Updated for C++ 20

A Tour of C++

Third Edition

Bjarne Stroustrup

C++ In-Depth Series Bjarne Stroustrup

FREE SAMPLE CHAPTER

A Tour of C++
Third Edition

C++ In-Depth Series
Bjarne Stroustrup, Series Editor

Visit **informit.com/series/indepth** for a complete list of available publications.

The **C++ In-Depth Series** is a collection of concise and focused books that provide real-world programmers with reliable information about the C++ programming language.

Selected by the designer and original implementor of C++, Bjarne Stroustrup, and written by carefully chosen experts in the field, each book in this series presents either a single topic, at a technical level appropriate to that topic, or a fast-paced overview, for a quick understanding of broader language features. In either case, the series' practical approach is designed to lift professionals (and aspiring professionals) to the next level of programming skill or knowledge.

A Tour of C++
Third 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

Cover photo by: Marco Pregnolato (Unsplash.com: @marco_pregnolato).
Author photo courtesy of Bjarne Stroustrup.

Visit us on the Web: informit.com/aw

Library of Congress Control Number: 2022938722

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

ISBN-13: 978-0-13-681648-5
ISBN-10: 0-13-681648-7
First printing, October 2022
ScoutAutomatedPrintCode

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 or C++11. Furthermore, the resulting programs are better checked by the compiler and run faster.

This book gives an overview of C++ as defined by C++20, the current ISO C++ standard, and implemented by the major C++ suppliers. In addition, it mentions a couple library components in current use, but not scheduled for inclusion into the standard until C++23.

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 day or two but, obviously, there is much more to writing good C++ than can be learned in that amount of time. 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; some stories may sound strange or even implausible. 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. I assume some technical maturity from my readers. 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. The reader is encouraged to search out additional and supporting material as needed. There is far more to the C++ ecosystem than just the facilities offered by ISO standard (e.g., libraries, build systems, analysis tools, and development environments). There is an enormous amount of material (of varying quality) available on the Web. Most readers will find useful tutorial and overview videos from conferences such as CppCon and Meeting C++. For technical details of the language and library offered by the ISO C++ standard, I recommend [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, I rarely identify language features as present in C, C++98, or later ISO standards. Such information can be found in Chapter 19 (History and Compatibility). I focus on fundamentals and try to be brief, but I have not completely resisted the temptation to overrepresent novel features, such as modules (§3.2.2), concepts (§8.2), and coroutines (§18.6). Slightly favoring recent developments 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

Thanks to all who helped complete and correct the earlier editions of *A Tour of C++*, especially to the students in my "Design Using C++" course at Columbia University. Thanks to Morgan Stanley for giving me time to write this third edition. Thanks to Chuck Allison, Guy Davidson, Stephen Dewhurst, Kate Gregory, Danny Kalev, Gor Nishanov, and J.C. van Winkel for reviewing the book and suggesting many improvements.

This book was set using troff by the author using macros originating from Brian Kernighan.

Manhattan, New York *Bjarne Stroustrup*

12

Containers

It was new. It was singular. It was simple.
It must succeed!
– H. Nelson

- Introduction
- **vector**
  Elements; Range Checking
- **list**
- **forward_list**
- **map**
- **unordered_map**
- Allocators
- Container Overview
- Advice

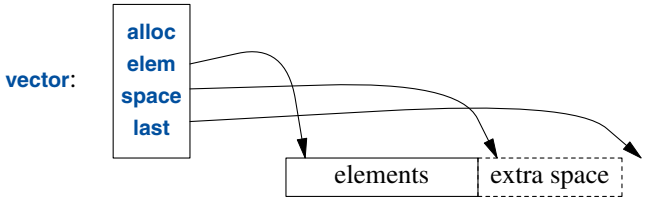
12.1 Introduction

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 §11.5 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**.

12.2 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. A typical implementation of **vector** (§5.2.2, §6.2) will consist of a handle holding pointers to the first element, one-past-the-last element, and one-past-the-last allocated space (§13.1) (or the equivalent information represented as a pointer plus offsets):



In addition, it holds an allocator (here, **alloc**), from which the **vector** can acquire memory for its elements. The default allocator uses **new** and **delete** to acquire and release memory (§12.7). Using a slightly advanced implementation technique, we can avoid storing any data for simple allocators in a **vector** object.

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. So, assuming that we have defined **<<** for **Entry**, we can write:

```
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 (§1.7):

```
void print_book(const vector<Entry>& book)
{
        for (const auto& x : book)      // for "auto" see §1.4
                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, assuming that we have defined **>>** for **Entry**, we can write:

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

This reads **Entry**s 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. To show how, consider an elaboration of the simple **Vector** from Chapter 5 and Chapter 7 using the representation indicated in the diagram above:

```
template<typename T>
class Vector {
    allocator<T> alloc;  // standard-library allocator of space for Ts
    T* elem;             // pointer to first element
    T* space;            // pointer to first unused (and uninitialized) slot
    T* last;             // pointer to last slot
public:
    // ...
    int size() const { return space–elem; }        // number of elements
    int capacity() const { return last–elem; }     // number of slots available for elements
    // ...
    void reserve(int newsz);              // increase capacity() to newsz
    // ...
    void push_back(const T& t);           // copy t into Vector
    void push_back(T&& t);                // move t into Vector
};
```

The standard-library **vector** has members **capacity()**, **reserve()**, and **push_back()**. The **reserve()** is used by users of **vector** and other **vector** members to make room for more elements. It may have to allocate new memory and when it does, it moves the elements to the new allocation. When **reserve()** moves elements to a new and larger allocation, any pointers to those elements will now point to the wrong location; they have become *invalidated* and should not be used.

Given **capacity()** and **reserve()**, implementing **push_back()** is trivial:

```
template<typename T>
void Vector<T>::push_back(const T& t)
{
    if (capacity()<=size())                 // make sure we have space for t
        reserve(size()==0?8:2*size());      // double the capacity
    construct_at(space,t);                  // initialize *space to t ("place t at space")
    ++space;
}
```

Now allocation and relocation of elements happens only infrequently. I used to use **reserve()** to try to improve performance, but that turned out to be a waste of effort: the heuristic used by **vector** is on average better than my guesses, so now I only explicitly use **reserve()** to avoid reallocation of elements when I want to use pointers to elements.

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

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

Copying and moving **vector**s are implemented by constructors and assignment operators as described in §6.2. 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 (§1.7) or move operations (§6.2.2) should be used.

The standard-library **vector** is very flexible and efficient. Use it as your default container; that is, use it unless you have a solid reason to use some other container. If you avoid **vector** because of vague concerns about "efficiency," measure. Our intuition is most fallible in matters of the performance of container uses.

12.2.1 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.

If you have a class hierarchy (§5.5) that relies on **virtual** functions to get polymorphic behavior, do not store objects directly in a container. Instead store a pointer (or a smart pointer; §15.2.1). For example:

```
vector<Shape> vs;               // No, don't - there is no room for a Circle or a Smiley (§5.5)
vector<Shape*> vps;             // better, but see §5.5.3 (don't leak)
vector<unique_ptr<Shape>> vups; // OK
```

12.2.2 Range Checking

The standard-library **vector** does not guarantee range checking. For example:

```
void silly(vector<Entry>& book)
{
    int i = book[book.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>
struct Vec : std::vector<T> {
    using vector<T>::vector;                 // use the constructors from vector (under the name Vec)

    T& operator[](int i) { return vector<T>::at(i); }                    // range check
    const T& operator[](int i) const { return vector<T>::at(i); }        // range check const objects; §5.2.1

    auto begin() { return Checked_iter<vector<T>>{*this}; }              // see §13.1
    auto end() { return Checked_iter<vector<T>>{*this, vector<T>::end()}; }
};
```

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 (§4.2).

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&) {
        cerr << "range error\n";
    }
}
```

The exception will be thrown, and then caught (§4.2). 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** (§11.2).

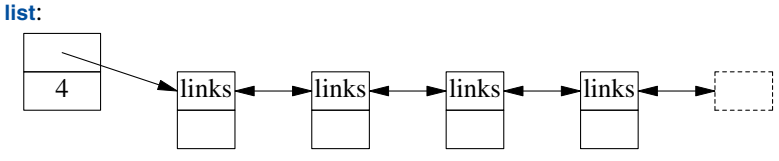
Why doesn't the standard guarantee range checking? Many performance-critical applications use **vector**s and checking all subscripting implies a cost on the order of 10%. Obviously, that cost can vary dramatically depending on hardware, optimizers, and an application's use of subscripting. However, experience shows that such overhead can lead people to prefer the far more unsafe built-in arrays. Even the mere fear of such overhead can lead to disuse. At least **vector** is easily range checked at debug time and we can build checked versions on top of the unchecked default.

A range-**for** avoids range errors at no cost by implicitly accessing all elements in the range. As long as their arguments are valid, the standard-library algorithms do the same to ensure the absence of range errors.

If you use **vector::at()** directly in your code, you don't need my **Vec** workaround. Furthermore, some standard libraries have range-checked **vector** implementations that offer more complete checking than **Vec**.

12.3 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 Chapter 13:

```
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 an element or insert a new element 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 (§13.1). 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:

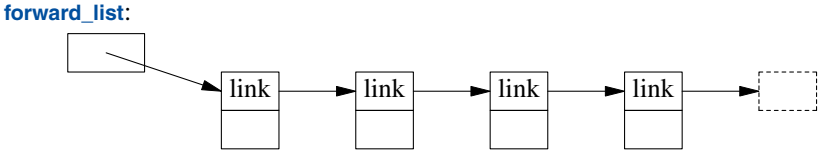
```
void f(const Entry& ee, list<Entry>::iterator p, list<Entry>::iterator q)
{
    phone_book.insert(p,ee);      // add ee before the element referred to by p
    phone_book.erase(q);          // remove the element referred to by q
}
```

For a **list**, **insert(p,elem)** inserts an element with a copy of the value **elem** before the element pointed to by **p**. Here, **p** may be an iterator pointing one-beyond-the-end of the **list**. Conversely, **erase(p)** removes the element pointed to by **p** and destroys it.

These **list** examples could be written identically using **vector** and (surprisingly, unless you understand machine architecture) often perform better with a **vector** than with a **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 **equal_range()**; §13.5, §15.3.3).

12.4 forward_list

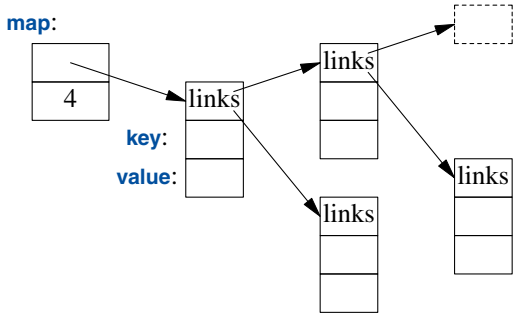
The standard library also offers a singly-linked list called **forward_list**:



A **forward_list** differs from a (doubly-linked) **list** by only allowing forward iteration. The point of that is to save space. There is no need to keep a predecessor pointer in each link and the size of an empty **forward_list** is just one pointer. A **forward_list** doesn't even keep its number of elements. If you need the number of elements, count. If you can't afford to count, you probably shouldn't use a **forward_list**.

12.5 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 balanced binary search tree (usually a red-black tree) called **map**:



In other contexts, a **map** is known as an associative array or a dictionary.

The standard-library **map** is a container of pairs of values optimized for lookup and insertion. We can use the same initializer as for **vector** and **list** (§12.2, §12.3):

```
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:

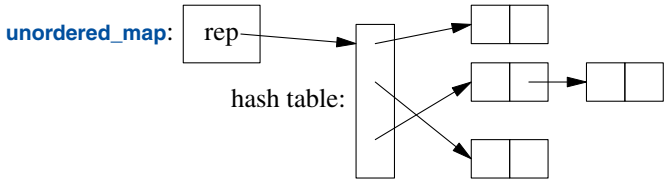
```
int get_number(const string& s)
{
    return phone_book[s];
}
```

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 and that just happens to be a reasonable value to represent an invalid telephone number.

If we wanted to avoid entering invalid numbers into our phone book, we could use find() and insert() (§12.8) instead of [ ].

12.6 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 a 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}
};
```

Like for a map, we can subscript an unordered_map:

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

The standard library provides a default hash function for strings as well as for other built-in and standard-library types. If necessary, we can provide our own. Possibly, the most common need for a custom hash function comes when we want an unordered container of one of our own types. A hash function is often implemented as a function object (§7.3.2). For example:

```
struct Record {
        string name;
        int product_code;
        // ...
};

struct Rhash {          // a hash function for Record
        size_t operator()(const Record& r) const
        {
                return hash<string>()(r.name) ^ hash<int>()(r.product_code);
        }
};

unordered_set<Record,Rhash> my_set; // set of Records using Rhash for lookup
```

Designing good hash functions is an art and often requires knowledge of the data to which it will be applied. Creating a new hash function by combining existing hash functions using exclusive-or (^) is simple and often very effective. However, be careful to ensure that every value that takes part in the hash really helps to distinguish the values. For example, unless you can have several names for the same product code (or several product codes for the same name), combining the two hashes provides no benefits.

We can avoid explicitly passing the **hash** operation by defining it as a specialization of the standard-library **hash**:

```
namespace std {             // make a hash function for Record

        template<> struct hash<Record> {
                using argument_type = Record;
                using result_type = size_t;

                result_type operator()(const Record& r) const
                {
                        return hash<string>()(r.name) ^ hash<int>()(r.product_code);
                }
        };
}
```

Note the differences between a **map** and an **unordered_map**:

- A **map** requires an ordering function (the default is **<**) and yields an ordered sequence.
- A **unordered_map** requires an equality function (the default is **==**); it does not maintain an order among its elements.

Given a good hash function, an **unordered_map** is much faster than a **map** for large containers. However, the worst-case behavior of an **unordered_map** with a poor hash function is far worse than that of a **map**.

12.7 Allocators

By default, standard-library containers allocate space using **new**. Operators **new** and **delete** provide a general free store (also called dynamic memory or heap) that can hold objects of arbitrary size and user-controlled lifetime. This implies time and space overheads that can be eliminated in many special cases. Therefore, the standard-library containers offer the opportunity to install allocators with specific semantics where needed. This has been used to address a wide variety of concerns related to performance (e.g., pool allocators), security (allocators that clean-up memory as part of deletion), per-thread allocation, and non-uniform memory architectures (allocating in specific memories with pointer types to match). This is not the place to discuss these important, but very specialized and often advanced techniques. However, I will give one example motivated by a real-world problem for which a pool allocator was the solution.

An important, long-running system used an event queue (see §18.4) using **vector**s as events that were passed as **shared_ptr**s. That way, the last user of an event implicitly deleted it:

```
struct Event {
    vector<int> data = vector<int>(512);
};

list<shared_ptr<Event>> q;

void producer()
{
    for (int n = 0; n!=LOTS; ++n) {
        lock_guard lk {m};          // m is a mutex; see §18.3
        q.push_back(make_shared<Event>());
        cv.notify_one();            // cv is a condition_variable; see §18.4
    }
}
```

From a logical point of view this worked nicely. It is logically simple, so the code is robust and maintainable. Unfortunately, this led to massive fragmentation. After 100,000 events had been passed among 16 producers and 4 consumers, more than 6GB of memory had been consumed.

The traditional solution to fragmentation problems is to rewrite the code to use a pool allocator. A pool allocator is an allocator that manages objects of a single fixed size and allocates space for many objects at a time, rather than using individual allocations. Fortunately, C++ offers direct support for that. The pool allocator is defined in the **pmr** (‘‘polymorphic memory resource’’) subnamespace of **std**:

```
pmr::synchronized_pool_resource pool;           // make a pool

struct Event {
    vector<int> data = vector<int>{512,&pool};  // let Events use the pool
};

list<shared_ptr<Event>> q {&pool};              // let q use the pool
```

```
void producer()
{
    for (int n = 0; n!=LOTS; ++n) {
        scoped_lock lk {m};        // m is a mutex (§18.3)
        q.push_back(allocate_shared<Event,pmr::polymorphic_allocator<Event>>{&pool});
        cv.notify_one();
    }
}
```

Now, after 100,000 events had been passed among 16 producers and 4 consumers, less than 3MB of memory had been consumed. That's about a 2000-fold improvement! Naturally, the amount of memory actually in use (as opposed to memory wasted to fragmentation) is unchanged. After eliminating fragmentation, memory use was stable over time so the system could run for months.

Techniques like this have been applied with good effects from the earliest days of C++, but generally they required code to be rewritten to use specialized containers. Now, the standard containers optionally take allocator arguments. The default is for the containers to use **new** and **delete**. Other polymorphic memory resources include

- **unsynchronized_polymorphic_resource**; like **polymorphic_resource** but can only be used by one thread.
- **monotonic_polymorphic_resource**; a fast allocator that releases its memory only upon its destruction and can only be used by one thread.

A polymorphic resource must be derived from **memory_resource** and define members **allocate()**, **deallocate()**, and **is_equal()**. The idea is for users to build their own resources to tune code.

12.8 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 (§12.2)
list<T>	A doubly-linked list (§12.3)
forward_list<T>	A singly-linked list
deque<T>	A double-ended queue
map<K,V>	An associative array (§12.5)
multimap<K,V>	A map in which a key can occur many times
unordered_map<K,V>	A map using a hashed lookup (§12.6)
unordered_multimap<K,V>	A multimap using a hashed lookup
set<T>	A set (a map with just a key and no value)
multiset<T>	A set in which a value can occur many times
unordered_set<T>	A set using a hashed lookup
unordered_multiset<T>	A multiset using a hashed lookup

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

The containers are defined in namespace **std** and presented in headers **<vector>**, **<list>**, **<map>**, etc. (§9.3.4). In addition, the standard library provides container adaptors **queue<T>**, **stack<T>**, and **priority_queue<T>**. Look them up if you need them. The standard library also provides more specialized container-like types, such as **array<T,N>** (§15.3.1) and **bitset<N>** (§15.3.2).

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:

Standard Container Operations (partial)	
value_type	The type of an element
p=c.begin()	**p** points to first element of **c**; also **cbegin()** for an iterator to **const**
p=c.end()	**p** points to one-past-the-last element of **c**; also **cend()** for an iterator to **const**
k=c.size()	**k** is the number of elements in **c**
c.empty()	Is **c** empty?
k=c.capacity()	**k** is the number of elements that **c** can hold without a new allocation
c.reserve(k)	Increase the capacity to **k**; if **k<=c.capacity()**, **c.reserve(k)** does nothing
c.resize(k)	Make the number of elements **k**; added elements have the default value **value_type{}**
c[k]	The **k**th element of **c**; zero-based; no range guaranteed checking
c.at(k)	The **k**th element of **c**; if out of range, throw **out_of_range**
c.push_back(x)	Add **x** at the end of **c**; increase the size of **c** by one
c.emplace_back(a)	Add **value_type{a}** at the end of **c**; increase the size of **c** by one
q=c.insert(p,x)	Add **x** before **p** in **c**
q=c.erase(p)	Remove element at **p** from **c**
c=c2	Assignment: copy all elements from **c2** to get **c==c2**
b=(c==c2)	Equality of all elements of **c** and **c2**; **b==true** if equal
x=(c<=>c2)	Lexicographical order of **c** and **c2**: **x<0** if **c** is less than **c2**, **x==0** if equal, and **0<x** if greater than. **!=**, **<**, **<=**, **>**, and **>=** are generated from **<=>**

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** (§4.3, Chapter 5), is an example of that. The uniformity of container interfaces 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 to different locations 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.

Consider the singly-linked list, **forward_list**, a container optimized for the empty sequence (§12.3). An empty **forward_list** occupies just one word, whereas an empty **vector** occupies three. Empty sequences, and sequences with only an element or two, are surprisingly common and useful.

An emplace operation, such as **emplace_back()** takes arguments for an element's constructor and builds the object in a newly allocated space in the container, rather than copying an object into the container. For example, for a **vector<pair<int,string>>** we could write:

```
v.push_back(pair{1,"copy or move"});    // make a pair and move it into v
v.emplace_back(1,"build in place");     // build a pair in v
```

For simple examples like this, optimizations can result in equivalent performance for both calls.

12.9 Advice

[1] An STL container defines a sequence; §12.2.
[2] STL containers are resource handles; §12.2, §12.3, §12.5, §12.6.
[3] Use **vector** as your default container; §12.2, §12.8; [CG: SL.con.2].
[4] For simple traversals of a container, use a range-**for** loop or a begin/end pair of iterators; §12.2, §12.3.
[5] Use **reserve()** to avoid invalidating pointers and iterators to elements; §12.2.
[6] Don't assume performance benefits from **reserve()** without measurement; §12.2.
[7] Use **push_back()** or **resize()** on a container rather than **realloc()** on an array; §12.2.
[8] Don't use iterators into a resized **vector**; §12.2 [CG: ES.65].
[9] Do not assume that **[ ]** range checks; §12.2.
[10] Use **at()** when you need guaranteed range checks; §12.2; [CG: SL.con.3].
[11] Use range-**for** and standard-library algorithms for cost-free avoidance of range errors; §12.2.2.
[12] Elements are copied into a container; §12.2.1.
[13] To preserve polymorphic behavior of elements, store pointers (built-in or user-defined); §12.2.1.
[14] Insertion operations, such as **insert()** and **push_back()**, are often surprisingly efficient on a **vector**; §12.3.
[15] Use **forward_list** for sequences that are usually empty; §12.8.
[16] When it comes to performance, don't trust your intuition: measure; §12.2.
[17] A **map** is usually implemented as a red-black tree; §12.5.
[18] An **unordered_map** is a hash table; §12.6.
[19] Pass a container by reference and return a container by value; §12.2.
[20] For a container, use the **()**-initializer syntax for sizes and the **{}**-initializer syntax for sequences of elements; §5.2.3, §12.2.
[21] Prefer compact and contiguous data structures; §12.3.
[22] A **list** is relatively expensive to traverse; §12.3.
[23] Use unordered containers if you need fast lookup for large amounts of data; §12.6.
[24] Use ordered containers (e.g., **map** and **set**) if you need to iterate over their elements in order; §12.5.
[25] Use unordered containers (e.g., **unordered_map**) for element types with no natural order (i.e., no reasonable **<**); §12.5.
[26] Use associative containers (e.g., **map** and **list**) when you need pointers to elements to be stable as the size of the container changes; §12.8.

[27] Experiment to check that you have an acceptable hash function; §12.6.
[28] A hash function obtained by combining standard hash functions for elements using the exclusive-or operator (^) is often good; §12.6.
[29] Know your standard-library containers and prefer them to handcrafted data structures; §12.8.
[30] If your application is suffering performance problems related to memory, minimize free store use and/or consider using a specialized allocator; §12.7.

This page intentionally left blank

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

D

E

F

G

H

I

J

K

L

M

N

O

P

Q

R

S

T

U

V

W

X

Y

Z