classes. It merely has some code to compile, and can't do that because of missing members. It's as simple as that.

23.2.2.1 Defining overloading members

Template meta programming comes to the rescue. Knowing that class template member functions are only instantiated when used, our plan is to design overloaded `add` member functions of which only one is going to be called (and thus instantiated). Our selection will be based on an additional (in addition to `Type` itself) template non-type parameter that indicates whether we'll use `Storage` for polymorphic or non-polymorphic classes. Our class `Storage` starts like this:

```
template <typename Type, bool isPolymorphic>
class Storage
```

Initially two *overloaded* versions of our `add` member are defined: one used with `Storage` objects storing polymorphic objects (using `true` as its template non-type argument) and one storing value class objects (using `false` as its template non-type argument).

Unfortunately we run into a small problem: functions cannot be overloaded by their argument *values* but only by their argument *types*. But the small problem may be solved. Realizing that types are defined by the combination of template names and their template arguments we may convert the values `true` and `false` into types using the knowledge from section 23.2.1.1 about how to convert integral values to types.

We'll provide one (private) `add` member with an `IntType<true>` parameter (implementing the polymorphic class) and another (private) `add` member with an `IntType<false>` parameter (implementing the non-polymorphic class).

In addition to these two private members a third (public) member `add` is defined calling the appropriate private `add` member by providing an `IntType` argument, constructed from `Storage`'s template non-type parameter.

Here are the implementations of the three `add` members:

```
// declared in Storage's private section:

template <typename Type, bool isPolymorphic>
void Storage<Type, isPolymorphic>::add(Type const &obj, IntType<true>)
{
    d_data.push_back(obj.clone());
}

template <typename Type, bool isPolymorphic>
void Storage<Type, isPolymorphic>::add(Type const &obj, IntType<false>)
{
    d_data.push_back(new Type(obj));
}

// declared in Storage's public section:

template <typename Type, bool isPolymorphic>
void Storage<Type, isPolymorphic>::add(Type const &obj)
{
    add(obj, IntType<isPolymorphic>());
}
```

The appropriate `add` member is instantiated and called because a primitive value can be converted to a type. Each of the possible template non-type values is thus used to define an overloaded class template member function.

Since class template members are only instantiated when used only one of the overloaded private `add` members is instantiated. Since the other one is never called (and thus never instantiated) compilation errors are prevented.

23.2.2.2 Class structure as a function of template parameters

Some software engineers have reservations when thinking about the `Storage` class that uses pointers to store copies of value class objects. Their argument is that value class objects can very well be stored by value, rather than by pointer. They'd rather store value class objects by value and polymorphic class objects by pointer.

Such distinctions frequently occur in template meta programming and the following `struct IfElse` may be used to obtain one of two types, depending on a `bool` selector value.

First define the *generic form* of the template:

```
template<bool selector, typename FirstType, typename SecondType>
struct IfElse
{
    typedef FirstType type;
};
```

Then define a partial specialization. The specialization represents a specific selector value (e.g., `false`) and leaves the remaining types open to further specification:

```
template<typename FirstType, typename SecondType>
struct IfElse<false, FirstType, SecondType>
{
    typedef SecondType type;
};
```

The former (generic) definition associates `FirstType` with the `IfElse::type` type definition, the latter definition (partially specialized for the logical value `false`) associates `SecondType` with the `IfElse::type` type definition.

The `IfElse` template allows us to define class templates whose data organization is conditional to the template's parameters. Using `IfElse` the `Storage` class may define *pointers* to store copies of polymorphic class type objects and *values* to store value class type objects:

```
template <typename Type, bool isPolymorphic>
class Storage
{
    typedef typename IfElse<isPolymorphic, Type *, Type>::type
            DataType;

    std::vector<DataType> d_data;

    private:
        void add(Type const &obj, IntType<true>);
        void add(Type const &obj, IntType<false>);
    public:
        void add(Type const &obj);
}

template <typename Type, bool isPolymorphic>
void Storage<Type, isPolymorphic>::add(Type const &obj, IntType<true>)
{
    d_data.push_back(obj.clone());
}
```

```
template <typename Type, bool isPolymorphic>
void Storage<Type, isPolymorphic>::add(Type const &obj, IntType<false>)
{
    d_data.push_back(obj);
}

template <typename Type, bool isPolymorphic>
void Storage<Type, isPolymorphic>::add(Type const &obj)
{
    add(obj, IntType<isPolymorphic>());
}
```

The above example uses `IfElse`'s `type`, defined by `IfElse` as either `FirstType` or `SecondType`. `IfElse`'s `type` defines the actual data type to use for `Storage`'s `vector` data type.

The remarkable result in this example is that the *data organization* of the `Storage` class now depends on its template arguments. Since the `isPolymorphic == true` situation uses different data types than the `isPolymorphic == false` situation, the overloaded private `add` members can utilize this difference immediately. E.g., `add(Type const &obj, IntType<false>)` uses direct copy construction to store a copy of `obj` in `d_vector`.

It is also possible to make a selection from multiple types as `IfElse` structs can be nested. Realize that using `IfElse` never has any effect on the size or execution time of the final executable program. The final program simply contains the appropriate type, conditional to the type that's eventually selected.

23.2.2.3 An illustrative example

The next example, defining `MapType` as a map having plain types or pointers for either its key or value types, illustrates this approach:

```
template <typename Key, typename Value, int selector>
class Storage
{
    typedef typename IfElse<
                selector == 1,              // if selector == 1:
                map<Key, Value>,            // use map<Key, Value>

                typename IfElse<
                    selector == 2,          // if selector == 2:
                    map<Key, Value *>,      // use map<Key, Value *>

                    typename IfElse<
                        selector == 3,      // if selector == 3:
                        map<Key *, Value>,  // use map<Key *, Value>
                                            // otherwise:
                        map<Key *, Value *> // use map<Key *, Value *>

                    >::type
                >::type
            >::type
            MapType;

    MapType d_map;
    public:
        void add(Key const &key, Value const &value);
    private:
        void add(Key const &key, Value const &value, IntType<1>);
       ...
};
template <typename Key, typename Value, int selector>
inline void Storage<selector, Key, Value>::add(Key const &key,
                                               Value const &value)
{
    add(key, value, IntType<selector>());
}
```

The principle used in the above examples is: if class templates may use data types that depend on template non-type parameters, an `IfElse` struct can be used to select the appropriate data types. Knowledge about the various data types may also be used to define overloaded member functions. The implementations of these overloaded members may then be optimized to the various data types. In programs only one of these alternate functions (the one that is optimized to the actually used data types) will then be instantiated.

The private `add` functions define the same parameters as the public `add` wrapper function, but add a specific `IntType` type, allowing the compiler to select the appropriate overloaded version based on the template's non-type selector parameter.

23.2.3 Templates: Iterations by Recursion

As there are no variables in template meta programming, there is no template equivalent to a `for` or `while` statement. However, iterations can always be rewritten as recursions. Recursions *are* supported by templates and so iterations can always be implemented as (tail) recursions.

To implement iterations by (tail) recursion do as follows:

- define a specialization implementing the end-condition;
- define all other steps using recursion.
- store intermediate values as `enum` values.

The compiler selects a more specialized template implementation over a more generic one. By the time the compiler reaches the end-condition the recursion stops since the specialization does not use recursion.

Most readers are probably familiar with the recursive implementation of the mathematical '*factorial*' operator, commonly represented by the exclamation mark (`!`): `n` factorial (so: `n!`) returns the successive products `n * (n - 1) * (n - 2) * ... * 1`, representing the number of ways `n` objects can be permuted. Interestingly, the factorial operator is itself usually defined by a *recursive* definition:

```
n! = (n == 0) ?
        1
    :
        n * (n - 1)!
```

To compute `n!` from a template, a template `Factorial` can be defined using an `int n` template non-type parameter. A specialization is defined for the case `n == 0`. The generic implementation uses recursion according to the factorial definition. Furthermore, the `Factorial` template defines an `enum` value '`value`' containing its factorial value. Here is the generic definition:

```
template <int n>
struct Factorial
{
    enum { value = n * Factorial<n - 1>::value };
};
```

Note how the expression assigning a value to '`value`' uses constant values that can be determined by the compiler. The value n is provided, and `Factorial<n - 1>` is computed using *template meta programming*. `Factorial<n-1>` in turn results in value that can be determined by the compiler (*viz.* `Factorial<n-1>::value`). `Factorial<n-1>::value` represents the `value` defined by the *type* `Factorial<n - 1>`. It is *not* the value returned by an *object* of that type. There are no objects here but merely values defined by types.

The recursion ends in a specialization. The compiler selects the specialization (provided for the terminating value 0) instead of the generic implementation whenever possible. Here is the specialization's implementation:

```
template <>
struct Factorial<0>
{
    enum { value = 1 };
};
```

The `Factorial` template can be used to determine, compile time, the number of permutations of a fixed number of objects. E.g.,

```
int main()
{
    cout << "The number of permutations of 5 objects = " <<
            Factorial<5>::value << "\n";
}
```

Once again, `Factorial<5>::value` is *not* evaluated at run-time, but at compile-time. The run-time equivalent of the above `cout` statement is, therefore:

```
int main()
{
    cout << "The number of permutations of 5 objects = " <<
            120 << "\n";
}
```

23.3 User-defined literals

In addition to the literal operators discussed in section 11.13 **C++** also offers a function template literal operator, matching the prototype

```
template <char ...Chars>
Type operator "" _identifier()
```

This variadic non-type parameter function template defines no parameters, but merely a variadic non-type parameter list.

Its argument must be an int constant, as is also expected by the literal operator defining an `unsigned long long int` parameter. All the characters of the int constant are passed as individual `char` non-type template arguments to the literal operator.

For example, if `_NM2km` is a literal operator function template, it can be called as `80_NM2km`. The function template is then actually called as `_NM2km<’8’, ’0’>()`. If this function template merely uses template meta programming techniques and only processes integral data then its actions can be performed completely at compile-time. To illustrate this, let’s assume `NM2km` only processes and returns unsigned values.

The function template `_NM2km` can forward its argument to a class template, defining an enum constant `value`, and that performs the required computations. Here is the implementation of the variadic literal operator function template `_NM2km`:

```
template <char ... Chars>
size_t constexpr operator "" _NM2km()
{
    return static_cast<size_t>(             // forward Chars to NM2km
            NM2km<0, Chars ...>::value * 1.852);
}
```

The class template `NM2km` defines three non-type parameters: `acc` accumulates the value, `c` is the first character of the variadic non-type parameters, while `...Chars` represents the remaining non-type parameters, contained in a non-type parameter pack. Since `c` is, at each recursive call, the next character from the original non-type parameter pack, the value so far multiplied by 10 plus the value of the next character is passed as the next accumulated value to its recursive call, together with the remaining elements of the parameter pack, represented by `Chars ...`:

```
template <size_t acc, char c, char  ...Chars>
struct NM2km
{
    enum
    {
        value = NM2km<10 * acc + c - '0', Chars ...>::value
    };
};
```

Eventually, the parameter pack is empty. For this case a partial specialization of `NM2km` is available:

```
template <size_t acc, char c>   // empty parameter pack
struct NM2km<acc, c>
{
    enum
    {
        value = 10 * acc + c - '0'
    };
};
```

This works fine, but of course not in cases where binary, octal, or hexadecimal values must also be interpreted. In that case we must first determine whether the first character(s) indicate a special number system. This can be determined by the class template `NM2kmBase`, that is now called from the `_NM2km` literal operator:

```
template <char ... Chars>
size_t constexpr operator "" _NM2km()
{
    return static_cast<size_t>(         // forward Chars to NM2kmBase
            NM2kmBase<Chars ...>::value * 1.852);
}
```

The `NM2kmBase` class template normally assumes the decimal number system, passing base value 10 and initial sum 0 to `NM2km`. The `NM2km` class template is provided with an additional (first) non-type parameter representing the base value of the number system to use. Here is `NM2kmBase`:

```
template <char ...Chars>
struct NM2kmBase
{
    enum
    {
        value = NM2km<10, 0, Chars ...>::value
    };
};
```

Partial specializations handle the different number systems, by inspecting the first (one or two) characters:

```
template <char ...Chars>
struct NM2kmBase<'0', Chars ...>        // "0..."
{
    enum
    {                                   // octal value: base 8
        value = NM2km<8, 0, Chars ...>::value
    };
};

template <char ...Chars>
struct NM2kmBase<'0', 'b', Chars ...>   // "0b..."
{
    enum
    {                                   // binary value: base 2
        value = NM2km<2, 0, Chars ...>::value
    };
};

template <char  ...Chars>
struct NM2kmBase<'0', 'x', Chars ...>   // "0x..."
{
    enum
    {                                   // hex value: base 16
        value = NM2km<16, 0, Chars ...>::value
    };
};
```

`NM2km` is implemented as before, albeit that it can now handle various number systems. The conversion from character to numeric value is left to a small support function template, `cVal`:

```
template <char c>
```

```
int constexpr cVal()
{
    return '0' <= c <= '9' ? c - '0' : 10 + c - 'a';
}

template <size_t base, size_t acc, char c, char  ...Chars>
struct NM2km
{
    enum
    {
        value = NM2km<base, base * acc + cVal<c>(),
                                      Chars ...>::value
    };
};

template <size_t base, size_t acc, char c>
struct NM2km<base, acc, c>
{
    enum { value = base * acc + cVal<c>() };
};
```

23.4 Template template parameters

Consider the following situation: a software engineer is asked to design a storage class `Storage`. Data stored in `Storage` objects may either make and store copies of the data or store the data as received. `Storage` objects may also either use a vector or a linked list as its underlying storage medium. How should the engineer tackle this request? Should four different `Storage` classes be designed?

The engineer's first reaction could be to develop an all-in `Storage` class. It could have two data members, a list and a vector, and its constructor could be provided with maybe an enum value indicating whether the data itself or new copies should be stored. The enum value can be used to initialize a series of pointers to member functions performing the requested tasks (e.g., using a vector to store the data or a list to store copies).

Complex, but doable. Then the engineer is asked to modify the class: in the case of new copies a custom-made allocation scheme should be used rather than the standard `new` operator. He's also asked to allow the use of yet another type of container, in addition to the vector and the list that were already part of the design. Maybe a `deque` would be preferred or maybe even a `stack`.

It's clear that the approach aiming at implementing all functionality and all possible combinations in one class doesn't scale. The class `Storage` soon becomes a monolithic giant which is hard to understand, maintain, test, and deploy.

One of the reasons why the big, all-encompassing class is hard to deploy and understand is that a well-designed class should *enforce constraints*: the design of the class should, by itself, disallow certain operations, violations of which should be detected by the compiler, rather than by a program that might terminate in a fatal error.

Think about the above request. If the class offers both an interface to access the vector data storage *and* an interface to access the list data storage, then it's likely that the class offers an overloaded `operator[]` member to access elements in the vector. This member, however, will be syntactically present, but semantically invalid when the *list* data storage is selected, which doesn't support `operator[]`.

Sooner or later, *users* of the monolithic all-encompassing class `Storage` will fall into the trap of using `operator[]` even though they've selected the list as the underlying data storage. The compiler won't be able to detect the error, which only appears once the program is running, confusing its users.

The question remains: how should the engineer proceed, when confronted with the above questions? It's time to introduce *policies*.

23.4.1 Policy classes - I

A *policy* defines (in some contexts: prescribes) a particular kind of behavior. In **C++** a *policy class* defines a certain part of the class interface. It may also define inner types, member functions, and data members.

In the previous section the problem of creating a class that might use any of a series of allocation schemes was introduced. These allocation schemes all depend on the actual data type to use, and so the 'template reflex' should kick in.

Allocation schemes should probably be defined as template classes, applying the appropriate allocation procedures to the data type at hand. When such allocation schemes are used by the familiar STL containers (like `std::vector, std::stack`, etc.), then such home-made allocation schemes should probably be derived from `std::allocator`, to provide for the requirements made by these containers. The class template `std::allocator` is declared by the `<memory>` header file and the three allocation schemes developed here were all derived from `std::allocator`.

Using in-class implementations for brevity the following allocation classes could be defined:

- No special allocation takes place, `Data` is used 'as is':

```
template <typename Data>
class PlainAlloc: public std::allocator<Data>
{
    template<typename IData>
    friend std::ostream &operator<<(std::ostream &out,
                                    PlainAlloc<IData> const &alloc);
    Data d_data;

    public:
        PlainAlloc()
        {}
        PlainAlloc(Data const &data)
        :
            d_data(data)
        {}
        PlainAlloc(PlainAlloc<Data> const &other)
        :
            d_data(other.d_data)
        {}
};
```

- The second allocation scheme uses the standard `new` operator to allocate a new copy of the data:

```
template <typename Data>
class NewAlloc: public std::allocator<Data>
{
    template<typename IData>
    friend std::ostream &operator<<(std::ostream &out,
                                    NewAlloc<IData> const &alloc);
    Data *d_data;

    public:
        NewAlloc()
        :
            d_data(0)
        {}
        NewAlloc(Data const &data)
        :
            d_data(new Data(data))
        {}
        NewAlloc(NewAlloc<Data> const &other)
        :
            d_data(new Data(*other.d_data))
        {}
        ~NewAlloc()
        {
            delete d_data;
        }
};
```

- The third allocation scheme uses the placement new operator (see section 9.1.5), requesting memory from a common pool (the implementation of the member `request`, obtaining the required amount of memory, is left as an exercise to the reader):

```
template<typename Data>
class PlacementAlloc: public std::allocator<Data>
{
    template<typename IData>
    friend std::ostream &operator<<(std::ostream &out,
                                    PlacementAlloc<IData> const &alloc);
    Data *d_data;

    static char s_commonPool[];
    static char *s_free;

    public:
        PlacementAlloc()
        :
            d_data(0)
        {}
        PlacementAlloc(Data const &data)
        :
            d_data(new(request()) Data(data))
        {}
        PlacementAlloc(PlacementAlloc<Data> const &other)
        :
            d_data(new(request()) Data(*other.d_data))
        {}
        ~PlacementAlloc()
        {
            d_data->~Data();
        }
    private:
        static char *request();
    };
```

The above three classes define *policies* that may be selected by the user of the class `Storage` introduced in the previous section. In addition to these classes, additional allocation schemes could be implemented by the user as well.

To apply the proper allocation scheme to the class `Storage`, `Storage` should be designed as a class template itself. The class also needs a template type parameter allowing users to specify the data type.

The data type to be used by a particular allocation scheme could of course be specified when specifying the allocation scheme to use. The class `Storage` would then have two template type parameters, one for the data type, one for the allocation scheme:

```
    template <typename Data, typename Scheme>
    class Storage ...
```

To use the class `Storage` we would then write, e.g.:

```
    Storage<string, NewAlloc<string>> storage;
```

Using `Storage` this way is fairly complex and potentially error-prone, as it requires the user to specify the data type twice. Instead, the allocation scheme should be specified using a new type of template parameter, not requiring the user to specify the data type required by the allocation scheme. This new kind of template parameter (in addition to the well-known *template type parameter* and *template non-type parameter*) is called the *template template parameter*.

Starting with the C++14 standard the keyword *class* in the syntactical form of template template parameters (`template <parameter specifications> class Name`) is no longer required. From that standard onward, the keyword `typename` can also be used (e.g., `template <parameter specifications> typename Name`).

23.4.2 Policy classes - II: template template parameters

Template template parameters allow us to specify a *class template* as a template parameter. By specifying a class template, it is possible to add a certain kind of behavior (called a *policy*) to an existing class template.

To specify an allocation *policy*, rather than an allocation `type` for the class `Storage` we rephrase its class template header: definition starts as follows:

```
    template <typename Data, template <typename> class Policy>
    class Storage...
```

The second template parameter is new. It is a *template template parameter*. It has the following elements:

- The keyword `template`, starting the template template parameter;
- The keyword `template` is followed (between angle brackets) by a list of template parameters that must be specified for the template template parameter. These parameters *may* be given names, but names are usually omitted as those names cannot be used in subsequent template definitions. On the other hand, providing formal names may help the reader of the template to understand the kind of templates that must be specified with the template template parameter.

- Template template parameters must match, in numbers and types (i.e., template type parameters, template non-type parameters, template template parameters) the template parameters that must be specified for the policy. This can be tricky, as some templates use default parameters that are hardly ever changed (like the allocation schemes for containers). Programmers may not immediately realize that these defaults exist and be confused when the compiler rejects such templates when trying to pass them as template template parameters for which these additional (default) parameters weren't specified. However, language offers a solution for this problem in the form of *alias templates*, introduced in section 23.5.
- Following the bracketed list the keyword `class` or `typename` *must* be specified.
- All parameters may be provided with default arguments. This is shown in the next example of a hypothetical class template:

  ```
  template <
      template <
          typename = std::string,
          int = 12,
          template <typename = int> class Inner = std::vector
      >
      class Policy
  >
  class Demo
  {
     ...
  };
  ```

  Here, the class template `Demo` expects a template template parameter named `Policy`, expecting three template parameters: a template type parameter (by default `std::string`); a template non-type parameter (by default having value 12); and `Policy` itself expects a template template parameter, called `Inner`, by default using an `int` as its template type parameter.

Policy classes are often an integral part of the class under consideration. Because of this they are often deployed as base classes. In the example the class `Policy` could be used as a base class of the class `Storage`.

The policy operates on the class `Storage`'s data type. Therefore the policy is informed about that data type as well. Our class `Storage` now begins like this:

```
template <typename Data, template <typename> class Policy>
class Storage: public Policy<Data>
```

This automatically allows us to use `Policy`'s members when implementing the members of the class `Storage`.

Our home-made allocation classes do not really provide us with many useful members. Except for the extraction operator they offer no immediate access to the data. This can easily be repaired by adding more members. E.g., the class `NewAlloc` could be augmented with operators allowing access to and modification of stored data:

```
    operator Data &()    // optionally add a `const' member too
    {
        return *d_data;
    }
    NewAlloc &operator=(Data const &data)
    {
```

```
            *d_data = data;
        }
```

The other allocation classes could be given comparable members.

Let's use the allocation schemes in some real code. The next example shows how `Storage` can be defined using some data type and an allocation scheme. We start out again with a class `Storage`:

```
    template <typename Data, template <typename> class Allocate>
    class Storage: public std::vector<Data, Allocate<Data>>
    {};
```

That's all we have to do. Note that `std::vector` formally has two template parameters. The first one is the vector's data type, which is always specified; the second one is the allocator used by the vector. Usually the allocator is left unspecified (in which case the default STL allocator is used), but here it is mentioned explicitly, allowing us to pass our own allocation policy to `Storage`.

All required functionality is inherited from the `vector` base class, while the policy is 'factored into the equation' using a template template parameter. Here's an example showing how this is done:

```
    Storage<std::string, NewAlloc> storage;

    copy(istream_iterator<std::string>(cin), istream_iterator<std::string>(),
            back_inserter(storage));

    cout << "Element index 1 is " << storage[1] << '\n';
    storage[1] = "hello";

    copy(storage.begin(), storage.end(),
          ostream_iterator<NewAlloc<std::string> >(cout, "\n"));
```

Since `Storage` objects are also `std::vector` objects the STL `copy` function can be used in combination with the *back_inserter* iterator to add some data to the `storage` object. Its elements can be accessed and modified using the index operator. Then `NewAlloc<std::string>` objects are inserted into `cout` (also using the `copy` function).

Interestingly, this is not the end of the story. Remember that our intention was to create a class allowing us to specify the *storage type* as well. What if we don't want to use a `vector`, but instead would like to use a `list`?

It's easy to change `Storage`'s setup so that a completely different storage type can be used on request, like a `deque`. To implement this, the storage class is parameterized as well, using yet another template template parameter:

```
    template <typename Data, template <typename> class AllocationPolicy,
              template <typename, typename> class Container = std::vector>
    class Storage: public Container<Data, AllocationPolicy<Data>>
    {};
```

The earlier example using a `Storage` object can be used again without requiring any modifications at all (except for the above redefinition). It clearly can't be used with a `list` container, as the `list` lacks `operator[]`. Trying to do so is immediately recognized by the compiler, producing an error if an attempt is made to use `operator[]` on, e.g., a `list`.[1] A `list` container, however can still be specified as the container to use. In that case a `Storage` is implemented as a `list`, offering `list`'s interface, rather than `vector`'s interface, to its users.

---

[1] A complete example showing the definition of the allocation classes and the class `Storage` as well as its use is provided in the **C++** Annotations's distribution in the file `yo/advancedtemplates/examples/storage.cc`.

23.4.2.1 The destructor of Policy classes

In the previous section policy classes were used as base classes of template classes. This resulted in the interesting observation that a policy class may serve as a *base class* of a derived class. As a policy class may act as a base class, a pointer or reference to such a policy class can be used to point or refer to the derived class using the policy.

This situation, although legal, should be avoided for various reasons:

- Destruction of a derived class object using the base class's destructor requires the implementation of a virtual destructor;
- A virtual destructor introduces overhead to a class that normally has no data members, but merely defines behavior: suddenly a `vtable` is required as well as a data member pointing to the vtable;
- Virtual member functions somewhat reduce the efficiency of code; virtual member functions use *dynamic polymorphism*, which in principle is undoing the advantages of *static polymorphism* as offered by templates;
- Virtual member functions in templates may result in *code bloat*: once an instantiation of a class's member is required, the class's vtable and *all* its virtual members must be implemented too.

To avoid these drawbacks, it is good practice to *prevent* the use of references or pointers to policy classes to refer or point to derived class objects. This is accomplished by providing policy classes with *non-virtual protected destructors*. With a non-virtual destructor there is no performance penalty and since its destructor is protected users cannot refer to classes derived from the policy class using a pointer or reference to the policy class.

23.4.3 Structure by Policy

Policy classes usually define behavior, not structure. Policy classes are normally used to parameterize some aspect of the behavior of classes that are derived from them. However, different policies may require different data members. These data members may also be defined by the policy classes. Policy classes may therefore be used to define both behavior and structure.

By providing a well-defined interface a class derived from a policy class may define member specializations using the different structures of policy classes to their advantage. For example, a plain pointer-based policy class could offer its functionality by resorting to **C**-style pointer juggling, whereas a `vector`-based policy class could use the vector's members directly.

In this example a generic class template `Size` could be designed expecting a container-like policy using features commonly found in containers, defining the data (and hence the structure) of the container specified in the policy. E.g.:

```
template <typename Data, template <typename> class Container>
struct Size: public Container<Data>
{
    size_t size()
    {                               // relies on the container's `size()'
```

```
                              // note: can't use `this->size()'
            return Container<Data>::size();
        }
    };
```

A specialization can now be defined for a much simpler storage class using, e.g., plain pointers (the implementation capitalizes on `first` and `second`, data members of `std::pair`. Cf. the example at the end of this section):

```
    template <typename Data>
    struct Size<Data, Plain>: public Plain<Data>
    {
        size_t size()
        {                             // relies on pointer data members
            return this->second - this->first;
        }
    };
```

Depending on the intentions of the template's author other members could be implemented as well.

To simplify the real use of the above templates, a generic wrapper class can be constructed: it uses the `Size` template matching the actually used storage type (e.g., a `std::vector` or some plain storage class) to define its structure:

```
    template <typename Data, template <typename> class Store>
    class Wrapper: public Size<Data, Store>
    {};
```

The above classes could now be used as follows (*en passant* showing an extremely basic `Plain` class):

```
    #include <iostream>
    #include <vector>

    template <typename Data>
    struct Plain: public std::pair<Data *, Data *>
    {};

    int main()
    {
        Wrapper<int, std::vector> wiv;
        std::cout << wiv.size() << "\n";

        Wrapper<int, Plain> wis;
        std::cout << wis.size() << "\n";
    }
```

The `wiv` object now defines vector-data, the `wis` object merely defines a `std::pair` object's data members.

23.5 Alias Templates

In addition to function and class templates, **C++** also uses templates to define an alias for a set of types. This is called an *alias template*. Alias templates can be specialized. The name of an alias template is a type name.

Alias templates can be used as arguments to template template parameters. This allows us to avoid the ‘unexpected default parameters’ you may encounter when using template template parameters. E.g., defining a template specifying a `template <typename> class Container` is fine, but it is impossible to specify a container like `vector` or `set` as template template argument, as `vector` and `set` containers also define a second template parameter, specifying their allocation policy.

Alias templates are defined like `using` declarations, specifying an alias for an existing (maybe partially or fully specialized) template type. In the following example `Vector` is defined as an alias for `vector`:

```
template <typename Type>
using Vector = std::vector<Type>;

Vector<int> vi;             // same as std::vector<int>
std::vector<int> vi2(vi);   // copy construction: OK
```

So, what’s the point of doing this? Looking at the `vector` container, we see that it defines two, rather than one, template parameters, the second parameter being the allocation policy `_Alloc`, by default set to `std::allocator<_Tp>`:

```
template<typename _Tp, typename _Alloc = std::allocator<_Tp> >
class vector: ...
```

Now define a class template `Generic` defining a template template parameter:

```
template <typename Type, template <typename> class Container>
class Generic: public Container<Type>
{
    ...
};
```

Most likely, `Generic` offers members made available by the container that is actually used to create the `Generic` object, and adds to those some members of it own. However, a simple container like `std::vector` cannot be used, as `std::vector` doesn’t match a `template <typename> class Container>` parameter; it requires a `template <typename, typename> class Container>` template template parameter.

The `Vector` alias template, however, *is* defined as a template having one template type parameter, and it uses the vector’s default allocator. Consequently, passing a `Vector` to `Generic` works fine:

```
Generic<int, Vector> giv;       // OK
Generic<int, std::vector> err;  // won't compile: 2nd argument mismatch
```

With the aid of a small alias template it is also possible to use a completely different kind of container, like a `map`, with `Generic`:

```
template <typename Type>
using MapString = std::map<Type, std::string>;

Generic<int, MapString> gim;    // uses map<int, string>
```

23.6 Trait classes

Scattered over the `std` namespace *trait classes* are found. E.g., most **C++** programmers have seen the compiler mentioning '`std::char_traits<char>`' when performing an illegal operation on `std::string` objects, as in `std::string s(1)`.

Trait classes are used to make compile-time decisions about types. Trait classes allow us to apply the proper code to the proper data type, be it a pointer, a reference, or a plain value, all this maybe in combination with `const`. The particular type of data to use can be inferred from the actual type that is specified (or implied) when the template is used. This can be fully automated, not requiring the template writer to make any decision.

Trait classes allow us to develop a `template <typename Type1, typename Type2, ...>` without the need to specify many specializations covering all combinations of, e.g., values, (const) pointers, or (const) references, which would soon result in an unmaintainable exponential explosion of template specializations (e.g., allowing these five different types for each template parameter already results in 25 combinations when two template type parameters are used: each must be covered by potentially different specializations).

Having available a trait class, the actual type can be inferred compile time, allowing the compiler to deduce whether or not the actual type is a pointer, a pointer to a member, or a const pointer, and to make comparable deductions in case the actual type is, e.g., an lvalue or rvalue reference type. This in turn allows us to write templates that define types like `argument_type`, `first_argument_type`, `second_argument_type` and `result_type`, which are required by several generic algorithms (e.g., count_if()).

A trait class usually performs no behavior. I.e., it has no constructor and no members that can be called. Instead, it defines a series of types and `enum` values that have certain values depending on the actual type that is passed to the trait class template. The compiler uses one of a set of available specializations to select the one appropriate for an actual template type parameter.

The point of departure when defining a trait template is a plain vanilla `struct`, defining the characteristics of a plain value type like an `int`. This sets the stage for specific specializations, modifying the characteristics for any other type that could be specified for the template.

To make matters concrete, assume the intent is to create a trait class `BasicTraits` telling us whether a type is a plain value type, a pointer type, an lvalue reference type or an rvalue reference type (all of which may or may not be `const` types).

Whatever the actually provided type, we want to be able to determine the 'plain' type (i.e., the type without any modifiers, pointers or references), the 'pointer type' and the 'reference type', allowing us to define in all cases, e.g., an rvalue reference to its built-in type, even though we passed a const pointer to that type.

Our point of departure, as mentioned, is a plain `struct` defining the required parameter. Maybe something like this:

```
template <typename T>
struct Basic
{
    typedef T Type;
    enum
    {
        isPointer = false,
        isConst = false,
        isRef = false,
        isRRef = false
        };
    };
```

Although some conclusions can be drawn by combining various `enum` values (e.g., a plain type is not a pointer or a reference or an rvalue reference or a const), it is good practice to provide a full implementation of trait classes, not requiring its users to construct these logical expressions themselves. Therefore, the basic decisions in a trait class are usually made by a nested trait class, leaving the task of creating appropriate logical expressions to a surrounding trait class.

So, the `struct Basic` defines the generic form of our inner trait class. Specializations handle specific details. E.g., a pointer type is recognized by the following specialization:

```
    template <typename T>
    struct Basic<T *>
    {
        typedef T Type;
        enum
        {
            isPointer = true,
            isConst = false,
            isRef = false,
            isRRef = false
        };
    };
```

whereas a pointer to a const type is matched with the next specialization:

```
    template <typename T>
    struct Basic<T const *>
    {
        typedef T Type;
        enum
        {
            isPointer = true,
            isConst = true,
            isRef = false,
            isRRef = false
        };
    };
```

Several other specializations should be defined: e.g., recognizing `const` value types or (rvalue) reference types. Eventually all these specializations are implemented as nested `struct`s of an outer class `BasicTraits`, offering the public traits class interface. The outline of the outer trait class is:

```
template <typename TypeParam>
class BasicTraits
{
    // Define specializations of the template `Base' here

    public:
        BasicTraits(BasicTraits const &other) = delete;

        typedef typename Basic<TypeParam>::Type ValueType;
        typedef ValueType *PtrType;
```

```
            typedef ValueType &RefType;
            typedef ValueType &&RvalueRefType;

            enum
            {
                isPointerType = Basic<TypeParam>::isPointer,
                isReferenceType = Basic<TypeParam>::isRef,
                isRvalueReferenceType = Basic<TypeParam>::isRRef,
                isConst = Basic<TypeParam>::isConst,
                isPlainType = not (isPointerType or isReferenceType or
                                   isRvalueReferenceType or isConst)
            };
    };
```

The trait class's public interface explicitly deletes its copy constructor. As it therefore defines no constructor at all and as it has no static members it does not offer any run-time executable code. All the trait class's facilities must therefore be used compile time.

A trait class template can be used to obtain the proper type, irrespective of the template type argument provided. It can also be used to select a proper specialization that depends on, e.g., the `const`-ness of a template type. Example:

```
cout <<
 "int: plain type? "     << BasicTraits<int>::isPlainType << "\n"
 "int: ptr? "            << BasicTraits<int>::isPointerType << "\n"
 "int: const? "          << BasicTraits<int>::isConst << "\n"
 "int *: ptr? "          << BasicTraits<int *>::isPointerType << "\n"
 "int const *: ptr? "    << BasicTraits<int const *>::isPointerType <<
                                                                 "\n"
 "int const: const? "    << BasicTraits<int const>::isConst << "\n"
 "int: reference? "      << BasicTraits<int>::isReferenceType << "\n"
 "int &: reference? "    << BasicTraits<int &>::isReferenceType << "\n"
 "int const &: ref ? "   << BasicTraits<int const &>::isReferenceType <<
                                                                   "\n"
 "int const &: const ? " << BasicTraits<int const &>::isConst << "\n"
 "int &&: r-reference? " << BasicTraits<int &&>::isRvalueReferenceType <<
                                                                   "\n"
 "int &&: const? " << BasicTraits<int &&>::isConst << "\n"
 "int const &&: r-ref ? "<< BasicTraits<int const &&>::
                                           isRvalueReferenceType << "\n"
 "int const &&: const ? "<< BasicTraits<int const &&>::isConst << "\n"
   "\n";

BasicTraits<int *>::ValueType           value = 12;
BasicTraits<int const *>::RvalueRefType rvalue = int(10);
BasicTraits<int const &&>::PtrType      ptr = new int(14);
cout << value << ' ' << rvalue << ' ' << *ptr << '\n';
```

23.6.1 Distinguishing class from non-class types

In the previous section the `BasicTraits` trait class was developed. Using specialized versions of a nested `struct Type` modifiers, pointers, references and values could be distinguished.

Knowing whether a type is a class type or not (e.g., the type represents a primitive type) could also be a useful bit of knowledge to a template developer. The class template developer might want to define a specialization when the template's type parameter represents a class type (maybe using some member function that should be available) and another specialization for non-class types.

This section addresses the question how a trait class can distinguish class types from non-class types.

In order to distinguish classes from non-class types a distinguishing feature that can be used at compile-time must be found. It may require some thinking to find such a distinguishing characteristic, but a good candidate eventually is found in the pointer to members syntactic construct. Pointers to members are only available for classes. Using the pointer to member construct as the distinguishing characteristic, a specialization can be developed that uses the pointer to member if available. Another specialization (or the generic template) does something else if the pointer to member construction is not available.

How can we distinguish a pointer to a member from 'a generic situation', not being a pointer to a member? Fortunately, such a distinction is possible. A function template specialization can be defined having a parameter which is a pointer to a member function. The generic function template then accepts any other argument. The compiler *selects* the former (specialized) function when the provided type is a class type as class types *may* support a pointer to a member. The interesting verb here is '*may*': the class does not *have* to define a pointer to member.

Furthermore, the compiler does not actually *call* any function: we're talking compile-time here. All the compiler does is to *select* the appropriate function by evaluating a constant expression.

So, our intended function template now looks like this:

```
template <typename ClassType>
static `some returntype'  fun(void (ClassType::*)());
```

The function's return type ('`(some returntype)`') will be defined shortly. Let's first have a closer look at the function's parameter. The function's parameter defines a pointer to a member returning `void`. Such a function does *not* have to exist for the concrete class-type that's specified when the function is used. In fact, *no* implementation is provided. The function `fun` is only declared as a *static* member in the trait class. It's not implemented and no trait class object is required to call it. What, then, is its use?

To answer the question we now have a look at the generic function template that should be used when the template's argument is *not* a class type. The language offers a 'worst case' parameter in its *ellipsis* parameter list. The ellipsis is a final resort the compiler may turn to if everything else fails. The generic function template specifies a plain ellipsis in its parameter list:

```
template <typename NonClassType>
static `some returntype' fun(...);
```

It would be an error to define the generic alternative as a function expecting an `int`. The compiler, when confronted with alternatives, favors the simplest, most specified alternative over a more complex, generic one. So, when providing `fun` with an argument it selects `int` whenever possible and it won't select `fun(void (ClassType::*)())`. When given the choice between `fun(void (ClassType::*)())` and `fun(...)` it selects the former unless it can't do that.

The question now becomes: what argument can be used for both a pointer to a member and for the ellipsis? Actually, there is such a 'one size fits all' argument: 0. The value 0 can be passed as argument value to functions defining an ellipsis parameter and to functions defining a pointers-to-member parameter.

But 0 does not specify a particular class. Therefore, `fun` must specify an explicit template argument, appearing in our code as `fun<Type>(0)`, with `Type` being the template type parameter of the trait class.

Now for the return type. The function's return type cannot be a simple value (like `true` or `false`). Our eventual intent is to provide the trait class with an enum telling us whether the trait class's template argument represents a class type or not. That enum becomes something like this:

```
enum { isClass = some class/non-class distinguishing expression } ;
```

The distinguishing expression cannot be

```
enum { isClass = fun<Type>(0) } ;
```

as `fun<Type>(0)` is not a constant expression and enum values *must* be defined by constant expressions so they can be determined at compile-time.

To determine `isClass`'s value we must find an expression allowing for compile-time discriminations between `fun<Type>(...)` and `fun<Type>(void (Type::*)())`.

In situations like these the `sizeof` operator often is our tool of choice as it is evaluated at compile-time. By defining different sized return types for the two `fun` declarations we are able to distinguish (at compile-time) which of the two `fun` alternatives is selected by the compiler.

The `char` type is by definition a type having size 1. By defining another type containing two consecutive `char` values a larger type is obtained. A `char [2]` is of course not a type, but a `char[2]` can be defined as a data member of a struct, and a struct *does* define a type. That struct then has a size exceeding 1. E.g.,

```
struct Char2
{
    char data[2];
};
```

`Char2` can be defined as a nested type of our traits class. The two `fun` function template declarations become:

```
template <typename ClassType>
static Char2 fun(void (ClassType::*)());

template <typename NonClassType>
static char fun(...);
```

Since `sizeof` expressions are evaluated at compile-time we can now determine `isClass`'s value:

```
enum { isClass = sizeof(fun<Type>(0)) == sizeof(Char2) };
```

This expression has several interesting implications:

- no `fun` function template is ever instantiated;
- the compiler considers `Type` and selects `fun`'s function template specialization if `Type` is a class type and the generic function template if not;
- From the selected function it determines the return type and thus the return type's size;
- Resulting in the proper evaluation of `isClass`.

Without requiring any instantiation the trait class can now provide an answer to the question whether a template type argument represents a class type or not. Marvelous!

23.6.2 Available type traits

C++ offers many facilities to identify and modifiy characteristics of types. Before using these facilities the `<type_traits>` header file must be included.

All facilities offered by `type_traits` are defined in the `std` namespace (omitted from the examples given below), allowing programmers to determine various characteristics of types and values.

In the description of available type traits the following concepts are encountered:

- *arithmetic type*: any integral or floating point type;
- *class type*: not a union type, without non-static data members, without virtual members, without virtual or non-empty base classes;
- *compound type*:
  - arrays of objects of a given type;
  - functions, which have parameters of a given type returning `void` or objects;
  - pointers to `void`, to objects, to functions, or to non-static class members;
  - references to objects or functions;
  - class, union or enumeration types;
- *fundamental type*: a built-in type;
- *integral type*: all types whose values represent integral numbers, as well as `bool` and all built-in types representing (possibly unicode) characters;
- *literal type*: a literal type is a scalar type; a trivial class type; or an array of literal type elements;
- *is_nothrow_... type trait*: a type trait to determine whether its template argument supports the specified non-throwing member. Such type traits return `false` unless `noexcept(true)` is used at the function's declaration. E.g.,

  ```
  struct NoThrow
  {
      NoThrow &operator=(SomeType const &rhs) noexept(true);
  };
  ```

- *trivial type*: trivial types are scalar types, trivial class types, arrays of such types and cv-qualified versions of these types;
- *trivial class type*: a class type having a trivial copy constructor, no non-trivial move constructor, a trivial destructor, a trivial default constructor or at least one `constexpr` constructor other than the copy or move constructor, and only has non-static data members and base classes of literal types;
- *trivial member function*: trivial member functions are never declared (other than `default`) in their class interfaces and (for default constructors or assignment operators) only perform byte-by-byte actions. Here are two examples: `struct Pod` only has trivial members as it doesn't explicitly declare any member function and its data member is *plain old data*. `struct Nonpod` is *not* plain old data. Although it doesn't explictly declare any member function either, its data member is a `std::string`, which itself isn't plain old data as `std::string` has non-trivial constructors:

  ```
  struct Pod
  {
  ```

```
    int x;
};

struct Nonpod
{
    std::string s;
};
```

When *type-condition* applies to a type, it must be a complete type, `void`, or an array of unknown size;

The following type traits are provided:

- `add_const<typename Type>::type` to add `const` to `Type`;
- `add_cv<typename Type>::type` to add `const volatile` to `Type`;
- `add_lvalue_reference<typename Type>::type` to add an lvalue reference to `Type`;
- `add_pointer<typename Type>::type` to add a pointer to `Type`;
- `add_rvalue_reference<typename Type>::type` to add an rvalue reference to `Type`;
- `add_volatile<typename Type>::type` to add `volatile` to `Type`;
- `conditional<bool cond, typename TrueType, typename FalseType>::type` to conditionally use `TrueType` if `cond` is true, `FalseType` if not;
- `template <typename Type> struct decay` defines the typename `type` obtained from `Type` after removing all cv-qualifiers and references from the specified template type argument. Moreover, it converts lvalue types to rvalue types, and arrays and functions to pointers. It resembles what happens if an argument is passed to a value-type parameter.
- `template <typename Type> decay_t` is shorthand for `typename decay<Type>::type`.
- `enable_if<bool cond, typename Type>::type` to conditionally define `Type` if `cond` is true;
- `is_abstract<typename Type>::value` to determine whether `Type` is an abstract type (e.g., an abstract base class) (*type-condition* applies);
- `is_arithmetic<typename Type>::value` to determine whether `Type` is an arithmetic type;
- `is_array<typename Type>::value` to determine whether `Type` is an array type;
- `is_assignable<typename To, typename From>::value` to determine whether an object of type `From` can be assigned to an object of type `To` (*type-condition* applies);
- `is_base_of<typename Base, typename Derived>::value` to determine whether `Base` is a base class of type `Derived`;
- `is_class<typename Type>::value` to determine whether `Type` is a class type;
- `is_compound<typename Type>::value` to determine whether `Type` is a compound type;
- `is_const<typename Type>::value` to determine whether `Type` is a const type;
- `is_constructible<typename Type, typename ...Args>::value` to determine whether `Type` is constructible from arguments in the `Args` parameter pack (*type-condition* applies to all types in `Args`);

- `is_convertible<typename From, typename To>::value` to determine whether a type `From` may be converted to a type `To` using a `static_cast`;
- `is_copy_assignable<typename Type>::value` to determine whether `Type` supports copy assignment (*type-condition* applies);
- `is_copy_constructible<typename Type>::value` to determine whether `Type` supports copy construction (*type-condition* applies);
- `is_default_constructible<typename Type>::value` to determine whether `Type` supports a default constructor (*type-condition* applies);
- `is_destructible<typename Type>::value` to determine whether `Type` has a non-deleted destructor (*type-condition* applies);
- `is_empty<typename Type>::value` to determine whether `Type` is a class type (not a union type), without non-static data members, virtual members, virtual or non-empty base classes (*type-condition* applies);
- `is_enum<typename Type>::value` to determine whether `Type` is an enum type;
- `is_floating_point<typename Type>::value` to determine whether `Type` is a floating point type;
- `is_function<typename Type>::value` to determine whether `Type` is a function type;
- `is_fundamental<typename Type>::value` to determine whether `Type` is a fundamental type;
- `is_integral<typename Type>::value` to determine whether `Type` is an integral type;
- `is_literal_type<typename Type>::value` to determine whether `Type` is a literal type (*type-condition* applies);
- `is_lvalue_reference<typename Type>::value` to determine whether `Type` is an lvalue reference;
- `is_member_function_pointer<typename Type>::value` to determine whether `Type` is a pointer to a non-static member function;
- `is_member_object_pointer<typename Type>::value` to determine whether `Type` is a pointer to a non-static data member;
- `is_member_pointer<typename Type>::value` to determine whether `Type` is a pointer to a member function;
- `is_move_assignable<typename Type>::value` to determine whether `Type` supports move assignment (*type-condition* applies);
- `is_move_constructible<typename Type>::value` to determine whether `Type` supports move construction (*type-condition* applies);
- `is_nothrow_assignable<typename To, typename From>::value` to determine whether `Type` supports an assignment operator not throwing exceptions (*type-condition* applies).
- `is_nothrow_constructible<typename Type, typename ...Args>::value` to determine whether a `Type` object can be constructed from arguments of types mentioned in the parameter pack not throwing exceptions (*type-condition* applies);
- `is_nothrow_copy_assignable<typename Type>::value` to determine whether `Type` supports a copy-assignment operator not throwing exceptions (*type-condition* applies);

- `is_nothrow_copy_constructible<typename Type>::value` to determine whether `Type` supports copy construction not throwing exceptions (*type-condition* applies);
- `is_nothrow_default_constructible<typename Type>::value` to determine whether `Type` supports a default constructor not throwing exceptions (*type-condition* applies);
- `is_nothrow_destructible<typename Type>::value` to determine whether `Type` supports a destructor not throwing exceptions (*type-condition* applies).
- `is_nothrow_move_assignable<typename Type>::value` to determine whether `Type` supports move assignment not throwing exceptions (*type-condition* applies);
- `is_nothrow_move_constructible<typename Type>::value` to determine whether `Type` supports a move constructor not throwing exceptions (*type-condition* applies);
- `is_object<typename Type>::value` to determine whether `Type` is an object (in contrast to scalar) type;
- `is_pod<typename Type>::value` to determine whether `Type` is an *aggregate* (*plain old data*, *type-condition* applies);
- `is_pointer<typename Type>::value` to determine whether `Type` is a pointer type;
- `is_polymorphic<typename Type>::value` to determine whether `Type` is a polymorphic type (*type-condition* applies);
- `is_reference<typename Type>::value` to determine whether `Type` is an (lvalue or rvalue) reference;
- `is_rvalue_reference<typename Type>::value` to determine whether `Type` is an rvalue reference;
- `is_same<typename First, typename Second>::value` to determine whether types `First` and `Second` are identical;
- `is_scalar<typename Type>::value` to determine whether `Type` is a scalar type (in contrast to an object type);
- `is_signed<typename Type>::value` to determine whether `Type` is a signed type;
- `is_standard_layout<typename Type>::value` to determine whether `Type` offers the standard layout (*type-condition* applies);
- `is_trivial<typename Type>::value` to determine whether `Type` is a trivial type (*type-condition* applies);
- `is_trivially_assignable<typename Dest, typename Src>::value` to determine whether an object or value of type `Src` can trivially be assigned to an object of type `Dest` (*type-condition* applies);
- `is_trivially_constructible<typename Type, typename ...Args>::value` to determine whether `Type` is trivially constructible from arguments in the `Args` parameter pack (*type-condition* applies to all types in `Args`);
- `is_trivially_copy_assignable<typename Type>::value` to determine whether `Type` supports a trivial assignment operator (*type-condition* applies);
- `is_trivially_copy_constructible<typename Type>::value` to determine whether `Type` is trivially copy-constructible (*type-condition* applies);
- `is_trivially_copyable<typename Type>::value` to determine whether `Type` is trivially copyable (*type-condition* applies);

- `is_trivially_default_constructible<typename Type>::value` to determine whether `Type` supports a trivial default constructor (*type-condition* applies);
- `is_trivially_default_destructible<typename Type>::value` to determine whether `Type` supports a trivial default destructor (*type-condition* applies);
- `is_trivially_move_assignable<typename Type>::value` to determine whether `Type` supports a trivial assignment operator (*type-condition* applies);
- `is_trivially_move_constructible<typename Type>::value` to determine whether `Type` is trivially move-constructible (*type-condition* applies);
- `is_union<typename Type>::value` to determine whether `Type` is a union type;
- `is_unsigned<typename Type>::value` to determine whether `Type` is an unsigned type;
- `is_void<typename Type>::value` to determine whether `Type` is `void`;
- `is_volatile<typename Type>::value` to determine whether `Type` is a `volatile` qualified type;
- `make_signed<typename Type>::type` to construct a signed type;
- `make_unsigned<typename Type>::type` to construct an unsigned type;
- `remove_all_extents<typename Type>::type` if `Type` is a (possibly multidimensional) array of `ElementType` values or objects then `typedef type` equals `ElementType`;
- `remove_const<typename Type>::type` to remove `const` from `Type`;
- `remove_cv<typename Type>::type` to remove `const` and/or `volatile` from `Type`;
- `remove_extent<typename Type>::type` if `Type` is an array of `ElementType` values or objects then `typedef type` equals `ElementType`. With multi-dimensional arrays `ElementType` is the type of the array from which its first array dimension has been removed;
- `remove_pointer<typename Type>::type` to remove a pointer from `Type`;
- `remove_reference<typename Type>::type` to remove a reference from `Type`;
- `remove_volatile<typename Type>::type` to remove `volatile` from `Type`;

23.7 Defining 'ErrorCodeEnum' and 'ErrorConditionEnum' enumerations

In section 4.3.2 the class `std::error_code` was introduced. One of its constructors accepts `ErrorCodeEnum` values, where `ErrorCodeEnum` is a template type name for enumerations that we may define ourselves containing symbols that are used as error code values. Another constructor expects an `int`-valued error code and a specification of an error category that uses those error codes.

Several error code enumerations and error categories are predefined by **C++** but it is also possible to define new `ErrorCodeEnums` and error categories. In this section constructing new `ErrorCodeEnums` is covered, in the next section designing new error categories is covered.

Defining new error code enumerations is an option when using `error_code` objects is attractive, but standard error code values (like the values defined by `enum class errc`) aren't appropriate. For example, when designing an interactive calculator, several errors may be encountered that are related to the way expressions are entered by the user. For those situations you might want to develop your own error code enumeration.

In this and the next section a bare bones approach to defining error code enumerations and error categories is adopted. No concrete, real-life like class is developed. I think the advantage of this is that this way it's easier to apply the principles to new real-life situations than if you first have to abstract the content of a real-life example yourself. Here we go:

- Our first step consists of defining our own enumeration. The enumeration contains symbols listing causes of errors. Newly defined error code enumerations must not associate value 0 with any of its symbols, as by convention value 0 indicates 'no error'.

  The `enum class CatErr` lists causes of errors that are associated with our (as yet to be designed) error category:

  ```
  enum class CatErr
  {
      Err1 = 1,            // causes of errors
      Err2,
      Err3
  };
  ```

- By itself, defining an `enum class` does not allow us to pass its values to `error_code` constructors. Before we can do that the `enum` must be 'promoted' to an *error_code_enum*. This 'promotion' is realized by specializing the trait class `std::is_error_code_enum` after which the `error_code(ErrorCodeEnum)` member template and the `make_error_code` function accept `CatErr` enumeration values. Interestingly, this requires us to add code to the `std` namespace. Normally this is not allowed, but in this case it is. The **C++** standard states:

  > 20.5.4.2.1 Namespace std
  > The behavior of a C++ program is undefined if it adds declarations or definitions to namespace std or to a namespace within namespace std unless otherwise specified.
  >
  > A program may add a template specialization for any standard library template to namespace std only if the declaration depends on a user-defined type and the specialization meets the standard library requirements for the original template and is not explicitly prohibited.

  Here is how the `is_error_code_enum` trait class is specialized:

  ```
  namespace std
  {
      template <>
      struct is_error_code_enum<CatErr>: public true_type
      {};
  }
  ```

This completes the definition of our own error code enumeration, whose symbols are now accepted by `error_code's` constructor.

Before we're able to design our own error category we must also have a look at 'higher order' causes of errors as represented by objects of the class `std::error_condition` (cf. section 10.9.2). Error conditions represent platform independent errors like syntax errors or non-existing requests.

In our bare bones implementation of an error category these higher order causes of errors are enumerated in the `enum class Cond` enumeration. It's defined similarly to `CatErr`.

- Our first step consists of defining the enumeration. As with error code enums its symbols should not be given the value 0. Here is the enumeration `Cond` whose symbols presumably represent platform independent causes of errors:

  ```
  enum class Cond
  ```

```
    {
        NoCond = -1,
        Cond1 = 1,
        Cond2,
        Cond3,
    };
```

- By itself, defining an `enum class` does not allow us to pass its values to `error_condition` constructors. Before we can do that the `enum` must be ‘promoted’ to an *error_condition_enum*. Also similar to `CatErr` this ‘promotion’ is realized by specializing the trait class `std::is_error_condition_enum`

  Here is how the `is_error_condition_enum` trait class is specialized:

```
    namespace std
    {
        template <>
        struct is_error_condition_enum<Cond>: public true_type
        {};
    }
```

We’re now ready for designing our own `error_category` class.

23.7.1 Deriving classes from std::error_category

In the previous section the error code enumerations `CatErr` and `Cond` were developed. The values of these enumerations specify, respectively, the direct and the platform independent causes of errors that may be encountered in the context of the new error category developed in this section.

Classes derived from `std::error_category` are designed as singleton classes and implement their own `name`, `message` and an `equivalent` members. Our class `Category` also declares a static member `instance` returning a reference to the class’s singleton object, which is compile-time initialized and is available by the time `instance` is called. Alternatively a dedicated function (like `Category_category`), analogously to the function `generic_category`, returning a reference to the `Category` object could be defined.

`CatErr` values, `Cond` values and textual descriptions of `CatErr's` values are combined in a `std::unordered_map` using `CatErr` as key, and a `struct POD` as value type. This map allows us to retrieve the platform independent error types and the descriptions that are associated with `CatErr` values.

Here is the interface of the class `Category`:

```
class Category: public std::error_category
{
    static Category s_instance;
    struct POD
    {
        Cond        cond;
        char const *msg;
    };

    static std::unordered_map<CatErr, POD> s_map;

    public:
            Category(Category const &other) = delete;

            static Category &instance();

            bool equivalent(std::error_code const &ec, int condNr)
                                            const noexcept override;
            bool equivalent(int ev, std::error_condition const &condition)
                                            const noexcept override;
            std::error_condition default_error_condition(int ev)
                                            const noexcept override;

            std::string message(int ce) const override;
            char const *name() const noexcept override;

        private:
            Category() = default;

            template <typename Enum>
            static constexpr Enum as(int err);
    };
```

Its `unordered_map s_map` provides the `Cond` values and verbal descriptions of the `CatErr` values given those `CatErr` values:

```
    unordered_map<CatErr, Category::POD> Category::s_map =
    {
        { CatErr::Err1, { Cond::Cond1, "Err1" } },
        { CatErr::Err2, { Cond::Cond2, "Err2" } },
        { CatErr::Err3, { Cond::Cond1, "Err3" } },
    };
```

The functions `make_error_code` and `make_error_condition` return, respectively, `error_code` and `error_condition` objects from, respectively, `CatErr` values and `Cond` values.

Their declarations can be provided below the `Category` class interface and their implementations pass the `Category` object to their constructors:

```
    std::error_code make_error_code(CatErr ce)
    {
        return { static_cast<int>(ce), Category::instance() };
    }

    std::error_condition make_error_condition(Cond ec)
    {
        return { static_cast<int>(ec), Category::instance() };
    }
```

The member `name` *must* be defined by classes derived from `error_category`. It simply returns a short string naming the category (e.g., `"Category"` for our `Category` class). Likewise, the member `message` *must* be redefined. Its implementation usually is slightly more complex than `name's` implementation: it expects a (cast to an `int`) `CatErr` value and uses that value to find the corresponding textual description in `s_map`. If found the description is returned; if not found then a short fallback message is returned:

```
    std::string Category::message(int ce) const
```

```
{
    auto iter = s_map.find(static_cast<CatErr>(ce));
    return iter != s_map.end() ? iter->second.msg : "No CatErr value";
}
```

The member `default_error_condition` receives a (cast to `int`) `CatErr` value. That value is used to find the associated `Cond` value. If the `int` received by the function does not represent a valid `CatErr` value then the fallback value `Cond::NoCond` is used. The function returns an `error_condition` object created by `make_error_condition` which receives the determined `Cond` value as its argument:

```
std::error_condition Category::default_error_condition(int ev)
                                                        const noexcept
{
    auto iter = s_map.find(as<CatErr>(ev));

    return make_error_condition(
                iter == s_map.end() ? Cond::NoCond : iter->second.cond
            );
}
```

What's left is implementing the two `equivalent` members. The first `equivalent` member (receiving a reference to an `error_code` object and a (cast to `int`) `Cond` value) determines the equivalence of the `Cond` value that is associated with the `error_code` object and the `Cond` value that is specified as the function's second argument. If these values are equal and the `error_code` object's category is equal to `Category` then the equivalence has been established and `true` is returned. Here is its implementation:

```
bool Category::equivalent(std::error_code const &ec, int condNr)
                                                        const noexcept
{
    if (*this != ec.category())
        return false;

    if (ec.value() == 0)                            // no error in ec?
        return condNr == 0;                         // then condNr must
                                                    // also be 0

    auto iter = s_map.find(as<CatErr>(ec.value())); // info associated
                                                    // with ec's CatErr

    return iter == s_map.end() ?
                    false                           // not found or
                :                                   // compare Cond values
                    iter->second.cond == as<Cond>(condNr);
}
```

The second `equivalent` member (receiving (as an `int`) `CatErr` value and an `error_condition` object) determines the equivalence of an `error_condition` object that is constructed from the `Cond` value that is associated with the `CatErr` value that was passed (as `int`) to the function and the `error_condition` object that was passed to the function as its second argument.

Here a prerequisite for concluding equivalence is that the error condition's category is `Category`. If that's the case then the function returns `true` if its `int` argument equals zero and the `condition` object also indicates no error. Alternatively, if the `condition` argument is equal to the `error_condition` object made from the `Cond` value associated with the `CatErr` value passed to the function as its first argument the equivalence has also been established and `true` is returned. Here is its implementation:

```
bool Category::equivalent(int ev, error_condition const &condition)
                                                          const noexcept
{
    if (ev == 0)                                      // no error? then
        return condition.category() == *this and     // categories must
               not static_cast<bool>(condition);     // be equal and
                                                      // condition must
                                                      // indicate no error

    auto iter = s_map.find(as<CatErr>(ev));      // find ev's Cond

    return iter == s_map.end()?
                false                            // no such CatErr
            :                                    // or compare conditions
                condition == make_error_condition(iter->second.cond);
}
```

So, in order to define your own category:

- define an enumeration which is ‘promoted’ to an `error_code_enum`;
- define an enumeration which is promoted to an `error_condition_enum`;
- define a new `error_category` class by deriving a class from `std::error_category`, define it as a singleton class and override its `default_error_condition`, `equivalent`, `message`, and `name` members.

23.8 Using ‘noexcept’ when offering the ‘strong guarantee’

When throwing exceptions while trying to achieve the strong guarantee a function’s actions are usually split in two parts

- First, usually on a temporary object, all operations that may throw are performed (which doesn’t affect the target object)
- Then, the target object is modified using operations that offer the *nothrow* guarantee.

The actions in the first step might be made *move aware* by using `std::move` (e.g., to assign the source’s values to a (possibly temporary) destination). However, using `std::move` can easily affect the source (e.g., when extending the source’s memory, moving the existing data to its new locations), which breaks the first step’s assumption, as the target object is now modified.

In this case (and generally) the move operation should not be allowed to throw exceptions. This, in turn, implies that it is difficult to write code which must offer a non-throwing moving constructor, if it uses (external) data types over which the moving constructor has no control. E.g.,

```
template <typename Type>
class MyClass
{
        Type d_f;
        public:
            MyClass() = default;
            MyClass(MyClass &&tmp)
            :
                d_f(move(tmp.d_f))
            {}
    };
```

Here, `MyClass`’s author has no control over the design of `Type`. If `Foreign` merely has a (possibly throwing) copy constructor, then the following code breaks the no-throw assumption underlying move constructors:

```
    MyClass<Foreign> s2{ move(MyClass<Foreign>()) };
```

If templates are able to detect whether `Type` has non-throwing move constructors then their implementations may be optimized by calling these move constructors (already modifying their targets in the first part of code offering the strong guarantee) in situations where otherwise the non-modifying, but more expensive copy constructor has to be used.

The `noexcept` keyword was introduced to allow such templates to perform such optimizations. As with `throw` lists, checking for `noexcept` is a run-time check, but the consequence of violating a `noexept` declaration are more serious than violating a `throw` list: violating `noexcept` results in calling `std::terminate`, terminating the program, possibly without unwinding the stack. In the context of the previous example, the following code is flawlessly accepted by the compiler, demonstrating that there is no compile-time checking of `noexcept`:

```
    class Foreign
    {
        public:
            Foreign() = default;
            Foreign(Foreign const &other) noexcept
            {
                throw 1;
            }
    };
```

However, when this class’s copy constructor is called, execution aborts with the following message:

```
    terminate called after throwing an instance of 'int'
    Abort
```

Keep in mind that the current purpose of `noexcept` is to allow templates to optimize their code by using move operations where the code must also be able to offer the string exception guarantee. Since `noexcept` also offers the conditional `noexcept(condition)` syntax (with `noexcept(true)` and `noexcept` having identical semantics), `noexcept` can be made conditional to the ‘noexcepting’ nature of template types. Note that this is not possible with `throw` lists.

The following rules of thumb by be used to decide whether or not to use `noexcept` in your code:

- General rule: don’t use `noexcept` (this is identical to the advise given for `throw` lists);
- Default implementations of constructors, copy- and move-assignment operators and destructors are provided with `noexcept(true)` if the compiler can deduce that composing types also offer `noexcept(true)`, allowing template optimizations using move operations where possible.

- Functions provided with `noexcept` declarations may *still* throw exceptions (see the example given above). In the end `noexcept` merely means that if such a function throws an exception `std::terminate` rather tha `std::unexpected` is called.

- Functions previously provided with an empty throw list (`throw()`) should be provided with `noexcept`.

- `noexcept` specifications are required when using the following std traits (declared in the `<type_traits>` header file):

  - `is_nothrow_constructible`
  - `is_nothrow_default_constructible`
  - `is_nothrow_move_constructible`
  - `is_nothrow_copy_constructible`
  - `is_nothrow_assignable`
  - `is_nothrow_move_assignable`
  - `is_nothrow_copy_assignable`
  - `is_nothrow_destructible`

  These type traits provide the member constant `value` which is `true` if the class (and possibly its argument type list) matches the characteristic after which the trait was named. E.g., if `MyClass(string const &) noexcept` is a constructor, then

  ```
  std::is_nothrow_constructible<MyClass, string>::value
  ```

  equals `true`. For the named members (like `is_nothrow_move_constructible`) parameter types do not have to be specified, as they are implied. E.g.,

  ```
  std::is_nothrow_move_constructible<MyClass>::value
  ```

  returns `true` if the move constructor has the `noexcept` modifier.

23.9 More conversions to class types

23.9.1 Types to types

Although *class* templates may be partially specialized, *function* templates may not. At times this is annoying. Assume a function template is available implementing a certain unary operator that could be used with the `transform` generic algorithm (cf. section 19.1.64):

```
template <typename Return, typename Argument>
Return chop(Argument const &arg)
{
    return Return{ arg };
}
```

Furthermore assume that if `Return` is `std::string` then the above implementation should not be used. Instead, with `std::string` a second argument `1` should always be provided. If `Argument` is a **C++** string, this would allow us to, e.g., return a copy of `arg` from which its first character has been chopped off.

Since `chop` is a function, it is not possible to define a partial specialization like this:

```
template <typename Argument>        // This won't compile!
std::string chop<std::string, Argument>(Argument const &arg)
{
    return std::string{ arg, 1 };
}
```

Although a function template cannot be partially specialized it *is* possible to use overloading, defining a second, dummy, `string` parameter:

```
template <typename Argument>
std::string chop(Argument const &arg, std::string)
{
    return std::string{ arg, 1 };
}
```

Instead of providing a `string` dummy argument the functions *could* use the `IntType` template (cf. section 23.2.1.1) to select the proper overloaded version. E.g., `IntType<0>` could be defined as the type of the second argument of the first overloaded `chop` function, and `IntType<1>` could be used for the second overloaded function. From the point of view of program efficiency this is an attractive option, as the provided `IntType` objects are extremely lightweight. `IntType` objects contain no data at all. But there's also an obvious disadvantage as there is no intuitively clear association between the `int` value used and the intended type.

Instead of defining arbitrary `IntType` types it is more attractive to use another lightweight solution, using an automatic type-to-type association. The `struct TypeType` is a lightweight type wrapper, much like `IntType`. Here is its definition:

```
template <typename T>
struct TypeType
{
    typedef T Type;
};
```

`TypeType` is also a lightweight type as it doesn't have any data fields either. `TypeType` allows us to use a natural type association for `chop`'s second argument. E.g, the overloaded functions can now be defined as follows:

```
template <typename Return, typename Argument>
Return chop(Argument const &arg, TypeType<Argument> )
{
    return Return{ arg };
}

template <typename Argument>
std::string chop(Argument const &arg, TypeType<std::string> )
{
    return std::string{ arg, 1 };
}
```

Using the above implementations any type can be specified for `Result`. If it happens to be a `std::string` the appropriate overloaded version is automatically selected. The following additional overload of the function `chop` capitalizes on this:

```
template <typename Result>
Result chop(char const *txt)     // char const * could also be a 2nd
{                                // template type parameter
    return chop(std::string{ txt }, TypeType<Result>{});
}
```

Using the third `chop` function, the following statement produces the text '`ello world`':

```
cout << chop<string>{ "hello world" } << '\n';
```

Template functions do not support partial specializations. But they can be overloaded. By providing overloads with dummy type-arguments that depend on other parameters and calling these overloads from a overloaded function that does not require the dummy type argument a situation similar to partial specializations with class templates can often be realized.

23.9.2 An empty type

At times (cf. section 23.10) an empty `struct` is a useful tool. It can be used as a *type* acting analogously to the final 0-byte in NTBSs. It can simply be defined as:

```
struct NullType
{};
```

23.9.3 Type convertibility

In what situations can a type `T` be used as a 'stand in' for another type `U`? Since **C++** is a strongly typed language the answer is surprisingly simple: `T`s can be used instead of `U`s if a `T` is accepted as argument in cases where `U`s are requested.

This reasoning is behind the following class which can be used to determine whether a type `T` can be used where a type `U` is expected. The interesting part is that no code is actually generated or executed. All decisions are made by the compiler.

In the second part of this section we'll show how the code developed in the first part can be used to detect whether a class `B` is a base class of another class `D` (the `is_base_of` template (cf. section 23.6.2) also provides an answer to this question). The code developed here closely follows the example provided by Alexandrescu (2001, p. 35).

First, a function `test` is designed accepting a type `U`. The function `test` returns a value of the as yet unknown type `Convertible`:

```
Convertible test(U const &);
```

The function `test` is never implemented. It is only declared. If a type `T` can be used instead of a type `U` then `T` can also be passed as argument to the above `test` function.

On the other hand, if the alternate type `T` cannot be used where a `U` is expected, then the compiler won't be able to use the above `test` function. Instead, it uses an alternative function that has a lower selection priority but that can *always* be used with *any* `T` type.

C (and **C++**) offer a very general parameter list, a parameter list that is always considered acceptable. This parameter list is the familiar *ellipsis* which represents the *worst* case the compiler may encounter. If everything else fails, then the function defining an ellipsis as its parameter list is selected.

Usually that's not a productive alternative, but in the current situation it is *exactly* what is needed. When confronted with two candidate functions, one of which defines an ellipsis parameter, the compiler selects the function defining the ellipsis parameter only if the alternative(s) can't be used.

Following the above reasoning an alternative function `test(...)` is declared as well. This alternate function does not return a `Convertible` value but a `NotConvertible` value:

```
NotConvertible test(...);
```

If `test`'s argument is of type `T` and if `T` can be converted to `U` then `test`'s return type is `Convertible`. Otherwise `NotConvertible` is returned.

This situation clearly shows similarities with the situation encountered in section 23.6.1 where the value `isClass` had to be determined compile time. Here two related problems must be solved:

- how do we obtain a `T` argument? This is more difficult than might be expected at first sight as it might not be possible to define a `T`. If type `T` does not define any constructor then no `T` object can be defined.
- how can `Convertible` be distinguished from `NotConvertible`?

The first problem is solved by realizing that no `T` *needs* to be defined. After all, the intent is to decide *compile-time* whether a type is convertible and not to define a `T` value or object. Defining objects is not a compile-time but a *run-time* matter.

By simply *declaring* a function returning a `T` we can tell the compiler where it should assume a `T`:

```
T makeT();
```

This mysterious function has the magical power of enticing the compiler into thinking that a `T` object comes out of it. However, this function needs a small modification before it will actually suit our needs. If, for whatever reason, `T` happens to be an array then the compiler will choke on `T makeT()` as functions cannot return arrays. This, however, is easily solved, as functions *can* return *references* to arrays. So the above declaration is changed into:

```
T const &makeT();
```

Next we pass a `T const &` to `test`: following code:

```
test(makeT())
```

Now that the compiler sees `test` being called with a `T const &` argument it decides that its return value is `Convertible` if a conversion is in fact possible. Otherwise it decides that its return value is `NotConvertible` (as the compiler, in that case, selected `test(...)`).

The second problem, distinguishing `Convertible` from `NotConvertible` is solved exactly the way `isClass` could be determined in section 23.6.1, *viz.* by making their sizes different. Having done so the following expression determines whether `T` is convertible from `U` or not:

```
isConvertible = sizeof(test(makeT())) == sizeof(Convertible);
```

By using `char` for `Convertible` and `Char2` (cf. section 23.6.1) for `NotConvertible` the distinction can be made.

The above can be summarized in a class template `LconvertibleToR`, having two template type parameters:

```
template <typename T, typename U>
class LconvertibleToR
{
    struct Char2
    {
        char array[2];
    };
    static T const &makeT();
    static char test(U const &);
    static Char2 test(...);

    public:
        LconvertibleToR(LconvertibleToR const &other) = delete;
        enum { yes = sizeof(test(makeT())) == sizeof(char) };
        enum { sameType = 0 };
};

template <typename T>
class LconvertibleToR<T, T>
{
    public:
        LconvertibleToR(LconvertibleToR const &other) = delete;
        enum { yes = 1 };
        enum { sameType = 1 };
};
```

As the class template deletes its copy constructor no object can be created. Only its `enum` values can be interrogated. The next example writes `1 0 1 0` when run from a `main` function:

```
cout <<
    LconvertibleToR<ofstream, ostream>::yes << " " <<
    LconvertibleToR<ostream, ofstream>::yes << " " <<
    LconvertibleToR<int, double>::yes << " " <<
    LconvertibleToR<int, string>::yes <<
    "\n";
```

23.9.3.1 Determining inheritance

Now that it is possible to determine type convertibility, it's easy to determine whether a type `Base` is a (public) base class of a type `Derived`.

Inheritance is determined by inspecting convertibility of (const) pointers. `Derived const *` can be converted to `Base const *` if

- both types are identical;
- `Base` is a public and unambiguous base class of `Derived`;
- and (usually not intended) if `Base` is void.

Assuming the last conversion isn't used inheritance can be determined using the following trait class `LBaseRDerived`. `LBaseRDerived` provides an enum `yes` which is 1 if the left type is a base class of the right type and both types are different:

```
template <typename Base, typename Derived>
struct LBaseRDerived
{
    LBaseRDerived(LBaseRDerived const &) = delete;
    enum {
        yes =
            LconvertibleToR<Derived const *, Base const *>::yes &&
            not LconvertibleToR<Base const *, void const *>::sameType
    };
};
```

If code should not consider a class to be its own base class, then the trait class `LBaseRtrulyDerived` can be used to perform a strict test. This trait class adds a test for type-equality:

```
template <typename Base, typename Derived>
struct LBaseRtrulyDerived
{
    LBaseRtrulyDerived(LBaseRtrulyDerived const &) = delete;
    enum {
        yes =
            LBaseRDerived<Base, Derived>::yes &&
            not LconvertibleToR<Base const *, Derived const *>::sameType
    };
};
```

Example: the next statement displays `1:  0, 2:  1, 3:  0, 4:  1, 5:  0` when executed from a `main` function:

```
cout << "\n" <<
    "1: " << LBaseRDerived<ofstream, ostream>::yes << ",  " <<
    "2: " << LBaseRDerived<ostream, ofstream>::yes << ",  " <<
    "3: " << LBaseRDerived<void, ofstream>::yes << ",  " <<
    "4: " << LBaseRDerived<ostream, ostream>::yes << ",  " <<
    "5: " << LBaseRtrulyDerived<ostream, ostream>::yes <<
    "\n";
```

23.10 Template TypeList processing

This section serves two purposes. It illustrates capabilities of the various template meta-programming techniques, which can be used as a source of inspiration when developing your own templates; and it offers a concrete example, illustrating some of the power offered by these techniques.

This section itself was inspired by Andrei Alexandrescu's (2001) book **Modern C++ design**. It diverts from Alexandrescu's book in its use of variadic templates which were not yet available when he wrote his book. Even so, the algorithms used by Alexandrescu are still useful when using variadic templates.

C++ offers the tuple to store and retrieve values of multiple types. Here the focus is merely on processing types. A simple struct `TypeList` is going to be used as our working horse for the upcoming subsections. Here is its definition:

```
template <typename ...Types>
struct TypeList
{
    TypeList(TypeList const &) = delete;
    enum { size = sizeof ...(Types) };
};
```

A typelist allows us to store any number of types. Here is an example storing the three types `char, short, int` in a `TypeList`:

```
TypeList<char, short, int>
```

23.10.1 The length of a TypeList

As the number of types in a parameter pack may be obtained using the `sizeof` operator (cf. section 22.5) it is easy to obtain the number of types that were specified with a certain `TypeList`. For example, the following statement displays the value 3:

```
std::cout << TypeList<int, char, bool>::size << '\n';
```

However, it's illustrative to see how the number of types specified with a `TypeList` could be determined if `sizeof` hadn't been available.

To obtain the number of types that were specified with a `TypeList` the following algorithm is used:

- If the `TypeList` contains no types, its size equals zero;
- If the `TypeList` contains types, its size equals 1 plus the number of types that follow its first type.

The algorithm uses recursion to define the length of a `TypeList`. In executable **C++** recursion could also be used in comparable situations. For example recursion can be used to determine the length of an NTBS:

```
size_t c_length(char const *cp)
{
    return *cp == 0 ? 0 : 1 + c_length(cp + 1);
}
```

While **C++** functions usually use iteration rather than recursion, iteration is not available to template meta programming algorithms. In template meta programming repetition *must* be implemented using recursion. Furthermore, while **C++** run-time code may use conditions to decide whether or not to start the next recursion template meta programming cannot do so. Template meta programming algorithms must resort to (partial) specializations. The specializations are used to select alternatives.

The number of types that are specified in a `TypeList` can be computed using the following alternate implementation of `TypeList`, using a generic `struct` declaration and two specialization for the empty and non-empty `TypeList` (cf. the above description of the algorithm):

```
template <typename ...Types>
struct TypeList;

template <typename Head, typename ...Tail>
struct TypeList<Head, Tail...>
{
    enum { size = 1 + TypeList<Tail...>::size };
};
template <>
struct TypeList<>
{
    enum { size = 0 };
};
```

23.10.2 Searching a TypeList

To determine whether a particular type (called *SearchType* below) is present in a given `TypeList`, an algorithm is used that either defines 'index' as -1 (if SearchType is not an element of the `TypeList`) or it defines 'index' as the index of the first occurrence of SearchType in the `TypeList`. The following algorithm is used:

- If the `TypeList` is empty, 'index' is -1;
- If the `TypeList`'s first element equals SearchType, 'index' is 0;
- Otherwise 'index' is:
  - -1 if searching for SearchType in `TypeList`'s tail results in 'index' == -1;
  - Otherwise (SearchType was found in `TypeList`'s tail) index is set to 1 + the index obtained when searching for SearchType in the `TypeList`'s tail.

The algorithm is implemented using a variadic template struct `ListSearch` expecting a parameter pack:

```
template <typename ...Types>
struct ListSearch
{
    ListSearch(ListSearch const &) = delete;
};
```

Specializations handle the alternatives mentioned with the algorithm:

- If `TypeList` is empty, 'index' is -1:

  ```
  template <typename SearchType>
  struct ListSearch<SearchType, TypeList<>>
  {
      ListSearch(ListSearch const &) = delete;
      enum { index = -1 };
  };
  ```

- If `TypeList`'s head equals SearchType, 'index' is 0. Note that `SearchType` is explicitly mentioned as the `TypeList`'s first element:

  ```
  template <typename SearchType, typename ...Tail>
  ```

```
struct ListSearch<SearchType, TypeList<SearchType, Tail...>>
{
    ListSearch(ListSearch const &) = delete;
    enum { index = 0 };
};
```

- Otherwise a search is performed on the `TypeList`'s tail. The index value returned by this search is stored in a `tmp` enum value, which is then used to determine index's value.

```
template <typename SearchType, typename Head, typename ...Tail>
struct ListSearch<SearchType, TypeList<Head, Tail...> >
{
    ListSearch(ListSearch const &) = delete;
    enum {tmp = ListSearch<SearchType, TypeList<Tail...>>::index};
    enum {index = tmp == -1 ? -1 : 1 + tmp};
};
```

Here is an example showing how `ListSearch` can be used:

```
std::cout <<
    ListSearch<char, TypeList<int, char, bool>>::index << "\n" <<
    ListSearch<float, TypeList<int, char, bool>>::index << "\n";
```

23.10.3 Selecting from a TypeList

The inverse operation of determining the index of a certain type in a `TypeList` is retrieving the type given its index. This inverse operation is the topic of this section.

The algorithm is implemented using a struct `TypeAt`. `TypeAt` uses a `typedef` to define the type matching a given index. But the index might be out of bounds. In that case we have several options:

- Use a static_assert to stop the compilation. This is an appropriate action if the index should simply not be out of bounds;
- Define a local type (e.g., `Null`) that should not be used as a type in the `TypeList`. This type is going to be returned when the index is out of bounds. Using this local type as one of the types in a `TypeList` is considered an error as its would conflict with the special meaning of `Null` as the type returned at an invalid index.
  To prevent `Null` from being returned by `TypeAt` a `static_assert` is used to catch the `Null` type when it is encountered while evaluating `TypeAt`;
- The struct `TypeAt` may define an enum value `validIndex` set to `true` if the index was valid and set to `false` if not.

The first alternative is implemented below. The other alternatives are not difficult to implement and are left as exercises for the reader. Here's how `TypeAt` works:

- The foundation consists of a variadic template struct `TypeAt`, expecting an index and a `TypeList`:

```
template <size_t index, typename Typelist>
struct TypeAt;
```

- If the typelist is empty a `static_assert` ends the compilation

  ```
  template <size_t index>
  struct TypeAt<index, TypeList<>>
  {
      static_assert(index < 0, "TypeAt index out of bounds");
      typedef TypeAt Type;
  };
  ```

- If the search index equals 0, define `Type` as the first type in the `TypeList`:

  ```
  template <typename Head, typename ...Tail>
  struct TypeAt<0, TypeList<Head, Tail...>>
  {
      typedef Head Type;
  };
  ```

- Otherwise, `Type` is defined as `Type` defined by `TypeAt<index - 1>` operating on the `TypeList`'s tail:

  ```
  template <size_t index, typename Head, typename ...Tail>
  struct TypeAt<index, TypeList<Head, Tail...>>
  {
      typedef typename TypeAt<index - 1, TypeList<Tail...>>::Type Type;
  };
  ```

Here is how `typeAt` can be used. Uncommenting the first variable definition causes a `TypeAt index out of bounds` compilation error:

```
    typedef TypeList<int, char, bool> list3;

//    TypeAt<3, list3>::Type invalid;
    TypeAt<0, list3>::Type intVariable = 13;
    TypeAt<2, list3>::Type boolVariable = true;

    cout << "The size of the first type is " <<
                sizeof(TypeAt<0, list3>::Type) << ", "
            "the size of the third type is " <<
                sizeof(TypeAt<2, list3>::Type) << "\n";

    if (typeid(TypeAt<1, list3>::Type) == typeid(char))
        cout << "The typelist's 2nd type is char\n";

    if (typeid(TypeAt<2, list3>::Type) != typeid(char))
        cout << "The typelist's 3nd type is not char\n";
```

23.10.4 Prefixing/Appending to a TypeList

Prepending or appending a type to a `TypeList` is easy and doesn't require recursive template meta programs. Two variadic template structs `Append` and `Prefix` and two specializations are all it takes.

Here are the declarations of the two variadic template structs:

```
    template <typename ...Types>
```

```
struct Append;

template <typename ...Types>
struct Prefix;
```

To append or prefix a new type to a typelist, specializations expect a typelist and a type to add. Then, they simply define a new `TypeList` also including the new type. The `Append` specialization shows that a template pack does not have to be used as the first argument when defining another variadic template type:

```
template <typename NewType, typename ...Types>
struct Append<TypeList<Types...>, NewType>
{
    typedef TypeList<Types..., NewType> List;
};

template <typename NewType, typename ...Types>
struct Prefix<NewType, TypeList<Types...>>
{
    typedef TypeList<NewType, Types...> List;
};
```

23.10.5 Erasing from a TypeList

It is also possible to erase types from a `TypeList`. Again, there are several possibilities, each resulting in a different algorithm.

- The type to erase is specified, and the first occurrence of that type is removed from the `TypeList`;
- The index of the type to erase is specified, and the type at that index position is erased from the `TypeList`;
- The type to erase is specified, and all occurrences of that type are removed from the `TypeList`.
- As a variant of erasure: we may want to erase all multiply occurring types in a `TypeList`, keeping each type only once.

Doubtlessly there are other ways of erasing types from a `TypeList`. Which ones are eventually implemented depends of course on the circumstances. As template meta programming is very powerful most if not all algorithms can probably be implemented. As an illustration of how to erase types from a `TypeList` the above-mentioned algorithms are now developed in the upcoming subsections.

23.10.5.1 Erasing the first occurrence

To erase the first occurrence of a specified `EraseType` from a `TypeList` a recursive algorithm is used once again. The template meta program uses a generic `Erase` struct and several specializations. The specializations define a type `List` containing the resulting `TypeList` after the erasure. Here is the algorithm:

- The foundation of the algorithm consists of a struct template `Erase` expecting the type to erase and a `TypeList`:

  ```
  template <typename EraseType, typename TypeList>
  ```

```
struct Erase;
```

- If the typelist is empty, there's nothing to erase, and an empty `TypeList` results:

```
template <typename EraseType>
struct Erase<EraseType, TypeList<>>
{
    typedef TypeList<> List;
};
```

- If the `TypeList`'s head matches the type to erase, then `List` becomes a `TypeList` containing the original `TypeList`'s tail types:

```
template <typename EraseType, typename ...Tail>
struct Erase<EraseType, TypeList<EraseType, Tail...>>
{
    typedef TypeList<Tail...> List;
};
```

- In all other cases the erase operation is applied to the `TypeList`'s tail. This results in a `TypeList` to which the orginal `TypeList`'s head must be prefixed. The `TypeList` returned by the prefix operation is then returned as `Erase::List`:

```
template <typename EraseType, typename Head, typename ...Tail>
struct Erase<EraseType, TypeList<Head, Tail...>>
{
    typedef typename
        Prefix<Head,
            typename Erase<EraseType, TypeList<Tail...>>::List
        >::List List;
};
```

Here is a statement showing how `Erase` can be used:

```
cout <<
        Erase<int, TypeList<char, double, int>>::List::size << '\n' <<
        Erase<char, TypeList<int>>::List::size << '\n' <<
        Erase<int, TypeList<int>>::List::size << '\n' <<
        Erase<int, TypeList<>>::List::size << "\n";
```

23.10.5.2 Erasing a type by its index

To erase a type from a `TypeList` by its index we again use a recursive template meta program. `EraseIdx` expects a `size_t` index value and a `TypeList` from which its $\mathtt{idx}^{th}$ (0-based) type must be erased. `EraseIdx` defines the type `List` containing the resulting `TypeList`. Here is the algorithm:

- The foundation of the algorithm consists of a struct template `EraseIdx` expecting the index of the type to erase and a `TypeList`:

```
template <size_t idx, typename TypeList>
struct EraseIdx;
```

- If the typelist is empty, there's nothing to erase, and an empty `TypeList` results:

  ```
  template <size_t idx>
  struct EraseIdx<idx, TypeList<>>
  {
      typedef TypeList<> List;
  };
  ```

- The recursion otherwise ends once `idx` becomes 0. At that point the `TypeList`'s first type is ignored and `List` is initialized to a `TypeList` containing the types in the orginal `TypeList`'s tail:

  ```
  template <typename EraseType, typename ...Tail>
  struct EraseIdx<0, TypeList<EraseType, Tail...>>
  {
      typedef TypeList<Tail...> List;
  };
  ```

- In all other cases `EraseIdx` is applied to the `TypeList`'s tail, providing it with a decremented value of `idx`. To the resulting `TypeList` the orginal `TypeList`'s head is prefixed. The `TypeList` returned by the prefix operation is then returned as `EraseIdx::List`:

  ```
  template <size_t idx, typename Head, typename ...Tail>
  struct EraseIdx<idx, TypeList<Head, Tail...>>
  {
      typedef typename Prefix<
                  Head,
                  typename EraseIdx<idx - 1, TypeList<Tail...>>::List
              >::List List;
  };
  ```

Here is a statement showing how `EraseIdx` can be used:

```
if
(
    typeid(TypeAt<2,
            EraseIdx<1,
               TypeList<int, char, size_t, double, int>>::List
            >::Type
    )
    == typeid(double)
)
    cout << "the third type is now a double\n";
```

23.10.5.3 Erasing all occurrences of a type

Erasing all types `EraseType` from a `TypeList` can easily be accomplished by applying the erasure procedure not only to the head of the `TypeList` but also to the `TypeList`'s tail.

Here is the algorithm, described in a slightly different order than `Erase`'s algorithm:

- If the `TypeList` is empty, there's nothing to erase, and an empty `TypeList` results. This is exactly what we do with `Erase`, so we can use inheritance to prevent us from having to duplicate elements of a template meta program:

  ```
  template <size_t idx>
  ```

```
struct EraseIdx<idx, TypeList<>>
{
    typedef TypeList<> List;
};
```

- The foundation of the algorithm is therefore a struct template `EraseAll` expecting the type to erase and a `TypeList` that is derived from `Erase`, thus already offering the empty `TypeList` handling specialization:

  ```
  template <typename EraseType, typename TypeList>
  struct EraseAll: public Erase<EraseType, TypeList>
  {};
  ```

- If `TypeList`'s head matches `EraseType` `EraseAll` is also applied to the `TypeList`'s tail, thus removing all occurrences of `EraseType` from `TypeList`:

  ```
  template <typename EraseType, typename ...Tail>
  struct EraseAll<EraseType, TypeList<EraseType, Tail...>>
  {
      typedef typename EraseAll<EraseType, TypeList<Tail...>>::List List;
  };
  ```

- In all other cases (i.e., `TypeList`'s head does *not* match `EraseType`) `EraseAll` is applied to the `TypeList`'s tail. The returned `TypeList` consists of the original `TypeList`'s initial type and the types of the `TypeList` returned by the recursive `EraseAll` call:

  ```
  template <typename EraseType, typename Head, typename ...Tail>
  struct EraseAll<EraseType, TypeList<Head, Tail...>>
  {
      typedef typename Prefix<
          Head,
          typename EraseAll<EraseType, TypeList<Tail...>>::List
      >::List List;
  };
  ```

Here is a statement showing how `EraseAll` can be used:

```
cout <<
    "After erasing size_t from "
        "TypeList<char, int, size_t, double, size_t>\n"
        "it contains " <<
            EraseAll<size_t,
                     TypeList<char, int, size_t, double, size_t>
            >::List::size << " types\n";
```

23.10.5.4 Erasing duplicates

To remove all duplicates from a `TypeList` all the `TypeList`'s first elements must be erased from the `TypeList`'s tail, applying the procedure recursively to the `TypeList`'s tail. The algorithm, outlined below, merely expects a `TypeList`:

- First, the generic `EraseDup` struct template is declared. `EraseDup` structures define a type `List` representing the `TypeList` that they generate. `EraseDup` calls expect a `TypeList` as their template type parameters:

  ```
  template <typename TypeList>
  struct EraseDup;
  ```

- If the `TypeList` is empty it can be returned empty and we're done:

  ```
  template <>
  struct EraseDup<TypeList<>>
  {
      typedef TypeList<> List;
  };
  ```

- In all other cases
  - `EraseDup` is first applied to the original `TypeList`'s tail. By definition this results in a `TypeList` from which all duplicates have been removed;
  - The `TypeList` returned by the previous step might contain the original `TypeList`'s initial type. If so, it is removed by applying `Erase` on the returned `TypeList`, specifying the original `TypeList`'s initial type as the type to remove;
  - The returned `TypeList` consists of the original `TypeList`'s initial type to which the types of the `TypeList` produced by the previous step are appended.

  This specialization is implemented like this:

  ```
  template <typename Head, typename ...Tail>
  struct EraseDup<TypeList<Head, Tail...>>
  {
      typedef typename EraseDup<TypeList<Tail...>>::List UniqueTail;
      typedef typename Erase<Head, UniqueTail>::List NewTail;

      typedef typename Prefix<Head, NewTail>::List List;
  };
  ```

Here is an example showing how `EraseDup` can be used:

```
cout <<
    "After erasing duplicates from "
         "TypeList<double, char, int, size_t, int, double, size_t>\n"
    "it contains " <<
    EraseDup<
        TypeList<double, char, int, size_t, int, double, size_t>
    >::List::size << " types\n";
```

23.11 Using a TypeList

In the previous sections the definition and some of the features of typelists were discussed. Most **C++** programmers consider typelists both exciting and an intellectual challenge, honing their skills in the area of recursive programming.

But there's more to typelist than a mere intellectual challenge. In the final sections of this chapter the following topics are covered:

- Creating classes from a typelist.
  Here the aim is to construct a new class consisting of instantiations of an existing basic template for each of the types mentioned in a provided typelist;
- Accessing data members from the thus constructed conglomerate class by index, rather than name.

Again, much of the material covered by these sections was inspired by Alexandrescu's (2001) book.

23.11.1 The Wrap and Multi class templates

To illustrate template meta programming concepts the template class `Multi` is now developed. The class template `Multi` *creates* a new class from a template template parameter `Policy` defining the data storage policy and a series of types from which `Multi` is eventually derived. It does so by passing its template parameters to its base class `MultiBase` that in turn creates a final class inheritance tree. Since we don't know how many types are going to be used `Multi` is defined as a variadic class template using a template pack `...Types`.

In fact, the types that are specified with `Multi` aren't that interesting. They primarily serve to 'seed' the class `Policy`. Therefore, rather than forwarding `Multi`'s types to `MultiBase` they are passed to `Policy` and the sequence of `Policy<Type>` types is then forwarded to `MultiBase`. `Multi`'s constructor expects initialization values for its various `Policy<Type>`s which are perfectly forwarded to `MultiBase`.

The class `Multi` (implementing its constructor in-class to save some space) shows how a template pack can be wrapped into a policy. Here is `Multi`'s definition:

```
template <template <typename> class Policy, typename ...Types>
struct Multi: public MultiBase<0, Policy<Types>...>
{
    typedef TypeList<Types...> PlainTypes;
    typedef MultiBase<0, Policy<Types>...> Base;

    enum { size = PlainTypes::size };

    Multi(Policy<Types> &&...types)
    :
        MultiBase<0, Policy<Types>...>(
                        std::forward<Policy<Types>>(types)...)
    {}
};
```

Unfortunately, the design as described contains some flaws.

- As the `Policy` template template parameter is defined as `template <typename> class Policy` it can only accept policies expecting one type argument. Contrary to this, `std::vector` is a template expecting two template arguments, the second one defining the allocation scheme used by `std::vector`. This allocation scheme is hardly ever changed, and most applications merely define objects of types like `vector<int>`, `vector<string>` etc.. Template template parameters must, however, be specified with the correct number and types of required template parameters so `vector` can't be specified as a policy for `Multi`. This can be solved by *wrapping* a more complex template in a simpler wrapper template, like so:

  ```
  template <class Type>
  struct Vector: public std::vector<Type>
  {
      Vector(std::initializer_list<Type> iniValues)
      :
          std::vector<Type>(iniValues)
      {}
  };
  ```

  Now `Vector` provides `std::vector`'s second parameter using its default template argument. Alternatively, a *template using declaration* could be used.

- If the `TypeList` contains two types like `int` and `double` and the policy class is `Vector`, then the `MultiBase` class eventually inherits from `vector<int>` and `vector<double>`. But if the `TypeList` contains identical types, like two `int` type specifications `MultiBase` would inherit from *two* `vector<int>` classes. Classes cannot be derived from identical base classes as that would make it impossible to distinguish among their members. Regarding this, Alexandrescu (2001) writes (p.67):

  > *There is one major source of annoyance...: you cannot use it when you have duplicate types in your `TypeList`.*
  > *.... There is no easy way to solve the ambiguity, [as the eventually derived class/FBB] ends up inheriting [the same base class/FBB] twice.*

There is a way around the problem of duplicate base class types. If instead of inheriting directly from base classes these base classes are first wrapped in unique type defining classes, then these unique classes can be used to access the base classes using principles of inheritance. As these unique type-defining wrapper classes are merely classes that are derived from the 'real' base classes they inherit (and thus: offer) the functionality of their base classes. A unique type defining wrapper class can be designed after the class IntType, defined earlier. The wrapper class we're looking combines class derivation with the uniqueness offered by `IntType`. The class template `UWrap` has two template parameters: one non-type parameter `idx` and one type parameter. By ensuring that each `UWrap` definition uses a unique `idx` value unique class types are created. These unique class types are then used as base classes of the derived class `MultiBase`:

```
template <size_t nr, typename Type>
struct UWrap: public Type
{
    UWrap(Type const &type)
    :
        Type(type)
    {}
};
```

Using `UWrap` it's easy to distinguish, e.g., two `vector<int>` classes: `UWrap<0, vector<int>>` could refer to the first `vector<int>`, `UWrap<1, vector<int>>` to the second vector.

Uniqueness of the various `UWrap` types is assured by the class template `MultiBase` as discussed in the next section.

It must also be possible to initialize a `Multi` class object. Its constructor therefore expects the initialization values for all its `Policy` values. So if a `Multi` is defined for `Vector, int, string` then its constructor can receive the matching initialization values. E.g.,

```
Multi<Vector, int, string> mvis({1, 2, 3}, {"one", "two", "three"});
```

23.11.2 The MultiBase class template

The class template `MultiBase` is `Multi`'s base class. It defines a class that, eventually, is derived from the list of `Policy` types that, in turn, were created by `Multi` using any additional types that were passed to it.

`MultiBase` itself has no concept of a `Policy`. To `MultiBase` the world appears to consist of a simple template pack whose types are used to define a class from. In addition to the `PolicyTypes` template pack, `MultiBase` also defines a `size_t nr` non-type parameter that is used to create unique `UWrap` types. Here is `MultiBase`'s generic class declaration:

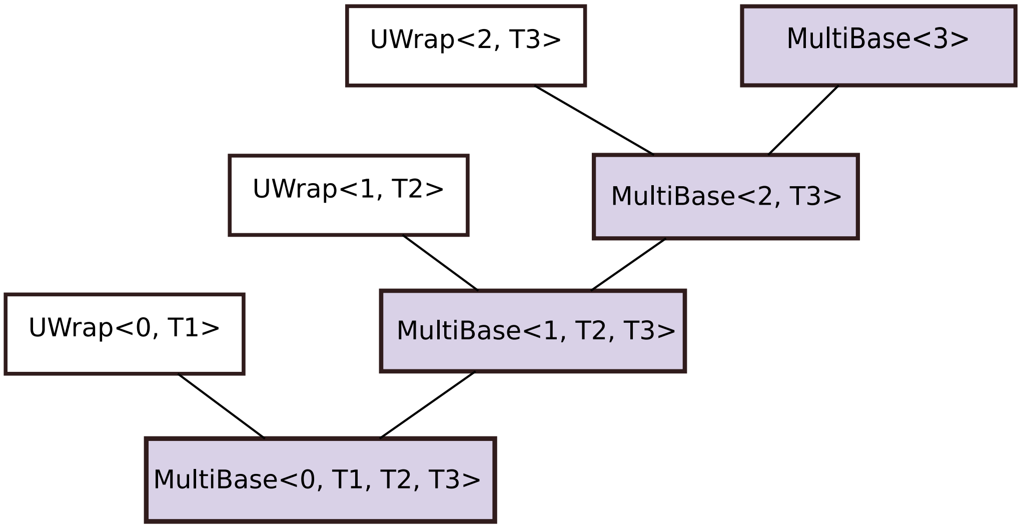

Figure 23.1: Layout of a MultiBase class hierarchy

```
template <size_t nr, typename ...PolicyTypes>
struct MultiBase;
```

Two specializations handle all possible `MultiBase` invocations. One specialization is a recursive template. This template handles the first type of `MultiBase`'s template parameter pack and recursively uses itself to handle the remaining types. The second specialization is invoked once the template parameter pack is exhausted and does nothing. Here is the definition of the latter specialization:

```
template <size_t nr>
struct MultiBase<nr>
{};
```

The recursively defined specialization is the interesting one. It performs the following tasks:

- It is derived from a unique `UWrap` type. The uniqueness is guaranteed by using `MultiBase`'s `nr` parameter when defining `UWrap`. In addition to `nr` the `UWrap` class receives the first type of the template parameter pack made available to `MultiBase`;
- It is also recursively derived from itself. The recursive `MultiBase` type is defined using as its first template argument an incremented `nr` value (thus ensuring the uniqueness of the `UWrap` types defined by recursive `MultiWrap` types). Its second template argument is the tail of the template parameter pack made available to `MultiBase`

An illustration showing the layout of the `MultiBase` class hierarchy is provided in figure 23.1.

`MultiBase`'s constructor simply receives the initialization values that were (originally) passed to the `Multi` object. Perfect forwarding is used to accomplish this. `MultiBase`'s constructor passes its first parameter value to its `UWrap` base class, also using perfect forwarding. `MultiBase`'s recursive definition is:

```
template <size_t nr, typename PolicyT1, typename ...PolicyTypes>
struct MultiBase<nr, PolicyT1, PolicyTypes...> :
                            public UWrap<nr, PolicyT1>,
                            public MultiBase<nr + 1, PolicyTypes...>
```

```
{
    typedef PolicyT1 Type;
    typedef MultiBase<nr + 1, PolicyTypes...> Base;

    MultiBase(PolicyT1 && policyt1, PolicyTypes &&...policytypes)
    :
        UWrap<nr, PolicyT1>(std::forward<PolicyT1>(policyt1)),
        MultiBase<nr + 1, PolicyTypes...>(
                            std::forward<PolicyTypes>(policytypes)...)
    {}
};
```

23.11.3 Support templates

The `Multi` class template defines `PlainTypes` as the `TypeList` holding all the types of its parameter pack. Each `MultiBase` derived from a `UWrap` type also defines a type `Type` representing the policy type that was used to define the `UWrap` type and a type `Base` representing the type of its nested `MultiBase` class.

These three type definitions allow us to access the types from which the `Multi` object was created as well as the values of those types.

The class template `typeAt`, is a pure template meta program class template (it has no run-time executable code). It expects a `size_t idx` template argument specifying the index of the policy type in a `Multi` type object as well as a `Multi` class type. It defines the type `Type` as the `Type` defined by `Multi`'s `MultiBase<idx, ...>` base class. Example:

```
typeAt<0, Multi<Vector, int, double>>::Type // Type is vector<int>
```

The class template `typeAt` defines (and uses) a nested class template `PolType` doing all the work. `PolType`'s generic definition specifies two template parameters: an index used to specify the index of the requested type and a typename initialized by a `MultiBase` type argument. `PolType`'s recursive definition recursively reduces its index non-type parameter, passing the next base class in `MultiBase`'s inheritance tree to the recursive call. As `PolType` eventually defines the type `Type` to be the requested policy type the recursive definition defines its `Type` as the type defined by the recursive call. The final (non-recursive) specialization defines the initial policy type of the `MultiBase` type as `Type`. Here is `typeAt`'s definition:

```
template <size_t index, typename Multi>
class typeAt
{
    template <size_t idx, typename MultiBase>
    struct PolType;

    template <size_t idx,
              size_t nr, typename PolicyT1, typename ...PolicyTypes>
    struct PolType<idx, MultiBase<nr, PolicyT1, PolicyTypes...>>
    {
        typedef typename PolType<
            idx - 1, MultiBase<nr + 1, PolicyTypes...>>::Type Type;
    };

    template <size_t nr, typename PolicyT1, typename ...PolicyTypes>
    struct PolType<0, MultiBase<nr, PolicyT1, PolicyTypes...>>
```

```
        {
            typedef PolicyT1 Type;
        };
    public:
        typeAt(typeAt const &) = delete;
        typedef typename PolType<index, typename Multi::Base>::Type Type;
    };
```

The types specified by `Multi`'s parameter pack can also be retrieved using a second helper class template: `plainTypeAt`. Example:

```
    plainTypeAt<0, Multi<Vector, int, double>>::Type // Type is int
```

The class template `plainTypeAt` uses a comparable (but simpler) implementation than `typeAt`. It is also a pure template meta program class template defining a nested class template `At`. `At` is implemented like `typeAt` but it visits the types of the original template pack that was passed to `Multi`, and made available by `Multi` as its `PlainTypes` type. Here is `plainTypeAt`'s definition:

```
    template <size_t index, typename Multi>
    class plainTypeAt
    {
        template <size_t idx, typename List>
        struct At;

        template <size_t idx, typename Head, typename ...Tail>
        struct At<idx, TypeList<Head, Tail...>>
        {
            typedef typename At<idx - 1, TypeList<Tail...>>::Type Type;
        };

        template <typename Head, typename ...Tail>
        struct At<0, TypeList<Head, Tail...>>
        {
            typedef Head Type;
        };

    public:
        plainTypeAt(plainTypeAt const &) = delete;
        typedef typename At<index, typename Multi::PlainTypes>::Type Type;
    };
```

Arguably the neatest support template is `get`. This is a function template defining `size_t idx` as its first template parameter and `typename Multi` as its second template parameter. The function template `get` defines one function parameter: a reference to a `Multi`, so it can deduce `Multi`'s type by itself. Knowing that it's a `Multi`, we reason that it is also a `UWrap<nr, PolicyType>` and therefore also a `PolicyType`, as the latter class is defined as a base class of `UWrap`.

Since class type objects can initialize references to their base classes the `PolicyType &` can be initialized by an appropriate `UWrap` reference, which in turn can be initialized by a `Multi` object. Since we can determine `PolicyType` using `TypeAt` (note that evaluating `typename typeAt<idx, Multi>::Type` is a purely compile-time matter), the `get` function can very well be implemented *inline* by a single `return` statement:

```
    template <size_t idx, typename Multi>
```

```
inline typename typeAt<idx, Multi>::Type &get(Multi &multi)
{
    return static_cast<
            UWrap<idx, typename typeAt<idx, Multi>::Type> &>(multi);
}
```

The intermediate `UWrap` cast is required to disambiguate between identical policy types (like two `vector<int>` types). As `UWrap` is uniquely determined by its `nr` template argument and this is the number argument that is passed to `get` ambiguities can easily be prevented.

23.11.4 Using Multi

Now that `Multi` and its support templates have been developed, how can a `Multi` be used?

A word of warning is in place. To reduce the size of the developed classes they were designed in a minimalist way. For example, the `get` function template cannot be used with `Multi const` objects and there is no default, or move constructor available for `Multi` types. `Multi` was designed to illustrate some of the possibilities of template meta programming and hopefully `Multi`'s implementation served that purpose well. But can it be used? If so, how?

This section provides some annotated examples. They may be concatenated to define a series of statements that could be placed in a `main` function's body, which would result in a working program.

- A simple `Policy` could be defined:

  ```
  template <typename Type>
  struct Policy
  {
      Type d_type;
      Policy(Type &&type)
      :
          d_type(std::forward<Type>(type))
      {}
  };
  ```

  `Policy` defines a data member and it can be used to define `Multi` objects:

  ```
  Multi<Policy, string> ms{ Policy<string>{ "hello" } };
  Multi<Policy, string, string> ms2s{ Policy<string>{ "hello" },
                                      Policy<string>{ "world" } };


   typedef Multi<Policy, string, int> MPSI;
   MPSI mpsi{ string{ "hello" }, 4 };
  ```

- To obtain the number of types defined by a `Multi` class or object either use the `::size` enum value (using the `Multi` class) or the `.size` member (using the `Multi` object):

  ```
  cout << "There are " << MPSI::size << " types in MPSI\n"
          "There are " << mpsi.size << " types in mpsi\n";
  ```

- Variables of constituting types can be defined using `plainTypeAt`:

  ```
  plainTypeAt<0, MPSI>::Type sx = "String type";
  plainTypeAt<1, MPSI>::Type ix = 12;
  ```

- Raw static casts can be used to obtain the constituent type:

```
cout << static_cast<Policy<string> &>(mpsi).d_type << '\n' <<
        static_cast<Policy<int> &>(mpsi).d_type << '\n';
```

- However, this won't work when the template parameter pack contains identical types, as a cast can't distinguish between identical `Policy<Type>` types. In that case `get` still works fine:

```
typedef Multi<Policy, int, int> MPII;
MPII mpii{ 4, 18 };

cout << get<0>(mpii).d_type << ' ' << get<1>(mpii).d_type << '\n';
```

- Here is an example wrapping a `std::vector` in a `Vector`:

```
typedef Multi<Vector, int, double> MVID;
MVID mi{ {1, 2, 3}, {1.2, 3.4, 5.6, 7.8} };
```

- Such a vector can be defined by its `Multi` type:

```
typeAt<0, Multi<Vector, int>>::Type vi = {1, 2, 3};
```

- Knowing that a `Vector` is a `std::vector`, the reference returned by `get` support index operators that can be used as left hand side or right hand side operands:

```
cout << get<0>(mi)[2] << '\n';
get<1>(mi)[3] = get<0>(mi)[0];
cout << get<1>(mi)[3] << '\n';
```

23.12 Expression Templates

Assume we are processing `std::vector` objects. Vectors may be assigned to each other, but that's about it. We've seen (cf. section 12.4.2) that its member functions tend to operate on the current vector, but arithmetic operations like addition, subtraction, multiplication and the like cannot be applied to pairs of vectors.

Implementing the, e.g., addition operator for vectors is not difficult. If `VecType` is our vector type, then implementing free functions like `VecType &&operator+(VecType const &lhs, VecType const &rhs)` and `VecType &&operator+(VecType &&lhs, VecType const &rhs)` performing the additions is a simple exercise (cf. chapter 11).

Now consider an expression like `one + two + three + four`. It takes four steps to compute this sum: first, `tmp = one` is computed, creating the eventual return value. The vector `tmp` becomes the eventual return value. Once it is available `tmp += two` is computed, followed by `tmp += three`, and finally by `tmp += four` (of course we shouldn't implement `std::vector::operator+=` as the std namespace is off-limits to us, and we shouldn't derive a class from `std::vector` offering `operator+=` according to Liskov's Substitution Principle (cf. section 14.7), but we could get around that.

Here we simply assume `operator+=` is available).

Here's how we might implement `operator+=` for `VecType`:

```
VecType &VecType::operator+=(VecType const &rhs)
{
        for (size_t idx = 0, end = size(); idx != end; ++idx)
            (*this)[idx] += rhs[idx];
        return *this;
    }
```

Consider this implementation: once we add `VecType` objects and such objects have `N` elements then we have to perform `2 * N` index evaluations. When adding `k VecType` objects this adds up to `2 * N * k` index expression evaluations (as eventually we also have to assign the elements of the resulting temporary object to the destination object): lots of index expression evaluations.

If instead we could manage to perform the evaluations ‘row by row’, we would only have to access each vector element only once (which in particular applies to the temporary object). In that case, when adding k objects, assigning the sums of their respective elements to a destination vector we have to compute `N * (k + 1)` index expressions (`'k'` for each of the vectors, `'1'` for the destination vector).

For `k == 1` the two methods are equally efficient in terms of index computations. But that’s not addition, that is assignment. So when adding any number of vectors, assigning their sum to a destination vector using expression templates is more efficient than the ordinary implementation of the addition operator. We’ll have a look at the design and implementation of expression templates in the coming sections.

23.12.1 Designing an Expression Template

As we’ve seen, when using a standard implementation of an expression like `one + two + three + four`, where the objects are vectors having `n` elements, then if we have `k` vectors we have to perform a total of `k * 2 * n` index evaluations.

Expression templates allow us to avoid many of these evaluations. When using expression templates these templates may access the vectors, but their elements are not accessed during addition operations.

Assuming our expression template is named ET, and we want to add `one + two + three`, then the first `+` operator merely creates `ET(one, two)`. Note that no addition is actually performed, `ET` merely stores (constant) references to `one` (becoming `ET's lhs` data member) and `two` (becoming `ET's rhs` data member). In general, `ET` stores references to the two arguments that are passed to its constructor.

At the next addition operator another `ET` is created. Its constructor arguments are, respectively, the `ET` object that has just been constructed for `one` and `two`, and the vector `three`. Again, no addition is performed by the ET objects.

This algorithm easily generalizes to any number of vectors. Parentheses can also be used. E.g., `(one + two) + (three + four)` results in

```
    ET(ET(one, two), ET(three, four))
```

Presumably, at some point we want to obtain the sum of the vectors. For this the expression template is provided with a conversion operator, converting the `ET` object to a vector, or maybe an assignment operator doing the same.

The conversion operator looks like this:

```
    operator ET::VecType() const
    {
        VecType retVal;
        retVal.reserve(size());

        for (size_t ix = 0, end = size(); ix != end; ++ix)
            new(&retVal[ix]) value_type((*this)[ix]);

        return retVal;
    }
```

Placement new is used for efficiency reasons: there's no need to initialize `retVal` with default values first. The really interesting part, however, is hidden behind the `(*this)[idx]` expression: at this point the real addition takes place.

`ET's` index operator simply adds the values returned by the corresponding index expressions of its `lhs` and `rhs` data members. If a data member refers to a vector then the corresponding vector element is used, adding it to the other data member's value. If a data member itself refers to an ET object, then that nested `ET` object's index operator performs the same addition on its own data members, returning their sum. So, an expression like `(*this)[0]` returns `first[0] + second[0] + third[0]`, and the computed sum is then stored in `retVal[0]` using placement new.

In this case the required number of index expression evaluations are `n * k` (for the n elements of the k vectors) plus n (for the n elements of `retVal`, adding up to `(k + 1) * n`).

Since `(k + 1) * n < 2 * k * n` for `k > 1` expression templates evaluate the requested addition more efficiently than the traditional implementation of `operator+`. An additional benefit of using expression templates is that they do not create additional temporary vector objects when parenthesized expressions are used.

23.12.2 Implementing an Expression Template

In this section we use a `typedef std::vector<int> IntVect` to illustrate the construction of an expression template.

Starting point is a simple `main` function, in which several `IntVect` objects are added. E.g.,

```
    int main()
    {
        IntVect one;
        IntVect two;
        IntVect three;
        IntVect four;

        // ... assume the IntVects somehow receive values

        four = one + two + three + four;
    }
```

At this point the code does not suggest that expression templates are going to be used. However, `operator+'s` implementation is special: it's a template merely returning an object constructed by `operator+`:

```
    template<typename LHS, typename RHS>
    BinExpr<LHS, RHS, plus> operator+(LHS const &lhs, RHS const &rhs)
    {
        return BinExpr<LHS, RHS, plus>{ lhs, rhs };
    }
```

Our expression template is called `BinExpr`. It has three template type parameters: two object types and a template template parameter performing the requested operation. Its declaration looks like this:

```
    template<typename LHS, typename RHS, template<typename> class Operation>
    struct BinExpr;
```

Since `LHS` and `RHS` can either be the data type that is processed by the expression template, or a `BinExpr` two different typenames are required. `Operation` is the operation that is performed by the expression template. By using a template template parameter we can use `BinExpr` to perform any operation we want, not just addition. Predefined function templates like `std::plus` can be used for the standard arithmetic operators; for other operators we can define our own function templates.

`BinExpr's` constructor initializes constant references to `lhs` and `rhs`. Its in-class implementation is

```
    BinExpr(LHS const &lhs, RHS const &rhs)
    :
        d_lhs(lhs),
        d_rhs(rhs)
    {}
```

To retrieve the resulting `IntVect` a conversion operator is defined. We already encountered its implementation (in the previous section). Here is it, as an in-class implemented `BinExpr` member:

```
    operator ObjType() const
    {
        ObjType retVal;
        retVal.reserve(size());

        for (size_t idx = 0, end = size(); idx != end; ++idx)
            new(&retVal[idx]) value_type((*this)[idx]);

        return retVal;
    }
```

We return to the type `ObjType` below. At this point it can be considered an `IntVect`. The member `size()` simply returns `d_lhs.size()`: in any sequence of `IntVect` additions `LHS` eventually is an `IntVect`, and so every `BinExpr` defines a valid `size()` like so:

```
    size_t size() const
    {
        return d_lhs.size();
    }
```

The only remaining member to implement is `operator[]`. Since it receives an index, it only needs to perform the requested operation on the corresponding index elements of its `d_lhs` and `d_rhs` data members. The beauty of expression templates is that if either one itself is a `BinExpr` that expression template in turn calls its `operator[]`, eventually performing the requested operation on all corresponding elements of all `IntVect` objects. Here is its implementation:

```
    value_type operator[](size_t ix) const
```

```
{
    static Operation<value_type> operation;

    return operation(d_lhs[ix], d_rhs[ix]);
}
```

This implementation uses another type: `value_type` which is the type of the elements of the vector type that is processed by the expression template. Like `ObjType` before, its definition is covered below. The static data member `operation` simply is an instantiation of the `Operation` type that is specified when constructing an `ExprType` object.

In the next section we take a closer look at `ObjType` and `value_type`.

23.12.3 The BasicType trait class and ordering classes

The `BinExpr` expression template needs to be aware of two types before it can instantiate objects. First, `ObjType` must be known, as this is the type of object that is handled by the expression template. `ObjType` objects contain values, and we require that the type of these values can be determined as `ObjType::value_type`. E.g., for our `IntVect` data type `value_type` is `int`.

In expressions like `one + two + three`, the `BinExpr` expression template receives two `IntVect` objects. This is always true: the `BinExpr` that is first constructed receives two `IntVect` objects. In this case `ObjType` is simply `LHS`, and `ObjType::value_type` is also available: either `value_type` is already defined by `LHS` or `BinExpr` *requires* that it defines type `value_type`.

Since arguments to `BinExpr` objects are not *always* of the basic `ObjType` type (`BinExpr` objects at the next nesting level receive at least one `BinExpr` argument) we need a way to determine `ObjType` from a `BinExpr`. For this we use a *trait class*. The trait class `BasicType` receives a typename template argument, and equates its type `ObjType` to the received template type argument:

```
template<typename Type>
struct BasicType
{
    typedef Type ObjType;
};
```

A specialization handles the case where `Type` in fact is a `BinExpr`: template<typename LHS, typename RHS, template<typename> class Operation>

```
template<typename LHS, typename RHS, template<typename> class Operation>
struct BasicType<BinExpr<LHS, RHS, Operation>>
{
    typedef typename BinExpr<LHS, RHS, Operation>::ObjType ObjType;
};
```

Since `BinExpr` *requires* that `ObjType::value_type` is a defined type, `value_type` has automatically been taken care of.

As `BinExpr` refers to `BasicType` and `BasicType` refers to `BinExpr` somewhere we must provide a forward declaration. As `BinExpr's` declaration has already been provided, we start with that declaration, resulting in:

```
BinExpr's declaration
```

```
BasicType's definition

BasicType's specialization (for BinExpr)

template<typename LHS, typename RHS, template<typename> class Operation>
class BinExpr
{
    LHS const &d_lhs;
    RHS const &d_rhs;

    public:
        typedef typename BasicType<RHS>::DataType DataType;
        typedef typename DataType::value_type value_type;

        // all BinExpr member functions
};
```

23.13 Concepts

C++ is a strongly typed language: a function `add(int lhs, int rhs)` doesn't accept `std::string` arguments, even though the actual operations (`lhs + rhs`) are identical for `ints` and `strings`.

Templates were introduced so we could design *recipes* for the compiler, allowing it to construct type-safe overloaded versions of functions and classes while keeping their type-safety.

A basic addition function template adding two values looks like this:

```
template <typename Type>
Type add(Type const &lhs, Type const &rhs)
{
    return lhs + rhs;
}
```

When this function template is called with arguments of types that do not support `operator+` then the compiler notices this, and it will generate an error. E.g., when calling

```
add(std::cerr, std::cout);
```

the `g++` compiler produces some 140 lines of error messages. It notices that there's no `operator+` for `std::ostream` objects, and then tells us what else we might have done (like adding two `ints`), and where the construction of the `add` function that should accept `std::ostream` arguments went wrong. In fact, 140 lines of error messages is rather benign. Getting several hundreds of lines is quite common, and sometimes the location of the error isn't mentioned at the top but somewhere near the end of the error message output.

The `C++20` standard introduced *concepts* allowing us to specify *requirements* for template types. When applying an appropriate concept to the definition of the `add` function template the compiler immediately pinpoints the error, telling us where and why the error occurred in some 15 instead of 140 lines of error messages.

The reduction of the number of lines of error messages by itself is a boon. But the fact that concepts allow us to consciously develop our templates, realizing what the precise requirements are for their use, is at least as important: it improves the template's documentation, and thus our understanding of templates.

Concepts may be considered the template's answer to the philosphy that lies behind a strongly typed language. By applying concepts to templates we can specify type-requirements rather than using the traditional 'shotgun empiricism' approach where templates are bluntly used, knowing that the compiler will complain if things are incorrect. In that sense concepts provide type definitions of types. Concepts have names and can (among other) be used in template headers where the concept names replace the traditional `typename` keywords.

As an opening illustration, assume that a concept `Addable` exists specifying that `operator+` must have been defined for the template's type. The above function template `add` can now be formulated as:

```
template<Addable Type>
Type add(Type const &lhs, Type const &rhs)
{
    return lhs + rhs;
}
```

From now on every type that is actually passed to `add` must be satisfy the `Addable` requirements. Here are two expressions using `add`:

```
add("first"s, "second"s);               // (1)
add(map<int, int>{}, map<int, int>{});  // (2)
```

Expression (1) flawlessly compiles as `string` objects can be added; expression (2) fails with the compiler reporting something like

```
error: use of function `Type add(const Type&, const Type&)
[with Type = std::unordered_map<int, int>]' with unsatisfied constraints
add(unordered_map<int, int>{}, unordered_map<int, int>{});
note: constraints not satisfied

Type add(const Type&, const Type&)
...
note: the required expression `(lh + rh)' is invalid
```

The error message's final 'note' clearly states the cause of the problem: you can't add maps.

The difference between the compiler's report using concepts and not using concepts again is impressive. When using the traditional `typename Type` specification in the template header the compiler produces some 17 kB of error messages, spread out over more than 200 lines.

In the following sections we cover how concepts are defined, what kind of requirements can be formulated, and how they can be used in practice.

23.13.1 Defining concepts

As a prelude before actually looking at how concepts are defined it is noted that concept names, like class names, type names, function names, and variable names should suggest their purposes. Don't name a concept '`Constraint`' or '`Concept`', but use names like '`Addable`' and '`HasValueType`'.

Concepts are templates. They start with a template header (the template headers shown in the examples define a single template type parameter, but multiple template parameters are also used).

In the previous section we used the concept `Addable`. Here is how it can be defined:

```
    template <typename Type>
    concept Addable =
        requires(Type lh, Type rh)
        {
            lh + rh;
        };
```

The concept's template header is followed by the keyword `concept`, the concept's name, and the assignment operator. Following the assignment operator *requirement specifications* are provided.

Semicolons end concept definitions. This concept uses a *simple requirement* (cf. section 23.13.2.1) indicating that `operator+` must have been defined for `Addable` templates' types.

Requirements come in many forms. A very simple form consists of just a `bool` value, which is sometimes useful when developing a concept. Such a concept looks like this:

```
template <typename Type>
    concept IsTrue =
        true;
```

But in most situations `requires` specifications are used. They resemble function definitions having parameter lists optionally defining variables of the types that specified in the concept's template header and compound statements specifying requirements.

Concepts are *never* instantiated. They are used compile-time to verify that template types satisfy the imposed requirements. Thus there's no need to use refererences in parameter lists of `requires` specifications. The concept `Addable` simply uses

```
    requires(Type lh, Type rh)
```

and there's no need to specify

```
    requires(Type const &lh, Type const &rh)
```

(That is, usually there is no need for this. In section 23.13.2.4 we encounter a situation where a more specific parameter definition might be appropriate.)

Here are two examples of templates using `concept Addable`. The first example uses `Addable` instead of `typedef` when specifying the template header, the second example appends the concept specification to the template header itself:

```
    template<Addable Type>
    Type add2(Type const &x, Type const &y)
    {
        return x + y;
    }

    template<typename Type>
        requires Addable<Type>
    Type add(Type const &x, Type const &y)
    {
        return x + y;
    }
```

Template declarations using concepts are specified accordingly. Simply replace the function template's body by a semicolon.

Concepts may also be defined by extending or combining existing concepts. *Nesting* concepts is covered in section 23.13.2.4.

Although concepts are templates, they cannot be specialized. If a concept should recognize specializations then these specializations must be handled by the concepts' definitions. Section 23.13.2.3 for an illustration

23.13.2 Requirements

The bodies of `requires` declarations contain define constraints to apply to template parameters. There are four types of requirements:

- *Simple requirements*: constraints on *facilities* (like requiring the availability of `operator+`);
- *Type requirements*: requiring the availability of (sub)types (like the sub-type `value_type`) which must be available when using standard `push_back` functions;
- *Compound requirements*: requiring types resulting from applying operators or returned by called (member) functions;
- *Nested requirements*: defining concepts in terms of already existing concepts.

Constraints must be compile-time verifiable.

When multiple constraints are specified, they must *all* be compile-time verifiable, and an actual type is only accepted by the compiler if all requirements could be satisfied.

23.13.2.1 Simple requirements

We've already encountered various examples of *simple requirements*: they specify the operations that must be supported by the variable(s) declared in the parameter lists of `requires` specifications. When the requirements refer to single variables single `Type` parameters suffice; when requirements involve different types then the concept's template head declares those different types and the `requires` parameter list will usually define variables of those different types. The `concept BasicMath` specifies two types, and uses four simple requirements to specify the four basic arithmetic operations:

```
template <typename LhsType, typename RhsType>
concept BasicMath =
    requires(LhsType lhs, RhsType rhs)
    {
        lhs + rhs;      // addition must be available
        lhs - rhs;      // subtraction must be available
        lhs * rhs;      // multiplication must be available
        lhs / rhs;      // division must be available
    };
```

Specifying constraints does not necessarily mean that the constraints as specified literally apply to run-time situations. To require the existence of the index operator the following simple requirement can be used:

```
template <typename Type>
```

```
concept HasIndex =
    requires(Type tp)
    {
        tp[0];
    };

template <HasIndex Type>
auto idx(Type const &obj, size_t idx)
{
    return obj[idx];
}
```

Here the *stand-in argument* 0 is used to specify the index operator's argument. The argument value used in the simple requirement really is a stand-in. The following code fragment compiles, as `string` supports the index operator. Athough argument 0 is used in the simple requirement specification the argument 5 is in fact being used:

```
string str;
idx(str, 5);
```

Other than `int` index types can be specified analogously. Here is an example showing how to define and use a concept `HasStrIndex` requiring the availability of `std::string` arguments of index operators:

```
template <typename Type>
concept HasStrIndex =
    requires(Type tp)
    {
        tp[std::string{}];
    };

template <HasStrIndex Type>
auto value(Type &obj, std::string const &key)
{
    return obj[key];
}

int main()
{
    std::map<std::string, double> msd;
    value(msd, "hi");
}
```

23.13.2.2 Type requirements

Sometimes templates must use sub-types of template types. Examples are templates assuming the existence of `iterator` (like `vector<int>::iterator`) or `value_type` which is used when calling `std::push_back`.

To specify that a sub-type must be available the concept's `requires` specification needs no parameters, but can directly refer to the subtype. It's also possible to combine type requirements with requirements that *do* define a non-empty parameter list, and so the `requires's` parameter list does not *have* to be empty. Here is a concept that specifies a plain type requirement:

```
template <typename Type>
concept HasValueType =
    requires()
    {
        typename Type::value_type;
    };
```

and here's a concept that combines a simple requirement with a type requirement:

```
template <typename Type>
concept Iteratable =
    requires(Type tp)
    {
        typename Type::iterator;
        tp.begin();
    };

template <Iteratable Type>
auto iter(Type const &obj)
{
    return obj.begin();
}
```

Calling `iter` with a `string` argument succeeds, calling it with a `queue` argument results in two error notes: no `Type::iterator` and no `tp.begin()`.

Types specified in type requirements don't necessarily have to refer to *types*. They may also specify be the names of nested classes or enumerations defined by `Type`. When specifying enumerations they do not have to be strongly typed.

23.13.2.3 Compound requirements

When return types of operations must satisfy certain requirements then *compound requirements* should be used. Compound requirements define type constraints on expressions embedded in compound statements. The `C++20` standard defines several concepts that can be used to specify such requirements (see also section 23.13.3 below). Here is an example:

```
template <typename Type, typename ReturnType>
concept Return =
    requires(Type par)
    {
                      // par[..] must return a `ReturnType'
        { par[0] } -> std::same_as<ReturnType>;
    };
```

This concept can now be used to specify requirements of template type parameters. E.g.,

```
template <typename Type, typename RetType>
    requires Return<Type, RetType>
Ret fun(Type tp)
{
    return tp[0];
}
```

Here arguments passed to `fun` must satify two requirements:

- they must provide an index operator accepting integral argument values;
- their index operators must return `std::string` values.

You may have noticed that the `std::same_as` concept receives only one template type argument, which (as if by magic) compares it with the type returned by the `par[0]` expression. When peeking at the available concepts in section 23.13.3 you will see that several of those concepts in fact define two template type parameters. When these concepts are used in compound requirements then the compiler passes the deduced type of the expression in the concept's compound statement (so that's the type of `par[0]` in the above example) to the concept's first type, and passes the explicitly specified type to the concept's second type.

Knowing this we can define our own concepts to use in compound expressions. We may define our own `same_as` concept as follows, using a separate class template `SameTypes`. `SameTypes` defines a `bool` value '`value`' which is used to decide about the concept's requirement. The class template `SameTypes` uses a specialization to handle the situation where both types are equal. Note that concepts themselves cannot be specialized:

```
template <typename Lhs, typename Rhs>
struct SameTypes            // generic: any two types
{
    static bool const value = false;
};
template <typename Lhs>
struct SameTypes<Lhs, Lhs>  //specialization: equal types
{
    static bool const value = true;
};

template<typename Compound, typename Specified>
concept Same = SameTypes::value;
```

Now the concept `Same` can be used instead of `std::same_as` by merely specifying the required type:

```
template <typename Type, typename ReturnType>
concept Return =
    requires(Type par)
    {
                          // par[..] must return a `ReturnType'
        { par[0] } -> Same<ReturnType>;
    };
```

Although in this case it isn't important which actual type is used as argument for which concept type parameter, the compiler specifies the compound expression's type as template argument for `Same's Compound` parameter whereas `ReturnType` is used as template argument for `Same's Specified` parameter.

Multiple type requirements can be specified by providing multiple compound requirements as in the following example:

```
template <typename Type>
concept MultiArgs =
        requires(Type lhs, Type rhs)
        {
            { lhs + rhs    } -> std::same_as<Type>;
            { lhs += rhs   } -> std::same_as<Type &>;
            { lhs.c_str() } -> std::same_as<char const *>;
        };
```

If it is required that the compound operation doesn't throw exceptions then `noexcept` can be written immediately following the compound requirement's late return type arrow (->). The `noexcept` specification itself may then optionally be followed by a type constraint.

Finally, the late return type specifications itself is optional, in which case the compound requirement acts like a simple requirement: it requires the existence of the expression that's specified in the compound statement. In this case: don't forget to add the semicolon following the closing parenthesis of the compound requirement:

```
    template <typename Type>
    concept Increment =
        requires(Type par)
        {
            { ++par };
            // same as:
            ++par;
        };
```

23.13.2.4 Nested requirements

Concepts can be nested. Being able to nest concepts is very useful as it allows us to hierarchically order concepts and to define concepts in terms of existing concepts.

In chapter 18 iterators were introduced (section 18.2). Commonly five conceptually different iterator types are distinguished:

- Input iterators are incrementable, and they support dereferencing to const values;
- Output iterators are like Input iterators, but they refer to non-const values;
- Forward iterators combine Input and Output iterators;
- Bidirectional iterators are like Forward iterators, but they also support decrement operators;
- RandomAccess iterators are like Bidirectional iterators, but these iterators also support addition and subtraction by any stepsize.

All iterator types support (in)equality checks and increment operators. Thus, at the basis of all iterators we find the requirements that iterators must be comparable and incrementable. Concepts covering those requirements are easily constructed (see also figure 23.2):

```
    template <typename Type>
    concept Comparable =
        requires (Type lhs, Type rhs)
        {
            lhs == rhs;
            lhs != rhs;
        };
```

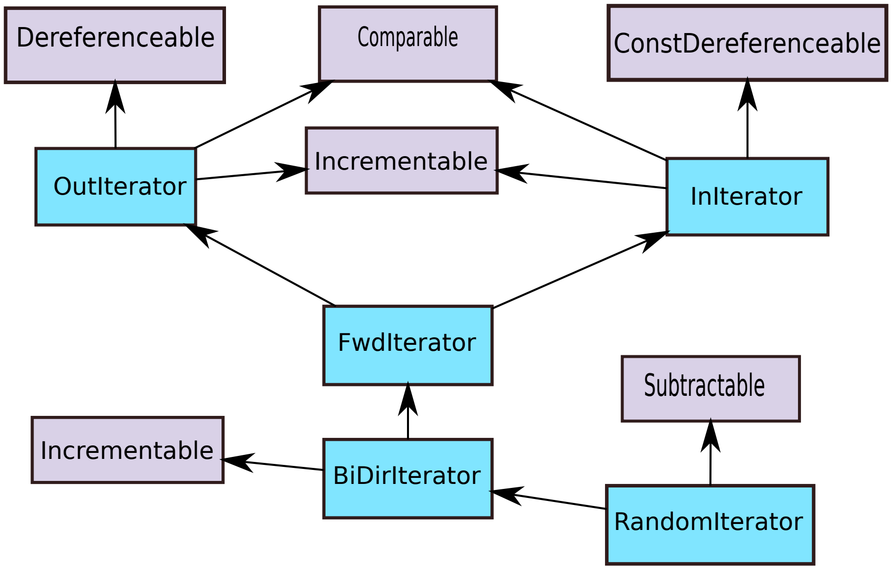
Dereferenceable
Comparable
ConstDereferenceable
OutIterator
Incrementable
InIterator
FwdIterator
Subtractable
Incrementable
BiDirIterator
RandomIterator

Figure 23.2: Concept Hierarchy

```
template <typename Type>
concept Incrementable =
    requires (Type type)
    {
        ++type;
        type++;
    };
```

Note that no type is specified following the `lhs == rhs` and `lhs != rhs` requirements, as those types are implied by their operators.

Two more concepts are defined: one allowing dereferencing pointers returning constant references and one returning modifiable references. To allow the compiler to verify those requirements we also implicitly require the (commonly encountered) existence of typename `Type::value_type`:

```
template <typename Type>
concept Dereferenceable =
    requires(Type type)
    {
        { *type } -> std::same_as<typename Type::value_type &>;
    };

template <typename Type>
concept ConstDereferenceable =
    requires(Type type)
    {
        { *type } -> std::same_as<typename Type::value_type const &>;
    };
```

Not much of a hierarchy so far, but that changes now that we're about to define concepts for iterators.

An input iterator is an iterator that is comparable, incrementable and const-dereferenceable. For each of these requirements concepts were defined which can be combined using boolean operators when defining the concept `InIterator`. Note that template type parameters of concepts *must* use the `typename` keyword. Concepts' template parameters cannot be constrained by specifying them in terms of existing concepts (which *is* possible when defining function and class templates).

Here is the definition of the concept `InIterator`. The function template `inFun` (below the concept `InIterator`) illustrates how a constrained template parameter type can be specified in template headers:

```
template <typename Type>
concept InIterator =
    Comparable<Type> and Incrementable<Type> and
    ConstDereferenceable<Type>;

template <InIterator Type>
void inFun(Type tp)
{}
```

The concept for output iterators (and its use, as in the function template `outFun`) is defined analogously. This time requiring dereferenceable types rather than const-dereferenceable types:

```
template <typename Type>
concept OutIterator =
    Comparable<Type> and Incrementable<Type> and
    Dereferenceable<Type>;

template <OutIterator Type>
void outFun(Type tp)
{}
```

For forward iterators the concept `FwdIterator` is defined. A forward iterator combines the characteristics of input and output iterators, and we may want to define a forward iterator by requiring the requirements of the `InIterator` and `OutIterator` concepts.

However, there's a slight problem. The following class (struct) defines const and non-const dereference operators and may be therefore be passed to functions expecting input or output iterators:

```
struct Iterable
{
    typedef int value_type;

    Iterable &operator++();
    Iterable operator++(int);

    int const &operator*() const;
    int &operator*();
};

bool operator==(Iterable const &lh, Iterable const &rh);
bool operator!=(Iterable const &lh, Iterable const &rh);
int  operator-(Iterable const &lh, Iterable const &rh);
```

But when a function template requires `ConstDerefenceable` arguments then the compiler notices that the overloaded member `int &operator*()` doesn't return an `int const &`. Even though `int const &operator*() const` is available compilation fails. This problem can be solved in two ways: noting that an `int &` can be converted to an `int const &` the predefined concept `std::convertible_to` instead of `std::same_as` can be used in `ConstDereferenceable`; alternatively its `requires` clause can specify `Type const &type` instead of just `Type type`. Here is a definition of `ConstDereferenceable` that, when defining the concept `FwdIter`, can be used in combination with `Dereferenceable`:

```
template <typename Type>
concept ConstDereferenceable =
    requires(Type const &type)
    {
        { *type } -> std::same_as<typename Type::value_type const &>;
    };
```

The final two iterator types pose no problems: the concept `BiIterator` requires the constraints of the concept `FwdIterator` as well as decrement operators, and finally the concept `RndIterator` requires the constraints of `BiIterator` and in addition iterator increments decrements for any step size as well as the possibility to subtract iterators:

```
template <typename Type>
concept BiIterator =
    FwdIterator<Type> and
    requires(Type type)
    {
        --type;
        type--;
    };

template <typename Type>
concept RndIterator =
    BiIterator<Type>
    and
    requires(Type lhs, Type rhs)
    {
        lhs += 0;
        lhs -= 0;
        lhs + 0;
        lhs - 0;
        { lhs - rhs } -> std::same_as<int>;
    };
```

23.13.3 Predefined concepts

In the previous section we covered defining concept requirements. When specifying some of the requirements already available concepts were used, like `std::same_as`. The C++20 standard provides some 30 predefined concepts which may be used to specify type requirements, to specify conversion requirements, and to specify more advanced requirements, sometimes accepting variadic template parameters. The currently predefined concepts are covered in the following subsections.

23.13.3.1 Concepts specifying one template type parameter

The following concepts specify just one template type parameter. Their generic form is

```
template <typename Type>
```

```
    concept Name =
        ... requirements ...
        ;
```

When used in compound requirements only their names have to be specified. For example (using the concept `std::boolean` (see below)), to require that a function `fun` receiving an argument of some type `Type` returns a boolean value, the following concept could be defined:

```
template<typename Type>
    concept BoolFun =
        requires(Type param)
        {
            { fun(param) } -> std::boolean;
        };
```

- `boolean`:
  requires that its type can be used in boolean expressions
- `copy_constructible`:
  requires that objects of its type supports copy- and move-construction;
- `copyable`:
  requires that objects of its type support copy- and move- construction and assignment, and that two objects of its type can be swapped;
- `default_initializable`:
  requires that objects of its type support default constructors;
- `destructible`:
  requires that the destructor of its type is defined as `noexcept(true)`;
- `equality_comparable`:
  requires that `operator==` is available to compare two objects of its type;
- `floating_point`:
  requires that its type is a floating-point type;
- `integral`:
  requires that its type is an integral type;
- `movable`:
  requires that its type supports moving and swapping. Note that full support for moving requires that its type supports move construction and move assignment;
- `move_constructible`:
  requires that its type supports move construction;
- `regular`:
  requires that its type satisfies the requirements of the `semiregular` and `equality_comparable` concepts;
- `semiregular`:
  requires that its type supports default construction, copying, moving, and swapping;
- `signed_integral`:
  requires that its type is a signed integral type;
- `swappable`:
  requires that two objects of the same type can be swapped. The generic variant (see below) is named `swappable_with`;

- `unsigned_integral`:
  requires that its type is an unsigned integral type;
- `totally_ordered`:
  requires that two objects of identical types can be ordered using the operators `==, !=, <, <=, >,` and `>=`. The requirements for ordering is *strict*: for any two objects `one` and `two` either `one < two, one == two,` or `one > two` is true. The generic variant is named `totally_ordered_with`.

23.13.3.2 Concepts specifying two template type parameters

The following concepts define two template type parameters. Their generic form is

```
    template <typename LHS, typename RHS>
    concept Name =
        ... requirements ...
        ;
```

When used in compound requirements the compiler deduces the type of the compound expression, and then uses that type as LHS. In the type requirement following the compound statement only the RHS type is specified. For example (using the concept `std::same_as` (see below)), to require that a function `fun`, receiving an argument of some type `Type`, returns a `std::string` the following concept can be defined:

```
template<typename Type>
    concept StringFun =
        requires(Type param)
        {
            { fun(param) } -> std::same_as<std::string>;
        };
```

- `assignable_from`:
  requires that RHS-typed expressions can be assigned to LHS-typed expressions;
- `common_reference_with`:
  requires that both types can be converted to an identical (reference) type. The concept is satisfied for two identical types, but also for two types where one of them is derived from the other. E.g.,

```
template <typename LHS, typename RHS>
concept CommonRef = std::common_reference_with<LHS, RHS>;

template <typename T1, typename T2>
    requires CommonRef<T1, T2>
void fun(T1 &&t1, T2 &&t2)
{}

struct B
{};

struct D1: public B
{
};
```

```
int main()
{
    fun(4, 'a');
    fun(4.5, 'a');

    D1 d1;
    B b;

    fun(b, d1);     // objects, rvalue refs:
    fun(D1{}, B{}); // all OK
}
```

- `common_with`:
  works like the previous concept;
- `convertible_to`:
  requires that the LHS type can automatically be converted to the RHS type:

```
template <typename LHS, typename RHS>
concept Convertible =
    requires(LHS lhs)
    {
        { lhs } -> std::convertible_to<RHS>;
    };

template <typename RHS, typename LHS>
    requires Convertible<LHS, RHS>
void fun(LHS lhs)
{}

int main()
{                            // note: LHS is the <...>'s type
    fun<double>(12);         // from int to double
    fun<int>(12.5);          // from double to int
    fun<std::string>("a");   // from NTBS to string
//  fun<std::string>(12);    // constraints not satisfied
}
```

- `derived_from`:
  requires that the LHS type is derived from the RHS type;
- `equality_comparable_with`:
  requires that operators `operator==` and `operator!=` are available to compare LHS- and RHS-type variables (in any order);
- `same_as`:
  requires that the LHS type is the same as the RHS type. Note that this concept acts rather strictly. For example, `std::same_as<long int, int>` does not satisfy the requirement. If such a strict equality isn't really required then `convertible_to` might offer a workable alternative;
- `swappable_with`:
  requires that two objects of possibly different types can be swapped. The more restrictive variant requiring objects of identical types is named `swappable`;
- `totally_ordered_with`:
  requires that two objects of possibly different types can be ordered using the operators `==`, `!=`, `<`, `<=`, `>`, and `>=`. The requirements for ordering is *strict*: for any two objects `one` and

`two` either `one < two`, `one == two`, or `one > two` is true. The more restrictive variant requiring objects of identical types is named `totally_ordered`.

23.13.3.3 Concepts specifying multiple template type parameters

Most predefined concepts expecting more than two parameters are variadic (cf. section 23.13.4).

- `constructible_from`:
  requires a LHS type and a variadic template parameter representing the types from which LHS can be constructed (which may be empty if a default constructor is suppported). Here is an example:

  ```
  template <typename LHS, typename ...Args>
  concept Constructible = std::constructible_from<LHS, Args...>;

  template <typename T1, typename ...Args>
      requires Constructible<T1, Args...>
  T1 fun(Args &&...t2)
  {
      return T1( std::forward<Args>(t2)... );
  }

  int main()
  {
      std::string s{ fun<std::string>(5, 'a') };
      std::string s2{ fun<std::string>() };   // slightly weird...
  }
  ```

- `equivalence_relation`:
  this concept defines three template type parameters. It is a synonym of the concept `std::relation` (see below);

- `invocable`:
  requires a LHS type and a variadic template parameter representing the types which are forwared as arguments to the function or functor specified as `invocable's` first argument. Here is an example:

  ```
  template <typename Function, typename ...Params>
  void fun(Function &&fun, Params &&...params)
      requires std::invocable<Function, Params ...>
  {
      fun(std::forward<Params>(params)...);
  }

  void hello(int value, char const *txt, std::string const &str)
  {
      std::cout << value << ' ' << txt << ' ' << str << '\n';
  }

  int main()
  {
      fun(hello, 1, "text", "string");    // promotions are still OK
      // fun(hello, 1);                   // WC: not invocable
  }
  ```

- `predicate`:
  requires a LHS type which is a predicate (functor or function returning a `bool` value), expecting arguments of the variadic template parameter RHS. Here is an example:

```
template <typename Container, typename Predicate>
concept Find_ifConcept =
    std::predicate<Predicate, typename Container::value_type>
    and
    requires(Container container)
    {
        { container.begin() } -> Iter;
        { container.end() }   -> Iter;
        { container.size() }  -> std::same_as<size_t>;
    };

template <typename Container, typename Predicate>
size_t findIdx_if(Container const &cont, size_t from, Predicate const &pred)
    requires Find_ifConcept<Container, Predicate>
{
    auto iter = std::find_if(cont.begin() + from, cont.end(), pred);
    return iter == cont.end() ? cont.size() : iter - cont.begin();
}

int main()
{
    std::cout << "Index at " <<
        findIdx_if(std::string{ "hello world" }, 0,
            [&](int ch)
            {
                return ch == ' ';
            }
        ) << '\n';

    int target = 4;
    fun(
        [&](int value)
        {
            return value == target;
        },
        4
    );
}
```

- `regular_invocable`:
  synonym of `invocable`;

- `relation`:
  this concept defines three template type parameters. The first parameter is a predicate whose function call operator expects two arguments. The arguments are of the types of the second and/or third template type parameters (any combination, any order). For example, the requirements of the `std::relation` concept are satisfied if the predicate's first template argument is `std::less`, the second argument is `int` and the third argument is `double`.

  In the following example `struct Less` is a functor comparing the two arguments of its function call operator. Next, the function `cmp` accepts such a struct type as predicate, verifying that the predicate and the arguments that are passed to the function satisfy the requirements of the `std::relation` concept. If so the functor's return value is returned.

Finally, in main `cmp` is first called with `int` and `double` arguments (which succeeds) and then with an `int` and a NTBS arguments: for the second call the constraints are not satisfied as `ints` and `NTBSs` can't be compared, and consequently compilation fails:

```
template <typename LHS, typename RHS>
struct Less
{
    bool operator()(LHS lhs, RHS rhs) const
    {
        return lhs < rhs;
    }
};

template <template<typename LHS, typename RHS> typename Pred,
          typename LHS, typename RHS>
bool cmp(LHS lhs, RHS rhs)
    requires std::relation<Pred<LHS, RHS>, LHS, RHS>
{
    return Pred<LHS, RHS>{}(lhs, rhs);
}

int main()
{
    std::cout << cmp <Less>(5, 4.9) << '\n';
    std::cout << cmp <Less>(5, "hello world") << '\n';
}
```

;

- `strict_weak_order`:
  this concept defines three template type parameters. The first parameter is the type of a predicate whose function call operator expects two arguments. The arguments are of the types of the second and/or third template type parameters (any combination, any order). The concept is satisfied if the predicate can verify that a strict weak order applies to its argument types. A relation is a strict weak ordering if
  - the predicate returns false if an object is compared to itself;
  - the relation is transitive: if `pred(one, two)` and `pred(two, three)` are both true, then `pred(one, three)` is also true;

23.13.4 Applying concepts to template parameter packs

As we have seen (cf. section 23.13.3.3) concepts may process template parameter packs. Such concepts are called *variadic concepts*. When defining concept-protected variadic function or class templates variadic concepts aren't always required. Consider the following function:

```
template <HasSize ...Types>
void fun(Types &&...obj)
{
    sum(std::forward<Types &&>(obj)...);
}
```

Here we see a variadic template, but it defines all its parameters as constrained types by simply mentioning the concept `HasSize` instead of just `typename`. The `HasSize` concept is very basic: it merely requires that `type.size()` exists, returning a `size_t`:

```
template <typename Types>
concept HasSize =
    requires (Types type)
    {
        { type.size() } -> std::same_as<size_t>;
    };
```

Once `fun` has verified that all its argument types satisfy the `HasSize` requirements no additional checks are necessary. The `fun` function template merely forwards its arguments to `sum`, a variadic template, that simply adds the return values of the `size()` members of its arguments:

```
size_t sum()
{
    return 0;
}

template <typename First, typename  ...Types>
size_t sum(First &&first, Types &&...types)
{
    return first.size() + sum(std::forward<Types>(types)...);
}
```

The wrapper function `fun` isn't really required. The variadic template function summing the various `size()` values itself can also be defined so that its types themselves must satisfy the `HasSize` concept. Here is the definition of the variadic function template `sum2` requiring precisely that:

```
size_t sum2()
{
    return 0;
}

template <HasSize First, HasSize  ...Types>
size_t sum2(First &&first, Types &&...types)
{
    return first.size() + sum2(std::forward<Types>(types)...);
}
```

And here is a `main` function calling `fun` and `sum2`:

```
int main()
{
    fun(queue<int>{}, vector<int>{}, string{});
    cout << sum2(queue<int>{}, vector<int>{}, string{}) << '\n';
}
```

On the other hand, the predefined concept `std::constructible_from` *is* a variadic concept, as it accepts a LHS template parameter and a RHS parameter pack. This concept is satisfied if the LHS parameter can be constructed from the types specified in its RHS parameter pack. After including `type_trait` defining and using such a concept is not very hard:

```
template <typename Class, typename ...Params>
concept Constructible = std::is_constructible<Class, Params ...>::value;
```

```
template <typename Class, typename ...Params>
    requires Constructible<Class, Params ...>
void fun(Class &&type, Params &&...params)
{}
```

The recipe for writing variadic concepts is not very complex:

- start the concept's definition with a template header specifying a parameter pack;
- pass the parameters to a type trait handling the pack;

To use the variadic concept in a function or class template its template parameters are simply forwarded to the concept (as shown in the above example).

When no predefined variadic type trait is available the variadic concept must use other means to determine whether its constraints are satisfied or not. In those cases define your own variadic type traits. For illustration let's assume we are looking for a variadic concept that can be used to verify that the types of all the arguments that are passed to a variadic function template are integral types. In this case there is no predefined type trait we can use, so we have to define it ourselves. We define the concept `IntegralOnly` as a variadic concept using our self-defined type trait `allIntegralTypes`, and thereupon use it when defining a function requiring that all of its arguments are integral values:

```
template <typename ...Types>
concept IntegralOnly = allIntegralTypes<Types ...>::value;

template <IntegralOnly ...Types>
void fun(Types ...types)
{}
```

The generic type trait `allIntegralTypes` merely specifies that it accepts any number of type parameters and uses specializations to handle specific cases. One specific case is the case were no types are specified which simply defines a `true static bool const` value:

```
template <typename ...Types>
struct allIntegralTypes;

template <>
struct allIntegralTypes<>
{
    static bool const value = true;
};
```

The type trait's partial specialization does the hard work: it determines whether the first type is integral and combines that (using `and`) with the `value` made available by the `struct allIntegralType` receiving the remaining types:

```
template <typename First, typename ...Types>
struct allIntegralTypes<First, Types ...>
{
    static bool const value = std::is_integral<First>::value and
                              allIntegralTypes<Types ...>::value;
};
```

The function `fun` can now be called with any number of arguments. As long as the arguments are integral types the compilation succeeds and `fun` can safely do its job.

23.13.5 Implementing constrained class members

When defining members of class templates outside of their class interfaces the members' template headers must match the class templates' template headers. This is no different when using concepts.

In the following example the concept `Addable` is used when defining the class template `Data`. The class `Data` declares a member `process`, implemented below the class interface. Like the class of which it is a member its header must also specify `Addable` (cf. section 23.13.1):

```
template <Addable Type>
class Data
{
    void process();
};

template <Addable Tp>       // The concept must be specified,
void Data<Tp>::process()    // but the formal type name
{                           // doesn't have to be `Type'
    ...
}
```

Comparably, if a class template member function can only be used when a constraint has been satisfied (but no additional constraints apply to other class members), the class template's header can use `typename` and the (additional) constraint can be tailored to members where applicable:

```
template <typename Type>    // generic template type parameter
class Data
{
    void process() requires Addable<Type>;  // additional requirement
};

template <typename X>
void Data<X>::process() requires Addable<X>
...
```

Types of member templates themselves may also be constrained. Here too the rule applies that the template headers of member implementations must match those of their declarations:

```
template <typename Type>
class Data
{
    template <Addable Tp>       // constraint applied to
    void process(Tp par);       // a member template
};

template <typename Type>
template <Addable Tp>
void Data<Type>::process(Tp par)
{
    ...
}
```

23.13.5.1 Constrained partial specializations

Class templates can be (partially) specialized. Specializations are commonly used to fine-tune implementations for specific types. Concepts can also be used when specializations are defined. Consider a `struct Handler` having the following generic implementation:

```
template <typename Tp>
struct Handler
{
    Handler()
    {
        std::cout << "Generic Handler\n";
    }
};
```

In addition to possibly type-related specializations (like a `struct Handler<Tp *> ...)` a specialization requiring the availability of the addition operator on `Tp` can be defined by requiring the concept `Addable`:

```
template <Addable Tp>       // constrain Tp to addable types
struct Handler<Tp>
{
    Handler()
    {
        std::cout << "Handler for types supporting operator+\n";
    }
};
```

When used in the following program (assuming all required headers were included), the first line of the output shows *Generic Handler*, while the second line shows *Handler for types supporting operator+*:

```
int main()
{
    Handler<std::vector<int>>{};    // generic
    Handler<int>{};                 // specialized
}
```

The compiler, compiling `main's` first statement, first looks for a specialized version of `Handler`. Although it finds one, that specialization requires the availability of `operator+`. As that operator is not available for `std::vector` the compiler does not use that specialization. Had this been the only available implementation, then the compiler would have reported a `constraints not satisfied` error. However, there's still the generic definition which *can* be used for `std::vector`. Therefore the compiler uses the generic definition (which is at the same time provides a nice illustration of the SFINAE (cf. section 21.15) principle).

When instantiating the second `Handler` object the addition operator *is* available, and so in that case the compiler selects the specialized version: where available, specializations are used; if not, then generic template definitions are used.

23.13.5.2 Function- and class template declarations

Constrained function- or class-templates can be declared as usual: instead of the implementations semicolons are used. When declaring a function- or class-template without constraint specifications then the function or class template is unconstrained and won't match existing constrained overloaded versions of such function or class templates. On the other hand, concepts can*not* be declared. So if a concept definition must be used in multiple source or header files then the concept definition normally is provided in a header file of its own which is then included by files using the concept.

Here are some simple examples illustrating how constrained function templates are declared:

```
    template <typename Type>    // advice: define concepts in
    concept Addable =      // separate headers.
        requires(Type lh, Type rh)
        {
            lh + rh;
        };

    template <typename Type>    // declares an unconstrained
    void fun();                 // function template

    template <Addable Type>  // declares a constrained overloaded
    void fun();                 // function template

    template <typename Type>    // same, requirement follows fun
    void fun() requires Addable<Type>;

    template <typename Type>    // same, requirement precedes fun
    requires Addable<Type> void fun();
```

When declaring class templates their requires-clauses must precede the class names. Also, when unconstrained class templates are available the constrained class templates are in fact specializations and must be declared accordingly:

```
    template <typename Type>    // unconstrained
    struct Data;                // declaration

    template <Addable Type>     // constrained declaration
    struct Data<Type>;          // (i.e., a specialization)

//  template <typename Type>    // same specialization
//  requires Addable<Type> struct Data<Type>;
```

Multiple constraints can also be declared:

```
    template <typename Type>        // used concepts
    concept C1 = true;
    template <typename Type>
    concept C2 = true;

    template <C1 Type>              // multiply constrained
    requires C2<Type> void fun();   //    function template

    template <typename Type>        // same, using 'and'
    requires C1<Type> and C2<Type> void fun();

    template <typename Type>        // same, trailing 'requires'
    void fun() requires C1<Type> and C2<Type>;
    template <typename Type>
    struct Multi;

    template <C1 Type>              // multiply constrained
    requires C2<Type> struct Multi<Type>; // class template
```

Although specializations may define different constraints (e.g., there may also be a concept `Subtractable`), a `Data` specialization for subtractable types might also be defined:

```
template <Subtractable Type>
struct Data<Type>
{};
```

But this is probably not what you want: when defining `Data<vector<int>>{}`, where `template<typename Type> Data` is merely declared, the compiler complains about an *incomplete type 'struct Data<std::vector<int>>'* as it cannot use the specialization for either `Addable` or `Subtractable`. So it falls back on the generic template, but for that one no implementation is available, and hence it's incomplete.

Defining a template requiring two types, the first being `Addable` and the second template argument being unrestricted, while a specialization is defined requiring a `Subtractable` type and an `int`, then that also does'n work as intended. In that case, the templates might be:

```
template <typename t1, typename t2> requires Addable<t1>
struct Data
{};

template <Subtractable Type>
struct Data<Type, int>
{};
```

Here, if the first template argument isn't a subtractable type (like a `vector<int>`), and the second argument *is* an `int` then the compiler simply won't use it because the 1st argument isn't a subtractable type.

Therefore it falls back to the first (generic) template definition. However, that one doesn't work either, because the first argument also isn't addable, and you receive complaints about `(lh + rh)` being ill-formed.

Now, as you specified `int` as the template's second argument chances are that you expected a complaint about `(lh - rh)` being ill formed, but that doesn't happen. In other words: using concepts still requires you to understand what's going on. Concepts help the compiler to pinpoint reasons for compilation failures, but in the end it's you who has to understand what you're doing in order to grasp what the compiler is trying to tell you.

Chapter 24

Coroutines

Consider the following assignment: design a program that offers a function `next` returning the next fibonacci number at subsequent calls.[1]

Here is an example of how such a program could be designed: it defines a class `Fibo` and in `main` `Fibo::next` is called to compute the next fibonacci number (for brevity the program uses a single source file):

```
#include <iostream>
#include <string>

using namespace std;

class Fibo
{
    size_t d_return = 0;
    size_t d_next = 1;

    public:
        size_t next();
};

size_t Fibo::next()
{
    size_t ret = d_return;       // the next fibonacci number

    d_return = d_next;           // at the next call: return d_next;
    d_next += ret;               // prepare d_next as the sum of the
                                 // original d_return and d_next
    return ret;
}

int main(int argc, char **argv)
{
    Fibo fibo;                   // create a Fibo object

    size_t sum = 0;
```

---

[1] Fibonacci numbers start with 0 and 1. The next fibonacci number is the sum of the last two fibonacci numbers. The sequence, therefore, starts with 0, 1, 1, 2, 3, 5, etc. In this and the following examples fibonacci sequences are frequently used for illustration, and not because they are inherently related to coroutines.

```
                                // use its 'next' member to obtain
    for (                       // the sequence of fibonacci numbers
        size_t begin = 0, end = argc == 1 ? 10 : stoul(argv[1]);
            begin != end;
                ++begin
    )
        sum += fibo.next();

    cout << sum << '\n';
}
```

Clearly the `next` member isn't all that complicated. But when it's called several actions are performed which themselves are unrelated to computing fibonacci numbers:

- Calling a function boils down to (ignoring the complications when copying and destroying value type argument objects and value type local objects):
  - pushing its arguments on the stack (note that `next` is a member function, so it *does* have an argument: the address of the object for which `next` is called);
  - pushing the number of bytes required for those arguments on the stack;
  - pushing the location of the next instruction to execute after completing the `next` function call on the stack;
  - pushing the location of the current function's stack frame on the stack;
  - copying the current stack pointer's value to a register (commonly called the *base pointer*), which register is then used to access `next's` arguments and local variables;
  - continuing execution at `next's` first instruction;
  - which first makes room on the stack for all of `next's` local variables.
- once `next's return` statement has been executed:
  - the stack pointer is reset to the value stored in the base pointer, thus removing local variables from the stack;
  - popping the base pointer, thus restoring access to the caller's stack frame;
  - popping the value of the caller's next instruction to execute from the stack;
  - reducing the size of the stack by the value currently at the top of the stack, holding the size of the function's arguments.

These steps, although they look like a lot, in practice don't take that much time, because most of them are performed by very fast register operations, and the computer' architecture is usually highly optimized for these steps.

Nonetheless, in situations where the functions themselves are short and simple (like `Fibo::next`) these steps, requiring stack- and register manipulations, might be considered unwelcome, raising the question whether they may be avoided.

C++ *coroutines* allow us to avoid executing the steps that are required when calling ordinary functions. The upcoming sections cover coroutines in depth, but here is, for starters, the coroutine's equivalent of `Fibo::next`:

```
#include "main.ih"

Fibo fiboCoro()
```

```
 4: {
 5:     size_t returnFibo = 0;
 6:     size_t next = 1;
 7:
 8:     while (true)
 9:     {
10:         size_t ret = returnFibo;
11:
12:         returnFibo = next;
13:         next += ret;
14:
15:         co_yield ret;
16:     }
17: }
```

Already now we can observe some characteristics of the `fiboCoro` coroutine:

- although coroutines *can* be defined as class members, this particular coroutine is not. It's a free function, which therefore doesn't have a (hidden) pointer pointing to the object calling the coroutine;
- more importantly: it defines local variables (especially those in lines 5, 6), which *keep their values* between successive calls. Such local variables are like static variables, but they're not. Each coroutine-call receives its own instances of its local variables;
- Lines 8 thru 16 define a continuous loop where each cycle computes the next fibonacci number;
- Once a fibonacci number is available the coroutine is *suspended* (at line 15) without loosing the just computed values, passing `ret` to the coroutine's caller (the keyword `co_yield` is one of three new keywords which can be used by coroutines; the other two being `co_await` and `co_return`).

While `fiboCoro` lays the foundation for obtaining a sequence of fibonacci numbers, resuming a coroutine doesn't mean calling a function the way the above member `Fibo::next` is called: there are no arguments; there is no preparation of local variables; and there is no stack handling. Instead there's merely a direct jump to the instruction just beyond the coroutine's suspension point. When the coroutine's code encounters the next suspension point (which occurs in `fiboCoro` at it's next cycle, when it again reaches its `co_yield` statement) then the program's execution simply jumps back to the instruction following the instruction that resumed the coroutine.

The `main` function using the coroutine looks very similar to the `main` function using the class `Fibo`:

```
#include "main.ih"

int main(int argc, char **argv)
{
    Fibo fibo = fiboCoro();

    size_t sum = 0;

    for (                          // the sequence of fibonacci numbers
        size_t begin = 0, end = argc == 1 ? 10 : stoul(argv[1]);
            begin != end;
                ++begin
    )
        sum += fibo.next();
15:
16:     cout << sum << '\n';
17: }
```

At line 5 `fiboCoro` is called, returning an (as yet not covered) `fibo` thing. This `fibo` thing is called a *coroutine handler*, and when (in line 14) `fibo.next()` is called, then *that* call resumes `fiboCoro`, which is then again suspended at its `co_yield` statement, returning the next available value through the handler's `next` function.

The core feature of coroutines is thus that they may suspend their execution, while keeping their current state (values of variables, location of the next instruction to be executed, etc.). Normally, once suspended, the coroutine's caller resumes its work beyond the instruction that returned the coroutine's next value, so those two functions (the coroutine and its caller) closely cooperate to complete the implemented algorithm. Co-routines are therefore also known as *cooperating routines*, which should not be confused with *concurrent* (multi-threaded) routines.

How this whole process works, and what its characteristics are, is covered in the upcoming sections.

24.1 Defining a coroutine

When defining coroutines the `<coroutine>` header file must be included.

A function is a coroutine once it uses the keywords `co_yield`, `co_await`, or `co_return`. A coroutines cannot use the `return` keyword, cannot define variadic parameters, and its return type must be an existing type, which defines the *coroutine's handler*.

Although coroutines appear to return objects (as suggested by the `Fibo` return type of the `Fibo fiboCoro()` coroutine defined in the previous section), in fact they do not. Instead coroutines return so-called 'handlers'. Such a handler is `fibo`, defined and used in the previous section's `main` function:

```
int main(int argc, char **argv)
{
    auto fibo = fiboCoro();
    ...
    sum += fibo.next();
    ...
}
```

The class `Fibo` itself defines the characteristics allowing the compiler to generate code storing the coroutine's arguments, its local variables, the location of the next instruction to execute when the coroutine returns or is suspended, and its so-called *promise_type* object on the heap. This only happens once, so when the coroutine is activated (as in `sum += fibo.next()`) the steps which are normally taken when a function is called are avoided, and instead the coroutine is immediately executed, using its already available local variables and arguments. Coroutine's handler classes are sometimes called `Future`, and their nested state classes *must* be known as the handler's `promise_type`. The names *future* and *promise_type* are completely unrelated to the `std::future` (cf. section 20.8) and `std::promise` (cd. section 20.12) types which are used in the context of multi threading. In fact, coroutines themselves are unrelated to multi threading, but are known as *cooperating routines*. Because the coroutines' handler and state classes are unrelated to the `future` and `promise` classes used in the context of multi threading in this chapter the terms *Handler* and `State` are generally used.

It's one thing to define a coroutine, but when using a coroutine its handler-class (the `Fibo` class in the current example) must also be defined. In addition, such a handler-class *must* define a nested class whose name *must* be publicly available as the handler's `promise_type`. The name `promise_type` doesn't very well cover its purpose, and using a more descriptive class name might be preferred. In that case a simple `typedef` specification in the handler class's public section can be used, as shown in the following basic design of the `Fibo` handler-class:

```
#include <coroutine>

class Fibo
{
    class State     // keeps track of the coroutine's state
    {
        ...
    };

    std::coroutine_handle<State> d_handle;

    public:
        typedef State promise_type;

        explicit Fibo(std::coroutine_handle<State> handle);
        ~Fibo();

        size_t next();
};
```

The coroutine's handler class has the following characteristics:

- it has a nested class (here: `State`) keeping track of the couroutine's state;
- it commonly defines a private data member of the type `std::coroutine_handle<State>`, e.g., `std::coroutine_handle<State> d_handle`, whose members are covered below;
- Unless the handling class's nested class is called `promise_type` a typedef must be provided to make the nested class name also known as `promise_type`;
- Other members are optional, although usually there is at least a member returning a value that's available in the coroutine's state, like the member `next` which was used in the example's `main` function:

  ```
  sum += fibo.next();
  ```

  The `next` member's current implementation resumes the coroutine. This doesn't mean that when `next` is called for the first time, that it's the very first activation of the coroutine: the call `auto fibo = fiboCoro()` comes first, and constructing and returning the coroutine's handler (thereby suspending the coroutine at its very first statement) is done automatically. At that point the caller receives the coroutine's handler object, and constructing and returning the handler object isn't visible in the coroutine's code (more about that in the next section). Once suspended at `co_yield` the value that's available in the coroutine's `State` is returned and made available to the coroutine's caller:

  ```
  size_t Fibo::next()
  {
      d_handle.resume();
      return d_handle.promise().value();
  }
  ```

The following members can be called via the Handler's `d_handle` data member:

- `void *address()` returning the address of the handler's `State` object;
- `void destroy()`, returning the `State` object's memory to the operating system. It ends the `State` object's existence. Usually the handler class's destructor calls `d_handle.destroy()`.
- `bool done()`, returning `true` when the coroutine has returned, and `false` if it's currently suspended;
- `coroutine_handle from_address(void *address)` returns a `coroutine_handle` corresponding to the address of a handler's `State` object, which address is passed to the function as its argument. A `nullptr` can also be passed to `from_address`;
- `explicit operator bool()`, returning `true` if `d_handle` is not a null-pointe. It's commonly used in the handler's destructor's `if (d_handle)` phrase. It returns `false` after assigning 0 (or `nullptr`) to `d_handle`. This operator and `static_cast<bool>(d_handle.address())` act identically (note that `d_handle.address()` is still valid after assigning 0 to `d_handle`, in which case it returns 0);
- `State &promise()`, returning a reference to the `Handler's State` class.
- `void resume()` (or `void operator()()`) resumes the execution of a suspended coroutine. Resuming a coroutine is only defined if the coroutine is actually suspended.

The `Handler's State` class keeps track of the coroutine's state. Its basic elements are covered in the next section.

24.1.1 The coroutine's State class (promise_type)

The class `Handler::State` keeps track of the coroutine's state. It must publicly be known as the class `Handler::promise_type`, which can be realized using a public typedef associating a more appropriately named class with '`promise_type`'.

In the current example the class name `State` is used, having the following interface:

```
class State
{
    size_t d_value;

    public:
        Fibo get_return_object();

        std::suspend_always yield_value(size_t value);

        static std::suspend_always initial_suspend();
        static std::suspend_always final_suspend() noexcept;
        static void unhandled_exception();

        static void return_void();

        size_t value() const;
};
```

This `State` class doesn't declare a constructor, so its default constructor is used. It's also possible to declare and define the default constructor. Alternatively, by declaring and defining a constructor that has the same parameters as its coroutine (or parameters that can be initialized by the coroutine's parameters) that constructor is called when the coroutine returns its handling object. E.g., if a coroutine's signature is

```
Handler coro(int value, string const &str);
```

and the `State` class has a constructor

```
Handler::State::State(int value, string const &str);
```

then that constructor is called. `State's` default constructor is called if such a constructor is not available. In addition to calling `State's` constructor a coroutine can also use an *awaiter* to pass arguments to the handler's `State` class. This method is covered in section 24.5.

The data member `d_value` and member function `value()` are specifically used by the class `Fibo`, and other coroutine state classes might declare other members. The remaining members are required, but the members returning `std::suspend_always` could also be declared as members returning `std::suspend_never`.

By returning the (empty) structs `suspend_always` the coroutine's actions are suspended until resumed. In practice `suspend_always` is used, and so the `..._suspend` members can be declared `static`, using these basic implementations:

```
inline std::suspend_always Fibo::State::initial_suspend()
{
    return {};
}
inline std::suspend_always Fibo::State::final_suspend() noexcept
{
    return {};
}
```

Likewise, the `unhandled_exception` member can be declared static when it simply retrows exceptions that may be thrown by the coroutine:

```
inline void Fibo::State::unhandled_exception()
{                // don't forget: #include <future>
    std::rethrow_exception(std::current_exception());
}
```

The (required) member `Fibo::State::get_return_object` returns an object of the coroutine's handling class (so: `Fibo`). The recipe is:

- pass the current object (which is the coroutine's state object) to the member `from_promise` of an anonymous object of the class `std::coroutine_handle<State>`;
- that anonymous object is a *handle* which is passed as argument to the constructor of the coroutine's handler class (i.e., the class `Fibo`);
- this `Fibo` object is then returned by `State::get_return_object`.

Here is `Fibo::State::get_return_object's` implementation:

```
inline Fibo Fibo::State::get_return_object()
{
    return Fibo{ std::coroutine_handle<State>::from_promise(*this) };
}
```

The member `Fibo:State::yield_value` can be overloaded for different argument types. In our `Fibo::State` there's only one `yield_value` member, storing its parameter value in the `State::d_value` data member. It also suspends the coroutine's execution as it returns `std::suspend_always`:

```
inline std::suspend_always Fibo::State::yield_value(size_t value)
{
    d_value = value;
    return {};
}
```

Now that the coroutine's handling class and its `State` subclass have been covered, let's have a closer look at what happens when the `main` function from the introductory section is executed. Here's `main` once again:

```
 1: int main(int argc, char **argv)
 2: {
 3:     auto fibo = fiboCoro();
 4:
 5:     size_t sum = 0;
 6:
 7:     for (                       // the sequence of fibonacci numbers
 8:         size_t begin = 0, end = argc == 1 ? 10 : stoul(argv[1]);
 9:             begin != end;
10:                 ++begin
11:     )
12:         sum += fibo.next();
13:
14:     cout << sum << '\n';
15: }
```

When called with argument '2' the following happens:

- at line 2 the program starts;
- at line 3 it looks as though `fiboCoroutine` is called (see the introduction section 24 for its definition), but before that:
  - `State::get_return_object` is called, returning a `Fibo` object. Note here that `fiboCoroutine` itself nowhere returns a `Fibo` object, even though its definition suggests that it does. The `get_return_object` member *does* call `Fibo's` constructor though, and this `Fibo` object is returned at line 3.
  - immediately after constructing the `Fibo` object the coroutine's execution is suspended (as `Fibo::State::initial_suspend` is automatically called).

  Next, still at line 3, the returned `Fibo` object is assigned to `fibo`. The current implementation uses `auto fibo = ...`, but `Fibo fibo = ...` may also be used. Using `auto` might be attractive if the name of the coroutine handling class's type is rather convoluted;

- `main's` execution continues at line 12 where `fibo.next()` is called;
- `fibo.next()` resumes the coroutine by calling `d_handle.resume()`. As this is the very first time that the coroutine is explicitly called it now starts its execution at the first statement written by the coroutine's author;
- the coroutine continues its execution until it reaches a `co_yield`, `co_await`, or `co_return` keyword. In this case it's `co_yield`, returning the current fibonacci value (`size_t ret`);
- since a `State::yield_value` member whose parameter type matches `ret's` type exists, that member is called, receiving `ret's` value as its argument. As `yield_value` returns `std::suspend_always` the coroutine is again suspended;
- once suspended control is returned to `Fibo::next's` next statement, where
- `Fibo's d_handle` uses its member `promise()` to reach the handler's `State` object, allowing `next` to return `State::value()` (which is the most recently computed fibonacci value, stored in the `State` object when `State::yield_value` was called). `Fibo::next()` returns that value;
- after completing line 12 the `for`-statement continues at line 7, once again reaching line 12.
- at subsequent iterations the coroutine continues beyond the statement where it was suspended (at its `co_yield` statement). So it doesn't continue at the coroutine's first statement but continues its execution by performing the statements of its `while (true)` statement until again reaching its `co_yield` statement, as described above;
- after two iteration the `for`-statement ends, and just before the program ends (at line 15) `Fibo's` destructor is automatically called, returning the memory allocated for the coroutine's data to the common pool.

24.1.1.1 What if 'suspend_never' is used?

What if, instead of returning `std::suspend_always` `State's` members return `std::suspend_never`? In that case the coroutine, once it has started, is is never suspended. If the program computing fibonacci numbers is then called with argument 2, the following happens:

- at line 2 the program starts;
- at line 3 it looks as though `fiboCoroutine` is called, but before that:
  - `State::get_return_object` is called, returning a `Fibo` object at line 3.
  - immediately after constructing the `Fibo` object the coroutine's execution continues, as this time `Fibo::State::initial_suspend` doesn't suspend. The `fibo` object, however, has been constructed since `auto fibo = ...` isn't an assignment but an initialization of the `fibo` object.
- Since the coroutine's execution isn't suspended, it starts to iterate, and so it calls `co_yield`. But although `Fibo::State::yield_value` is called at `co_yield` calls the coroutine isn't suspended, as `yield_value` now returns `suspend_never`.
- So the coroutine continues its loop, assigning the next fibonacci number to `State::d_value` at each subsequent iteration. Since the loop isn't suspended and since there's no other exit from the loop, the program continues until it's terminated by some signal (like ctrl-C).

24.1.2 Simplifying the state class

Since the coroutine handler's state classes can often use the shown minimal implementations for its members, it might be attractive to define those members in a separate base-class, thus simplifying the state class's interface and implementation.

Looking at the `Fibo::State` class, its members `initial_suspend`, `final_suspend` and `unhandled_exception` are good candidates for such a base class. By defining the base class as a class template, receiving the coroutine handler's class name and the handler's state class name as its template type parameters then it can also provide the handler's `get_return_object` member.

Here is how this base class can be defined. It is used by the coroutine handler's state classes developed in this chapter:

```
#include <cstddef>
#include <future>
#include <coroutine>

template <typename Handler, typename State>
struct PromiseBase
{
    Handler get_return_object();

    static std::suspend_always initial_suspend();
    static std::suspend_always final_suspend() noexcept;
    static void unhandled_exception();
    static void return_void();
};


template <typename Handler, typename State>
inline void PromiseBase<Handler, State>::return_void()
{}

template <typename Handler, typename State>
inline std::suspend_always PromiseBase<Handler, State>::initial_suspend()
{
    return {};
}

template <typename Handler, typename State>
inline std::suspend_always PromiseBase<Handler, State>::final_suspend() noexcept
{
    return {};
}

template <typename Handler, typename State>
inline void PromiseBase<Handler, State>::unhandled_exception()
{
    std::rethrow_exception(std::current_exception());
}

template <typename Handler, typename State>
inline Handler PromiseBase<Handler, State>::get_return_object()
{
    return Handler{ std::coroutine_handle<State>::from_promise(
                                                            static_cast<State &>(*this) )
                      };
    }
```

24.2 Embedding coroutines in classes

Coroutines do not have to be free functions (i.e., outside of classes). They can also very well be defined as class members, in which case they have full access to the members of their class.

In this section we develop a class `Floats` that can either write or read binary `float` values to or from files. An object of this class is used in `main`, calling its member `run` to either write or read a binary file[2]:

```
    int main(int argc, char **argv)
    {
        Floats floats(argc, argv);
        floats.run();
    }
```

The program is called with two arguments: `r` for reading, or `w` for writing, and the name of the binary file as its second argument.

The member `Floats:run` uses pointers to members to call either `read` or `write`:

```
    class Reader;
    class Writer;

    class Floats
    {
        enum Action
        {
            READ,
            WRITE,
            ERROR,
        };

        Action d_action;
        std::string d_filename;                     // name of the binary file

        static void (Floats::*s_action[])() const;  // pointers to read and write

        public:
            Floats(int argc, char **argv);
            void run() const;

        private:
            void read() const;
            Reader coRead() const;

            void write() const;
            static Writer coWrite();
```

---

[2] the full program is available in the distribution's `coroutines/demo/readbinary` directory

```
};

inline void Floats::run() const
{
    (this->*s_action[d_action])();
}
```

The member `read` reads the binary file, using the coroutine `coRead`. When `coRead` is called the usual actions are performed: implicitly the coroutine `Reader's State` member `get_return_object` is called to obtain the coroutine's handler, and the coroutine is suspended. Next the handler returned by `get_return_object` is made available as the `read` function's `reader` object:

```
void Floats::read() const
{
    Reader reader = coRead();           // coRead: the coroutine
                                        // reader: the coroutine's handler
    while (auto opt = reader.next())    // retrieve the next value
        cout << opt.value() << ' ';

    cout << '\n';
}
```

Once the `reader` object is available the member `read` enters a `while` loop repeatedly calling `reader.next()`. At this point the following happens:

- the coroutine is resumed, reading the next value from the binary file (if it's available);
- the coroutine suspends itself again, returning the just obtained value (or it indicates that all values have been processed);
- once `next` has returned, the `read` function again continues, either ending its `while`-statement or showing the retrieved `float`.

When resumed for the first time (so when `reader.next()` is called for the first time) the `coRead` coroutine opens the file, and then, in a `while`-statement, determines the next available value. If that succeeds the coroutine is again suspended, using `co_yield` to pass the just read value on to `read`, or (if no value could be obtained) the coroutine ends by calling `co_return`. Here is the `Floats::coRead` coroutine:

```
Reader Floats::coRead() const
{
    ifstream in{ d_filename };

    while (true)
    {
        float value;
        in.read(reinterpret_cast<char *>(&value), sizeof(float));

        if (not in)
            co_return;          // if not: end the coroutine

        co_yield value;
    }
}
```

Since `coRead` doesn’t have to access any of `Float’s` members it can be declared as a `static` member.

Likewise, the member `write` (re)writes the binary file, using the coroutine `coWrite`, following the same procedure as used by `read` to obtain the `writer` coroutine handler:

```
void Floats::write() const
{
    ofstream out{ d_filename };

    Writer writer = coWrite();          // coWrite: the coroutine,
                                        // writer: the coroutine's handler
    cout << "Enter values (one per prompt), enter 'q' to quit\n";

    while (true)
    {
        cout << "? ";
        auto opt = writer.next();       // retrieve the next value
        if (not opt)                    // stop if no more values
            break;
        out.write(&opt.value()[0], sizeof(float));
    }
}
```

The member `Floats::coWrite` behaves like `Floats::coRead`, but writes instead of reads values to the binary file. Here is `coWrite`, defined as a normal (non-static) member, as it uses `Floats::d_filename`:

```
Writer Floats::coWrite()
{
    while (true)
    {
        float value;
        if (not (cin >> value))       // get the next value
            co_return;          // if not: end the coroutine


        Writer::ValueType ret;  // value to return

        ret = Writer::ValueType{ string{
                    reinterpret_cast<char const *>(&value),
                    reinterpret_cast<char const *>(&value + 1) }
                };

        co_yield ret;
    }
}
```

The `Reader` and `Writer` handler classes are covered next.

24.2.1 The ‘Reader’ coroutine handler

The essence of the `Reader` class is that its `State` subclass receives a value from the coroutine (`coRead`) at the coroutine’s `co_yield` statement. `Reader::State` receives the value that’s passed to `co_yield` as argument of its `yield_value` member, which stores the received `float` value in its `std::optional<float> d_value` data member.

The `Reader` class itself must define a constructor receiving a handle to its `State` class , and should define a destructor. Its `next` member simply returns the value that's stored in its `State` class to `next's` caller. Here is `Reader's` complete header file:

```
#include <iostream>
#include <optional>

#include "../../promisebase/promisebase.h"

struct Reader
{
    typedef std::optional<float> ValueType;

    private:
        class State: public PromiseBase<Reader, State>
        {
            ValueType d_value;

            public:
                std::suspend_always yield_value(float value);
                void return_void();
                ValueType const &value() const;
        };

        std::coroutine_handle<State> d_handle;

    public:
        typedef State promise_type;

        explicit Reader(std::coroutine_handle<State> handle);
        ~Reader();

        ValueType const &next();
};
```

`Reader's` and `Reader::State's` members have (except for `Reader::next`) very short implementations which can very well be defined inline:

```
inline std::suspend_always Reader::State::yield_value(float value)
{
    d_value = value;
    return {};
}

inline void Reader::State::return_void()
{
    d_value = ValueType{};
}

inline Reader::ValueType const &Reader::State::value() const
{
    return d_value;
}

inline Reader::Reader(std::coroutine_handle<State> handle)
:
    d_handle(handle)
{}

inline Reader::~Reader()
{
    if (d_handle)
        d_handle.destroy();
}
```

`Reader::next` performs two tasks: it resumes the coroutine, and then, once the coroutine is again suspended (at its `co_yield` statement), it returns the value stored in the `Reader::State` object. It can access its `State` class object via `d_handle.promise()`, returning the value stored in that object:

```
Reader::ValueType const &Reader::next()
{
    d_handle.resume();
    return d_handle.promise().value();
}
```

24.2.2 The 'Writer' coroutine handler

The `Writer` class closely resembles the `Reader` class. It uses a different value type, as it must write `float` values to the output stream using their binary representations, but other than that there aren't that many difference with the `Reader` class. Here is its interface and the implementations of its `yield_value` member that differs from that of the `Reader` class:

```
struct Writer
{
    typedef std::optional<std::string> ValueType;

    private:
        class State: public PromiseBase<Writer, State>
        {
            ValueType d_value;

            public:
                std::suspend_always yield_value(ValueType &value);
                void return_void();
                ValueType const &value() const;
        };

        std::coroutine_handle<State> d_handle;

    public:
        typedef State promise_type;

        explicit Writer(std::coroutine_handle<State> handle);
        ~Writer();
```

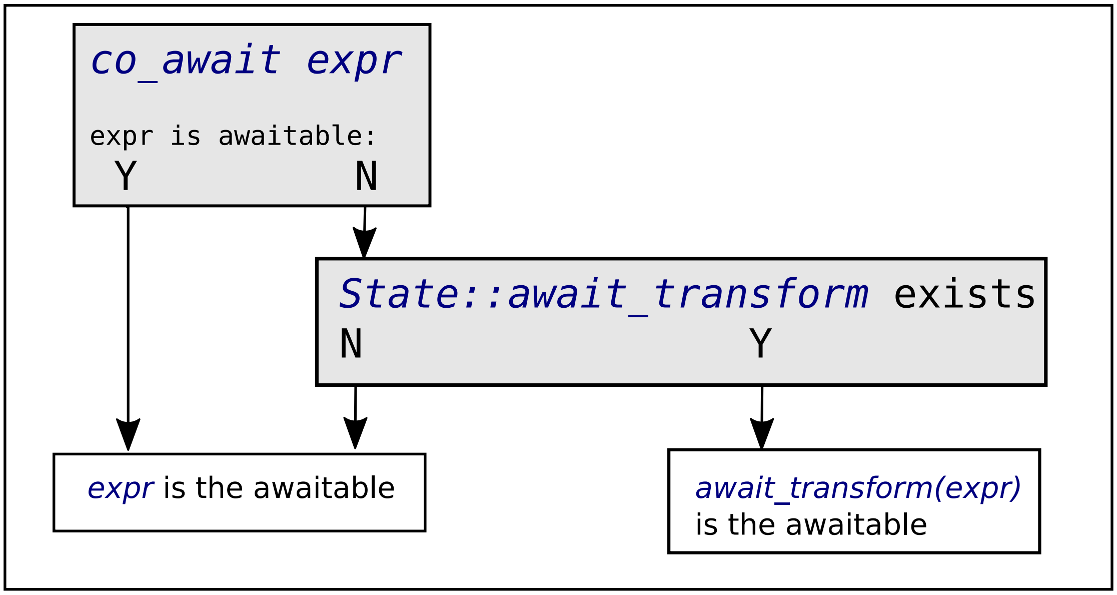

Figure 24.1: co_await

```
        ValueType const &next();
};

inline std::suspend_always Writer::State::yield_value(ValueType &value)
{
    d_value = std::move(value);
    return {};
}
```

24.3 ‘Awaitables’, ‘Awaiters’ and ‘co_await’

So far we’ve encountered `co_yield` and `co_return`. What about `co_await`? The verb *to await* is more formal than *to wait*, but the two verbs mean the same. The added level of formality of *to await* is illustrated by a second description offered by the *Merrian Webster* dictionary: *to remain in abeyance until*, and *abeyance’s* meaning takes us home again: *a state of temporary inactivity* or *suspension*. So when `co_await` is used the coroutine enters a state of temporary inactivity, i.e., it is suspended. In that sense `co_yield` is no different, as it also suspends the coroutine, but different from `co_yield` `co_await` expects a so-called *awaitable* expression. I.e., an expression resulting in an `Awaitable`, or that is convertible to an `Awaitable` object (see also figure 24.1). Figure 24.1 shows that the expression that’s passed to `co_await` may be an `Awaitable` object, or if the coroutine handle’s `State` class has a member `await_transform` accepting an argument of some `expr's` type, the value returned by `await_transform` is the `Awaitable` (cf. figure 24.2). These `await_transform` members may be overloaded, so in any concrete situation several `Awaitable` types could be used.

The `Awaiter` type that’s eventually used is either an object of `co_await's expr's` type, or it is the return type of the (implicitly called when defined) coroutine handler’s `State::await_transform(expr)` member.

Thus, the `Awaitable` object is a *middle-man*, that’s only used to obtain an `Awaiter` object. The `Awaiter` is the real work-horse in the context of `co_await`.

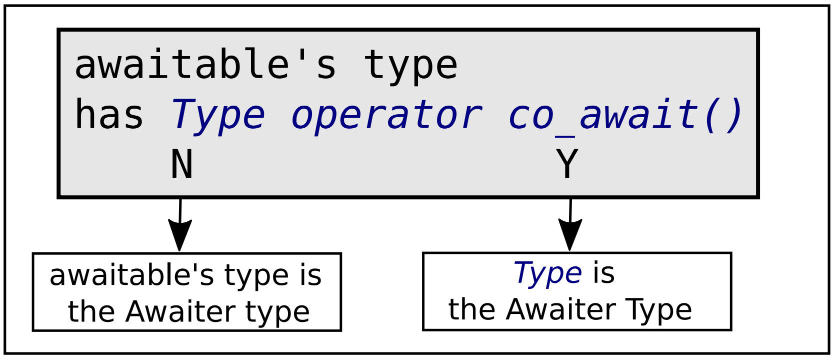
awaitable's type
has Type operator co_await()
N
Y
awaitable's type is the Awaiter type
Type is the Awaiter Type

Figure 24.2: awaitable

`Awaitable` classes may define a member `Awaiter Awaitable::operator co_await()`, which may also be provided as a free function (`Awaiter operator co_await(Awaitable &&)`). If such a `co_await` conversion operator is available then it is used to obtain the `Awaiter` object from the `Awaitable` object. If such a conversion operator is *not* available then the `Awaitable` object *is* the `Awaiter` object.

As an aside: the types `Awaitable` and `Awaiter` are used here as formal class names, and in actual programs the software engineer is free to use other (maybe more descriptive) names.

24.4 The class ‘Awaiter’

Once the `Awaiter` object is available its member `bool await_ready()` is called. If it returns `true` then the coroutine is not suspended, but continues beyond its `co_await` statement (in which case the `Awaitable` object and `Awaiter::await_ready` were apparently able to avoid suspending the coroutine).

If `await_ready` returns `false` `Awaiter::await_suspend(handle)` is called. Its `handle` argument is the handle (e.g., `d_handle`) of the current coroutine's handler object. Note that at this point the coroutine has already been suspended, and the coroutine's handle could even be transferred to another thread (in which case the current thread must of course not be allowed to resume the current coroutine). The member `await_suspend` may return `void, bool,` or some coroutine's handle (optionally its own handle). As illustrated in figure 24.3, when returning `void` or `true` the coroutine is suspended and the coroutine's caller continues its execution beyond the statement that activated the coroutine. If `false` is returned the coroutine is not suspended, and resumes beyond the `co_await` statement. If a coroutine's handle is returned (not a reference return type, but value return type) then the coroutine whose handle is returned is resumed (assuming that another coroutine's handle is returned than the current coroutine is suspended, and the other coroutine (which was suspended up to now) is resumed; in the next section this process is used to implement a finite state automaton using coroutines)

If, following `await_suspend`, the current coroutine is again resumed, then just before that the `Awaiter` object calls `Awaiter::await_resume()`, and `await_resume’s` return value is returned by the `co_await` expression (`await_resume`) frequently defines a `void` return type, as in

```
static void Awaiter::await_resume() const
{}
```

In the next section a finite state automaton is implemented using coroutines. Their handler classes are also `Awaiter` types, with `await_ready` returning `false` and `await_resume` doing nothing.

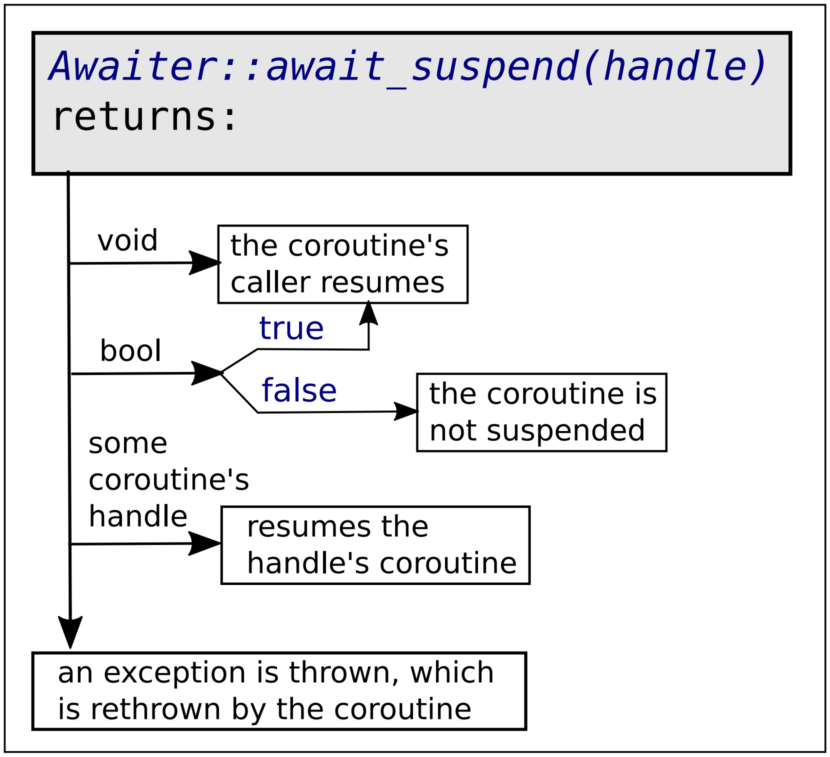
Awaiter::await_suspend(handle)
returns:
void
the coroutine's caller resumes
true
bool
false
the coroutine is not suspended
some coroutine's handle
resumes the handle's coroutine
an exception is thrown, which is rethrown by the coroutine

Figure 24.3: awaiter

Thus their definitions can be provided by a class `Awaiter` acting as base class of the coroutines' handler classes. `Awaiter` only needs a simple header file:

```
struct Awaiter
{
    static bool await_ready();
    static void await_resume();
};

inline bool Awaiter::await_ready()
{
    return false;
}

inline void Awaiter::await_resume()
{}
```

24.5 Accessing State from inside coroutines

As we've seen, when a coroutine starts it constructs and returns an object of its handler class. The handler class contains a subclass whose object keeps track of the coroutine's state. In this chapter that subclass is named `State`, and a `typedef` is used to make it known as `promise_type` which is required by the standard facilities made available for coroutines.

When coroutines are suspended at `co_yield` statements, the yielded values are passed to `State` class's `yield_value` members whose parameter types match the types of the yielded values.

In this section we reverse our point of view, and discuss a method allowing the coroutine to reach facilities of the `State` class. We've already encountered one way to pass information from the coroutine to the `State` class: if the `State` class's constructor defines the same parameters as the coroutine itself then that constructor is used, receiving the coroutine's parameters as arguments.

But let's assume that the coroutine performs a continuous loop containing several, maybe conditional, `co_yield` statements, and we want to inform the `State` class what the current iteration cycle is. In that case a parameter is less suitable, as tracking the cycle number is in fact a job for one of the local variables of the coroutine, which would look something like this:

```
Handler coroutine()
{
    size_t cycleNr = 0;
    // make cycleNr available to tt(Handler's State) class
    while (true)
    {
        ++cycleNr;       // now also known to tt(Handler's State)
        ...              // the coroutine at work, using various co_yield
                         // statements
    }
}
```

Awaiters can also be used in these kinds of situations, setting up communication lines between coroutines and the `State` classes of their `Handler` class objects. As an illustration, the original fibocoro coroutine 24 was slightly modified:

```
 1: Fibo fiboCoroutine()
 2: {
 3:     size_t returnFibo = 0;
 4:     size_t next = 1;
 5:     size_t cycle = 0;
 6:
 7:     co_await Awaiter{ cycle };
 8:     cerr << "Loop starts\n";
 9:
10:     while (true)
11:     {
12:         ++cycle;
13:
14:         size_t ret = returnFibo;
15:
16:         returnFibo = next;
17:         next += ret;
18:
19:         co_yield ret;
20:     }
21: }
```

- At line 5 `size_t cycle` is defined, keeping track of the coroutine's iteration cycle;
- Line 7 contains a `co_await` statemenent, passing `co_await` an object that receives the `cycle`, which is the variable the `Handler's State` should know about;
- At line 12 `cycle` is incremented, so it contains the current iteration cycle.

The `Awaiter` object, since there's no `State::await_transform` member, is an awaitable. Neither does `Awaiter` have a `Type operator co_await()`, so the anonymous `Awaiter` object is indeed an Awaiter.

Being the Awaiter, it defines three members: `await_ready`, merely returning `false`, as the coroutine's execution must be suspended at the `co_await` statement; `await_suspend(handle)`, receiving a handle to the coroutine's `Handler's State` object; and `await_resume`, which doesn't have to do anything at all:

```
class Awaiter
{
    size_t const &d_cycle;

    public:
        Awaiter(size_t const &cycle);

        bool await_suspend(Fibo::Handle handle) const;

        static bool await_ready();
        static void await_resume();
};

inline Awaiter::Awaiter(size_t const &cycle)
:
    d_cycle(cycle)
{}

inline bool Awaiter::await_ready()
{
    return false;
}

inline void Awaiter::await_resume()
{}
```

The member `await_suspend` uses the received handle to access the `State` object, passing `cycle` to `State::setCycle`:

```
bool Awaiter::await_suspend(Fibo::Handle handle) const
{
    handle.promise().setCycle(d_cycle);
    return false;
}
```

In the next section (24.6) we use `await_suspend` to switch from one coroutine to another, but that's not required here. So the member returns `false`, and thus continues its execution once it has passed `cycle` to `State::setCycle`. This way coroutines can pass information to the `Handler's State` object, which could define a data member `size_t const *d_cycle` and a member `setCycle`, using `d_cycle` in, e.g., `yield_value`:

```
inline void Fibo::State::setCycle(size_t const &cycle)
{
    d_cycle = &cycle;
}
```

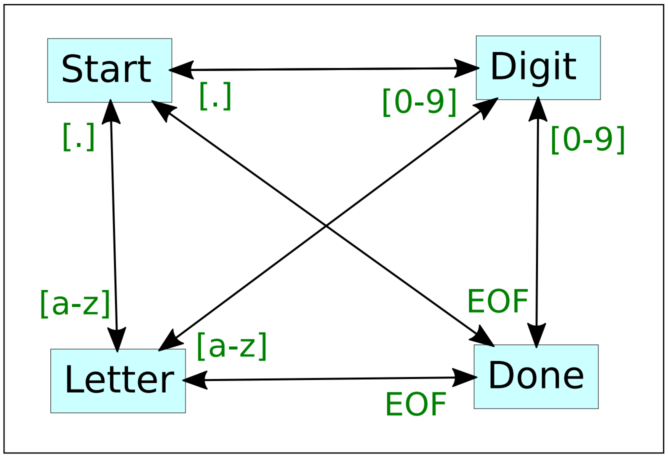

Figure 24.4: Finite State Automaton

```
std::suspend_always Fibo::State::yield_value(size_t value)
{
    std::cerr << "Got " << value << " at cycle " << *d_cycle << '\n';
    d_value = value;
    return {};
}
```

24.6 Finite State Automatons via coroutines

Finite state automatons (FSAs) are usually implemented via *state x input* matrices. For example, when using `Flexc++` to recognize letters, digits or other characters it defines three input categories, and 4 states (the first state being the INITIAL state determining the next state based on the character read from the scanner's input stream, the other three being the states that handle characters from their specific categories).

FSAs can also be implemented using coroutines. When using coroutines each coroutine handles a specific input category, and determines the category to use next, given the current input category. Figure 24.4 shows a simple FSA: at `Start` a digit takes us to `Digit`, a letter to `Letter`, at any other character we remain in `Start`, and at end of file (EOF) we end the FSA at state `Done`. `Digit` and `Letter` act analogously.

This FSA uses four coroutines: `coStart, coDigit, coLetter`, and `coDone`, each returning their own handlers (like a `Start` handler returned by `coStart`, a `Digit` handler by `coDigit`, etc.). Here is `coStart`:

```
Start coStart()
{
    char ch;
    while (cin.get(ch))
    {
        if (isalpha(ch))
        {
            cout << "at `" << ch << "' from start to letter\n";
            co_await g_letter;
        }
        else if (isdigit(ch))
12:         {
13:             cout << "at `" << ch << "' from start to digit\n";
14:             co_await g_digit;
15:         }
16:         else
17:             cout << "at char #" << static_cast<int>(ch) <<
18:                     ": remain in start\n";
19:     }
20:     co_await g_done;
21: }
```

The flow of this coroutine is probably self-explanatory, but note the `co_await` statements at lines 9, 14, and 20: at these lines the `co_awaits` realize the switch from the current coroutine to another. How that's realized is soon described.

The coroutines `coDigit` and `coLetter` perform similar actions, but `coDone`, called at EOF, simply returns, thus ending the coroutine-based processing of the input stream. Here's `coDone`, simply using `co_return` to end its lifetime:

```
Done coDone()
{
    cout << "at EOF: done\n";
    co_return;
}
```

Now take a look at this short input file to be processed by the program:

```
a
1
a1
1a
```

when processing this input the program shows its state changes:

```
at `a' from start to letter
at char #10: from letter to start
at `1' from start to digit
at char #10: from digit to start
at `a' from start to letter
at `1' from letter to digit
at char #10: from digit to start
at `1' from start to digit
at `a' from digit to letter
at char #10: from letter to start
at EOF: done
```

Since coroutines are normally suspended once activated, the `Start` handler privides a member `go` starting the FSA by resuming its coroutine:

```
void  Start::go()
{
    d_handle.resume();      // maybe protect using 'if (d_handle)'
}
```

The `main` function merely activates the `Start` coroutine, but the coroutines might of course also be embedded in something like a `class FSA`, and `main` might offer an option to process a file argument instead of using redirection. Here's `main`:

```
int main()
{
    g_start.go();
}
```

24.6.1 The 'Start' handler class

As illustrated, there are various ways to obtain an Awaiter from a `co_await expr` statement. The shortest route goes like this:

- According to figure 24.1 `expr` is an awaitable if the *current* coroutine's `State` class does *not* have an `await_transform` member. In that case `expr` is the awaitable;
- According to figure 24.2 if `expr's` type does *not* have an `operator co_await` member then `expr's` type is the `Awaiter`.

So, the nested `Start::State` class only has to provide the standard members of the coroutine handler's `State` class. As those are all provided by the generic `PromiseBase` class (section 24.1.2) `State` needs no additional members:

```
            // nested under the Start handler class:
struct State: public PromiseBase<Start, State>
{};
```

Similar considerations apply to the other three handler classes: their `State` classes are also derived from `PromiseBase<Handler, State>`. However, as the `coDone` coroutine also uses `co_return`, the `Done::State` state class must have its own a `return_void` member:

```
            // nested under the Done handler class:
struct State: public PromiseBase<Done, State>
{
    void return_void() const;
};
            // implementation in done.h:
inline void Done::State::return_void() const
{}
```

As our FSA allows transitions from `Digit` and `Letter` back to `Start` the `Start` handler class itself is an Awaiter (as are `Digit, Letter,` and `Done`). Section 24.4 described the requirements and basic definition of Awaiter classes.

From the point of view of FSAs the most interesting part is how to switch from one coroutine to another. As illustrated in figure 24.3 this requires a member `await_suspend` which *receives* the handle of the coroutine using the `co_await` statement, and returns *some coroutine's* handle. So:

- `co_await expr` is used, where `expr` is a coroutine's handler, which is also an Awaiter;
- the current coroutine passes its own handle to `expr's await_suspend` member;

- the handle returned by `expr's await_suspend` member determines which coroutine is resumed, suspending the coroutine using `co_await`;
- `expr` returns its own handle, thereby realizing the FSA's state switch from the current coroutine to `expr's` coroutine.

Here is the interface of `coStart's` handler class as well as the definition of its `await_suspend` member. Since the `coStart` coroutine may be resumed by several other coroutines it is unknown which coroutine's handle was passed to `Start::await_suspend`, and so `await_suspend` is a member template, which simply returns `Start's` handle.

```
class Start: public Awaiter
{
    struct State: public PromiseBase<Start, State>
    {};

    std::coroutine_handle<State> d_handle;

    public:
        typedef State promise_type;
        typedef std::coroutine_handle<State> Handle;

        explicit Start(Handle handle);
        ~Start();

        void go();

                // this and the  members in Awaiter are required for Awaiters
        template <typename HandleType>
        std::coroutine_handle<State> await_suspend(HandleType &handle);
};

template <typename HandleType>
inline std::coroutine_handle<Start::State>
                                  Start::await_suspend(HandleType &handle)
{
    return d_handle;
}
```

As the member `Start's wait_suspend` returns `Start's d_handle`, the coroutine containing the `co_await g_start` statement is suspended, and the `co_start` coroutine is resumed (see also figure 24.3).

The implementations of the `Start` handler's constructor and destructor are straightforward: the constructor stores the coroutine's handle in its `d_handle` data member, the destructor uses the (language provided) member `destroy` to properly end the `Start::State's` coroutine handle. Here are their implementations:

```
Start::Start(Handle handle)
:
    d_handle(handle)
{}

Start::~Start()
{
        if (d_handle)
            d_handle.destroy();
    }
```

24.6.2 Completing the Finite State Automaton

The `Digit` and `Letter` coroutines handler classes are implemented like `Start`. Like `coStart`, which continues its execution when a non-digit and non-letter character is received, `coDigit` continues for as long as digit characters are received, and `coLetter` continues for as long as letter characters are received.

As we've seen in section 24.6 the implementation of `coDone` is a bit different: it doesn't have to do anything, and the `coDone` coroutine simply ends at its `co_return` statement. Coroutine execution (as well as the FSA program) then ends following `main's g_start.go()` call.

The complete implementation of the coroutine-based FSA program is available in the Annotation's distribution under the directory `yo/coroutines/demo/fsa`.

24.7 Recursive coroutines

Like ordinary functions coroutines can recursively be called. An essential characteristic of coroutines is that when they're used they look no different than ordinary functions. It's merely in the implementation that coroutines differ from ordinary functions.

For starters, consider a very simple interactive program that produces a series of numbers until the user ends the program or enters `q`:

```
 1: int main()
 2: {
 3:     Recursive rec = recursiveCoro(true);
 4:
 5:     while (true)
 6:     {
 7:         cout << rec.next() << "\n"
 8:                 "? ";
 9:
10:         string line;
11:         if (not getline(cin, line) or line == "q")
12:             break;
13:     }
14: }
```

At line 3 the `recursiveCoro` coroutine is called, returning its handler `rec`. In line 7 its member `next` is called, returning the next value produced by `recursiveCoro`. The function `recursiveCoro` could have been any function returning an object of a class that has a `next` member. For now ignoring recursion, `recursiveCoro` could look like this:

```
 1: namespace
 2: {
 3:     size_t s_value = 0;
 4: }
 5:
```

```
 6: Recursive recursiveCoro(bool recurse)
 7: {
 8:     while (true)
 9:     {
10:         for (size_t idx = 0; idx != 2; ++idx)
11:             co_yield ++s_value;
12: 
13:         // here recursiveCoro will recursively be called
14: 
15:         for (size_t idx = 0; idx != 2; ++idx)
16:             co_yield ++s_value;
17:     }
18: }
```

The coroutine merely produces the sequence of non-negative integral numbers, starting at 0. Its two for-loops (lines 10 and 15) are there merely for illustrative purposes, and the recursive call will be placed between those for-loops. The variable `s_value` is defined outside the coroutine (instead of using `static s_value = 0` inside), as recursively called coroutines must all access the same `s_value` variable. There's no magic here: just two for-statements in a continuously iterating while-statement.

The interface of the returned `Recursive` object isn't complex either:

```
class Recursive
{
    class State: public PromiseBase<Recursive, State>
    {
        size_t d_value;

        public:
            std::suspend_always yield_value(size_t value);
            size_t value() const;
    };

    private:
        typedef std::coroutine_handle<State> Handle;
        Handle d_handle;

    public:
        typedef State promise_type;

        explicit Recursive(Handle handle);
        ~Recursive();

        size_t next();
        bool done() const;
};
```

The required members of its `State` class are available in `PromiseBase` (cf. section 24.1.2) and do not have to be modified. As `recursiveCoro co_yields` values, the `State::yield_value` member stores those values in its `d_value` data member:

```
std::suspend_always Recursive::State::yield_value(size_t value)
{
    d_value = value;
```

```
        return {};
    }
```

Its member `value` is an accessor, returning `d_value`. When recursion is used the recursive calls end at some point. When `recursiveCoro` functions end `State::return_void` is called. It doesn't have to do anything, so `PromiseBase's` empty implementation perfectly does the job.

The `Recursive` handling class's own interface starts at line 12. Its `d_handle` data member (line 14) is initialized by its constructor (line 19), which is all the constructor has to do. The handler's destructor only has to call `d_handle.destroy()` to return the memory used by its `State` object.

The remaining members are `next` and `done`. These, too, are implemented straight-forwardly. The member `done` will shortly be used in the recursive implementation of `recursiveCoro`, and it just returns the value returned by `d_handle.done()`.

When the member `next` is called the coroutine is in its suspended state (which is what happens when it's initially called (cf. line 3 in the above `main` function) and thereafter when it uses `co_yield` (lines 11 and 16 in the above implementation of `recursiveCoro`)). So it resumes the coroutine, and when the coroutine is again suspended, it returns the (next available) value stored in the handler's `State` object:

```
    size_t Recursive::next()
    {
        d_handle.resume();
        return d_handle.promise().value();
    }
```

24.7.1 Recursively calling recursiveCoro

Now we change the non-recursive `recursiveCoro` coroutine into a recursively called coroutine. To activate recursion `recursiveCoro` is modified by adding some extra statements below line 8:

```
 1: Recursive recursiveCoro(bool recurse)
 2: {
 3:     while (true)
 4:     {
 5:         for (size_t idx = 0; idx != 2; ++idx)
 6:             co_yield ++s_value;
 7:
 8:         // here recursiveCoro will recursively be called
 9:
10:         if (not recurse)
11:             break;
12:
13:         Recursive rec = recursiveCoro(false);
14:
15:         while (true)
16:         {
17:             size_t value = rec.next();
18:             if (rec.done())
19:                 break;
20:
21:             co_yield value;
22:         }
23:
24:         for (size_t idx = 0; idx != 2; ++idx)
25:             co_yield ++s_value;
26:     }
27: }
```

Recursion is activated when the parameter `recurse` is `true`, which is passed to `recursiveCoro` when initially called by `main`. It is then recursively called in line 13, now using `false` as its argument. Consider what happens when it's recursively called: the while-loop is entered and the for-statement at line 5 is executed, 'co_yielding' two values. Next, in line 10, the loop ends, terminating the recursion. This implicitly calls `co_return`. It's also possible to do that explicitly, using

```
if (not recurse)
    co_return;
```

Going back to the initial call: once `rec` (line 13) is available, a nested while-loop is entered (line 15), receiving the next value obtained by the recursive call (line 17). That `next` call resumes the nested coroutine, which, as just described, returns two values when executing line 5's for-statement. But then, when it's resumed for the third time, it doesn't actually `co_yield` a newly computed value, but calls `co_return` (because of lines 10 and 11), thus *ending* the recursive call. At that point the coroutine's `State` class's member `done` returns `true`, which value is available through `ret.done()` (line 18). Once that happens the while loop at line 15 ends, and the non-recursive coroutine continues at line 24. If the recursively called coroutine *does* compute a value, `rec.done()` returns `false`, and `value` produced by `rec` is 'co_yielded' by the non-recursively called coroutine, making it available to `main`. So in that latter case the value co_yielded by the recursively called coroutine is co_yielded by the initially called coroutine, where it is retrieved by `main`: there's a sequence of `co_yield` statements from the most deeply nested coroutine to the coroutine that's called by `main`, at which point the value is finally collected in `main`.

The `next..done` implementation used here resembles the way streams are read: first try to extract information from a stream. If that succeeds, use the value; if not, do something else:

```
while (true)
{
    cin >> value;
    if (not cin)
        break;
    process(value);
}
```

Functions like `getline` and overloaded extraction operators may combine the extraction and the test. That's of course also possible when using coroutines. Defining `next` as

```
bool Recursive::next(size_t *value)
{
    d_handle.resume();
    if (d_handle.done())        // no more values
        return false;
    *value = d_handle.promise().value();
    return true;
}
```

allows us to change the while loop at line 15 into:

```
size_t value;
```

```
    while (rec.next(&value))
        co_yield value;
```

24.7.2 Beyond a single recursive call

In the introductory section the `fiboCoro` coroutine was presented. In this section the `fiboCoro` coroutine is going to be used by the `recursiveCoro` coroutine, using multiple levels of recursion.

To concentrate on the recursion process the `fiboCoroutine's` handler is defined in `main` as a global object, so it can directly be used by every recursive call of `recursiveCoro`. Here is the `main` function, using `bool Recursive::next(size_t *value)`, and it also defines the global object `g_fibo`:

```
Fibo g_fibo = fiboCoro();

int main()
{
    Recursive rec = recursiveCoro(0);

    size_t value;
    while (rec.next(&value))
    {
        cout << value << "\n"
                "? ";

        string line;
        if (not getline(cin, line) or line == "q")
            break;
    }
}
```

The `Recursive` class interface is identical to the one developed in the previous section, except for the `Recursive::done` member (which is not used anymore and was therefore removed from the interface), and changing `next` member's signature as shown. It's implementation was altered accordingly:

```
bool Recursive::next(size_t *value)
{
    d_handle.resume();

    if (d_handle.done())
        return false;

    *value = d_handle.promise().value();
    return true;
}
```

In fact, the only thing that has to be modified to process deeper recursion levels is the `recursiveCoro` coroutine itself. Here is its modified version:

```
Recursive recursiveCoro(size_t level)
{
    while (true)
```

```
 4:     {
 5:         for (size_t idx = 0; idx != 2; ++idx)
 6:             co_yield g_fibo.next();
 7:
 8:         if (level < 5)
 9:         {
10:             Recursive rec = recursiveCoro(level + 1);
11:             size_t value;
12:             while (rec.next(&value))
13:                 co_yield value;
14:         }
15:
16:         for (size_t idx = 0; idx != 2; ++idx)
17:             co_yield g_fibo.next();
18:
19:         if (level > 0)
20:             break;
21:     }
22: }
```

This implementation strongly resembles the 1-level recursive coroutine. Now multiple levels of recursion are allowed, and the maximum recursion level is set at 5. The coroutine knows its own recursion level via its `size_t level` parameter, and it recurses as long as `level` is less than 5 (line 8). At each level two series of two fibonacci values are computed (in the for-statements at lines 5 and 16). After the second for-statement the coroutine ends unless it's the coroutine that's called from `main`, in which case `level` is 0. The decision to end (recursively called) coroutines is made in line 19.

In this implementation the maximum recursion level is set to a fixed value. It's of course also possible that the coroutine itself decides that further recursion is pointless. Consider the situation where directory entries are examined, and where subdirectories are handled recursively. The recursive directory visiting coroutine might then have an implementation like this:

```
 1: Recursive recursiveCoro(string const &directory)
 2: {
 3:     chdir(directory.c_str());                       // change to the directory
 4:
 5:     while ((entry = nextEntry()))                   // visit all its entries
 6:     {
 7:         string const &name = entry.name();
 8:         co_yield name;                              // yield the entry's name
 9:
10:         if (entry.type() == DIRECTORY)              // a directory?
11:         {
12:             string path = pathName(directory, name);  // get the full path
13:             co_yield path;                            // yield the full path
14:
15:             auto rec = recursiveCoro(path);         // visit the entries of
16:             string next;                            // the subdir (and of its
17:             while (rec.next(&next))                 // subdirs)
18:                 co_yield next;                      // and yield them
19:         }
20:     }
21: }
```

In this variant the (not implemented here) function `nextEntry` (line 5) produces all directory entries in sequence, and if an entry represents a directory (line 10), the same process is performed recursively (line 15), yielding its entries to the current coroutine's caller (line 18).

24.8 Coroutine iterators

The previous examples predominantly used while-statements to obtain the values returned by coroutines, many generic algorithms (as well as range-based for-loops) depend on the availability of `begin` and `end` members returning iterators.

Coroutines (or actually, their handling classes) may also define `begin` and `end` members returning iterators. In practice those iterators are input iterators (cf. section 18.2), providing access to the values co_yielded by their coroutines. Section 22.14 specifies their requirements. For plain types (like `size_t` which is co_yielded by `Fibo::next`) iterators should provide the following members:

- a prefix increment operator (`Iterator &operator++()`);
- a dereference operator (`Type &operator*()`);
- comparison operators (`bool operator==(Iterator const &other)`) (and maybe `operator!=` returning its complement).

The `Iterator` class is a value class. However, except for copy- and move-constructions, `Iterator` objects can only be constructed by `Recursive's begin` and `end` members. It has a private constructor and declares `Recursive` as its friend:

```
class Iterator
{
    friend bool operator==(Iterator const &lhs, Iterator const &rhs);
    friend class Recursive;

    Handle d_handle;

    public:
        Iterator &operator++();
        size_t operator*() const;

    private:
        Iterator(Handle handle);
};
```

`Iterator's` constructor receives `Recursive::d_handle`, so it can use its own `d_handle` to control `recursiveCoro's` behavior:

```
Recursive::Iterator::Iterator(Handle handle)
:
    d_handle(handle)
{}
```

The member `Recursive::begin` ensures that `Iterator::operator*` can immediately provide the next available value by resuming the coroutine. If that succeeds it passes `d_handle` to `Iterator's` constructor. If there are no values it returns 0, which is the `Iterator` that's also returned by `Recursive::end`:

```
Recursive::Iterator Recursive::begin()
```

```
{
    if (d_handle.promise().level() == 0)
        g_fibo.reset();

    d_handle.resume();
    return Iterator{ d_handle.done() ? 0 : d_handle };
}

Recursive::Iterator Recursive::end()
{
    return Iterator{ 0 };
}
```

The dereference operator simply calls and returns the value returned by `State::value()` and the prefix increment operator resumes the coroutine. If no value was produced it assigns 0 to its `d_handle`, resulting in `true` when compared to the iterator returned by `Recursive::end`:

```
size_t Recursive::Iterator::operator*() const
{
    return d_handle.promise().value();
}

Recursive::Iterator &Recursive::Iterator::operator++()
{
    d_handle.resume();

    if (d_handle.done())
        d_handle = 0;

    return *this;
}
```

24.9 Visiting directories using coroutines

Because coroutines are usually suspended once they have produced some intermediate but useful result they offer an alternative to stack-based approaches in which recursion is often used.

This section covers a coroutine that visits all elements of (nested) directories, listing all their pathnames relative to the original starting directory. First a more traditional approach is covered, using a class having a member that recursively visits directory elements. Thereafter a coroutine is described performing the same job. Finally, some statistics about execution times of both approaches are discussed.

24.9.1 The ‘Dir’ class showing directory entries

Here a class `Dir` is developed (recursively) showing all entries in and below a specified directory. The program defines a class `Dir`, used by `main`:

```
int main(int argc, char **argv)
{
    Dir dir{ argc == 1 ? "." : argv[1] };
```

```
        while (char const *entryPath = dir.entry())
            cout << entryPath << '\n';
    }
```

The class `Dir`, like the coroutine based implementation in the next section, uses the `'dirent'` **C** struct. As we prefer typenames starting with capitals, `Dir` contains a simple `typedef dirent DirEntry` so **C**'s typename doesn't have to be used.

`Dir` defines just a few data members: `d_dirPtr` stores the pointer returned by **C**'s function `opendir`; `d_recursive` points to a `Dir` entry that's used to handle a sub-directory of the current directory; `d_entry` is the name of the directory returned by `Dir::entry` member, which is refreshed at each call; `d_path` stores the name of the directory visited by a `Dir` object; and `d_entryPath` is `d_entry's` path name, starting at the initial directory name. Here is `Dir's` class interface:

```
    class Dir
    {
        typedef dirent DirEntry;

        DIR *d_dirPtr = 0;
        Dir *d_recursive = 0;

        char const *d_entry;         // returned by entry()
        std::string d_path;          // Dir's directory name, ending in '/'
        std::string d_entryPath;

        public:
            Dir(char const *dir);    // dir: the name of the directory to visit
            ~Dir();

            char const *entry();
    };
```

`Dir's` constructor prepares its object for inspection of the entries of the directory whose name is received as its argument: it calls `opendir` for that directory, and prepares its `d_path` data member:

```
    Dir::Dir(char const *dir)
    :
        d_dirPtr(opendir(dir)),              // prepare the entries
        d_path( dir )
    {
        if (d_path.back() != '/')            // ensure that dirs end in '/'
            d_path += '/';
    }
```

Once a `Dir` object's lifetime ends its destructor simply calls `closedir` to return the memory allocated by `opendir`:

```
    inline Dir::~Dir()
    {
        closedir(d_dirPtr);
    }
```

The member `entry` performs two tasks: first, if a recursion is active then *if* a recursive entry is available, that entry is returned. Otherwise, if no recursive entry is available `d_recursive's` memory is deleted, and `d_recursive` is set to 0:

```
        // first part
    if (d_recursive)                                    // recursion active
    {
        if (char const *entry = d_recursive->entry())   // next entry
            return entry;                               // return it

        delete d_recursive;                             // delete the object
        d_recursive = 0;                                // end the recursion
    }
```

The second part is executed if there's no recursion or once all the recursive entries have been obtained. In that case all entries of the current directory are retrieved, skipping the two mere-dot entries. If the thus obtained entry is the name of a directory then `d_recursive` stores the address of a newly allocated `Dir` object (which is then handled at `Dir::entry's` next call) and the just received entry name is returned:

```
        // second part
    while (DirEntry const *dirEntry = readdir(d_dirPtr))// visit all entries
    {
        char const *name = dirEntry->d_name;            // get the name

        if (name == "."s or name == ".."s)              // ignore dot-names
            continue;

        name = (d_entryPath = d_path + name).c_str();   // entry-name
                                                        // (as path)

        if (dirEntry->d_type == DT_DIR)                 // a subdir?
            d_recursive = new Dir{ name };              // handle it next

        return name;                                    // return the entry
    }
```

The member `Dir::entry` itself consists of these two parts, returning zero (no more entries) once the second part's while-loop ends:

```
    char const *Dir::entry()
    {
        // first part here

        // second part here

        return 0;
    }
```

Thus, the `class Dir` essentially requires one single member function, using recursion to visit all directory entries that exist in or below the specified starting directory. All sources of this program are available in the distribution's `yo/coroutines/demo/dir` directory.

24.9.2 Visiting directories using coroutines

In this section a coroutine-based implementation of a program recursively showing all directory entries is discussed. The program was based on facilities offered by Lewis Baker's `cppcoro library`[3].

---

[3] https://github.com/lewissbaker/cppcoro

The source files of this program are available in the distribution's `yo/coroutines/demo/corodir` directory. It uses the same `DirEntry` type definition as used in the previous section, and defines `typedef std::pair<DirEntry, char const *> Pair` to access a `DirEntry` and its path name.

The program's `main` function strongly resembles the `main` function using the class `Dir`, but this time `main` uses the `visitAllEntries` coroutine:

```
int main(int argc, char **argv)
{
    char const *path = argc == 1 ? "." : argv[1];

    for (auto [entry, entryPath ]: visitAllEntries(path))
        cout << entryPath << '\n';
}
```

The `main` function uses a range-based for-loop to show the entries produced by the `visitAllEntries` coroutine, which are the files and directories that are (recursively) found in a specified starting directory.

Three coroutines are used to process directories. The `visitAllEntries` coroutine returns a `RecursiveGenerator<Pair>` as its handler. Like `main`, the `visitAllEntries` coroutine also uses a range-based for-loop (line 3) to retrieve directory entries. The coroutine yields `Pair` objects (line 5) or the results from nested directories (line 9). Its handler (a `RecursiveGenerator`) is a class template, defined in Lewis Baker's `cppcoro` library:

```
 1: RecursiveGenerator<Pair> visitAllEntries(char const *path)
 2: {
 3:     for (auto &entry_pair: dirPathEntries(path))
 4:     {
 5:         co_yield entry_pair;
 6:
 7:         auto [entry, entry_path] = entry_pair;
 8:         if (entry.d_type == DT_DIR)
 9:             co_yield visitAllEntries(entry_path);
10:     }
11: }
```

Directory entries are made available by a second coroutine, `dirPathEntries`. At each entry `visitAllEntries` is suspended (line 5), allowing `main` to show its full path. At lines 7 and 8 the types of the entries are inspected. If the received entry refers to a sub-directory then `visitAllEntries` yields, recursively calling itself, and thus yielding the sub-directory's entries. Once all entries have been processed the range-based for-loop ends, and the coroutine ends by automatically calling `co_return`.

The coroutine yielding directory entries is `dirPathEntries`, whose handler is an object of another `cppcoro` class, `Generator<Pair>`:

```
Generator<Pair> dirPathEntries(char const *path)
{
    for (auto const &entry: dirEntries(path))
        co_yield make_pair(entry,
                     (string{path} + '/' + entry.d_name).c_str());
}
```

The `dirPathEntries` coroutine performs a cosmetic task: it receives the path name of a directory, and calls a third coroutine (`dirEntries`) to retrieve the successive elements of that directory (line 3). As long as there are entries the coroutine is suspended, yielding `Pair` objects consisting of the values returned by `dirEntry` and the full path names of those entries (lines 4 and 5). Eventually, as with `visitAllEntries, co_return` ends the coroutine.

The third coroutine is `dirEntries`, returning a `Generator<DirEntry` handler:

```
 1: Generator<DirEntry> dirEntries(char const *path)
 2: {
 3:     DIR *dirPtr = opendir(path);
 4:
 5:     while (auto entry = readdir(dirPtr))
 6:     {
 7:         if (accept(*entry))
 8:             co_yield *entry;
 9:     }
10:     closedir(dirPtr);
11: }
```

This coroutine, like the `Dir` class from the previous section, uses **C**'s `opendir, readdir`, and `closedir` triplet of functions. As coroutines resume their actions beyond their suspension points these functions can now all be used in a single coroutine. When `dirEntries` starts, it calls `opendir` (line 3). Then, as long as there are entries (line 5) and those entries are neither the current nor the parent directory (line 7, checked by `accept`, not listed here), the coroutine is suspended, yielding the obtained entry (line 8). Its while-loop ends once all entries have been retrieved. At that point `closedir` is called (line 10), and the coroutine ends.

24.9.3 Functions vs. coroutines

Coroutines might be considered severe competitors of ordinary functions. After all, there's no repeated stack handling required between successive activations: `co_yields` simply suspend coroutines, leaving all their data, ready to be (re)used, in the heap.

In many situations coroutines are considered more attractive at an intuitive level: already in the introductory section of this chapter they were characterized as *cooperating routines*, where the coroutine cooperates with its caller, producing the caller's requested information as if the coroutine is part of the caller's code. But although it formally isn't it *can* conceptually be considered part of the caller's code, as it doesn't have to be called again and again during the caller's lifetime: once activated the coroutine remains available in memory and doesn't have to be called again when it's resumed. Coroutines are *cooperating* in that sense: they can in fact be considered part of the caller's code. In this way they really differ from independent functions which, when called repeatedly, are called again and again 'from scratch', implying intensive stack operations.

On the other hand, using coroutines is way more complex than using 'traditional' functions. The source files of the discussed `Dir` class required some 100 lines of source code, whereas the coroutine based implementation needed about 700 lines of code. But maybe that's not a fair comparison. Maybe the `cppcoro` library's sources shouldn't be considered, like when we're using --say-- strings, streams and vectors, in which case we also ignore the sizes of their sources when they're used in our programs. If we *do* ignore the sizes of `cppcoro' s` sources, then the coroutine based implementation in fact requires *fewer* lines of code than the `Dir` class, as the `Generator` and `RecursiveGenerator` handler classes are provided by the `cppcoro` library.

Eventually, implementing parts of algorithms with coroutines, instead of using the (functions based) structured programming approach, might simply be a matter of taste. But maybe, as coroutines allow us to split up algorithms in separate parts which are not using stack-based activations, the efficiency of coroutine-based implementations exceeds the efficiency of implementations using separate supoprt functions. To get some information about the efficiency of programs using coroutines vs. programs that use separate support functions the `class Dir` based program and the `coroDir` based program was each run five times, processing a large multi-directory, multi-file structure, containing over 400.000 entries. The execution times of each of the five runs are highly comparable. The following table shows the average clock-times, the average user-times, and the average system-times for the `class Dir` based program and the `coroDir` based program:

	time		
	real	user	system
class Dir	82	22	59
coroDir	88	25	62

Although the `class Dir` implementation uses slightly less time than the `coroDir` implementatin, the differences are small, and should not be interpreted as an indication that (maybe different from what was expected) coroutine based implementations are inherently slower than function based implementations. Furthermore, coroutines themselves often call ordinary functions (like `readdir` called by `coroDir's` coroutine `dirEntries`), which still require stack-handling.

The conclusion at the end of this chapter is therefore that, yes, coroutines are available in **C++**, but they require lots of effort before they can be used. Some libraries (like `cppcoro`) are available, but they're not (yet?) part of the software that comes standard with your **C++** compiler. However, the underlying philosophy (being able to use cooperating routines) certainly is attractive, although it doesn't necessarily result in more efficient programs than programs which are developed using the traditional structured programming approach. And so, in the end, whether or not to use coroutines might simply boil down to a matter of taste.

Chapter 25

Concrete Examples

In this chapter concrete examples of **C++** programs, classes and templates are presented. Topics covered by the **C++** Annotations such as virtual functions, `static` members, etc. are illustrated in this chapter. The examples roughly follow the organization of earlier chapters.

As an additional topic, not just providing examples of **C++** the subjects of scanner and parser generators are covered. We show how these tools may be used in **C++** programs. These additional examples assume a certain familiarity with the concepts underlying these tools, like grammars, parse-trees and parse-tree decoration. Once the input for a program exceeds a certain level of complexity, it's attractive to use scanner- and parser-generators to create the code doing the actual input processing. One of the examples in this chapter describes the usage of these tools in a **C++** environment.

25.1 Using file descriptors with 'streambuf' classes

25.1.1 Classes for output operations

Reading and writing from and to *file descriptors* are not part of the **C++** standard. But on most operating systems file descriptors *are* available and can be considered a device. It seems natural to use the class `std::streambuf` as the starting point for constructing classes interfacing such file descriptor devices.

Below we'll construct classes that can be used to write to a device given its file descriptor. The devices may be files, but they could also be pipes or sockets. Section 25.1.2 covers reading from such devices; section 25.2.3 reconsiders redirection, discussed earlier in section 6.6.2.

Using the `streambuf` class as a base class it is relatively easy to design classes for output operations. The only member function that *must* be overridden is the (virtual) member `int streambuf::overflow(int c)`. This member's responsibility is to write characters to the device. If `fd` is an output file descriptor and if output should not be buffered then the member `overflow()` can simply be implemented as:

```
class UnbufferedFD: public std::streambuf
{
    public:
        virtual int overflow(int c);
        ...
};
```

```
int UnbufferedFD::overflow(int c)
{
    if (c != EOF)
    {
        if (write(d_fd, &c, 1) != 1)
            return EOF;
    }
    return c;
}
```

The argument received by `overflow` is either written to the file descriptor (and returned from `overflow`), or `EOF` is returned.

This simple function does not use output buffering. For various reasons, using a buffer is usually a good idea (see also the next section).

When output buffering is used, the `overflow` member is a bit more complex as it is only called when the buffer is full. Once the buffer is full, we *first* have to flush the buffer. Flushing the buffer is the responsibility of the (virtual) function `streambuf::sync`. Since `sync` is a virtual function, classes derived from `streambuf` may redefine `sync` to flush a buffer `streambuf` itself doesn't know about.

Overriding `sync` and using it in `overflow` is not all that has to be done. When the object of the class defining the buffer reaches the end of its lifetime the buffer may be only partially full. In that situation the buffer must also be flushed. This is easily done by simply calling `sync` from the class's destructor.

Now that we've considered the consequences of using an output buffer, we're almost ready to design our derived class. Several more features are added as well, though:

- First, we should allow the user of the class to specify the size of the output buffer.
- Second, it should be possible to construct an object of our class before the file descriptor is actually known. Later, in section 25.2 we'll encounter a situation where this feature is actually used.

To save some space in the **C++** Annotations, the successful completion of the functions designed here is not checked in the example code. In 'real life' implementations these checks should of course not be omitted. Our class `OFdnStreambuf` has the following characteristics:

- Its member functions use low-level functions operating on file descriptors. So apart from `streambuf` the `<unistd.h>` header file must have been read by the compiler before its member functions can be compiled.
- The class is derived from `std::streambuf`.
- It defines three data members. These data members keep track of, respectively, the size of the buffer, the file descriptor, and the buffer itself. Here is the full class interface

```
    class OFdnStreambuf: public std::streambuf
    {
        int     d_fd = -1;
        size_t  d_bufsize = 0;
        char   *d_buffer = 0;

        public:
            OFdnStreambuf() = default;
            OFdnStreambuf(int fd, size_t bufsize = 1);
            virtual ~OFdnStreambuf();
            void open(int fd, size_t bufsize = 1);
        private:
            virtual int sync();
            virtual int overflow(int c);
    };
```

- Its default constructor merely initializes the buffer to 0. Slightly more interesting is its constructor expecting a file descriptor and a buffer size. This constructor passes its arguments on to the class's `open` member (see below). Here are the constructors:

```
    inline OFdnStreambuf::OFdnStreambuf(int fd, size_t bufsize)
    {
        open(fd, bufsize);
    }
```

- The destructor calls `sync`, flushing any characters stored in the output buffer to the device. In implementations not using a buffer the destructor can be given a default implementation:

```
    inline OFdnStreambuf::~OFdnStreambuf()
    {
        if (d_buffer)
        {
            sync();
            delete[] d_buffer;
        }
    }
```

  This implementation does not close the device. It is left as an exercise to the reader to change this class in such a way that the device is optionally closed (or optionally remains open). This approach was adopted by, e.g., the `Bobcat library`[1]. See also section 25.1.2.2.

- The `open` member initializes the buffer. Using `streambuf::setp`, the begin and end points of the buffer are defined. This is used by the `streambuf` base class to initialize `streambuf::pbase`, `streambuf::pptr`, and `streambuf::epptr`:

```
    inline void OFdnStreambuf::open(int fd, size_t bufsize)
    {
        d_fd = fd;
        d_bufsize = bufsize == 0 ? 1 : bufsize;
        delete[] d_buffer;
        d_buffer = new char[d_bufsize];
        setp(d_buffer, d_buffer + d_bufsize);
    }
```

- The member `sync` flushes the as yet unflushed content of the buffer to the device. After the flush the buffer is reinitialized using `setp`. After successfully flushing the buffer `sync` returns 0:

```
    inline int OFdnStreambuf::sync()
    {
        if (pptr() > pbase())
        {
            write(d_fd, d_buffer, pptr() - pbase());
            setp(d_buffer, d_buffer + d_bufsize);
```

---

[1] http://fbb-git.gitlab.io/bobcat/

```
        }
        return 0;
    }
```

- The member `streambuf::overflow` is also overridden. Since this member is called from the `streambuf` base class when the buffer is full it should first call `sync` to flush the buffer to the device. Next it should write the character `c` to the (now empty) buffer. The character `c` should be written using `pptr` and `streambuf::pbump`. Entering a character into the buffer should be implemented using available `streambuf` member functions, rather than 'by hand' as doing so might invalidate `streambuf`'s internal bookkeeping. Here is `overflow`'s implementation:

```
    inline int OFdnStreambuf::overflow(int c)
    {
        sync();
        if (c != EOF)
        {
            *pptr() = c;
            pbump(1);
        }
        return c;
    }
```

The next program uses the `OFfdStreambuf` class to copy its standard input to file descriptor `STDOUT_FILENO`, which is the symbolic name of the file descriptor used for the standard output:

```
#include <string>
#include <iostream>
#include <istream>
#include "fdout.h"
using namespace std;

int main(int argc, char **argv)
{
    OFdnStreambuf   fds(STDOUT_FILENO, 500);
    ostream         os(&fds);

    switch (argc)
    {
        case 1:
            for (string  s; getline(cin, s); )
                os << s << '\n';
            os << "COPIED cin LINE BY LINE\n";
        break;

        case 2:
            cin >> os.rdbuf();      // Alternatively, use:  cin >> &fds;
            os << "COPIED cin BY EXTRACTING TO os.rdbuf()\n";
        break;

        case 3:
            os << cin.rdbuf();
            os << "COPIED cin BY INSERTING cin.rdbuf() into os\n";
        break;
    }
}
```

25.1.2 Classes for input operations

When classes for input operation are derived from `std::streambuf`, they should be provided with an input buffer of at least one character. The one-character input buffer allows for the use of the member functions `istream::putback` or `istream::ungetc`. Strictly speaking it is not necessary to implement a buffer in classes derived from `streambuf`. But using buffers in these classes is strongly advised. Their implementation is very simple and straightforward and the applicability of such classes is greatly improved. Therefore, all our classes derived from the class `streambuf` define a buffer of *at least* one character.

25.1.2.1 Using a one-character buffer

When deriving a class (e.g., `IFdStreambuf`) from `streambuf` using a buffer of one character, at least its member `streambuf::underflow` should be overridden, as this member eventually receives all requests for input. The member `streambuf::setg` is used to inform the `streambuf` base class of the size and location of the input buffer, so that it is able to set up its input buffer pointers accordingly. This ensures that `streambuf::eback`, `streambuf::gptr`, and `streambuf::egptr` return correct values.

The class `IFdStreambuf` is designed like this:

- Its member functions use low-level functions operating on file descriptors. Therefore, in addition to `streambuf`, the `<unistd.h>` header file must have been read by the compiler before its member functions can be compiled.
- Like most classes designed for input operations, this class is derived from `std::streambuf` as well.
- The class defines two data members, one of them a fixed-sized one character buffer. The data members are defined as `protected` data members so that derived classes (e.g., see section 25.1.2.3) can access them. Here is the full class interface:

  ```
  class IFdStreambuf: public std::streambuf
  {
      protected:
          int     d_fd;
          char    d_buffer[1];
      public:
          IFdStreambuf(int fd);
      private:
          int underflow();
  };
  ```

- The constructor initializes the buffer. However, the initialization sets `gptr`'s return value equal to `egptr`'s return value. This implies that the buffer is empty so `underflow` is immediately called to fill the buffer:

  ```
  inline IFdStreambuf::IFdStreambuf(int fd)
  :
      d_fd(fd)
  {
      setg(d_buffer, d_buffer + 1, d_buffer + 1);
  }
  ```

- Finally `underflow` is overridden. The buffer is refilled by reading from the file descriptor. If this fails (for whatever reason), `EOF` is returned. More sophisticated implementations could act more intelligently here, of course. If the buffer could be refilled, `setg` is called to set up `streambuf`'s buffer pointers correctly:

```
inline int IFdStreambuf::underflow()
{
    if (read(d_fd, d_buffer, 1) <= 0)
        return EOF;

    setg(d_buffer, d_buffer, d_buffer + 1);
    return static_cast<unsigned char>(*gptr());
}
```

The following `main` function shows how `IFdStreambuf` can be used:

```
int main()
{
    IFdStreambuf fds(STDIN_FILENO);
    istream      is(&fds);

    cout << is.rdbuf();
}
```

25.1.2.2 Using an n-character buffer

How complex would things get if we decided to use a buffer of substantial size? Not that complex. The following class allows us to specify the size of a buffer, but apart from that it is basically the same class as `IFdStreambuf` developed in the previous section. To make things a bit more interesting, in the class `IFdNStreambuf` developed here, the member `streambuf::xsgetn` is also overridden, to optimize reading a series of characters. Also a default constructor is provided that can be used in combination with the `open` member to construct an `istream` object before the file descriptor becomes available. In that case, once the descriptor becomes available, the `open` member can be used to initiate the object's buffer. Later, in section 25.2, we'll encounter such a situation.

To save some space, the success of various calls was not checked. In 'real life' implementations, these checks should of course not be omitted. The class `IFdNStreambuf` has the following characteristics:

- Its member functions use low-level functions operating on file descriptors. So apart from `streambuf` the `<unistd.h>` header file must have been read by the compiler before its member functions can be compiled.
- As usual, it is derived from `std::streambuf`.
- Like the class `IFdStreambuf` (section 25.1.2.1), its data members are protected. Since the buffer's size is configurable, this size is kept in a dedicated data member, `d_bufsize`:

```
class IFdNStreambuf: public std::streambuf
{
    protected:
        int         d_fd = -1;
        size_t      d_bufsize = 0;
        char*       d_buffer = 0;
    public:
        IFdNStreambuf() = default;
        IFdNStreambuf(int fd, size_t bufsize = 1);
        virtual ~IFdNStreambuf();
```

```
            void open(int fd, size_t bufsize = 1);
        private:
            virtual int underflow();
            virtual std::streamsize xsgetn(char *dest, std::streamsize n);
    };
```

- The default constructor does not allocate a buffer. It can be used to construct an object before the file descriptor becomes known. A second constructor simply passes its arguments to `open`. `Open` will then initialize the object so that it can actually be used:

  ```
  inline IFdNStreambuf::IFdNStreambuf(int fd, size_t bufsize)
  {
      open(fd, bufsize);
  }
  ```

- Once the object has been initialized by `open`, its destructor will both delete the object’s buffer and use the file descriptor to close the device:

  ```
  IFdNStreambuf::~IFdNStreambuf()
  {
      if (d_bufsize)
      {
          close(d_fd);
          delete[] d_buffer;
      }
  }
  ```

  Even though the device is closed in the above implementation this may not always be desirable. In cases where the open file descriptor is already available the intention may be to use that descriptor repeatedly, each time using a newly constructed `IFdNStreambuf` object. It is left as an exercise to the reader to change this class in such a way that the device may optionally be closed. This approach was followed in, e.g., the `Bobcat library`[2].

- The `open` member simply allocates the object’s buffer. It is assumed that the calling program has already opened the device. Once the buffer has been allocated, the base class member `setg` is used to ensure that `streambuf::eback` `streambuf::gptr` and `streambuf::egptr` return correct values:

  ```
  void IFdNStreambuf::open(int fd, size_t bufsize)
  {
      d_fd = fd;
      d_bufsize =  bufsize == 0 ? 1 : bufsize;
      delete[] d_buffer;
      d_buffer = new char[d_bufsize];
      setg(d_buffer, d_buffer + d_bufsize, d_buffer + d_bufsize);
  }
  ```

- The overridden member `underflow` is implemented almost identically to `IFdStreambuf`’s (section 25.1.2.1) member. The only difference is that the current class supports buffers of larger sizes. Therefore, more characters (up to `d_bufsize`) may be read from the device at once:

  ```
  int IFdNStreambuf::underflow()
  {
      if (gptr() < egptr())
  ```

---

[2] http://fbb-git.gitlab.io/bobcat/

```
            return *gptr();

        int nread = read(d_fd, d_buffer, d_bufsize);

        if (nread <= 0)
            return EOF;

        setg(d_buffer, d_buffer, d_buffer + nread);
        return static_cast<unsigned char>(*gptr());
    }
```

- Finally `xsgetn` is overridden. In a loop, `n` is reduced until 0, at which point the function terminates. Alternatively, the member returns if `underflow` fails to obtain more characters. This member optimizes the reading of series of characters. Instead of calling `streambuf::sbumpc` `n` times, a block of `avail` characters is copied to the destination, using `streambuf::gbump` to consume `avail` characters from the buffer using one function call:

```
    std::streamsize IFdNStreambuf::xsgetn(char *dest, std::streamsize n)
    {
        int nread = 0;

        while (n)
        {
            if (!in_avail())
            {
                if (underflow() == EOF)
                    break;
            }

            int avail = in_avail();

            if (avail > n)
                avail = n;

            memcpy(dest + nread, gptr(), avail);
            gbump(avail);

            nread += avail;
            n -= avail;
        }

        return nread;
    }
```

The member function `xsgetn` is called by `streambuf::sgetn`, which is a `streambuf` member. Here is an example illustrating the use of this member function with an `IFdNStreambuf` object:

```
#include <unistd.h>
#include <iostream>
#include <istream>
#include "ifdnbuf.h"
using namespace std;

int main()
{
```

```
                                // internally: 30 char buffer
        IFdNStreambuf fds(STDIN_FILENO, 30);

        char buf[80];           // main() reads blocks of 80
                                // chars
        while (true)
        {
            size_t n = fds.sgetn(buf, 80);
            if (n == 0)
                break;
            cout.write(buf, n);
        }
    }
```

25.1.2.3 Seeking positions in ‘streambuf’ objects

When devices support *seek operations*, classes derived from `std::streambuf` should override the members `streambuf::seekoff` and `streambuf::seekpos`. The class `IFdSeek`, developed in this section, can be used to read information from devices supporting seek operations. The class `IFdSeek` was derived from `IFdStreambuf`, so it uses a character buffer of just one character. The facilities to perform seek operations, which are added to our new class `IFdSeek`, ensure that the input buffer is reset when a seek operation is requested. The class could also be derived from the class `IFdNStreambuf`. In that case the arguments to reset the input buffer must be adapted so that its second and third parameters point beyond the available input buffer. Let’s have a look at the characteristics of `IFdSeek`:

- As mentioned, `IFdSeek` is derived from `IFdStreambuf`. Like the latter class, `IFdSeek`’s member functions use facilities declared in `unistd.h`. So, the header file `<unistd.h>` must have been read by the compiler before it can compile the class’s members functions. To reduce the amount of typing when specifying types and constants from `streambuf` and `std::ios`, several `typedef`s are defined by the class. These typedefs refer to types that are defined in the header file `<ios>`, which must therefore also be included before the compiler can compile `IFdSeek`’s class interface:

```
    class IFdSeek: public IFdStreambuf
    {
        typedef std::streambuf::pos_type        pos_type;
        typedef std::streambuf::off_type        off_type;
        typedef std::ios::seekdir               seekdir;
        typedef std::ios::openmode              openmode;

        public:
            IFdSeek(int fd);
        private:
            pos_type seekoff(off_type offset, seekdir dir, openmode);
            pos_type seekpos(pos_type offset, openmode mode);
    };
```

- The class has a very basic interface. Its (only) constructor expects the device’s file descriptor. It has no special tasks to perform and just calls its base class constructor:

```
    inline IFdSeek::IFdSeek(int fd)
    :
        IFdStreambuf(fd)
    {}
```

- The member `seek_off` is responsible for performing the actual seek operations. It calls `lseek` to seek a new position in a device whose file descriptor is known. If seeking succeeds, `setg` is called to define an already empty buffer, so that the base class's `underflow` member refills the buffer at the next input request.

```
IFdSeek::pos_type IFdSeek::seekoff(off_type off, seekdir dir, openmode)
{
    pos_type pos =
        lseek
        (
            d_fd, off,
            (dir ==  std::ios::beg) ? SEEK_SET :
            (dir ==  std::ios::cur) ? SEEK_CUR :
                                      SEEK_END
        );

    if (pos < 0)
        return -1;

    setg(d_buffer, d_buffer + 1, d_buffer + 1);
    return pos;
}
```

- Finally, the companion function `seekpos` is overridden as well: it is actually defined as a call to `seekoff`:

```
inline IFdSeek::pos_type IFdSeek::seekpos(pos_type off, openmode mode)
{
    return seekoff(off, std::ios::beg, mode);
}
```

Here is an example of a program using the class `IFdSeek`. If this program is given its own source file using input redirection then seeking is supported (and with the exception of the first line, every other line is shown twice):

```
#include "fdinseek.h"
#include <string>
#include <iostream>
#include <istream>
#include <iomanip>
using namespace std;

int main()
{
    IFdSeek fds(0);
    istream is(&fds);
    string  s;

    while (true)
    {
        if (!getline(is, s))
            break;

        streampos pos = is.tellg();
```

```
            cout << setw(5) << pos << ": `" << s << "'\n";

            if (!getline(is, s))
                break;

            streampos pos2 = is.tellg();

            cout << setw(5) << pos2 << ": `" << s << "'\n";

            if (!is.seekg(pos))
            {
                cout << "Seek failed\n";
                break;
            }
        }
    }
```

25.1.2.4 Multiple 'unget' calls in 'streambuf' objects

`Streambuf` classes and classes derived from `streambuf` should support *at least* ungetting the last read character. Special care must be taken when *series* of `unget` calls must be supported. In this section the construction of a class supporting a configurable number of `istream::unget` or `istream::putback` calls is discussed.

Support for multiple (say 'n') `unget` calls is implemented by reserving an initial section of the input buffer, which is gradually filled up to contain the last `n` characters read. The class is implemented as follows:

- Once again, the class is derived from `std::streambuf`. It defines several data members, allowing the class to perform the bookkeeping required to maintain an unget-buffer of a configurable size:

  ```
  class FdUnget: public std::streambuf
  {
      int     d_fd;
      size_t  d_bufsize;
      size_t  d_reserved;
      char   *d_buffer;
      char   *d_base;
      public:
          FdUnget(int fd, size_t bufsz, size_t unget);
          virtual ~FdUnget();
      private:
          int underflow();
  };
  ```

- The class's constructor expects a file descriptor, a buffer size and the number of characters that can be ungot or pushed back as its arguments. This number determines the size of a *reserved* area, defined as the first `d_reserved` bytes of the class's input buffer.
  - The input buffer will always be at least one byte larger than `d_reserved`. So, a certain number of bytes may be read. Once `d_reserved` bytes have been read at most `d_reserved` bytes can be ungot.
  - Next, the starting point for reading operations is configured. It is called `d_base`, pointing to a location `d_reserved` bytes beyond the location represented by `d_buffer`. This is always the location where buffer refills start.

  - Now that the buffer has been constructed, we're ready to define `streambuf`'s buffer pointers using `setg`. As no characters have been read yet, all pointers are set to point to `d_base`. If `unget` is called at this point, no characters are available, and `unget` (correctly) fails.
  - Eventually, the refill buffer's size is determined as the number of allocated bytes minus the size of the reserved area.

  Here is the class's constructor:

```
FdUnget::FdUnget(int fd, size_t bufsz, size_t unget)
:
    d_fd(fd),
    d_reserved(unget)
{
    size_t allocate =
            bufsz > d_reserved ?
                bufsz
            :
                d_reserved + 1;

    d_buffer = new char[allocate];

    d_base = d_buffer + d_reserved;
    setg(d_base, d_base, d_base);

    d_bufsize = allocate - d_reserved;
}
```

- The class's destructor simply returns the memory allocated for the buffer to the common pool:

```
inline FdUnget::~FdUnget()
{
    delete[] d_buffer;
}
```

- Finally, `underflow` is overridden as follows:
  - First `underflow` determines the number of characters that could potentially be ungot. If that number of characters are ungot, the input buffer is exhausted. So this value may be any value between 0 (the initial state) or the input buffer's size (when the reserved area has been filled up completely, and all current characters in the remaining section of the buffer have also been read);
  - Next the number of bytes to move into the reserved area is computed. This number is at most `d_reserved`, but it is set equal to the actual number of characters that can be ungot if this value is smaller;
  - Now that the number of characters to move into the reserved area is known, this number of characters is moved from the input buffer's end to the area immediately before `d_base`;
  - Then the buffer is refilled. This all is standard, but notice that reading starts from `d_base` and not from `d_buffer`;
  - Finally, `streambuf`'s read buffer pointers are set up. `Eback` is set to `move` locations before `d_base`, thus defining the guaranteed unget-area, `gptr` is set to `d_base`, since that's the location of the first read character after a refill, and `egptr` is set just beyond the location of the last character read into the buffer.

Here is `underflow`’s implementation:

```
    int FdUnget::underflow()
    {
        size_t ungetsize = gptr() - eback();
        size_t move = std::min(ungetsize, d_reserved);

        memcpy(d_base - move, egptr() - move, move);

        int nread = read(d_fd, d_base, d_bufsize);
        if (nread <= 0)       // none read -> return EOF
            return EOF;

        setg(d_base - move, d_base, d_base + nread);

        return static_cast<unsigned char>(*gptr());
    }
```

An example using FdUnget

The next example program illustrates the use of the class `FdUnget`. It reads at most 10 characters from the standard input, stopping at `EOF`. A guaranteed unget-buffer of 2 characters is defined in a buffer holding 3 characters. Just before reading a character, the program tries to unget at most 6 characters. This is, of course, not possible; but the program nicely ungets as many characters as possible, considering the actual number of characters read:

```
    #include "fdunget.h"
    #include <string>
    #include <iostream>
    #include <istream>
    using namespace std;

    int main()
    {
        FdUnget fds(0, 3, 2);
        istream is(&fds);
        char    c;

        for (int idx = 0; idx < 10; ++idx)
        {
            cout << "after reading " << idx << " characters:\n";
            for (int ug = 0; ug <= 6; ++ug)
            {
                if (!is.unget())
                {
                    cout
                    << "\tunget failed at attempt " << (ug + 1) << "\n"
                    << "\trereading: '";

                    is.clear();
                    while (ug--)
                    {
                        is.get(c);
                        cout << c;
                    }
                    cout << "'\n";
                    break;
                }
            }

            if (!is.get(c))
            {
                cout << " reached\n";
                break;
            }
            cout << "Next character: " << c << '\n';
        }
    }
    /*
        Generated output after 'echo abcde | program':

        after reading 0 characters:
                unget failed at attempt 1
                rereading: ''
        Next character: a
        after reading 1 characters:
                unget failed at attempt 2
                rereading: 'a'
        Next character: b
        after reading 2 characters:
                unget failed at attempt 3
                rereading: 'ab'
        Next character: c
        after reading 3 characters:
                unget failed at attempt 4
                rereading: 'abc'
        Next character: d
        after reading 4 characters:
                unget failed at attempt 4
                rereading: 'bcd'
        Next character: e
        after reading 5 characters:
                unget failed at attempt 4
                rereading: 'cde'
        Next character:

        after reading 6 characters:
                unget failed at attempt 4
                rereading: 'de
        '
         reached
    */
```

25.1.3 Fixed-sized field extraction from istream objects

Usually when extracting information from `istream` objects `operator>>`, the standard extraction operator is perfectly suited for the task as in most cases the extracted fields are white-space (or otherwise clearly) separated from each other. But this does not hold true in all situations. For example, when a web-form is posted to some processing script or program, the receiving program may receive the form field's values as *url-encoded* characters: letters and digits are sent unaltered, blanks are sent as `+` characters, and all other characters start with `%` followed by the character's ascii-value represented by its two digit hexadecimal value.

When decoding url-encoded information, simple hexadecimal extraction won't work, as that extracts as many hexadecimal characters as available, instead of just two. Since the letters `a-f`` and `0-9` are legal hexadecimal characters, a text like `My name is `Ed'`, url-encoded as

```
My+name+is+%60Ed%27
```

results in the extraction of the hexadecimal values `60ed` and `27`, instead of `60` and `27`. The name `Ed` disappears from view, which is clearly not what we want.

In this case, having seen the `%`, we could extract 2 characters, put them in an `istringstream` object, and extract the hexadecimal value from the `istringstream` object. A bit cumbersome, but doable. Other approaches are possible as well.

The class `Fistream` for *fixed-sized field istream* defines an `istream` class supporting both fixed-sized field extractions and blank-delimited extractions (as well as unformatted `read` calls). The class may be initialized as a *wrapper* around an existing `istream`, or it can be initialized using the name of an existing file. The class is derived from `istream`, allowing all extractions and operations supported by `istream`s in general. `Fistream` defines the following data members:

- `d_filebuf`: a filebuffer used when `Fistream` reads its information from a named (existing) file. Since the filebuffer is only needed in that case, and since it must be allocated dynamically, it is defined as a `unique_ptr<filebuf>` object.
- `d_streambuf`: a pointer to `Fistream`'s `streambuf`. It points to `d_filebuf` when `Fistream` opens a file by name. When an existing `istream` is used to construct an `Fistream`, it points to the existing `istream`'s `streambuf`.
- `d_iss`: an `istringstream` object used for the fixed field extractions.
- `d_width`: a `size_t` indicating the width of the field to extract. If 0 no fixed field extractions is used, but information is extracted from the `istream` base class object using standard extractions.

Here is the initial section of `Fistream`'s class interface:

```
class Fistream: public std::istream
{
    std::unique_ptr<std::filebuf> d_filebuf;
    std::streambuf *d_streambuf;
    std::istringstream d_iss;
    size_t d_width;
```

As stated, `Fistream` objects can be constructed from either a filename or an existing `istream` object. The class interface therefore declares two constructors:

```
        Fistream(std::istream &stream);
        Fistream(char const *name,
            std::ios::openmode mode = std::ios::in);
```

When an `Fistream` object is constructed using an existing `istream` object, the `Fistream`'s `istream` part simply uses the `stream`'s `streambuf` object:

```
Fistream::Fistream(istream &stream)
```

```
:
    istream(stream.rdbuf()),
    d_streambuf(rdbuf()),
    d_width(0)
{}
```

When an `fstream` object is constructed using a filename, the `istream` base initializer is given a new `filebuf` object to be used as its `streambuf`. Since the class's data members are not initialized before the class's base class has been constructed, `d_filebuf` can only be initialized thereafter. By then, the `filebuf` is only available as `rdbuf`, returning a `streambuf`. However, as it is actually a `filebuf`, a `static_cast` is used to cast the `streambuf` pointer returned by `rdbuf` to `a filebuf *`, so `d_filebuf` can be initialized:

```
Fistream::Fistream(char const *name, ios::openmode mode)
:
    istream(new filebuf()),
    d_filebuf(static_cast<filebuf *>(rdbuf())),
    d_streambuf(d_filebuf.get()),
    d_width(0)
{
    d_filebuf->open(name, mode);
}
```

25.1.3.1 Member functions and example

There is only one additional public member: `setField(field const &)`. This member defines the size of the next field to extract. Its parameter is a reference to a `field` class, a *manipulator class* defining the width of the next field.

Since a `field &` is mentioned in `Fistream`'s interface, `field` must be declared before `Fistream`'s interface starts. The class `field` itself is simple and declares `Fistream` as its friend. It has two data members: `d_width` specifies the width of the next field, and `d_newWidth` which is set to `true` if `d_width`'s value should actually be used. If `d_newWidth` is false, `Fistream` returns to its standard extraction mode. The class `field` has two constructors: a default constructor, setting `d_newWidth` to `false`, and a second constructor expecting the width of the next field to extract as its value. Here is the class `field`:

```
    class field
    {
        friend class Fistream;
        size_t d_width;
        bool     d_newWidth;

        public:
            field(size_t width);
            field();
    };

    inline field::field(size_t width)
    :
        d_width(width),
        d_newWidth(true)
    {}
    inline field::field()
    :
        d_newWidth(false)
    {}
```

Since `field` declares `Fistream` as its friend, `setField` may inspect `field`'s members directly.

Time to return to `setField`. This function expects a reference to a `field` object, initialized in one of three different ways:

- `field()`: When `setField`'s argument is a `field` object constructed by its default constructor the next extraction will use the same field width as the previous extraction.
- `field(0)`: When this `field` object is used as `setField`'s argument, fixed-sized field extraction stops, and the `Fistream` acts like any standard `istream` object again.
- `field(x)`: When the `field` object itself is initialized by a non-zero size_t value `x`, then the next field width is `x` characters wide. The preparation of such a field is left to `setBuffer`, `Fistream`'s only private member.

Here is `setField`'s implementation:

```
std::istream &Fistream::setField(field const &params)
{
    if (params.d_newWidth)                  // new field size requested
        d_width = params.d_width;           // set new width

    if (!d_width)                           // no width?
        rdbuf(d_streambuf);                 // return to the old buffer
    else
        setBuffer();                        // define the extraction buffer

    return *this;
}
```

The private member `setBuffer` defines a buffer of `d_width + 1` characters and uses `read` to fill the buffer with `d_width` characters. The buffer is an NTBS. This buffer is used to initialize the `d_iss` member. `Fistream`'s `rdbuf` member is used to extract the `d_str`'s data via the `Fistream` object itself:

```
void Fistream::setBuffer()
{
    char *buffer = new char[d_width + 1];

    rdbuf(d_streambuf);                         // use istream's buffer to
    buffer[read(buffer, d_width).gcount()] = 0; // read d_width chars,
                                                // terminated by a 0-byte
    d_iss.str(buffer);
    delete[] buffer;

    rdbuf(d_iss.rdbuf());                       // switch buffers
}
```

Although `setField` could be used to configure `Fistream` to use or not to use fixed-sized field extraction, using manipulators is probably preferable. To allow `field` objects to be used as manipulators an overloaded extraction operator was defined. This extraction operator accepts `istream &` and a `field const &` objects. Using this extraction operator, statements like

```
fis >> field(2) >> x >> field(0);
```

are possible (assuming `fis` is a `Fistream` object). Here is the overloaded `operator>>`, as well as its declaration:

```
istream &std::operator>>(istream &str, field const &params)
{
    return static_cast<Fistream *>(&str)->setField(params);
}
```

Declaration:

```
namespace std
{
    istream &operator>>(istream &str, FBB::field const &params);
}
```

Finally, an example. The following program uses a `Fistream` object to url-decode url-encoded information appearing at its standard input:

```
    int main()
    {
        Fistream fis(cin);

        fis >> hex;
        while (true)
        {
            size_t x;
            switch (x = fis.get())
            {
                case '\n':
                    cout << '\n';
                break;
                case '+':
                    cout << ' ';
                break;
                case '%':
                    fis >> field(2) >> x >> field(0);
                // FALLING THROUGH
                default:
                    cout << static_cast<char>(x);
                break;
                case EOF:
                return 0;
            }
        }
    }
    /*
        Generated output after:
            echo My+name+is+%60Ed%27 | a.out
        My name is `Ed'
    */
```

25.2 The 'fork' system call

From the **C** programming language the `fork` system call is well known. When a program needs to start a new process, `system` can be used. The function `system` requires the program to wait for the *child process* to terminate. The more general way to spawn subprocesses is to use `fork`.

In this section we investigate how **C++** can be used to wrap classes around a complex system call like `fork`. Much of what follows in this section directly applies to the Unix operating system, and the discussion therefore focuses on that operating system. Other systems usually provide comparable facilities. What follows is closely related to the *Template Design Pattern* (cf. *Gamma et al.* (1995) Design Patterns, Addison-Wesley)

When `fork` is called, the current program is duplicated in memory, thus creating a new process. Following this duplication both processes continue their execution just below the `fork` system call. The two processes may inspect `fork`'s return value: the return value in the original process (called the *parent process*) differs from the return value in the newly created process (called the *child process*):

- In the *parent process* `fork` returns the *process ID* of the (child) process that was created by the `fork` system call. This is a positive integer value.
- In the *child process* `fork` returns 0.
- If `fork` fails, -1 is returned.

25.2.1 A basic Fork class

A basic `Fork` class should hide all bookkeeping details of a system call like `fork` from its users. The class `Fork` developed here does just that. The class itself only ensures the proper execution of the `fork` system call. Normally, `fork` is called to start a child process, usually boiling down to the execution of a separate process. This child process may expect input at its standard input stream and/or may generate output to its standard output and/or standard error streams. `Fork` does not know all this, and does not have to know what the child process will do. `Fork` objects should be able to start their child processes.

`Fork`'s constructor cannot know what actions its child process should perform. Similarly, it cannot know what actions the parent process should perform. For these kind of situations, the *template method design pattern* was developed. According to Gamma c.s., the *template method design pattern*

> "Define(s) the skeleton of an algorithm in an operation, deferring some steps to subclasses. [The] Template Method (design pattern) lets subclasses redefine certain steps of an algorithm, without changing the algorithm's structure."

This design pattern allows us to define an *abstract base class* already providing the essential steps related to the `fork` system call, deferring the implementation of other parts of the `fork` system call to subclasses.

The `Fork` abstract base class has the following characteristics:

- It defines a data member `d_pid`. In the parent process this data member contains the child's *process id* and in the child process it has the value 0. Its public interface declares only two members:

  - a `fork` member function, responsible for the actual forking (i.e., it creates the (new) child process);
  - a `virtual` destructor `~Fork` (having an empty body).

  Here is `Fork`'s interface:

```
class Fork
{
    int d_pid;

    public:
        virtual ~Fork();
        void fork();

    protected:
        int pid() const;
        int waitForChild();                 // returns the status

    private:
        virtual void childRedirections();
        virtual void parentRedirections();

        virtual void childProcess() = 0;    // pure virtual members
        virtual void parentProcess() = 0;
};
```

- All other non-virtual member functions are declared in the class's `protected` section and can thus *only* be used by derived classes. They are:
  - `pid()`: The member function `pid` allows derived classes to access the system `fork`'s return value:

```
inline int Fork::pid() const
{
    return d_pid;
}
```

  - `waitForChild()`: The member `int waitForChild` can be called by parent processes to wait for the completion of their child processes (as discussed below). This member is declared in the class interface. Its implementation is:

```
#include "fork.ih"

int Fork::waitForChild()
{
    int status;

    waitpid(d_pid, &status, 0);

    return WEXITSTATUS(status);
}
```

    This simple implementation returns the child's *exit status* to the parent. The called system function `waitpid` *blocks* until the child terminates.

- When `fork` system calls are used, *parent processes* and *child processes* must always be distinguished. The main distinction between these processes is that `d_pid` becomes the child's process-id in the parent process, while `d_pid` becomes 0 in the child process itself. Since these two processes must always be distinguished (and present), their implementation by classes derived from `Fork` is enforced by `Fork`'s interface: the members `childProcess`, defining the child process' actions and `parentProcess`, defining the parent process' actions were defined as pure virtual functions.

- communication between parent- and child processes may use standard streams or other facilities, like *pipes* (cf. section 25.2.5). To facilitate this inter-process communication, derived classes *may* implement:
  - `childRedirections()`: this member should be overridden by derived classes if any standard stream (`cin, cout,`) or `cerr` must be redirected in the *child* process (cf. section 25.2.3). By default it has an empty implementation;
  - `parentRedirections()`: this member should be overridden by derived classes if any standard stream (`cin, cout,`) or `cerr` must be redirected in the *parent* process. By default it has an empty implementation.

Redirection of the standard streams is necessary if parent and child processes must communicate with each other via the standard streams. Here are their default definitions. Since these functions are virtual functions they should not be implemented inline, but in their own source file:

```
void Fork::childRedirections()
{}
void Fork::parentRedirections()
{}
```

25.2.2 Parents and Children

The member function `fork` calls the system function `fork` (Caution: since the system function `fork` is called by a member function having the same name, the `::` scope resolution operator must be used to prevent a recursive call of the member function itself). The function `::fork`'s return value determines whether `parentProcess` or `childProcess` is called. Maybe redirection is necessary. `Fork::fork`'s implementation calls `childRedirections` just before calling `childProcess`, and `parentRedirections` just before calling `parentProcess`:

```
#include "fork.ih"

void Fork::fork()
{
    if ((d_pid = ::fork()) < 0)
        throw "Fork::fork() failed";

    if (d_pid == 0)                 // childprocess has pid == 0
    {
        childRedirections();
        childProcess();
        exit(1);                    // we shouldn't come here:
    }                               // childProcess() should exit

    parentRedirections();
    parentProcess();
}
```

In `fork.cc` the class's *internal header file* `fork.ih` is included. This header file takes care of the inclusion of the necessary system header files, as well as the inclusion of `fork.h` itself. Its implementation is:

```
#include "fork.h"
#include <cstdlib>
#include <unistd.h>
#include <sys/types.h>
#include <sys/wait.h>
```

Child processes should not return: once they have completed their tasks, they should terminate. This happens automatically when the child process performs a call to a member of the `exec...` family, but if the child itself remains active, then it must make sure that it terminates properly. A child process normally uses `exit` to terminate itself, but note that `exit` prevents the activation of destructors of objects defined at the same or more superficial nesting levels than the level at which `exit` is called. Destructors of globally defined objects *are* activated when `exit` is used. When using `exit` to terminate `childProcess`, it should either itself call a support member function defining all nested objects it needs, or it should define all its objects in a compound statement (e.g., using a `throw` block) calling `exit` beyond the compound statement.

Parent processes should normally wait for their children to complete. Terminating child processes inform their parents that they are about to terminate by sending a *signal* that should be caught by their parents. If child processes terminate and their parent processes do not catch those signals then such child processes remain visible as so-called *zombie* processes.

If parent processes must wait for their children to complete, they may call the member `waitForChild`. This member returns the exit status of a child process to its parent.

There exists a situation where the *child* process *continues* to live, but the *parent* dies. This is a fairly natural event: parents tend to die before their children do. In our context (i.e. **C++**), this is called a *daemon* program. In a daemon the parent process dies and the child program continues to run as a child of the basic `init` process. Again, when the child eventually dies a signal is sent to its 'step-parent' `init`. This does not create a zombie as `init` catches the termination signals of all its (step-) children. The construction of a daemon process is very simple, given the availability of the class `Fork` (cf. section 25.2.4).

25.2.3 Redirection revisited

Earlier, in section 6.6.2 streams were redirected using the `ios::rdbuf` member function. By assigning the `streambuf` of a stream to another stream, both stream objects access the same `streambuf`, thus implementing redirection at the level of the programming language itself.

This may be fine within the context of a **C++** program, but once we leave that context the redirection terminates. The operating system does not know about `streambuf` objects. This situation is encountered, e.g., when a program uses a `system` call to start a subprogram. The example program at the end of this section uses **C++** redirection to redirect the information inserted into `cout` to a file, and then calls

```
system("echo hello world")
```

to echo a well-known line of text. Since `echo` writes its information to the standard output, this would be the program's redirected file if the operating system would recognize **C++**'s redirection.

But redirection doesn't happen. Instead, `hello world` still appears at the program's standard output and the redirected file is left untouched. To write `hello world` to the redirected file redirection must be realized at the operating system level. Some operating systems (e.g., Unix and friends) provide system calls like `dup` and `dup2` to accomplish this. Examples of the use of these system calls are given in section 25.2.5.

Here is the example of the *failing redirection* at the system level following **C++** redirection using `streambuf` redirection:

```
#include <iostream>
#include <fstream>
#include <cstdlib>
using namespace std;

int main()
{
    ofstream of("outfile");

    streambuf *buf = cout.rdbuf(of.rdbuf());
    cout << "To the of stream\n";
    system("echo hello world");
    cout << "To the of stream\n";
    cout.rdbuf(buf);
}
/*
    Generated output: on the file `outfile'

    To the of stream
    To the of stream

    On standard output:

    hello world
*/
```

25.2.4 The ‘Daemon’ program

Applications exist in which the only purpose of `fork` is to start a child process. The parent process terminates immediately after spawning the child process. If this happens, the child process continues to run as a child process of `init`, the always running first process on Unix systems. Such a process is often called a *daemon*, running as a background process.

Although the next example can easily be constructed as a plain **C** program, it was included in the **C++** Annotations because it is so closely related to the current discussion of the `Fork` class. I thought about adding a `daemon` member to that class, but eventually decided against it because the construction of a daemon program is very simple and requires no features other than those currently offered by the class `Fork`. Here is an example illustrating the construction of such a daemon program. Its child process doesn't do `exit` but `throw 0` which is caught by the `catch` clause of the child's `main` function. Doing this ensures that any objects defined by the child process are properly destroyed:

```
#include <iostream>
#include <unistd.h>
#include "fork.h"

class Daemon: public Fork
{
    virtual void parentProcess()        // the parent does nothing.
    {}
    virtual void childProcess()         // actions by the child
    {
        sleep(3);
                                        // just a message...
        std::cout << "Hello from the child process\n";
        throw 0;                        // The child process ends
    }
};

int main()
try
{
    Daemon{}.fork();
}
catch(...)
{}

/*
    Generated output:
The next command prompt, then after 3 seconds:
Hello from the child process
*/
```

25.2.5 The class ‘Pipe’

Redirection at the system level requires the use of *file descriptor*, created by the `pipe` system call. When two processes want to communicate using such file descriptors, the following happens:

- The process constructs two *associated file descriptors* using the `pipe` system call. One of the file descriptors is used for writing, the other file descriptor is used for reading.
- Forking takes place (i.e., the system `fork` function is called), duplicating the file descriptors. Now we have four file descriptors as the child process and the parent process both have their own copies of the two file descriptors created by `pipe`.
- One process (say, the parent process) uses the file descriptors for *reading*. It should close its file descriptor intended for *writing*.
- The other process (say, the child process) uses the file descriptors for *writing*. It should therefore close its file descriptor intended for *reading*.
- All information written by the child process to the file descriptor intended for writing, can now be read by the parent process from the corresponding file descriptor intended for reading, thus establishing a communication channel between the child and the parent process.

Though basically simple, errors may easily creep in. Functions of file descriptors available to the two processes (child or parent) may easily get mixed up. To prevent bookkeeping errors, the bookkeeping may be properly set up once, to be hidden thereafter inside a class like the `Pipe` class developed here. Let’s have a look at its characteristics (before using functions like `pipe` and `dup` the compiler must have read the `<unistd.h>` header file):

- The `pipe` system call expects a pointer to two `int` values, representing, respectively, the file descriptor used for reading and the file descriptor used for writing. To avoid confusion, the class `Pipe` defines an `enum` having values associating the indices of the array of 2-`int`s with symbolic constants. The two file descriptors themselves are stored in a data member `d_fd`. Here is the initial section of the class’s interface:

```
    class Pipe
```

```
{
    enum    RW { READ, WRITE };
    int     d_fd[2];
```

- The class only needs a default constructor. This constructor calls `pipe` to create a set of associated file descriptors used for accessing both ends of a pipe:

```
Pipe::Pipe()
{
    if (pipe(d_fd))
        throw "Pipe::Pipe(): pipe() failed";
}
```

- The members `readOnly` and `readFrom` are used to configure the pipe's reading end. The latter function is used when using redirection. It is provided with an alternate file descriptor to be used for reading from the pipe. Usually this alternate file descriptor is `STDIN_FILENO`, allowing `cin` to extract information from the pipe. The former function is merely used to configure the reading end of the pipe. It closes the matching writing end and returns a file descriptor that can be used to read from the pipe:

```
int Pipe::readOnly()
{
    close(d_fd[WRITE]);
    return d_fd[READ];
}
void Pipe::readFrom(int fd)
{
    readOnly();

    redirect(d_fd[READ], fd);
    close(d_fd[READ]);
}
```

- `writeOnly` and two `writtenBy` members are available to configure the writing end of a pipe. The former function is only used to configure the writing end of the pipe. It closes the reading end, and returns a file descriptor that can be used for writing to the pipe:

```
int Pipe::writeOnly()
{
    close(d_fd[READ]);
    return d_fd[WRITE];
}
void Pipe::writtenBy(int fd)
{
    writtenBy(&fd, 1);
}
void Pipe::writtenBy(int const *fd, size_t n)
{
    writeOnly();

    for (size_t idx = 0; idx < n; idx++)
        redirect(d_fd[WRITE], fd[idx]);

    close(d_fd[WRITE]);
}
```

For the latter member two overloaded versions are available:

  - `writtenBy(int fd)` is used to configure *single* redirection, so that a specific file descriptor (usually `STDOUT_FILENO` or `STDERR_FILENO`) can be used to write to the pipe;
  - `(writtenBy(int const *fd, size_t n))` may be used to configure *multiple* redirection, providing an array argument containing file descriptors. Information written to any of these file descriptors is actually written to the pipe.

- The class has one private data member, `redirect`, used to set up redirection through the `dup2` system call. This function expects two file descriptors. The first file descriptor represents a file descriptor that can be used to access the device's information; the second file descriptor is an alternate file descriptor that may also be used to access the device's information. Here is `redirect`'s implementation:

```
void Pipe::redirect(int d_fd, int alternateFd)
{
    if (dup2(d_fd, alternateFd) < 0)
        throw "Pipe: redirection failed";
}
```

Now that redirection can be configured easily using one or more `Pipe` objects, we'll use `Fork` and `Pipe` in various example programs.

25.2.6 The class 'ParentSlurp'

The class `ParentSlurp`, derived from `Fork`, starts a child process executing a stand-alone program (like `/bin/ls`). The (standard) output of the executed program is not shown on the screen but is read by the parent process.

For demonstration purposes the parent process writes the lines it receives to its standard output stream, prepending linenumbers to the lines. It is attractive to redirect the parent's standard *input* stream to allow the parent to read the *output* from the child process using its `std::cin` *input* stream. Therefore, the only pipe in the program is used as an *input* pipe for the parent, and an *output* pipe for the child.

The class `ParentSlurp` has the following characteristics:

- It is derived from `Fork`. Before starting `ParentSlurp`'s class interface, the compiler must have read `fork.h` and `pipe.h`. The class only uses one data member, a `Pipe` object `d_pipe`.
- As `Pipe`'s constructor already defines a pipe, and as `d_pipe` is automatically initialized by `ParentSlurp`'s default constructor, which is implicitly provided, all additional members only exist for `ParentSlurp`'s own benefit so they can be defined in the class's (implicit) `private` section. Here is the class's interface:

```
class ParentSlurp: public Fork
{
    Pipe    d_pipe;

    virtual void childRedirections();
    virtual void parentRedirections();
    virtual void childProcess();
    virtual void parentProcess();
};
```

- The `childRedirections` member configures the writing end of the pipe. So, all information written to the child's standard output stream ends up in the pipe. The big advantage of this is that no additional streams are needed to write to a file descriptor:

  ```
  inline void ParentSlurp::childRedirections()
  {
      d_pipe.writtenBy(STDOUT_FILENO);
  }
  ```

- The `parentRedirections` member, configures the reading end of the pipe. It does so by connecting the reading end of the pipe to the parent's standard input file descriptor (`STDIN_FILENO`). This allows the parent to perform extractions from `cin`, not requiring any additional streams for reading.

  ```
  inline void ParentSlurp::parentRedirections()
  {
      d_pipe.readFrom(STDIN_FILENO);
  }
  ```

- The `childProcess` member only needs to concentrate on its own actions. As it only needs to execute a program (writing information to its standard output), the member can consist of one single statement:

  ```
  inline void ParentSlurp::childProcess()
  {
      execl("/bin/ls", "/bin/ls", 0);
  }
  ```

- The `parentProcess` member simply 'slurps' the information appearing at its standard input. Doing so, it actually reads the child's output. It copies the received lines to its standard output stream prefixing line numbers to them:

  ```
  void ParentSlurp::parentProcess()
  {
      std::string     line;
      size_t    nr = 1;

      while (getline(std::cin, line))
          std::cout << nr++ << ": " << line << '\n';

      waitForChild();
  }
  ```

The following program simply constructs a `ParentSlurp` object, and calls its `fork()` member. Its output consists of a numbered list of files in the directory where the program is started. Note that the program also needs the `fork.o, pipe.o` and `waitforchild.o` object files (see earlier sources):

```
int main()
{
    ParentSlurp{}.fork();
}
/*
    Generated Output (example only, actually obtained output may differ):

    1: a.out
```

```
        2: bitand.h
        3: bitfunctional
        4: bitnot.h
        5: daemon.cc
        6: fdinseek.cc
        7: fdinseek.h
        ...
*/
```

25.2.7 Communicating with multiple children

The next step up the ladder is the construction of a child-process monitor. Here, the parent process is responsible for all its child processes, but it also must read their standard output. The user enters information at the standard input of the parent process. A simple *command language* is used for this:

- `start`: this starts a new child process. The parent returns the child's ID (a number) to the user. The ID is thereupon be used to identify a particular child process;
- `<nr> text` sends "`text`" to the child process having ID `<nr>`;
- `stop <nr>` terminates the child process having ID `<nr>`;
- `exit` terminates the parent as well as all its child processes.

If a child process hasn't received text for some time it will complain by sending a message to the parent-process. Those messages are simply transmitted to the user by copying them to the standard output stream.

A problem with programs like our monitor is that they allow *asynchronous input* from multiple sources. Input may appear at the standard input as well as at the input-sides of pipes. Also, multiple output channels are used. To handle situations like these, the `select` system call was developed.

25.2.7.1 The class 'Selector': interface

The `select` system call was developed to handle asynchronous *I/O multiplexing*. The `select` system call is used to handle, e.g., input appearing simultaneously at a set of file descriptors.

The `select` function is rather complex, and its full discussion is beyond the **C++** Annotations' scope. By encapsulating `select` in a `class Selector`, hiding its details and offering an intuitively attractive interface, its use is simplified. The `Selector` class has these features:

- Efficiency. As most of `Select`'s members are very small, most members can be implemented inline. The class requires quite a few data members. Most of these data members belong to types that require some system headers to be included first:

  ```
  #include <limits.h>
  #include <unistd.h>
  #include <sys/time.h>
  #include <sys/types.h>
  ```

- The class interface can now be defined. The data type `fd_set` is a type designed to be used by `select` and variables of this type contain the set of file descriptors on which `select` may sense some activity. Furthermore, `select` allows us to fire an *asynchronous alarm*. To set the alarm time, the class `Selector` defines a `timeval` data member. Other members are used for internal bookkeeping purposes. Here is the class `Selector`’s interface:

```
class Selector
{
    fd_set          d_read;
    fd_set          d_write;
    fd_set          d_except;
    fd_set          d_ret_read;
    fd_set          d_ret_write;
    fd_set          d_ret_except;
    timeval         d_alarm;
    int             d_max;
    int             d_ret;
    int             d_readidx;
    int             d_writeidx;
    int             d_exceptidx;

    public:
        Selector();

        int exceptFd();
        int nReady();
        int readFd();
        int wait();
        int writeFd();
        void addExceptFd(int fd);
        void addReadFd(int fd);
        void addWriteFd(int fd);
        void noAlarm();
        void rmExceptFd(int fd);
        void rmReadFd(int fd);
        void rmWriteFd(int fd);
        void setAlarm(int sec, int usec = 0);

    private:
        int checkSet(int *index, fd_set &set);
        void addFd(fd_set *set, int fd);
};
```

25.2.7.2 The class ‘Selector’: implementation

Selector’s member functions serve the following tasks:

- `Selector()`: the (default) constructor. It clears the read, write, and execute `fd_set` variables, and switches off the alarm. Except for `d_max`, the remaining data members do not require specific initializations:

```
Selector::Selector()
{
    FD_ZERO(&d_read);
    FD_ZERO(&d_write);
    FD_ZERO(&d_except);
    noAlarm();
```

```
        d_max = 0;
    }
```

- `int wait()`: this member *blocks* until the *alarm* times out or until activity is sensed at any of the file descriptors monitored by the `Selector` object. It throws an exception when the `select` system call itself fails:

```
    int Selector::wait()
    {
        timeval t = d_alarm;

        d_ret_read = d_read;
        d_ret_write = d_write;
        d_ret_except = d_except;

        d_readidx = 0;
        d_writeidx = 0;
        d_exceptidx = 0;

        d_ret = select(d_max, &d_ret_read, &d_ret_write, &d_ret_except,
                       t.tv_sec == -1 && t.tv_usec == -1 ? 0 : &t);

        if (d_ret < 0)
            throw "Selector::wait()/select() failed";

        return d_ret;
    }
```

- `int nReady`: this member function's return value is only defined when `wait` has returned. In that case it returns 0 for an alarm-timeout, -1 if `select` failed, and otherwise the number of file descriptors on which activity was sensed:

```
    inline int Selector::nReady()
    {
        return d_ret;
    }
```

- `int readFd()`: this member function's return value is also only defined after `wait` has returned. Its return value is -1 if no (more) input file descriptors are available. Otherwise the next file descriptor available for reading is returned:

```
    inline int Selector::readFd()
    {
        return checkSet(&d_readidx, d_ret_read);
    }
```

- `int writeFd()`: operating analogously to `readFd`, it returns the next file descriptor to which output is written. It uses `d_writeidx` and `d_ret_read` and is implemented analogously to `readFd`;
- `int exceptFd()`: operating analogously to `readFd`, it returns the next exception file descriptor on which activity was sensed. It uses `d_except_idx` and `d_ret_except` and is implemented analogously to `readFd`;
- `void setAlarm(int sec, int usec = 0)`: this member activates `Select`'s alarm facility. At least the number of seconds to wait for the alarm to go off must be specified. It simply

assigns values to `d_alarm`’s fields. At the next `Select::wait` call, the alarm fires (i.e., `wait` returns with return value 0) once the configured alarm-interval has passed:

```
inline void Selector::setAlarm(int sec, int usec)
{
    d_alarm.tv_sec  = sec;
    d_alarm.tv_usec = usec;
}
```

- `void noAlarm()`: this member switches off the alarm, by simply setting the alarm interval to a very long period:

```
inline void Selector::noAlarm()
{
    setAlarm(-1, -1);
}
```

- `void addReadFd(int fd)`: this member adds a file descriptor to the set of input file descriptors monitored by the `Selector` object. The member function `wait` returns once input is available at the indicated file descriptor:

```
inline void Selector::addReadFd(int fd)
{
    addFd(&d_read, fd);
}
```

- `void addWriteFd(int fd)`: this member adds a file descriptor to the set of output file descriptors monitored by the `Selector` object. The member function `wait` returns once output is available at the indicated file descriptor. Using `d_write`, it is implemented analogously to `addReadFd`;
- `void addExceptFd(int fd)`: this member adds a file descriptor to the set of exception file descriptors to be monitored by the `Selector` object. The member function `wait` returns once activity is sensed at the indicated file descriptor. Using `d_except`, it is implemented analogously to `addReadFd`;
- `void rmReadFd(int fd)`: this member removes a file descriptor from the set of input file descriptors monitored by the `Selector` object:

```
inline void Selector::rmReadFd(int fd)
{
    FD_CLR(fd, &d_read);
}
```

- `void rmWriteFd(int fd)`: this member removes a file descriptor from the set of output file descriptors monitored by the `Selector` object. Using `d_write`, it is implemented analogously to `rmReadFd`;
- `void rmExceptFd(int fd)`: this member removes a file descriptor from the set of exception file descriptors to be monitored by the `Selector` object. Using `d_except`, it is implemented analogously to `rmReadFd`;

The class’s remaining (two) members are support members, and should not be used by non-member functions. Therefore, they are declared in the class’s `private` section:

- The member `addFd` adds a file descriptor to a `fd_set`:

```
void Selector::addFd(fd_set *set, int fd)
```

```
    {
        FD_SET(fd, set);
        if (fd >= d_max)
            d_max = fd + 1;
    }
```

- The member `checkSet` tests whether a file descriptor (`*index`) is found in a `fd_set`:

```
    int Selector::checkSet(int *index, fd_set &set)
    {
        int &idx = *index;

        while (idx < d_max && !FD_ISSET(idx, &set))
            ++idx;

        return idx == d_max ? -1 : idx++;
    }
```

25.2.7.3 The class 'Monitor': interface

The `monitor` program uses a `Monitor` object doing most of the work. The class `Monitor`'s public interface only offers a default constructor and one member, `run`, to perform its tasks. All other member functions are located in the class's `private` section.

`Monitor` defines the `private` enum `Commands`, symbolically listing the various commands its input language supports, as well as several data members. Among the data members are a `Selector` object and a `map` using child order numbers as its keys and pointer to `Child` objects (see section 25.2.7.7) as its values. Furthermore, `Monitor` has a static array member `s_handler[]`, storing pointers to member functions handling user commands.

A destructor should be implemented as well, but its implementation is left as an exercise to the reader. Here is `Monitor`'s interface, including the interface of the nested class `Find` that is used to create a function object:

```
class Monitor
{
    enum Commands
    {
        UNKNOWN,
        START,
        EXIT,
        STOP,
        TEXT,
        sizeofCommands
    };

    typedef std::map<int, std::shared_ptr<Child>> MapIntChild;

    friend class Find;
    class Find
    {
        int     d_nr;
        public:
            Find(int nr);
            bool operator()(MapIntChild::value_type &vt) const;
    };

    Selector    d_selector;
    int         d_nr;
    MapIntChild d_child;

    static void (Monitor::*s_handler[])(int, std::string const &);
    static int s_initialize;

    public:
        enum Done
        {};

        Monitor();
        void run();

    private:
        static void killChild(MapIntChild::value_type it);
        static int initialize();

        Commands    next(int *value, std::string *line);
        void    processInput();
        void    processChild(int fd);

        void    createNewChild(int, std::string const &);
        void    exiting(int = 0, std::string const &msg = std::string{});
        void    sendChild(int value, std::string const &line);
        void    stopChild(int value, std::string const &);
        void    unknown(int, std::string const &);
};
```

Since there’s only one non-class type data member, the class’s constructor is a very simple function which could be implemented inline:

```
inline Monitor::Monitor()
:
    d_nr(0)
{}
```

25.2.7.4 The class ‘Monitor’: s_handler

The array `s_handler`, storing pointers to functions needs to be initialized as well. This can be accomplished in several ways:

- Since the `Commands` enumeration only specifies a fairly limited set of commands, compile-time initialization could be considered:

```
    void (Monitor::*Monitor::s_handler[])(int, string const &)  =
    {
        &Monitor::unknown,              // order follows enum Command's
        &Monitor::createNewChild,       // elements
        &Monitor::exiting,
        &Monitor::stopChild,
        &Monitor::sendChild,
    };
```

The advantage of this is that it's simple, not requiring any run-time effort. The disadvantage is of course relatively complex maintenance. If for some reason `Commands` is modified, `s_handler` must be modified as well. In cases like these, compile-time initialization often is asking for trouble. There is a simple alternative though.

- Looking at `Monitor`'s interface we see a static data member `s_initialize` and a static member function `initialize`. The static member function handles the initialization of the `s_handler` array. It explicitly assigns the array's elements and any modification in ordering of `enum Commands`' values is automatically accounted for by recompiling `initialize`:

```
    void (Monitor::*Monitor::s_handler[sizeofCommands])(int, string const &);

    int Monitor::initialize()
    {
        s_handler[UNKNOWN] =    &Monitor::unknown;
        s_handler[START] =      &Monitor::createNewChild;
        s_handler[EXIT] =       &Monitor::exiting;
        s_handler[STOP] =       &Monitor::stopChild;
        s_handler[TEXT] =       &Monitor::sendChild;
        return 0;
    }
```

  The member `initialize` is a static member and so it can be called to initialize `s_initialize`, a static `int` variable. The initialization is enforced by placing the initialization statement in the source file of a function that is known to be executed. It could be `main`, but if we're `Monitor`'s maintainers and only have control over the library containing `Monitor`'s code then that's not an option. In those cases the source file containing the destructor is a *very* good candidate. If a class has only one constructor and it's *not* defined inline then the constructor's source file is a good candidate as well. In `Monitor`'s current implementation the initialization statement is put in `run`'s source file, reasoning that `s_handler` is only needed when `run` is used.

25.2.7.5 The class 'Monitor': the member 'run'

`Monitor`'s core activities are performed by `run`. It performs the following tasks:

- Initially, the `Monitor` object only monitors its standard input. The set of input file descriptors to which `d_selector` listens is initialized to `STDIN_FILENO`.
- Then, in a loop `d_selector`'s `wait` function is called. If input on `cin` is available, it is processed by `processInput`. Otherwise, the input has arrived from a child process. Information sent by children is processed by `processChild`.
- To prevent *zombies*, the child processes must catch *their* children's termination signals. This is discussed below.

  As noted by Ben Simons (`ben at mrxfx dot com`) `Monitor` must not catch the termination signals. Instead, the process spawning child processes has that responsibility (the underlying principle being that a parent process is responsible for its child processes; a child process, in turn, is responsible for its own child processes).
- As stated, `run`'s source file also defines and initializes `s_initialize` to ensure the proper initialization of the `s_handler` array.

Here is `run`’s implementation and `s_initialize`’s definition:

```
#include "monitor.ih"

int Monitor::s_initialize = Monitor::initialize();

void Monitor::run()
{
    d_selector.addReadFd(STDIN_FILENO);

    while (true)
    {
        cout << "? " << flush;
        try
        {
            d_selector.wait();

            int fd;
            while ((fd = d_selector.readFd()) != -1)
            {
                if (fd == STDIN_FILENO)
                    processInput();
                else
                    processChild(fd);
            }
            cout << "NEXT ...\n";
        }
        catch (char const *msg)
        {
            exiting(1, msg);
        }
    }
}
```

The member function `processInput` reads the commands entered by the user using the program’s standard input stream. The member itself is rather simple. It calls `next` to obtain the next command entered by the user, and then calls the corresponding function using the matching element of the `s_handler[]` array. Here are the members `processInput` and `next`:

```
void Monitor::processInput()
{
    string line;
    int    value;
    Commands cmd = next(&value, &line);
    (this->*s_handler[cmd])(value, line);
}


Monitor::Commands Monitor::next(int *value, string *line)
{
    if (!getline(cin, *line))
        exiting(1, "Monitor::next(): reading cin failed");

    if (*line == "start")
        return START;
        if (*line == "exit" || *line == "quit")
        {
            *value = 0;
            return EXIT;
        }

        if (line->find("stop") == 0)
        {
            istringstream istr(line->substr(4));
            istr >> *value;
            return !istr ? UNKNOWN : STOP;
        }

        istringstream istr(line->c_str());
        istr >> *value;
        if (istr)
        {
            getline(istr, *line);
            return TEXT;
        }

        return UNKNOWN;
    }
```

All other input sensed by `d_select` is created by child processes. Because `d_select`'s `readFd` member returns the corresponding input file descriptor, this descriptor can be passed to `processChild`. Using a `IFdStreambuf` (see section 25.1.2.1), its information is read from an input stream. The communication protocol used here is rather basic. For every line of input sent to a child, the child replies by sending back exactly one line of text. This line is then read by `processChild`:

```
    void Monitor::processChild(int fd)
    {
        IFdStreambuf ifdbuf(fd);
        istream istr(&ifdbuf);
        string line;

        getline(istr, line);
        cout << d_child[fd]->pid() << ": " << line << '\n';
    }
```

The construction `d_child[fd]->pid()` used in the above source deserves some special attention. `Monitor` defines the data member `map<int, shared_ptr<Child>> d_child`. This map contains the child's order number as its key, and a (shared) pointer to the `Child` object as its value. A shared pointer is used here, rather than a `Child` object, since we want to use the facilities offered by the map, but don't want to copy a `Child` object time and again.

25.2.7.6 The class 'Monitor': example

Now that `run`'s implementation has been covered, we'll concentrate on the various commands users might enter:

- When the `start` command is issued, a new child process is started. A new element is added to `d_child` by the member `createNewChild`. Next, the `Child` object should start its activities, but the `Monitor` object can not wait for the child process to complete its activities, as there is no well-defined endpoint in the near future, and the user probably wants to be able to enter more commands. Therefore, the `Child` process must run as a *daemon*. So the forked process terminates immediately, but its own child process continues to run (in the background). Consequently, `createNewChild` calls the child's `fork` member. Although it is the child's `fork` function that is called, it is still the monitor program wherein that `fork` function is called. So, the *monitor* program is duplicated by `fork`. Execution then continues:

- At the `Child`'s `parentProcess` in its parent process;
- At the `Child`'s `childProcess` in its child process

As the `Child`'s `parentProcess` is an empty function, returning immediately, the `Child`'s parent process effectively continues immediately below `createNewChild`'s `cp->fork()` statement. As the child process never returns (see section 25.2.7.7), the code below `cp->fork()` is never executed by the `Child`'s child process. This is exactly as it should be.

In the parent process, `createNewChild`'s remaining code simply adds the file descriptor that's available for reading information from the child to the set of input file descriptors monitored by `d_select`, and uses `d_child` to establish the association between that file descriptor and the `Child` object's address:

```
void Monitor::createNewChild(int, string const &)
{
    Child *cp = new Child{ ++d_nr };

    cp->fork();

    int fd = cp->readFd();

    d_selector.addReadFd(fd);
    d_child[fd].reset(cp);

    cerr << "Child " << d_nr << " started\n";
}
```

- Direct communication with the child is required for the `stop <nr>` and `<nr> text` commands. The former command terminates child process `<nr>`, by calling `stopChild`. This function locates the child process having the order number using an anonymous object of the class `Find`, nested inside `Monitor`. The class `Find` simply compares the provided `nr` with the children's order number returned by their `nr` members:

```
inline Monitor::Find::Find(int nr)
:
    d_nr(nr)
{}
inline bool Monitor::Find::operator()(MapIntChild::value_type &vt) const
{
    return d_nr == vt.second->nr();
}
```

If the child process having order number `nr` was found, its file descriptor is removed from `d_selector`'s set of input file descriptors. Then the child process itself is terminated by the static member `killChild`. The member `killChild` is declared as a *static* member function, as it is used as function argument of the `for_each` generic algorithm by `exiting` (see below). Here is `killChild`'s implementation:

```
void Monitor::killChild(MapIntChild::value_type it)
{
        if (kill(it.second->pid(), SIGTERM))
            cerr << "Couldn't kill process " << it.second->pid() << '\n';

        // reap defunct child process
        int status = 0;
        while( waitpid( it.second->pid(), &status, WNOHANG) > -1)
            ;
    }
```

Having terminated the specified child process, the corresponding `Child` object is destroyed and its pointer is removed from `d_child`:

```
    void Monitor::stopChild(int nr, string const &)
    {
        auto it = find_if(d_child.begin(), d_child.end(), Find{ nr });

        if (it == d_child.end())
            cerr << "No child number " << nr << '\n';
        else
        {
            d_selector.rmReadFd(it->second->readFd());
            d_child.erase(it);
        }
    }
```

- The command `<nr> text` sends `text` to child process `nr` using the member function `sendChild`. This function also uses a `Find` object to locate the child-process having order number `nr`, and simply inserts the text into the writing end of a pipe connected to that child process:

```
    void Monitor::sendChild(int nr, string const &line)
    {
        auto it = find_if(d_child.begin(), d_child.end(), Find(nr));

        if (it == d_child.end())
            cerr << "No child number " << nr << '\n';
        else
        {
            OFdnStreambuf ofdn{ it->second->writeFd() };
            ostream out(&ofdn);

            out << line << '\n';
        }
    }
```

- When users enter `exit` or `quit` the member `exiting` is called. It terminates all child processes using the `for_each` generic algorithm (see section 19.1.18) to visit all elements of `d_child`. Then the program itself ends:

```
    void Monitor::exiting(int value, string const &msg)
    {
        for_each(d_child.begin(), d_child.end(), killChild);
        if (msg.length())
            cerr << msg << '\n';
        throw value;
    }
```

The program’s `main` function is simple and needs no further comment:

```
int main()
try
{
    Monitor{}.run();
}
catch (int exitValue)
{
    return exitValue;
}
```

25.2.7.7 The class ‘Child’

When the `Monitor` object starts a child process, it creates an object of the class `Child`. The `Child` class is derived from the class `Fork`, allowing it to operate as a *daemon* (as discussed in the previous section). Since `Child` is a daemon class, we know that its parent process must be defined as an empty function. Its `childProcess` member has a non-empty implementation. Here are the characteristics of the class `Child`:

- The `Child` class has two `Pipe` data members, to handle communications between its own child- and parent processes. As these pipes are used by the `Child`’s child process, their names refer to the child process. The child process reads from `d_in`, and writes to `d_out`. Here is the interface of the class `Child`:

```
class Child: public Fork
{
    Pipe                d_in;
    Pipe                d_out;

    int         d_parentReadFd;
    int         d_parentWriteFd;
    int         d_nr;

    public:
        Child(int nr);
        virtual ~Child();
        int readFd() const;
        int writeFd() const;
        int pid() const;
        int nr() const;
    private:
        virtual void childRedirections();
        virtual void parentRedirections();
        virtual void childProcess();
        virtual void parentProcess();
};
```

- The `Child`’s constructor simply stores its argument, a child-process order number, in its own `d_nr` data member:

```
inline Child::Child(int nr)
:
    d_nr(nr)
{}
```

- The `Child`'s child process obtains commands from its standard input stream and writes its output to its standard output stream. Since the actual communication channels are pipes, redirections must be used. The `childRedirections` member looks like this:

```
void Child::childRedirections()
{
    d_in.readFrom(STDIN_FILENO);
    d_out.writtenBy(STDOUT_FILENO);
}
```

- Although the parent process performs no actions, it must configure some redirections. Realizing that the names of the pipes indicate their functions in the child process. So the parent *writes* to `d_in` and *reads* from `d_out`. Here is `parentRedirections`:

```
void Child::parentRedirections()
{
    d_parentReadFd = d_out.readOnly();
    d_parentWriteFd = d_in.writeOnly();
}
```

- The `Child` object exists until it is destroyed by the `Monitor`'s `stopChild` member. By allowing its creator, the `Monitor` object, to access the parent-side ends of the pipes, the `Monitor` object can communicate with the `Child`'s child process via those pipe-ends. The members `readFd` and `writeFd` allow the `Monitor` object to access these pipe-ends:

```
inline int Child::readFd() const
{
    return d_parentReadFd;
}
inline int Child::writeFd() const
{
    return d_parentWriteFd;
}
```

- The `Child` object's child process performs two tasks:
  - It must reply to information appearing at its standard input stream;
  - If no information has appeared within a certain time frame (the implementations uses an interval of five seconds), then a message is written to its standard output stream.

  To implement this behavior, `childProcess` defines a local `Selector` object, adding `STDIN_FILENO` to its set of monitored input file descriptors.

  Then, in an endless loop, `childProcess` waits for `selector.wait()` to return. When the alarm goes off it sends a message to its standard output (hence, into the writing pipe). Otherwise, it echoes the messages appearing at its standard input to its standard output. Here is the `childProcess` member:

```
void Child::childProcess()
{
    Selector    selector;
    size_t    message = 0;

    selector.addReadFd(STDIN_FILENO);
    selector.setAlarm(5);

    while (true)
```

```
        {
            try
            {
                if (!selector.wait())       // timeout
                    cout << "Child " << d_nr << ": standing by\n";
                else
                {
                    string  line;
                    getline(cin, line);
                    cout << "Child " << d_nr << ":" << ++message << ": " <<
                                                        line << '\n';
                }
            }
            catch (...)
            {
                    cout << "Child " << d_nr << ":" << ++message << ": " <<
                                "select() failed" << '\n';
            }
        }
        exit(0);
    }
```

- Two accessors are defined allowing the `Monitor` object to obtain the `Child`'s process ID and its order number:

```
    inline int Child::pid() const
    {
        return Fork::pid();
    }
    inline int Child::nr() const
    {
        return d_nr;
    }
```

- A `Child` process terminates when the user enters a `stop` command. When an existing child process number was entered, the corresponding `Child` object is removed from `Monitor`'s `d_child` map. As a result, its destructor is called. `Child`'s destructor calls `kill` to terminate its child, and then waits for the child to terminate. Once its child has terminated, the destructor has completed its work and returns, thus completing the erasure from `d_child`. The current implementation fails if the child process doesn't react to the `SIGTERM` signal. In this demonstration program this does not happen. In 'real life' more elaborate killing-procedures may be required (e.g., using `SIGKILL` in addition to `SIGTERM`). As discussed in section 10.12 it *is* important to ensure the proper destruction. Here is the `Child`'s destructor:

```
    Child::~Child()
    {
        if (pid())
        {
            cout << "Killing process " << pid() << "\n";
            kill(pid(), SIGTERM);
            int status;
            wait(&status);
        }
    }
```

25.3 Adding binary operators to classes

As we've seen in section 11.6 binary operators expecting `const &` arguments can be implemented using a member implementing the operation, only offering the basic exception guarantee. This latter function can in turn be implemented using the binary assignment member. The following examples illustrated this approach for a fictitious class `Binary`:

```
class Binary
{
    public:
        Binary();
        Binary(int value);
            // copy and move constructors are available by default, or
            // they can be explicitly declared and implemented.

        Binary &operator+=(Binary const &other) &;     // see the text
        Binary &&operator+=(Binary const &other) &&;

    private:
        void add(Binary const &rhs);

    friend Binary operator+(Binary const &lhs, Binary const &rhs);
    friend Binary operator+(Binary &&lhs, Binary const &rhs);
};
```

Eventually, the implementation of binary operators depends on the availability of the member implementing the basic binary operation, modifying the object calling that member (i.e., `void Binary::add(Binary const &)` in the example).

Since template functions are not instantiated before they are actually used we can call non-existing functions from template functions that are never instantiated. If such a template function is never instantiated, nothing happens; if it is (accidentally) instantiated, then the compiler generates an error message, complaining about the missing function.

This allows us to implement all binary operators, movable and non-movable, as templates. In the following subsections we develop the class template `Binops`, prividing binary operators. A complete implementation of a class `Derived` illustrating how addition and insertion operators can be added to a class is provided in the file `annotations/yo/concrete/examples/binopclasses.cc` in the **C++** Annotations' source archive.

25.3.1 Merely using operators

In section 11.6 addition operators are implemented in terms of a support member `add`. This is less attractive when developing function templates, as `add` is a private member, requiring us to provide friend declarations for all function templates so they may access the private `add` member.

At the end of section 11.6 we saw that `add's` implementation can be provided by `operator+=(Class const &rhs) &&`. This operator may thereupon be used when implementing the remaining addition operators:

```
inline Binary &operator+=(Binary const &rhs) &
{
    return *this = Binary{*this} += rhs;
}
```

```
Binary operator+(Binary &&lhs, Binary const &rhs)
{
    return std::move(lhs) += rhs;
}

Binary operator+(Binary const &lhs, Binary const &rhs)
{
    return Binary{lhs} += rhs;
}
```

In this implementation `add` is no longer required. The plain binary operators are free functions, which supposedly can easily be converted to function templates. E.g.,

```
template <typename Binary>
Binary operator+(Binary const &lhs, Binary const &rhs)
{
    return Binary{lhs} += rhs;
}
```

25.3.1.1 To namespace or not to namespace?

When using the function template `Binary operator+(Binary const &lhs, Binary const &rhs)`, however, we may encounter a subtle and unexpected complication. Consider the following program. When run, it displays the value 12, rather than 1:

```
enum Values
{
    ZERO,
    ONE
};

template <typename Tp>
Tp operator+(Tp const &lhs, Tp const &rhs)
{
    return static_cast<Tp>(12);
};

int main()
{
    cout << (ZERO + ONE);        // shows 12
}
```

This complication can be avoided by defining the operators in their own namespace, but then all classes using the binary operator also have to be defined in that namespace, which is not a very attractive restriction. Fortunately, there is a better alternative: using the CRTP (cf. section 22.12).

25.3.2 The CRTP and defining operator function templates

When deriving classes from a class template `Binops`, using the CRTP the operators are defined for arguments of the class `Binops<Derived>`: a base class receiving the derived class as its template argument.

Thus the class `Binops` as well as the additional operators are defined, expecting `Binops<Derived>` type of arguments:

```
template <class Derived>
struct Binops
{
    Derived &operator+=(Derived const &rhs) &;
};

template <typename Derived>
Derived operator+(Binops<Derived> const &lhs, Derived const &rhs)
{
    return Derived{static_cast<Derived const &>(lhs) } += rhs;
}
// analogous implementation for Binops<Derived> &&lhs
```

This way, a class that derives from `Binops`, and that provides an `operator+=` member which is bound to an rvalue reference object, suddenly also provides all other binary addition operators:

```
class Derived: public Binops<Derived>
{
    ...
    public:
        ...
        Derived &&operator+=(Derived const &rhs) &&
};
```

All, but one....

The operator that's not available is the compound addition operator, bound to an lvalue reference. As its function name is identical to the one in the class `Derived`, it is not automatically visible at the user level.

Although this problem can simply be solved by providing the class `Derived` with a `using Binops<Derived>::operator+=` declaration, it is not a very attractive solution, as separate using declarations have to be provided for each binary operator that is implemented in the class `Derived`.

But a *much* more attractive solution exists. A beautiful out-of-the-box solution, completely avoiding the hidden base class operator, was proposed by Wiebe-Marten Wijnja. Wiebe-Marten conjectured that `operator+=`, bound to an lvalue reference could also very well be defined as a *free* function. In that case no inheritance is used and therefore no function hiding occurs. Consequently, the `using` directive can be avoided.

The implementation of this free `operator+=` function looks like this:

```
template <class Derived>
Derived &operator+=(Binops<Derived> &lhs, Derived const &rhs)
{
    Derived tmp{ Derived{ static_cast<Derived &>(lhs) } += rhs };
    tmp.swap(static_cast<Derived &>(lhs));
    return static_cast<Derived &>(lhs);
}
```

The flexibility of this design can be further augmented once we realize that the right-hand side operand doesn't have to be a `Derived` class object. Consider `operator<<`: oftentimes shifts are bit-shifts, using a `size_t` to specify the number of bits to shift. In fact, the type of the right-hand side operand can completely be generalized by defining a second template type parameter, which is used to specify the right-hand side's operand type. It's up to the `Derived` class to specify the argument type of its `operator+=` (or any other binary compound operator), whereafter the compiler will deduce the types of the right-hand side operands for the remaining binary operators. Here is the final implementation of the free `operator+=` function:

```
template <class Derived, typename Rhs>
Derived &operator+=(Binops<Derived> &lhs, Rhs const &rhs)
{
    Derived tmp{ Derived{ static_cast<Derived &>(lhs) } += rhs };
    tmp.swap(static_cast<Derived &>(lhs));
    return static_cast<Derived &>(lhs);
}
```

25.3.3 Insertion and extraction

Classes also frequently define overloaded insertion and extraction operators. Since there are no 'compound insertion operators' the design shown so far cannot be used when overloading these operators. Instead using standardized member function signatures is advocated: `void insert(std::ostream &out) const` to insert an object into an `ostream` and `void extract(std::istream &in) const` to extract an object from an `istream`. As these functions are only used by, respectively, the insertion and extraction operators, they can be declared in the `Derived` class's private interface. Instead of declaring the insertion and extraction operators friends of the class `Derived` a single `friend Binops<Derived>` is specified. This allows `Binops<Derived>` to define private, inline `iWrap` and `eWrap` members, merely calling, respectively, `Derived's insert` and `extract` members:

```
template <typename Derived>
inline void Binops<Derived>::iWrap(std::ostream &out) const
{
    static_cast<Derived const &>(*this).insert(out);
}
```

`Binops<Derived>` then declares the insertion and extraction operators as its friends, allowing these operators to call, respectively, `iWrap` and `eWrap`. Note that the software engineer designing the class `Derived` only has to provide a `friend Binops<Derived>` declaration. Here is the implementation of the overloaded insertion operator:

```
template <typename Derived>
std::ostream &operator<<(std::ostream &out, Binops<Derived> const &obj)
{
    obj.iWrap(out);
    return out;
}
```

This completes the coverage of the essentials of a class template `Binops` potentially offering binary operators and insertion/extraction operators for any class derived from `Binops`. Finally, as noted at the beginning of this section, a complete implementation of a class offering addition and insertion operators is provided in the file `annotations/yo/concrete/examples/binopclasses.cc` in the **C++** Annotations' source archive.

25.4 Distinguishing lvalues from rvalues with operator[]()

A problem with `operator[]` is that it can't distinguish between its use as an *lvalue* and as an *rvalue*. It is a familiar misconception to think that

```
    Type const &operator[](size_t index) const
```

is used as *rvalue* (as the object isn't modified), and that

```
    Type &operator[](size_t index)
```

is used as *lvalue* (as the returned value can be modified).

The compiler, however, distinguishes between the two operators only by the `const`-status of the object for which `operator[]` is called. With `const` objects the former operator is called, with non-`const` objects the latter is always used. It is always used, irrespective of it being used as lvalue or rvalue.

Being able to distinguish between lvalues and rvalues can be very useful. Consider the situation where a class supporting `operator[]` stores data of a type that is very hard to copy. With data like that reference counting (e.g., using `shared_ptr`s) is probably used to prevent needless copying.

As long as `operator[]` is used as rvalue there's no need to copy the data, but the information *must* be copied if it is used as lvalue.

The *Proxy Design Pattern* (cf. *Gamma et al.* (1995)) can be used to distinguish between lvalues and rvalues. With the Proxy Design Pattern an object of another class (the Proxy class) is used to act as a *stand in* for the 'real thing'. The proxy class offers functionality that cannot be offered by the data themselves, like distinguishing between its use as lvalue or rvalue. A proxy class can be used in many situations where access to the real data cannot or should not be directly provided. In this regard *iterator* types are examples of proxy classes as they create a layer between the real data and the software using the data. Proxy classes could also dereference pointers in a class storing its data by pointers.

In this section we concentrate on the distinction between using `operator[]` as lvalue and rvalue. Let's assume we have a class `Lines` storing lines from a file. Its constructor expects the name of a stream from which the lines are read and it offers a non-const `operator[]` that can be used as lvalue or rvalue (the `const` version of `operator[]` is omitted as it causes no confusion because it is always used as rvalue):

```
    class Lines
    {
        std::vector<std::string> d_line;

        public:
            Lines(std::istream &in);
            std::string &operator[](size_t idx);
    };
```

To distinguish between lvalues and rvalues we must find distinguishing characteristics of lvalues and rvalues that we can exploit. Such distinguishing characteristics are `operator=` (which is always used as lvalue) and the conversion operator (which is always used as rvalue). Rather than having `operator[]` return a `string &` we can let it return a `Proxy` object that is able to distinguish between its use as lvalue and rvalue.

The class `Proxy` thus needs `operator=(string const &other)` (acting as lvalue) and `operator std::string const &() const` (acting as rvalue). Do we need more operators? The `std::string` class also offers `operator+=`, so we should probably implement that operator as well. Plain characters can also be assigned to `string` objects (even using their numeric values). As `string` objects cannot be *constructed* from plain characters *promotion* cannot be used with `operator=(string const &other)` if the right-hand side argument is a character. Implementing `operator=(char value)` could therefore also be considered. These additional operators are left out of the current implementation but 'real life' proxy classes should consider implementing these additional operators as well. Another subtlety is that `Proxy`'s `operator std::string const &() const` is not used when using `ostream`'s insertion operator or `istream`'s extraction operator as these operators are implemented as templates not recognizing our `Proxy` class type. So when stream insertion and extraction is required (it probably is) then `Proxy` must be given its own overloaded insertion and extraction operator. Here is an implementation of the overloaded insertion operator inserting the object for which `Proxy` is a stand-in:

```
inline std::ostream &operator<<(std::ostream &out, Lines::Proxy const &proxy)
{
    return out << static_cast<std::string const &>(proxy);
}
```

There's no need for any code (except `Lines`) to create or copy `Proxy` objects. `Proxy`'s constructor should therefore be made private, and `Proxy` can declare `Lines` to be its friend. In fact, `Proxy` is intimately related to `Lines` and can be defined as a nested class. In the revised `Lines` class `operator[]` no longer returns a `string` but instead a `Proxy` is returned. Here is the revised `Lines` class, including its nested `Proxy` class:

```
    class Lines
    {
        std::vector<std::string> d_line;

        public:
            class Proxy;
            Proxy operator[](size_t idx);
            class Proxy
            {
                friend Proxy Lines::operator[](size_t idx);
                std::string &d_str;
                Proxy(std::string &str);
                public:
                    std::string &operator=(std::string const &rhs);
                    operator std::string const &() const;
            };
            Lines(std::istream &in);
    };
```

`Proxy`'s members are very lightweight and can usually be implemented inline:

```
    inline Lines::Proxy::Proxy(std::string &str)
    :
        d_str(str)
    {}
    inline std::string &Lines::Proxy::operator=(std::string const &rhs)
    {
        return d_str = rhs;
    }
    inline Lines::Proxy::operator std::string const &() const
    {
        return d_str;
    }
```

The member `Lines::operator[]` can also be implemented inline: it merely returns a `Proxy` object initialized with the `string` associated with index `idx`.

Now that the class `Proxy` has been developed it can be used in a program. Here is an example using the `Proxy` object as lvalue or rvalue. On the surface `Lines` objects won't behave differently from `Lines` objects using the original implementation, but by adding an identifying `cout` statement to `Proxy`'s members it can be shown that `operator[]` behaves differently when used as lvalue or as rvalue:

```
    int main()
    {
        ifstream in("lines.cc");
        Lines lines(in);

        string s = lines[0];         // rvalue use
        lines[0] = s;                // lvalue use
        cout << lines[0] << '\n';    // rvalue use
        lines[0] = "hello world";    // lvalue use
        cout << lines[0] << '\n';    // rvalue use
    }
```

25.5 Implementing a 'reverse_iterator'

In section 22.14.1 the construction of iterators and reverse iterators was discussed. In that section the iterator was constructed as an inner class in a class derived from a vector of pointers to strings.

An object of this nested iterator class handles the dereferencing of the pointers stored in the vector. This allowed us to sort the *strings* pointed to by the vector's elements rather than the *pointers*.

A drawback of this is that the class implementing the iterator is closely tied to the derived class as the iterator class was implemented as a nested class. What if we would like to provide any class derived from a container class storing pointers with an iterator handling pointer-dereferencing?

In this section a variant of the earlier (nested class) approach is discussed. Here the iterator class is defined as a class template, not only parameterizing the data type to which the container's elements point but also the container's iterator type itself. Once again, we concentrate on developing a *RandomIterator* as it is the most complex iterator type.

Our class is named `RandomPtrIterator`, indicating that it is a random iterator operating on pointer values. The class template defines three template type parameters:

- The first parameter specifies the derived class type (`Class`). Like before, `RandomPtrIterator`'s constructor is private. Therefore `friend` declarations are needed to allow client classes to construct `RandomPtrIterators`. However, a `friend class Class` cannot be used as template parameter types cannot be used in `friend class ...` declarations. But this is a minor problem as not every member of the client class needs to construct iterators. In fact, only `Class`'s `begin` and `end` members must construct iterators. Using the template's first parameter, friend declarations can be specified for the client's `begin` and `end` members.

- The second template parameter parameterizes the container’s iterator type (`BaseIterator`);
- The third template parameter indicates the data type to which the pointers point (`Type`).

`RandomPtrIterator` has one private data member, a `BaseIterator`. Here is the class interface and the constructor’s implementation:

```
#include <iterator>

template <typename Class, typename BaseIterator, typename Type>
class RandomPtrIterator:
      public std::iterator<std::random_access_iterator_tag, Type>
{
    friend RandomPtrIterator<Class, BaseIterator, Type> Class::begin();
    friend RandomPtrIterator<Class, BaseIterator, Type> Class::end();

    BaseIterator d_current;

    RandomPtrIterator(BaseIterator const &current);

    public:
        bool operator!=(RandomPtrIterator const &other) const;
        int operator-(RandomPtrIterator const &rhs) const;
        RandomPtrIterator operator+(int step) const;
        Type &operator*() const;
        bool operator<(RandomPtrIterator const &other) const;
        RandomPtrIterator &operator--();
        RandomPtrIterator operator--(int);
        RandomPtrIterator &operator++();
        RandomPtrIterator operator++(int);
        bool operator==(RandomPtrIterator const &other) const;
        RandomPtrIterator operator-(int step) const;
        RandomPtrIterator &operator-=(int step);
        RandomPtrIterator &operator+=(int step);
        Type *operator->() const;
};

template <typename Class, typename BaseIterator, typename Type>
RandomPtrIterator<Class, BaseIterator, Type>::RandomPtrIterator(
                                BaseIterator const &current)
:
    d_current(current)
{}
```

Looking at its `friend` declarations, we see that the members `begin` and `end` of a class `Class`, returning a `RandomPtrIterator` object for the types `Class, BaseIterator` and `Type` are granted access to `RandomPtrIterator`’s private constructor. That is exactly what we want. The `Class`’s `begin` and `end` members are declared as *bound friends*.

All `RandomPtrIterator`’s remaining members are public. Since `RandomPtrIterator` is just a generalization of the nested class `iterator` developed in section 22.14.1, re-implementing the required member functions is easy and only requires us to change `iterator` into `RandomPtrIterator` and to change `std::string` into `Type`. For example, `operator<`, defined in the class `iterator` as

```
inline bool operator<(StringPtr::iterator const &lhs,
                      StringPtr::iterator const &rhs)
{
    return lhs.d_current < rhs.d_current;
}
```

is now implemented as:

```
    template <typename Class, typename BaseIterator, typename Type>
    bool RandomPtrIterator<Class, BaseIterator, Type>::operator<(
                                RandomPtrIterator const &other) const
    {
        return **d_current < **other.d_current;
    }
```

Some additional examples: `operator*`, defined in the class `iterator` as

```
inline std::string &StringPtr::iterator::operator*() const
{
    return **d_current;
}
```

is now implemented as:

```
    template <typename Class, typename BaseIterator, typename Type>
    Type &RandomPtrIterator<Class, BaseIterator, Type>::operator*() const
    {
        return **d_current;
    }
```

The pre- and postfix increment operators are now implemented as:

```
    template <typename Class, typename BaseIterator, typename Type>
    RandomPtrIterator<Class, BaseIterator, Type>
    &RandomPtrIterator<Class, BaseIterator, Type>::operator++()
    {
        ++d_current;
        return *this;
    }
    template <typename Class, typename BaseIterator, typename Type>
    RandomPtrIterator<Class, BaseIterator, Type>
    RandomPtrIterator<Class, BaseIterator, Type>::operator++(int)
    {
        return RandomPtrIterator(d_current++);
    }
```

Remaining members can be implemented accordingly, their actual implementations are left as exercises to the reader (or can be obtained from the `cplusplus.yo.zip` archive, of course).

Re-implementing the class `StringPtr` developed in section 22.14.1 is not difficult either. Apart from including the header file defining the class template `RandomPtrIterator`, it only requires a single modification. Its `iterator` typedef must now be associated with a `RandomPtrIterator`. Here is the full class interface and the class's inline member definitions:

```
    #ifndef INCLUDED_STRINGPTR_H_
```

```
#define INCLUDED_STRINGPTR_H_

#include <vector>
#include <string>
#include "iterator.h"

class StringPtr: public std::vector<std::string *>
{
    public:
        typedef RandomPtrIterator
                <
                    StringPtr,
                    std::vector<std::string *>::iterator,
                    std::string
                >
                    iterator;

        typedef std::reverse_iterator<iterator> reverse_iterator;

        iterator begin();
        iterator end();
        reverse_iterator rbegin();
        reverse_iterator rend();
};

inline StringPtr::iterator StringPtr::begin()
{
    return iterator(this->std::vector<std::string *>::begin() );
}
inline StringPtr::iterator StringPtr::end()
{
    return iterator(this->std::vector<std::string *>::end());
}
inline StringPtr::reverse_iterator StringPtr::rbegin()
{
    return reverse_iterator(end());
}
inline StringPtr::reverse_iterator StringPtr::rend()
{
    return reverse_iterator(begin());
}
#endif
```

Including `StringPtr`'s modified header file into the program given in section 22.14.2 results in a program behaving identically to its earlier version. In this case `StringPtr::begin` and `StringPtr::end` return iterator objects constructed from a template definition.

25.6 Using ‘bisonc++’ and ‘flexc++’

The example discussed below digs into the peculiarities of using parser- and scanner generators generating **C++** sources. Once the input for a program exceeds a certain level of complexity, it becomes attractive to use scanner- and parser-generators generating the code which does the actual input recognition.

The examples in this and subsequent sections assume that the reader knows how to use the scanner generator `flex` and the parser generator `bison`. Both `bison` and `flex` are well documented elsewhere. The original predecessors of `bison` and `flex`, called `yacc` and `lex` are described in several books, e.g. in O'Reilly's book `'lex & yacc'`[3].

Scanner- and parser generators are also available as free software. Both `bison` and `flex` are usually part of software distributions or they can be obtained from `ftp://prep.ai.mit.edu/pub/non-gnu`. `Flex` creates a `C++` class when `%option c++` is specified.

For parser generators the program `bison` is available. In the early 90's *Alain Coetmeur* (`coetmeur@icdc.fr`[4]) created a **C++** variant (`bison++`) creating a parser class. Although the `bison++` program produces code that can be used in **C++** programs it also shows many characteristics that are more suggestive of a **C** context than a **C++** context. In January 2005 I rewrote parts of Alain's `bison++` program, resulting in the original version of the program **bisonc++**. Then, in May 2005 a complete rewrite of the `bisonc++` parser generator was completed (version number 0.98). Current versions of `bisonc++` can be downloaded from `https://fbb-git.gitlab.io/bisoncpp/`. Binary versions for various architectures are available as, e.g., `Debian`[5] package (including `bisonc++`'s documentation).

`Bisonc++` creates a cleaner parser class than `bison++`. In particular, it derives the parser class from a base-class, containing the parser's token- and type-definitions as well as all member functions which should not be (re)defined by the programmer. As a result of this approach, the generated parser class is very small, declaring only members that are actually defined by the programmer (as well as some other members, generated by `bisonc++` itself, implementing the parser's `parse()` member). One member that is *not* implemented by default is `lex`, producing the next lexical token. When the directive `%scanner` (see section 25.6.2.1) is used, `bisonc++` produces a standard implementation for this member; otherwise it must be implemented by the programmer.

In early 2012 the program **flexc++** `http://flexcpp.org/` reached its initial release. Like `bisonc++` it is part of the `Debian linux distribution`[6].

Jean-Paul van Oosten (j.p.van.oosten@rug.nl<`j.p.van.oosten@rug.nl`>) and Richard Berendsen (richardberendsen@xs4all.nl<`richardberendsen@xs4all.nl`>) started the `flexc++` project in 2008 and the final program was completed by Jean-Paul and me between 2010 and 2012.

These sections of the **C++** Annotations focus on `bisonc++` as our *parser generator* and `flexc++` as our lexical scanner generator. Previous releases of the **C++** Annotations were using `flex` as the scanner generator.

Using `flex++` and `bisonc++` `class`-based scanners and parsers are generated. The advantage of this approach is that the interface to the scanner and the parser tends to become cleaner than without using `class` interfaces. Furthermore, classes allow us to get rid of most if not all global variables, making it easy to use multiple parsers in one program.

Below two example programs are developed. The first example only uses `flexc++`. The generated scanner monitors the production of a file from several parts. That example focuses on the lexical scanner and on switching files while churning through the information. The second example uses both `flexc++` and `bisonc++` to generate a scanner and a parser transforming standard arithmetic expressions to their postfix notations, commonly used in code generated by compilers and in `HP`-calculators. In the second example the emphasis is mainly on `bisonc++` and on composing a scanner object inside a generated parser.

---

[3] http://www.oreilly.com/catalog/lex

[4] mailto:coetmeur@icdc.fr

[5] http://www.debian.org

[6] http://www.debian.org

25.6.1 Using ‘flexc++’ to create a scanner

The lexical scanner developed in this section is used to monitor the production of a file from several subfiles. The setup is as follows: the input-language defines `#include` directives, followed by a text string specifying the file (path) which should be included at the location of the `#include`.

In order to avoid complexities irrelevant to the current example, the format of the `#include` statement is restricted to the form `#include <filepath>`. The file specified between the angle brackets should be available at the location indicated by `filepath`. If the file is not available, the program terminates after issuing an error message.

The program is started with one or two filename arguments. If the program is started with just one filename argument, the output is written to the standard output stream `cout`. Otherwise, the output is written to the stream whose name is given as the program’s second argument.

The program defines a maximum nesting depth. Once this maximum is exceeded, the program terminates after issuing an error message. In that case, the filename stack indicating where which file was included is printed.

An additional feature of the program is that (standard **C++**) comment-lines are ignored. Include-directives in comment-lines are also ignored.

The program is created in five major steps:

- First, the file `lexer` is constructed, containing the input-language specifications.
- From the specifications in `lexer` the requirements for the `class Scanner` evolve. The `Scanner` class derives from the base class `ScannerBase` generated by `flexc++`.
- Next, `main` is constructed. A `Scanner` object is created inspecting the command-line arguments. If successful, the scanner’s member `lex` is called to produce the program’s output.
- Now that the global setup of the program has been specified, the member functions of the various classes are implemented.
- Finally, the program is compiled and linked.

25.6.1.1 The derived class ‘Scanner’

The function matching the regular expression rules (`lex`) is a member of the class `Scanner`. Since `Scanner` is derived from `ScannerBase`, it has access to all of `ScannerBase`’s protected members that execute the lexical scanner’s regular expression matching algorithm.

Looking at the regular expressions themselves, notice that we need rules to recognize comment, `#include` directives, and all remaining characters. This all is fairly standard practice. When an `#include` directive is sensed, the directive is parsed by the scanner. This too is common practice. Our lexical scanner performs the following tasks:

- As usual, preprocessor directives are not analyzed by a parser, but by the lexical scanner;
- The scanner uses a mini scanner to extract the filename from the directive, throwing a exception if this fails;
- If the filename could be extracted, processing switches to the next stream, controlling for a maximum nesting depth.
- Once the end of the current file has been reached processing automatically returns to the previous file, restoring the previous file name and line number. The scanner returns 0 if all files have been processed.

25.6.1.2 The lexical scanner specification file

The lexical scanner specification file is organized comparably to the one used for `flex` in **C** contexts. However, in **C++** contexts, `flexc++` creates a class `Scanner`, rather than just a scanner function.

Flexc++'s specification file consists of two sections:

- The specification file's first section is `flexc++`'s *symbol area*, used to define symbols, like a mini scanner, or *options*. The following options are suggested:
  - `%debug`: includes *debugging* code into the code generated by `flexc++`. Calling the member function `setDebug(true)` activates this debugging code at run-time. When activated, information about the matching process is written to the standard output stream. The execution of debug code is suppressed after calling the member function `setDebug(false)`.
  - `%filenames`: defines the base-name of the class header files generated by `flexc++`. By default the class name (itself using the default `Scanner`) is used.

  Here is the specification files' symbol area:

```
%filenames scanner
%debug
%max-depth 3

%x      comment
%x      include
```

- The specification file's second section is a *rules section* in which the regular expressions and their associated actions are defined. In the example developed here, the lexer should copy information from the standard input stream (`std::cin`) to the standard output stream (`std::cout`). For this the predefined macro `ECHO` can be used. Here are the rules:

```
%%
    // The comment-rules: comment is ignored.
//.*                    // ignore eoln comment
"/*"                    begin(StartCondition__::comment);
<comment>{
    .|\n                // ignore all characters in std C comment
    "*/"                begin(StartCondition__::INITIAL);
}

    // File switching: #include <filepath>
#include[ \t]+"<"      begin(StartCondition__::include);
<include>{
    [^ \t>]+            d_nextSource = matched();
    ">"[ \t]*\n         switchSource();
    .|\n                throw runtime_error("Invalid include statement");
}

    // The default rule: echo anything else to std::cout
.|\n                    echo();
```

25.6.1.3 Implementing 'Scanner'

The `class Scanner` is generated once by **flexc++**. This class has access to several members defined by its base class `ScannerBase`. Some of these members have public access rights and can be used by code external to the class `Scanner`. These members are extensively documented in the **flexc++**(1) man-page, and the reader is referred to this man-page for further information.

Our scanner performs the following tasks:

- it matches regular expressions, ignoring comment, and writing the matched text to the standard output stream;
- it switches to other files, and returns to the previous file once a file has completely been processed, ending the lexical scan once the end of the first input file has been reached.

The `#include` statements in the input allow the scanner to distill the name of the file where the scanning process must continue. This file name is stored in a local variable `d_nextSource` and a member `stackSource` handles the switch to the next source. Nothing else is required. Pushing and popping input files is handled by the scanner's members `pushStream` and `popStream`, provided by `flexc++`. `Scanner`'s interface, therefore, only needs one additional function declaration: `switchSource`.

Switching streams is handled as follows: once the scanner has extracted a filename from an `#include` directive, a switch to another file is realized by `switchSource`. This member calls `pushStream`, defined by `flexc++`, to stack the current input stream and to switch to the stream whose name is stored in `d_nextSource`. This also ends the `include` mini-scanner, so to return the scanner to its default scanning mode `begin(StartCondition__::INITIAL)` is called. Here is its source:

```
#include "scanner.ih"

void Scanner::switchSource()
{
    pushStream(d_nextSource);
    begin(StartCondition__::INITIAL);
}
```

The member `pushStream`, defined by `flexc++`, handles all necessary checks, throwing an exception if the file could not be opened or if too many files are stacked.

The member performing the lexical scan is defined by `flexc++` in `Scanner::lex`, and this member can be called by code to process the tokens returned by the scanner.

25.6.1.4 Using a 'Scanner' object

The program using our `Scanner` is very simple. It expects a filename indicating where to start the scanning process.

The program first checks the number of arguments. If at least one argument was given, then that argument is passed to `Scanner`'s constructor, together with a second argument `"-"`, indicating that the output should go to the standard output stream.

If the program receives more than one argument debug output, extensively documenting the lexical scanner's actions, is written to the standard output stream as well.

Next the `Scanner`'s `lex` member is called. If anything fails, a `std::exception` is thrown, which is caught by `main`'s try-block's catch clause. Here is the program's source:

```
#include "lexer.ih"
```

```
int main(int argc, char **argv)
try
{
    if (argc == 1)
    {
        cerr << "Filename argument required\n";
        return 1;
    }

    Scanner scanner(argv[1], "-");

    scanner.setDebug(argc > 2);

    return scanner.lex();
}
catch (exception const &exc)
{
    cerr << exc.what() << '\n';
    return 1;
}
```

25.6.1.5 Building the program

The final program is constructed in two steps. These steps are given for a Unix system, on which `flexc++` and the GNU **C++** compiler `g++` have been installed:

- First, the lexical scanner's source is created using `flexc++`. For this the following command can be given:

  ```
  flexc++ lexer
  ```

- Next, all sources are compiled and linked:

  ```
  g++ -Wall *.cc
  ```

`Flexc++` can be downloaded from `https://fbb-git.gitlab.io/flexcpp/`, and requires the `bobcat` library, which can be downloaded from `http://fbb-git.gitlab.io/bobcat/`.

25.6.2 Using 'bisonc++' and 'flexc++'

Once an input language exceeds a certain level of complexity, a *parser* is often used to control the complexity of the language. In this case, a *parser generator* can be used to generate the code verifying the input's grammatical correctness. The lexical scanner (preferably composed into the parser) provides chunks of the input, called *tokens*. The parser then processes the series of tokens generated by the lexical scanner.

Starting point when developing programs that use both parsers and scanners is the grammar. The grammar defines a *set of tokens* that can be returned by the lexical scanner (called the *scanner* below).

Finally, auxiliary code is provided to 'fill in the blanks': the actions performed by the parser and by the scanner are not normally specified literally in the grammar rules or lexical regular expressions, but should be implemented in *member functions*, called from the parser's rules or which are associated with the scanner's regular expressions.

In the previous section we've seen an example of a **C++** class generated by `flexc++`. In the current section we concentrate on the parser. The parser can be generated from a grammar specification file, processed by the program `bisonc++`. The grammar specification file required by `bisonc++` is similar to the file processed by `bison` (or `bison++`, `bisonc++`'s predecessor, written in the early nineties by *Alain Coetmeur*).

In this section a program is developed converting *infix expressions*, where binary operators are written between their operands, to *postfix expressions*, where operators are written behind their operands. Also, the unary operator `-` is converted from its prefix notation to a postfix form. The unary `+` operator is ignored as it requires no further actions. In essence our little calculator is a micro compiler, transforming numeric expressions into assembly-like instructions.

Our calculator recognizes a rather basic set of operators: multiplication, addition, parentheses, and the unary minus. We'll distinguish real numbers from integers, to illustrate a subtlety in bison-like grammar specifications. That's all. The purpose of this section is, after all, to illustrate the construction of a **C++** program that uses both a parser and a lexical scanner, rather than to construct a full-fledged calculator.

In the coming sections we'll develop the grammar specification for `bisonc++`. Then, the regular expressions for the scanner are specified. Following that, the final program is constructed.

25.6.2.1 The 'bisonc++' specification file

The grammar specification file required by `bisonc++` is comparable to the specification file required by `bison`. Differences are related to the class nature of the resulting parser. Our calculator distinguishes real numbers from integers, and supports a basic set of arithmetic operators.

`Bisonc++` should be used as follows:

- As usual, a grammar is defined. With `bisonc++` this is no different, and `bisonc++` grammar definitions are for all practical purposes identical to `bison`'s grammar definitions.
- Having specified the grammar and (usually) some declarations `bisonc++` can generate files defining the parser class and the implementation of the member function `parse`.
- All class members (except those that are required for the proper functioning of the member `parse`) must be separately implemented. Of course, they should also be declared in the parser class's header. At the very least the member `lex` must be implemented. This member is called by `parse` to obtain the next available token. However, `bisonc++` offers a facility providing a standard implementation of the function `lex`. The member function `error(char const *msg)` is given a simple default implementation that may be modified by the programmer. The member function `error` is called when `parse` detects (syntactic) errors.
- The parser can now be used in a program. A very simple example would be:

```
int main()
{
    Parser parser;
    return parser.parse();
}
```

The `bisonc++` specification file has two sections:

- The *declaration section*. In this section bison's tokens, and the priority rules for the operators are declared. However, `bisonc++` also supports several new declarations. These new declarations are important and are discussed below.

- The *rules section*. The grammatical rules define the grammar. This section is identical to the one required by `bison`, albeit that some members that were available in `bison` and `bison++` are obsolete in `bisonc++`, while other members can be used in a wider context. For example, **ACCEPT** and **ABORT** can be called from any member called from the parser's action blocks to terminate the parsing process.

Readers familiar with `bison` may note that there is no *header section* anymore. Header sections are used by bison to provide for the necessary declarations allowing the compiler to compile the **C** function generated by `bison`. In **C++** declarations are part of or already used by class definitions. Therefore, a parser generator generating a **C++** class and some of its member functions does not require a header section anymore.

The declaration section The declaration section contains several sets of declarations, among which definitions of all the tokens used in the grammar and the priorities and associativities of the mathematical operators. Moreover, several new and important specifications can be used here as well. Those relevant to our current example and only available in `bisonc++` are discussed here. The reader is referred to `bisonc++`'s man-page for a full description.

- **%baseclass-preinclude** `header`
  Use `header` as the pathname to the file pre-included in the parser's base-class header. This declaration is useful in situations where the base class header file refers to types which might not yet be known. E.g., with `%union` a `std::string *` field might be used. Since the class `std::string` might not yet be known to the compiler once it processes the base class header file we need a way to inform the compiler about these classes and types. The suggested procedure is to use a pre-include header file declaring the required types. By default `header` is surrounded by double quotes (using, e.g., `#include "header"`). When the argument is surrounded by angle brackets `#include <header>` is included. In the latter case, quotes might be required to escape interpretation by the shell (e.g., using `-H '<header>'`).

- **%filenames** `header`
  Defines the generic name of all generated files, unless overridden by specific names. By default the generated files use the class-name as the generic file name.

- **%scanner** `header`
  Use `header` as the pathname to the file pre-included in the parser's class header. This file should define a class `Scanner`, offering a member `int lex()` producing the next token from the input stream to be analyzed by the parser generated by `bisonc++`. When this option is used the parser's member `int lex()` is predefined as (assuming the default parser class name `Parser` is used):

  ```
  inline int Parser::lex()
  {
      return d_scanner.lex();
  }
  ```

  and an object `Scanner d_scanner` is composed into the parser. The `d_scanner` object is constructed by its default constructor. If another constructor is required, the parser class may be provided with an appropriate (overloaded) parser constructor after having constructed the default parser class header file using `bisonc++`. By default `header` is surrounded by double quotes (using, e.g., `#include "header"`). When the argument is surrounded by angle brackets `#include <header>` is included.

- **%stype** `typename`
  The type of the semantic value of tokens. The specification `typename` should be the name of an unstructured type (e.g., `size_t`). By default it is `int`. See `YYSTYPE` in `bison`. It should

not be used if a `%union` specification is used. Within the parser class, this type may be used as `STYPE`.

- **%union** `union-definition`
  Acts identically to the `bison` declaration. As with `bison` this generates a union for the parser's semantic type. The union type is named `STYPE`. If no `%union` is declared, a simple stack-type may be defined using the `%stype` declaration. If no `%stype` declaration is used, the default stacktype (`int`) is used.

An example of a `%union` declaration is:

```
%union
{
    int     i;
    double  d;
};
```

In pre-C++11 code a union cannot contain objects as its fields, as constructors cannot be called when a union is created. This means that a `string` cannot be a member of the union. A `string *`, however, *is* a possible union member. It might also be possible to use *unrestricted unions* (cf. section 9.9), having class type objects as fields.

As an aside: the scanner does not have to know about such a union. It can simply pass its scanned text to the parser through its `matched` member function. For example using a statement like

```
$$.i = A2x(d_scanner.matched());
```

matched text is converted to a value of an appropriate type.

Tokens and non-terminals can be associated with union fields. This is strongly advised, as it prevents type mismatches, since the compiler may then check for type correctness. At the same time, the bison specific variables `$$`, `$1`, `$2`, etc. may be used, rather than the full field specification (like `$$.i`). A non-terminal or a token may be associated with a union field using the `<fieldname>` specification. E.g.,

```
%token <i> INT          // token association (deprecated, see below)
       <d> DOUBLE
%type  <i> intExpr      // non-terminal association
```

In the example developed here, both the tokens and the non-terminals can be associated with a union field. However, as noted before, the scanner does not have to know about all this. In our opinion, it is cleaner to let the scanner do just one thing: scan texts. The *parser*, knowing what the input is all about, may then convert strings like `"123"` to an integer value. Consequently, the association of a union field and a token is discouraged. Below, while describing the grammar's rules, this is further illustrated.

In the `%union` discussion the `%token` and `%type` specifications should be noted. They are used to specify the tokens (terminal symbols) that can be returned by the scanner, and to specify the return types of non-terminals. Apart from `%token` the token declarators `%left`, `%right`, and `%nonassoc` can be used to specify the associativity of operators. The tokens mentioned at these indicators are interpreted as tokens indicating operators, associating in the indicated direction. The precedence of operators is defined by their order: the first specification has the lowest priority. To overrule a certain precedence in a certain context `%prec` can be used. As all this is standard `bisonc++` practice, it isn't further elaborated here. The documentation provided with `bisonc++`'s distribution should be consulted for further reference.

Here is the specification of the calculator's declaration section:

```
%filenames parser
%scanner ../scanner/scanner.h

%union {
    int i;
    double d;
};

%token  INT DOUBLE

%type   <i> intExpr
%type   <d> doubleExpr

%left   '+'
%left   '*'
%right  UnaryMinus
```

In the declaration section `%type` specifiers are used, associating the `intExpr` rule's value (see the next section) to the `i`-field of the semantic-value union, and associating `doubleExpr`'s value to the `d`-field. This approach, admittedly, is rather complex, as expression rules must be included for each of the supported union types. Alternatives are definitely possible, and involve the use of *polymorphic semantic values*, covered in detail in the `Bisonc++ user guide`[7].

The grammar rules The rules and actions of the grammar are specified as usual. The grammar for our little calculator is given below. There are quite a few rules, but they illustrate various features offered by `bisonc++`. In particular, note that no action block requires more than a single line of code. This keeps the grammar simple, and therefore enhances its readability and understandability. Even the rule defining the parser's proper termination (the empty line in the `line` rule) uses a single member function called `done`. The implementation of that function is simple, but it is worth while noting that it calls **Parser::ACCEPT**, showing that **ACCEPT** can be called indirectly from a production rule's action block. Here are the grammar's production rules:

```
    lines:
        lines
        line
    |
        line
    ;

    line:
        intExpr
        '\n'
        {
            display($1);
        }
    |
        doubleExpr
        '\n'
        {
            display($1);
```

---

[7] http://fbb-git.gitlab.io/bisoncpp/manual/bisonc++.html

```
        }
    |
        '\n'
        {
            done();
        }
    |
        error
        '\n'
        {
            reset();
        }
    ;

    intExpr:
        intExpr '*' intExpr
        {
            $$ = exec('*', $1, $3);
        }
    |
        intExpr '+' intExpr
        {
            $$ = exec('+', $1, $3);
        }
    |
        '(' intExpr ')'
        {

            $$ = $2;
        }
    |
        '-' intExpr         %prec UnaryMinus
        {
            $$ = neg($2);
        }
    |
        INT
        {
            $$ = convert<int>();
        }
    ;

    doubleExpr:
        doubleExpr '*' doubleExpr
        {
            $$ = exec('*', $1, $3);
        }
    |
        doubleExpr '*' intExpr
        {
            $$ = exec('*', $1, d($3));
        }
    |
        intExpr '*' doubleExpr
        {
            $$ = exec('*', d($1), $3);
        }
    |
        doubleExpr '+' doubleExpr
        {
            $$ = exec('+', $1, $3);
        }
    |
        doubleExpr '+' intExpr
        {
            $$ = exec('+', $1, d($3));
        }
    |
        intExpr '+' doubleExpr
        {
            $$ = exec('+', d($1), $3);
        }
    |
        '(' doubleExpr ')'
        {
            $$ = $2;
        }
    |
        '-' doubleExpr         %prec UnaryMinus
        {

            $$ = neg($2);
        }
    |
        DOUBLE
        {
            $$ = convert<double>();
        }
    ;
```

This grammar is used to implement a simple calculator in which integer and real values can be negated, added, and multiplied and in which standard priority rules can be overruled by parentheses. The grammar shows the use of typed nonterminal symbols: `doubleExpr` is linked to real (double) values, `intExpr` is linked to integer values. Precedence and type association is defined in the parser's definition section.

The Parser's header file Several class members called from the grammar are defined as member templates. `Bisonc++` generates multiple files, among which the file defining the parser's class. Functions called from the production rule's action blocks are usually member functions of the parser. These member functions must be declared and defined. Once `bisonc++` has generated the header file defining the parser's class, that header file isn't automatically rewritten, allowing the programmer to add new members to the parser class whenever required. Here is '`parser.h`' as used in our little calculator:

```
#ifndef Parser_h_included
#define Parser_h_included

#include <iostream>
#include <sstream>
#include <bobcat/a2x>
```

```
#include "parserbase.h"
#include "../scanner/scanner.h"

#undef Parser
class Parser: public ParserBase
{
    std::ostringstream d_rpn;
    // $insert scannerobject
    Scanner d_scanner;

    public:
        int parse();

    private:
        template <typename Type>
        Type exec(char c, Type left, Type right);

        template <typename Type>
        Type neg(Type op);

        template <typename Type>
        Type convert();

        void display(int x);
        void display(double x);
        void done() const;
        void reset();
        void error(char const *msg);
        int lex();
        void print();

        static double d(int i);

    // support functions for parse():

        void executeAction(int d_ruleNr);
        void errorRecovery();
        int lookup(bool recovery);
        void nextToken();
        void print__();
};

inline double Parser::d(int i)
{
    return i;
}

template <typename Type>
Type Parser::exec(char c, Type left, Type right)
{
    d_rpn << " " << c << " ";
    return c == '*' ? left * right : left + right;
}

template <typename Type>
```

```
Type Parser::neg(Type op)
{
    d_rpn << " n ";
    return -op;
}

template <typename Type>
Type Parser::convert()
{
    Type ret = FBB::A2x(d_scanner.matched());
    d_rpn << " " << ret << " ";
    return ret;
}

inline void Parser::error(char const *msg)
{
    std::cerr << msg << '\n';
}

inline int Parser::lex()
{
    return d_scanner.lex();
}

inline void Parser::print()
{}

#endif
```

25.6.2.2 The ‘flexc++’ specification file

The flex-specification file used by the calculator is simple: blanks are ignored, single characters are returned, and numeric values are returned as either `Parser::INT` or `Parser::DOUBLE` tokens.

The `flexc++` directive `%interactive` is provided since the calculator is a program actively interacting with its human user.

Here is the complete `flexc++` specification file:

```
%interactive
%filenames scanner

%%

[ \t]                       // ignored

[0-9]+                      return Parser::INT;

"."[0-9]*                   |
[0-9]+("."[0-9]*)?          return Parser::DOUBLE;

.|\n                        return matched()[0];
```

25.6.2.3 Building the program

The calculator is built using `bisonc++` and `flexc++`. Here is the implementation of the calculator’s `main` function:

```
#include "parser/parser.h"

using namespace std;

int main()
{
    Parser parser;

    cout << "Enter (nested) expressions containing ints, doubles, *, + and "
            "unary -\n"
            "operators. Enter an empty line to stop.\n";

    return parser.parse();
}
```

The parser’s files `parse.cc` and `parserbase.h` are generated by the command:

```
    bisonc++ grammar
```

The file `parser.h` is created only once, to allow the developer to add members to the `Parser` class occe the need for them arises.

The program `flexc++` is used to create a lexical scanner:

```
    flexc++ lexer
```

On Unix systems a command like

```
    g++ -Wall -o calc *.cc -lbobcat -s
```

can be used to compile and link the source of the main program and the sources produced by the scanner and parser generators. The example uses the `A2x` class, which is part of the `bobcat` library (cf. section 25.6.1.5) (the bobcat library is available on systems offering either `bisonc++` or `flexc++`). `Bisonc++` can be downloaded from

`http://fbb-git.gitlab.io/bisoncpp/`.

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