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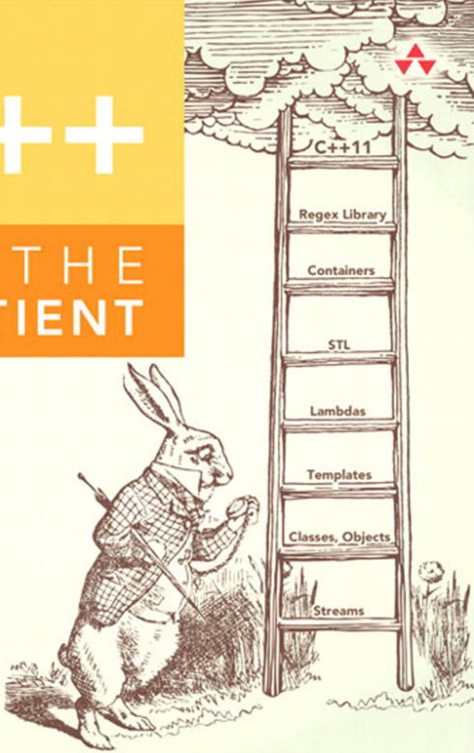

BRIAN OVERLAND

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Brian Overland

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Once more, for Colin.

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Preface

Congratulations! With this book, *C++ for the Impatient,* you have in your hands the quickest and easiest way to learn the latest state-of-the-art features in C++, especially features in the new C++11 specification and other features added in recent years.

The new technology is not difficult to understand once it's explained clearly. But some of the concepts are at first so abstract and alien that it can take weeks of pounding your head against a wall, wondering when you're going to "get it." Too many descriptions (although written by knowledgeable experts) are unable to break through the conceptual barrier that makes it hard to learn something new.

I wrote this book in part so that you wouldn't have to go through those weeks and months of frustration. Learning this material shouldn't be difficult.

C++ for the Impatient also provides quick, ready reference to all of C++'s features (or at least the great majority of them), ranging from the most basic building blocks of the language, up to and including refined uses of the C++ library.

How This Book Is Different: Learning C++11

My statement that this book is "the quickest and easiest way to learn the latest, state-of-the-art features" is a strong claim. It's backed up by a number of techniques.

- Dozens of easy-to-follow figures. Sometimes a picture really is worth a thousand words. Or sometimes ten thousand.
- Simple, relevant examples. Many or most programming books are written in part to convince you how smart the author is. My goal is to make *you* feel smart. And that means short, easy-to-digest examples.
- Frequent use of syntax diagrams, summarizing grammar at a glance.
- Simple explanations of important concepts—but only to the extent necessary to understand why a feature was added to C++ and how it's used.

Who Should Buy This Book?

The quick answer: almost anyone serious about learning and using C++.

- For advanced beginners: If you haven't learned any programming language before, you'll need additional help from a teacher or (at minimum) a more elementary text. But Chapter 1, "C++ Fundamentals," and the Sample Apps in each chapter are intended to be especially helpful for beginners.
- For intermediate and advanced programmers: No matter how advanced you may be, it's likely you're still coming up to speed on at least some of the newer and more advanced features of C++, especially C++11. If that's the case, this book is for you.
- For all programmers: Unlike other books, *C++ for the Impatient* features a concise write-up on each operator and each individual function, class, and object in the C++ library, including
  - Syntax summaries, showing arguments and types at a glance
  - A concise description of what each function, object, or operator does
  - A short illustrative example (although longer examples are used where helpful)

Examples and Exercises

Having the right example is often what makes the difference in learning new technology. So, in addition to the short examples for each individual function and operator, I provide one or two complete programs—Sample Apps—at the end of most chapters.

Each of these programs does something entertaining, useful, or both. They include intriguing games and puzzles. I've selected these Sample Apps because they make heavy use of the major technology in the chapter while at the same time being easy to follow.

Because this book is more a reference than a primer, I don't include exercises on every other page. However, I do include them after each Sample App. These are graduated and numbered, beginning with easier ones and leading up to the more truly challenging.

The best way to learn is by doing. I challenge you to complete the exercises in the book. If you can do them all, you can consider yourself quite an expert and an accomplished C++ programmer!

To find answers to these exercises (although it's cheating to look before you've at least tried to solve them yourself), you can go to informit.com/title/9780321888020. For information on other books of mine, you can go to brianoverland.com

Requirements: Your Version of C++

C++ is probably the most popular programming language in the world today. Although there are other excellent tools available for specific platforms (such as C#, Java, and Objective C), C++ still reigns as the most important, general-purpose language for writing and maintaining serious stand-alone applications.

Within the first few years after C++'s introduction, compiler vendors added important new features. This book assumes your compiler supports all of the following current features.

- Templates: This feature helps make code reusable; freeing you from having to solve the same general problems over and over again.
- The Standard Template Library (STL), providing flexible containers and reusable searching, sorting, and data processing routines: Potentially, these can save you a significant amount of work no matter what data types you work on.
- String class: The classic C-string type is still supported, but the STL **string** class is easier, safer, and more convenient to use than the old null-terminated C-string type.
- Specialized cast operators: These help result in more reliable, easier-to-debug programs.
- Structured exception handing: This is a superior way to handle errors, although it is mainly of use to programmers writing source code thousands of lines long.

One thing I do *not* assume in this book is that your compiler supports all the new features in the C++11 specification. As of this writing, some of the new features are not supported even by the major compiler vendors such as Microsoft, although they soon will be.

In order to make this book easier to use, therefore, all the sections and chapters that make use of the C++11 specification are clearly marked as such. The code in the rest of the book should run on any professional-grade compiler produced in the past several years.

C++11

Although this book doesn't assume that your compiler supports all the features in the C++11 specification, it is particularly useful if your compiler does support some or all of the new features.

The move from previous versions of C++ to C++11 is a major jump. Although the new specification is backward-compatible with past versions of C++, it opens up exciting new possibilities in software development.

This book explores all of these major new areas in C++11.

- Move semantics: The C++ library takes advantage of new technology by replacing copy operations, whenever possible, with *moves*. The difference is analogous to moving a document from one folder on your internal drive to another instead of copying it. You may have noticed that a move between folders is practically instantaneous, while copying can take time.

  Now this same improved performance is available to data within your own programs. Sometimes copying is unnecessary, and data transfers (or moves) are much faster. *Move semantics* can often speed up your programs without any action on your part. However, you can optimize your programs even further by facilitating move semantics in your own classes as explained in Appendix A, "A Painless Introduction to Rvalue References (C++11)."
- Lambda functions: Traditional programming techniques require you to define a function in one place and call it in another; this is fine most of the time, but sometimes it's inconvenient to search through all your source code to find a definition. Using the lambda technology enables you to define a function at the very point it is used, which can be extremely convenient.
- Improved syntax for class declarations: The ability to declare classes is one of the most important parts of the C++ language. Although C++ has been around for some time, up until now some things have been more difficult than they ideally should be. C++11 provides significantly improved syntax, such as inherited constructors for derived classes and more convenient ways to specify default values.
- Extended features of the C++ library: C++11 brings many new capabilities to the standard library, including a full-featured regular-expression library, which provides powerful tools for searching, matching, and replacing patterns of text. There are many other new capabilities as well, including improved randomization techniques and unordered (hash-table) containers. Such containers—although they lose the ability to step through elements in a meaningful order—provide much faster lookup times for database applications and data dictionaries. This is another way C++11 can significantly increase program performance.
- Smart pointers: Pointers are an important part of the C++ language, and they get their full due in this book, but applications can be made more error-free and easier to manage by the use of smart pointers, which automatically release memory when they go out of scope. This book describes exactly how the new **shared_ptr** and **unique_ptr** types work.
- Improvements to the core language: Finally, C++11 provides a series of improvements to the core language, such as range-based **for**, which reduces the chance of errors and is more concise than standard **for** statements. Range-based **for** takes advantage of each container's built-in knowledge of where it begins and ends. C++11 provides other improvements as well.

As Bjarne Stroustrup has said about C++11, it's effectively "a whole new language." Learning the new capabilities will enable you to produce higher-quality, more efficient and bug-free programs. You should find that the rewards, over time, repay the effort in learning these new features many times over.

Appendix B, "Summary of New Features in C++11," describes all these new features in greater detail.

Appendix C, "ASCII Codes," presents ASCII codes according to decimal and hexidecimal values.

Learning about Object Orientation

The approach of this book is to clearly lay out the mechanics of classes and objects in C++, explaining computer science concepts where needed to understand the technology.

For a more in-depth discussion of the background to object orientation and the history of C++, I recommend Bjarne Stroustrup's *The C++ Programming Language, Fourth Edition* (Addison-Wesley, 2013), which is long but is an excellent resource.

Other texts are available that attempt to teach how to "think objects" in more depth than I do in this book—although again, I cover the basic concepts. *C++ Primer, Fifth Edition* (Addison-Wesley, 2013) by Stanley B. Lippman, Josée Lajoie, and Barbara E. Moo, is a good place to start.

If you are really starting from scratch, with no background in C, C++, or a language in the C family, I humbly recommend my own book, *C++ Without Fear, Second Edition* (Prentice Hall, 2011).

Typographic Conventions

Typographic conventions for syntax summaries, I've found, can be helpful as long as those conventions don't get out of hand. In this book, I adhere to light use of these conventions. See Table P.1.

Throughout the book, I make extensive use of bold and italics in syntax displays; but I use brackets to indicate optional items only occasionally, because these can be confused with literal brackets. But the text always clarifies how I intend to use them.

Here is an example of these syntax conventions taken from Chapter 2, "Data":

[*sign*]*digits***.***digits***E***exponent*

In this case, both the decimal point (**.**) and the **E** are intended literally and so are in bold font. Each set of *digits* is a sequence of the numerals 0 through 9. The *exponent* is likewise a series of digits. Each of these is a string of numerals that you supply. The brackets (which are not in bold in this case) indicate that the *sign* is an optional minus sign (–) that can either appear or not appear.

TABLE P.1 Typographic Conventions

Style	Description
Keyword	Keywords and punctuation in bold are meant to be typed exactly as shown. Note that C++ is case-sensitive; so for the keyword **if**, enter "if" into your programming code but not "If" or "IF."
Placeholder	Placeholders are in italics: These are items that you supply. Typically, they are function, class, or variable names that you choose, but they can be something more complex, such as an entire statement.
[optional]	Occasionally, I use brackets (not in bold!) to indicate an optional item. In this case, the brackets are not intended literally but indicate something that may or may not be included as you choose. However, brackets in bold are intended literally, and in those cases, I mention that they are intended that way.
item**,** item…	Ellipses indicate an item that may be repeated any number of times. (Note that the comma is intended literally, but the ellipses are not.)

A Final Word

When Alice followed the White Rabbit down the rabbit hole, she was at first bewildered by the strange people and animals she encountered. So it is when learning new concepts. You wonder if you ever should have left your quiet garden and drawing room behind with their comfortable surroundings, as you encounter characters who say odd things and use peculiar logic.

You may find yourself asking: What was wrong with the old, familiar world I left behind? But hopefully, like Alice, you'll find yourself in Wonderland.

Personally, I feel the trip should always be interesting and even fun. Because this book is a reference, there are some chapters you won't want to read from beginning to end, any more than you'd read an encyclopedia that way. But the sections on the new technology are meant to be read like articles, as well as being texts you can come back to and refer to again and again. Above all, I hope they communicate a feel for why I found the new concepts both useful and intriguing.

Like me, you may be impatient. There is so much to learn and only so much time to learn it. I know that I'm like the White Rabbit, wanting to understand all that I see at first glance so that I can use the new tools to get to my destination quickly. I don't want to stand around trying to figure out what I'm doing there.

C++11 is almost a new language, despite its being backward-compatible. And learning a new language (to continue the Wonderland analogy) is like slaying the mythical Jabberwocky. It's a strange, multiheaded, whimsical beast, and it looks like it's too big to ever conquer; but with the right sword in hand, you shouldn't be afraid. Before you know it, you'll have completed the quest. And then you can imagine me saying:

"And, hast though slain the Jabberwock?
Come to my arms, my beamish boy!
Oh frabjous day! Callooh! Callay!"
He chortled in his joy."

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About the Author

With long experience in both technology and training people to use it, **Brian Overland** is uniquely qualified to write books that simplify difficult concepts. He began programming professionally in C in the 1980s, working on a software-driven irrigation system used all over the globe. He also taught programming and English composition at a community college while writing film and drama reviews. At Microsoft, he spent a decade rising from tester and tech-support specialist to project lead and manager. As a project lead of Visual Basic 1.0, he played a key role in bringing easy Windows programming to the world and explaining how to use it; he was also a member of the Visual C++ team. He has since written many successful books and founded his own high-tech company.

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◆ ◆ ◆ CHAPTER 20

C++11 Regular-Expression Library

Applications such as Microsoft Word have long supported pattern-matching, or *regular-expression,* capabilities. Using C and C++, it was always possible to write your own regular-expression engines, but it required sophisticated, complex programming—and usually a degree in computer science. Now C++11 makes these capabilities directly available to you, without your having to write a regular-expression engine yourself.

Regular expressions are of practical value in many programs, as they can aid with the task of *lexical analysis*—intelligently breaking up pieces of an input string—as well as tasks such as converting from one text-file format (such as HTML) to another.

I've found that when the C++11 regular expression library is explained in a straightforward, simple manner, it's easy to use. This chapter doesn't describe all the endless variations on the regex function-call syntax, but it does explain all the basic functionality: how to do just about anything you'd want to do.

20.1 Overview of C++11 Regular Expressions

Before using any regular-expression functions, include the <regex> header.

```
#include <regex>
```

A regular expression is a string that uses special characters—in combination with ordinary characters—to create a text pattern. That pattern can then be used to match another string, search it, or identify a substring as the target of a search-and-replace function.

For example, consider a simple pattern: a string consisting only of the digits 0 through 9, and nothing else. A decimal integer, assuming it has no plus or minus sign, fulfills this pattern.

With the C++11 regular-expression syntax, this pattern can be expressed as:

```
[0-9]+
```

In this regular-expression pattern, only the “0” and “9” are intended literally. The other characters—“[”, “]”, “-”, and “+”—each have a special meaning.

The brackets specify a range of characters:

`[`*`range`*`]`

This syntax says, “Match any one character in the specified range. The following examples specify different ranges.

```
[abc]          // Match a, b, or c.
[A-Z]          // Match any letter in range A to Z.
[a-zA-Z]       // Match any letter.
```

The other special character used in this example is the plus sign (+).

`expr+`

This syntax says, “Match the preceding expression, *expr*, one or more times. The plus sign is a pattern modifier, so it means that *expr*+, taken as a whole, matches one or more instances of *expr.*

Here are some examples:

```
a+            // Match a, aa, aaa, etc.
(ab)+         // Match ab, abab, ababab, etc.
ab+           // Match ab, abb, abbb, abbbb, etc.
```

Notice what a difference the parentheses make. Parentheses have a special role in forming *groups*. As with braces and the plus sign (+), parentheses are special characters; they have to be “escaped” to be rendered literally—that is, you have to use backslashes if you want to match actual parentheses in the target string.

You should now see why “[0-9]+” matches a string that consists of one or more digits. This pattern attempts to match a single digit and then says, “Match that one or more times.” Again, the plus sign is a pattern modifier, so it matches [0-9] one or more times *instead of* matching it just once, not one or more times *in addition to* matching it once (which would’ve meant a total of two or more times overall).

The following statements attempt to match this regular-expression string against a target string. In this context, *match* means that the target string must match the regular-expression string completely.

```
#include <regex>
#include <string>
#include <iostream>
. . .
```

```
std::regex  reg1("[0-9]+");
if (std::regex_match("123000", reg1)) {
     std::cout << "It's a match!" << std::endl;
}
```

You can test a series of strings this way:

```
using std::cout;
using std::endl;
using std::regex;

regex  reg1("[0-9]+");
string str1("123000");
string str2("123000.0");

bool b = regex_match(str1, reg1);
cout << str1 << (b ? " is " : " is not ");
cout << "a match." << endl;

b = regex_match(str2, reg1);
cout << str2 << (b ? " is " : " is not ");
cout << "a match." << endl;
```

These statements print out:

```
123000 is a match.
123000.0 is not a match.
```

The string “123000.0” does not result in a match because **regex_match** attempts to match the entire target string; if it cannot, it returns **false**. The **regex_search** function, in contrast, returns **true** if any substring matches. Therefore, the following function call returns **true**, because the substring consisting of the first six characters matches the pattern specified earlier for reg1.

```
std::regex_search("123000.0", reg1)
```

Generally speaking, every regular-expression operation begins by initializing a **regex** object with a pattern; this object can then be given as input to **regex_match** or **regex_search**. Creating a regex object builds a regular-expression engine, which is compiled at runtime (!), so for best performance, create as few new regular expression objects as you need to.

Here are some other useful patterns:

```
using std::regex;
regex reg2("[0-9]*");           // Match 0 or more digits.
regex reg3("(\\+|-)?[0-9]+");   // Match digit string with
                                //  optional + or - sign.
```

reg2 uses an asterisk (*) rather than a plus sign (+). The asterisk modifies the regular expression to mean, "Match zero or more copies of the preceding expression." Therefore, reg2 matches an empty string as well as a digit string.

reg3 matches a digit string with an optional sign. The "or" symbol (|) means match the expression on either side of this symbol:

```
"a|b"    // Match a or b but not both.
```

Putting "a|b" into a group (using parentheses) and then following it with a question mark (?), makes the entire group optional.

The following expression means, "Optionally match a plus sign or a minus sign, but not both."

```
"(\\+|-)?"
```

Because the plus sign (+) has special meaning, it must be "escaped" by using backslashes. More about that in the next section.

Note

There's a more concise way to write the expression in this case. Most symbols lose their special meaning inside brackets and do not need to be escaped. Even the minus sign (-) does not need to be escaped unless it occurs in between two other characters, indicating a run of characters (as in "[a-z]"). So the pattern just shown could be more concisely expressed as:

```
"[+-]?"
```

The limitation of a range, however, is that it is used just to match a single character, so the range syntax, [], is less general than "or" (|).

20.2 Dealing with Escape Sequences (\)

Escape sequences are a little tricky in C++ regular expressions, because they occur in two contexts.

- C++ assigns special meaning to the backslash within a string literal and requires it to be escaped to be read as an actual backslash: To represent a single backslash, it's necessary to place double backslashes (\\) in the source code. (Exception: Raw literals, supported by C++11, remove the need to escape characters.)
- The regular-expression interpreter also recognizes a backslash as the escape character. To render a special character literally, you must precede it with a backslash (\).

Consequently, if you want to render a special character literally, then, within a C++ literal string, you must precede the character with *two backslashes,* not just one.

For example, suppose you want to specify a pattern that matches an actual plus sign (+). The pattern is specified in source code this way:

```
std::regex  reg("\\+");
```

When the C++ compiler reads the literal, "\\+", it interprets \\ as an escape sequence that represents a single backslash. The actual string data that gets stored in memory is therefore:

```
\+
```

This is the string read by the regular-expression interpreter. It interprets "\+" as an actual plus sign (+).

Consider the following regular-expression pattern:

```
std::regex  reg("\\++");
```

Notice what's going on here: The first three characters (\\+) represent a literal plus sign (+). The fourth character (+) has its usual—and special—meaning; this second plus sign modifies the overall pattern to mean, "Match one or more copies of the preceding expression." The string as a whole therefore matches any of the following:

```
+
++
+++++
```

How do you represent a literal backslash, should you ever need to do that? That is, what is the regular-expression pattern that matches a target string consisting of one or more backslashes? The answer is that you need *four* backslashes.

```
using std::regex;
regex  reg("\\\\+");   // Matches one or more backslashes.
```

This regular-expression object, reg, would match any of the following:

```
str1[] = "\\"         // Represents "\".
str2[] = "\\\\"       // Represents "\\".
str3[] = "\\\\\\"     // Represents "\\\".
```

Note that if you use raw-string literals, supported by the C++11 specification, you don't have to deal with C literal-string escape conventions, so this example would be coded as:

```
regex  reg(R"\\+");    // Matches one or more backslashes.
str1[] = R"\"          // Represents "\".
str2[] = R"\\"         // Represents "\\".
str3[] = R"\\\"        // Represents "\\\".
```

The use of **R** does not change the format of the strings (which is still **const char***); it merely changes how literal text inside the quoted string is interpreted.

20.3 Constructing a RegEx String

The previous two sections provided an introduction to regular-expression patterns. The next several sections summarize the syntax rules, beginning with the syntax for matching individual characters.

This chapter adopts the default grammar used by the C++11 regular-expression library, which is a modified ECMAScript grammar. Although it's possible to use variations, the C++11 default is more versatile and expressive than the alternative grammars.

20.3.1 Matching Characters

The following special expressions match an individual character belonging to a group, such as letters or digits. This section also describes special conditions such as beginning-of-line or word boundary.

In the following list, a *range* may be a list of characters (not separated by spaces or commas, which themselves are characters). A *range* may optionally use a dash (minus sign) to indicate a run beginning with one character, up to and including another. Characters are ordered according to their underlying numeric (ASCII) value. For example, "[a-z]" matches all lowercase letters.

- `.`

  Matches any one character other than a newline. For example, the following pattern string matches almost any single character:

  `"."`

- **`[`*`range`*`]`**

  Matches any one character in the specified range. For example, the following pattern string matches any single letter in the range "a" to "m". It also matches "z".

  `"[a-mz]"`

  Most characters lose their special meaning inside the brackets. The minus sign gains special meaning to indicate a run of characters as in the example just shown, but only if it appears between two other characters inside the range. The following expression matches any one of the characters "+", "*", "/", or "-". None of these need to be escaped.

```
"[+*/-]"
```

- **[^*range*]**

  Matches any character *not* in the specified range. For example, the following pattern string matches any single character *other* than "a", "b", or "c":

  ```
  "[^abc]"
  ```

- **\n**

  Matches a newline. When using this in a C++ literal string meant to be part of a regular-expression pattern-matching string (as opposed to an actual embedded newline), remember that two backslashes must be used. For example:

  ```
  "\\n"
  ```

- **\t**

  Matches a tab character.

- **\f**

  Matches a form feed.

- **\r**

  Matches a carriage return.

- **\v**

  Matches a vertical tab.

- **\x*hh***

  Matches a character specified as a hexadecimal code. For example:

  ```
  "\\xf3"
  ```

- **\u*hhhh***

  Matches a Unicode character specified as a hexadecimal code. For example:

  ```
  "\\u02f3"
  ```

- **\d**

  Matches any digit character. This is equivalent to:

  ```
  [0-9]
  ```

- **\D**

  Matches any character other than a digit. This is equivalent to:

  ```
  [^0-9]
  ```

- **`\s`**

  Matches any whitespace character.

- **`\S`**

  Matches any character other than a whitespace character.

- **`\w`**

  Matches any digit, letter, or underscore.

- **`\W`**

  Matches any character other than a digit, letter, or underscore.

- **`\b`**

  Matches a word boundary. A word must begin or end at this position, or there is no match. Words are made up of alphanumeric characters and are delimited by whitespaces and punctuation. For example, the following string matches any word beginning with “c” and ending with “t”, such as “cat” or “containment”. It does not match “caution”.

  ```
  "\\bc[a-zA-Z]*t\\b"
  ```

- **`\B`**

  Not a word boundary. For example, the following pattern matches a portion of a word beginning with “a.” It will match “at” embedded in “cat”, but it will not match “at” if it occurs as a stand-alone word.

  ```
  "\\Ba[a-zA-Z]*"
  ```

- **`^`**

  Beginning of line: The next character is matched only if it is the first character in the text to be examined or occurs just after a newline.

  ```
  "^Barney"
  ```

- **`$`**

  End of line: The previous character matched (if any) must be the last character in the line of text.

20.3.2 Pattern Modifiers

Regular-expression pattern matching becomes more interesting when you modify a pattern to indicate possible repetitions. This feature, as much as anything else, makes the regular-expression technology a powerful and versatile tool for searching and replacing text.

In the following list, *expr* is an expression. For example, in the string “[0-9]+”, “[0-9]” is an expression and the + operator modifies its meaning.

An operator associates with the character closest to it, except where brackets or parentheses are used, in which case the operator refers to the whole range or group that precedes it.

- *`expr`*`*`

  Matches zero or more instances of *expr*. For example, the following string matches an empty string or a digit string:

  ```
  "[0-9]*"
  ```

- *`expr`*`+`

  Matches one or more instances of *expr*. For example, the following string matches a digit string of length one or greater.

  ```
  "[0-9]+"
  ```

- *`expr`*`?`

  Matches either one or zero instances of *expr*. The *expr* thereby becomes an optional item that can appear at most once. For example, the following string matches a minus sign or an empty string.

  ```
  "-?"
  ```

- *`expr1`*`|`*`expr2`*

  Matches *expr1* or *expr2*, but not both. For example, the following regular-expression string matches “aa” or “bb” but not “aabb”.

  ```
  "(aa)|(bb)"
  ```

  This expression can be made optional by placing it in a larger group and then using the ? operator. In that case, “aa” may appear, “bb” may appear, or they may both be omitted.

  ```
  "((aa)|(bb))?"
  ```

- *`expr`*`{`*`n`*`}`

  Matches exactly *n* instances of *expr*. For example, the following pattern string matches a target string containing exactly ten copies of capital “A”.

  ```
  "A{10}"
  ```

- *`expr`*`{`*`n`*`,}`

  Matches *n* or more instances of *expr*. For example, the following pattern string matches a target string consisting of three or more digits.

  ```
  "[0-9]{3,}"
  ```

- `expr{n,m}`

  Matches at least *n*, but no more than *m*, instances of *expr*. For example, the following pattern string matches a digit string no more than seven digits long.

  ```
  "[0-9]{1,7}"
  ```

- `(expr)`

  Forms a group. *expr* is considered as a unit when modified by other special characters, as in (*expr*)+, (*expr*)*, and so on. For example, the following pattern string matches "AbcAbcAbc" in the target string:

  ```
  "(Abc){3}"
  ```

  Another important effect of parentheses is that they cause the expression inside to be "tagged," as explained in the next section.

20.3.3 Recurring Groups

Much of the power of regular expressions comes from the ability to look for repetitions of a group. The syntax:

```
\n
```

refers to a previously tagged group. The expressions \1, \2, and \3 refer to the first three groups. Remember that C++ string literals use the backslash as an escape character, so the expressions "\1", "\2", and "\3" must be rendered as \\1, \\2, and \\3, and so on, in C++ source code (unless you're using raw string literals).

For example, the following expression—expressed as a string literal—matches aa, bb, and cc:

```
"(a|b|c)\\1"
```

This expression first matches a, b, or c. Whatever is matched is *tagged*. The regex pattern must then immediately match this tagged character again if it is to match the overall expression.

It will therefore match aa and bb, but not ab.

The next example is more practical: It finds a repeated word, in which a single space separates the two words:

```
"([A-Za-z]+) \\1"
```

This expression says, "Match a series of one or more letters. Tag the characters in this group. Then match a space. Finally, match an exact recurrence of the tagged characters." The following strings would therefore be matched:

```
"the the"
"Monday Monday"
"Rabbit Rabbit"
```

20.3.4 Character Classes

The C++11 grammar also provides a series of character classes that can be used to help specify a range. For example, the following expression specifies a range consisting of any letter:

```
[[:alpha:]]
```

This is equivalent to:

```
[A-Za-z]
```

The following expression specifies a range consisting of any letter or punctuation character:

```
[[:alpha:][:punct:]]
```

Descriptions of the character classes follow.

- **`[:alnum:]`**
  Any letter or digit.
- **`[:alpha:]`**
  Any letter.
- **`[:blank:]`**
  A space or tab character.
- **`[:cntrl:]`**
  Any control character. (These are not printable.)
- **`[:digit:]`**
  Any decimal digit.
- **`[:graph:]`**
  Any printable character that is not a whitespace.
- **`[:lower:]`**
  Any lowercase letter.
- **`[:print:]`**
  Any printable character, including whitespaces.

- **`[:punct:]`**

  Any punctuation character.

- **`[:space:]`**

  A whitespace character, such as a blank space, tab, or newline.

- **`[:upper:]`**

  Any uppercase letter.

- **`[:xdigit:]`**

  A hexadecimal digit: This includes digits, as well as uppercase and lowercase letters.

20.4 Matching and Searching Functions

This section summarizes the syntax for the matching and searching functions. Don't forget to include the <regex> header. Also, remember that regex symbols are part of the **std** namespace, so either include a **using** statement or identify each name with its **std** prefix.

```
#include <regex>
using std::regex;
```

Next, you need to specify a regular-expression pattern by creating a **regex** object:

```
regex  name(pattern_string [,flags])
```

This regex constructor includes an optional *flags* argument. The most useful flag is **regex_constants::icase**, which turns off case sensitivity.

regex objects are unusual in that they are compiled and built at runtime, not compile time. Consequently, you want to create as few **regex** objects as possible, because creating many such objects impacts runtime performance. You should make your **regex** objects global variables, or pass them by reference if you need to.

After constructing a **regex** object, you can perform matching and searching by calling the **regex_match** and **regex_search** functions. Each of these returns a Boolean value. The **regex_match** function returns **true** if the *target_string* matches the pattern stored in *regex_obj* exactly: That is, the entire *target_string* must match the pattern completely.

```
regex_match(target_string, regex_obj)
```

The **regex_search** function returns **true** if the target string contains any substring that matches the pattern stored in *regex_obj*.

regex_search(*target_string*, *regex_obj***)**

For example, consider the task of finding a repeated word in the sentence:

```
The the cow jumped over the the moon.
```

The following statements execute this search:

```
#include <regex>
#include <string>
#include <iostream>
using std::string;
using std::cout;
using std::endl;
. . .
std::regex reg1("([A-Za-z]+) \\1");
string target = "The the cow jumped over the the moon.";
if (std::regex_search(target, reg1)) {
     cout << "A repeated word was found." << endl;
}
```

The call to **regex_search** failed to find the first repeated-word occurrence ("The the") because the first word was capitalized and the second was not. That did not matter in this instance, because there was another repeated-word sequence ("the the"). However, sometimes you are interested in getting the position of the first match, so it can matter.

To find the position of the first substring found, it's necessary to include another argument:

regex_search(*target_string*, *match_info*, *regex_obj***)**

The *match_info* argument is an object of type **cmatch**, **smatch**, or **wmatch**, corresponding to the following formats: C-string, **string** object, and wide-character string. The format must match the type of *target_string*; in this case, the **string** class is used for the target string, so *match_info* must have type **smatch**.

For example:

```
std::smatch sm;
std::regex reg1("([A-Za-z]+) \\1");
std::string target="The the cow jumped over the the moon.";
bool b = std::regex_search(target, sm, reg1);
```

The *match_info* object (sm in this case) can be used to obtain information about the search, as follows:

```
match_obj.str()            // Return the matched string
match_obj.position()    // Return the position of the matched string
```

For example, the following call finds the position of the first repeated word:

```
std::smatch sm;
std::regex reg1("([A-Za-z]+) \\1");
std::string target="The the cow jumped over the the moon.";
bool b = std::regex_search(target, sm, reg1);
cout << "Match found at pos. " << sm.position() << endl;
cout << "Pattern found was: " << sm.str() << endl;
```

These statements print:

```
Match was found at pos. 24
Pattern found was: the the
```

Turning off case sensitivity causes a match to be found at position 0 instead.

```
std::regex reg1("([A-Za-z]+) \\1", regex_constants::icase);
```

You can also obtain information about groups—patterns enclosed in parentheses—within the matched string. This information only applies to groups within the *first* substring found; **regex_search** finds only one substring and then it stops searching. (The next section describes how to find multiple substrings.)

```
match_obj.str(n)        // Return nth group within the matched substring
match_obj.position(n)   // Return position of nth group
```

For example, you can use *match_object* (sm in this case) to get information on the group found *within* the first matched substring.

```
cout << "Text of sub-group: " << sm.str(1);
```

Assuming case sensitivity is turned off, this prints:

```
Text of sub-group: The
```

20.5 "Find All," or Iterative, Searches

When searching for substrings, you typically want to find all the matching substrings rather than just the first one. The easiest way to do this is to use an iterative search.

This technique involves creating two iterators: one that iterates through a target string and is associated with a **regex** object, and another that is simply an "end" condition.

```
sregex_iterator  iter_name(str_obj.begin(), str_obj.end(), regex_obj);
sregex_iterator  end_iter_name;
```

This second declaration—the one that creates *end_iter_name*—should strike you as something new: an uninitialized iterator that has a use. This is different from other STL containers, which require a call to their **end** function to get an end-position iterator. Not so with regex iterators: An uninitialized regex iterator automatically represents the ending position—one position past the end of the string.

The **sregex_iterator** type is an adapter that uses a template, **regex_iterator**, with the **string** class. You can build iterators upon other string types.

With these two declarations in place—providing an iterator and an end position—it's then an easy matter to iterate through all the substrings found. For example:

```
#include <regex>
#include <string>
using std::regex;
using std::sregex_iterator;
using std::string;

regex reg1("([A-Za-z]+) \\1", std::regex_constants::icase);
string target = "The the cow jumped over the the moon";
sregex_iterator it(target.begin(), target.end(), reg1);
sregex_iterator reg_end;
for (; it != reg_end; ++it) {
     std::cout << "Substring found: ";
     std::cout << it->str() << ", Position: ";
     std::cout << it->position() << std::endl;
}
```

These statements print:

```
Substring found: The the, Position: 0
Substring found: the the, Position: 24
```

This next example finds all words beginning with an uppercase or lowercase "B". Case sensitivity must be turned off in order to find "Barney" as well as "bat" and "big". In addition, the word-boundary character (\b) is used to ensure that the only patterns found are those in which the letter "B" comes at the beginning of the word.

```
regex reg2("\\bB[a-z]*", regex_constants::icase);
string bstr = "Barney goes up to bat with a big stick.";
sregex_iterator it(bstr.begin(), bstr.end(), reg2);
sregex_iterator reg_end;
for (; it != reg_end; ++it) {
     std::cout << "Substring found: ";
     std::cout << it->str() << ", Position: ";
     std::cout << it->position() << std::endl;
}
```

These statements print:

```
Substring found: Barney, Position: 0
Substring found: bat, Position: 18
Substring found: big, Position: 29
```

20.6 Replacing Text

One of the most powerful regular-expression capabilities is to selectively search-and-replace patterns within a string of text. Here's one possible use (out of zillions): to transform a target string by replacing each repeated pair of words with just one word.

For example, given this text:

```
The cow cow jumped over the the moon.
```

it would be useful to produce a string consisting of:

```
The cow jumped over the moon.
```

The **regex_replace** function performs this task by returning the transformed string. It has the following syntax:

`regex_replace(`*`target_string`*`, `*`regex_obj`*`, `*`replacement_pattern_str`***`);`**

The *replacement_pattern_str* is a string that can contain the following special sequences (in addition to ordinary characters).

- **`$&`**

  Refers to the entire matched string.

- **`$`***`n`*

  Refers to the nth group within the matched string. For example, "$1" refers to the first group of characters tagged by the regex object; "$2" refers to the second group of tagged characters (if there is one), and so on. The example that follows should clarify.

- **`$$`**

  A literal dollar sign ($).

The following declarations set up a search-and-replace designed to fix the repeated-word pattern, replacing it, where found, with one copy of the word.

```
using std::regex;
using std::regex_replace;
using std::string;
```

```
regex reg1("([A-Za-z]+) \\1");  // Find double word.
string replacement = "$1";      // Replace with one word.
```

With these objects defined, the following statements execute search-and-replace on the string shown earlier.

```
string target = "The cow cow jumped over the the moon.";
string result = regex_replace(target, reg1, replacement);
std::cout << result << std::endl;
```

The output is:

```
The cow jumped over the moon.
```

which is what we wanted.

Let's review how this works. When the text "cow cow" was matched by the regular-expression object, the first occurrence of "cow" was tagged because it matched the expression inside the parentheses: "([A-Za-z]+)". The rest of the expression, " \\1", indicated that the regex object then needed to match a space, followed by a recurrence of the tagged characters, to match the overall expression. Therefore, "cow" gets tagged and "cow cow" matches the entire regular expression.

The replacement pattern, "$1", causes the matched text—"cow cow"—to be replaced by "cow", the tagged group. Suppose the replacement pattern were "XX$1YY$1ZZ$1". Then the replacement text would have been "XXcowYYcowZZcow" and *that* would have replaced "cow cow".

Characters not matched by the regex object, reg1, are just copied into the result as they are. So, for example, the words "jumped over" are copied without being transformed.

Here's an example of another regex object and replacement-pattern string: When used with the call to **regex_replace** shown earlier, these result in the switching of two words separated by an ampersand (&). For example, "boy&girl" would be replaced by "girl&boy" and vice versa.

```
regex reg1("([A-Za-z]+)&([A-Za-z]+)");  // Find word&word
string replacement = "$2&$1";           // Switch order.
```

The **regex_replace** function is particularly convenient. It isn't necessary to iterate through the target string. Instead, **regex_replace** carries out replacements on all the substrings matching the pattern in the regex object, while leaving the rest of the text alone.

20.7 String Tokenizing

Although the functionality in the preceding sections can perform nearly any form of pattern matching, C++11 also provides string-tokenizing functionality that is a superior alternative to the C-library **strtok** function. Tokenization is the process of breaking a string into a series of individual words, or *tokens*.

To take advantage of this feature, use the following syntax, in which *str* represents a **string** object containing the target string:

```
sregex_token_iterator  iter_name(str.begin(), str.end(), regex_obj, -1);
sregex_token_iterator  end_iter_name;
```

As with **sregex_iterator**, **sregex_token_iterator** is an adapter built on top of the **string** class; you can use the underlying template, **regex_token_iterator**, with other kinds of strings.

sregex_token_iterator performs a range of operations, most of which are similar to what the standard iterator does, as described in Section 20.5, " "Find All," or Iterative Searches." Specifying -1 as the fourth argument makes the function skip over any patterns matching the *regex_obj*, causing the iterator to iterate through the tokens—which consist of text between each occurrence of the pattern.

For example, the following statements find each word, in which words are delimited by any series of spaces and/or commas.

```
#include <regex>
#include <string>
using std::regex;
using std::string;
using std::sregex_token_iterator;
. . .
// Delimiters are spaces (\s) and/or commas
regex re("[\\s,]+");
string s = "The White Rabbit,  is very,late.";
sregex_token_iterator it(s.begin(), s.end(), re, -1);
sregex_token_iterator reg_end;
for (; it != reg_end; ++it) {
     std::cout << it->str() << std::endl;
}
```

These statements, when executed, print the following, ignoring spaces and commas (except as to recognize them as delimiters):

```
The
White
```

```
Rabbit
is
very
late.
```

20.8 Catching RegEx Exceptions

Catching exceptions can be important when working with regular expressions, especially if you build a new regular-expression string at runtime or let the end user specify a pattern.

Remember that a regular expression object is compiled at runtime. If the pattern is ill-formed, the program throws an exception, causing abrupt termination unless the exception is caught. Catching the exception enables you to terminate more gracefully, or even—if you choose—continue execution after taking appropriate action (such as reporting the error to the user).

Regular-expression errors belong to the **regex_error** class, which is declared in the <regex> header and is part of the **std** namespace.

```
#include <regex>
using std::regex_error;
```

The **regex_error** class supports a **what** function, which returns a text string, and a **code** function, which returns an integer. The following example (which assumes the appropriate **#include** directives and **using** statements have been given) responds to a poorly formed **regex** object.

```
try {
     regex re("*\\bW[a-z]*");
     string s = "The White Rabbit is very late.";
     if (regex_search(s, re)) {
          cout << "Search string found." << endl;
     }
} catch (regex_error e) {
     cout << e.what() << endl;
     cout << "CODE IS: " << e.code() << endl;
}
```

When these statements are run, the program prints:

```
regex_error(error_badrepeat):
One of *?+{ was not preceded by a valid regular expression.
CODE IS: 10
```

The error is thrown as soon as there is an attempt to build a bad regular expression (because the regular-expression object, remember, is compiled at runtime).

```
regex re("*\\bW[a-z]*");  // Throws an exception!
```

Here you should be able to see the problem. The first use of the asterisk (*)—which means to repeat the preceding expression zero or more times—was not preceded by any expression; it was therefore not a meaningful use of regular-expression grammar. This is duly reported as a “badrepeat” error as long as exception handling is provided as just shown.

20.9 Sample App: RPN Calculator

In C++ *Without Fear,* 2nd Edition (Prentice Hall), I presented a Reverse Polish Notation (RPN) calculator as one of the more advanced examples. In this section, I present a superior version of that app.

An RPN calculator lets the user enter arbitrarily long arithmetic expressions in postfix notation. For example, to add 3 and 4, you specify not “3 + 4” but:

```
3 4 +
```

This might at first seem counterintuitive until you realize it’s an elegant notational system that does away with the need for parentheses. For example, the RPN expression:

```
3 4 + 10 1.5 + *
```

is equivalent to the following standard (infix) expression:

```
(3 + 4) * (10 + 1.5)
```

With RPN, an operator always applies to the expressions that precede it. In this case, the asterisk (*) applies to the expressions “3 4 +” and “10 1.5 +”, which produce 7 and 11.5, respectively. Multiplication is finally applied to produce 80.5. The RPN grammar can be summarized as:

expression <= *number*
expression <= *expression expression op*

Calculations: The stack mechanism, described in Section 16.3, “The stack Template,” is what powers this application. When the program reads a number, it pushes that number onto the stack. When the program reads an operator, it pops the top two values off the stack, performs a calculation, and pushes the result back onto the stack.

Lexical analysis: It's easy enough to interpret a line of input in which spaces separate operators as well as numbers. The more challenging problem is to recognize operators as both tokens *and* separators so that some of the spaces are optional. For example, it would be desirable to interpret:

```
3 44*5  1.2+/
```

as if it were written as:

```
3 44 * 5 1.2 + /
```

The **strtok** function is inadequate for this task. So is the **regex_token_iterator** function. The solution is to use a **regex_iterator** and search for sequences of characters that constitute either of the following:

- A number, consisting of consecutive digits with or without a fractional portion, such as "3", "44", or "100.507"
- Any of several operators: +, -, *, or /

With this approach, it's not necessary to have spaces on either side of an operator, although spaces are freely permitted. The following will work just fine:

```
3 4+ 1 2+*
```

The code for the application follows.

```
#include <iostream>
#include <string>
#include <cctype>
#include <regex>
#include <stack>

using std::cout;         // Alternatively, you can use
using std::cin;          //  using namespace std;
using std::endl;
using std::string;
using std::regex;
using std::sregex_iterator;
using std::stack;

void process_token(string s);
stack<double> st;

main() {
     string instr;
     string num_pattern("[0-9]+(\\.[0-9]*)?");
     string op_pattern("[+*/-]");
```

```
    regex re(num_pattern + "|" + op_pattern);
    while (true) {
        cout << "Enter expression (or ENTER to exit): ";
        getline(cin, instr);
        if (instr.length() == 0) { break; }
        sregex_iterator it(instr.begin(), instr.end(), re);
        sregex_iterator it_end;
        for (;it != it_end; ++it) {
             process_token(it->str());
        }
        if (!st.empty()) {
             cout << "The value is: " << st.top() << endl;
        }
    };
    return 0;
}

void process_token(string s) {
    // If s contains any char that is NOT an op,
    //  consider it a number by default.
    if (s.find_first_not_of("+*/-") != s.npos) {
         st.push(atof(s.c_str()));
    } else {
         double op2 = st.top(); st.pop();
         double op1 = st.top(); st.pop();
         switch(s[0]) {
         case '+': st.push(op1 + op2); break;
         case '-': st.push(op1 - op2); break;
         case '*': st.push(op1 * op2); break;
         case '/': st.push(op1 / op2); break;
         }
    }
}
```

This program illustrates a couple of important features of regular-expression grammar. First, as mentioned earlier, special characters such as “*” and “+” do not need to be escaped when they occur inside brackets (although brackets themselves would need to be escaped to be treated literally, of course). Also, the minus sign (-) does not need to be escaped, because it does not occur between two other characters.

```
    string op_pattern("[+*/-]");
```

Another interesting feature is that order is potentially significant. The **regex** object in this application searches for a digit string first and *then* for an operator. This order makes Exercise 2 possible.

Exercises

1. The following string pattern almost works but fails to separate numbers from operators in some cases. (Fortunately, the sample application contains the correct pattern.) Without looking at the application, determine what's wrong with the following regular expression:

   ```
   [0-9]+(.[0-9]*)?
   ```

2. Add support for a leading minus sign so that "-100", for example, is interpreted as a negative number. Ambiguities arise if the minus sign (-) is simply a unary operator in addition to being a binary operator (which it already is). But if you make the minus sign an optional part of a digit string, the user can add spaces for clarity as needed. Questions: Why does this exercise depend on the **regex** object looking for a digit string first and operators second? What would happen if it looked for operators first?
3. In the sample application, numbers of the form "33" and "33.03" are both accepted; "0.333" and "3." are also. However, strings with no integer portion and no leading zero—such as ".333"—are not accepted. Revise the expression for number_pattern so that it accepts digit strings such as ".333" in addition to the other formats.
4. Extend the floating-point format even further, to accept the following scientific-notation formats:

   digits`E`*digits*
   digits.*digits*`E`*digits*

5. Each time an operator is processed, the application assumes there are at least two values on the stack. If there are less than two, the user has entered too many operators. Revise the application to handle this situation by reporting the error and then continuing rather than incorrectly popping the stack (which causes program failure if you let it happen). Hint: Check the size of the stack.
6. Add other operators, such as a binary ^ operator, to perform exponentiation: "2 3 ^" should produce 2 to the 3rd power. Also add the tilde (~) as a unary operator to perform arithmetic negation (multiplying by -1). Finally, add the == and != operators to perform test-for-equality and test-for-inequality. These operators, which are Boolean, should each return either 1 or 0.
7. As a *really* advanced exercise (not for the faint of heart), enable the RPN calculator to read symbols and assign values by using a single equal sign (=) as an assignment operator. Build a symbol table by using the **map** template. Whenever a symbol—that is, a name—appears in any context other than the left side of an assignment, look up its value in the map.

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