Learning Perl the Hard Way

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Chapter 1

Arrays and Scalars

This chapter presents two of the built-in types, arrays and scalars. A scalar is a value that Perl treats as a single unit, like a number or a word. An array is an ordered collection of elements, where the elements are scalars.

This chapter describes the statements and operators you need to read command-line arguments, define and invoke subroutines, parse parameters, and read the contents of files. The chapter ends with a short program that demonstrates these features.

In addition, the chapter introduces an important concept in Perl: context.

1.1 Echo

The UNIX utility called `echo` takes any number of command-line arguments and prints them. Here is a perl program that does almost the same thing:

```
print @ARGV;
```

The program contains one print statement. Like all statements, it ends with a semi-colon. Like all generalizations, the previous sentence is false. This is the first of many times in this book when I will skip over something complicated and try to give you a simple version to get you started. If the details are important later, we'll get back to them.

The operand of the print operator is `@ARGV`. The "at" symbol indicates that `@ARGV` is an array variable; in fact, it is a built-in variable that refers to an array of strings that contains whatever command-line arguments are provided when the program executes.

There are several ways to execute a Perl program, but the most common is to put a "shebang" line at the beginning that tells the shell where to find the program called `perl` that compiles and executes Perl programs. On my system, I typed `whereis perl` and found it in `/usr/bin`, hence:

```
#!/usr/bin/perl
print @ARGV;
```

I put those lines in a file named `echo.pl`, because files that contain Perl programs usually have the extension `pl`. I used the command

```
$ chmod +ox echo.pl
```

to tell my system that `echo.pl` is an executable file, so now I can execute the program like this:

```
$ ./echo.pl
```

Now would be a good time to put down the book and figure out how to execute a Perl program on your system. When you get back, try something like this:

```
$ ./echo.pl command line arguments
commandlinearguments$
```

Sure enough, it prints the arguments you provide on the command line, although there are no spaces between words and no newline at the end of the line (which is why the `$` prompt appears on the same line).

We can solve these problems using the double-quote operator and the
`n` sequence.

```
print "@ARGV\n";
```

It might be tempting to think that the argument here is a string, but it is more accurate to say that it is an expression that, when evaluated, yields a string. When Perl evaluates a double-quoted expression, it performs variable interpolation and backslash interpolation.

Variable interpolation: When the name of a variable appears in double quotes, it is replaced by the value of the variable.

Backslash interpolation: When a sequence beginning with a backslash ( ) appears in double quotes, it is replaced with the character specified by the sequence.

In this case, the
`n` sequence is replaced with a single newline character.

Now when you run the program, it prints the arguments as they appear on the command line.

```
$ ./echo.pl command line arguments
command line arguments
$
```

Since the output ends with a newline, the prompt appears at the beginning of the next line. But why is Perl putting spaces between the words now? The reason is:

The way a variable is evaluated depends on context!

In this case, the variable appears in double quotes, so it is evaluated in **interpolative context**. It is an array variable, and in interpolative context, the elements of the array are joined using the separator specified by the built-in variable `$"`. The default value is a space.

1.2 Errors

What could possibly go wrong? Only three things:

Compile-time error: Perl compiles the entire program before it starts execution. If there is a syntax error anywhere in the program, the compiler prints an error message and stops without attempting to run the program.

Run-time error: If the program compiles successfully, it will start executing, but if anything goes wrong during execution, the run-time system prints an error message and stops the program.

Semantic error: In some cases, the program compiles and runs without any errors, but it doesn't do what the programmer intended. Of course, only the programmer knows what was intended, so semantic errors are in the eye of the beholder.

To see an example of a compile-time error, try spelling `print` wrong. When you try to run the program, you should get a compiler message like this:

```
String found where operator expected at ./echo.pl line 3,
near "prin "@ARGV\n""
        (Do you need to predeclare prin?)
syntax error at ./echo.pl line 3, near "prin "@ARGV\n""
Execution of ./echo.pl aborted due to compilation errors.
```

The message includes a lot of information, but some of it is difficult to interpret, especially when you are not familiar with Perl. As you are experimenting with a new language, I suggest that you make deliberate errors in order to get familiar with the most common error messages.

As a second example, try misspelling the name of a variable. This program:

```
print "@ARG\n";
```

yields this output:

```
$ ./echo.pl command line arguments

$
```

Since there is no variable named `@ARG`, Perl gives it the default value, which is the empty list. In effect, Perl ignores what is almost certainly an error and tries to run the program anyway. This sort of behavior is occasionally helpful, but normally we would like the compiler to help us find errors, not obscure them. We can use the `strict` pragma to change the compiler's behavior.

A pragma is a module that controls the behavior of Perl. To use the `strict` pragma, add the following line to your program:

```
use strict;
```

Now if you misspell the name of a variable, you get something like this:

```
Global symbol "@ARG" requires explicit package name.
```

Like many compiler messages, this one is misleading, but it contains hints about where the problem is, if nothing else.

1.3 Subroutines

If you have written programs longer than one hundred lines or so, I don't need to tell you how important it is to organize programs into subroutines. But for some reason, many Perl programmers seem to be allergic to them.

Well, different authors will recommend different styles, but I tend to use a lot of subroutines. In fact, when I start a new project, I usually write a subroutine with the same name as the program, and start the program by invoking it.

```
sub echo {
    print "@_\n";
}
echo @ARGV
```

This program does the same thing as the previous one; it's just more complicated.

All subroutine declarations start with `sub` followed by the name of the subroutine and the body. The body of the subroutine is a **block** of statements enclosed in squiggly-braces. In this case, the block contains a single statement.

The variable `@_` is a built-in variable that refers to the array of values the subroutine got as parameters.

1.4 Local variables

The keyword `my` creates a new local variable. The following subroutine creates a local variable named `params` and assigns a copy of the parameters to it.

```
sub echo {
    my @params = @_;
    print "@params\n";
}
```

If you leave out the word `my`, Perl assumes that you are creating a global variable. If you are using the `strict` pragma, it will complain. Try it so you will know what the error message looks like.

1.5 Array elements

To access the elements of an array, use the bracket operator:

```
    print "$params[0] $params[2]\n";
```

The numbers in brackets are indices. This statement prints the element of `@param` with the index 0 and the element with index 2. The dollar sign indicates that the elements of the array are **scalar** values.

A scalar is a simple value that is treated as a unit with no parts, as opposed to array values, which are composed of elements. There are three types of scalar

values: numbers, strings, and references. In this case, the elements of the array are strings.

To store a scalar value, you have to use a scalar variable.

```
my $word = $params[0];
print "$word\n";
```

The dollar sign at the beginning of `$word` indicates that it is a scalar variable.

Since the name of the array is `@params`, it is tempting to write something like

```
# the following statement is wrong
my $word = @params[0];
```

The first line of this example is a comment. Comments begin with the hash character (`#`) and end at the end of the line.

As the comment indicates, the second line of the example is not correct, but as usual Perl tries to execute it anyway. As it happens, the result is correct, so it would be easy to miss the error. Again, there is a pragma that modifies Perl's behavior so that it checks for things like this. If you add the following line to the program:

```
use warnings;
```

you get a warning like this:

```
Scalar value @params[0] better written as $params[0].
```

While you are learning Perl, it is a good idea to use `strict` and `warnings` to help you catch errors. Later, when you are working on bigger programs, it is a good idea to use `strict` and `warnings` to enforce good programming practice. In other words, you should always use them.

You can get more than one element at a time from an array by putting a list of indices in brackets. The following program creates an array variable named `@words` and assigns to it a new array that contains elements 0 and 2 from `@params`.

```
my @words = @params[0, 2];
print "@words\n";
```

The new array is called a **slice**.

1.6 Arrays and scalars

So far, we have seen two of Perl's built-in types, arrays and scalars. Array variables begin with `@` and scalar variables begin with `$`. In many cases, expressions that yield arrays begin with `@` and expressions that yield scalars begin with `$`. But not always. Remember:

The way an expression is evaluated depends on context!

In an assignment statement, the left side determines the context. If the left side is a scalar, the right side is evaluated in **scalar context**. If the left side is an array, the right side is evaluated in **list context**.

If an array is evaluated in list context, it yields the number of elements in the array. The following program

```
my $word = @params;
print "$word\n";
```

prints the number of parameters. I will leave it up to you to see what happens if you evaluate a scalar in a list context.

1.7 List literals

One way to assign a value to an array variable is to use a list literal. A list literal is an expression that yields a list value. Here is the standard list example.

```
my @list = (1, 2, 3);
print "@list\n";
```

Most of the time, you can pretend that lists and arrays are the same thing. There are some differences, but for now the only one we are likely to run into is this: when you evaluate a list in a scalar context, you get the last element of the list. The following program prints `3`.

```
my $scalar = (1, 2, 3);
print "$scalar\n";
```

But when you assign a list to an array variable, the result is an array value. So the following program prints the length of the list, which is `3`.

```
my @list = (1, 2, 3);
my $scalar = @list;
print "$scalar\n";
```

The difference is subtle.

1.8 List assignment

When a list of variables appears on the left side of an assignment, Perl performs list assignment. The right side is evaluated in list context, and then the first element of the result is assigned to the first variable, the second element to the second variable, and so on.

A common use of this feature is to assign values from a parameter list to local variables.

The following subroutine assigns the first parameter to `p1`, the second to `p2`, and a list of the remaining parameters to `@params`.

```
sub echo {
    my ($p1, $p2, @params) = @_;
    print "$p1 $p2 @params\n";
}
```

The argument of `print` is a double-quoted expression that uses variable interpolation to display the values of the parameters. This sort of print statement is often useful for debugging. Whenever there is an error in a subroutine, I start by printing the values of the parameters.

1.9 The `shift` operator

Another way to do the same thing (because in Perl there's always another way to do the same thing) is to use the `shift` operator.

`shift` takes an array as an argument and does two things: it remove the first element of the list and returns the value it removed. Like many operators, `shift` has both a **side effect** (modifying the array) and a **return value** (the result of the operation).

The following subroutine is the same as the previous one:

```
sub echo {
    my $p1 = shift @_;
    my $p2 = shift @_;
    print "$p1 $p2 @_\n";
}
```

If you invoke `shift` without an argument, is uses `@_` by default. In this example, it is possible (and common) to omit the argument.

1.10 File handles

To read the contents of a file, you have to use the `open` operator to get a **file handle**, and then use the file handle to read lines.

The operand of `open` is a list of two terms: an arbitrary name for the file handle, and the name of the file you want to open. The name of the file I want to open is `/usr/share/dict/words`, which contains a long list of English words.

```
open FILE, "/usr/share/dict/words";
```

In this case, the identifier `FILE` is global. An alternative is to create a local variable that contains an **indirect file handle**.

```
open my $fh, "/usr/share/dict/words";
```

By convention, the name of a global variable is all capital, and the name of a local variable is lower case. In either case, we can use the angle operator to read a line from the file:

```
my $first = <FILE>;
my $first = <$fh>;
```

To be more precise, I should say that *in a scalar context*, the angle operator reads one line. What do you think it does in a list context?

When we get to the end of the file, the angle operator returns `undef`, which is a special value Perl uses for undefined variables, and for unusual conditions like the end of a file. Inside a `while` loop, `undef` is considered a false **truth value**, so it is common to use the angle operator in a loop like this:

```
    while (my $line = <FILE>) {
        print $line;
    }
```

1.11 cat

The UNIX `cat` utility takes a list of file names as command-line arguments, and prints the contents of the files. Here is a Perl program that does pretty much the same thing.

```
use strict;
use warnings;

sub print_file {
    my $file = shift;
    open FILE, $file;
    while (my $line = <FILE>) {
        print $line;
    }
}

sub cat {
    while (my $file = shift) {
        print_file $file;
    }
}

cat @ARGV;
```

There are two subroutines here, `print_file` and `cat`. The last line of the program invokes `cat`, passing the command-line arguments as parameters.

`cat` uses the `shift` operator inside a `while` statement in order to iterate through the list of file names. When the list is empty, `shift` returns `undef` and the loop terminates.

Each time through the loop, `cat` invokes `print_file`, which opens the file and then uses a `while` loop to print the contents.

Notice that cat and print_file both have local variables named $file. Naturally, there is no conflict between local variables in different subroutines.

The definition of a subroutine has to appear before it is invoked. If you type in this program (and you should), try rearranging the order of the subroutines and see what error messages you get.

1.12 foreach and @_

In the previous section, I used the shift operator and a while loop to iterate through the parameter list. A more common way to do the same thing is to use a foreach statement.

```
# the loop from cat
foreach my $file (@_) {
    print_file $file;
}
```

When a foreach statement is executed, the expression in parentheses is evaluated once, in list context. Then the first element of the list is assigned to the named variable ($file) and the body of the loop is executed. The body of the loop is executed once for each element of the list, in order.

If you don't provide a loop variable, Perl uses $_ as a default. So we could write the same loop like this:

```
# the loop from cat
foreach (@_) {
    print_file $_;
}
```

When the angle operator appears in a while loop, it also uses $_ as a default loop variable, so we could write the loop in print_file like this:

```
# the loop from print_file
while (<FILE>) {
    print $_;
}
```

Using the default loop variable has one advantage and one disadvantage. The advantage is that many of the built-in operators use $_ as a default parameter, so you can leave it out:

```
# the loop from print_file
while (<FILE>) {
    print;
}
```

The disadvantage is that $_ is global, so changing it it one subroutine affects other parts of the program. For example, try printing the value of $_ in cat, like this:

```
# the loop from cat
foreach (@_) {
    print_file $_;
    print $_;
}
```

After `print_line` executes, the value of `$_` is `undef`, because that is the terminating condition of the loop in `print_line`.

In this example, it is probably better to use explicit, local loop variables. Why? Because the name of the variable contains useful documentation. In `cat`, it is clear that we are iterating over a list of files, and in `print_file` it is clear that we are iterating over the lines of the file. Using the default loop variable is more concise, but it obscures the function of the program.

1.13 Exercises

Exercise 1.1 The `glob` operator takes a pattern as an argument and returns a list of all the files that match the given pattern. A common use of `glob` is to list the files in a directory.

```
my @files = glob "$dir/*";
```

The pattern `$dir/*` means "all the files in the directory whose name is stored in `$dir`". See the documentation of `glob` for examples of other patterns.

Write a subroutine called `print_dir` that takes the name of a directory as a parameter and that prints the file in that directory, one per line.

Exercise 1.2 Modify the previous subroutine so that instead of printing the name of the file, it prints the contents of the file, using `print_file`.

Exercise 1.3 The operator `-d` tests whether a given file is a directory (as opposed to a plain file). The following example prints "directory!" if the variable `$file` contains the name of a directory.

```
if (-d $file) {
    print "directory!";
}
```

Modify `cat.pl` so that if any of the command line arguments are directories, it invokes `print_dir` to print the contents of the files in the directory.

Chapter 2

Regular expressions

2.1 Pattern matching

The pattern binding operator (`=~`) compares a string on the left to a pattern on the right and returns true if the string matches the pattern. For example, if the pattern is a sequence of characters, the the string matches if it contains the sequence.

```
if ($line =~ "abc") { print $line; }
```

In my dictionary, the only word that contains this pattern is "Babcock".

More often, the pattern on the right side is a match pattern, which looks like this: `m/abc/`. The pattern between the slashes can be any **regular expression**, which means that in addition to simple characters, it can also contain **metacharacters** with special meanings. A common metacharacter is `.`, which looks like a period, but is actually a wild card that can match any character.

For example, the regular expression `pa..u.e` matches any string that contains the characters `pa` and then exactly two characters, and then `u` and then exactly one character, and then `e`. In my dictionary, four words fit the description: "departure", "departures", "pasture", and "pastures".

The following subroutine takes two parameters, a pattern and a file. It reads each line from the file and prints the ones that match the pattern. This sort of thing is very useful for cheating at crossword puzzles.

```
sub grep_file {
    my $pattern = shift;
    my $file = shift;
    open FILE, $file;

    while (my $line = <FILE>) {
        if ($line =~ m/$pattern/) { print $line }
    }
}
```

I called this subroutine `grep_file` after the UNIX utility `grep`, which does almost the same thing.

In passing, notice that the last statement in a block doesn't need a semi-colon.

Exercise 2.1 Write a program called `grep.pl` that takes a pattern and a list of files as command line arguments, and that traverses each file printing lines that match the pattern. Warning: in this case it is not a good idea to create a subroutine named `grep` because there is already a function named `grep`. Try it, so you will know what the error message looks like, then choose a different name.

2.2 Anchors

Although the previous program is useful for cheating at crossword puzzles, we can make it better with anchors. Anchors allow you to specify where in the line the pattern has to appear.

For example, imagine that the clue is "Grazing place," and you have filled in the following letters: p, blank, blank, blank, u, blank, e. If you seach the dictionary using the pattern `p...u.e`, you get 57 words, including the surprising ''Winnipesaukee".

You can narrow the search using the `^` metacharacter, which means that the pattern has to begin at the beginning of the line. Using the pattern `^p...u.e`, we narrow the search to only 38 words, including "procurements" and "protuberant".

Again, we can narrow the search using the `$` metacharacter, which means that the pattern has to end at the end of the line. With the pattern `^p...u.e$`, we get only 12 words, of which only one means anything line "Grazing place". The rejects include "perjure" and "profuse".

2.3 Quantifiers

A **quantifier** is a part of a regular expression that controls how many times a sequence must appear. For example, the quantifier `{2}` means that the pattern must appear twice. It is, however, a little tricky to use, because it applies to a part of a pattern called an **atom**.

A character in a pattern is an atom, and so is a sequence of characters in parentheses. So the pattern `ab{2}` matches any word with a `a` followed by two `b`s, but the pattern `(ba){2}` requires the sequence `ba` to be repeated twice, as in the capital of Swaziland, which is Mbabane. The pattern `(.es.){3}` matches any word where the pattern `.es.` appears three times. There's only one in my dictionary: "restlessness".

The `?` quantifier specifies that an atom is optional; that is, it may appear 0 or 1 times. So the pattern `(un)?usual` matches both "usual" and "unusual".

Similarly, the `+` quantifier means that an atom can appear one or more times, and the `*` quantifier means that an atom can appear any number of times, including 0.

So far, I have been talking about regular expressions in terms of pattern matching. But there is another way to think about them: a regular expression is a way to denote a set of strings. In the simplest example, the regular expression `abc` represents the set that contains one string: `abc`. With quantifiers, the sets are more interesting. For example, the regular expression `a+` represents the set that contains `a`, `aa`, `aaa`, `aaaa`, and so on. It happens to be an infinite set, so it is convenient that we can represent it so concisely.

The expressions `a+` and `a*` almost represent the same set. The difference is that `a*` also contains the empty string.

Exercise 2.2 Write a regular expression that matches any word that starts with `pre` and ends in `al`; for example, "prejudicial" and "prenatal."

2.4 Alternation

The `|` metacharacter is like the conjunction "or"; it means either the previous atom or the next atom. So the regular expression `Nina|Pinta|Santa Maria` represents a set containing three strings: the names of Columbus's ships. Of the three, only Nina appears in my dictionary.

The expression `^(un|in)` matches any word that begins with either `un` or `in`.

If you find yourself conjoining a set of characters, like `a|b|c|d|e`, there is an easier way. The bracket metacharacters define a **character class**, which matches any single character in the set. So the expression `^[abcde]` matches any word that starts with one of the letters in brackets, and `^[abcde]+$` matches any word that contains only those characters, from start to finish, like "acceded". What set of five letters do you think yields the most words? I don't know the answer, but the best I found was `[eastr]`, which matches 133 words. What set of five letters yields the longest word? Again, I don't know the answer, but the best I could do was `[nesit]`, which includes "intensities".

Inside brackets, the hyphen metacharacter specifies a range of characters, so `[1-5]` matches the digits from `1` to `5`, and `[a-emnx-z]` is equivalent to `[abcdemnxyz]`.

Also inside brackets, the carot metacharacter negates the character class, so `[^0-9]` matches anything that is *not* a digit, and `^[^-]` matches anything that does not start with a hyphen.

Several character classes are predefined, and can be specified with backslash sequences like `\d`, which matches any digit. It is equivalent to `[0-9]`. Similarly `\s` matches any whitespace character (space, tab, newline, return, form feed), and `\w` matches a so-called "word character" (upper or lower case letter, digit, and, of course, underscore).

Exercise 2.3

- Find all the words that begin with `a|b` and end with `a|b`. The list should include "adverb" and "balalaika".
- Find all the words that either start and end with `a` or start and end with `b`. The list should include "alfalfa" and "bathtub", but not "absorb" or "bursa".
- Find all the words that begin with `un` or `in` and have exactly 17 letters.
- Find all the words that begin with `un` or `in` or `non` and have more than 17 letters.

2.5 Capture sequences

In a regular expression, parentheses do double-duty. As we have already seen, they group a sequence of characters into an atom so that, for example, a quantifier can apply to a sequence rather than a single letter. In addition, they indicate a part of the matching string that should be **captured**; that is, stored for later use.

For example, the pattern `http:(.*)` matches any URL that begins with `http:`, but it also saves the rest of the URL in the variable named `$1`. The following fragment checks a line for a URL and then prints everything that appears after `http:`.

```
my $pattern = "http:(.*)";
if ($line =~ m/$pattern/) { print "$1\n" }
```

If we are also interested in URLs that use `ftp`, we could write something like this:

```
my $pattern = "(ftp|http):(.*)";
if ($line =~ m/$pattern/) { print "$1, $2\n" }
```

Since there are two sequences in parentheses, the match creates two variables, `$1` and `$2`. These variables are called **backreferences**, and the strings they refer to are **captured strings**.

Capture sequences can be nested. For example, the regular expression `((ftp|http):(.*))` creates three variables: `$1` corresponds the outermost capture sequence, which yields the entire matching string; `$2` and `$3` correspond to the two nested sequences.

2.6 Minimal matching

If we extend the previous example, we encounter a property of regular expressions that is often problematic: quantifiers are greedy. Let's say we want to parse a URL like `http://www.gnu.org/philosophy/free-sw.html` and separate the machine name (`www.gnu.org`) from the file name (`philosophy/free-sw.html`). We might try something like this:

```
my $pattern = "(ftp|http)://(.*)/(.*)";
if ($line =~ m/$pattern/) { print "$1, $2, $3\n" }
```

But the result would be this:

```
http, www.gnu.org/philosophy, free-sw.html
```

The first quantifier (`.*`) performed a **maximal match**, grabbing not only the machine name, but also the first part of the file name. What we intended was a **minimal match**, which would stop at the *first* slash character.

We can change the behavior of the quantifiers by adding a question mark. The pattern `(ftp|http)://(.*?)/(.*)` does what we wanted. The quantifiers `*?`, `+?`, and `??` are the same as `*`, `+`, and `?`, except that they perform minimal matching.

2.7 Extended patterns

As regular expressions get longer, they get harder to read and debug. In the previous examples, I have tried to help by assigning the pattern to a variable and then using the variable inside the match operator `m//`. But that only gets you so far.

An alternative is to use the extended pattern format, which looks like this:

```
if ($line =~ m{
                    (ftp|http)  # protocol
                    ://
                    (.*?)       # machine name (minimal)
                    /
                    (.*)        # file name
                }x
   )
{ print "$1, $2, $3\n" }
```

The pattern begins with `m{` and ends with `}x`. The `x` indicates extended format; it is one of several modifiers that can appear at the end of a regular expression.

The rest of the statement is standard, except that the arrangement of the statements and punctuation is unusual.

The most important features of the extended format are the use of whitespace and comments, both of which make the expression easier to read and debug.

2.8 Some operators

Perl provides a set of operators that might be best described as a superset of the C operators. The mathematical operators `+`, `-`, `*` and `/` have their usual meanings, and `%` is the modulus operator. In addition, `**` performs exponentiation.

The comparison operators `>`, `<`, `==`, `>=`, `<=` and `!=` perform *numerical* comparisons, but the operators `gt`, `lt`, `eq`, `ge`, `le` and `ne` perform *string* comparison. In both cases, Perl converts the operands to the appropriate types automatically. So the expression `10 lt 2` performs string comparison even though both operands are numbers, and the result is true.

`<=>` is called the "spaceship" operator. Its value is 1 if the left operand is numerically bigger, -1 if the right operand is bigger, and 0 if they are equal.

There are two sets of logical operators: `&&` is the same as `and`, and `||` is the same as `or`. Actually, there is one difference. The textual operators have lower precedence than the corresponding symbolic operators.

2.9 Prefix operators

We have already used several prefix operators, including `print`, `shift`, and `open`. These operators are followed by a list of operands, usually separated by commas. The operands are evaluated in list context, and then "flattened" into a single list.

There is an alternative syntax for a prefix operator that makes it behave like a C function call. For example, the following pairs of statements are equivalent:

```
print $1, $2;
print($1, $2);
shift @_;
shift(@_);
open FILE, $file;
open(FILE, $file);
```

In a sense, the parentheses are optional, but there is a little more to it than that, because the two syntaxes have different precedence. Normally that wouldn't matter much, except that there is a common idiom for error-handling that looks like this:

```
open FILE, $file or die "couldn't open $file\n";
```

The `die` operator prints its operands and then ends the program. The `or` operator performs **short circuit evaluation**, which means that it only evaluates as much of the expression as necessary, reading from right to left.

If the `open` succeeds, it returns a true value, so the `or` operator stops without executing `die` (because `true or x` is always true, no matter what `x` is).

Since `or` and `||` are equivalent, you might assume that it would be equally correct to write

```
open FILE, $file || die "couldn't open $file\n";
```

Unfortunately, because `||` has higher priority than `or`, this expression computes `$file || die "couldn't open $file\n"` first, which yields the value of `$file`, so `die` never executes, even if the file doesn't exist.

One way to avoid this problem is to use `or`. Another way is to use the function call syntax for `open`. The following works because function call syntax is evaluated in the order you would expect.

```
open(FILE, $file) || die "couldn't open $file\n";
```

While we are at it, I should mention that there are two special variables that can generate more helpful error messages.

```
die "$0: Couldn't open $file: $!\n"
```

`$0` contains the name of the program that is running, and `$!` contains a textual description of the most recent error message. This idiom is so common that it is a good idea to encapsulate it in a subroutine:

```
sub croak { die "$0: @_: $!\n" }
```

I borrowed the name `croak` from *Programming Perl*, by Wall, Christiansen and Orwant.

2.10 Subroutine semantics

In the previous chapter I said that the special name `@_` in a subroutine refers to the list of parameters. To make that statement more precise, I should say that the elements of the parameter list are **aliases** for the scalars provided as arguments. An alias is an alternative way to refer to a variable. In other words, `@_` can be used to access and modify variables that are used as arguments.

For example, `swap` takes two parameters and swaps their values:

```
sub swap {
    ($_[0], $_[1]) = ($_[1], $_[0]);
}
```

In a list assignment, the right side is evaluated before any of the assignments are performed, so there is no need for a temporary variable to perform the swap.

The following code tests `swap`:

```
my $one = 1;
my $two = 2;
swap($one, $two);
print "$one, $two\n",
```

Sure enough, the output is `2, 1`. Since `swap` attempts to modify its parameters, it is illegal to invoke it with constant values. The expression `swap(1,2)` yields:

```
Modification of a read-only value attempted in ./swap.pl
```

On the other hand, we can invoke it with a list:

```
my @list = (1, 2);
swap(@list);
print "@list\n";
```

When a list appears as an argument, it is "flattened"; that is; the elements of the list are added to the parameter list. So the following code *does not* swap two lists:

```
my @list1 = (1, 2);
my @list2 = (3, 4);
swap(@list1, @list2);
print "@list1 @list2\n";
```

Instead, `swap` gets a list of four scalars as parameters, and it swaps the first two. The output is `2 1 3 4`.

2.11 Exercises

Exercise 2.4 In a regular expression, the backslash sequence `\1` refers to the first (prior) capture sequence in the same expression. As you might guess, `\2` refers to the second sequence, and so on.

Write a regular expression that matches all lines that begin and end with the same character.

Exercise 2.5

Chapter 3

Hashes

3.1 Stack operators

As a simple implementation of a stack, you can use the `push` and `pop` operators on an array. `push` adds an element to the end of an array; `pop` removes and returns the last element.

```
my @list = (1, 2);
push @list, 3;
```

At this point, `@list` contains `1 2 3`.

```
my $elt = pop @list;
```

At this point, `$elt` contains `3` and `@list` is back to `1 2`.

When we are using a list as a stack, the names `push` and `pop` are appropriate. For example, one use of a stack is to reverse the elements of a list. The following subroutine takes a list as a parameter and returns a new list with the same elements in reverse order.

```
sub rev {
    my @stack;
    foreach (@_) { push @stack, $_; }

    my @list;
    while (my $elt = pop @stack) {
        push @list, $elt;
    }
    return @list;
}
```

The first loop traverses the parameter list and pops each element onto a local stack. The second loop pops the elements off `stack` and adds them to `list`, which is the return value.

Exercise 3.1 Perl also provides an operator named `reverse` that does almost the same thing as `rev`, except that it modifies the parameter list rather than creating a new one. Modify `rev` so that it works the same way.

The point of this exercise is just to demonstrate the stack operators. If you really had to write your own version of `reverse`, you would probably skip the stack and swap the elements in place.

```
sub rev3 {
    for (my $i = 0; $i < @_/2; $i++) {
        swap ($_[$i], $_[-$i-1]);
    }
    return @_;
}
```

This subroutine demonstrates a `for` loop, which is similar to the same statement in C, including the increment operator `++`.

It also takes advantage of negative indices, which count from the end of the array. So, when `i=0`, the expression `-$i-1` is `-1`, which refers to the last element of the array.

3.2 Queue operators

We have already seen `shift`, which removes and returns the first element of a list. In the same way that `push` and `pop` implement a stack, `push` and `shift` implement a queue.

In addition, `unshift` adds a new element at the beginning of an array. `shift` and `unshift` are often used for parsing a stream of tokens.

3.3 Hashes

A has is a collection of scalar values, like an array. The difference is that the elements of an array are ordered, and accessed using numbers called indices; the elements of a hash are unordered, and accessed using scalar values called keys.

Just as scalars are identified by the `$` prefix, and arrays are identified by the `@` prefix, hashes begin with a percent sign (`%`). Just as the index of an array appears in square brackets, the key of a hash appears in squiggly braces.

```
my %hash;
$hash{do} = "a deer, a female deer";
$hash{re} = "a drop of golden sun";
$hash{mi} = "what it's all about";
```

The first line creates a local hash named `%hash`. The next three lines assign values with the keys `do`, `re` and `me`. These keys are strings, so we could have put them in double quotes, but in the context of a hash key, Perl understands that they are strings.

Hashes are sometimes called **associative arrays** because they create an association between keys and values. In this example, the key `do` is associated with the string `a deer, a female deer`, and so on.

The `keys` operators returns a list of the keys in a hash. The expression `keys %hash` yields `mi do re`. Notice that the keys are in no particular order; it depends on how the hash is implemented, and might even change if you run the program again (although probably not).

Here is a loop that traverses the list of keys and prints the corresponding values.

```
foreach my $key (keys %hash) {
    print "$key => $hash{$key}\n";
}
```

The result of this loop looks like this:

```
mi => what it's all about
do => a deer, a female deer
re => a drop of golden sun
```

My use of the double arrow symbol () isn't a coincidence. The double arrow can also be used to assign a set of key-value pairs to a hash.

```
%hash = (
    do => "a deer, a female deer",
    re => "a drop of golden sun",
    mi => "what it's all about",
);
```

Another way to traverse a hash is with the `each` operator. Each time `each` is called, it returns the next key-value pair from the hash as a two-element list. Internally, `each` keeps track of which pairs have already been traversed.

The following is a common idiom for traversing a hash.

```
while ((my $key, my $value) = each %hash) {
    print "$key => $value\n";
}
```

Finally, the `values` operator returns a list of the values in a hash.

```
my @values = values %hash;
```

Of course, you can traverse the list of values, but there is no way to look up a value and get the corresponding key. In fact, there might be more than one key associated with a given value.

3.4 Frequency table

One use for a hash is to count the number of times a word in used in a document. To demonstrate this application, we will start with a copy of `grep.pl` from the previous chapter. It contains a subroutine that opens a file and traverses the lines. With a few small changes, it looks like this:

```
sub read_file {
    my $file = shift;
    open (FILE, $file) || croak "Couldn't open $file";

    while (my $line = <FILE>) {
        read_line $line;
    }
}
```

As `read_file` gets each line from the file, it invokes `read_line` to process the line. `read_line` uses the `split` operator to break the line into words, then traverses the list of words.

```
sub read_line {
    our %hash;

    my @list = split " ", shift;
    foreach my $word (@list) {
        $hash{$word}++;
    }
}
```

The first parameter of `split` is a regular expression that is used to decide where to split the string. In this case, the expression is trivial; it's the space character.

The first line of the subroutine creates the hash. The keyword `our` indicates that it is a **global variable**, so we will be able to access it from other subroutines.

The workhorse of this subroutine is the expression `$hash{$word}++`, which finds the value in the hash that corresponds to the given word and increases it. When a word appears for the first time, Perl magically does the right thing, making a new key-value pair and initialzing the value to zero.

To print the results, we can write another subroutine that accesses the global `hash`.

```
sub print_hash {
    our %hash;

    my @list = keys %hash;
    print "@list\n";
}
```

Exercise 3.2

- Using the subroutines in this chapter, write a program that reads a text file and counts the number of times each word is used. Hint: use the `lc` operator to convert words to lower case, and the first argument of `split` to list the characters that should separate words. You can download the text of many out-of-copyright books from `gutenberg.net`.
- Modify the program so that it prints the number of unique words that appear in the book.

- Modify the program so that it prints the most commonly used word and the number of times it appears.

3.5 sort

The `sort` operator sorts the elements of a list, usually in the order determined by the string comparison operator. For example, the following version of `print_hash` prints the keys in alphabetical order:

```
sub print_hash {
    my @list = sort keys our %hash;
    print "@list\n";
}
```

If you want the list sorted in a different order, you can provide a special subroutine that compares two values and returns 1 if the first is greater (by whatever definition of "greater), -1 if the second is greater, and zero if they are equal.

For example, to sort the values numerically, we could provide this subroutine:

```
sub numerically { $a <=> $b }
```

Inside the subroutine, the special names `$a` and `$b` refer to the elements being compared. Now we can use `sort` like this:

```
my @list = sort numerically values our %hash;
```

The values from the hash are sorted from low to high. Unfortunately, this doesn't help us find the most common words, because we can't look up a value to get the associated word.

On the other hand, we can provide a comparison subroutine that compares keys by looking up their associated values:

```
sub byvalue {
    our %hash;
    $hash{$b} <=> $hash{$a};
}
```

And then sort the keys by value like this:

```
my @list = sort byvalue keys our %hash;
```

Exercise 3.3 Modify the program from the previous section to print the 20 most common words in a file and their frequencies.

The most common word in *The Great Gatsby*, by F. Scott Fitzgerald, is "the", which appears 2403 times, followed by "and", which appears 1573. The most frequent non-boring word is "Gatsby", which comes in 32nd on the list with 197 appearances.

3.6 Set membership

Hashes are frequently used to check whether an element is a member of a set. For example, we could read the list of words in `/usr/share/dict/words` and build a hash that contains an entry for each word.

The following subroutine takes a line from the dictionary and makes an entry for it in a hash.

```
sub dict_line {
    our %dict;
    my $word = lc shift;
    chomp $word;
    $dict{$word}++;
}
```

The first line declares the global hash named `%dict`. The second line gets the parameter and converts it to lower case. The third line uses `chomp` to remove the newline character from the end of the word. The last line makes the entry in the dictionary.

Now we can check whether a word is in the dictionary by checking whether a hash entry with the given key is defined. The `defined` operator tells whether an expression is defined.

```
if (!defined $dict{$word}) { print "*" }
```

When the body of an `if` statement is short, it is common to write it on a single line, and omit the semi-colon on the last statement in the block. It is also common to take advantage of the alternative syntax

```
print "*" if !defined $dict{$word};
```

which simplifies the punctuation a little.

Applying this analysis to *The Great Gatsby* yields some surprising lapses in my dictionary, like “coupe” and “yacht”, and some surprising vocabulary in the book, like “pasquinade” (public ridicule of an individual) and “echolalia” (the involuntary repetition of sounds made by others).

3.7 References to subroutines

At this point we find ourselves traversing two files, a dictionary and a text, and performing different operations on the lines. Of course, we could copy the code that opens and traverses a file, but it might be better to generalize `read_file` so that it takes a second argument, which is a reference to the subroutine it should use to process each line.

```
sub read_file {
    my $file = shift;
    my $subref = shift || \&read_line;

    open (FILE, $file) || croak "Couldn't open $file";
```

```
    while (my $line = <FILE>) {
        $subref->($line);
    }
}
```

The second line uses `shift` to read the second parameter. If the result is undefined (that is, if there is no second parameter), then it uses the default value `\&read_line`, which is a reference to a subroutine. Strictly speaking, `&read_line` is the name of the subroutine, and the backslash makes a reference to it.

Notice that `$subref` is a scalar variable, which is a hint that references are scalar values.

Inside the loop we see the syntax for invoking a subroutine when we have a reference to it. The arrow operator (`->`) is one of several ways to **dereference** a reference; that is, use the value the reference refers to. The argument in parentheses is just an argument like the ones we've seen before.

Now to read the dictionary, we can invoke `read_line` with a second parameter.

```
read_file "/usr/share/dict/words", \&dict_line;
```

Again, the expression `\&dict_line` is a reference to the subroutine whose name is technically `&dict_line`.

Exercise 3.4 Grab the text of your favorite book from `gutenberg.net` and make a list of the words in the book that aren't in your dictionary.

3.8 Hashes as parameters

When a hash is passed as a parameter, it is converted to an alternating list of keys and values. For example, the following subroutine

```
sub print_hash {
    print "@_\n";
}
```

produces the following abstruseness

```
mi what it's all about do a deer, a female deer re a drop of golden sun
```

One solution is to convert the list back to a hash:

```
sub print_hash {
    my %hash = @_;
    while ((my $key, my $value) = each %hash) {
        print "$key => $value\n";
    }
}
```

For the vast majority of applications, the performance of that solution would be just fine, but for a very large hash, it would be better to pass the hash by **reference**.

When we invoke `print_hash`, we pass a reference to the hash, which we create with the backslash operator.

```
print_hash \%hash;
```

Inside `print_hash`, we assign the reference to a scalar named `$hashref`, and then use the `%` prefix to **dereference** it; that is, to access the hash that `$hashref` refers to.

```
sub print_hash {
    my $hashref = shift;
    while ((my $key, my $value) = each %$hashref) {
        print "$key => $value\n";
    }
}
```

References can be syntactically awkward, but they are useful and versatile, so we will be seeing more of them.

3.9 Markov generator

To demonstrate some of the features we have been looking at, I am going to develop a program that reads a text and analyses the frequency of various word combinations, and then generates a new, random text that has the same frequencies. The result is usually entertainingly nonsensical, often bordering on parody.

For example, given the text of *The Great Gatsby*, the generator produces the following:

> "Why CANDLES?" objected Daisy, frowning. She snapped them out to the garage, Wilson was so sick that he was in he answered, "That's my affair," before he went there. A pause. "I don't like mysteries," I answered. "And I think of you." This included me. Mr. Sloane and the real snow, our snow, began to melt away until gradually I became aware now of a burglar blowing a safe.

Given the first three chapters of this book, it produces:

> One way to refer to a variable appears in double quotes, so it would be easy to miss the error. Again, there is an array of strings that contains only those characters, from start to finish, like "acceded". What set of characters, so matches anything that does not start with sub followed by "love" and "tender, love", although there are no spaces between the words now?

...which probably makes as much sense as the original.

The first step is to analyze the text by looking at all the three-word combinations. For each two-word prefix, we would like to know all the words that might come next, and how often each occurs. For example, in Elvis' immortal words

```
love me tender, love me true.
```

The prefix "love me" appears twice, followed by either "tender," or "true." Also, the prefix "me tender," which is followed by "love" and "tender, love", which is followed by "me".

To complete the analysis, we can build a hash that maps from prefixes to the list of words that can follow.

```
me tender, => love
love me => tender, true.
tender, love => me
```

As we traverse a file, we can build the set of prefixes by keeping a queue of three words, adding each new word to the end and then removing a word from the beginning. Once again, we can use `read_file`, giving it a reference to a subroutine named `triple_line`.

```
read_file $file, \&triple_line;
```

`triple_line` just splits the line into words and invokes `triple_word`

```
sub triple_line {
    my @list = split " ", shift;
    foreach my $word (@list) {
        triple_word $word;
    }
}
```

In `triple_word`, we store the most recent prefix in a global variable named `prefix`.

```
sub triple_word {
    our @prefix;
    my $word = shift;

    if (@prefix == 2) {
        print "@prefix => $word\n";
        shift @prefix;
    }
    push @prefix, $word;
}
```

When the length of the prefix is two, we can print an entry and remove a word from the beginning. Otherwise, we just add the word to the end. The output is

```
love me => tender,
me tender, => love
tender, love => me
love me => true.
```

What we need now is a hash that maps from each prefix to a list of words. There are several ways to do that. The simplest is to store the list of words as a string, which can be stored as a value in a hash because it is a scalar. But if the lists are long, we might get better performance by storing the words in an array. An array is not a legal value in a hash, but a reference to an array is.

Here is a version of `triple_word` that uses a hash to map from a prefix to an array reference.

```
sub triple_word {
    our (@prefix, %hash);
    my $word = shift;

    if (@prefix == 2) {
        my $key = join " ", @prefix;

        my $aref = $hash{$key};
        push @$aref, $word;
        $hash{$key} = $aref;

        shift @prefix;
    }
    push @prefix, $word;
}
```

In the `if` statement, the `join` operator concatenates the elements of `@prefix` into a string we can use as a key.

The next three lines do the real work. First we look up the key and get an array reference. To dereference the array, we add the `@` prefix to the scalar `$aref`, and use `push` to append the new word.

The third line is only necessary if we are making a new entry. If the key was already in the table, then modifying the array is all we have to do.

In passing, notice that the declarations `our` and `my` can apply to a list of variables.

Exercise 3.5 This example is meant to demonstrate the use of array references, but if we don't expect the arrays to be very long, it is much easier to use strings instead. Rewrite `triple_word` so that the values in the hash are strings. Hint: consider the `.=` operator.

3.10 Random text

Now that we have analyzed the original text, we would like to generate a random text that has the same combinations of words with the same frequency.

The first step is to choose a random prefix from the hash. The `rand` operator chooses a random (floating-point) number between 0 and its parameter (up to but not including the parameter. So the expression `rand @list` chooses a random index from a given list (because when the list is evaluated in a scalar context, it yields its length).

The subroutine `rand_elt` chooses and return a random element of the parameter list.

```
sub rand_elt { $_[rand @_] }
```

Now choosing a random key from the hash is easy.

```
my $prefix = rand_elt keys %hash;
```

Next we look up the prefix in the hash, split the string of words into a list, and choose a random element.

```
my $words = $hash{$prefix};
my $word = rand_elt split " ", $words;
```

Finally, we can form the next prefix by splitting the old prefix, shifting the first word, and appending the new word.

```
my @triple = split " ", $prefix;
shift @triple;
$prefix = "@triple $word";
```

Exercise 3.6 Write a subroutine called `random_text` that generates a random text by starting with a random key from the hash and then choosing random words from the list of successors. Analyze your favorite text and generate a new text using the hash you computed.

3.11 Exercises

Exercise 3.7 The text analysis implementation in this chapter is not very efficient for large files, because as the suffix lists get longer, it gets more expensive to add new words. A possible solution is to use a hash to hold the possible suffixes and their frequencies. This implementation saves space, since each suffix is stored once, and time, since the cost of adding an entry to a hash doesn't depend on the number of previous entries. One drawback of this approach is that it is harder to generate random text.

- Change the implementation of the text analysis so that is uses a hash instead of an array of suffixes.
- Change the implementation of the random text generation so that it chooses words from a hash of suffixes. The probability of choosing a word should be proportional to the number of times it appears.

Exercise 3.8 If each value in a hash appears only once, the hash is **invertible**, which means we can great a new hash with all the same key-value pairs, but where the values become keys, and vice versa.

Write a subroutine that takes a hash as a parameter and returns its inverse. For purposes of the exercise, you should traverse the elements of the hash, but you should also be aware of the following very clever implementation:

```
sub invert_hash {
    my %hash = reverse @_;
    return %hash;
}
```

When the hash is passed as a parameter, it is converted to an alternating list of keys and values. Reversed, it becomes a list of values and keys, and when assigned to a hash, it is converted back to a hash.

The `return` statement is optional. By default, the result of a subroutine is the value of the last expression.

Chapter 4

Objects

When we say that a language is object-oriented, we usually mean that it provides syntactic features that are intended specifically to support object-oriented programming. By that definition, Perl is not really an object-oriented language. On the other hand, there are many ways to write object-oriented programs in Perl, and many of the language's features are well-suited for it.

At the most basic level, an object is a reference. Starting there, this chapter will present the various features that are typically used to write object-oriented Perl.

4.1 Packages

Although you can think of any reference as an object, it might make you more comfortable to assign your objects to classes. In Perl, you create a class by defining a **package** and then using the `bless` operator to assign objects to the new class.

The `package` statement marks the beginning of a new package. All subsequent variable and subroutine declarations are added to the current package, until the end of the current file (or code block), or another package statement.

The following example declares a global variable named `value` and then starts a package named `Fred`. Inside the new package, we can create another variable with the same name without conflict, because the new package has its own **namespace**. The print statement refers to the variable in the current package, which has the value `home`;

```
our $value = "away";
package Fred;
our $value = "home";
print "$value\n";
```

Strictly speaking, what we have been calling "global" variables are really **package variables**. All variables belong to a package; if you don't create your own package, the default name is `main`.

To refer to a variable in another package, you have to use a **fully-qualified name**, which includes the name of the package and the name of the variable. In previous example, we could access the first variable with the expression `$main::value`, which has the value `away`.

4.2 The `bless` operator

Any reference can be considered an object, but the most common kind of object is a reference to a hash. The keys of the hash are the **instance variables** of the object. So, the simplest way to create an object is to create a reference to a hash. We have already seen one way to do that, using the backslash operator.

```
my %hash;
my $hashref = \%hash;
```

Another way to do the same thing is to use squiggly braces.

```
my $nobody = { };
my $person = { name => "Allen B. Downey",
               webpage => "allendowney.com" };
```

The first example creates an empty hash and makes `$nobody` refer to it. The second example creates a hash with two key-value pairs (and a plug for the author!).

Now we just have to tell Perl that this object belongs to a particular class. The following example declares a `Person` package, creates an object, and assigns the object to the `Person` class.

```
package Person;
my $person = { name => "Allen B. Downey",
               webpage => "allendowney.com" };

bless $person, "Person";
```

Now, when we invoke a method on this object (which we'll see shortly), Perl knows what package to find the method in.

4.3 Methods

A **method** is just a subroutine that takes an object as its first parameter. For example, `name` takes a `Person` as a parameter and returns the value of the instance variable `name`.

```
sub name {
    my $self = shift;
    my %hash = %$self;
```

```
    return $hash{name};
}
```

Since a `Person` is a reference to a hash, we have to dereference it before we can look up the key `name`. The arrow operator provides a more convenient way to do both at the same time.

```
sub name {
    my $self = shift;
    return $self->{name};
}
```

`name` is an example of an **accessor method**, since it provides access to one of the instance variables.

To invoke this method, we can just pass a `Person` object as a parameter.

```
my $name = name $person;
```

Or we can use the arrow operator.

```
my $name = $person->name;
```

The latter might help maintain the illusion that you are using an object-oriented language.

It is often convenient to provide a single accessor that both sets and reads an instance variable.

```
sub name {
    my $self = shift;
    if (@_) { $self->{name} = shift };
    return $self->{name};
}
```

Again, the first parameter is the object. If there is a second parameter, it is used to update `name`. Either way, the current value of `name` is returned.

And again, there are two ways to invoke this method. The object can appear explicitly as the first parameter, like this:

```
name $person, "Nella B. Yenwod";
```

Or we can use the arrow operator. Unfortunately, we can't use the arrow operator with a list of parameters:

```
$person->name "Nella B. Yenwod";     # WRONG
```

But you can solve this problem with parentheses.

```
$person->name("Nella B. Yenwod");
```

In situations like this, Perl enthusiasts like to point out that "There's more than one way to do it," which they abbreviate TMTOWTDI. Perl detractors sometimes come back with FORHOTDW, which stands for, "For obscure reasons, half of them don't work".

4.4 Constructors

A constructor is a method, any method, that creates and returns a new object. By convention, constructors are often named `new`. Here is a `Person` constructor.

```
sub new {
    my $self = { @_ };
    bless $self, "Person";
}
```

The parameters are a list of keys and values that are used to initialize the hash. So you could invoke the constructor like this:

```
my $person = new(name => "Allen B. Downey");
```

But it is more common to invoke a constructor using the name of the class:

```
my $person = Person->new(name => "Allen B. Downey");
```

In that case, the class name is sent as the first parameter in the list, so we can use it as the second parameter for `bless`:

```
sub new {
    my $class = shift;
    my $self = { @_ };
    bless $self, $class;
}
```

This is a standard idiom for object constructors. Whenever you write a new class, you can start by copying this method.

4.5 Printing objects

For purposes of debugging, you will almost always want a method that prints the state of an object. Here is a simple version named `print`.

```
sub print {
    my $self = shift;
    while ((my $key, my $value) = each %$self) {
        print "$key => $value\n";
    }
}
```

Because the argument is a reference to a hash, we have to use the expression `%$self` to dereference it.

This method just prints the keys and values from the hash. If some of the values are references, Perl prints the type of the reference and its unique identifier. You might want to add code to this method to print the contents of the object in a more informative way.

4.6 Heaps

To demonstrate a more interesting object, we're going to write an implementation of a heap. If you are not familiar with heaps, you should consult a data structures textbook, or `How to Think Like a Computer Scientist: Java Version`, which is available from `thinkapjava.com`.

In order to develop the code gradually, we'll start with a heap of numbers. Here is the package declaration and constructor:

```
package Heap;

sub new {
    my $class = shift;
    my $self = { aref => [ "" ],
                 next  =>  1
                 @_};
    bless $self, $class;
}
```

The instance variables are a reference to an array (cleverly named `aref`) and a number named `next` that keeps track of the next available position in the array. The expression `[ "" ]` creates a reference to an array with a single element, an empty string. We won't use the first element of the array, so we are putting an empty string there as a place keeper. The initial value of `next` is the index of the first position we will use, `1`.

As usual, it is a good idea to have a method that prints the state of an object.

```
sub print {
    my $self = shift;
    my $next = $self->{next};
    my $aref = $self->{aref};
    print "array => @$aref\n";
    print "next => $next\n";
}
```

Since `$self->{aref}` is a reference to an array, we have to dereference it to print its contents. `$self->{next}` is a scalar, so all we have to do is print it.

4.7 Heap::add

The `add` method takes two parameters, the heap and the value we want to add it it. It puts the value into the next available location in the array and then increments `next`.

```
sub add {
    my ($self, $value) = @_;
    my $index = $self->{next};
    $self->{aref}[$index] = $value;
    $self->{next}++;
}
```

`$index` is a local copy of the instance variable `next`. We can use its value as an index into `aref`, but in order to update `next`, we have to use the writable expression `$self->{next}`.

Personally, I am surprised that we can access the elements of the array using the bracket operator. After all, `$self->{aref}` is a reference to an array, not an array, and normally Perl doesn't deference automatically.

Consider the following examples:

```
my @array = ( 1, 2, 3 );
my $aref  = [ 1, 2, 3 ];
```

The first line creates a list and assigns it to an array named `@array`. The second line creates a reference to an array and assigns it to a scalar named `$aref`. We can use square brackets to access the elements of `@array`, so the expression `$array[1]` has the value 2. But the expression `$aref[1]` is illegal. You will get something like

```
Global symbol "@aref" requires explicit package name
```

because Perl thinks you are asking for the second element of an array named `@aref`. The usual solution is to use the arrow operator, as in `$aref->[1]`, which dereferences `$aref` and then gets element 1.

So, if we put an array reference in a hash, like this

```
my %hash;
$hash{aref} = $aref;
```

then how do we access its elements? You would think we should use the arrow operator again, as in `$hash{aref}->[1]`. Actually, that works, but it is not the most common form. It turns out that you can get the reference out of the hash and dereference it at the same time, as in `$hash{aref}[1]`.

About now, you may be feeling a sharp pain near your temple. That's normal. Ignore it.

We can test `add` and `print` by putting some random numbers into a heap:

```
my $heap = Heap->new;
for (my $i=0; $i<10; $i++) {
    $heap->add (rand 100);
}
$heap->print;
```

If you try it, you should see an array of ten random numbers between 0 and 100, and the value of `next` should be 10.

4.8 Heap::remove

Here is a version of `remove` that removes and returns the first element in the array, and moves the last element into the first position.

```
sub remove {
    my $self = shift;
    my $aref = $self->{aref};

    my $result = $aref->[1];
    $aref->[1] = pop @$aref;
    $self->{next}--;

    return $result
}
```

As usual, the first line gets the parameter. The second line makes a local copy of the array reference `aref`. If the value of an instance variable is a reference, we can **unpack** it by assigning it to a local variable. Because it is a reference, we can use it for both reading and writing the array.

The next three lines (1) store the first element of the heap, which is the result we'll return, (2) move the last element of the heap up to the front (for reasons that will become clear soon), and (3) decrement `next`, which sets it to the index of the now-available location we just emptied.

We can test `remove` with the following loop:

```
for (1..10) {
    my $value = $heap->remove;
    print "$value\n";
}
```

The double-dot operator builds a list of the elements from 1 to 10. When the `for` statement is applied to a list, it behaves like a `foreach` statement. If you run this code, it will print the elements of the heap, but not in numerical order, yet (and not even in the order they were added).

A better alternative is to implement `Heap::empty`:

```
sub empty {
    my $self = shift;
    return $self->{next} == 1;
}
```

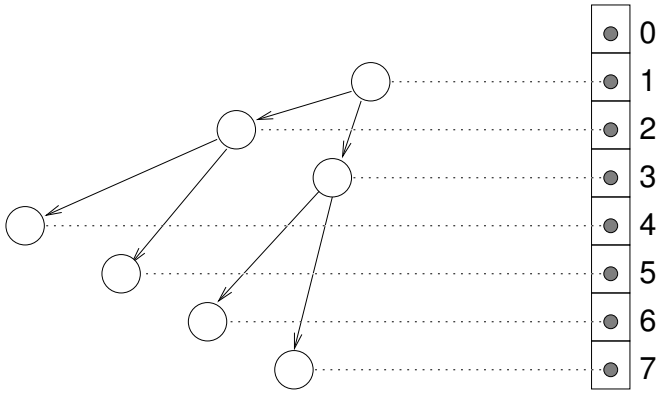
Then we can use an `until` statement to empty the heap:

```
until ($heap->empty) {
    my $value = $heap->remove;
    $value->print;
}
```

`until` is the same as `while`, except that it inverts the condition.

4.9 Trickle up

A fundamental idea in this implementation of a heap is that there is a relationship between the elements of the array and the nodes in a tree. This relationship is shown in the following figure.



Another way to say the same thing is that the nodes of the tree are stored in the array in **level order**, that is, all the nodes from one level, left to right, followed by all the nodes from the next level, and so on.

Because we skipped element 0 and started with element 1, it is easy to find the parent and children of a given node using index arithmetic. For example, for the node with index i, the left child has the index $2i$, the right child has index $2i + 1$, and the parent has the index $\lfloor i/2 \rfloor$.

In order for a tree to be considered a heap, it has to have the **heap property**:

> Every node must be greater than or equal to its children.

If this property holds, then the largest element in the heap must be at the root. As we add elements to the heap, we can maintain the heap property by putting the new element at the end and allowing it to "trickle up" into the right position.

Here is a more complete implementation of `Heap::add`:

```
sub add {
    my ($self, $value) = @_;
    my $i = $self->{next};
    $self->{aref}[$i] = $value;

    while ($i > 1) {
        my $parent = POSIX::floor($i/2);
        last if $self->compare($i, $parent) <= 0;
        $self->swap($i, $parent);
        $i = $parent;
    }
    $self->{next}++;
}
```

The index of the new element is `i`. The `while` loop continues until `i` gets to the root (element 1). Inside the loop, we compute the parent of the current node. The `floor` function belongs to the module `POSIX`, which contains the standard POSIX 1003.1 identifiers, including lots of mathematical functions. Before you can use them, of course, you have to `use POSIX;`

The `last` statement exits the loop if the current node is less than or equal to its parent. The following statement

```
last if $self->compare($i, $parent) <= 0;
```

is equivalent to

```
if ($self->compare($i, $parent) <= 0) {
    last;
}
```

but it requires less punctuation, and some people think it is more readable because it puts the action before the condition.

The `compare` method takes two indices as parameters and compares the corresponding elements.

```
sub compare {
    my ($self, $i, $j) = @_;
    my $x = $self->{aref}[$i];
    my $y = $self->{aref}[$j];
    if (!defined $x) {
        if (!defined $y) {
            return 0;
        } else {
            return -1;
        }
    }
    if (!defined $y) { return 1 }
    return $x <=> $y;
}
```

If both elements exist, then we use the spaceship operator to compare them. The rest of the method deals with the cases where one or more of the elements are undefined.

The `swap` method takes two indices as parameters and swaps the corresponding elements.

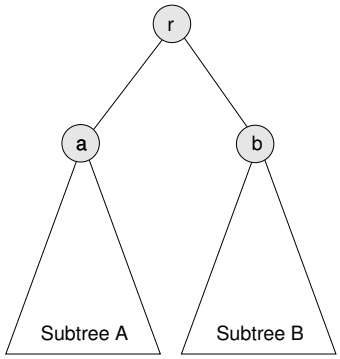
```
sub swap {
    my ($self, $i, $j) = @_;
    my $aref = $self->{aref};
    ($aref->[$i], $aref->[$j]) = ($aref->[$j], $aref->[$i]);
}
```

The first line gets the parameters, and the second unpacks `aref`. The third line uses list assignment to swap elements.

At this point, if you run the test code again, the first element you remove should be the largest. That's because `add` establishes the heap property. But `remove` doesn't maintain it.

4.10 Trickle down

It is often useful to think of a tree as a root node with two subtrees, as shown in this figure:



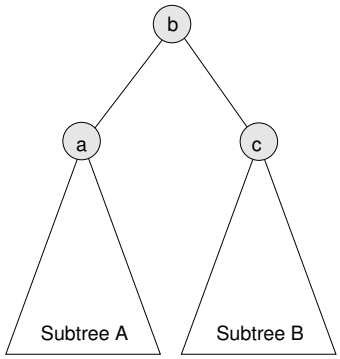
The value at the root is `r`. The value at the root of Subtree A is `a` and the value at the root of Subtree B is `b`.

If the tree is a heap, then `r` is the largest value in the heap and `a` and `b` are the largest values in their respective subtrees.

Once we remove `r`, we have to restore the heap property. One way to do that is to remove the last element of the array, which we'll call `c`, and put it at the root.

Of course, the chances are that the last value is not the highest, so putting it at the root breaks the heap property. Fortunately it is easy to restore. We know that the largest value in the heap is either `a` or `b`. Therefore we can select whichever is larger and swap it with the value at the root.

Arbitrarily, let's say that `b` is larger. Since we know it is the highest value left in the heap, we can put it at the root and put `c` at the top of Subtree B. Now the situation looks like this:



Again, `c` is the value we copied from the last element in the array and `b` is the highest value left in the heap. Since we haven't changed Subtree A at all, we know that it is still a heap. The only problem is that we don't know if Subtree B is a heap, since we just stuck a (probably low) value at its root.

So we haven't completely solved the problem, but we have taken a step in the right direction, and the result is a smaller version of the same problem. All we have to do now is reheapify Subtree B.

Here is an updated version of `Heap::remove`

```
sub remove {
    my $self = shift;
    my $aref = $self->{aref};

    my $result = $aref->[1];
    $aref->[1] = pop @$aref;
    $self->{next}--;

    $self->reheapify(1);        # reheapify the tree
    return $result
}
```

The only difference is that we invoke `reheapify` to restore the heap property. Here is the implementation.

```
sub reheapify {
    my ($self, $i) = @_;
    my $left = 2 * $i;
    my $right = 2 * $i + 1;

    my $winleft = $self->compare($i, $left) >= 0;
    my $winright = $self->compare($i, $right) >= 0;
    return if $winleft and $winright;

    if ($self->compare ($left, $right) > 0) {
        $self->swap($i, $left);
        $self->reheapify($left);
    } else {
        $self->swap($i, $right);
        $self->reheapify($right);
    }
}
```

The first three lines get the parameters (as usual) and compute the indices of the children.

The next two lines compare the root node to each of its children and store the results. If the root is greater than either of its children, we can return immediately. Otherwise we have to find the larger of the children and swap.

If we swap with the left child, we have to invoke `reheapify` on the left subtree,

and vice versa. But either way, we only make one recursive invocation, so the number of recursions is just the height of the tree.

4.11 Exercises

Exercise 4.1 This implementation demonstrates the basic mechanisms of a heap, but it is not all that useful because it can only store scalars. We would like to be able to put any kind of object into a heap, as long as we have a way to compare objects.

- Write a new package called `Thing`. Write a constructor and a method that prints the instance variables of a `Thing` object.
- Modify the test code so that, instead of adding random numbers to the heap, it adds `Thing` objects with an instance variable named `priority`. For now, the priority of the Things should be a random number, but in general the **priority** of an object in a heap is the value that determines the order objects are removed.
- Write an accessor method for `Thing` named priority. You will not be surprised to hear that it should return the object's priority.
- Modify the test code so that when it removed objects from the heap, it invokes `print` on them.
- At this point, you should be able to add and remove objects from the heap, but they are probably not coming out in the right order because `compare` doesn't know how to compare Things. Modify `compare` so that instead of comparing references to objects (whatever that means), it invokes the method `priority` on each object and compares the results.

If everything goes according to plan, your heap implementation should be **polymorphic** in the sense that it can hold many kind of objects as elements, and it will work correctly as long as the objects have an instance variable named `priority`.

Save your implementation in a file named `heap.pl`; we will need it in the next chapter.

Chapter 5

Modules

In this chapter, we develop an implementation of a Huffman code, which is interesting enough in its own right, but it also serves as a demonstration of several Perl features. First, we will transform the heap program from the previous chapter into a full-fledged Perl module. Next we will define two new classes, one of which inherits from the other. Finally, as an example of a linked data structure, we will implement a binary tree.

5.1 Variable-length codes

If you are familiar with Morse code, you know that it is a system for encoding the letters of the alphabet as a series of dots and dashes. For example, the famous signal `...---...` represents the letters SOS, which comprise an internationally-recognized call for help. This table shows the rest of the codes:

A	.-	N	-.	1	.----	.	.-.-.-
B	-...	O	---	2	..---	,	--..--
C	-.-.	P	.--.	3	...--	?	..--..
D	-..	Q	--.-	4	....-	(	-.--.
E	.	R	.-.	5	.....	)	-.--.-
F	..-.	S	...	6	-....	-	-....-
G	--.	T	-	7	--...	"	.-..-.
H	....	U	..-	8	---..	_	..--.-
I	..	V	...-	9	----.	'	.----.
J	.---	W	.--	0	-----	:	---...
K	-.-	X	-..-	/	-..-.	;	-.-.-.
L	.-..	Y	-.--	+	.-.-.	$	...-..-
M	--	Z	--..	=	-...-		

Notice that some codes are longer than others. By design, the most common letters have the shortest codes. Since there are a limited number of short codes, that means that less common letters and symbols have longer codes. A typical

message will have more short codes than long ones, which minimizes the average transmission time per letter.

Codes like this are called variable-length codes. In this chapter, we will look at an algorithm for generating a variable-length code called a **Huffman code**. It is an interesting algorithm in its own right, but it also makes a useful exercise because its implementation uses a variety of data structures.

Here is an outline of the next few sections:

- First, we will use a sample of English text to generate a table of characters and their frequencies.
- The heart of a Huffman code is the Huffman tree. We will use the frequency table to build the Huffman tree, and then use the tree to encode and decode sequences.
- Finally, we will traverse the Huffman tree and built a code table, which contains the sequence of dots and dashes for each letter.

5.2 The frequency table

Since the goal is to give short codes to common letters, we have to know how often each letter occurs. In Edgar Allen Poe's short story "The Gold Bug," one of the characters uses letter frequencies to crack a cypher. He explains,

> "Now, in English, the letter which most frequently occurs is e. Afterwards, the succession runs thus: a o i d h n r s t u y c f g l m w b k p q x z. E however predominates so remarkably that an individual sentence of any length is rarely seen, in which it is not the prevailing character."

So our first mission is to see whether Poe got it right. To check, I chose as my sample the text of "The Gold Bug" itself, which I downloaded from `gutenberg.net`.

Exercise 5.1 Write a program that counts the number of times each letter appears in a sample text. Download the text of your favorite public-domain short story, and analyze the frequency of the letters.

You can traverse the characters in a string by using `split` with an empty string as a separator. The result is a list of characters. The following example splits a string and prints one character per line.

```
my @list = split "", $line;
foreach (@list) {
    print "$_\n";
}
```

5.3 Modules

We have already seen how to use an existing module with the `use` statement. Now we will see how to create a new module.

In an object-oriented program, a module is usually a file that defines a package. Starting with the heap implementation from the previous chapter, we can create a module in just a few steps:

1. Rename the file from `heap.pl`, which indicates that it is a program, to `heap.pm`, which indicates that it is a module.

2. Remove or comment out the test code. When a program uses a module, Perl executes the module at compile time. You can put executable code in a module if you want to, but most of the time modules only contain subroutines and variable declarations.

3. The shebang line at the beginning of the file is unnecessary, since we will never execute a module from the command line.

4. The last expression in the module should be a "true" value, which indicates that the module executed successfully. By convention, the last statement is `1;`

Exercise 5.2 Convert `heap.pl` from the previous chapter into a module named `heap.pm`, and add the statement `use heap;` to `huffman.pl`. Make sure you can compile and run the program, even if it doesn't use anything from the heap module yet.

Exercise 5.3 Write a class called `Pair` that represents a letter-frequency pair. Pair objects should contain instance variables named `letter` and `frequency`, and provide methods with the same names that access them. In addition, Pair should provide a method named `priority` that returns the frequency.

Now sort the letter-frequency pairs from the frequency table by traversing the set of keys, building `Pair` objects, adding the Pairs to a heap, removing the Pairs from the heap, and printing them in descending order by frequency.

How good was Poe's guess about the most frequent letters?

5.4 The Huffman Tree

The next step is to assemble the Huffman tree. Each node of the tree contains a letter and its frequency, and pointers to the left and right nodes.

To assemble the Huffman tree, we start by creating a set of singleton trees, one for each entry in the frequency table. Then we build the tree from the bottom up, starting with the least-frequent letters and iteratively joining subtrees until we have a single tree that contains all the letters.

Here is the algorithm in more detail.

1. For each entry in the frequency table, create a singleton Huffman tree and add it to a heap. When we remove a tree from the heap, we get the one with the lowest frequency.

2. Remove two trees from the heap and join them by creating a new parent node that refers to the removed nodes. The frequency of the parent node is the sum of the frequencies of the children.

3. If the heap is empty, we are done. Otherwise, put the new tree into the heap and go to Step 2.

An example will make this clearer. To keep things managable, we will use a sample text that only contains the letters `adenrst`:

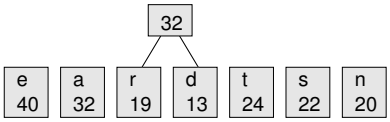
> Eastern Tennessee anteaters ensnare and eat red ants, detest ant antennae (a tart taste) and dread Antarean anteater-eaters. Rare Andean deer eat tender sea reeds, aster seeds and rats' ears. Dessert? Rats' asses.

This eloquent treatise on the eating habits of various fauna yields the following frequency table:

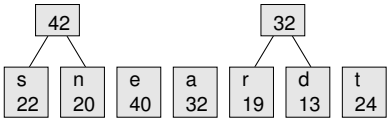
```
e       40
a       32
t       24
s       22
n       20
r       19
d       13
```

So after Step 1, the heap looks like this:

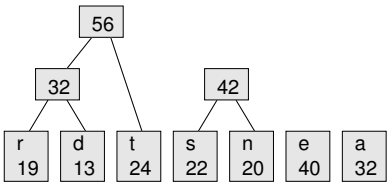
In Step 2, we remove the two trees with the lowest frequency (`r` and `d`) and join them by creating a parent node with frequency 32. The letter value for the internal nodes is irrelevant, so it is omitted from the figures. When we put the new tree back in the heap, the result looks like this:



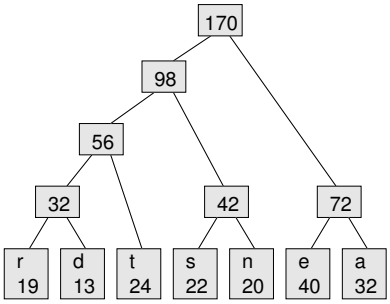
Now we repeat the process, combining `s` and `n`:



After the next interation, we have the following collection of trees. By the way, a collection of trees is called a **forest**.



After two more iterations, there is only one tree left:



This is the Huffman tree for the sample text. Actually, it is not the only one, because each time we join two trees, we choose arbitrarily which goes on the left and which on the right, and when there is a tie in the heap, the choice is arbitrary. So there may be many possible trees for a given sample.

So how to we get a code from the Huffman tree? The code for each letter is determined by the path from the root of the tree to the leaf that contains the letter. For example, the path from the root to `s` is left-right-left. If we represent a left with `.` and a right with `-` (another arbitrary choice) we get the following code table.

```
e       -.
a       --
t       ..-
s       .-.
n       .--
r       ....
d       ...-
```

Notice that we have achieved the goal: the most frequent letters have the shortest codes.

Exercise 5.4 By hand, figure out a Huffman tree for the following frequency table:

```
e       93
s       71
r       57
t       53
n       49
i       44
d       43
```

```
o       37
```

5.5 Inheritance

One way to implement `HuffTree` is to extend `Pair` from Exercise 5.3. A new class specifies its parent class (or classes) by declaring an array named `@ISA`, which is pronounced "is a", because it is meant to indicate that the new class "is a" subset of the parent class.

```
package HuffTree;
our @ISA = "Pair";
```

Exercise 5.5 Write methods named `left` and `right` that access the instance variables with the same names. These variables will contain references to other HuffTrees, making it possible to assemble nodes into a tree.

The `HuffTree` class inherits `new`, `letter`, `frequency` and `priority` from `Pair`. As you would expect, you can override an inherited method if you need a different implementation. In this case, when we remove a HuffTree from the heap, we want to get the one with the lowest frequency, so we have to override `priority` like this:

```
sub priority {
    my $self = shift;
    return -$self->{frequency};
}
```

The highest frequency gets the lowest priority.

5.6 Building the Huffman tree

Given the frequency table, we can build the Huffman tree in two steps. First, we traverse the frequency table and build a singleton tree for each entry, and add the singletons to a heap:

```
    my $heap = Heap->new;
    my $tree;
    while ((my $key, my $value) = each %freqtab) {
        print "$key\t$value\n";
        my $tree = HuffTree->new( letter => $key,
                                  frequency => $value );
        $heap->add($tree);
    }
```

The second step is to assemble the tree using the algorithm in Section 5.4.

```
    while (1) {
        my $left = $heap->remove;
        my $right = $heap->remove;
```

```
        my $freq = $left->frequency + $right->frequency;

        $tree = HuffTree->new( frequency => $freq );
        $tree->left($left);
        $tree->right($right);

        last if $heap->empty;
        $heap->add($tree);
    }
```

For the internal nodes of the tree, we set the `frequency` but we leave `letter` undefined.

When the loop exits, all the trees have been assembled into one, and `$tree` refers to the root node.

Exercise 5.6 Assemble this code into a method named `hufftree` that reads the package variable named `%freqtab`, builds a HuffTree, and assigns it to a package variable named `$hufftree`.

5.7 Building the code table

The code for a given letter is determined by the path from the root of the Huffman tree to the leaf node that contains the letter. To encode a letter, we might have to search the entire tree.

This process is much more efficient if we traverse the tree once, compute all the codes, and record them in a code table.

As we traverse the tree, we want to keep track of the path we are on. At first, that might seem hard, but there is a natural way to perform this computation recursively. Here is the key observation: if the path from the root to a given node is represented by a string of dots and dashes called `path`, then the path to the left child of the node is `$path . "."` and the path to the right child is `$path . "-"` (the dot operator performs string concatenation).

Here is an implementation of this algorithm:

```
sub codetab {
    our %codetab;
    my ($tree, $path) = @_;

    if (defined ($tree->letter)) {
        $codetab{$tree->letter} = $path;
        return;
    }
    codetab($tree->left, "$path.");
    codetab($tree->right, "$path-");
}
```

If the value of `letter` is defined, that means we have reached a leaf node, so we can make an entry in the code table and return. Otherwise, we make recursive calls to traverse the left and right subtrees.

Initially, we invoke `codetab` with the root of the tree and an empty string as parameters:

```
codetab $hufftree, "";
```

Exercise 5.7

a. Type in the `codetab` method and test it with your Huffman tree.

b. Write a subroutine called `print_codetab` that prints the entries in the code table. You should see that common letter have short codes and rare letters have long codes. Compare your Huffman code with Morse code. Which has longer codes?

c. Write a subroutine called `encode` that traverses a string, looks up each character in the code table, and returns the encoding of the string.

5.8 Decoding

When we receive an encoded message, we use the Huffman tree to decode it. Here is the algorithm:

1. Start at the root of the HuffTree.
2. If the next symbol is `-`, go to the left child; otherwise, go to the right child.
3. If you are at a leaf node, get the letter from the node and append it to the result. Go back to the root.
4. Go to Step 2.

Consider the code `..--.--`, as an example. Starting at the top of the tree, we go left-left-right and get to the letter `t`. Then we start at the root again, go right-left and get to the letter `e`. Back to the top, then right-right, and we get the letter `a`. If the code is well-formed, we should be at a leaf node when the code ends. In this case the message is my beverage of choice, tea.

Exercise 5.8 Use the example HuffTree to decode the following words:

a. `.-.--.--..---`

b. `.-...--.-......-.`

c. `...--.-.....`

d. `-.--.-...-`

Notice that until you start decoding, you can't tell how many letters there are or where the boundaries fall.

Exercise 5.9

a. Write a method called `decode` that takes a string of dots and dashes and that uses the Huffman tree to decode the string and return the result.

b. Test your method my using `encode` to encode a string and `decode` to decode it.

Exercise 5.10 The implementation I have sketched in this chapter is partly object-oriented, since it uses `Pair` and `HuffTree` objects, but the Huffman package is just a collection of subroutines, not a class. Since it uses package variables for `%freqtab`, `$hufftree` and `%codetab`, a program that uses this package can only have one Huffman code at a time.

To make this design more versatile, rewrite the program to define a `Huffman` class that contains `$freqtab`, `$hufftree` and `$codetab` as instance variables. Notice that, in this implementation, the frequency and code tables have to be references to hashes.

What are the pros and cons of the two implementations?

Chapter 6

Callbacks and pipes

In this chapter, we will develop two programs. One, named `get.pl`, uses HTTP to download a file from a Web site. The other, named `mirror.pl`, takes a URI as a parameter and uses `get.pl` to download it. As `get.pl` discovers unvisited links, `mirror.pl` creates additional processes to download them.

These programs demonstrate the use of callbacks, which provide a flexible way to interact with existing code in modules, and pipes, which provide a simple form of inter-process communication. Along the way, we will play with some standard (and some less standard) Perl modules like `URI`, `HTTP::Request`, `HTML::Parser`, and `IO::Select`.

6.1 URIs

One of the most powerful features of Perl is its extensive library of modules. Many of these modules are available from the Comprehensive Perl Archive Network (CPAN), conveniently located at `cpan.org`.

Some modules are more standard than others. Some Perl Core Modules can be considered part of the language. Other modules, like the ones we will use in this chapter, are included in the vast majority of Perl installations.

Different modules offer different interfaces. The ones we will see in this chapter tend to be object-oriented. They define a new class of objects and the methods that operate on them. Others, like `POSIX`, provide a set of subroutines.

To get warmed up, we'll start with a simple class called URI, which stands for **Uniform Resource Identifier**. A URI is pretty much the same thing as a URL, which identifies a resource in the World Wide Web (see Section 2.6).

Here is a program that takes a URL as a string, creates a new URI object, and converts it to canonical form:

```
use URI;

sub main {
    my $uris = shift || "http://www.slashdot.com";
    my $uri = URI->new($uris)->canonical;
    $uris = $uri->as_string;
    print "$uris\n";
}

main @ARGV;
```

The first line of `main` gets the parameter from the list of command-line arguments. If the list is empty, it uses the default value `http://www.slashdot.com`. The second line creates a URI object, and then invokes `canonical`, which returns the original object if it is already in canonical form, or a new object if, for example, the original uses non-standard capitalization or a redundant port number. Here is an example:

```
$ ./uri.pl HTTP://www.Slashdot.org:80/Index.html
http://www.slashdot.org/Index.html
```

`canonical` converts `HTTP` to `http`, and makes the machine name all lower case. But the file name is case sensitive, so it is unchanged. The port specifier `:80` is unnecessary because 80 is the standard port for the web server.

URI also provides methods that extract the various parts of a URI:

```
    my $scheme = $uri->scheme;
    my $authority = $uri->authority;
    my $path = $uri->path;
```

The **scheme** is usually the protocol name, like `http` or `ftp`. The **authority** is usually the name of the machine that provides this resource. The **path** is the complete file name (including its parent directories).

6.2 HTTP GET

In order to retrieve a file from a web server, a client has to issue an HTTP GET request and wait for a response. The World-Wide Web Library for Perl (LWP) provides a set of objects and methods that make it almost trivial to implement a web client.

The three components we will use are `UserAgent`, `Request` and `Response`.

```
use LWP::UserAgent;
use HTTP::Request;
use HTTP::Response;
```

`Request` objects represent the messages sent from client to server; `Response` objects represent the replies. A `UserAgent` provides the capability to send and receive these messages. Here is the simplest form of an HTTP GET request.

```
my $ua = LWP::UserAgent->new;
my $request = HTTP::Request->new(GET => $uri);
my $response = $ua->request($request);
print $response->content;
```

The first line simply creates a UserAgent. The second line create the `Request` object, specifying the URI and the fact that this is a GET request (as opposed to HEAD or POST, for example).

To get the file, we tell the UserAgent to process the request. The result is a Response object that contains the content of the file along with the header. The last line extracts and prints the content.

For more information about all three classes (and more) see the LWP documentation at `http://search.cpan.org/dist/libwww-perl/`.

6.3 Callbacks

In the previous section, we used the `request` method in the UserAgent class to download an entire file and then write the contents in a local file. But often the performance of wide-area networks is slow (compared to local processing) and unpredictable. It would be more efficient to start writing the file as soon as the first packet arrives, so that we can interleave network arrivals with disk accesses.

The `request` method can accept a second argument, which is a reference to a subroutine. As packets of data arrive, `request` invokes the given function, passing in chunks of the file. A subroutine that is passed as a parameter and then invoked by the receiver is called a **callback**. Here is an example:

```
sub callback {
    my $chunk = shift;
    print FILE $chunk;
}
```

Now we can invoke `request` like this:

```
open FILE, ">", $file or croak "Couldn't open $file";
my $request = HTTP::Request->new(GET => $uri);
my $response = $ua->request($request, \&callback);
```

Exercise 6.1 Assemble the code in this section into a program named `get.pl` that downloads a file using a callback subroutine to write chunks of data as they arrive. Add a line to `callback` to print the length of each chunk. Do you see a pattern? Can you figure out what determines the sizes of the chunks?

6.4 Mirroring

The next step for this program is to turn it into a tool that **mirrors** a web page. That is, we would like to make a local file (or directory) that has the same name and contents as a file (or directory) on a remote site.

To do that, we'll write a few lines of code to create a directory, if necessary, and then open the file. Given the path part of the URI, we find the parent directory using the `dirname` method from the `File::Basename` package.

```
    my $path = $uri->path;
    my $dir = $uri->authority . File::Basename::dirname $path;
\end{verbatim}

The next step is to create the directory.

\begin{verbatim}
    my $res = system "mkdir -p $dir";
    if ($res != 0) { croak "Couldn't create directory $dir" };
```

The system operator creates a subprocess and executes the given command. In this case, the command is `mkdir`, which is the UNIX command that makes a new directory. The `-p` option tells `mkdir` to create any parent directories that are needed, and not to complain if some of them already exist.

Annoyingly, the return values from many UNIX commands do not follow the Perl convention. In Perl, any true value indicates success and the false value indicates an error. For most UNIX commands, the value 0 indicates success, and all other values are error codes.

The last step is to assemble the file name and open the file.

```
    my $file = $uri->authority . $path;
    open FILE, ">", $file or croak "Couldn't open $file";
```

We are using the `authority` part of the URI as the top-level directory, so that all the pages we get from a given site go into the same directory.

Exercise 6.2 Modify `get.pl` so that when it downloads a file, it stores it in a local directory and file that mirror the original site.

Exercise 6.3 There is a detail of HTTP that makes this part of the program a little tricky. If a URI identifies a directory (rather than a file), the server looks for a file in the directory named `index.html` and sends it. Unfortunately, there is no sure way to know, looking at a URI, whether it identifies a directory.

One way to handle this problem is to check whether the path part of a URI ends in `.html`. If not, the program could append `/index.html` to the path. But there are a number of ways this solution could fail. As an exercise, you might want to investigate better ways to handle this problem.

6.5 Parsing

As we read the contents of a Web page, we might also like to extract the links it contains. The simplest way to do that is to look for patterns that match the `<a>` tag. But there is a module called `HTML::Parser` that is even easier (once you figure out how to use it), and gives us another chance to use callbacks.

Before we start parsing, we have to create a Parser object.

```
our $p = HTML::Parser->new(
               start_h => [\&start_tag, "tagname, attr"] );
```

The parameters we send to the constructor are, as usual, a list of instance variables and their values. In this case, the instance variable is `start_h`, which specifies a handler that will be invoked when the parser sees a start tag. A `handler` is a kind of callback that is invoked to handle a particular kind of event. The Parser uses handlers for several other kinds of events, including `end_h`, which handles end tags, and `text_h` which handles plain text that is not part of a tag.

The value of `start_h` is a list that contains a reference to the callback, which is cleverly named `start_tag`, and a string that specifies what information should be passed as parameters to the callback. In this case, we want the name of the tag and a hash that contains the attributes that appear in the tag.

For example, the following HTML generates a text link.

```
<a href="http://allendowney.com">my web page</a>
```

When this code is parsed, it generates three events. The first is a start tag with tagname `a` and a hash of attributes that contains one entry, `href => http://allendowney.com`. The next event is a text event with the text `my web page`. The last event is an end tag with tagname `a` (and no attributes).

Here is a version of `start_tag` that waits for `<a>` links and prints the URI they refer to.

```
sub start_tag {
    my ($tagname, $attr) = @_;
    if ($tagname eq "a") {
        my $href = $attr->{href};
        print "$href\n";
    }
}
```

The Parser object is incremental, which means that you can invoke `parse` repeatedly, passing any size chunk of HTML code. This capability works well with the code from the previous section that stores the incoming file in chunks. We can modify `callback` so that it stores each chunk in a file *and* passes it to the Parser.

```
sub callback {
    my $line = shift;
    our $p->parse($line);
    print FILE $line;
}
```

Callbacks are a versatile way to integrate a module with your program. The biggest drawback is that the flow of execution in the program can get complicated. In this case, when a chunk of a file arrives, the UserAgent invokes `callback`, which passes the chunk to the Parser. If the chunk contains a start tag, the Parser invokes `start_tag`.

6.6 Absolute and relative URIs

The URIs we have seen so far have been **absolute**, which means that they include the scheme, authority, and path. The references that appear in `<a>` tags can be **relative**, which means that they include only a path.

For example, `http://allendowney.com/index.html` is the absolute URI of a file. If that file contains a relative URI as a reference, we assume that the reference is relative to the parent of the current file. For example, a reference to `projects.html` would be understood to refer to `http://allendowney.com/projects.html`. The parent of the current file is called the `base` URI.

The URI class provides methods for converting from relative to absolute URIs, and back. The `abs` method converts a relative URI to an absolute URI, given the base URI as a parameter. Here is an example.

```
my $base = URI->new("http://allendowney.com/index.html");
my $rel = URI->new("projects.html");
my $abs = $rel->abs($base);
print "$abs\n";
```

The output of this code fragment is `http://allendowney.com/projects.html`.

Exercise 6.4 Modify `start_tag` so that whenever it find a relative URI, it converts it to an absolute URI using the URI of the current page as a base.

Exercise 6.5 Modify `start_tag` so that it only prints "internal" links; that is, links to URIs that have the same authority as the base URI.

6.7 Multiple processes

At this point we have a program that downloads a given URI, stores the result in an appropriately named file, and prints the URIs of any links it finds. We will use this program as a component of a **robot**, which is a program that traverses a Web site by downloading files and following links until it gets all the files (or at least all the files that can be reached by following links from the initial URI).

For several reasons, it is useful to make programs like this **multithreaded**, which means that there are several threads of execution running concurrently. The reasons are:

- Networks are slow compared to local processing, so it is often faster to run several network connections at the same time.
- Network performance is highly variable. When one connection is slow or stalled, another might be making progress.

Of course, if you have multiple connections to the same site, they compete with each other for resources in the network and on the server. So there is a point where increasing the number of connections is no longer useful.

6.8 Family planning

In the next couple of sections, we will develop a parent program that creates child processes to download files. The parent program will start with a single URI, and create a single child to download it. As the child discovers unvisited links, the parent will create additional children to download them. The role of the parent is to control the number of children that run concurrently and to maintain a list of URIs that are waiting to be downloaded.

Here is the main loop of the program.

```
sub main {
    our @list = @_;
    our %seen;
    our $procs = 0;
    our $s = IO::Select->new();

    while (1) {
        while (@list > 0 && $procs < 6) {
            get shift @list;
        }
        my @ready = $s->can_read;

        foreach my $fh (@ready) {
            process $fh;
        }
        last if (@list == 0 && $procs == 0);
    }
}
```

`@list` is the list of URIs waiting to be downloaded. Initially we get the list from the command-line arguments. `%seen` is a hash that contains the URIs we have already downloaded. Before we add a URI to `@list`, we make sure is is not already in `%seen`. `$procs` is the number of child processes currently running.

`$s` is an IO::Select object, which provides a convenient interface to the `select` system call. Right in the middle of the main loop, we invoke `can_read` on this object to get a list of the file handles that have data ready to read; that is, the list of child processes that have found a link.

The main loop contains two inner loops. The first controls the number of child processes; the second collects links from the children and adds them to the list.

The main loop exits when `@list` is empty and there are no child processes.

6.9 Creating children

Each time through the main loop, we check `@list` and create up to 6 child processes. For each element in the list, we invoke `get`.

```
sub get {
    our (%seen, $procs, $s);
    my $uris = shift;

    open my $fh, "./get.pl $uris |" or croak "can't fork";
    $seen{$uris}++;
    $procs++;
    $s->add($fh);
}
```

We have used the `open` operator before to open files. Here, we are using `open` to create a pipe. A **pipe** is a child process that communicates with the parent process through a file handle. In this case, the child process generates output using the `print` operator, and the parent reads it though the file handle.

If the `open` operator succeeds, we update `%seen` and `$procs`, and then add the new file handle, `$fh`, to the list of file handles being monitored by the Select object. Back in the main loop, when we invoke `can_read`, it tells us which of the file handles are ready to be read.

6.10 Talking back to parents

`can_read` doesn't complete until one or more file handles are ready. When it completes, we traverse the list of file handles and invoke `process` for each one.

```
sub process {
    our (@list, %seen, $procs, $s);
    my $fh = shift;
    my $line = <$fh>;
    chomp $line;

    if ($line eq "done") {
        close $fh;
        $s->remove($fh);
        $procs--;
    } else {
        push @list, $line unless defined $seen{$line};
    }
}
```

`process` uses the angle operator to read a single line from the given file handle, and `chomp` to remove the newline character.

Sometimes it is not a good idea to use the angle operator with `select`, but in this case, we know that whenever a child process produces data, it produces an entire line. So if a file handle is ready to be read, we know that we can read an entire line. Otherwise, the angle operator might block waiting for a child to produce the rest of a line.

`process` handles two cases. If the line we read is `done`, then we know the child process is done and we can close the file handle, remove it from the list of file handles in the Select object, and decrement the number of processes.

If the line is a link discovered by a child process, we add it to the list of URIs waiting to be downloaded, unless it is already in `%seen`.

Exercise 6.6 Assemble the code from the previous sections into a program named `mirror.pl` and test it by downloading files from a friendly Web site. You should use some caution, because the program as written is very aggressive. Downloading multiple files at the same time from the same site imposes a lot of load on the server. Robots are supposed to be more polite than than. For more information, see the documentation of `LWP::RobotUA`, which is a variation of UserAgent that imposes delays between downloads.

6.11 Exercises

Exercise 6.7 After you have made a local copy of a Web site, you might want to update it periodically. Of course, you could just download all the files (and any new ones) again, but it would be more efficient to download only the new files and the files that have been modified.

Modify the mirror program so that, before downloading a file, it checks whether you already have a local copy. If so, then it should get the modification date of the local file and issue a conditional request that will only download the file again if it has been modified since the last time you downloaded it.

Hints: see the `stat` command and the `File::Stat` modules for two ways to get the modification time of a local file. See the documentation of `HTTP::Headers` to see how to make a conditional request.

Exercise 6.8 The mirror program in this chapter doesn't handle redirection. If an HTML request is redirected, the URI of the file that is provided won't have the same name as the URI that was requested. For example, if you ask for `http://www.slashdot.com`, you actually get `http://slashdot.org/`

Ideally, the mirror program should invoke `base` on the Response object and use the reply to determine the file name. Unfortunately, if we use the callback form of `UserAgent::request`, we don't get the Response object until the transfer is complete.

As a challenge, think of several ways you could work around this problem and, if you are feeling ambitious, implement the one you think is best.

Exercise 6.9 The mirror program in this chapter doesn't handle fragments, which are URIs that refer to a part of a Web page. See the documentation of `URI` for more information and think about how you might fix the program.