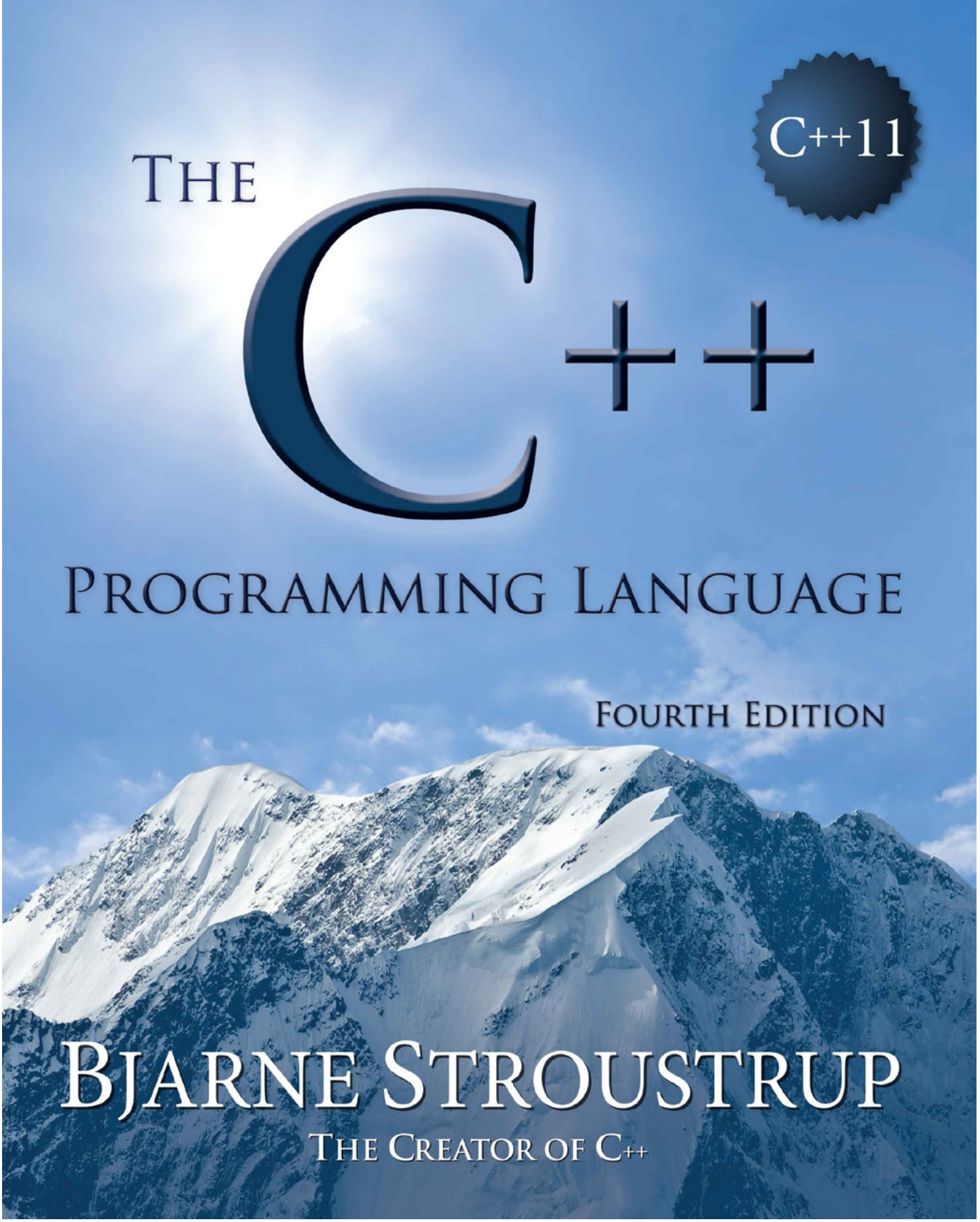

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The C++ Programming Language

Fourth Edition

Bjarne Stroustrup

Addison-Wesley

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Preface

All problems in computer science
can be solved by another level of indirection,
except for the problem of too many layers of indirection.
– David J. Wheeler

C++ feels like a new language. That is, I can express my ideas more clearly, more simply, and more directly in C++11 than I could in C++98. Furthermore, the resulting programs are better checked by the compiler and run faster.

In this book, I aim for *completeness*. I describe every language feature and standard-library component that a professional programmer is likely to need. For each, I provide:

- *Rationale*: What kinds of problems is it designed to help solve? What principles underlie the design? What are the fundamental limitations?
- *Specification*: What is its definition? The level of detail is chosen for the expert programmer; the aspiring language lawyer can follow the many references to the ISO standard.
- *Examples*: How can it be used well by itself and in combination with other features? What are the key techniques and idioms? What are the implications for maintainability and performance?

The use of C++ has changed dramatically over the years and so has the language itself. From the point of view of a programmer, most of the changes have been improvements. The current ISO standard C++ (ISO/IEC 14882-2011, usually called C++11) is simply a far better tool for writing quality software than were previous versions. How is it a better tool? What kinds of programming styles and techniques does modern C++ support? What language and standard-library features support those techniques? What are the basic building blocks of elegant, correct, maintainable, and efficient C++ code? Those are the key questions answered by this book. Many answers are not the same as you would find with 1985, 1995, or 2005 vintage C++: progress happens.

C++ is a general-purpose programming language emphasizing the design and use of type-rich, lightweight abstractions. It is particularly suited for resource-constrained applications, such as those found in software infrastructures. C++ rewards the programmer who takes the time to master

techniques for writing quality code. C++ is a language for someone who takes the task of programming seriously. Our civilization depends critically on software; it had better be quality software.

There are billions of lines of C++ deployed. This puts a premium on stability, so 1985 and 1995 C++ code still works and will continue to work for decades. However, for all applications, you can do better with modern C++; if you stick to older styles, you will be writing lower-quality and worse-performing code. The emphasis on stability also implies that standards-conforming code you write today will still work a couple of decades from now. All code in this book conforms to the 2011 ISO C++ standard.

This book is aimed at three audiences:

- C++ programmers who want to know what the latest ISO C++ standard has to offer,
- C programmers who wonder what C++ provides beyond C, and
- People with a background in application languages, such as Java, C#, Python, and Ruby, looking for something ''closer to the machine'' – something more flexible, something offering better compile-time checking, or something offering better performance.

Naturally, these three groups are not disjoint – a professional software developer masters more than just one programming language.

This book assumes that its readers are programmers. If you ask, ''What's a for-loop?'' or ''What's a compiler?'' then this book is not (yet) for you; instead, I recommend my *Programming: Principles and Practice Using C++* to get started with programming and C++. Furthermore, I assume that readers have some maturity as software developers. If you ask ''Why bother testing?'' or say, ''All languages are basically the same; just show me the syntax'' or are confident that there is a single language that is ideal for every task, this is not the book for you.

What features does C++11 offer over and above C++98? A machine model suitable for modern computers with lots of concurrency. Language and standard-library facilities for doing systems-level concurrent programming (e.g., using multicores). Regular expression handling, resource management pointers, random numbers, improved containers (including, hash tables), and more. General and uniform initialization, a simpler **for**-statement, move semantics, basic Unicode support, lambdas, general constant expressions, control over class defaults, variadic templates, user-defined literals, and more. Please remember that those libraries and language features exist to support programming techniques for developing quality software. They are meant to be used in combination – as bricks in a building set – rather than to be used individually in relative isolation to solve a specific problem. A computer is a universal machine, and C++ serves it in that capacity. In particular, C++'s design aims to be sufficiently flexible and general to cope with future problems undreamed of by its designers.

Acknowledgments

In addition to the people mentioned in the acknowledgment sections of the previous editions, I would like to thank Pete Becker, Hans-J. Boehm, Marshall Clow, Jonathan Coe, Lawrence Crowl, Walter Daugherty, J. Daniel Garcia, Robert Harle, Greg Hickman, Howard Hinnant, Brian Kernighan, Daniel Krügler, Nevin Liber, Michel Michaud, Gary Powell, Jan Christiaan van Winkel, and Leor Zolman. Without their help this book would have been much poorer.

Thanks to Howard Hinnant for answering many questions about the standard library.

Andrew Sutton is the author of the Origin library, which was the testbed for much of the discussion of emulating concepts in the template chapters, and of the matrix library that is the topic of Chapter 29. The Origin library is open source and can be found by searching the Web for ‘‘Origin’’ and ‘‘Andrew Sutton.’’

Thanks to my graduate design class for finding more problems with the ‘‘tour chapters’’ than anyone else.

Had I been able to follow every piece of advice of my reviewers, the book would undoubtedly have been much improved, but it would also have been hundreds of pages longer. Every expert reviewer suggested adding technical details, advanced examples, and many useful development conventions; every novice reviewer (or educator) suggested adding examples; and most reviewers observed (correctly) that the book may be too long.

Thanks to Princeton University’s Computer Science Department, and especially Prof. Brian Kernighan, for hosting me for part of the sabbatical that gave me time to write this book.

Thanks to Cambridge University’s Computer Lab, and especially Prof. Andy Hopper, for hosting me for part of the sabbatical that gave me time to write this book.

Thanks to my editor, Peter Gordon, and his production team at Addison-Wesley for their help and patience.

College Station, Texas *Bjarne Stroustrup*

Preface to the Third Edition

Programming is understanding.
– Kristen Nygaard

I find using C++ more enjoyable than ever. C++'s support for design and programming has improved dramatically over the years, and lots of new helpful techniques have been developed for its use. However, C++ is not *just* fun. Ordinary practical programmers have achieved significant improvements in productivity, maintainability, flexibility, and quality in projects of just about any kind and scale. By now, C++ has fulfilled most of the hopes I originally had for it, and also succeeded at tasks I hadn't even dreamt of.

This book introduces standard C++† and the key programming and design techniques supported by C++. Standard C++ is a far more powerful and polished language than the version of C++ introduced by the first edition of this book. New language features such as namespaces, exceptions, templates, and run-time type identification allow many techniques to be applied more directly than was possible before, and the standard library allows the programmer to start from a much higher level than the bare language.

About a third of the information in the second edition of this book came from the first. This third edition is the result of a rewrite of even larger magnitude. It offers something to even the most experienced C++ programmer; at the same time, this book is easier for the novice to approach than its predecessors were. The explosion of C++ use and the massive amount of experience accumulated as a result makes this possible.

The definition of an extensive standard library makes a difference to the way C++ concepts can be presented. As before, this book presents C++ independently of any particular implementation, and as before, the tutorial chapters present language constructs and concepts in a ''bottom up'' order so that a construct is used only after it has been defined. However, it is much easier to use a well-designed library than it is to understand the details of its implementation. Therefore, the standard library can be used to provide realistic and interesting examples well before a reader can be assumed to understand its inner workings. The standard library itself is also a fertile source of programming examples and design techniques.

This book presents every major C++ language feature and the standard library. It is organized around language and library facilities. However, features are presented in the context of their use.

† ISO/IEC 14882, Standard for the C++ Programming Language.

That is, the focus is on the language as the tool for design and programming rather than on the language in itself. This book demonstrates key techniques that make C++ effective and teaches the fundamental concepts necessary for mastery. Except where illustrating technicalities, examples are taken from the domain of systems software. A companion, *The Annotated C++ Language Standard*, presents the complete language definition together with annotations to make it more comprehensible.

The primary aim of this book is to help the reader understand how the facilities offered by C++ support key programming techniques. The aim is to take the reader far beyond the point where he or she gets code running primarily by copying examples and emulating programming styles from other languages. Only a good understanding of the ideas behind the language facilities leads to mastery. Supplemented by implementation documentation, the information provided is sufficient for completing significant real-world projects. The hope is that this book will help the reader gain new insights and become a better programmer and designer.

Acknowledgments

In addition to the people mentioned in the acknowledgement sections of the first and second editions, I would like to thank Matt Austern, Hans Boehm, Don Caldwell, Lawrence Crowl, Alan Feuer, Andrew Forrest, David Gay, Tim Griffin, Peter Juhl, Brian Kernighan, Andrew Koenig, Mike Mowbray, Rob Murray, Lee Nackman, Joseph Newcomer, Alex Stepanov, David Vandevoorde, Peter Weinberger, and Chris Van Wyk for commenting on draft chapters of this third edition. Without their help and suggestions, this book would have been harder to understand, contained more errors, been slightly less complete, and probably been a little bit shorter.

I would also like to thank the volunteers on the C++ standards committees who did an immense amount of constructive work to make C++ what it is today. It is slightly unfair to single out individuals, but it would be even more unfair not to mention anyone, so I'd like to especially mention Mike Ball, Dag Brück, Sean Corfield, Ted Goldstein, Kim Knuttila, Andrew Koenig, Dmitry Lenkov, Nathan Myers, Martin O'Riordan, Tom Plum, Jonathan Shopiro, John Spicer, Jerry Schwarz, Alex Stepanov, and Mike Vilot, as people who each directly cooperated with me over some part of C++ and its standard library.

After the initial printing of this book, many dozens of people have mailed me corrections and suggestions for improvements. I have been able to accommodate many of their suggestions within the framework of the book so that later printings benefitted significantly. Translators of this book into many languages have also provided many clarifications. In response to requests from readers, I have added appendices D and E. Let me take this opportunity to thank a few of those who helped: Dave Abrahams, Matt Austern, Jan Bielawski, Janina Mincer Daszkiewicz, Andrew Koenig, Dietmar Kühl, Nicolai Josuttis, Nathan Myers, Paul E. Sevinç, Andy Tenne-Sens, Shoichi Uchida, Ping-Fai (Mike) Yang, and Dennis Yelle.

Murray Hill, New Jersey *Bjarne Stroustrup*

Preface to the Second Edition

The road goes ever on and on.
– Bilbo Baggins

As promised in the first edition of this book, C++ has been evolving to meet the needs of its users. This evolution has been guided by the experience of users of widely varying backgrounds working in a great range of application areas. The C++ user-community has grown a hundredfold during the six years since the first edition of this book; many lessons have been learned, and many techniques have been discovered and/or validated by experience. Some of these experiences are reflected here.

The primary aim of the language extensions made in the last six years has been to enhance C++ as a language for data abstraction and object-oriented programming in general and to enhance it as a tool for writing high-quality libraries of user-defined types in particular. A ''high-quality library,'' is a library that provides a concept to a user in the form of one or more classes that are convenient, safe, and efficient to use. In this context, *safe* means that a class provides a specific type-safe interface between the users of the library and its providers; *efficient* means that use of the class does not impose significant overheads in run-time or space on the user compared with hand-written C code.

This book presents the complete C++ language. Chapters 1 through 10 give a tutorial introduction; Chapters 11 through 13 provide a discussion of design and software development issues; and, finally, the complete C++ reference manual is included. Naturally, the features added and resolutions made since the original edition are integral parts of the presentation. They include refined overloading resolution, memory management facilities, and access control mechanisms, type-safe linkage, **const** and **static** member functions, abstract classes, multiple inheritance, templates, and exception handling.

C++ is a general-purpose programming language; its core application domain is systems programming in the broadest sense. In addition, C++ is successfully used in many application areas that are not covered by this label. Implementations of C++ exist from some of the most modest microcomputers to the largest supercomputers and for almost all operating systems. Consequently, this book describes the C++ language itself without trying to explain a particular implementation, programming environment, or library.

This book presents many examples of classes that, though useful, should be classified as ''toys.'' This style of exposition allows general principles and useful techniques to stand out more clearly than they would in a fully elaborated program, where they would be buried in details. Most

of the useful classes presented here, such as linked lists, arrays, character strings, matrices, graphics classes, associative arrays, etc., are available in ''bulletproof'' and/or ''goldplated'' versions from a wide variety of commercial and non-commercial sources. Many of these ''industrial strength'' classes and libraries are actually direct and indirect descendants of the toy versions found here.

This edition provides a greater emphasis on tutorial aspects than did the first edition of this book. However, the presentation is still aimed squarely at experienced programmers and endeavors not to insult their intelligence or experience. The discussion of design issues has been greatly expanded to reflect the demand for information beyond the description of language features and their immediate use. Technical detail and precision have also been increased. The reference manual, in particular, represents many years of work in this direction. The intent has been to provide a book with a depth sufficient to make more than one reading rewarding to most programmers. In other words, this book presents the C++ language, its fundamental principles, and the key techniques needed to apply it. Enjoy!

Acknowledgments

In addition to the people mentioned in the acknowledgements section in the preface to the first edition, I would like to thank Al Aho, Steve Buroff, Jim Coplien, Ted Goldstein, Tony Hansen, Lorraine Juhl, Peter Juhl, Brian Kernighan, Andrew Koenig, Bill Leggett, Warren Montgomery, Mike Mowbray, Rob Murray, Jonathan Shopiro, Mike Vilot, and Peter Weinberger for commenting on draft chapters of this second edition. Many people influenced the development of C++ from 1985 to 1991. I can mention only a few: Andrew Koenig, Brian Kernighan, Doug McIlroy, and Jonathan Shopiro. Also thanks to the many participants of the ''external reviews'' of the reference manual drafts and to the people who suffered through the first year of X3J16.

Murray Hill, New Jersey *Bjarne Stroustrup*

Preface to the First Edition

Language shapes the way we think,
and determines what we can think about.
– B.L.Whorf

C++ is a general purpose programming language designed to make programming more enjoyable for the serious programmer. Except for minor details, C++ is a superset of the C programming language. In addition to the facilities provided by C, C++ provides flexible and efficient facilities for defining new types. A programmer can partition an application into manageable pieces by defining new types that closely match the concepts of the application. This technique for program construction is often called *data abstraction.* Objects of some user-defined types contain type information. Such objects can be used conveniently and safely in contexts in which their type cannot be determined at compile time. Programs using objects of such types are often called *object based*. When used well, these techniques result in shorter, easier to understand, and easier to maintain programs.

The key concept in C++ is *class*. A class is a user-defined type. Classes provide data hiding, guaranteed initialization of data, implicit type conversion for user-defined types, dynamic typing, user-controlled memory management, and mechanisms for overloading operators. C++ provides much better facilities for type checking and for expressing modularity than C does. It also contains improvements that are not directly related to classes, including symbolic constants, inline substitution of functions, default function arguments, overloaded function names, free store management operators, and a reference type. C++ retains C's ability to deal efficiently with the fundamental objects of the hardware (bits, bytes, words, addresses, etc.). This allows the user-defined types to be implemented with a pleasing degree of efficiency.

C++ and its standard libraries are designed for portability. The current implementation will run on most systems that support C. C libraries can be used from a C++ program, and most tools that support programming in C can be used with C++.

This book is primarily intended to help serious programmers learn the language and use it for nontrivial projects. It provides a complete description of C++, many complete examples, and many more program fragments.

Acknowledgments
C++ could never have matured without the constant use, suggestions, and constructive criticism of many friends and colleagues. In particular, Tom Cargill, Jim Coplien, Stu Feldman, Sandy Fraser, Steve Johnson, Brian Kernighan, Bart Locanthi, Doug McIlroy, Dennis Ritchie, Larry Rosler, Jerry Schwarz, and Jon Shopiro provided important ideas for development of the language. Dave Presotto wrote the current implementation of the stream I/O library.

In addition, hundreds of people contributed to the development of C++ and its compiler by sending me suggestions for improvements, descriptions of problems they had encountered, and compiler errors. I can mention only a few: Gary Bishop, Andrew Hume, Tom Karzes, Victor Milenkovic, Rob Murray, Leonie Rose, Brian Schmult, and Gary Walker.

Many people have also helped with the production of this book, in particular, Jon Bentley, Laura Eaves, Brian Kernighan, Ted Kowalski, Steve Mahaney, Jon Shopiro, and the participants in the C++ course held at Bell Labs, Columbus, Ohio, June 26-27, 1985.

Murray Hill, New Jersey *Bjarne Stroustrup*

2

A Tour of C++: The Basics

The first thing we do, let's
kill all the language lawyers.
– Henry VI, Part II

- Introduction
- The Basics
  Hello, World!; Types, Variables, and Arithmetic; Constants; Tests and Loops; Pointers, Arrays, and Loops
- User-Defined Types
  Structures; Classes; Enumerations
- Modularity
  Separate Compilation; Namespaces; Error Handling
- Postscript
- Advice

2.1 Introduction

The aim of this chapter and the next three is to give you an idea of what C++ is, without going into a lot of details. This chapter informally presents the notation of C++, C++'s model of memory and computation, and the basic mechanisms for organizing code into a program. These are the language facilities supporting the styles most often seen in C and sometimes called *procedural programming*. Chapter 3 follows up by presenting C++'s abstraction mechanisms. Chapter 4 and Chapter 5 give examples of standard-library facilities.

The assumption is that you have programmed before. If not, please consider reading a textbook, such as *Programming: Principles and Practice Using C++* [Stroustrup,2009], before continuing here. Even if you have programmed before, the language you used or the applications you wrote may be very different from the style of C++ presented here. If you find this ''lightning tour'' confusing, skip to the more systematic presentation starting in Chapter 6.

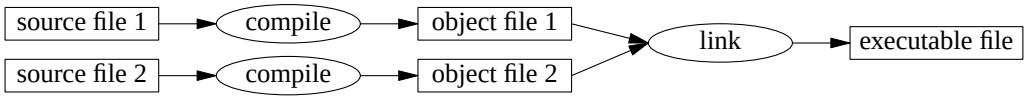
This tour of C++ saves us from a strictly bottom-up presentation of language and library facilities by enabling the use of a rich set of facilities even in early chapters. For example, loops are not discussed in detail until Chapter 10, but they will be used in obvious ways long before that. Similarly, the detailed description of classes, templates, free-store use, and the standard library are spread over many chapters, but standard-library types, such as **vector**, **string**, **complex**, **map**, **unique_ptr**, and **ostream**, are used freely where needed to improve code examples.

As an analogy, think of a short sightseeing tour of a city, such as Copenhagen or New York. In just a few hours, you are given a quick peek at the major attractions, told a few background stories, and usually given some suggestions about what to see next. You do *not* know the city after such a tour. You do *not* understand all you have seen and heard. To really know a city, you have to live in it, often for years. However, with a bit of luck, you will have gained a bit of an overview, a notion of what is special about the city, and ideas of what might be of interest to you. After the tour, the real exploration can begin.

This tour presents C++ as an integrated whole, rather than as a layer cake. Consequently, it does not identify language features as present in C, part of C++98, or new in C++11. Such historical information can be found in §1.4 and Chapter 44.

2.2 The Basics

C++ is a compiled language. For a program to run, its source text has to be processed by a compiler, producing object files, which are combined by a linker yielding an executable program. A C++ program typically consists of many source code files (usually simply called *source files*).



An executable program is created for a specific hardware/system combination; it is not portable, say, from a Mac to a Windows PC. When we talk about portability of C++ programs, we usually mean portability of source code; that is, the source code can be successfully compiled and run on a variety of systems.

The ISO C++ standard defines two kinds of entities:

- *Core language features*, such as built-in types (e.g., **char** and **int**) and loops (e.g., **for**-statements and **while**-statements)
- *Standard-library components*, such as containers (e.g., **vector** and **map**) and I/O operations (e.g., **<<** and **getline()**)

The standard-library components are perfectly ordinary C++ code provided by every C++ implementation. That is, the C++ standard library can be implemented in C++ itself (and is with very minor uses of machine code for things such as thread context switching). This implies that C++ is sufficiently expressive and efficient for the most demanding systems programming tasks.

C++ is a statically typed language. That is, the type of every entity (e.g., object, value, name, and expression) must be known to the compiler at its point of use. The type of an object determines the set of operations applicable to it.

2.2.1 Hello, World!

The minimal C++ program is

```
int main() { }          // the minimal C++ program
```

This defines a function called **main**, which takes no arguments and does nothing (§15.4).

Curly braces, **{ }**, express grouping in C++. Here, they indicate the start and end of the function body. The double slash, **//**, begins a comment that extends to the end of the line. A comment is for the human reader; the compiler ignores comments.

Every C++ program must have exactly one global function named **main()**. The program starts by executing that function. The **int** value returned by **main()**, if any, is the program's return value to "the system." If no value is returned, the system will receive a value indicating successful completion. A nonzero value from **main()** indicates failure. Not every operating system and execution environment make use of that return value: Linux/Unix-based environments often do, but Windows-based environments rarely do.

Typically, a program produces some output. Here is a program that writes **Hello, World!**:

```
#include <iostream>

int main()
{
    std::cout << "Hello, World!\n";
}
```

The line **#include <iostream>** instructs the compiler to *include* the declarations of the standard stream I/O facilities as found in **iostream**. Without these declarations, the expression

```
std::cout << "Hello, World!\n"
```

would make no sense. The operator **<<** ("put to") writes its second argument onto its first. In this case, the string literal **"Hello, World!\n"** is written onto the standard output stream **std::cout**. A string literal is a sequence of characters surrounded by double quotes. In a string literal, the backslash character **** followed by another character denotes a single "special character." In this case, **\n** is the newline character, so that the characters written are **Hello, World!** followed by a newline.

The **std::** specifies that the name **cout** is to be found in the standard-library namespace (§2.4.2, Chapter 14). I usually leave out the **std::** when discussing standard features; §2.4.2 shows how to make names from a namespace visible without explicit qualification.

Essentially all executable code is placed in functions and called directly or indirectly from **main()**. For example:

```
#include <iostream>
using namespace std;        // make names from std visible without std:: (§2.4.2)

double square(double x)     // square a double precision floating-point number
{
    return x*x;
}
```

```
void print_square(double x)
{
    cout << "the square of " << x << " is " << square(x) << "\n";
}

int main()
{
    print_square(1.234);    // print: the square of 1.234 is 1.52276
}
```

A "return type" **void** indicates that a function does not return a value.

2.2.2 Types, Variables, and Arithmetic

Every name and every expression has a type that determines the operations that may be performed on it. For example, the declaration

```
int inch;
```

specifies that **inch** is of type **int**; that is, **inch** is an integer variable.

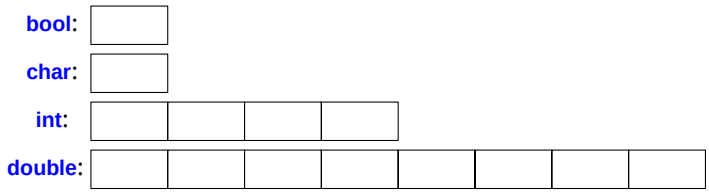
A *declaration* is a statement that introduces a name into the program. It specifies a type for the named entity:

- A *type* defines a set of possible values and a set of operations (for an object).
- An *object* is some memory that holds a value of some type.
- A *value* is a set of bits interpreted according to a type.
- A *variable* is a named object.

C++ offers a variety of fundamental types. For example:

```
bool      // Boolean, possible values are true and false
char      // character, for example, 'a', ' z', and '9'
int       // integer, for example, 1, 42, and 1066
double    // double-precision floating-point number, for example, 3.14 and 299793.0
```

Each fundamental type corresponds directly to hardware facilities and has a fixed size that determines the range of values that can be stored in it:



A **char** variable is of the natural size to hold a character on a given machine (typically an 8-bit byte), and the sizes of other types are quoted in multiples of the size of a **char**. The size of a type is implementation-defined (i.e., it can vary among different machines) and can be obtained by the **sizeof** operator; for example, **sizeof(char)** equals **1** and **sizeof(int)** is often **4**.

The arithmetic operators can be used for appropriate combinations of these types:

```
x+y     // plus
+x      // unary plus
x−y     // minus
−x      // unary minus
x*y     // multiply
x/y     // divide
x%y     // remainder (modulus) for integers
```

So can the comparison operators:

```
x==y    // equal
x!=y    // not equal
x<y     // less than
x>y     // greater than
x<=y    // less than or equal
x>=y    // greater than or equal
```

In assignments and in arithmetic operations, C++ performs all meaningful conversions (§10.5.3) between the basic types so that they can be mixed freely:

```
void some_function()    // function that doesn't return a value
{
    double d = 2.2;     // initialize floating-point number
    int i = 7;          // initialize integer
    d = d+i;            // assign sum to d
    i = d*i;            // assign product to i (truncating the double d*i to an int)
}
```

Note that `=` is the assignment operator and `==` tests equality.

C++ offers a variety of notations for expressing initialization, such as the `=` used above, and a universal form based on curly-brace-delimited initializer lists:

```
double d1 = 2.3;
double d2 {2.3};

complex<double> z = 1;          // a complex number with double-precision floating-point scalars
complex<double> z2 {d1,d2};
complex<double> z3 = {1,2};     // the = is optional with { ... }

vector<int> v {1,2,3,4,5,6};    // a vector of ints
```

The `=` form is traditional and dates back to C, but if in doubt, use the general `{}`-list form (§6.3.5.2). If nothing else, it saves you from conversions that lose information (narrowing conversions; §10.5):

```
int i1 = 7.2;       // i1 becomes 7
int i2 {7.2};       // error: floating-point to integer conversion
int i3 = {7.2};     // error: floating-point to integer conversion (the = is redundant)
```

A constant (§2.2.3) cannot be left uninitialized and a variable should only be left uninitialized in extremely rare circumstances. Don't introduce a name until you have a suitable value for it. User-defined types (such as `string`, `vector`, `Matrix`, `Motor_controller`, and `Orc_warrior`) can be defined to be implicitly initialized (§3.2.1.1).

When defining a variable, you don't actually need to state its type explicitly when it can be deduced from the initializer:

```
auto b = true;      // a bool
auto ch = 'x';      // a char
auto i = 123;       // an int
auto d = 1.2;       // a double
auto z = sqrt(y);   // z has the type of whatever sqrt(y) returns
```

With **auto**, we use the **=** syntax because there is no type conversion involved that might cause problems (§6.3.6.2).

We use **auto** where we don't have a specific reason to mention the type explicitly. "Specific reasons" include:

- The definition is in a large scope where we want to make the type clearly visible to readers of our code.
- We want to be explicit about a variable's range or precision (e.g., **double** rather than **float**).

Using **auto**, we avoid redundancy and writing long type names. This is especially important in generic programming where the exact type of an object can be hard for the programmer to know and the type names can be quite long (§4.5.1).

In addition to the conventional arithmetic and logical operators (§10.3), C++ offers more specific operations for modifying a variable:

```
x+=y    // x = x+y
++x     // increment: x = x+1
x-=y    // x = x-y
--x     // decrement: x = x-1
x*=y    // scaling: x = x*y
x/=y    // scaling: x = x/y
x%=y    // x = x%y
```

These operators are concise, convenient, and very frequently used.

2.2.3 Constants

C++ supports two notions of immutability (§7.5):

- **const**: meaning roughly "I promise not to change this value" (§7.5). This is used primarily to specify interfaces, so that data can be passed to functions without fear of it being modified. The compiler enforces the promise made by **const**.
- **constexpr**: meaning roughly "to be evaluated at compile time" (§10.4). This is used primarily to specify constants, to allow placement of data in memory where it is unlikely to be corrupted, and for performance.

For example:

```
const int dmv = 17;                          // dmv is a named constant
int var = 17;                                // var is not a constant
constexpr double max1 = 1.4*square(dmv);     // OK if square(17) is a constant expression
constexpr double max2 = 1.4*square(var);     // error: var is not a constant expression
const double max3 = 1.4*square(var);         // OK, may be evaluated at run time
```

```
double sum(const vector<double>&);          // sum will not modify its argument (§2.2.5)
vector<double> v {1.2, 3.4, 4.5};           // v is not a constant
const double s1 = sum(v);                   // OK: evaluated at run time
constexpr double s2 = sum(v);               // error: sum(v) not constant expression
```

For a function to be usable in a *constant expression*, that is, in an expression that will be evaluated by the compiler, it must be defined **constexpr**. For example:

```
constexpr double square(double x) { return x*x; }
```

To be **constexpr**, a function must be rather simple: just a **return**-statement computing a value. A **constexpr** function can be used for non-constant arguments, but when that is done the result is not a constant expression. We allow a **constexpr** function to be called with non-constant-expression arguments in contexts that do not require constant expressions, so that we don't have to define essentially the same function twice: once for constant expressions and once for variables.

In a few places, constant expressions are required by language rules (e.g., array bounds (§2.2.5, §7.3), case labels (§2.2.4, §9.4.2), some template arguments (§25.2), and constants declared using **constexpr**). In other cases, compile-time evaluation is important for performance. Independently of performance issues, the notion of immutability (of an object with an unchangeable state) is an important design concern (§10.4).

2.2.4 Tests and Loops

C++ provides a conventional set of statements for expressing selection and looping. For example, here is a simple function that prompts the user and returns a Boolean indicating the response:

```
bool accept()
{
    cout << "Do you want to proceed (y or n)?\n";    // write question

    char answer = 0;
    cin >> answer;                                  // read answer

    if (answer == 'y') return true;
    return false;
}
```

To match the **<<** output operator (''put to''), the **>>** operator (''get from'') is used for input; **cin** is the standard input stream. The type of the right-hand operand of **>>** determines what input is accepted, and its right-hand operand is the target of the input operation. The **\n** character at the end of the output string represents a newline (§2.2.1).

The example could be improved by taking an **n** (for ''no'') answer into account:

```
bool accept2()
{
    cout << "Do you want to proceed (y or n)?\n";    // write question

    char answer = 0;
    cin >> answer;                                  // read answer
```

```
        switch (answer) {
        case 'y':
            return true;
        case 'n':
            return false;
        default:
            cout << "I'll take that for a no.\n";
            return false;
        }
    }
```

A **switch**-statement tests a value against a set of constants. The case constants must be distinct, and if the value tested does not match any of them, the **default** is chosen. If no **default** is provided, no action is taken if the value doesn't match any case constant.

Few programs are written without loops. For example, we might like to give the user a few tries to produce acceptable input:

```
bool accept3()
{
    int tries = 1;
    while (tries<4) {
        cout << "Do you want to proceed (y or n)?\n";    // write question
        char answer = 0;
        cin >> answer;                                   // read answer

        switch (answer) {
        case 'y':
            return true;
        case 'n':
            return false;
        default:
            cout << "Sorry, I don't understand that.\n";
            ++tries;    // increment
        }
    }
    cout << "I'll take that for a no.\n";
    return false;
}
```

The **while**-statement executes until its condition becomes **false**.

2.2.5 Pointers, Arrays, and Loops

An array of elements of type **char** can be declared like this:

```
char v[6];          // array of 6 characters
```

Similarly, a pointer can be declared like this:

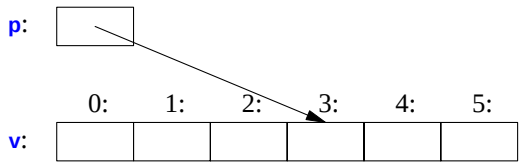
```
char* p;            // pointer to character
```

In declarations, **[]** means "array of" and * means "pointer to." All arrays have **0** as their lower

bound, so **v** has six elements, **v[0]** to **v[5]**. The size of an array must be a constant expression (§2.2.3). A pointer variable can hold the address of an object of the appropriate type:

```
char* p = &v[3];        // p points to v's fourth element
char x = *p;            // *p is the object that p points to
```

In an expression, prefix unary * means "contents of" and prefix unary **&** means "address of." We can represent the result of that initialized definition graphically:



Consider copying ten elements from one array to another:

```
void copy_fct()
{
    int v1[10] = {0,1,2,3,4,5,6,7,8,9};
    int v2[10];                 // to become a copy of v1

    for (auto i=0; i!=10; ++i)  // copy elements
        v2[i]=v1[i];
    // ...
}
```

This **for**-statement can be read as "set **i** to zero; while **i** is not **10**, copy the **i**th element and increment **i**." When applied to an integer variable, the increment operator, **++**, simply adds **1**. C++ also offers a simpler **for**-statement, called a range-**for**-statement, for loops that traverse a sequence in the simplest way:

```
void print()
{
    int v[] = {0,1,2,3,4,5,6,7,8,9};

    for (auto x : v)            // for each x in v
        cout << x << '\n';

    for (auto x : {10,21,32,43,54,65})
        cout << x << '\n';
    // ...
}
```

The first range-**for**-statement can be read as "for every element of **v**, from the first to the last, place a copy in **x** and print it." Note that we don't have to specify an array bound when we initialize it with a list. The range-**for**-statement can be used for any sequence of elements (§3.4.1).

If we didn't want to copy the values from **v** into the variable **x**, but rather just have **x** refer to an element, we could write:

```
void increment()
{
    int v[] = {0,1,2,3,4,5,6,7,8,9};

    for (auto& x : v)
        ++x;
    // ...
}
```

In a declaration, the unary suffix `&` means "reference to." A reference is similar to a pointer, except that you don't need to use a prefix `*` to access the value referred to by the reference. Also, a reference cannot be made to refer to a different object after its initialization. When used in declarations, operators (such as `&`, `*`, and `[]`) are called *declarator operators*:

```
T a[n];     // T[n]: array of n Ts (§7.3)
T* p;       // T*: pointer to T (§7.2)
T& r;       // T&: reference to T  (§7.7)
T f(A);     // T(A): function taking an argument of type A returning a result of type T (§2.2.1)
```

We try to ensure that a pointer always points to an object, so that dereferencing it is valid. When we don't have an object to point to or if we need to represent the notion of "no object available" (e.g.,for an end of a list), we give the pointer the value `nullptr` ("the null pointer"). There is only one `nullptr` shared by all pointer types:

```
double* pd = nullptr;
Link<Record>* lst = nullptr;    // pointer to a Link to a Record
int x = nullptr;                // error: nullptr is a pointer not an integer
```

It is often wise to check that a pointer argument that is supposed to point to something, actually points to something:

```
int count_x(char* p, char x)
    // count the number of occurrences of x in p[]
    // p is assumed to point to a zero-terminated array of char (or to nothing)
{
    if (p==nullptr) return 0;
    int count = 0;
    for (; *p!=0; ++p)
        if (*p==x)
            ++count;
    return count;
}
```

Note how we can move a pointer to point to the next element of an array using `++` and that we can leave out the initializer in a `for`-statement if we don't need it.

The definition of `count_x()` assumes that the `char*` is a *C-style string*, that is, that the pointer points to a zero-terminated array of `char`.

In older code, `0` or `NULL` is typically used instead of `nullptr` (§7.2.2). However, using `nullptr` eliminates potential confusion between integers (such as `0` or `NULL`) and pointers (such as `nullptr`).

2.3 User-Defined Types

We call the types that can be built from the fundamental types (§2.2.2), the **const** modifier (§2.2.3), and the declarator operators (§2.2.5) *built-in types*. C++'s set of built-in types and operations is rich, but deliberately low-level. They directly and efficiently reflect the capabilities of conventional computer hardware. However, they don't provide the programmer with high-level facilities to conveniently write advanced applications. Instead, C++ augments the built-in types and operations with a sophisticated set of *abstraction mechanisms* out of which programmers can build such high-level facilities. The C++ abstraction mechanisms are primarily designed to let programmers design and implement their own types, with suitable representations and operations, and for programmers to simply and elegantly use such types. Types built out of the built-in types using C++'s abstraction mechanisms are called *user-defined types*. They are referred to as classes and enumerations. Most of this book is devoted to the design, implementation, and use of user-defined types. The rest of this chapter presents the simplest and most fundamental facilities for that. Chapter 3 is a more complete description of the abstraction mechanisms and the programming styles they support. Chapter 4 and Chapter 5 present an overview of the standard library, and since the standard library mainly consists of user-defined types, they provide examples of what can be built using the language facilities and programming techniques presented in Chapter 2 and Chapter 3.

2.3.1 Structures

The first step in building a new type is often to organize the elements it needs into a data structure, a **struct**:

```
struct Vector {
    int sz;           // number of elements
    double* elem;     // pointer to elements
};
```

This first version of **Vector** consists of an **int** and a **double***.

A variable of type **Vector** can be defined like this:

```
Vector v;
```

However, by itself that is not of much use because **v**'s **elem** pointer doesn't point to anything. To be useful, we must give **v** some elements to point to. For example, we can construct a **Vector** like this:

```
void vector_init(Vector& v, int s)
{
    v.elem = new double[s];   // allocate an array of s doubles
    v.sz = s;
}
```

That is, **v**'s **elem** member gets a pointer produced by the **new** operator and **v**'s **size** member gets the number of elements. The **&** in **Vector&** indicates that we pass **v** by non-**const** reference (§2.2.5, §7.7); that way, **vector_init()** can modify the vector passed to it.

The **new** operator allocates memory from an area called *the free store* (also known as *dynamic memory* and *heap*; §11.2).

A simple use of **Vector** looks like this:

```
double read_and_sum(int s)
    // read s integers from cin and return their sum; s is assumed to be positive
{
    Vector v;
    vector_init(v,s);           // allocate s elements for v
    for (int i=0; i!=s; ++i)
        cin>>v.elem[i];         // read into elements

    double sum = 0;
    for (int i=0; i!=s; ++i)
        sum+=v.elem[i];         // take the sum of the elements
    return sum;
}
```

There is a long way to go before our **Vector** is as elegant and flexible as the standard-library **vector**. In particular, a user of **Vector** has to know every detail of **Vector**'s representation. The rest of this chapter and the next gradually improve **Vector** as an example of language features and techniques. Chapter 4 presents the standard-library **vector**, which contains many nice improvements, and Chapter 31 presents the complete **vector** in the context of other standard-library facilities.

I use **vector** and other standard-library components as examples

- to illustrate language features and design techniques, and
- to help you learn and use the standard-library components.

Don't reinvent standard-library components, such as **vector** and **string**; use them.

We use **.** (dot) to access **struct** members through a name (and through a reference) and **–>** to access **struct** members through a pointer. For example:

```
void f(Vector v, Vector& rv, Vector* pv)
{
    int i1 = v.sz;          // access through name
    int i2 = rv.sz;         // access through reference
    int i4 = pv->sz;        // access through pointer
}
```

2.3.2 Classes

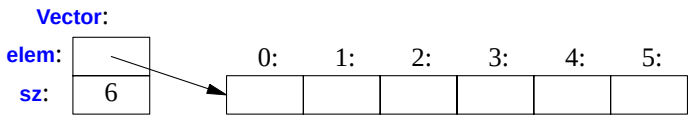
Having the data specified separately from the operations on it has advantages, such as the ability to use the data in arbitrary ways. However, a tighter connection between the representation and the operations is needed for a user-defined type to have all the properties expected of a "real type." In particular, we often want to keep the representation inaccessible to users, so as to ease use, guarantee consistent use of the data, and allow us to later improve the representation. To do that we have to distinguish between the interface to a type (to be used by all) and its implementation (which has access to the otherwise inaccessible data). The language mechanism for that is called a *class*. A class is defined to have a set of *members*, which can be data, function, or type members. The interface is defined by the **public** members of a class, and **private** members are accessible only through that interface. For example:

```
class Vector {
public:
    Vector(int s) :elem{new double[s]}, sz{s} { }    // construct a Vector
    double& operator[](int i) { return elem[i]; }    // element access: subscripting
    int size() { return sz; }
private:
    double* elem;  // pointer to the elements
    int sz;        // the number of elements
};
```

Given that, we can define a variable of our new type **Vector**:

```
Vector v(6);    // a Vector with 6 elements
```

We can illustrate a **Vector** object graphically:



Basically, the **Vector** object is a "handle" containing a pointer to the elements (**elem**) plus the number of elements (**sz**). The number of elements (6 in the example) can vary from **Vector** object to **Vector** object, and a **Vector** object can have a different number of elements at different times (§3.2.1.3). However, the **Vector** object itself is always the same size. This is the basic technique for handling varying amounts of information in C++: a fixed-size handle referring to a variable amount of data "elsewhere" (e.g., on the free store allocated by **new**; §11.2). How to design and use such objects is the main topic of Chapter 3.

Here, the representation of a **Vector** (the members **elem** and **sz**) is accessible only through the interface provided by the **public** members: **Vector()**, **operator[]()**, and **size()**. The **read_and_sum()** example from §2.3.1 simplifies to:

```
double read_and_sum(int s)
{
    Vector v(s);                    // make a vector of s elements
    for (int i=0; i!=v.size(); ++i)
        cin>>v[i];                  // read into elements

    double sum = 0;
    for (int i=0; i!=v.size(); ++i)
        sum+=v[i];                  // take the sum of the elements
    return sum;
}
```

A "function" with the same name as its class is called a *constructor*, that is, a function used to construct objects of a class. So, the constructor, **Vector()**, replaces **vector_init()** from §2.3.1. Unlike an ordinary function, a constructor is guaranteed to be used to initialize objects of its class. Thus, defining a constructor eliminates the problem of uninitialized variables for a class.

`Vector(int)` defines how objects of type `Vector` are constructed. In particular, it states that it needs an integer to do that. That integer is used as the number of elements. The constructor initializes the `Vector` members using a member initializer list:

```
:elem{new double[s]}, sz{s}
```

That is, we first initialize `elem` with a pointer to `s` elements of type `double` obtained from the free store. Then, we initialize `sz` to `s`.

Access to elements is provided by a subscript function, called `operator[]`. It returns a reference to the appropriate element (a `double&`).

The `size()` function is supplied to give users the number of elements.

Obviously, error handling is completely missing, but we'll return to that in §2.4.3. Similarly, we did not provide a mechanism to "give back" the array of `double`s acquired by `new`; §3.2.1.2 shows how to use a destructor to elegantly do that.

2.3.3 Enumerations

In addition to classes, C++ supports a simple form of user-defined type for which we can enumerate the values:

```
enum class Color { red, blue, green };
enum class Traffic_light { green, yellow, red };

Color col = Color::red;
Traffic_light light = Traffic_light::red;
```

Note that enumerators (e.g., `red`) are in the scope of their `enum class`, so that they can be used repeatedly in different `enum class`es without confusion. For example, `Color::red` is `Color`'s `red` which is different from `Traffic_light::red`.

Enumerations are used to represent small sets of integer values. They are used to make code more readable and less error-prone than it would have been had the symbolic (and mnemonic) enumerator names not been used.

The `class` after the `enum` specifies that an enumeration is strongly typed and that its enumerators are scoped. Being separate types, `enum class`es help prevent accidental misuses of constants. In particular, we cannot mix `Traffic_light` and `Color` values:

```
Color x = red;              // error: which red?
Color y = Traffic_light::red; // error: that red is not a Color
Color z = Color::red;       // OK
```

Similarly, we cannot implicitly mix `Color` and integer values:

```
int i = Color::red;         // error: Color::red is not an int
Color c = 2;                // error: 2 is not a Color
```

If you don't want to explicitly qualify enumerator names and want enumerator values to be `int`s (without the need for an explicit conversion), you can remove the `class` from `enum class` to get a "plain `enum`" (§8.4.2).

By default, an `enum class` has only assignment, initialization, and comparisons (e.g., `==` and `<`; §2.2.2) defined. However, an enumeration is a user-defined type so we can define operators for it:

```
Traffic_light& operator++(Traffic_light& t)
        // prefix increment: ++
{
        switch (t) {
        case Traffic_light::green:      return t=Traffic_light::yellow;
        case Traffic_light::yellow:     return t=Traffic_light::red;
        case Traffic_light::red:        return t=Traffic_light::green;
        }
}

Traffic_light next = ++light;           // next becomes Traffic_light::green
```

C++ also offers a less strongly typed ''plain'' **enum** (§8.4.2).

2.4 Modularity

A C++ program consists of many separately developed parts, such as functions (§2.2.1, Chapter 12), user-defined types (§2.3, §3.2, Chapter 16), class hierarchies (§3.2.4, Chapter 20), and templates (§3.4, Chapter 23). The key to managing this is to clearly define the interactions among those parts. The first and most important step is to distinguish between the interface to a part and its implementation. At the language level, C++ represents interfaces by declarations. A *declaration* specifies all that's needed to use a function or a type. For example:

```
double sqrt(double);        // the square root function takes a double and returns a double

class Vector {
public:
        Vector(int s);
        double& operator[](int i);
        int size();
private:
        double* elem;  // elem points to an array of sz doubles
        int sz;
};
```

The key point here is that the function bodies, the function *definitions*, are ''elsewhere.'' For this example, we might like for the representation of **Vector** to be ''elsewhere'' also, but we will deal with that later (abstract types; §3.2.2). The definition of **sqrt()** will look like this:

```
double sqrt(double d)           // definition of sqrt()
{
        // ... algorithm as found in math textbook ...
}
```

For **Vector**, we need to define all three member functions:

```
Vector::Vector(int s)                   // definition of the constructor
        :elem{new double[s]}, sz{s}     // initialize members
{
}
```

```
double& Vector::operator[](int i)          // definition of subscripting
{
    return elem[i];
}

int Vector::size()                         // definition of size()
{
    return sz;
}
```

We must define **Vector**'s functions, but not **sqrt()** because it is part of the standard library. However, that makes no real difference: a library is simply some ''other code we happen to use'' written with the same language facilities as we use.

2.4.1 Separate Compilation

C++ supports a notion of separate compilation where user code sees only declarations of types and functions used. The definitions of those types and functions are in separate source files and compiled separately. This can be used to organize a program into a set of semi-independent code fragments. Such separation can be used to minimize compilation times and to strictly enforce separation of logically distinct parts of a program (thus minimizing the chance of errors). A library is often a separately compiled code fragments (e.g., functions).

Typically, we place the declarations that specify the interface to a module in a file with a name indicating its intended use. For example:

```
// Vector.h:

class Vector {
public:
    Vector(int s);
    double& operator[](int i);
    int size();
private:
    double* elem;       // elem points to an array of sz doubles
    int sz;
};
```

This declaration would be placed in a file **Vector.h**, and users will *include* that file, called a *header file*, to access that interface. For example:

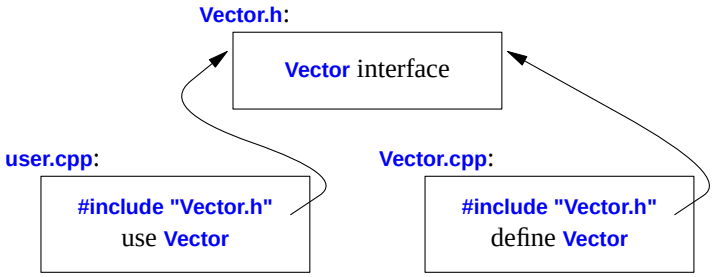
```
// user.cpp:

#include "Vector.h"        // get Vector's interface
#include <cmath>           // get the the standard-library math function interface including sqrt()
using namespace std;       // make std members visible (§2.4.2)
```

```
double sqrt_sum(Vector& v)
{
        double sum = 0;
        for (int i=0; i!=v.size(); ++i)
                sum+=sqrt(v[i]);                    // sum of square roots
        return sum;
}
```

To help the compiler ensure consistency, the **.cpp** file providing the implementation of **Vector** will also include the **.h** file providing its interface:

```
// Vector.cpp:

#include "Vector.h" // get the interface

Vector::Vector(int s)
        :elem{new double[s]}, sz{s}
{
}

double& Vector::operator[](int i)
{
        return elem[i];
}

int Vector::size()
{
        return sz;
}
```

The code in **user.cpp** and **Vector.cpp** shares the **Vector** interface information presented in **Vector.h**, but the two files are otherwise independent and can be separately compiled. Graphically, the program fragments can be represented like this:



Strictly speaking, using separate compilation isn't a language issue; it is an issue of how best to take advantage of a particular language implementation. However, it is of great practical importance. The best approach is to maximize modularity, represent that modularity logically through language features, and then exploit the modularity physically through files for effective separate compilation (Chapter 14, Chapter 15).

2.4.2 Namespaces

In addition to functions (§2.2.1, Chapter 12), classes (Chapter 16), and enumerations (§2.3.3, §8.4), C++ offers *namespaces* (Chapter 14) as a mechanism for expressing that some declarations belong together and that their names shouldn't clash with other names. For example, I might want to experiment with my own complex number type (§3.2.1.1, §18.3, §40.4):

```
namespace My_code {
        class complex { /* ... */ };
        complex sqrt(complex);
        // ...
        int main();
}

int My_code::main()
{
        complex z {1,2};
        auto z2 = sqrt(z);
        std::cout << '{' << z2.real() << ',' << z2.imag() << "}\n";
        // ...
};

int main()
{
        return My_code::main();
}
```

By putting my code into the namespace **My_code**, I make sure that my names do not conflict with the standard-library names in namespace **std** (§4.1.2). The precaution is wise, because the standard library does provide support for **complex** arithmetic (§3.2.1.1, §40.4).

The simplest way to access a name in another namespace is to qualify it with the namespace name (e.g., **std::cout** and **My_code::main**). The "real **main()**" is defined in the global namespace, that is, not local to a defined namespace, class, or function. To gain access to names in the standard-library namespace, we can use a **using**-directive (§14.2.3):

```
using namespace std;
```

Namespaces are primarily used to organize larger program components, such as libraries. They simplify the composition of a program out of separately developed parts.

2.4.3 Error Handling

Error handling is a large and complex topic with concerns and ramifications that go far beyond language facilities into programming techniques and tools. However, C++ provides a few features to help. The major tool is the type system itself. Instead of painstakingly building up our applications from the built-in types (e.g., **char**, **int**, and **double**) and statements (e.g., **if**, **while**, and **for**), we build more types that are appropriate for our applications (e.g., **string**, **map**, and **regex**) and algorithms (e.g., **sort()**, **find_if()**, and **draw_all()**). Such higher level constructs simplify our programming, limit our opportunities for mistakes (e.g., you are unlikely to try to apply a tree traversal to a dialog box),

and increase the compiler's chances of catching such errors. The majority of C++ constructs are dedicated to the design and implementation of elegant and efficient abstractions (e.g., user-defined types and algorithms using them). One effect of this modularity and abstraction (in particular, the use of libraries) is that the point where a run-time error can be detected is separated from the point where it can be handled. As programs grow, and especially when libraries are used extensively, standards for handling errors become important.

2.4.3.1 Exceptions

Consider again the **Vector** example. What *ought* to be done when we try to access an element that is out of range for the vector from §2.3.2?

- The writer of **Vector** doesn't know what the user would like to have done in this case (the writer of **Vector** typically doesn't even know in which program the vector will be running).
- The user of **Vector** cannot consistently detect the problem (if the user could, the out-of-range access wouldn't happen in the first place).

The solution is for the **Vector** implementer to detect the attempted out-of-range access and then tell the user about it. The user can then take appropriate action. For example, **Vector::operator[]()** can detect an attempted out-of-range access and throw an **out_of_range** exception:

```
double& Vector::operator[](int i)
{
    if (i<0 || size()<=i) throw out_of_range{"Vector::operator[]"};
    return elem[i];
}
```

The **throw** transfers control to a handler for exceptions of type **out_of_range** in some function that directly or indirectly called **Vector::operator[]()**. To do that, the implementation will unwind the function call stack as needed to get back to the context of that caller (§13.5.1). For example:

```
void f(Vector& v)
{
    // ...
    try { // exceptions here are handled by the handler defined below

        v[v.size()] = 7; // try to access beyond the end of v
    }
    catch (out_of_range) {    // oops: out_of_range error
        // ... handle range error ...
    }
    // ...
}
```

We put code for which we are interested in handling exceptions into a **try**-block. That attempted assignment to **v[v.size()]** will fail. Therefore, the **catch**-clause providing a handler for **out_of_range** will be entered. The **out_of_range** type is defined in the standard library and is in fact used by some standard-library container access functions.

Use of the exception-handling mechanisms can make error handling simpler, more systematic, and more readable. See Chapter 13 for further discussion, details, and examples.

2.4.3.2 Invariants

The use of exceptions to signal out-of-range access is an example of a function checking its argument and refusing to act because a basic assumption, a *precondition*, didn't hold. Had we formally specified **Vector**'s subscript operator, we would have said something like "the index must be in the [**0**:**size()**) range," and that was in fact what we tested in our **operator[]()**. Whenever we define a function, we should consider what its preconditions are and if feasible test them (see §12.4, §13.4).

However, **operator[]()** operates on objects of type **Vector** and nothing it does makes any sense unless the members of **Vector** have "reasonable" values. In particular, we did say "**elem** points to an array of **sz** doubles" but we only said that in a comment. Such a statement of what is assumed to be true for a class is called a *class invariant*, or simply an *invariant*. It is the job of a constructor to establish the invariant for its class (so that the member functions can rely on it) and for the member functions to make sure that the invariant holds when they exit. Unfortunately, our **Vector** constructor only partially did its job. It properly initialized the **Vector** members, but it failed to check that the arguments passed to it made sense. Consider:

```
Vector v(−27);
```

This is likely to cause chaos.

Here is a more appropriate definition:

```
Vector::Vector(int s)
{
    if (s<0) throw length_error{};
    elem = new double[s];
    sz = s;
}
```

I use the standard-library exception **length_error** to report a non-positive number of elements because some standard-library operations use that exception to report problems of this kind. If operator **new** can't find memory to allocate, it throws a **std::bad_alloc**. We can now write:

```
void test()
{
    try {
        Vector v(−27);
    }
    catch (std::length_error) {
        // handle negative size
    }
    catch (std::bad_alloc) {
        // handle memory exhaustion
    }
}
```

You can define your own classes to be used as exceptions and have them carry arbitrary information from a point where an error is detected to a point where it can be handled (§13.5).

Often, a function has no way of completing its assigned task after an exception is thrown. Then, "handling" an exception simply means doing some minimal local cleanup and rethrowing the exception (§13.5.2.1).

The notion of invariants is central to the design of classes, and preconditions serve a similar role in the design of functions. Invariants

- helps us to understand precisely what we want
- forces us to be specific; that gives us a better chance of getting our code correct (after debugging and testing).

The notion of invariants underlies C++'s notions of resource management supported by constructors (§2.3.2) and destructors (§3.2.1.2, §5.2). See also §13.4, §16.3.1, and §17.2.

2.4.3.3 Static Assertions

Exceptions report errors found at run time. If an error can be found at compile time, it is usually preferable to do so. That's what much of the type system and the facilities for specifying the interfaces to user-defined types are for. However, we can also perform simple checks on other properties that are known at compile time and report failures as compiler error messages. For example:

```
static_assert(4<=sizeof(int), "integers are too small");   // check integer size
```

This will write `integers are too small` if `4<=sizeof(int)` does not hold, that is, if an `int` on this system does not have at least 4 bytes. We call such statements of expectations *assertions*.

The `static_assert` mechanism can be used for anything that can be expressed in terms of constant expressions (§2.2.3, §10.4). For example:

```
constexpr double C = 299792.458;                    // km/s

void f(double speed)
{
    const double local_max = 160.0/(60*60);         // 160 km/h == 160.0/(60*60) km/s

    static_assert(speed<C,"can't go that fast");    // error: speed must be a constant
    static_assert(local_max<C,"can't go that fast"); // OK

    // ...
}
```

In general, `static_assert(A,S)` prints `S` as a compiler error message if `A` is not `true`.

The most important uses of `static_assert` come when we make assertions about types used as parameters in generic programming (§5.4.2, §24.3).

For runtime-checked assertions, see §13.4.

2.5 Postscript

The topics covered in this chapter roughly correspond to the contents of Part II (Chapters 6–15). Those are the parts of C++ that underlie all programming techniques and styles supported by C++. Experienced C and C++ programmers, please note that this foundation does not closely correspond to the C or C++98 subsets of C++ (that is, C++11).

2.6 Advice

[1] Don’t panic! All will become clear in time; §2.1.
[2] You don’t have to know every detail of C++ to write good programs; §1.3.1.
[3] Focus on programming techniques, not on language features; §2.1.

3

A Tour of C++: Abstraction Mechanisms

Don't Panic!
– Douglas Adams

- Introduction
- Classes
  Concrete Types; Abstract Types; Virtual Functions; Class Hierarchies
- Copy and Move
  Copying Containers; Moving Containers; Resource Management; Suppressing Operations
- Templates
  Parameterized Types; Function Templates; Function Objects; Variadic Templates; Aliases
- Advice

3.1 Introduction

This chapter aims to give you an idea of C++'s support for abstraction and resource management without going into a lot of detail. It informally presents ways of defining and using new types (*user-defined types*). In particular, it presents the basic properties, implementation techniques, and language facilities used for *concrete classes*, *abstract classes*, and *class hierarchies*. Templates are introduced as a mechanism for parameterizing types and algorithms with (other) types and algorithms. Computations on user-defined and built-in types are represented as functions, sometimes generalized to *template functions* and *function objects*. These are the language facilities supporting the programming styles known as *object-oriented programming* and *generic programming*. The next two chapters follow up by presenting examples of standard-library facilities and their use.

The assumption is that you have programmed before. If not, please consider reading a textbook, such as *Programming: Principles and Practice Using C++* [Stroustrup,2009], before continuing here. Even if you have programmed before, the language you used or the applications you wrote may be very different from the style of C++ presented here. If you find this ''lightning tour'' confusing, skip to the more systematic presentation starting in Chapter 6.

As in Chapter 2, this tour presents C++ as an integrated whole, rather than as a layer cake. Consequently, it does not identify language features as present in C, part of C++98, or new in C++11. Such historical information can be found in §1.4 and Chapter 44.

3.2 Classes

The central language feature of C++ is the *class*. A class is a user-defined type provided to represent a concept in the code of a program. Whenever our design for a program has a useful concept, idea, entity, etc., we try to represent it as a class in the program so that the idea is there in the code, rather than just in our head, in a design document, or in some comments. A program built out of a well chosen set of classes is far easier to understand and get right than one that builds everything directly in terms of the built-in types. In particular, classes are often what libraries offer.

Essentially all language facilities beyond the fundamental types, operators, and statements exist to help define better classes or to use them more conveniently. By ''better,'' I mean more correct, easier to maintain, more efficient, more elegant, easier to use, easier to read, and easier to reason about. Most programming techniques rely on the design and implementation of specific kinds of classes. The needs and tastes of programmers vary immensely. Consequently, the support for classes is extensive. Here, we will just consider the basic support for three important kinds of classes:

- Concrete classes (§3.2.1)
- Abstract classes (§3.2.2)
- Classes in class hierarchies (§3.2.4)

An astounding number of useful classes turn out to be of these three kinds. Even more classes can be seen as simple variants of these kinds or are implemented using combinations of the techniques used for these.

3.2.1 Concrete Types

The basic idea of *concrete classes* is that they behave ''just like built-in types.'' For example, a complex number type and an infinite-precision integer are much like built-in **int**, except of course that they have their own semantics and sets of operations. Similarly, a **vector** and a **string** are much like built-in arrays, except that they are better behaved (§4.2, §4.3.2, §4.4.1).

The defining characteristic of a concrete type is that its representation is part of its definition. In many important cases, such as a **vector**, that representation is only one or more pointers to more data stored elsewhere, but it is present in each object of a concrete class. That allows implementations to be optimally efficient in time and space. In particular, it allows us to

- place objects of concrete types on the stack, in statically allocated memory, and in other objects (§6.4.2);
- refer to objects directly (and not just through pointers or references);
- initialize objects immediately and completely (e.g., using constructors; §2.3.2); and
- copy objects (§3.3).

The representation can be private (as it is for **Vector**; §2.3.2) and accessible only through the member functions, but it is present. Therefore, if the representation changes in any significant way, a user must recompile. This is the price to pay for having concrete types behave exactly like built-in

types. For types that don't change often, and where local variables provide much-needed clarity and efficiency, this is acceptable and often ideal. To increase flexibility, a concrete type can keep major parts of its representation on the free store (dynamic memory, heap) and access them through the part stored in the class object itself. That's the way **vector** and **string** are implemented; they can be considered resource handles with carefully crafted interfaces.

3.2.1.1 An Arithmetic Type

The "classical user-defined arithmetic type" is **complex**:

```
class complex {
        double re, im;  // representation: two doubles
public:
        complex(double r, double i) :re{r}, im{i} {}     // construct complex from two scalars
        complex(double r) :re{r}, im{0} {}               // construct complex from one scalar
        complex() :re{0}, im{0} {}                       // default complex: {0,0}

        double real() const { return re; }
        void real(double d) { re=d; }
        double imag() const { return im; }
        void imag(double d) { im=d; }

        complex& operator+=(complex z) { re+=z.re, im+=z.im; return *this; }   // add to re and im
                                                                               // and return the result
        complex& operator−=(complex z) { re−=z.re, im−=z.im; return *this; }

        complex& operator*=(complex);    // defined out-of-class somewhere
        complex& operator/=(complex);    // defined out-of-class somewhere
};
```

This is a slightly simplified version of the standard-library **complex** (§40.4). The class definition itself contains only the operations requiring access to the representation. The representation is simple and conventional. For practical reasons, it has to be compatible with what Fortran provided 50 years ago, and we need a conventional set of operators. In addition to the logical demands, **complex** must be efficient or it will remain unused. This implies that simple operations must be inlined. That is, simple operations (such as constructors, **+=**, and **imag()**) must be implemented without function calls in the generated machine code. Functions defined in a class are inlined by default. An industrial-strength **complex** (like the standard-library one) is carefully implemented to do appropriate inlining.

A constructor that can be invoked without an argument is called a *default constructor*. Thus, **complex()** is **complex**'s default constructor. By defining a default constructor you eliminate the possibility of uninitialized variables of that type.

The **const** specifiers on the functions returning the real and imaginary parts indicate that these functions do not modify the object for which they are called.

Many useful operations do not require direct access to the representation of **complex**, so they can be defined separately from the class definition:

```
complex operator+(complex a, complex b) { return a+=b; }
complex operator−(complex a, complex b) { return a−=b; }
complex operator−(complex a) { return {−a.real(), −a.imag()}; }      // unary minus
complex operator*(complex a, complex b) { return a*=b; }
complex operator/(complex a, complex b) { return a/=b; }
```

Here, I use the fact that an argument passed by value is copied, so that I can modify an argument without affecting the caller's copy, and use the result as the return value.

The definitions of `==` and `!=` are straightforward:

```
bool operator==(complex a, complex b)        // equal
{
    return a.real()==b.real() && a.imag()==b.imag();
}

bool operator!=(complex a, complex b)        // not equal
{
    return !(a==b);
}

complex sqrt(complex);

// ...
```

Class `complex` can be used like this:

```
void f(complex z)
{
    complex a {2.3};            // construct {2.3,0.0} from 2.3
    complex b {1/a};
    complex c {a+z*complex{1,2.3}};
    // ...
    if (c != b)
        c = −(b/a)+2*b;
}
```

The compiler converts operators involving `complex` numbers into appropriate function calls. For example, `c!=b` means `operator!=(c,b)` and `1/a` means `operator/(complex{1},a)`.

User-defined operators (''overloaded operators'') should be used cautiously and conventionally. The syntax is fixed by the language, so you can't define a unary `/`. Also, it is not possible to change the meaning of an operator for built-in types, so you can't redefine `+` to subtract `int`s.

3.2.1.2 A Container

A *container* is an object holding a collection of elements, so we call `Vector` a container because it is the type of objects that are containers. As defined in §2.3.2, `Vector` isn't an unreasonable container of `double`s: it is simple to understand, establishes a useful invariant (§2.4.3.2), provides range-checked access (§2.4.3.1), and provides `size()` to allow us to iterate over its elements. However, it does have a fatal flaw: it allocates elements using `new` but never deallocates them. That's not a good idea because although C++ defines an interface for a garbage collector (§34.5), it is not

guaranteed that one is available to make unused memory available for new objects. In some environments you can't use a collector, and sometimes you prefer more precise control of destruction (§13.6.4) for logical or performance reasons. We need a mechanism to ensure that the memory allocated by the constructor is deallocated; that mechanism is a *destructor*:

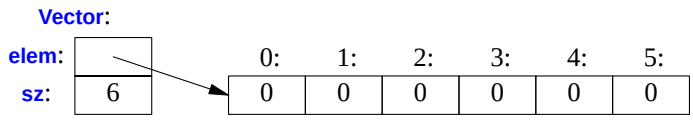
```
class Vector {
private:
    double* elem;       // elem points to an array of sz doubles
    int sz;
public:
    Vector(int s) :elem{new double[s]}, sz{s}       // constructor: acquire resources
    {
        for (int i=0; i!=s; ++i) elem[i]=0;         // initialize elements
    }

    ~Vector() { delete[] elem; }                    // destructor: release resources

    double& operator[](int i);
    int size() const;
};
```

The name of a destructor is the complement operator, `~`, followed by the name of the class; it is the complement of a constructor. `Vector`'s constructor allocates some memory on the free store (also called the *heap* or *dynamic store*) using the `new` operator. The destructor cleans up by freeing that memory using the `delete` operator. This is all done without intervention by users of `Vector`. The users simply create and use `Vector`s much as they would variables of built-in types. For example:

```
void fct(int n)
{
    Vector v(n);

    // ... use v ...

    {
        Vector v2(2*n);
        // ... use v and v2 ...
    } // v2 is destroyed here

    // ... use v ..

} // v is destroyed here
```

`Vector` obeys the same rules for naming, scope, allocation, lifetime, etc., as does a built-in type, such as `int` and `char`. For details on how to control the lifetime of an object, see §6.4. This `Vector` has been simplified by leaving out error handling; see §2.4.3.

The constructor/destructor combination is the basis of many elegant techniques. In particular, it is the basis for most C++ general resource management techniques (§5.2, §13.3). Consider a graphical illustration of a `Vector`:



The constructor allocates the elements and initializes the **Vector** members appropriately. The destructor deallocates the elements. This *handle-to-data model* is very commonly used to manage data that can vary in size during the lifetime of an object. The technique of acquiring resources in a constructor and releasing them in a destructor, known as *Resource Acquisition Is Initialization* or *RAII*, allows us to eliminate ''naked **new** operations,'' that is, to avoid allocations in general code and keep them buried inside the implementation of well-behaved abstractions. Similarly, ''naked **delete** operations'' should be avoided. Avoiding naked **new** and naked **delete** makes code far less error-prone and far easier to keep free of resource leaks (§5.2).

3.2.1.3 Initializing Containers

A container exists to hold elements, so obviously we need convenient ways of getting elements into a container. We can handle that by creating a **Vector** with an appropriate number of elements and then assigning to them, but typically other ways are more elegant. Here, I just mention two favorites:

- *Initializer-list constructor*: Initialize with a list of elements.
- **push_back()**: Add a new element at the end (at the back of) the sequence.

These can be declared like this:

```
class Vector {
public:
    Vector(std::initializer_list<double>);      // initialize with a list
    // ...
    void push_back(double);                     // add element at end increasing the size by one
    // ...
};
```

The **push_back()** is useful for input of arbitrary numbers of elements. For example:

```
Vector read(istream& is)
{
    Vector v;
    for (double d; is>>d;)          // read floating-point values into d
        v.push_back(d);             // add d to v
    return v;
}
```

The input loop is terminated by an end-of-file or a formatting error. Until that happens, each number read is added to the **Vector** so that at the end, **v**'s size is the number of elements read. I used a **for**-statement rather than the more conventional **while**-statement to keep the scope of **d** limited to the loop. The implementation of **push_back()** is discussed in §13.6.4.3. The way to provide **Vector** with a move constructor, so that returning a potentially huge amount of data from **read()** is cheap, is explained in §3.3.2.

The **std::initializer_list** used to define the initializer-list constructor is a standard-library type known to the compiler: when we use a **{}**-list, such as **{1,2,3,4}**, the compiler will create an object of type **initializer_list** to give to the program. So, we can write:

```
Vector v1 = {1,2,3,4,5};          // v1 has 5 elements
Vector v2 = {1.23, 3.45, 6.7, 8};  // v2 has 4 elements
```

Vector's initializer-list constructor might be defined like this:

```
Vector::Vector(std::initializer_list<double> lst)      // initialize with a list
    :elem{new double[lst.size()]}, sz{lst.size()}
{
    copy(lst.begin(),lst.end(),elem);          // copy from lst into elem
}
```

3.2.2 Abstract Types

Types such as **complex** and **Vector** are called *concrete types* because their representation is part of their definition. In that, they resemble built-in types. In contrast, an *abstract type* is a type that completely insulates a user from implementation details. To do that, we decouple the interface from the representation and give up genuine local variables. Since we don't know anything about the representation of an abstract type (not even its size), we must allocate objects on the free store (§3.2.1.2, §11.2) and access them through references or pointers (§2.2.5, §7.2, §7.7).

First, we define the interface of a class **Container** which we will design as a more abstract version of our **Vector**:

```
class Container {
public:
    virtual double& operator[](int) = 0;      // pure virtual function
    virtual int size() const = 0;             // const member function (§3.2.1.1)
    virtual ~Container() {}                   // destructor (§3.2.1.2)
};
```

This class is a pure interface to specific containers defined later. The word **virtual** means ''may be redefined later in a class derived from this one.'' Unsurprisingly, a function declared **virtual** is called a *virtual function*. A class derived from **Container** provides an implementation for the **Container** interface. The curious **=0** syntax says the function is *pure virtual*; that is, some class derived from **Container** *must* define the function. Thus, it is not possible to define an object that is just a **Container**; a **Container** can only serve as the interface to a class that implements its **operator[]()** and **size()** functions. A class with a pure virtual function is called an *abstract class*.

This **Container** can be used like this:

```
void use(Container& c)
{
    const int sz = c.size();

    for (int i=0; i!=sz; ++i)
        cout << c[i] << '\n';
}
```

Note how **use()** uses the **Container** interface in complete ignorance of implementation details. It uses **size()** and **[]** without any idea of exactly which type provides their implementation. A class that provides the interface to a variety of other classes is often called a *polymorphic type* (§20.3.2).

As is common for abstract classes, **Container** does not have a constructor. After all, it does not have any data to initialize. On the other hand, **Container** does have a destructor and that destructor is **virtual**. Again, that is common for abstract classes because they tend to be manipulated through references or pointers, and someone destroying a **Container** through a pointer has no idea what resources are owned by its implementation; see also §3.2.4.

A container that implements the functions required by the interface defined by the abstract class **Container** could use the concrete class **Vector**:

```
class Vector_container : public Container {    // Vector_container implements Container
    Vector v;
public:
    Vector_container(int s) : v(s) { }      // Vector of s elements
    ~Vector_container() {}

    double& operator[](int i) { return v[i]; }
    int size() const { return v.size(); }
};
```

The **:public** can be read as ‘‘is derived from’’ or ‘‘is a subtype of.’’ Class **Vector_container** is said to be *derived* from class **Container**, and class **Container** is said to be a *base* of class **Vector_container**. An alternative terminology calls **Vector_container** and **Container** *subclass* and *superclass*, respectively. The derived class is said to inherit members from its base class, so the use of base and derived classes is commonly referred to as *inheritance*.

The members **operator[]()** and **size()** are said to *override* the corresponding members in the base class **Container** (§20.3.2). The destructor (**~Vector_container()**) overrides the base class destructor (**~Container()**). Note that the member destructor (**~Vector()**) is implicitly invoked by its class’s destructor (**~Vector_container()**).

For a function like **use(Container&)** to use a **Container** in complete ignorance of implementation details, some other function will have to make an object on which it can operate. For example:

```
void g()
{
    Vector_container vc {10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0};
    use(vc);
}
```

Since **use()** doesn’t know about **Vector_container**s but only knows the **Container** interface, it will work just as well for a different implementation of a **Container**. For example:

```
class List_container : public Container {// List_container implements Container
    std::list<double> ld;       // (standard-library) list of doubles (§4.4.2)
public:
    List_container() { }        // empty List
    List_container(initializer_list<double> il) : ld{il} { }
    ~List_container() {}
```

```
        double& operator[](int i);
        int size() const { return ld.size(); }

};

double& List_container::operator[](int i)
{
        for (auto& x : ld) {
                if (i==0) return x;
                --i;
        }
        throw out_of_range("List container");
}
```

Here, the representation is a standard-library `list<double>`. Usually, I would not implement a container with a subscript operation using a `list`, because performance of `list` subscripting is atrocious compared to `vector` subscripting. However, here I just wanted to show an implementation that is radically different from the usual one.

A function can create a `List_container` and have `use()` use it:

```
void h()
{
        List_container lc = { 1, 2, 3, 4, 5, 6, 7, 8, 9 };
        use(lc);
}
```

The point is that `use(Container&)` has no idea if its argument is a `Vector_container`, a `List_container`, or some other kind of container; it doesn't need to know. It can use any kind of `Container`. It knows only the interface defined by `Container`. Consequently, `use(Container&)` needn't be recompiled if the implementation of `List_container` changes or a brand-new class derived from `Container` is used.

The flip side of this flexibility is that objects must be manipulated through pointers or references (§3.3, §20.4).

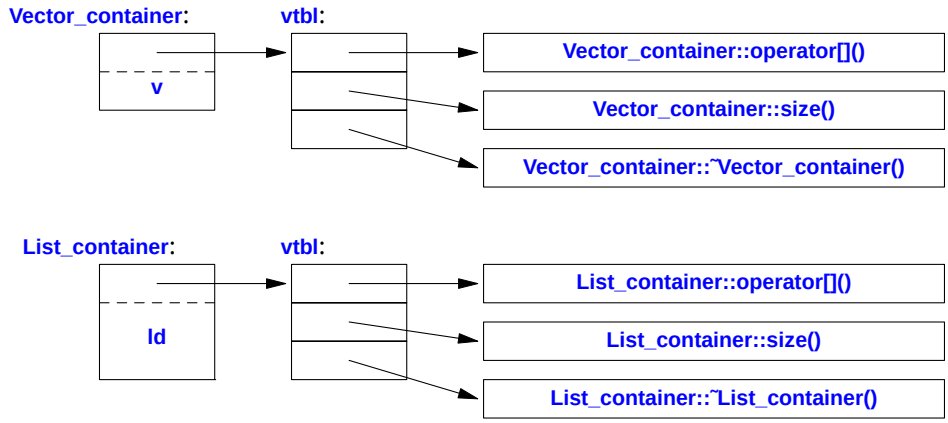
3.2.3 Virtual Functions

Consider again the use of `Container`:

```
void use(Container& c)
{
        const int sz = c.size();

        for (int i=0; i!=sz; ++i)
                cout << c[i] << '\n';
}
```

How is the call `c[i]` in `use()` resolved to the right `operator[]()`? When `h()` calls `use()`, `List_container`'s `operator[]()` must be called. When `g()` calls `use()`, `Vector_container`'s `operator[]()` must be called. To achieve this resolution, a `Container` object must contain information to allow it to select the right function to call at run time. The usual implementation technique is for the compiler to convert the name of a virtual function into an index into a table of pointers to functions. That table is usually

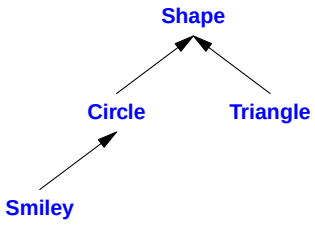
called the *virtual function table* or simply the **vtbl**. Each class with virtual functions has its own **vtbl** identifying its virtual functions. This can be represented graphically like this:



The functions in the **vtbl** allow the object to be used correctly even when the size of the object and the layout of its data are unknown to the caller. The implementation of the caller needs only to know the location of the pointer to the **vtbl** in a **Container** and the index used for each virtual function. This virtual call mechanism can be made almost as efficient as the "normal function call" mechanism (within 25%). Its space overhead is one pointer in each object of a class with virtual functions plus one **vtbl** for each such class.

3.2.4 Class Hierarchies

The **Container** example is a very simple example of a class hierarchy. A *class hierarchy* is a set of classes ordered in a lattice created by derivation (e.g., **: public**). We use class hierarchies to represent concepts that have hierarchical relationships, such as "A fire engine is a kind of a truck which is a kind of a vehicle" and "A smiley face is a kind of a circle which is a kind of a shape." Huge hierarchies, with hundreds of classes, that are both deep and wide are common. As a semi-realistic classic example, let's consider shapes on a screen:



The arrows represent inheritance relationships. For example, class **Circle** is derived from class **Shape**. To represent that simple diagram in code, we must first specify a class that defines the general properties of all shapes:

```
class Shape {
public:
        virtual Point center() const =0;        // pure virtual
        virtual void move(Point to) =0;

        virtual void draw() const = 0;          // draw on current "Canvas"
        virtual void rotate(int angle) = 0;

        virtual ~Shape() {}                     // destructor
        // ...
};
```

Naturally, this interface is an abstract class: as far as representation is concerned, *nothing* (except the location of the pointer to the **vtbl**) is common for every **Shape**. Given this definition, we can write general functions manipulating vectors of pointers to shapes:

```
void rotate_all(vector<Shape*>& v, int angle) // rotate v's elements by angle degrees
{
        for (auto p : v)
                p->rotate(angle);
}
```

To define a particular shape, we must say that it is a **Shape** and specify its particular properties (including its virtual functions):

```
class Circle : public Shape {
public:
        Circle(Point p, int rr);            // constructor

        Point center() const { return x; }
        void move(Point to) { x=to; }

        void draw() const;
        void rotate(int) {}                 // nice simple algorithm
private:
        Point x;    // center
        int r;      // radius
};
```

So far, the **Shape** and **Circle** example provides nothing new compared to the **Container** and **Vector_container** example, but we can build further:

```
class Smiley : public Circle {   // use the circle as the base for a face
public:
        Smiley(Point p, int r) : Circle{p,r}, mouth{nullptr} { }

        ~Smiley()
        {
                delete mouth;
                for (auto p : eyes) delete p;
        }
```

```
        void move(Point to);

        void draw() const;
        void rotate(int);

        void add_eye(Shape* s) { eyes.push_back(s); }
        void set_mouth(Shape* s);
        virtual void wink(int i);          // wink eye number i

        // ...

    private:
        vector<Shape*> eyes;               // usually two eyes
        Shape* mouth;
    };
```

The `push_back()` member function adds its argument to the `vector` (here, `eyes`), increasing that vector's size by one.

We can now define `Smiley::draw()` using calls to `Smiley`'s base and member `draw()`s:

```
    void Smiley::draw()
    {
        Circle::draw();
        for (auto p : eyes)
            p->draw();
        mouth->draw();
    }
```

Note the way that `Smiley` keeps its eyes in a standard-library `vector` and deletes them in its destructor. `Shape`'s destructor is `virtual` and `Smiley`'s destructor overrides it. A virtual destructor is essential for an abstract class because an object of a derived class is usually manipulated through the interface provided by its abstract base class. In particular, it may be deleted through a pointer to a base class. Then, the virtual function call mechanism ensures that the proper destructor is called. That destructor then implicitly invokes the destructors of its bases and members.

In this simplified example, it is the programmer's task to place the eyes and mouth appropriately within the circle representing the face.

We can add data members, operations, or both as we define a new class by derivation. This gives great flexibility with corresponding opportunities for confusion and poor design. See Chapter 21. A class hierarchy offers two kinds of benefits:

- *Interface inheritance*: An object of a derived class can be used wherever an object of a base class is required. That is, the base class acts as an interface for the derived class. The `Container` and `Shape` classes are examples. Such classes are often abstract classes.
- *Implementation inheritance*: A base class provides functions or data that simplifies the implementation of derived classes. `Smiley`'s uses of `Circle`'s constructor and of `Circle::draw()` are examples. Such base classes often have data members and constructors.

Concrete classes – especially classes with small representations – are much like built-in types: we define them as local variables, access them using their names, copy them around, etc. Classes in class hierarchies are different: we tend to allocate them on the free store using `new`, and we access

them through pointers or references. For example, consider a function that reads data describing shapes from an input stream and constructs the appropriate **Shape** objects:

```
enum class Kind { circle, triangle, smiley };

Shape* read_shape(istream& is)    // read shape descriptions from input stream is
{
    // ... read shape header from is and find its Kind k ...

    switch (k) {
    case Kind::circle:
        // read circle data {Point,int} into p and r
        return new Circle{p,r};
    case Kind::triangle:
        // read triangle data {Point,Point,Point} into p1, p2, and p3
        return new Triangle{p1,p2,p3};
    case Kind::smiley:
        // read smiley data {Point,int,Shape,Shape,Shape} into p, r, e1 ,e2, and m
        Smiley* ps = new Smiley{p,r};
        ps->add_eye(e1);
        ps->add_eye(e2);
        ps->set_mouth(m);
        return ps;
    }
}
```

A program may use that shape reader like this:

```
void user()
{
    std::vector<Shape*> v;
    while (cin)
        v.push_back(read_shape(cin));
    draw_all(v);                    // call draw() for each element
    rotate_all(v,45);               // call rotate(45) for each element
    for (auto p : v) delete p;      // remember to delete elements
}
```

Obviously, the example is simplified – especially with respect to error handling – but it vividly illustrates that **user()** has absolutely no idea of which kinds of shapes it manipulates. The **user()** code can be compiled once and later used for new **Shape**s added to the program. Note that there are no pointers to the shapes outside **user()**, so **user()** is responsible for deallocating them. This is done with the **delete** operator and relies critically on **Shape**'s virtual destructor. Because that destructor is virtual, **delete** invokes the destructor for the most derived class. This is crucial because a derived class may have acquired all kinds of resources (such as file handles, locks, and output streams) that need to be released. In this case, a **Smiley** deletes its **eyes** and **mouth** objects.

Experienced programmers will notice that I left open two obvious opportunities for mistakes:

- A user might fail to **delete** the pointer returned by **read_shape()**.
- The owner of a container of **Shape** pointers might not **delete** the objects pointed to.

In that sense, functions returning a pointer to an object allocated on the free store are dangerous.

One solution to both problems is to return a standard-library **unique_ptr** (§5.2.1) rather than a "naked pointer" and store **unique_ptr**s in the container:

```
unique_ptr<Shape> read_shape(istream& is) // read shape descriptions from input stream is
{
    // read shape header from is and find its Kind k

    switch (k) {
    case Kind::circle:
        // read circle data {Point,int} into p and r
        return unique_ptr<Shape>{new Circle{p,r}};        // §5.2.1
    // ...
}

void user()
{
    vector<unique_ptr<Shape>> v;
    while (cin)
        v.push_back(read_shape(cin));
    draw_all(v);                // call draw() for each element
    rotate_all(v,45);           // call rotate(45) for each element
} // all Shapes implicitly destroyed
```

Now the object is owned by the **unique_ptr** which will **delete** the object when it is no longer needed, that is, when its **unique_ptr** goes out of scope.

For the **unique_ptr** version of **user()** to work, we need versions of **draw_all()** and **rotate_all()** that accept **vector<unique_ptr<Shape>>**s. Writing many such **_all()** functions could become tedious, so §3.4.3 shows an alternative.

3.3 Copy and Move

By default, objects can be copied. This is true for objects of user-defined types as well as for built-in types. The default meaning of copy is memberwise copy: copy each member. For example, using **complex** from §3.2.1.1:

```
void test(complex z1)
{
    complex z2 {z1};    // copy initialization
    complex z3;
    z3 = z2;            // copy assignment
    // ...
}
```

Now **z1**, **z2**, and **z3** have the same value because both the assignment and the initialization copied both members.

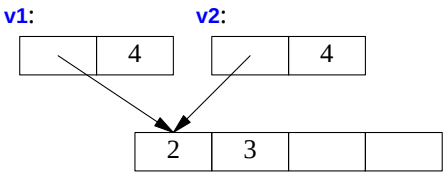
When we design a class, we must always consider if and how an object might be copied. For simple concrete types, memberwise copy is often exactly the right semantics for copy. For some sophisticated concrete types, such as **Vector**, memberwise copy is not the right semantics for copy, and for abstract types it almost never is.

3.3.1 Copying Containers

When a class is a *resource handle*, that is, it is responsible for an object accessed through a pointer, the default memberwise copy is typically a disaster. Memberwise copy would violate the resource handle's invariant (§2.4.3.2). For example, the default copy would leave a copy of a **Vector** referring to the same elements as the original:

```
void bad_copy(Vector v1)
{
        Vector v2 = v1;         // copy v1's representation into v2
        v1[0] = 2;              // v2[0] is now also 2!
        v2[1] = 3;              // v1[1] is now also 3!
}
```

Assuming that **v1** has four elements, the result can be represented graphically like this:



Fortunately, the fact that **Vector** has a destructor is a strong hint that the default (memberwise) copy semantics is wrong and the compiler should at least warn against this example (§17.6). We need to define better copy semantics.

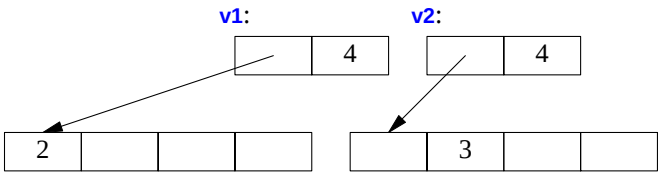
Copying of an object of a class is defined by two members: a *copy constructor* and a *copy assignment*:

```
class Vector {
private:
        double* elem;  // elem points to an array of sz doubles
        int sz;
public:
        Vector(int s);                          // constructor: establish invariant, acquire resources
        ~Vector() { delete[] elem; }            // destructor: release resources

        Vector(const Vector& a);                // copy constructor
        Vector& operator=(const Vector& a);     // copy assignment

        double& operator[](int i);
        const double& operator[](int i) const;

        int size() const;
};
```

A suitable definition of a copy constructor for **Vector** allocates the space for the required number of elements and then copies the elements into it, so that after a copy each **Vector** has its own copy of the elements:

```
Vector::Vector(const Vector& a)     // copy constructor
    :elem{new double[sz]},          // allocate space for elements
     sz{a.sz}
{
    for (int i=0; i!=sz; ++i)       // copy elements
        elem[i] = a.elem[i];
}
```

The result of the `v2=v1` example can now be presented as:



Of course, we need a copy assignment in addition to the copy constructor:

```
Vector& Vector::operator=(const Vector& a)      // copy assignment
{
    double* p = new double[a.sz];
    for (int i=0; i!=a.sz; ++i)
        p[i] = a.elem[i];
    delete[] elem;          // delete old elements
    elem = p;
    sz = a.sz;
    return *this;
}
```

The name `this` is predefined in a member function and points to the object for which the member function is called.

A copy constructor and a copy assignment for a class `X` are typically declared to take an argument of type `const X&`.

3.3.2 Moving Containers

We can control copying by defining a copy constructor and a copy assignment, but copying can be costly for large containers. Consider:

```
Vector operator+(const Vector& a, const Vector& b)
{
    if (a.size()!=b.size())
        throw Vector_size_mismatch{};

    Vector res(a.size());
    for (int i=0; i!=a.size(); ++i)
        res[i]=a[i]+b[i];
    return res;
}
```

Returning from a + involves copying the result out of the local variable res and into some place where the caller can access it. We might use this + like this:

```
void f(const Vector& x, const Vector& y, const Vector& z)
{
    Vector r;
    // ...
    r = x+y+z;
    // ...
}
```

That would be copying a Vector at least twice (one for each use of the + operator). If a Vector is large, say, 10,000 doubles, that could be embarrassing. The most embarrassing part is that res in operator+() is never used again after the copy. We didn't really want a copy; we just wanted to get the result out of a function: we wanted to *move* a Vector rather than to *copy* it. Fortunately, we can state that intent:

```
class Vector {
    // ...

    Vector(const Vector& a);              // copy constructor
    Vector& operator=(const Vector& a);   // copy assignment

    Vector(Vector&& a);                   // move constructor
    Vector& operator=(Vector&& a);        // move assignment
};
```

Given that definition, the compiler will choose the *move constructor* to implement the transfer of the return value out of the function. This means that r=x+y+z will involve no copying of Vectors. Instead, Vectors are just moved.

As is typical, Vector's move constructor is trivial to define:

```
Vector::Vector(Vector&& a)
    :elem{a.elem},      // "grab the elements" from a
     sz{a.sz}
{
    a.elem = nullptr;       // now a has no elements
    a.sz = 0;
}
```

The && means ''rvalue reference'' and is a reference to which we can bind an rvalue (§6.4.1). The word ''rvalue'' is intended to complement ''lvalue,'' which roughly means ''something that can appear on the left-hand side of an assignment.'' So an rvalue is – to a first approximation – a value that you can't assign to, such as an integer returned by a function call, and an rvalue reference is a reference to something that nobody else can assign to. The res local variable in operator+() for Vectors is an example.

A move constructor does *not* take a const argument: after all, a move constructor is supposed to remove the value from its argument. A *move assignment* is defined similarly.

A move operation is applied when an rvalue reference is used as an initializer or as the right-hand side of an assignment.

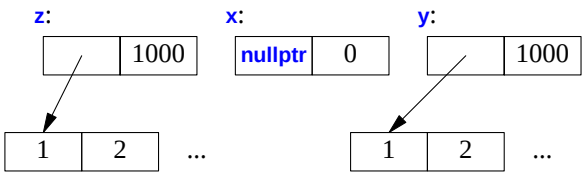
After a move, a moved-from object should be in a state that allows a destructor to be run. Typically, we should also allow assignment to a moved-from object (§17.5, §17.6.2).

Where the programmer knows that a value will not be used again, but the compiler can't be expected to be smart enough to figure that out, the programmer can be specific:

```
Vector f()
{
    Vector x(1000);
    Vector y(1000);
    Vector z(1000);
    // ...
    z = x;              // we get a copy
    y = std::move(x);   // we get a move
    // ...
    return z;           // we get a move
};
```

The standard-library function **move()** returns an rvalue reference to its argument.

Just before the **return** we have:



When **z** is destroyed, it too has been moved from (by the **return**) so that, like **x**, it is empty (it holds no elements).

3.3.3 Resource Management

By defining constructors, copy operations, move operations, and a destructor, a programmer can provide complete control of the lifetime of a contained resource (such as the elements of a container). Furthermore, a move constructor allows an object to move simply and cheaply from one scope to another. That way, objects that we cannot or would not want to copy out of a scope can be simply and cheaply moved out instead. Consider a standard-library **thread** representing a concurrent activity (§5.3.1) and a **Vector** of a million **double**s. We can't copy the former and don't want to copy the latter.

```
std::vector<thread> my_threads;

Vector init(int n)
{
    thread t {heartbeat};               // run heartbeat concurrently (on its own thread)
    my_threads.push_back(move(t));      // move t into my_threads
    // ... more initialization ...
```

```
        Vector vec(n);
        for (int i=0; i<vec.size(); ++i) vec[i] = 777;
        return vec;                                  // move res out of init()
}

auto v = init();  // start heartbeat and initialize v
```

This makes resource handles, such as **Vector** and **thread**, an alternative to using pointers in many cases. In fact, the standard-library "smart pointers," such as **unique_ptr**, are themselves resource handles (§5.2.1).

I used the standard-library **vector** to hold the **thread**s because we don't get to parameterize **Vector** with an element type until §3.4.1.

In very much the same way as **new** and **delete** disappear from application code, we can make pointers disappear into resource handles. In both cases, the result is simpler and more maintainable code, without added overhead. In particular, we can achieve *strong resource safety*; that is, we can eliminate resource leaks for a general notion of a resource. Examples are **vector**s holding memory, **thread**s holding system threads, and **fstream**s holding file handles.

3.3.4 Suppressing Operations

Using the default copy or move for a class in a hierarchy is typically a disaster: given only a pointer to a base, we simply don't know what members the derived class has (§3.2.2), so we can't know how to copy them. So, the best thing to do is usually to *delete* the default copy and move operations, that is, to eliminate the default definitions of those two operations:

```
class Shape {
public:
        Shape(const Shape&) =delete;                 // no copy operations
        Shape& operator=(const Shape&) =delete;

        Shape(Shape&&) =delete;                      // no move operations
        Shape& operator=(Shape&&) =delete;

        ~Shape();
        // ...
};
```

Now an attempt to copy a **Shape** will be caught by the compiler. If you need to copy an object in a class hierarchy, write some kind of clone function (§22.2.4).

In this particular case, if you forgot to **delete** a copy or move operation, no harm is done. A move operation is *not* implicitly generated for a class where the user has explicitly declared a destructor. Furthermore, the generation of copy operations is deprecated in this case (§44.2.3). This can be a good reason to explicitly define a destructor even where the compiler would have implicitly provided one (§17.2.3).

A base class in a class hierarchy is just one example of an object we wouldn't want to copy. A resource handle generally cannot be copied just by copying its members (§5.2, §17.2.2).

The **=delete** mechanism is general, that is, it can be used to suppress any operation (§17.6.4).

3.4 Templates

Someone who wants a vector is unlikely always to want a vector of **double**s. A vector is a general concept, independent of the notion of a floating-point number. Consequently, the element type of a vector ought to be represented independently. A *template* is a class or a function that we parameterize with a set of types or values. We use templates to represent concepts that are best understood as something very general from which we can generate specific types and functions by specifying arguments, such as the element type **double**.

3.4.1 Parameterized Types

We can generalize our vector-of-doubles type to a vector-of-anything type by making it a **template** and replacing the specific type **double** with a parameter. For example:

```
template<typename T>
class Vector {
private:
    T* elem;   // elem points to an array of sz elements of type T
    int sz;
public:
    Vector(int s);                  // constructor: establish invariant, acquire resources
    ~Vector() { delete[] elem; }    // destructor: release resources

    // ... copy and move operations ...

    T& operator[](int i);
    const T& operator[](int i) const;
    int size() const { return sz; }
};
```

The **template<typename T>** prefix makes **T** a parameter of the declaration it prefixes. It is C++'s version of the mathematical "for all T" or more precisely "for all types T."

The member functions might be defined similarly:

```
template<typename T>
Vector<T>::Vector(int s)
{
    if (s<0) throw Negative_size{};
    elem = new T[s];
    sz = s;
}

template<typename T>
const T& Vector<T>::operator[](int i) const
{
    if (i<0 || size()<=i)
        throw out_of_range{"Vector::operator[]"};
    return elem[i];
}
```

Given these definitions, we can define **Vector**s like this:

```
Vector<char> vc(200);          // vector of 200 characters
Vector<string> vs(17);         // vector of 17 strings
Vector<list<int>> vli(45);     // vector of 45 lists of integers
```

The **>>** in **Vector<list<int>>** terminates the nested template arguments; it is not a misplaced input operator. It is not (as in C++98) necessary to place a space between the two **>**s.

We can use **Vector**s like this:

```
void write(const Vector<string>& vs)          // Vector of some strings
{
    for (int i = 0; i!=vs.size(); ++i)
        cout << vs[i] << '\n';
}
```

To support the range-**for** loop for our **Vector**, we must define suitable **begin()** and **end()** functions:

```
template<typename T>
T* begin(Vector<T>& x)
{
    return &x[0];          // pointer to first element
}

template<typename T>
T* end(Vector<T>& x)
{
    return x.begin()+x.size(); // pointer to one-past-last element
}
```

Given those, we can write:

```
void f2(const Vector<string>& vs)  // Vector of some strings
{
    for (auto& s : vs)
        cout << s << '\n';
}
```

Similarly, we can define lists, vectors, maps (that is, associative arrays), etc., as templates (§4.4, §23.2, Chapter 31).

Templates are a compile-time mechanism, so their use incurs no run-time overhead compared to "handwritten code" (§23.2.2).

3.4.2 Function Templates

Templates have many more uses than simply parameterizing a container with an element type. In particular, they are extensively used for parameterization of both types and algorithms in the standard library (§4.4.5, §4.5.5). For example, we can write a function that calculates the sum of the element values of any container like this:

```
template<typename Container, typename Value>
Value sum(const Container& c, Value v)
{
    for (auto x : c)
        v+=x;
    return v;
}
```

The `Value` template argument and the function argument `v` are there to allow the caller to specify the type and initial value of the accumulator (the variable in which to accumulate the sum):

```
void user(Vector<int>& vi, std::list<double>& ld, std::vector<complex<double>>& vc)
{
    int x = sum(vi,0);                      // the sum of a vector of ints (add ints)
    double d = sum(vi,0.0);                 // the sum of a vector of ints (add doubles)
    double dd = sum(ld,0.0);                // the sum of a list of doubles
    auto z = sum(vc,complex<double>{});     // the sum of a vector of complex<double>
                                            // the initial value is {0.0,0.0}
}
```

The point of adding `int`s in a `double` would be to gracefully handle a number larger than the largest `int`. Note how the types of the template arguments for `sum<T,V>` are deduced from the function arguments. Fortunately, we do not need to explicitly specify those types.

This `sum()` is a simplified version of the standard-library `accumulate()` (§40.6).

3.4.3 Function Objects

One particularly useful kind of template is the *function object* (sometimes called a *functor*), which is used to define objects that can be called like functions. For example:

```
template<typename T>
class Less_than {
    const T val;    // value to compare against
public:
    Less_than(const T& v) :val(v) { }
    bool operator()(const T& x) const { return x<val; } // call operator
};
```

The function called `operator()` implements the ‘‘function call,’’ ‘‘call,’’ or ‘‘application’’ operator `()`.

We can define named variables of type `Less_than` for some argument type:

```
Less_than<int> lti {42};            // lti(i) will compare i to 42 using < (i<42)
Less_than<string> lts {"Backus"};   // lts(s) will compare s to "Backus" using < (s<"Backus")
```

We can call such an object, just as we call a function:

```
void fct(int n, const string & s)
{
    bool b1 = lti(n);       // true if n<42
    bool b2 = lts(s);       // true if s<"Backus"
    // ...
}
```

Such function objects are widely used as arguments to algorithms. For example, we can count the occurrences of values for which a predicate returns `true`:

```
template<typename C, typename P>
int count(const C& c, P pred)
{
        int cnt = 0;
        for (const auto& x : c)
                if (pred(x))
                        ++cnt;
        return cnt;
}
```

A *predicate* is something that we can invoke to return `true` or `false`. For example:

```
void f(const Vector<int>& vec, const list<string>& lst, int x, const string& s)
{
        cout << "number of values less than " << x
                << ": " << count(vec,Less_than<int>{x})
                << '\n';
        cout << "number of values less than " << s
                << ": " << count(lst,Less_than<string>{s})
                << '\n';
}
```

Here, `Less_than<int>{x}` constructs an object for which the call operator compares to the `int` called `x`; `Less_than<string>{s}` constructs an object that compares to the `string` called `s`. The beauty of these function objects is that they carry the value to be compared against with them. We don't have to write a separate function for each value (and each type), and we don't have to introduce nasty global variables to hold values. Also, for a simple function object like `Less_than` inlining is simple, so that a call of `Less_than` is far more efficient than an indirect function call. The ability to carry data plus their efficiency make function objects particularly useful as arguments to algorithms.

Function objects used to specify the meaning of key operations of a general algorithm (such as `Less_than` for `count()`) are often referred to as *policy objects*.

We have to define `Less_than` separately from its use. That could be seen as inconvenient. Consequently, there is a notation for implicitly generating function objects:

```
void f(const Vector<int>& vec, const list<string>& lst, int x, const string& s)
{
        cout << "number of values less than " << x
                << ": " << count(vec,[&](int a){ return a<x; })
                << '\n';
        cout << "number of values less than " << s
                << ": " << count(lst,[&](const string& a){ return a<s; })
                << '\n';
}
```

The notation `[&](int a){ return a<x; }` is called a *lambda expression* (§11.4). It generates a function object exactly like `Less_than<int>{x}`. The `[&]` is a *capture list* specifying that local names used (such as `x`) will be passed by reference. Had we wanted to ''capture'' only `x`, we could have said

so: [&x]. Had we wanted to give the generated object a copy of x, we could have said so: [=x]. Capture nothing is [], capture all local names used by reference is [&], and capture all local names used by value is [=].

Using lambdas can be convenient and terse, but also obscure. For nontrivial actions (say, more than a simple expression), I prefer to name the operation so as to more clearly state its purpose and to make it available for use in several places in a program.

In §3.2.4, we noticed the annoyance of having to write many functions to perform operations on elements of vectors of pointers and unique_ptrs, such as draw_all() and rotate_all(). Function objects (in particular, lambdas) can help by allowing us to separate the traversal of the container from the specification of what is to be done with each element.

First, we need a function that applies an operation to each object pointed to by the elements of a container of pointers:

```
template<class C, class Oper>
void for_all(C& c, Oper op)            // assume that C is a container of pointers
{
    for (auto& x : c)
        op(*x);            // pass op() a reference to each element pointed to
}
```

Now, we can write a version of user() from §3.2.4 without writing a set of _all functions:

```
void user()
{
    vector<unique_ptr<Shape>> v;
    while (cin)
        v.push_back(read_shape(cin));
    for_all(v,[](Shape& s){ s.draw(); });          // draw_all()
    for_all(v,[](Shape& s){ s.rotate(45); });      // rotate_all(45)
}
```

I pass a reference to Shape to a lambda so that the lambda doesn't have to care exactly how the objects are stored in the container. In particular, those for_all() calls would still work if I changed v to a vector<Shape*>.

3.4.4 Variadic Templates

A template can be defined to accept an arbitrary number of arguments of arbitrary types. Such a template is called a *variadic template*. For example:

```
template<typename T, typename... Tail>
void f(T head, Tail... tail)
{
    g(head);    // do something to head
    f(tail...); // try again with tail
}

void f() { }        // do nothing
```

The key to implementing a variadic template is to note that when you pass a list of arguments to it,

you can separate the first argument from the rest. Here, we do something to the first argument (the **head**) and then recursively call **f()** with the rest of the arguments (the **tail**). The ellipsis, **...**, is used to indicate ''the rest'' of a list. Eventually, of course, **tail** will become empty and we need a separate function to deal with that.

We can call this **f()** like this:

```
int main()
{
        cout << "first: ";
        f(1,2.2,"hello");

        cout << "\nsecond: "
        f(0.2,'c',"yuck!",0,1,2);
        cout << "\n";
}
```

This would call **f(1,2.2,"hello")**, which will call **f(2.2,"hello")**, which will call **f("hello")**, which will call **f()**. What might the call **g(head)** do? Obviously, in a real program it will do whatever we wanted done to each argument. For example, we could make it write its argument (here, **head**) to output:

```
template<typename T>
void g(T x)
{
        cout << x << " ";
}
```

Given that, the output will be:

```
first: 1 2.2 hello
second: 0.2 c yuck! 0 1 2
```

It seems that **f()** is a simple variant of **printf()** printing arbitrary lists or values – implemented in three lines of code plus their surrounding declarations.

The strength of variadic templates (sometimes just called *variadics*) is that they can accept any arguments you care to give them. The weakness is that the type checking of the interface is a possibly elaborate template program. For details, see §28.6. For examples, see §34.2.4.2 (N-tuples) and Chapter 29 (N-dimensional matrices).

3.4.5 Aliases

Surprisingly often, it is useful to introduce a synonym for a type or a template (§6.5). For example, the standard header **<cstddef>** contains a definition of the alias **size_t**, maybe:

```
using size_t = unsigned int;
```

The actual type named **size_t** is implementation-dependent, so in another implementation **size_t** may be an **unsigned long**. Having the alias **size_t** allows the programmer to write portable code.

It is very common for a parameterized type to provide an alias for types related to their template arguments. For example:

```
template<typename T>
class Vector {
public:
    using value_type = T;
    // ...
};
```

In fact, every standard-library container provides `value_type` as the name of its value type (§31.3.1). This allows us to write code that will work for every container that follows this convention. For example:

```
template<typename C>
using Element_type = typename C::value_type;

template<typename Container>
void algo(Container& c)
{
    Vector<Element_type<Container>> vec; // keep results here
    // ...
}
```

The aliasing mechanism can be used to define a new template by binding some or all template arguments. For example:

```
template<typename Key, typename Value>
class Map {
    // ...
};

template<typename Value>
using String_map = Map<string,Value>;

String_map<int> m; // m is a Map<string,int>
```

See §23.6.

3.5 Advice

[1] Express ideas directly in code; §3.2.
[2] Define classes to represent application concepts directly in code; §3.2.
[3] Use concrete classes to represent simple concepts and performance-critical components; §3.2.1.
[4] Avoid ‘‘naked’’ `new` and `delete` operations; §3.2.1.2.
[5] Use resource handles and RAII to manage resources; §3.2.1.2.
[6] Use abstract classes as interfaces when complete separation of interface and implementation is needed; §3.2.2.
[7] Use class hierarchies to represent concepts with inherent hierarchical structure; §3.2.4.

[8] When designing a class hierarchy, distinguish between implementation inheritance and interface inheritance; §3.2.4.
[9] Control construction, copy, move, and destruction of objects; §3.3.
[10] Return containers by value (relying on move for efficiency); §3.3.2.
[11] Provide strong resource safety; that is, never leak anything that you think of as a resource; §3.3.3.
[12] Use containers, defined as resource handle templates, to hold collections of values of the same type; §3.4.1.
[13] Use function templates to represent general algorithms; §3.4.2.
[14] Use function objects, including lambdas, to represent policies and actions; §3.4.3.
[15] Use type and template aliases to provide a uniform notation for types that may vary among similar types or among implementations; §3.4.5.

4

A Tour of C++: Containers and Algorithms

Why waste time learning
when ignorance is instantaneous?
– Hobbes

- Libraries
  Standard-Library Overview; The Standard-Library Headers and Namespace
- Strings
- Stream I/O
  Output; Input; I/O of User-Defined Types
- Containers
  vector; **list**; **map**; **unordered_map**; Container Overview
- Algorithms
  Use of Iterators; Iterator Types; Stream Iterators; Predicates; Algorithm Overview; Container Algorithms
- Advice

4.1 Libraries

No significant program is written in just a bare programming language. First, a set of libraries is developed. These then form the basis for further work. Most programs are tedious to write in the bare language, whereas just about any task can be rendered simple by the use of good libraries.

Continuing from Chapters 2 and 3, this chapter and the next give a quick tour of key standard-library facilities. I assume that you have programmed before. If not, please consider reading a textbook, such as *Programming: Principles and Practice Using C++* [Stroustrup,2009], before continuing. Even if you have programmed before, the libraries you used or the applications you wrote may be very different from the style of C++ presented here. If you find this ''lightning tour'' confusing, you might skip to the more systematic and bottom-up language presentation starting in Chapter 6. Similarly, a more systematic description of the standard library starts in Chapter 30.

I very briefly present useful standard-library types, such as **string**, **ostream**, **vector**, **map** (this chapter), **unique_ptr**, **thread**, **regex**, and **complex** (Chapter 5), as well as the most common ways of using them. Doing this allows me to give better examples in the following chapters. As in Chapter 2 and Chapter 3, you are strongly encouraged not to be distracted or discouraged by an incomplete understanding of details. The purpose of this chapter is to give you a taste of what is to come and to convey a basic understanding of the most useful library facilities.

The specification of the standard library is almost two thirds of the ISO C++ standard. Explore it, and prefer it to home-made alternatives. Much though have gone into its design, more still into its implementations, and much effort will go into its maintenance and extension.

The standard-library facilities described in this book are part of every complete C++ implementation. In addition to the standard-library components, most implementations offer ''graphical user interface'' systems (GUIs), Web interfaces, database interfaces, etc. Similarly, most application development environments provide ''foundation libraries'' for corporate or industrial ''standard'' development and/or execution environments. Here, I do not describe such systems and libraries. The intent is to provide a self-contained description of C++ as defined by the standard and to keep the examples portable, except where specifically noted. Naturally, a programmer is encouraged to explore the more extensive facilities available on most systems.

4.1.1 Standard-Library Overview

The facilities provided by the standard library can be classified like this:

- Run-time language support (e.g., for allocation and run-time type information); see §30.3.
- The C standard library (with very minor modifications to minimize violations of the type system); see Chapter 43.
- Strings and I/O streams (with support for international character sets and localization); see Chapter 36, Chapter 38, and Chapter 39. I/O streams is an extensible framework to which users can add their own streams, buffering strategies, and character sets.
- A framework of containers (such as **vector** and **map**) and algorithms (such as **find()**, **sort()**, and **merge()**); see §4.4, §4.5, Chapters 31-33. This framework, conventionally called the STL [Stepanov,1994], is extensible so users can add their own containers and algorithms.
- Support for numerical computation (such as standard mathematical functions, complex numbers, vectors with arithmetic operations, and random number generators); see §3.2.1.1 and Chapter 40.
- Support for regular expression matching; see §5.5 and Chapter 37.
- Support for concurrent programming, including **thread**s and **lock**s; see §5.3 and Chapter 41. The concurrency support is foundational so that users can add support for new models of concurrency as libraries.
- Utilities to support template metaprogramming (e.g., type traits; §5.4.2, §28.2.4, §35.4), STL-style generic programming (e.g., **pair**; §5.4.3, §34.2.4.1), and general programming (e.g., **clock**; §5.4.1, §35.2).
- ''Smart pointers'' for resource management (e.g., **unique_ptr** and **shared_ptr**; §5.2.1, §34.3) and an interface to garbage collectors (§34.5).
- Special-purpose containers, such as **array** (§34.2.1), **bitset** (§34.2.2), and **tuple** (§34.2.4.2).

The main criteria for including a class in the library were that:

- it could be helpful to almost every C++ programmer (both novices and experts),
- it could be provided in a general form that did not add significant overhead compared to a simpler version of the same facility, and
- that simple uses should be easy to learn (relative to the inherent complexity of their task).

Essentially, the C++ standard library provides the most common fundamental data structures together with the fundamental algorithms used on them.

4.1.2 The Standard-library Headers and Namespace

Every standard-library facility is provided through some standard header. For example:

```
#include<string>
#include<list>
```

This makes the standard **string** and **list** available.

The standard library is defined in a namespace (§2.4.2, §14.3.1) called **std**. To use standard library facilities, the **std::** prefix can be used:

```
std::string s {"Four legs Good; two legs Baaad!"};
std::list<std::string> slogans {"War is peace", "Freedom is Slavery", "Ignorance is Strength"};
```

For simplicity, I will rarely use the **std::** prefix explicitly in examples. Neither will I always **#include** the necessary headers explicitly. To compile and run the program fragments here, you must **#include** the appropriate headers (as listed in §4.4.5, §4.5.5, and §30.2) and make the names they declare accessible. For example:

```
#include<string>            // make the standard string facilities accessible
using namespace std;        // make std names available without std:: prefix

string s {"C++ is a general−purpose programming language"};    // OK: string is std::string
```

It is generally in poor taste to dump every name from a namespace into the global namespace. However, in this book, I use the standard library almost exclusively and it is good to know what it offers. So, I don't prefix every use of a standard library name with **std::**. Nor do I **#include** the appropriate headers in every example. Assume that done.

Here is a selection of standard-library headers, all supplying declarations in namespace **std**:

Selected Standard Library Headers (continues)			
<algorithm>	**copy()**, **find()**, **sort()**	§32.2	§iso.25
<array>	**array**	§34.2.1	§iso.23.3.2
<chrono>	**duration**, **time_point**	§35.2	§iso.20.11.2
<cmath>	**sqrt()**, **pow()**	§40.3	§iso.26.8
<complex>	**complex**, **sqrt()**, **pow()**	§40.4	§iso.26.8
<fstream>	**fstream**, **ifstream**, **ofstream**	§38.2.1	§iso.27.9.1
<future>	**future**, **promise**	§5.3.5	§iso.30.6
<iostream>	**istream**, **ostream**, **cin**, **cout**	§38.1	§iso.27.4

Selected Standard Library Headers (continued)			
<map>	map, multimap	§31.4.3	§iso.23.4.4
<memory>	unique_ptr, shared_ptr, allocator	§5.2.1	§iso.20.6
<random>	default_random_engine, normal_distribution	§40.7	§iso.26.5
<regex>	regex, smatch	Chapter 37	§iso.28.8
<string>	string, basic_string	Chapter 36	§iso.21.3
<set>	set, multiset	§31.4.3	§iso.23.4.6
<sstream>	istrstream, ostrstream	§38.2.2	§iso.27.8
<thread>	thread	§5.3.1	§iso.30.3
<unordered_map>	unordered_map, unordered_multimap	§31.4.3.2	§iso.23.5.4
<utility>	move(), swap(), pair	§35.5	§iso.20.1
<vector>	vector	§31.4	§iso.23.3.6

This listing is far from complete; see §30.2 for more information.

4.2 Strings

The standard library provides a `string` type to complement the string literals. The `string` type provides a variety of useful string operations, such as concatenation. For example:

```
string compose(const string& name, const string& domain)
{
    return name + '@' + domain;
}

auto addr = compose("dmr","bell−labs.com");
```

Here, `addr` is initialized to the character sequence `dmr@bell−labs.com`. "Addition" of strings means concatenation. You can concatenate a `string`, a string literal, a C-style string, or a character to a `string`. The standard `string` has a move constructor so returning even long `string`s by value is efficient (§3.3.2).

In many applications, the most common form of concatenation is adding something to the end of a `string`. This is directly supported by the `+=` operation. For example:

```
void m2(string& s1, string& s2)
{
    s1 = s1 + '\n';   // append newline
    s2 += '\n';       // append newline
}
```

The two ways of adding to the end of a `string` are semantically equivalent, but I prefer the latter because it is more explicit about what it does, more concise, and possibly more efficient.

A `string` is mutable. In addition to `=` and `+=`, subscripting (using `[]`) and substring operations are supported. The standard-library `string` is described in Chapter 36. Among other useful features, it provides the ability to manipulate substrings. For example:

```
string name = "Niels Stroustrup";

void m3()
{
        string s = name.substr(6,10);       // s = "Stroustrup"
        name.replace(0,5,"nicholas");       // name becomes "nicholas Stroustrup"
        name[0] = toupper(name[0]);         // name becomes "Nicholas Stroustrup"
}
```

The `substr()` operation returns a `string` that is a copy of the substring indicated by its arguments. The first argument is an index into the `string` (a position), and the second is the length of the desired substring. Since indexing starts from `0`, `s` gets the value `Stroustrup`.

The `replace()` operation replaces a substring with a value. In this case, the substring starting at `0` with length `5` is `Niels`; it is replaced by `nicholas`. Finally, I replace the initial character with its uppercase equivalent. Thus, the final value of `name` is `Nicholas Stroustrup`. Note that the replacement string need not be the same size as the substring that it is replacing.

Naturally, `string`s can be compared against each other and against string literals. For example:

```
string incantation;

void respond(const string& answer)
{
        if (answer == incantation) {
                // perform magic
        }
        else if (answer == "yes") {
                // ...
        }
        // ...
}
```

The `string` library is described in Chapter 36. The most common techniques for implementing `string` are presented in the `String` example (§19.3).

4.3 Stream I/O

The standard library provides formatted character input and output through the `iostream` library. The input operations are typed and extensible to handle user-defined types. This section is a very brief introduction to the use of `iostream`s; Chapter 38 is a reasonably complete description of the `iostream` library facilities.

Other forms of user interaction, such as graphical I/O, are handled through libraries that are not part of the ISO standard and therefore not described here.

4.3.1 Output

The I/O stream library defines output for every built-in type. Further, it is easy to define output of a user-defined type (§4.3.3). The operator `<<` (“put to”) is used as an output operator on objects of

type **ostream**; **cout** is the standard output stream and **cerr** is the standard stream for reporting errors. By default, values written to **cout** are converted to a sequence of characters. For example, to output the decimal number **10**, we can write:

```
void f()
{
    cout << 10;
}
```

This places the character **1** followed by the character **0** on the standard output stream.

Equivalently, we could write:

```
void g()
{
    int i {10};
    cout << i;
}
```

Output of different types can be combined in the obvious way:

```
void h(int i)
{
    cout << "the value of i is ";
    cout << i;
    cout << '\n';
}
```

For **h(10)**, the output will be:

```
the value of i is 10
```

People soon tire of repeating the name of the output stream when outputting several related items. Fortunately, the result of an output expression can itself be used for further output. For example:

```
void h2(int i)
{
    cout << "the value of i is " << i << '\n';
}
```

This **h2()** produces the same output as **h()**.

A character constant is a character enclosed in single quotes. Note that a character is output as a character rather than as a numerical value. For example:

```
void k()
{
    int b = 'b';        // note: char implicitly converted to int
    char c = 'c';
    cout << 'a' << b << c;
}
```

The integer value of the character **'b'** is **98** (in the ASCII encoding used on the C++ implementation that I used), so this will output **a98c**.

4.3.2 Input

The standard library offers **istream**s for input. Like **ostream**s, **istream**s deal with character string representations of built-in types and can easily be extended to cope with user-defined types.

The operator **>>** (''get from'') is used as an input operator; **cin** is the standard input stream. The type of the right-hand operand of **>>** determines what input is accepted and what is the target of the input operation. For example:

```
void f()
{
        int i;
        cin >> i;          // read an integer into i

        double d;
        cin >> d;          // read a double-precision floating-point number into d
}
```

This reads a number, such as **1234**, from the standard input into the integer variable **i** and a floating-point number, such as **12.34e5**, into the double-precision floating-point variable **d**.

Often, we want to read a sequence of characters. A convenient way of doing that is to read into a **string**. For example:

```
void hello()
{
        cout << "Please enter your name\n";
        string str;
        cin >> str;
        cout << "Hello, " << str << "!\n";
}
```

If you type in **Eric** the response is:

```
Hello, Eric!
```

By default, a whitespace character (§7.3.2), such as a space, terminates the read, so if you enter **Eric Bloodaxe** pretending to be the ill-fated king of York, the response is still:

```
Hello, Eric!
```

You can read a whole line (including the terminating newline character) using the **getline()** function. For example:

```
void hello_line()
{
        cout << "Please enter your name\n";
        string str;
        getline(cin,str);
        cout << "Hello, " << str << "!\n";
}
```

With this program, the input **Eric Bloodaxe** yields the desired output:

```
Hello, Eric Bloodaxe!
```

The newline that terminated the line is discarded, so **cin** is ready for the next input line.

The standard strings have the nice property of expanding to hold what you put in them; you don't have to precalculate a maximum size. So, if you enter a couple of megabytes of semicolons, the program will echo pages of semicolons back at you.

4.3.3 I/O of User-Defined Types

In addition to the I/O of built-in types and standard **string**s, the **iostream** library allows programmers to define I/O for their own types. For example, consider a simple type **Entry** that we might use to represent entries in a telephone book:

```
struct Entry {
    string name;
    int number;
};
```

We can define a simple output operator to write an **Entry** using a *{"name",number}* format similar to the one we use for initialization in code:

```
ostream& operator<<(ostream& os, const Entry& e)
{
    return os << "{\"" << e.name << "\", " << e.number << "}";
}
```

A user-defined output operator takes its output stream (by reference) as its first argument and returns it as its result. See §38.4.2 for details.

The corresponding input operator is more complicated because it has to check for correct formatting and deal with errors:

```
istream& operator>>(istream& is, Entry& e)
    // read { "name" , number } pair. Note: formatted with { " " , and }
{
    char c, c2;
    if (is>>c && c=='{' && is>>c2 && c2=='"') { // start with a { "
        string name;                    // the default value of a string is the empty string: ""
        while (is.get(c) && c!='"')     // anything before a " is part of the name
            name+=c;

        if (is>>c && c==',') {
            int number = 0;
            if (is>>number>>c && c=='}') { // read the number and a }
                e = {name,number};      // assign to the entry
                return is;
            }
        }
    }
    is.setf(ios_base::failbit);         // register the failure in the stream
    return is;
}
```

An input operation returns a reference to its **istream** which can be used to test if the operation

succeeded. For example, when used as a condition, `is>>c` means "Did we succeed at reading from `is` into `c`?"

The `is>>c` skips whitespace by default, but `is.get(c)` does not, so that this `Entry`-input operator ignores (skips) whitespace outside the name string, but not within it. For example:

```
{ "John Marwood Cleese" , 123456        }
{"Michael Edward Palin",987654}
```

We can read such a pair of values from input into an `Entry` like this:

```
for (Entry ee; cin>>ee; )   // read from cin into ee
    cout << ee << '\n';     // write ee to cout
```

The output is:

```
{"John Marwood Cleese", 123456}
{"Michael Edward Palin", 987654}
```

See §38.4.1 for more technical details and techniques for writing input operators for user-defined types. See §5.5 and Chapter 37 for a more systematic technique for recognizing patterns in streams of characters (regular expression matching).

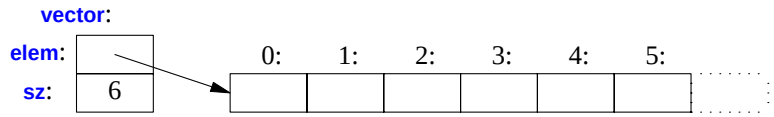
4.4 Containers

Most computing involves creating collections of values and then manipulating such collections. Reading characters into a `string` and printing out the `string` is a simple example. A class with the main purpose of holding objects is commonly called a *container*. Providing suitable containers for a given task and supporting them with useful fundamental operations are important steps in the construction of any program.

To illustrate the standard-library containers, consider a simple program for keeping names and telephone numbers. This is the kind of program for which different approaches appear "simple and obvious" to people of different backgrounds. The `Entry` class from §4.3.3 can be used to hold a simple phone book entry. Here, we deliberately ignore many real-world complexities, such as the fact that many phone numbers do not have a simple representation as a 32-bit `int`.

4.4.1 vector

The most useful standard-library container is `vector`. A `vector` is a sequence of elements of a given type. The elements are stored contiguously in memory:



The `Vector` examples in §3.2.2 and §3.4 give an idea of the implementation of `vector` and §13.6 and §31.4 provide an exhaustive discussion.

We can initialize a vector with a set of values of its element type:

```
vector<Entry> phone_book = {
        {"David Hume",123456},
        {"Karl Popper",234567},
        {"Bertrand Arthur William Russell",345678}
};
```

Elements can be accessed through subscripting:

```
void print_book(const vector<Entry>& book)
{
        for (int i = 0; i!=book.size(); ++i)
                cout << book[i] << '\n';
}
```

As usual, indexing starts at 0 so that book[0] holds the entry for David Hume. The vector member function size() gives the number of elements.

The elements of a vector constitute a range, so we can use a range-for loop (§2.2.5):

```
void print_book(const vector<Entry>& book)
{
        for (const auto& x : book)      // for "auto" see §2.2.2
                cout << x << '\n';
}
```

When we define a vector, we give it an initial size (initial number of elements):

```
vector<int> v1 = {1, 2, 3, 4};          // size is 4
vector<string> v2;                      // size is 0
vector<Shape*> v3(23);                  // size is 23; initial element value: nullptr
vector<double> v4(32,9.9);              // size is 32; initial element value: 9.9
```

An explicit size is enclosed in ordinary parentheses, for example, (23), and by default the elements are initialized to the element type's default value (e.g., nullptr for pointers and 0 for numbers). If you don't want the default value, you can specify one as a second argument (e.g., 9.9 for the 32 elements of v4).

The initial size can be changed. One of the most useful operations on a vector is push_back(), which adds a new element at the end of a vector, increasing its size by one. For example:

```
void input()
{
        for (Entry e; cin>>e;)
                phone_book.push_back(e);
}
```

This reads Entrys from the standard input into phone_book until either the end-of-input (e.g., the end of a file) is reached or the input operation encounters a format error. The standard-library vector is implemented so that growing a vector by repeated push_back()s is efficient.

A vector can be copied in assignments and initializations. For example:

```
vector<Entry> book2 = phone_book;
```

Copying and moving of vectors are implemented by constructors and assignment operators as described in §3.3. Assigning a vector involves copying its elements. Thus, after the initialization of book2, book2 and phone_book hold separate copies of every Entry in the phone book. When a vector holds many elements, such innocent-looking assignments and initializations can be expensive. Where copying is undesirable, references or pointers (§7.2, §7.7) or move operations (§3.3.2, §17.5.2) should be used.

4.4.1.1 Elements

Like all standard-library containers, vector is a container of elements of some type T, that is, a vector<T>. Just about any type qualifies as an element type: built-in numeric types (such as char, int, and double), user-defined types (such as string, Entry, list<int>, and Matrix<double,2>), and pointers (such as const char*, Shape*, and double*). When you insert a new element, its value is copied into the container. For example, when you put an integer with the value 7 into a container, the resulting element really has the value 7. The element is not a reference or a pointer to some object containing 7. This makes for nice compact containers with fast access. For people who care about memory sizes and run-time performance this is critical.

4.4.1.2 Range Checking

The standard-library vector does not guarantee range checking (§31.2.2). For example:

```
void silly(vector<Entry>& book)
{
    int i = book[ph.size()].number;      // book.size() is out of range
    // ...
}
```

That initialization is likely to place some random value in i rather than giving an error. This is undesirable, and out-of-range errors are a common problem. Consequently, I often use a simple range-checking adaptation of vector:

```
template<typename T>
class Vec : public std::vector<T> {
public:
    using vector<T>::vector; // use the constructors from vector (under the name Vec); see §20.3.5.1

    T& operator[](int i)                 // range check
        { return vector<T>::at(i); }

    const T& operator[](int i) const     // range check const objects; §3.2.1.1
        { return vector<T>::at(i); }
};
```

Vec inherits everything from vector except for the subscript operations that it redefines to do range checking. The at() operation is a vector subscript operation that throws an exception of type out_of_range if its argument is out of the vector's range (§2.4.3.1, §31.2.2).

For **Vec**, an out-of-range access will throw an exception that the user can catch. For example:

```
void checked(Vec<Entry>& book)
{
    try {
        book[book.size()] = {"Joe",999999};    // will throw an exception
        // ...
    }
    catch (out_of_range) {
        cout << "range error\n";
    }
}
```

The exception will be thrown, and then caught (§2.4.3.1, Chapter 13). If the user doesn't catch an exception, the program will terminate in a well-defined manner rather than proceeding or failing in an undefined manner. One way to minimize surprises from uncaught exceptions is to use a **main()** with a **try**-block as its body. For example:

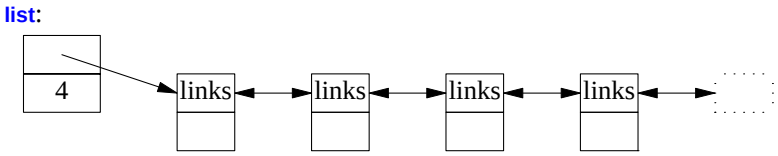
```
int main()
try {
    // your code
}
catch (out_of_range) {
    cerr << "range error\n";
}
catch (...) {
    cerr << "unknown exception thrown\n";
}
```

This provides default exception handlers so that if we fail to catch some exception, an error message is printed on the standard error-diagnostic output stream **cerr** (§38.1).

Some implementations save you the bother of defining **Vec** (or equivalent) by providing a range-checked version of **vector** (e.g., as a compiler option).

4.4.2 list

The standard library offers a doubly-linked list called **list**:



We use a **list** for sequences where we want to insert and delete elements without moving other elements. Insertion and deletion of phone book entries could be common, so a **list** could be appropriate for representing a simple phone book. For example:

```
list<Entry> phone_book = {
    {"David Hume",123456},
```

```
        {"Karl Popper",234567},
        {"Bertrand Arthur William Russell",345678}
};
```

When we use a linked list, we tend not to access elements using subscripting the way we commonly do for vectors. Instead, we might search the list looking for an element with a given value. To do this, we take advantage of the fact that a **list** is a sequence as described in §4.5:

```
int get_number(const string& s)
{
        for (const auto& x : phone_book)
                if (x.name==s)
                        return x.number;
        return 0;  // use 0 to represent "number not found"
}
```

The search for **s** starts at the beginning of the list and proceeds until **s** is found or the end of **phone_book** is reached.

Sometimes, we need to identify an element in a **list**. For example, we may want to delete it or insert a new entry before it. To do that we use an *iterator*: a **list** iterator identifies an element of a **list** and can be used to iterate through a **list** (hence its name). Every standard-library container provides the functions **begin()** and **end()**, which return an iterator to the first and to one-past-the-last element, respectively (§4.5, §33.1.1). Using iterators explicitly, we can – less elegantly – write the **get_number()** function like this:

```
int get_number(const string& s)
{
        for (auto p = phone_book.begin(); p!=phone_book.end(); ++p)
                if (p->name==s)
                        return p->number;
        return 0;  // use 0 to represent "number not found"
}
```

In fact, this is roughly the way the terser and less error-prone range-**for** loop is implemented by the compiler. Given an iterator **p**, ***p** is the element to which it refers, **++p** advances **p** to refer to the next element, and when **p** refers to a class with a member **m**, then **p->m** is equivalent to **(*p).m**.

Adding elements to a **list** and removing elements from a **list** is easy:

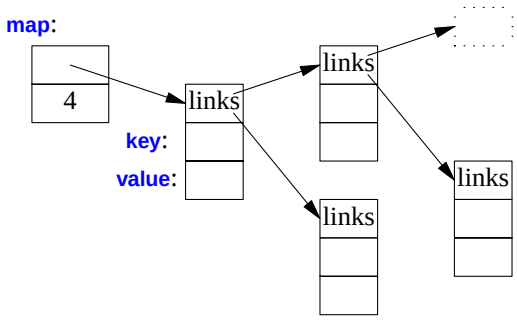
```
void f(const Entry& ee, list<Entry>::iterator p, list<Entry>::iterator q)
{
        phone_book.insert(p,ee);        // add ee before the element referred to by p
        phone_book.erase(q);            // remove the element referred to by q
}
```

For a more complete description of **insert()** and **erase()**, see §31.3.7.

These **list** examples could be written identically using **vector** and (surprisingly, unless you understand machine architecture) perform better with a small **vector** than with a small **list**. When all we want is a sequence of elements, we have a choice between using a **vector** and a **list**. Unless you have a reason not to, use a **vector**. A **vector** performs better for traversal (e.g., **find()** and **count()**) and for sorting and searching (e.g., **sort()** and **binary_search()**).

4.4.3 map

Writing code to look up a name in a list of *(name,number)* pairs is quite tedious. In addition, a linear search is inefficient for all but the shortest lists. The standard library offers a search tree (a red-black tree) called **map**:



In other contexts, a **map** is known as an associative array or a dictionary. It is implemented as a balanced binary tree.

The standard-library **map** (§31.4.3) is a container of pairs of values optimized for lookup. We can use the same initializer as for **vector** and **list** (§4.4.1, §4.4.2):

```
map<string,int> phone_book {
        {"David Hume",123456},
        {"Karl Popper",234567},
        {"Bertrand Arthur William Russell",345678}
};
```

When indexed by a value of its first type (called the *key*), a **map** returns the corresponding value of the second type (called the *value* or the *mapped type*). For example:

```
int get_number(const string& s)
{
        return phone_book[s];
}
```

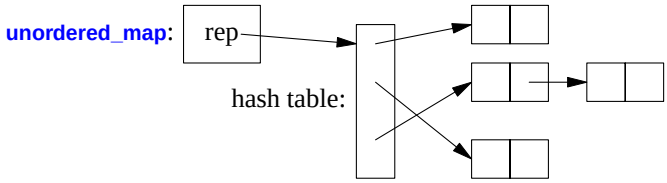
In other words, subscripting a **map** is essentially the lookup we called **get_number()**. If a **key** isn't found, it is entered into the **map** with a default value for its **value**. The default value for an integer type is **0**; the value I just happened to choose represents an invalid telephone number.

If we wanted to avoid entering invalid numbers into our phone book, we could use **find()** and **insert()** instead of **[]** (§31.4.3.1).

4.4.4 unordered_map

The cost of a **map** lookup is **O(log(n))** where **n** is the number of elements in the **map**. That's pretty good. For example, for a **map** with 1,000,000 elements, we perform only about 20 comparisons and indirections to find an element. However, in many cases, we can do better by using a hashed lookup rather than comparison using an ordering function, such as **<**. The standard-library hashed

containers are referred to as ‘‘unordered’’ because they don’t require an ordering function:



For example, we can use an unordered_map from <unordered_map> for our phone book:

```
unordered_map<string,int> phone_book {
        {"David Hume",123456},
        {"Karl Popper",234567},
        {"Bertrand Arthur William Russell",345678}
};
```

As for a map, we can subscript an unordered_map:

```
int get_number(const string& s)
{
        return phone_book[s];
}
```

The standard-library unordered_map provides a default hash function for strings. If necessary, you can provide your own (§31.4.3.4).

4.4.5 Container Overview

The standard library provides some of the most general and useful container types to allow the programmer to select a container that best serves the needs of an application:

Standard Container Summary	
vector<T>	A variable-size vector (§31.4)
list<T>	A doubly-linked list (§31.4.2)
forward_list<T>	A singly-linked list (§31.4.2)
deque<T>	A double-ended queue (§31.2)
set<T>	A set (§31.4.3)
multiset<T>	A set in which a value can occur many times (§31.4.3)
map<K,V>	An associative array (§31.4.3)
multimap<K,V>	A map in which a key can occur many times (§31.4.3)
unordered_map<K,V>	A map using a hashed lookup (§31.4.3.2)
unordered_multimap<K,V>	A multimap using a hashed lookup (§31.4.3.2)
unordered_set<T>	A set using a hashed lookup (§31.4.3.2)
unordered_multiset<T>	A multiset using a hashed lookup (§31.4.3.2)

The unordered containers are optimized for lookup with a key (often a string); in other words, they are implemented using hash tables.

The standard containers are described in §31.4. The containers are defined in namespace **std** and presented in headers **<vector>**, **<list>**, **<map>**, etc. (§4.1.2, §30.2). In addition, the standard library provides container adaptors **queue<T>** (§31.5.2), **stack<T>** (§31.5.1), **deque<T>** (§31.4), and **priority_queue<T>** (§31.5.3). The standard library also provides more specialized container-like types, such as a fixed-size array **array<T,N>** (§34.2.1) and **bitset<N>** (§34.2.2).

The standard containers and their basic operations are designed to be similar from a notational point of view. Furthermore, the meanings of the operations are equivalent for the various containers. Basic operations apply to every kind of container for which they make sense and can be efficiently implemented. For example:

- **begin()** and **end()** give iterators to the first and one-beyond-the-last elements, respectively.
- **push_back()** can be used (efficiently) to add elements to the end of a **vector**, **forward_list**, **list**, and other containers.
- **size()** returns the number of elements.

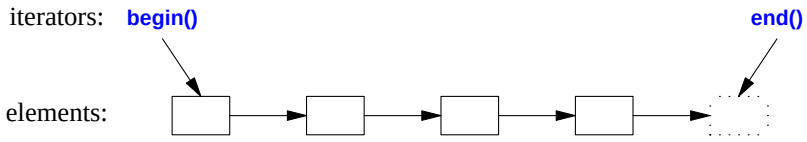
This notational and semantic uniformity enables programmers to provide new container types that can be used in a very similar manner to the standard ones. The range-checked vector, **Vector** (§2.3.2, §2.4.3.1), is an example of that. The uniformity of container interfaces also allows us to specify algorithms independently of individual container types. However, each has strengths and weaknesses. For example, subscripting and traversing a **vector** is cheap and easy. On the other hand, **vector** elements are moved when we insert or remove elements; **list** has exactly the opposite properties. Please note that a **vector** is usually more efficient than a **list** for short sequences of small elements (even for **insert()** and **erase()**). I recommend the standard-library **vector** as the default type for sequences of elements: you need a reason to choose another.

4.5 Algorithms

A data structure, such as a list or a vector, is not very useful on its own. To use one, we need operations for basic access such as adding and removing elements (as is provided for **list** and **vector**). Furthermore, we rarely just store objects in a container. We sort them, print them, extract subsets, remove elements, search for objects, etc. Consequently, the standard library provides the most common algorithms for containers in addition to providing the most common container types. For example, the following sorts a **vector** and places a copy of each unique **vector** element on a **list**:

```
bool operator<(const Entry& x, const Entry& y)     // less than
{
    return x.name<y.name;          // order Entrys by their names
}

void f(vector<Entry>& vec, list<Entry>& lst)
{
    sort(vec.begin(),vec.end());                        // use < for order
    unique_copy(vec.begin(),vec.end(),lst.begin());     // don't copy adjacent equal elements
}
```

The standard algorithms are described in Chapter 32. They are expressed in terms of sequences of elements. A *sequence* is represented by a pair of iterators specifying the first element and the one-beyond-the-last element:



In the example, **sort()** sorts the sequence defined by the pair of iterators **vec.begin()** and **vec.end()** – which just happens to be all the elements of a **vector**. For writing (output), you need only to specify the first element to be written. If more than one element is written, the elements following that initial element will be overwritten. Thus, to avoid errors, **lst** must have at least as many elements as there are unique values in **vec**.

If we wanted to place the unique elements in a new container, we could have written:

```
list<Entry> f(vector<Entry>& vec)
{
    list<Entry> res;
    sort(vec.begin(),vec.end());
    unique_copy(vec.begin(),vec.end(),back_inserter(res)); // append to res
    return res;
}
```

A **back_inserter()** adds elements at the end of a container, extending the container to make room for them (§33.2.2). Thus, the standard containers plus **back_inserter()**s eliminate the need to use error-prone, explicit C-style memory management using **realloc()** (§31.5.1). The standard-library **list** has a move constructor (§3.3.2, §17.5.2) that makes returning **res** by value efficient (even for **list**s of thousands of elements).

If you find the pair-of-iterators style of code, such as **sort(vec.begin(),vec.end())**, tedious, you can define container versions of the algorithms and write **sort(vec)** (§4.5.6).

4.5.1 Use of Iterators

When you first encounter a container, a few iterators referring to useful elements can be obtained; **begin()** and **end()** are the best examples of this. In addition, many algorithms return iterators. For example, the standard algorithm **find** looks for a value in a sequence and returns an iterator to the element found:

```
bool has_c(const string& s, char c)      // does s contain the character c?
{
    auto p = find(s.begin(),s.end(),c);
    if (p!=s.end())
        return true;
    else
        return false;
}
```

Like many standard-library search algorithms, **find** returns **end()** to indicate "not found." An equivalent, shorter, definition of **has_c()** is:

```
bool has_c(const string& s, char c)       // does s contain the character c?
{
    return find(s.begin(),s.end(),c)!=s.end();
}
```

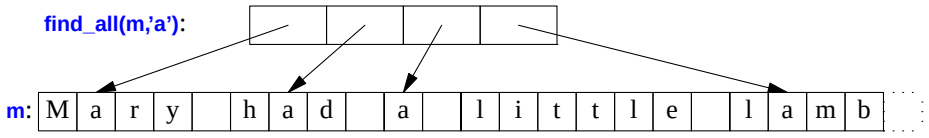
A more interesting exercise would be to find the location of all occurrences of a character in a string. We can return the set of occurrences as a **vector** of **string** iterators. Returning a **vector** is efficient because of **vector** provides move semantics (§3.3.1). Assuming that we would like to modify the locations found, we pass a non-**const** string:

```
vector<string::iterator> find_all(string& s, char c)       // find all occurrences of c in s
{
    vector<string::iterator> res;
    for (auto p = s.begin(); p!=s.end(); ++p)
        if (*p==c)
            res.push_back(p);
    return res;
}
```

We iterate through the string using a conventional loop, moving the iterator **p** forward one element at a time using **++** and looking at the elements using the dereference operator *. We could test **find_all()** like this:

```
void test()
{
    string m {"Mary had a little lamb"};
    for (auto p : find_all(m,'a'))
        if (*p!='a')
            cerr << "a bug!\n";
}
```

That call of **find_all()** could be graphically represented like this:



Iterators and standard algorithms work equivalently on every standard container for which their use makes sense. Consequently, we could generalize **find_all()**:

```
template<typename C, typename V>
vector<typename C::iterator> find_all(C& c, V v)       // find all occurrences of v in c
{
    vector<typename C::iterator> res;
    for (auto p = c.begin(); p!=c.end(); ++p)
        if (*p==v)
            res.push_back(p);
    return res;
}
```

The `typename` is needed to inform the compiler that `C`'s `iterator` is supposed to be a type and not a value of some type, say, the integer `7`. We can hide this implementation detail by introducing a type alias (§3.4.5) for `Iterator`:

```
template<typename T>
using Iterator<T> = typename T::iterator;

template<typename C, typename V>
vector<Iterator<C>> find_all(C& c, V v)          // find all occurrences of v in c
{
        vector<Iterator<C>> res;
        for (auto p = c.begin(); p!=c.end(); ++p)
                if (*p==v)
                        res.push_back(p);
        return res;
}
```

We can now write:

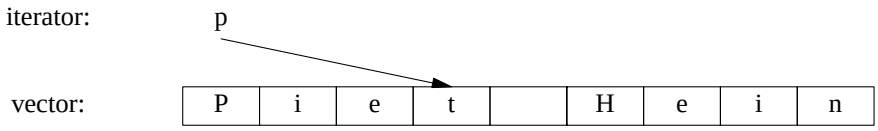
```
void test()
{
        string m {"Mary had a little lamb"};
        for (auto p : find_all(m,'a'))                  // p is a string::iterator
                if (*p!='a')
                        cerr << "string bug!\n";

        list<double> ld {1.1, 2.2, 3.3, 1.1};
        for (auto p : find_all(ld,1.1))
                if (*p!=1.1)
                        cerr << "list bug!\n";

        vector<string> vs { "red", "blue", "green", "green", "orange", "green" };
        for (auto p : find_all(vs,"green"))
                if (*p!="green")
                        cerr << "vector bug!\n";

        for (auto p : find_all(vs,"green"))
                *p = "vert";
}
```

Iterators are used to separate algorithms and containers. An algorithm operates on its data through iterators and knows nothing about the container in which the elements are stored. Conversely, a container knows nothing about the algorithms operating on its elements; all it does is to supply iterators upon request (e.g., `begin()` and `end()`). This model of separation between data storage and algorithm delivers very general and flexible software.

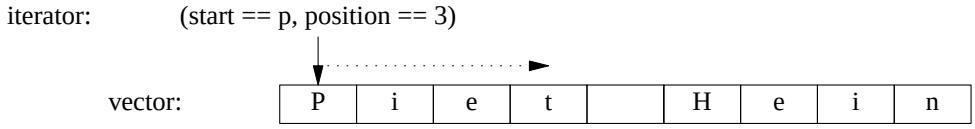
4.5.2 Iterator Types

What are iterators really? Any particular iterator is an object of some type. There are, however, many different iterator types, because an iterator needs to hold the information necessary for doing

its job for a particular container type. These iterator types can be as different as the containers and the specialized needs they serve. For example, a **vector**'s iterator could be an ordinary pointer, because a pointer is quite a reasonable way of referring to an element of a **vector**:

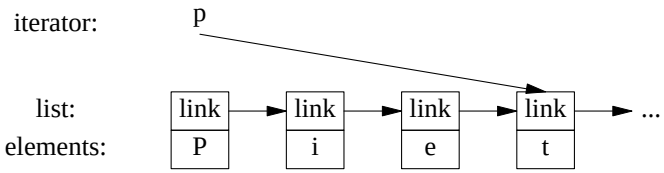


Alternatively, a **vector** iterator could be implemented as a pointer to the **vector** plus an index:



Using such an iterator would allow range checking.

A **list** iterator must be something more complicated than a simple pointer to an element because an element of a **list** in general does not know where the next element of that **list** is. Thus, a **list** iterator might be a pointer to a link:



What is common for all iterators is their semantics and the naming of their operations. For example, applying **++** to any iterator yields an iterator that refers to the next element. Similarly, * yields the element to which the iterator refers. In fact, any object that obeys a few simple rules like these is an iterator (§33.1.4). Furthermore, users rarely need to know the type of a specific iterator; each container ''knows'' its iterator types and makes them available under the conventional names **iterator** and **const_iterator**. For example, **list<Entry>::iterator** is the general iterator type for **list<Entry>**. We rarely have to worry about the details of how that type is defined.

4.5.3 Stream Iterators

Iterators are a general and useful concept for dealing with sequences of elements in containers. However, containers are not the only place where we find sequences of elements. For example, an input stream produces a sequence of values, and we write a sequence of values to an output stream. Consequently, the notion of iterators can be usefully applied to input and output.

To make an **ostream_iterator**, we need to specify which stream will be used and the type of objects written to it. For example:

```
ostream_iterator<string> oo {cout};      // write strings to cout
```

The effect of assigning to `*oo` is to write the assigned value to `cout`. For example:

```
int main()
{
    *oo = "Hello, ";      // meaning cout<<"Hello, "
    ++oo;
    *oo = "world!\n";     // meaning cout<<"world!\n"
}
```

This is yet another way of writing the canonical message to standard output. The `++oo` is done to mimic writing into an array through a pointer.

Similarly, an `istream_iterator` is something that allows us to treat an input stream as a read-only container. Again, we must specify the stream to be used and the type of values expected:

```
istream_iterator<string> ii {cin};
```

Input iterators are used in pairs representing a sequence, so we must provide an `istream_iterator` to indicate the end of input. This is the default `istream_iterator`:

```
istream_iterator<string> eos {};
```

Typically, `istream_iterator`s and `ostream_iterator`s are not used directly. Instead, they are provided as arguments to algorithms. For example, we can write a simple program to read a file, sort the words read, eliminate duplicates, and write the result to another file:

```
int main()
{
    string from, to;
    cin >> from >> to;                  // get source and target file names

    ifstream is {from};                 // input stream for file "from"
    istream_iterator<string> ii {is};   // input iterator for stream
    istream_iterator<string> eos {};    // input sentinel

    ofstream os{to};                    // output stream for file "to"
    ostream_iterator<string> oo {os,"\n"};  // output iterator for stream

    vector<string> b {ii,eos};          // b is a vector initialized from input [ii:eos)
    sort(b.begin(),b.end());            // sort the buffer

    unique_copy(b.begin(),b.end(),oo);  // copy buffer to output, discard replicated values

    return !is.eof() || !os;            // return error state (§2.2.1, §38.3)
}
```

An `ifstream` is an `istream` that can be attached to a file, and an `ofstream` is an `ostream` that can be attached to a file. The `ostream_iterator`'s second argument is used to delimit output values.

Actually, this program is longer than it needs to be. We read the strings into a `vector`, then we `sort()` them, and then we write them out, eliminating duplicates. A more elegant solution is not to

store duplicates at all. This can be done by keeping the **string**s in a **set**, which does not keep duplicates and keeps its elements in order (§31.4.3). That way, we could replace the two lines using a **vector** with one using a **set** and replace **unique_copy()** with the simpler **copy()**:

```
set<string> b {ii,eos};          // collect strings from input
copy(b.begin(),b.end(),oo);      // copy buffer to output
```

We used the names **ii**, **eos**, and **oo** only once, so we could further reduce the size of the program:

```
int main()
{
    string from, to;
    cin >> from >> to;              // get source and target file names

    ifstream is {from};             // input stream for file "from"
    ofstream os {to};               // output stream for file "to"

    set<string> b {istream_iterator<string>{is},istream_iterator<string>{}}; // read input
    copy(b.begin(),b.end(),ostream_iterator<string>{os,"\n"});               // copy to output

    return !is.eof() || !os;        // return error state (§2.2.1, §38.3)
}
```

It is a matter of taste and experience whether or not this last simplification improves readability.

4.5.4 Predicates

In the examples above, the algorithms have simply ‘‘built in’’ the action to be done for each element of a sequence. However, we often want to make that action a parameter to the algorithm. For example, the **find** algorithm (§32.4) provides a convenient way of looking for a specific value. A more general variant looks for an element that fulfills a specified requirement, a *predicate* (§3.4.2). For example, we might want to search a **map** for the first value larger than **42**. A **map** allows us to access its elements as a sequence of *(key,value)* pairs, so we can search a **map<string,int>**’s sequence for a **pair<const string,int>** where the **int** is greater than **42**:

```
void f(map<string,int>& m)
{
    auto p = find_if(m.begin(),m.end(),Greater_than{42});
    // ...
}
```

Here, **Greater_than** is a function object (§3.4.3) holding the value (**42**) to be compared against:

```
struct Greater_than {
    int val;
    Greater_than(int v) : val{v} { }
    bool operator()(const pair<string,int>& r) { return r.second>val; }
};
```

Alternatively, we could use a lambda expression (§3.4.3):

```
int cxx = count_if(m.begin(), m.end(), [](const pair<string,int>& r) { return r.second>42; });
```

4.5.5 Algorithm Overview

A general definition of an algorithm is ‘‘a finite set of rules which gives a sequence of operations for solving a specific set of problems [and] has five important features: Finiteness ... Definiteness ... Input ... Output ... Effectiveness’’ [Knuth,1968,§1.1]. In the context of the C++ standard library, an algorithm is a function template operating on sequences of elements.

The standard library provides dozens of algorithms. The algorithms are defined in namespace **std** and presented in the **<algorithm>** header. These standard-library algorithms all take sequences as inputs (§4.5). A half-open sequence from **b** to **e** is referred to as [**b**:**e**). Here are a few I have found particularly useful:

Selected Standard Algorithms	
p=find(b,e,x)	**p** is the first **p** in [**b**:**e**) so that ∗**p==x**
p=find_if(b,e,f)	**p** is the first **p** in [**b**:**e**) so that **f(**∗**p)==true**
n=count(b,e,x)	**n** is the number of elements ∗**q** in [**b**:**e**) so that ∗**q==x**
n=count_if(b,e,f)	**n** is the number of elements ∗**q** in [**b**:**e**) so that **f(**∗**q,x)**
replace(b,e,v,v2)	Replace elements ∗**q** in [**b**:**e**) so that ∗**q==v** by **v2**
replace_if(b,e,f,v2)	Replace elements ∗**q** in [**b**:**e**) so that **f(**∗**q)** by **v2**
p=copy(b,e,out)	Copy [**b**:**e**) to [**out**:**p**)
p=copy_if(b,e,out,f)	Copy elements ∗**q** from [**b**:**e**) so that **f(**∗**q)** to [**out**:**p**)
p=unique_copy(b,e,out)	Copy [**b**:**e**) to [**out**:**p**); don’t copy adjacent duplicates
sort(b,e)	Sort elements of [**b**:**e**) using **<** as the sorting criterion
sort(b,e,f)	Sort elements of [**b**:**e**) using **f** as the sorting criterion
(p1,p2)=equal_range(b,e,v)	[**p1**:**p2**) is the subsequence of the sorted sequence [**b**:**e**) with the value **v**; basically a binary search for **v**
p=merge(b,e,b2,e2,out)	Merge two sorted sequences [**b**:**e**) and [**b2**:**e2**) into [**out**:**p**)

These algorithms, and many more (see Chapter 32), can be applied to elements of containers, **string**s, and built-in arrays.

4.5.6 Container Algorithms

A sequence is defined by a pair of iterators [**begin**:**end**). This is general and flexible, but most often, we apply an algorithm to a sequence that is the contents of a container. For example:

```
sort(v.begin(),v.end());
```

Why don’t we just say **sort(v)**? We can easily provide that shorthand:

```
namespace Estd {
    using namespace std;

    template<class C>
    void sort(C& c)
    {
        sort(c.begin(),c.end());
    }
```

```
        template<class C, class Pred>
        void sort(C& c, Pred p)
        {
                sort(c.begin(),c.end(),p);
        }

        // ...
}
```

I put the container versions of **sort()** (and other algorithms) into their own namespace **Estd** (''extended **std**'') to avoid interfering with other programmers' uses of namespace **std**.

4.6 Advice

[1] Don't reinvent the wheel; use libraries; §4.1.
[2] When you have a choice, prefer the standard library over other libraries; §4.1.
[3] Do not think that the standard library is ideal for everything; §4.1.
[4] Remember to **#include** the headers for the facilities you use; §4.1.2.
[5] Remember that standard-library facilities are defined in namespace **std**; §4.1.2.
[6] Prefer **string**s over C-style strings (a **char***; §2.2.5); §4.2, §4.3.2.
[7] **iostream**s are type sensitive, type-safe, and extensible; §4.3.
[8] Prefer **vector<T>**, **map<K,T>**, and **unordered_map<K,T>** over **T[]**; §4.4.
[9] Know your standard containers and their tradeoffs; §4.4.
[10] Use **vector** as your default container; §4.4.1.
[11] Prefer compact data structures; §4.4.1.1.
[12] If in doubt, use a range-checked vector (such as **Vec**); §4.4.1.2.
[13] Use **push_back()** or **back_inserter()** to add elements to a container; §4.4.1, §4.5.
[14] Use **push_back()** on a **vector** rather than **realloc()** on an array; §4.5.
[15] Catch common exceptions in **main()**; §4.4.1.2.
[16] Know your standard algorithms and prefer them over handwritten loops; §4.5.5.
[17] If iterator use gets tedious, define container algorithms; §4.5.6.

5

A Tour of C++: Concurrency and Utilities

When you wish to instruct,
be brief.
– Cicero

- Introduction
- Resource Management
  unique_ptr and **shared_ptr**
- Concurrency
  Tasks and **thread**s; Passing Arguments; Returning Results; Sharing Data; Communicating Tasks
- Small Utility Components
  Time; Type Functions; **pair** and **tuple**
- Regular Expressions
- Math
  Mathematical Functions and Algorithms; Complex Numbers; Random Numbers; Vector Arithmetic; Numeric Limits
- Advice

5.1 Introduction

From an end-user's perspective, the ideal standard library would provide components directly supporting essentially every need. For a given application domain, a huge commercial library can come close to that ideal. However, that is not what the C++ standard library is trying to do. A manageable, universally available, library cannot be everything to everybody. Instead, the C++ standard library aims to provide components that are useful to most people in most application areas. That is, it aims to serve the intersection of all needs rather than their union. In addition, support for a few widely important application areas, such as mathematical computation and text manipulation, have crept in.

5.2 Resource Management

One of the key tasks of any nontrivial program is to manage resources. A resource is something that must be acquired and later (explicitly or implicitly) released. Examples are memory, locks, sockets, thread handles, and file handles. For a long-running program, failing to release a resource in a timely manner (''a leak'') can cause serious performance degradation and possibly even a miserable crash. Even for short programs, a leak can become an embarrassment, say by a resource shortage increasing the run time by orders of magnitude.

The standard library components are designed not to leak resources. To do this, they rely on the basic language support for resource management using constructor/destructor pairs to ensure that a resource doesn't outlive an object responsible for it. The use of a constructor/destructor pair in **Vector** to manage the lifetime of its elements is an example (§3.2.1.2) and all standard-library containers are implemented in similar ways. Importantly, this approach interacts correctly with error handling using exceptions. For example, the technique is used for the standard-library lock classes:

```
mutex m; // used to protect access to shared data
// ...
void f()
{
    unique_lock<mutex> lck {m};  // acquire the mutex m
    // ... manipulate shared data ...
}
```

A **thread** will not proceed until **lck**'s constructor has acquired its **mutex**, **m** (§5.3.4). The corresponding destructor releases the resource. So, in this example, **unique_lock**'s destructor releases the **mutex** when the thread of control leaves **f()** (through a return, by ''falling off the end of the function,'' or through an exception throw).

This is an application of the ''Resource Acquisition Is Initialization'' technique (RAII; §3.2.1.2, §13.3). This technique is fundamental to the idiomatic handling of resources in C++. Containers (such as **vector** and **map**), **string**, and **iostream** manage their resources (such as file handles and buffers) similarly.

5.2.1 unique_ptr and shared_ptr

The examples so far take care of objects defined in a scope, releasing the resources they acquire at the exit from the scope, but what about objects allocated on the free store? In **<memory>**, the standard library provides two ''smart pointers'' to help manage objects on the free store:

[1] **unique_ptr** to represent unique ownership (§34.3.1)
[2] **shared_ptr** to represent shared ownership (§34.3.2)

The most basic use of these ''smart pointers'' is to prevent memory leaks caused by careless programming. For example:

```
void f(int i, int j)     // X* vs. unique_ptr<X>
{
    X* p = new X;                 // allocate a new X
    unique_ptr<X> sp {new X};     // allocate a new X and give its pointer to unique_ptr
    // ...
```

```
        if (i<99) throw Z{};            // may throw an exception
        if (j<77) return;               // may return "early"
        p->do_something();              // may throw an exception
        sp->do_something();             // may throw an exception
        // ...
        delete p;                       // destroy *p
}
```

Here, we ''forgot'' to delete `p` if `i<99` or if `j<77`. On the other hand, `unique_ptr` ensures that its object is properly destroyed whichever way we exit `f()` (by throwing an exception, by executing `return`, or by ''falling off the end''). Ironically, we could have solved the problem simply by *not* using a pointer and *not* using `new`:

```
void f(int i, int j)      // use a local variable
{
        X x;
        // ...
}
```

Unfortunately, overuse of `new` (and of pointers and references) seems to be an increasing problem.

However, when you really need the semantics of pointers, `unique_ptr` is a very lightweight mechanism with no space or time overhead compared to correct use of a built-in pointer. Its further uses include passing free-store allocated objects in and out of functions:

```
unique_ptr<X> make_X(int i)
        // make an X and immediately give it to a unique_ptr
{
        // ... check i, etc. ...
        return unique_ptr<X>{new X{i}};
}
```

A `unique_ptr` is a handle to an individual object (or an array) in much the same way that a `vector` is a handle to a sequence of objects. Both control the lifetime of other objects (using RAII) and both rely on move semantics to make `return` simple and efficient.

The `shared_ptr` is similar to `unique_ptr` except that `shared_ptr`s are copied rather than moved. The `shared_ptr`s for an object share ownership of an object and that object is destroyed when the last of its `shared_ptr`s is destroyed. For example:

```
void f(shared_ptr<fstream>);
void g(shared_ptr<fstream>);

void user(const string& name, ios_base::openmode mode)
{
        shared_ptr<fstream> fp {new fstream(name,mode)};
        if (!*fp) throw No_file{};   // make sure the file was properly opened

        f(fp);
        g(fp);
        // ...
}
```

Now, the file opened by **fp**'s constructor will be closed by the last function to (explicitly or implicitly) destroy a copy of **fp**. Note that **f()** or **g()** may spawn a task holding a copy of **fp** or in some other way store a copy that outlives **user()**. Thus, **shared_ptr** provides a form of garbage collection that respects the destructor-based resource management of the memory-managed objects. This is neither cost free nor exorbitantly expensive, but does make the lifetime of the shared object hard to predict. Use **shared_ptr** only if you actually need shared ownership.

Given **unique_ptr** and **shared_ptr**, we can implement a complete ''no naked **new**'' policy (§3.2.1.2) for many programs. However, these ''smart pointers'' are still conceptually pointers and therefore only my second choice for resource management – after containers and other types that manage their resources at a higher conceptual level. In particular, **shared_ptr**s do not in themselves provide any rules for which of their owners can read and/or write the shared object. Data races (§41.2.4) and other forms of confusion are not addressed simply by eliminating the resource management issues.

Where do we use ''smart pointers'' (such as **unique_ptr**) rather than resource handles with operations designed specifically for the resource (such as **vector** or **thread**)? Unsurprisingly, the answer is ''when we need pointer semantics.''

- When we share an object, we need pointers (or references) to refer to the shared object, so a **shared_ptr** becomes the obvious choice (unless there is an obvious single owner).
- When we refer to a polymorphic object, we need a pointer (or a reference) because we don't know the exact type of the object referred to or even its size), so a **unique_ptr** becomes the obvious choice.
- A shared polymorphic object typically requires **shared_ptr**s.

We do *not* need to use a pointer to return a collection of objects from a function; a container that is a resource handle will do that simply and efficiently (§3.3.2).

5.3 Concurrency

Concurrency – the execution of several tasks simultaneously – is widely used to improve throughput (by using several processors for a single computation) or to improve responsiveness (by allowing one part of a program to progress while another is waiting for a response). All modern programming languages provide support for this. The support provided by the C++ standard library is a portable and type-safe variant of what has been used in C++ for more than 20 years and is almost universally supported by modern hardware. The standard-library support is primarily aimed at supporting systems-level concurrency rather than directly providing sophisticated higher-level concurrency models; those can be supplied as libraries built using the standard-library facilities.

The standard library directly supports concurrent execution of multiple threads in a single address space. To allow that, C++ provides a suitable memory model (§41.2) and a set of atomic operations (§41.3). However, most users will see concurrency only in terms of the standard library and libraries built on top of that. This section briefly gives examples of the main standard-library concurrency support facilities: **thread**s, **mutex**es, **lock()** operations, **packaged_task**s, and **future**s. These features are built directly upon what operating systems offer and do not incur performance penalties compared with those.

5.3.1 Tasks and threads

We call a computation that can potentially be executed concurrently with other computations a *task*. A *thread* is the system-level representation of a task in a program. A task to be executed concurrently with other tasks is launched by constructing a **std::thread** (found in **<thread>**) with the task as its argument. A task is a function or a function object:

```
void f();                   // function

struct F {                  // function object
    void operator()();      // F's call operator (§3.4.3)
};

void user()
{
    thread t1 {f};          // f() executes in separate thread
    thread t2 {F()};        // F()() executes in separate thread

    t1.join();              // wait for t1
    t2.join();              // wait for t2
}
```

The **join()**s ensure that we don't exit **user()** until the threads have completed. To "join" means to "wait for the thread to terminate."

Threads of a program share a single address space. In this, threads differ from processes, which generally do not directly share data. Since threads share an address space, they can communicate through shared objects (§5.3.4). Such communication is typically controlled by locks or other mechanisms to prevent data races (uncontrolled concurrent access to a variable).

Programming concurrent tasks can be *very* tricky. Consider possible implementations of the tasks **f** (a function) and **F** (a function object):

```
void f() { cout << "Hello "; }

struct F {
    void operator()() { cout << "Parallel World!\n"; }
};
```

This is an example of a bad error: Here, **f** and **F()** each use the object **cout** without any form of synchronization. The resulting output would be unpredictable and could vary between different executions of the program because the order of execution of the individual operations in the two tasks is not defined. The program may produce "odd" output, such as

```
PaHerallllel o World!
```

When defining tasks of a concurrent program, our aim is to keep tasks completely separate except where they communicate in simple and obvious ways. The simplest way of thinking of a concurrent task is as a function that happens to run concurrently with its caller. For that to work, we just have to pass arguments, get a result back, and make sure that there is no use of shared data in between (no data races).

5.3.2 Passing Arguments

Typically, a task needs data to work upon. We can easily pass data (or pointers or references to the data) as arguments. Consider:

```
void f(vector<double>& v);      // function do something with v

struct F {                      // function object: do something with v
        vector<double>& v;
        F(vector<double>& vv) :v{vv} { }
        void operator()();      // application operator; §3.4.3
};

int main()
{
        vector<double> some_vec {1,2,3,4,5,6,7,8,9};
        vector<double> vec2 {10,11,12,13,14};

        thread t1 {f,some_vec};  // f(some_vec) executes in a separate thread
        thread t2 {F{vec2}};     // F(vec2)() executes in a separate thread

        t1.join();
        t2.join();
}
```

Obviously, `F{vec2}` saves a reference to the argument vector in `F`. `F` can now use that array and hopefully no other task accesses `vec2` while `F` is executing. Passing `vec2` by value would eliminate that risk.

The initialization with `{f,some_vec}` uses a `thread` variadic template constructor that can accept an arbitrary sequence of arguments (§28.6). The compiler checks that the first argument can be invoked given the following arguments and builds the necessary function object to pass to the thread. Thus, if `F::operator()()` and `f()` perform the same algorithm, the handling of the two tasks are roughly equivalent: in both cases, a function object is constructed for the `thread` to execute.

5.3.3 Returning Results

In the example in §5.3.2, I pass the arguments by non-`const` reference. I only do that if I expect the task to modify the value of the data referred to (§7.7). That's a somewhat sneaky, but not uncommon, way of returning a result. A less obscure technique is to pass the input data by `const` reference and to pass the location of a place to deposit the result as a separate argument:

```
void f(const vector<double>& v, double* res);// take input from v;  place result in *res

class F {
public:
        F(const vector<double>& vv, double* p) :v{vv}, res{p} { }
        void operator()();              // place result in *res
```

```
private:
        const vector<double>& v;            // source of input
        double* res;                        // target for output
};

int main()
{
        vector<double> some_vec;
        vector<double> vec2;
        // ...

        double res1;
        double res2;

        thread t1 {f,some_vec,&res1}; // f(some_vec,&res1) executes in a separate thread
        thread t2 {F{vec2,&res2}};          // F{vec2,&res2}() executes in a separate thread

        t1.join();
        t2.join();

        cout << res1 << ' ' << res2 << '\n';
}
```

I don't consider returning results through arguments particularly elegant, so I return to this topic in §5.3.5.1.

5.3.4 Sharing Data

Sometimes tasks need to share data. In that case, the access has to be synchronized so that at most one task at a time has access. Experienced programmers will recognize this as a simplification (e.g., there is no problem with many tasks simultaneously reading immutable data), but consider how to ensure that at most one task at a time has access to a given set of objects.

The fundamental element of the solution is a **mutex**, a "mutual exclusion object." A **thread** acquires a mutex using a **lock()** operation:

```
mutex m; // controlling mutex
int sh;  // shared data

void f()
{
        unique_lock<mutex> lck {m}; // acquire mutex
        sh += 7;                    // manipulate shared data
}       // release mutex implicitly
```

The **unique_lock**'s constructor acquires the mutex (through a call **m.lock()**). If another thread has already acquired the mutex, the thread waits ("blocks") until the other thread completes its access. Once a thread has completed its access to the shared data, the **unique_lock** releases the **mutex** (with a call **m.unlock()**). The mutual exclusion and locking facilities are found in **<mutex>**.

The correspondence between the shared data and a **mutex** is conventional: the programmer simply has to know which **mutex** is supposed to correspond to which data. Obviously, this is error-prone, and equally obviously we try to make the correspondence clear through various language means. For example:

```
class Record {
public:
        mutex rm;
        // ...
};
```

It doesn't take a genius to guess that for a **Record** called **rec**, **rec.rm** is a **mutex** that you are supposed to acquire before accessing the other data of **rec**, though a comment or a better name might have helped a reader.

It is not uncommon to need to simultaneously access several resources to perform some action. This can lead to deadlock. For example, if **thread1** acquires **mutex1** and then tries to acquire **mutex2** while **thread2** acquires **mutex2** and then tries to acquire **mutex1**, then neither task will ever proceed further. The standard library offers help in the form of an operation for acquiring several locks simultaneously:

```
void f()
{
        // ...
        unique_lock<mutex> lck1 {m1,defer_lock};    // defer_lock: don't yet try to acquire the mutex
        unique_lock<mutex> lck2 {m2,defer_lock};
        unique_lock<mutex> lck3 {m3,defer_lock};
        // ...
        lock(lck1,lck2,lck3);                       // acquire all three locks
        // ... manipulate shared data ...
} // implicitly release all mutexes
```

This **lock()** will only proceed after acquiring all its **mutex** arguments and will never block (''go to sleep'') while holding a **mutex**. The destructors for the individual **unique_lock**s ensure that the **mutex**es are released when a **thread** leaves the scope.

Communicating through shared data is pretty low level. In particular, the programmer has to devise ways of knowing what work has and has not been done by various tasks. In that regard, use of shared data is inferior to the notion of call and return. On the other hand, some people are convinced that sharing must be more efficient than copying arguments and returns. That can indeed be so when large amounts of data are involved, but locking and unlocking are relatively expensive operations. On the other hand, modern machines are very good at copying data, especially compact data, such as **vector** elements. So don't choose shared data for communication because of ''efficiency'' without thought and preferably not without measurement.

5.3.4.1 Waiting for Events

Sometimes, a **thread** needs to wait for some kind of external event, such as another **thread** completing a task or a certain amount of time having passed. The simplest ''event'' is simply time passing. Consider:

```
using namespace std::chrono;      // see §35.2

auto t0 = high_resolution_clock::now();
this_thread::sleep_for(milliseconds{20});
auto t1 = high_resolution_clock::now();
cout << duration_cast<nanoseconds>(t1−t0).count() << " nanoseconds passed\n";
```

Note that I didn't even have to launch a **thread**; by default, **this_thread** refers to the one and only thread (§42.2.6).

I used **duration_cast** to adjust the clock's units to the nanoseconds I wanted. See §5.4.1 and §35.2 before trying anything more complicated than this with time. The time facilities are found in **<chrono>**.

The basic support for communicating using external events is provided by **condition_variable**s found in **<condition_variable>** (§42.3.4). A **condition_variable** is a mechanism allowing one **thread** to wait for another. In particular, it allows a **thread** to wait for some *condition* (often called an *event*) to occur as the result of work done by other **thread**s.

Consider the classical example of two **thread**s communicating by passing messages through a **queue**. For simplicity, I declare the **queue** and the mechanism for avoiding race conditions on that **queue** global to the producer and consumer:

```
class Message {      // object to be communicated
    // ...
};

queue<Message> mqueue;          // the queue of messages
condition_variable mcond;       // the variable communicating events
mutex mmutex;                   // the locking mechanism
```

The types **queue**, **condition_variable**, and **mutex** are provided by the standard library.

The **consumer()** reads and processes **Message**s:

```
void consumer()
{
    while(true) {
        unique_lock<mutex> lck{mmutex};      // acquire mmutex
        while (mcond.wait(lck)) /* do nothing */;   // release lck and wait;
                                             // re-acquire lck upon wakeup
        auto m = mqueue.front();             // get the message
        mqueue.pop();
        lck.unlock();                        // release lck
        // ... process m ...
    }
}
```

Here, I explicitly protect the operations on the **queue** and on the **condition_variable** with a **unique_lock** on the **mutex**. Waiting on **condition_variable** releases its lock argument until the wait is over (so that the queue is non-empty) and then reacquires it.

The corresponding **producer** looks like this:

```
void producer()
{
    while(true) {
        Message m;
        // ... fill the message ...
        unique_lock<mutex> lck {mmutex};      // protect operations
        mqueue.push(m);
        mcond.notify_one();                   // notify
    }                                         // release lock (at end of scope)
}
```

Using **condition_variable**s supports many forms of elegant and efficient sharing, but can be rather tricky (§42.3.4).

5.3.5 Communicating Tasks

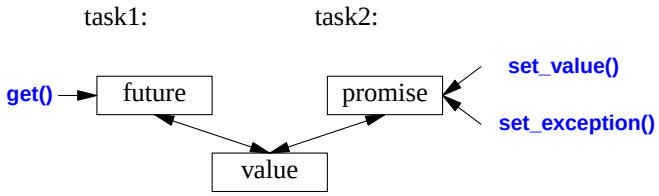
The standard library provides a few facilities to allow programmers to operate at the conceptual level of tasks (work to potentially be done concurrently) rather than directly at the lower level of threads and locks:

[1] **future** and **promise** for returning a value from a task spawned on a separate thread
[2] **packaged_task** to help launch tasks and connect up the mechanisms for returning a result
[3] **async()** for launching of a task in a manner very similar to calling a function.

These facilities are found in **<future>**.

5.3.5.1 future and promise

The important point about **future** and **promise** is that they enable a transfer of a value between two tasks without explicit use of a lock; "the system" implements the transfer efficiently. The basic idea is simple: When a task wants to pass a value to another, it puts the value into a **promise**. Somehow, the implementation makes that value appear in the corresponding **future**, from which it can be read (typically by the launcher of the task). We can represent this graphically:



If we have a **future<X>** called **fx**, we can **get()** a value of type **X** from it:

```
X v = fx.get();   // if necessary, wait for the value to get computed
```

If the value isn't there yet, our thread is blocked until it arrives. If the value couldn't be computed, **get()** might throw an exception (from the system or transmitted from the task from which we were trying to **get()** the value).

The main purpose of a promise is to provide simple ‘‘put’’ operations (called set_value() and set_exception()) to match future’s get(). The names ‘‘future’’ and ‘‘promise’’ are historical; please don’t blame me. They are yet another fertile source of puns.

If you have a promise and need to send a result of type X to a future, you can do one of two things: pass a value or pass an exception. For example:

```
void f(promise<X>& px)   // a task: place the result in px
{
        // ...
        try {
                X res;
                // ... compute a value for res ...
                px.set_value(res);
        }
        catch (...) {           // oops: couldn't compute res
                // pass the exception to the future's thread:
                px.set_exception(current_exception());
        }
}
```

The current_exception() refers to the caught exception (§30.4.1.2).

To deal with an exception transmitted through a future, the caller of get() must be prepared to catch it somewhere. For example:

```
void g(future<X>& fx)           // a task: get the result from fx
{
        // ...
        try {
                X v = fx.get();   // if necessary, wait for the value to get computed
                // ... use v ...
        }
        catch (...) {           // oops: someone couldn't compute v
                // ... handle error ...
        }
}
```

5.3.5.2 packaged_task

How do we get a future into the task that needs a result and the corresponding promise into the thread that should produce that result? The packaged_task type is provided to simplify setting up tasks connected with futures and promises to be run on threads. A packaged_task provides wrapper code to put the return value or exception from the task into a promise (like the code shown in §5.3.5.1). If you ask it by calling get_future, a packaged_task will give you the future corresponding to its promise. For example, we can set up two tasks to each add half of the elements of a vector<double> using the standard-library accumulate() (§3.4.2, §40.6):

```
double accum(double* beg, double * end, double init)
    // compute the sum of [beg:end) starting with the initial value init
{
    return accumulate(beg,end,init);
}

double comp2(vector<double>& v)
{
    using Task_type = double(double*,double*,double);        // type of task

    packaged_task<Task_type> pt0 {accum};                    // package the task (i.e., accum)
    packaged_task<Task_type> pt1 {accum};

    future<double> f0 {pt0.get_future()};                    // get hold of pt0's future
    future<double> f1 {pt1.get_future()};                    // get hold of pt1's future

    double* first = &v[0];
    thread t1 {move(pt0),first,first+v.size()/2,0};          // start a thread for pt0
    thread t2 {move(pt1),first+v.size()/2,first+v.size(),0}; // start a thread for pt1

    // ...

    return f0.get()+f1.get();                                // get the results
}
```

The `packaged_task` template takes the type of the task as its template argument (here `Task_type`, an alias for `double(double*,double*,double)`) and the task as its constructor argument (here, `accum`). The `move()` operations are needed because a `packaged_task` cannot be copied.

Please note the absence of explicit mention of locks in this code: we are able to concentrate on tasks to be done, rather than on the mechanisms used to manage their communication. The two tasks will be run on separate threads and thus potentially in parallel.

5.3.5.3 async()

The line of thinking I have pursued in this chapter is the one I believe to be the simplest yet still among the most powerful: Treat a task as a function that may happen to run concurrently with other tasks. It is far from the only model supported by the C++ standard library, but it serves well for a wide range of needs. More subtle and tricky models, e.g., styles of programming relying on shared memory, can be used as needed.

To launch tasks to potentially run asynchronously, we can use `async()`:

```
double comp4(vector<double>& v)
    // spawn many tasks if v is large enough
{
    if (v.size()<10000) return accum(v.begin(),v.end(),0.0);

    auto v0 = &v[0];
    auto sz = v.size();
```

```
        auto f0 = async(accum,v0,v0+sz/4,0.0);              // first quarter
        auto f1 = async(accum,v0+sz/4,v0+sz/2,0.0);         // second quarter
        auto f2 = async(accum,v0+sz/2,v0+sz*3/4,0.0);       // third quarter
        auto f3 = async(accum,v0+sz*3/4,v0+sz,0.0);         // fourth quarter

        return f0.get()+f1.get()+f2.get()+f3.get();  // collect and combine the results
    }
```

Basically, **async()** separates the ''call part'' of a function call from the ''get the result part,'' and separates both from the actual execution of the task. Using **async()**, you don't have to think about threads and locks. Instead, you think just in terms of tasks that potentially compute their results asynchronously. There is an obvious limitation: Don't even think of using **async()** for tasks that share resources needing locking – with **async()** you don't even know how many **thread**s will be used because that's up to **async()** to decide based on what it knows about the system resources available at the time of a call. For example, **async()** may check whether any idle cores (processors) are available before deciding how many **thread**s to use.

Please note that **async()** is not just a mechanism specialized for parallel computation for increased performance. For example, it can also be used to spawn a task for getting information from a user, leaving the ''main program'' active with something else (§42.4.6).

5.4 Small Utility Components

Not all standard-library components come as part of obviously labeled facilities, such as ''containers'' or ''I/O.'' This section gives a few examples of small, widely useful components:

- **clock** and **duration** for measuring time.
- Type functions, such as **iterator_traits** and **is_arithmetic**, for gaining information about types.
- **pair** and **tuple** for representing small potentially heterogeneous sets of values.

The point here is that a function or a type need not be complicated or closely tied to a mass of other functions and types to be useful. Such library components mostly act as building blocks for more powerful library facilities, including other components of the standard library.

5.4.1 Time

The standard library provides facilities for dealing with time. For example, here is the basic way of timing something:

```
using namespace std::chrono;      // see §35.2

auto t0 = high_resolution_clock::now();
do_work();
auto t1 = high_resolution_clock::now();
cout << duration_cast<milliseconds>(t1−t0).count() << "msec\n";
```

The clock returns a **time_point** (a point in time). Subtracting two **time_point**s gives a **duration** (a period of time). Various clocks give their results in various units of time (the clock I used measures **nanoseconds**), so it is usually a good idea to convert a **duration** into a known unit. That's what **duration_cast** does.

The standard-library facilities for dealing with time are found in the subnamespace **std::chrono** in **<chrono>** (§35.2).

Don't make statements about ''efficiency'' of code without first doing time measurements. Guesses about performance are most unreliable.

5.4.2 Type Functions

A *type function* is a function that is evaluated at compile-time given a type as its argument or returning a type. The standard library provides a variety of type functions to help library implementers and programmers in general to write code that take advantage of aspects of the language, the standard library, and code in general.

For numerical types, **numeric_limits** from **<limits>** presents a variety of useful information (§5.6.5). For example:

```
constexpr float min = numeric_limits<float>::min();      // smallest positive float (§40.2)
```

Similarly, object sizes can be found by the built-in **sizeof** operator (§2.2.2). For example:

```
constexpr int szi = sizeof(int); // the number of bytes in an int
```

Such type functions are part of C++'s mechanisms for compile-time computation that allow tighter type checking and better performance than would otherwise have been possible. Use of such features is often called *metaprogramming* or (when templates are involved) *template metaprogramming* (Chapter 28). Here, I just present two facilities provided by the standard library: **iterator_traits** (§5.4.2.1) and type predicates (§5.4.2.2).

5.4.2.1 iterator_traits

The standard-library **sort()** takes a pair of iterators supposed to define a sequence (§4.5). Furthermore, those iterators must offer random access to that sequence, that is, they must be *random-access iterators*. Some containers, such as **forward_list**, do not offer that. In particular, a **forward_list** is a singly-linked list so subscripting would be expensive and there is no reasonable way to refer back to a previous element. However, like most containers, **forward_list** offers *forward iterators* that can be used to traverse the sequence by algorithms and **for**-statements (§33.1.1).

The standard library provides a mechanism, **iterator_traits** that allows us to check which kind of iterator is supported. Given that, we can improve the range **sort()** from §4.5.6 to accept either a **vector** or a **forward_list**. For example:

```
void test(vector<string>& v, forward_list<int>& lst)
{
    sort(v);    // sort the vector
    sort(lst);  // sort the singly-linked list
}
```

The techniques needed to make that work are generally useful.

First, I write two helper functions that take an extra argument indicating whether they are to be used for random-access iterators or forward iterators. The version taking random-access iterator arguments is trivial:

```
template<typename Ran>                                          // for random-access iterators
void sort_helper(Ran beg, Ran end, random_access_iterator_tag)  // we can subscript into [beg:end)
{
    sort(beg,end);      // just sort it

}
```

The version for forward iterators is almost as simple; just copy the list into a **vector**, sort, and copy back again:

```
template<typename For>                                  // for forward iterators
void sort_helper(For beg, For end, forward_iterator_tag)  // we can traverse [beg:end)
{
    vector<decltype(*beg)> v {beg,end};   // initialize a vector from [beg:end)
    sort(v.begin(),v.end());
    copy(v.begin(),v.end(),beg);          // copy the elements back
}
```

The **decltype()** is a built-in type function that returns the declared type of its argument (§6.3.6.3). Thus, **v** is a **vector<X>** where **X** is the element type of the input sequence.

The real ''type magic'' is in the selection of helper functions:

```
template<typname C>
void sort(C& c)
{
    using Iter = Iterator_type<C>;
    sort_helper(c.begin(),c.end(),Iterator_category<Iter>{});
}
```

Here, I use two type functions: **Iterator_type<C>** returns the iterator type of **C** (that is, **C::iterator**) and then **Iterator_category<Iter>{}** constructs a ''tag'' value indicating the kind of iterator provided:

- **std::random_access_iterator_tag** if **C**'s iterator supports random access.
- **std::forward_iterator_tag** if **C**'s iterator supports forward iteration.

Given that, we can select between the two sorting algorithms at compile time. This technique, called *tag dispatch* is one of several used in the standard library and elsewhere to improve flexibility and performance.

The standard-library support for techniques for using iterators, such as tag dispatch, comes in the form of a simple class template **iterator_traits** from **<iterator>** (§33.1.3). This allows simple definitions of the type functions used in **sort()**:

```
template<typename C>
    using Iterator_type = typename C::iterator;    // C's iterator type

template<typename Iter>
    using Iterator_category = typename std::iterator_traits<Iter>::iterator_category;  // Iter's category
```

If you don't want to know what kind of ''compile-time type magic'' is used to provide the standard-library features, you are free to ignore facilities such as **iterator_traits**. But then you can't use the techniques they support to improve your own code.

5.4.2.2 Type Predicates

A standard-library type predicate is a simple type function that answers a fundamental question about types. For example:

```
bool b1 = Is_arithmetic<int>();       // yes, int is an arithmetic type
bool b2 = Is_arithmetic<string>();    // no, std::string is not an arithmetic type
```

These predicates are found in **<type_traits>** and described in §35.4.1. Other examples are **is_class**, **is_pod**, **is_literal_type**, **has_virtual_destructor**, and **is_base_of**. They are most useful when we write templates. For example:

```
template<typename Scalar>
class complex {
        Scalar re, im;
public:
        static_assert(Is_arithmetic<Scalar>(), "Sorry, I only support complex of arithmetic types");
        // ...
};
```

To improve readability compared to using the standard library directly, I defined a type function:

```
template<typename T>
constexpr bool Is_arithmetic()
{
        return std::is_arithmetic<T>::value ;
}
```

Older programs use **::value** directly instead of **()**, but I consider that quite ugly and it exposes implementation details.

5.4.3 pair and tuple

Often, we need some data that is just data; that is, a collection of values, rather than an object of a class with a well-defined semantics and an invariant for its value (§2.4.3.2, §13.4). In such cases, we could define a simple **struct** with an appropriate set of appropriately named members. Alternatively, we could let the standard library write the definition for us. For example, the standard-library algorithm **equal_range** (§32.6.1) returns a **pair** of iterators specifying a sub-sequence meeting a predicate:

```
template<typename Forward_iterator, typename T, typename Compare>
        pair<Forward_iterator,Forward_iterator>
        equal_range(Forward_iterator first, Forward_iterator last, const T& val, Compare cmp);
```

Given a sorted sequence [**first**:**last**), **equal_range()** will return the **pair** representing the subsequence that matches the predicate **cmp**. We can use that to search in a sorted sequence of **Record**s:

```
auto rec_eq = [](const Record& r1, const Record& r2) { return r1.name<r2.name;};// compare names

void f(const vector<Record>& v)          // assume that v is sorted on its "name" field
{
        auto er = equal_range(v.begin(),v.end(),Record{"Reg"},rec_eq);
```

```
        for (auto p = er.first; p!=er.second; ++p)      // print all equal records
            cout << *p;                                 // assume that << is defined for Record
}
```

The first member of a **pair** is called **first** and the second member is called **second**. This naming is not particularly creative and may look a bit odd at first, but such consistent naming is a boon when we want to write generic code.

The standard-library **pair** (from **<utility>**) is quite frequently used in the standard library and elsewhere. A **pair** provides operators, such as **=**, **==**, and **<**, if its elements do. The **make_pair()** function makes it easy to create a **pair** without explicitly mentioning its type (§34.2.4.1). For example:

```
void f(vector<string>& v)
{
    auto pp = make_pair(v.begin(),2);   // pp is a pair<vector<string>::iterator,int>
    // ...
}
```

If you need more than two elements (or less), you can use **tuple** (from **<utility>**; §34.2.4.2). A **tuple** is a heterogeneous sequence of elements; for example:

```
tuple<string,int,double> t2("Sild",123, 3.14);  // the type is explicitly specified

auto t = make_tuple(string("Herring"),10, 1.23);    // the type is deduced
                                                    // t is a tuple<string,int,double>

string s = get<0>(t); // get first element of tuple
int x = get<1>(t);
double d = get<2>(t);
```

The elements of a **tuple** are numbered (starting with zero), rather than named the way elements of **pair**s are (**first** and **second**). To get compile-time selection of elements, I must unfortunately use the ugly **get<1>(t)**, rather than **get(t,1)** or **t[1]** (§28.5.2).

Like **pair**s, **tuple**s can be assigned and compared if their elements can be.

A **pair** is common in interfaces because often we want to return more than one value, such as a result and an indicator of the quality of that result. It is less common to need three or more parts to a result, so **tuple**s are more often found in the implementations of generic algorithms.

5.5 Regular Expressions

Regular expressions are a powerful tool for text processing. They provide a way to simply and tersely describe patterns in text (e.g., a U.S. ZIP code such as **TX 77845**, or an ISO-style date, such as **2009−06−07**) and to efficiently find such patterns in text. In **<regex>**, the standard library provides support for regular expressions in the form of the **std::regex** class and its supporting functions. To give a taste of the style of the **regex** library, let us define and print a pattern:

```
regex pat (R"(\w{2}\s*\d{5}(−\d{4})?)");    // ZIP code pattern: XXddddd-dddd and variants
cout << "pattern: " << pat << '\n';
```

People who have used regular expressions in just about any language will find `\w{2}\s*\d{5}(-\d{4})?` familiar. It specifies a pattern starting with two letters `\w{2}` optionally followed by some space `\s*` followed by five digits `\d{5}` and optionally followed by a dash and four digits `-\d{4}`. If you are not familiar with regular expressions, this may be a good time to learn about them ([Stroustrup,2009], [Maddock,2009], [Friedl,1997]). Regular expressions are summarized in §37.1.1.

To express the pattern, I use a *raw string literal* (§7.3.2.1) starting with `R"(` and terminated by `)"`. This allows backslashes and quotes to be used directly in the string.

The simplest way of using a pattern is to search for it in a stream:

```
int lineno = 0;
for (string line; getline(cin,line);) {              // read into line buffer
    ++lineno;
    smatch matches;                                  // matched strings go here
    if (regex_search(line,matches,pat))              // search for pat in line
        cout << lineno << ": " << matches[0] << '\n';
}
```

The `regex_search(line,matches,pat)` searches the `line` for anything that matches the regular expression stored in `pat` and if it finds any matches, it stores them in `matches`. If no match was found, `regex_search(line,matches,pat)` returns `false`. The `matches` variable is of type `smatch`. The ''s'' stands for ''sub'' and an `smatch` is a `vector` of sub-matches. The first element, here `matches[0]`, is the complete match.

For a more complete description see Chapter 37.

5.6 Math

C++ wasn't designed primarily with numerical computation in mind. However, C++ is heavily used for numerical computation and the standard library reflects that.

5.6.1 Mathematical Functions and Algorithms

In `<cmath>`, we find the ''usual mathematical functions,'' such as `sqrt()`, `log()`, and `sin()` for arguments of type `float`, `double`, and `long double` (§40.3). Complex number versions of these functions are found in `<complex>` (§40.4).

In `<numeric>`, we find a small set of generalized numerical algorithms, such as `accumulate()`. For example:

```
void f()
{
    list<double> lst {1, 2, 3, 4, 5, 9999.99999};
    auto s = accumulate(lst.begin(),lst.end(),0.0); // calculate the sum
    cout << s << '\n';                              // print 10014.9999
}
```

These algorithms work for every standard-library sequence and can have operations supplied as arguments (§40.6).

5.6.2 Complex Numbers

The standard library supports a family of complex number types along the lines of the **complex** class described in §2.3. To support complex numbers where the scalars are single-precision floating-point numbers (**float**s), double-precision floating-point numbers (**double**s), etc., the standard library **complex** is a template:

```
template<typename Scalar>
class complex {
public:
        complex(const Scalar& re ={}, const Scalar& im ={});
        // ...
};
```

The usual arithmetic operations and the most common mathematical functions are supported for complex numbers. For example:

```
void f(complex<float> fl, complex<double> db)
{
        complex<long double> ld {fl+sqrt(db)};
        db += fl*3;
        fl = pow(1/fl,2);
        // ...
}
```

The **sqrt()** and **pow()** (exponentiation) functions are among the usual mathematical functions defined in **<complex>**. For more details, see §40.4.

5.6.3 Random Numbers

Random numbers are useful in many contexts, such as testing, games, simulation, and security. The diversity of application areas is reflected in the wide selection of random number generators provided by the standard library in **<random>**. A random number generator consists of two parts:

[1] an *engine* that produces a sequence of random or pseudo-random values.
[2] a *distribution* that maps those values into a mathematical distribution in a range.

Examples of distributions are **uniform_int_distribution** (where all integers produced are equally likely), **normal_distribution** (''the bell curve''), and **exponential_distribution** (exponential growth); each for some specified range. For example:

```
using my_engine = default_random_engine;            // type of engine
using my_distribution = uniform_int_distribution<>; // type of distribution

my_engine re {};                                    // the default engine
my_distribution one_to_six {1,6};                   // distribution that maps to the ints 1..6
auto die = bind(one_to_six,re);                     // make a generator

int x = die();                                      // roll the die: x becomes a value in [1:6]
```

The standard-library function **bind()** makes a function object that will invoke its first argument (here, **one_to_six**) given its second argument (here, **re**) as its argument (§33.5.1). Thus a call **die()** is equivalent to a call **one_to_six(re)**.

Thanks to its uncompromising attention to generality and performance one expert has deemed the standard-library random number component ''what every random number library wants to be when it grows up.'' However, it can hardly be deemed ''novice friendly.'' The **using** statements makes what is being done a bit more obvious. Instead, I could just have written:

```
auto die = bind(uniform_int_distribution<>{1,6}, default_random_engine{});
```

Which version is the more readable depends entirely on the context and the reader.

For novices (of any background) the fully general interface to the random number library can be a serious obstacle. A simple uniform random number generator is often sufficient to get started. For example:

```
Rand_int rnd {1,10};                // make a random number generator for [1:10]
int x = rnd();                      // x is a number in [1:10]
```

So, how could we get that? We have to get something like **die()** inside a class **Rand_int**:

```
class Rand_int {
public:
    Rand_int(int low, int high) :dist{low,high} { }
    int operator()() { return dist(re); }          // draw an int
private:
    default_random_engine re;
    uniform_int_distribution<> dist;
};
```

That definition is still ''expert level,'' but the *use* of **Rand_int()** is manageable in the first week of a C++ course for novices. For example:

```
int main()
{
    Rand_int rnd {0,4};         // make a uniform random number generator

    vector<int> histogram(5);           // make a vector of size 5
    for (int i=0; i!=200; ++i)
        ++histogram[rnd()];             // fill histogram with the frequencies of numbers [0:4]

    for (int i = 0; i!=mn.size(); ++i) {    // write out a bar graph
        cout << i << '\t';
        for (int j=0; j!=mn[i]; ++j) cout << '*';
        cout << endl;
    }
}
```

The output is a (reassuringly boring) uniform distribution (with reasonable statistical variation):

```
0    ****************************************
1    ****************************************
2    ******************************
3    ****************************************
4    ****************************************
```

There is no standard graphics library for C++, so I use "ASCII graphics." Obviously, there are lots of open source and commercial graphics and GUI libraries for C++, but in this book I'll restrict myself to ISO standard facilities.

For more information about random numbers, see §40.7.

5.6.4 Vector Arithmetic

The **vector** described in §4.4.1 was designed to be a general mechanism for holding values, to be flexible, and to fit into the architecture of containers, iterators, and algorithms. However, it does not support mathematical vector operations. Adding such operations to **vector** would be easy, but its generality and flexibility precludes optimizations that are often considered essential for serious numerical work. Consequently, the standard library provides (in **<valarray>**) a **vector**-like template, called **valarray**, that is less general and more amenable to optimization for numerical computation:

```
template<typename T>
class valarray {
    // ...
};
```

The usual arithmetic operations and the most common mathematical functions are supported for **valarray**s. For example:

```
void f(valarray<double>& a1, valarray<double>& a2)
{
    valarray<double> a = a1*3.14+a2/a1;        // numeric array operators *, +, /, and =
    a2 += a1*3.14;
    a = abs(a);
    double d = a2[7];
    // ...
}
```

For more details, see §40.5. In particular, **valarray** offers stride access to help implement multidimensional computations.

5.6.5 Numeric Limits

In **<limits>**, the standard library provides classes that describe the properties of built-in types – such as the maximum exponent of a **float** or the number of bytes in an **int**; see §40.2. For example, we can assert that a **char** is signed:

```
static_assert(numeric_limits<char>::is_signed,"unsigned characters!");
static_assert(100000<numeric_limits<int>::max(),"small ints!");
```

Note that the second assert (only) works because **numeric_limits<int>::max()** is a **constexpr** function (§2.2.3, §10.4).

5.7 Advice

[1] Use resource handles to manage resources (RAII); §5.2.
[2] Use **unique_ptr** to refer to objects of polymorphic type; §5.2.1.
[3] Use **shared_ptr** to refer to shared objects; §5.2.1.
[4] Use type-safe mechanisms for concurrency; §5.3.
[5] Minimize the use of shared data; §5.3.4.
[6] Don't choose shared data for communication because of "efficiency" without thought and preferably not without measurement; §5.3.4.
[7] Think in terms of concurrent tasks, rather than threads; §5.3.5.
[8] A library doesn't have to be large or complicated to be useful; §5.4.
[9] Time your programs before making claims about efficiency; §5.4.1.
[10] You can write code to explicitly depend on properties of types; §5.4.2.
[11] Use regular expressions for simple pattern matching; §5.5.
[12] Don't try to do serious numeric computation using only the language; use libraries; §5.6.
[13] Properties of numeric types are accessible through **numeric_limits**; §5.6.5.