A Tour of C++

Second Edition

Bjarne Stroustrup

C++ In-Depth Series Bjarne Stroustrup

A Tour of C++
Second Edition

A Tour of C++
Second Edition

Bjarne Stroustrup

Addison-Wesley

Boston • Columbus • New York • San Francisco • Amsterdam • Cape Town
Dubai • London • Madrid • Milan • Munich • Paris • Montreal • Toronto • Delhi • Mexico City
São Paulo • Sydney • Hong Kong • Seoul • Singapore • Taipei • Tokyo

Visit us on the Web: informit.com/aw

Library of Congress Control Number: 2018941627

This book was typeset in Times and Helvetica by the author.

ISBN-13: 978-0-13-499783-4
ISBN-10: 0-13-499783-2
First printing, June 2018
1 18

Contents

This page intentionally left blank

Preface

When you wish to instruct,
be brief.
– Cicero

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

This book gives an overview of C++ as defined by C++17, the current ISO C++ standard, and implemented by the major C++ suppliers. In addition, it mentions concepts and modules, as defined in ISO Technical Specifications and in current use, but not scheduled for inclusion into the standard until C++20.

Like other modern languages, C++ is large and there are a large number of libraries needed for effective use. This thin book aims to give an experienced programmer an idea of what constitutes modern C++. It covers most major language features and the major standard-library components. This book can be read in just a few hours but, obviously, there is much more to writing good C++ than can be learned in a day. However, the aim here is not mastery, but to give an overview, to give key examples, and to help a programmer get started.

The assumption is that you have programmed before. If not, please consider reading a textbook, such as *Programming: Principles and Practice Using C++ (Second edition)* [Stroustrup,2014], 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.

Think of a 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 given some suggestions about what to do next. You do *not* know the city after such a tour. You do *not* understand all you have seen and heard. You do *not* know how to navigate the formal and informal rules that govern life in the city. 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 the major C++ language features as they support programming styles, such as object-oriented and generic programming. It does not attempt to provide a detailed, reference-manual, feature-by-feature view of the language. In the best textbook tradition, I try to explain a feature before I use it, but that is not always possible and not everybody reads the text strictly sequentially. So, the reader is encouraged to use the cross references and the index.

Similarly, this tour presents the standard libraries in terms of examples, rather than exhaustively. It does not describe libraries beyond those defined by the ISO standard. The reader can search out supporting material as needed. [Stroustrup,2013] and [Stroustrup,2014] are examples of such material, but there is an enormous amount of material (of varying quality) available on the Web, e.g., [Cppreference]. For example, when I mention a standard-library function or class, its definition can easily be looked up, and by examining its documentation, many related facilities can be found.

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, C++14, or C++17. Such information can be found in Chapter 16 (History and Compatibility). I focus on fundamentals and try to be brief, but I have not completely resisted the temptation to overrepresent novel features. This also seems to satisfy the curiosity of many readers who already know some older version of C++.

A programming language reference manual or standard simply states what can be done, but programmers are often more interested in learning how to use the language well. This aspect is partly addressed in the selection of topics covered, partly in the text, and specifically in the advice sections. More advice about what constitutes *good modern* C++ can be found in the C++ Core Guidelines [Stroustrup,2015]. The core guidelines can be a good source for further exploration of the ideas presented in this book. You may note a remarkable similarity of the advice formulation and even the numbering of advice between the Core Guidelines and this book. One reason is that the first edition of *A Tour of C++* was a major source of the initial Core Guidelines.

Acknowledgments

Some of the material presented here is borrowed from TC++PL4 [Stroustrup,2013], so thanks to all who helped completing that book.

Thanks to all who help complete and correct the first edition of ''A Tour of C++.''

Thanks to Morgan Stanley for giving me time to write this second edition. Thanks to the Columbia University Spring 2018 ''Design Using C++'' class for finding many a typo and bug in an early draft of this book and for making many constructive suggestions.

Thanks to Paul Anderson, Chuck Allison, Peter Gottschling, William Mons, Charles Wilson, and Sergey Zubkov for reviewing the book and suggesting many improvements.

Manhattan, New York *Bjarne Stroustrup*

3

Modularity

Don't interrupt me while I'm interrupting.
– Winston S. Churchill

- Introduction
- Separate Compilation
- Modules
- Namespaces
- Error Handling
  Exceptions; Invariants; Error-Handling Alternatives; Contracts; Static Assertions
- Function Arguments and Return Values
  Argument Passing; Value Return; Structured Binding
- Advice

3.1 Introduction

A C++ program consists of many separately developed parts, such as functions (§1.2.1), user-defined types (Chapter 2), class hierarchies (§4.5), and templates (Chapter 6). 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; §4.3). 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 we use.

There can be many declarations for an entity, such as a function, but only one definition.

3.2 Separate Compilation

C++ supports a notion of separate compilation where user code sees only declarations of the types and functions used. The definitions of those types and functions are in separate source files and are 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 collection of 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**. Users then *include* that file, called a *header file*, to access that interface. For example:

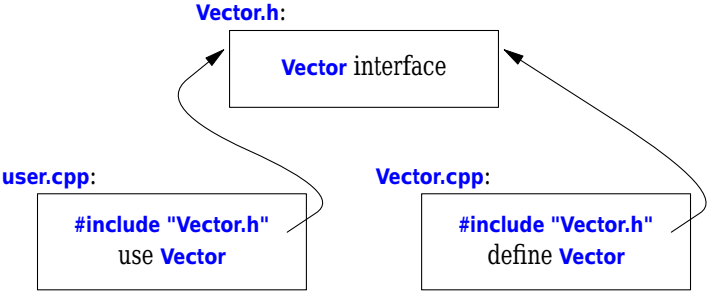
```
// user.cpp:

#include "Vector.h"        // get Vector's interface
#include <cmath>           // get the standard-library math function interface including sqrt()

double sqrt_sum(Vector& v)
{
        double sum = 0;
        for (int i=0; i!=v.size(); ++i)
                sum+=std::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 Vector's interface

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

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 to program organization is to think of the program as a set of modules with well-defined dependencies, represent that modularity logically through language features, and then exploit the modularity physically through files for effective separate compilation.

A **.cpp** file that is compiled by itself (including the **h** files it **#include**s) is called a *translation unit*. A program can consist of many thousand translation units.

3.3 Modules (C++20)

The use of **#include**s is a very old, error-prone, and rather expensive way of composing programs out of parts. If you **#include header.h** in 101 translation units, the text of **header.h** will be processed by the compiler 101 times. If you **#include header1.h** before **header2.h** the declarations and macros in **header1.h** might affect the meaning of the code in **header2.h**. If instead you **#include header2.h** before **header1.h**, it is **header2.h** that might affect the code in **header1.h**. Obviously, this is not ideal, and in fact it has been a major source of cost and bugs since 1972 when this mechanism was first introduced into C.

We are finally about to get a better way of expressing physical modules in C++. The language feature, called **module**s is not yet ISO C++, but it is an ISO Technical Specification [ModulesTS]. Implementations are in use, so I risk recommending it here even though details are likely to change and it may be years before everybody can use it in production code. Old code, in this case code using **#include**, can "live" for a very long time because it can be costly and time consuming to update.

Consider how to express the **Vector** and **use()** example from §3.2 using **module**s:

```
// file Vector.cpp:

module;   // this compilation will define a module

// ... here we put stuff that Vector might need for its implementation ...
```

```
export module Vector;     // defining the module called "Vector"

export 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;
};

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

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

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

export int size(const Vector& v) { return v.size(); }
```

This defines a **module** called **Vector**, which exports the class **Vector**, all its member functions, and the non-member function **size()**.

The way we use this **module** is to **import** it where we need it. For example:

```
// file user.cpp:

import Vector;            // get Vector's interface
#include <cmath>          // get the standard-library math function interface including sqrt()

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

I could have **import**ed the standard library mathematical functions also, but I used the old-fashioned **#include** just to show that you can mix old and new. Such mixing is essential for gradually upgrading older code from using **#include** to **import**.

The differences between headers and modules are not just syntactic.

- A module is compiled once only (rather than in each translation unit in which it is used).
- Two modules can be **import**ed in either order without changing their meaning.
- If you import something into a module, users of your module do not implicitly gain access to (and are not bothered by) what you imported: **import** is not transitive.

The effects on maintainability and compile-time performance can be spectacular.

3.4 Namespaces

In addition to functions (§1.3), classes (§2.3), and enumerations (§2.5), C++ offers *namespaces* 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 (§4.2.1, §14.4):

```
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** (§3.4). That precaution is wise, because the standard library does provide support for **complex** arithmetic (§4.2.1, §14.4).

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.

If repeatedly qualifying a name becomes tedious or distracting, we can bring the name into a scope with a **using**-declaration:

```
void my_code(vector<int>& x, vector<int>& y)
{
    using std::swap;          // use the standard-library swap
    // ...
    swap(x,y);                // std::swap()
    other::swap(x,y);         // some other swap()
    // ...
}
```

A **using**-declaration makes a name from a namespace usable as if it was declared in the scope in which it appears. After **using std::swap**, it is exactly as if **swap** had been declared in **my_code()**.

To gain access to all names in the standard-library namespace, we can use a **using**-directive:

```
using namespace std;
```

A **using**-directive makes unqualified names from the named namespace accessible from the scope in which we placed the directive. So after the **using**-directive for **std**, we can simply write **cout** rather than **std::cout**. By using a **using**-directive, we lose the ability to selectively use names from that namespace, so this facility should be used carefully, usually for a library that's pervasive in an application (e.g., **std**) or during a transition for an application that didn't use **namespace**s.

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

3.5 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 types (e.g., **string**, **map**, and **regex**) and algorithms (e.g., **sort()**, **find_if()**, and **draw_all()**) that are appropriate for our applications. 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 errors. The majority of C++ language 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 such abstraction 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. It is a good idea to articulate a strategy for error handling early on in the development of a program.

3.5.1 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?

- 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).

Assuming that out-of-range access is a kind of error that we want to recover from, the solution is for the **Vector** implementer to detect the attempted out-of-range access and 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. That is, the exception handling mechanism will exit scopes and functions as needed to get back to a caller that has expressed interest in handling that kind of exception, invoking destructors (§4.2.2) along the way as needed. 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& err) {     // oops: out_of_range error
                // ... handle range error ...
                cerr << err.what() << '\n';
        }
        // ...
}
```

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

I caught the exception by reference to avoid copying and used the **what()** function to print the error message put into it at the **throw**-point.

Use of the exception-handling mechanisms can make error handling simpler, more systematic, and more readable. To achieve that, don't overuse **try**-statements. The main technique for making error handling simple and systematic (called *Resource Acquisition Is Initialization; RAII*) is explained in §4.2.2. The basic idea behind RAII is for a constructor to acquire all resources necessary for a class to operate and have the destructor release all resources, thus making resource release guaranteed and implicit.

A function that should never throw an exception can be declared **noexcept**. For example:

```
void user(int sz) noexcept
{
    Vector v(sz);
    iota(&v[0],&v[sz],1);        // fill v with 1,2,3,4... (see §14.3)
    // ...
}
```

If all good intent and planning fails, so that **user()** still throws, **std::terminate()** is called to immediately terminate the program.

3.5.2 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[]()**. The [**a**:**b**) notation specifies a half-open range, meaning that **a** is part of the range, but **b** is not. Whenever we define a function, we should consider what its preconditions are and consider whether to test them (§3.5.3). For most applications it is a good idea to test simple invariants; see also §3.5.4.

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{"Vector constructor: negative size"};
    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& err) {
        // handle negative size
    }
    catch (std::bad_alloc& err) {
        // 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 (§3.5.1).

Often, a function has no way of completing its assigned task after an exception is thrown. Then, ''handling'' an exception means doing some minimal local cleanup and rethrowing the exception. For example:

```
void test()
{
    try {
        Vector v(−27);
    }
    catch (std::length_error&) {    // do something and rethrow
        cerr << "test failed: length error\n";
        throw;      // rethrow
    }
    catch (std::bad_alloc&) {       // Ouch! this program is not designed to handle memory exhaustion
        std::terminate();       // terminate the program
    }
}
```

In well-designed code `try`-blocks are rare. Avoid overuse by systematically using the RAII technique (§4.2.2, §5.3).

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

- help us to understand precisely what we want
- force 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 (Chapter 4) and destructors (§4.2.2, §13.2).

3.5.3 Error-Handling Alternatives

Error handling is a major issue in all real-world software, so naturally there are a variety of approaches. If an error is detected and it cannot be handled locally in a function, the function must somehow communicate the problem to some caller. Throwing an exception is C++'s most general mechanism for that.

There are languages where exceptions are designed simply to provide an alternate mechanism for returning values. C++ is not such a language: exceptions are designed to be used to report failure to complete a given task. Exceptions are integrated with constructors and destructors to provide a coherent framework for error handling and resource management (§4.2.2, §5.3). Compilers are optimized to make returning a value much cheaper than throwing the same value as an exception.

Throwing an exception is not the only way of reporting an error that cannot be handled locally. A function can indicate that it cannot perform its alotted task by:

- throwing an exception
- somehow return a value indicating failure
- terminating the program (by invoking a function like **terminate()**, **exit()**, or **abort()**).

We return an error indicator (an ''error code'') when:

- A failure is normal and expected. For example, it is quite normal for a request to open a file to fail (maybe there is no file of that name or maybe the file cannot be opened with the permissions requested).
- An immediate caller can reasonably be expected to handle the failure.

We throw an exception when:

- An error is so rare that a programmer is likely to forget to check for it. For example, when did you last check the return value of **printf()**?
- An error cannot be handled by an immediate caller. Instead, the error has to percolate back to an ultimate caller. For example, it is infeasible to have every function in an application reliably handle every allocation failure or network outage.
- New kinds of errors can be added in lower-modules of an application so that higher-level modules are not written to cope with such errors. For example, when a previously single-threaded application is modified to use multiple threads or resources are placed remotely to be accessed over a network.
- No suitable return path for errors codes are available. For example, a constructor does not have a return value for a ''caller'' to check. In particular, constructors may be invoked for several local variables or in a partially constructed complex object so that clean-up based on error codes would be quite complicated.
- The return path of a function is made more complicated or expensive by a need to pass both a value and an error indicator back (e.g., a **pair**; §13.4.3), possibly leading to the use of out-parameters, non-local error-status indicators, or other workarounds.
- The error has to be transmitted up a call chain to an ''ultimate caller.'' Repeatedly checking an error-code would be tedious, expensive, and error-prone.
- The recovery from errors depends on the results of several function calls, leading to the need to maintain local state between calls and complicated control structures.
- The function that found the error was a callback (a function argument), so the immediate caller may not even know what function was called.
- An error implies that some ''undo action'' is needed.

We terminate when

- An error is of a kind from which we cannot recover. For example, for many – but not all – systems there is no reasonable way to recover from memory exhaustion.
- The system is one where error-handling is based on restarting a thread, process, or computer whenever a non-trivial error is detected.

One way to ensure termination is to add **noexcept** to a function so that a **throw** from anywhere in the function's implementation will turn into a **terminate()**. Note that there are applications that can't accept unconditional terminations, so alternatives must be used.

Unfortunately, these conditions are not always logically disjoint and easy to apply. The size and complexity of a program matters. Sometimes the tradeoffs change as an application evolves. Experience is required. When in doubt, prefer exceptions because their use scales better, and don't require external tools to check that all errors are handled.

Don't believe that all error codes or all exceptions are bad; there are clear uses for both. Furthermore, do not believe the myth that exception handling is slow; it is often faster than correct handling of complex or rare error conditions, and of repeated tests of error codes.

RAII (§4.2.2, §5.3) is essential for simple and efficient error-handling using exceptions. Code littered with **try**-blocks often simply reflects the worst aspects of error-handling strategies conceived for error codes.

3.5.4 Contracts

There is currently no general and standard way of writing optional run-time tests of invariants, preconditions, etc. A contract mechanism is proposed for C++20 [Garcia,2016] [Garcia,2018]. The aim is to support users who want to rely on testing to get programs right – running with extensive run-time checks – but then deploy code with minimal checks. This is popular in high-performance applications in organizations that rely on systematic and extensive checking.

For now, we have to rely on ad hoc mechanisms. For example, we could use a command-line macro to control a run-time check:

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

The standard library offers the debug macro, **assert()**, to assert that a condition must hold at run time. For example:

```
void f(const char* p)
{
    assert(p!=nullptr);   // p must not be the nullptr
    // ...
}
```

If the condition of an **assert()** fails in ''debug mode,'' the program terminates. If we are not in debug mode, the **assert()** is not checked. That's pretty crude and inflexible, but often sufficient.

3.5.5 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 most

properties that are known at compile time and report failures to meet our expectations 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 (§1.6). For example:

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

void f(double speed)
{
    constexpr 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`. If you don't want a specific message printed, leave out the `S` and the compiler will supply a default message:

```
static_assert(4<=sizeof(int));      // use default message
```

The default message is typically the source location of the `static_assert` plus a character representation of the asserted predicate.

The most important uses of `static_assert` come when we make assertions about types used as parameters in generic programming (§7.2, §13.9).

3.6 Function Arguments and Return Values

The primary and recommended way of passing information from one part of a program to another is through a function call. Information needed to perform a task is passed as arguments to a function and the results produced are passed back as return values. For example:

```
int sum(const vector<int>& v)
{
    int s = 0;
    for (const int i : v)
        s += i;
    return s;
}

vector fib = {1,2,3,5,8,13,21};

int x = sum(fib);           // x becomes 53
```

There are other paths through which information can be passed between functions, such as global variables (§1.5), pointer and reference parameters (§3.6.1), and shared state in a class object (Chapter 4). Global variables are strongly discouraged as a known source of errors, and state should typically be shared only between functions jointly implementing a well-defined abstraction (e.g., member functions of a class; §2.3).

Given the importance of passing information to and from functions, it is not surprising that there are a variety of ways of doing it. Key concerns are:

- Is an object copied or shared?
- If an object is shared, is it mutable?
- Is an object moved, leaving an "empty object" behind (§5.2.2)?

The default behavior for both argument passing and value return is "copy" (§1.9), but some copies can implicitly be optimized to moves.

In the **sum()** example, the resulting **int** is copied out of **sum()** but it would be inefficient and pointless to copy the potentially very large **vector** into **sum()**, so the argument is passed by reference (indicated by the **&**; §1.7).

The **sum()** has no reason to modify its argument. This immutability is indicated by declaring the **vector** argument **const** (§1.6), so the **vector** is passed by **const**-reference.

3.6.1 Argument Passing

First consider how to get values into a function. By default we copy ("pass-by-value") and if we want to refer to an object in the caller's environment, we use a reference ("pass-by-reference"). For example:

```
void test(vector<int> v, vector<int>& rv)       // v is passed by value; rv is passed by reference
{
        v[1] = 99;      // modify v (a local variable)
        rv[2] = 66;     // modify whatever rv refers to
}

int main()
{
        vector fib = {1,2,3,5,8,13,21};
        test(fib,fib);
        cout << fib[1] << ' ' << fib[2] << '\n';        // prints 2 66
}
```

When we care about performance, we usually pass small values by-value and larger ones by-reference. Here "small" means "something that's really cheap to copy." Exactly what "small" means depends on machine architecture, but "the size of two or three pointers or less" is a good rule of thumb.

If we want to pass by reference for performance reasons but don't need to modify the argument, we pass-by-**const**-reference as in the **sum()** example. This is by far the most common case in ordinary good code: it is fast and not error-prone.

It is not uncommon for a function argument to have a default value; that is, a value that is considered preferred or just the most common. We can specify such a default by a *default function argument*. For example:

```
void print(int value, int base =10);   // print value in base "base"

print(x,16);      // hexadecimal
print(x,60);      // sexagesimal (Sumerian)
print(x);         // use the dafault: decimal
```

This is a notationally simpler alternative to overloading:

```
void print(int value, int base);       // print value in base "base"

void print(int value)                  // print value in base 10
{
    print(value,10);
}
```

3.6.2 Value Return

Once we have computed a result, we need to get it out of the function and back to the caller. Again, the default for value return is to copy and for small objects that's ideal. We return ''by reference'' only when we want to grant a caller access to something that is not local to the function. For example:

```
class Vector {
public:
    // ...
    double& operator[](int i) { return elem[i]; }      // return reference to ith element
private:
    double* elem;         // elem points to an array of sz
    // ...
};
```

The `i`th element of a `Vector` exists independently of the call of the subscript operator, so we can return a reference to it.

On the other hand, a local variable disappears when the function returns, so we should not return a pointer or reference to it:

```
int& bad()
{
    int x;
    // ...
    return x;  // bad: return a reference to the local variable x
}
```

Fortunately, all major C++ compilers will catch the obvious error in `bad()`.

Returning a reference or a value of a ''small'' type is efficient, but how do we pass large amounts of information out of a function? Consider:

```
Matrix operator+(const Matrix& x, const Matrix& y)
{
    Matrix res;
    // ... for all res[i,j], res[i,j] = x[i,j]+y[i,j] ...
    return res;
}

Matrix m1, m2;
// ...
Matrix m3 = m1+m2;      // no copy
```

A **Matrix** may be *very* large and expensive to copy even on modern hardware. So we don't copy, we give **Matrix** a move constructor (§5.2.2) and very cheaply move the **Matrix** out of **operator+()**. We do *not* need to regress to using manual memory management:

```
Matrix* add(const Matrix& x, const Matrix& y)      // complicated and error-prone 20th century style
{
    Matrix* p = new Matrix;
    // ... for all *p[i,j], *p[i,j] = x[i,j]+y[i,j] ...
    return p;
}

Matrix m1, m2;
// ...
Matrix* m3 = add(m1,m2);      // just copy a pointer
// ...
delete m3;                    // easily forgotten
```

Unfortunately, returning large objects by returning a pointer to it is common in older code and a major source of hard-to-find errors. Don't write such code. Note that **operator+()** is as efficient as **add()**, but far easier to define, easier to use, and less error-prone.

If a function cannot perform its required task, it can throw an exception (§3.5.1). This can help avoid code from being littered with error-code tests for "exceptional problems."

The return type of a function can be deduced from its return value. For example:

```
auto mul(int i, double d) { return i*d; }      // here, "auto" means "deduce the return type"
```

This can be convenient, especially for generic functions (function templates; §6.3.1) and lambdas (§6.3.3), but should be used carefully because a deduced type does not offer a stable interface: a change to the implementation of the function (or lambda) can change the type.

3.6.3 Structured Binding

A function can return only a single value, but that value can be a class object with many members. This allows us to efficiently return many values. For example:

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

```
Entry read_entry(istream& is)        // naive read function (for a better version, see §10.5)
{
        string s;
        int i;
        is >> s >> i;
        return {s,i};
}

auto e = read_entry(cin);

cout << "{ " << e.name << " , " << e.value << " }\n";
```

Here, `{s,i}` is used to construct the `Entry` return value. Similarly, we can ''unpack'' an `Entry`'s members into local variables:

```
auto [n,v] = read_entry(is);
cout << "{ " << n << " , " << v << " }\n";
```

The `auto [n,v]` declares two local variables `n` and `v` with their types deduced from `read_entry()`'s return type. This mechanism for giving local names to members of a class object is called *structured binding*.

Consider another example:

```
map<string,int> m;
// ... fill m ...
for (const auto [key,value] : m)
        cout << "{" << key "," << value << "}\n";
```

As usual, we can decorate `auto` with `const` and `&`. For example:

```
void incr(map<string,int>& m)        // increment the value of each element of m
{
        for (auto& [key,value] : m)
                ++value;
}
```

When structured binding is used for a class with no private data, it is easy to see how the binding is done: there must be the same number of names defined for the binding as there are nonstatic data members of the class, and each name introduced in the binding names the corresponding member. There will not be any difference in the object code quality compared to explicitly using a composite object; the use of structured binding is all about how best to express an idea.

It is also possible to handle classes where access is through member functions. For example:

```
complex<double> z = {1,2};
auto [re,im] = z+2;                  // re=3; im=2
```

A `complex` has two data members, but its interface consists of access functions, such as `real()` and `imag()`. Mapping a `complex<double>` to two local variables, such as `re` and `im` is feasible and efficient, but the technique for doing so is beyond the scope of this book.

3.7 Advice

[1] Distinguish between declarations (used as interfaces) and definitions (used as implementations); §3.1.
[2] Use header files to represent interfaces and to emphasize logical structure; §3.2; [CG: SF.3].
[3] **#include** a header in the source file that implements its functions; §3.2; [CG: SF.5].
[4] Avoid non-inline function definitions in headers; §3.2; [CG: SF.2].
[5] Prefer **module**s over headers (where **module**s are supported); §3.3.
[6] Use namespaces to express logical structure; §3.4; [CG: SF.20].
[7] Use **using**-directives for transition, for foundational libraries (such as **std**), or within a local scope; §3.4; [CG: SF.6] [CG: SF.7].
[8] Don't put a **using**-directive in a header file; §3.4; [CG: SF.7].
[9] Throw an exception to indicate that you cannot perform an assigned task; §3.5; [CG: E.2].
[10] Use exceptions for error handling only; §3.5.3; [CG: E.3].
[11] Use error codes when an immediate caller is expected to handle the error; §3.5.3.
[12] Throw an exception if the error is expected to perculate up through many function calls; §3.5.3.
[13] If in doubt whether to use an exception or an error code, prefer exceptions; §3.5.3.
[14] Develop an error-handling strategy early in a design; §3.5; [CG: E.12].
[15] Use purpose-designed user-defined types as exceptions (not built-in types); §3.5.1.
[16] Don't try to catch every exception in every function; §3.5; [CG: E.7].
[17] Prefer RAII to explicit **try**-blocks; §3.5.1, §3.5.2; [CG: E.6].
[18] If your function may not throw, declare it **noexcept**; §3.5; [CG: E.12].
[19] Let a constructor establish an invariant, and throw if it cannot; §3.5.2; [CG: E.5].
[20] Design your error-handling strategy around invariants; §3.5.2; [CG: E.4].
[21] What can be checked at compile time is usually best checked at compile time; §3.5.5 [CG: P.4] [CG: P.5].
[22] Pass ''small'' values by value and ''large'' values by references; §3.6.1; [CG: F.16].
[23] Prefer pass-by-**const**-reference over plain pass-by-reference; _module.arguments_; [CG: F.17].
[24] Return values as function-return values (rather than by out-parameters); §3.6.2; [CG: F.20] [CG: F.21].
[25] Don't overuse return-type deduction; §3.6.2.
[26] Don't overuse structured binding; using a named return type is often clearer documentation; §3.6.3.

I

Index

Knowledge is of two kinds.
We know a subject ourselves,
or we know where
we can find information on it.
– Samuel Johnson

Token

A

B

C

F

G

H

I

J

K

L

M

N

O

P

R

S

T

U

V

W

X

Z

Credits

Page ii: “I have made this letter longer than usual, because I lack the time to make it short.” Pascal, B. (1904). The provincial letters of Blaise Pascal, J.M. Dent.

Page x: “When you wish to instruct, be brief”, Marcus Tullius Cicero - Horace for English Readers, Being a Translation of the Poems of Quintus Horatius Flaccus into English Prose, trans. E.C. Wickham (Oxford: Clarendon Press, 1903).

Page 1: “The first thing we do, let’s kill all the language lawyers”, paraphrasing William Shakesphere - Henry The Sixth, Part 2 Act 4, scene 2, 71–78.

Page 21: “Don’t Panic!”, Neil Gaiman, Don’t Panic: The Official Hitchhiker’s Guide to the Galaxy Companion Pocket Books, 1988.

Page 29: “Don’t interrupt me while I’m interrupting”, Winston Churchill (1966). “The Irrepressible Churchill: Stories, Sayings and Impressions of Sir Winston Churchill”, World Publishing Company.

Page 49: “Those types are not ‘abstract’; they are as real as int and float”, Doug McIlroy.

Page 67: “When someone says I want a programming language in which I need only say what I wish done, give him a lollipop”, Alan Perlis ACM-SIGPLAN ’82, Epigrams in Programming.

Page 95: “Programming: you have to start with interesting algorithms”, Alex Stepanov.

Page 109: “Why waste time learning when ignorance is instantaneous?”, Watterson, B. (1992). Attack of the deranged mutant killer monster snow goons: A Calvin and Hobbes collection. Kansas City: Andrews and McMeel.

Page 113: “Prefer the standard to the offbeat”, Strunk, W., & White, E. B. (1959). The elements of style. N.Y: Macmillan.

Page 125: “What you see is all you get”, Kernighan, B. W., & Ritchie, D. M. (1988). The C programming language. Upper Saddle River NJ: Prentice Hall.

Page 141: “It was new. It was singular. It was simple. It must succeed!”, Horatio Nelson.

Page 153: “Do not multiply entities beyond necessity.” William Occam.

Page 160: “a finite set of rules….Input ... Output ... Effectiveness”, Donald E. Knuth: The Art of Computer Programming. Addison-Wesley, Reading, Massachusetts. 1968.

Page 167: “The time you enjoy wasting is not wasted time.” Bertrand Russell.

Page 193: “The purpose of computing is insight, not numbers”, Hamming, R. W. (1962). Numerical methods for scientists and engineers.

Page 193: “... but for the student, numbers are often the best road to insight.” A first course in numerical analysis, Anthony Ralston, McGraw-Hill, 1965.

Page 201: “Keep it simple: as simple as possible, but no simpler”, Albert Einstein.

Page 215: “Hurry Slowly (festina lente)”, Octavius, Caesar Augustus quoted in Alison Jones, Stephanie Pickering, Megan Thomson (1997). Chambers dictionary of quotations, Chambers.