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Introduction

Welcome to “The Rust Programming Language,” an introductory book about Rust. Rust is a programming language that’s focused on safety, speed, and concurrency. Its design lets you create programs that have the performance and control of a low-level language, but with the powerful abstractions of a high-level language. These properties make Rust suitable for programmers who have experience in languages like C and are looking for a safer alternative, as well as those from languages like Python who are looking for ways to write code that performs better without sacrificing expressiveness.

Rust performs the majority of its safety checks and memory management decisions at compile time, so that your program’s runtime performance isn’t impacted. This makes it useful in a number of use cases that other languages aren’t good at: programs with predictable space and time requirements, embedding in other languages, and writing low-level code, like device drivers and operating systems. It’s also great for web applications: it powers the Rust package registry site, crates.io! We’re excited to see what *you* create with Rust.

This book is written for a reader who already knows how to program in at least one programming language. After reading this book, you should be comfortable writing Rust programs. We’ll be learning Rust through small, focused examples that build on each other to demonstrate how to use various features of Rust as well as how they work behind the scenes.

Contributing to the book

This book is open source. If you find an error, please don’t hesitate to file an issue or send a pull request on GitHub. Please see CONTRIBUTING.md for more details.

Installation

The first step to using Rust is to install it. You’ll need an internet connection to run the commands in this chapter, as we’ll be downloading Rust from the internet.

We’ll be showing off a number of commands using a terminal, and those lines all start with `$`. You don’t need to type in the `$` character; they are there to indicate the start of each command. You’ll see many tutorials and examples around the web that follow this convention:

`$` for commands run as a regular user, and `#` for commands you should be running as an administrator. Lines that don't start with `$` are typically showing the output of the previous command.

Installing on Linux or Mac

If you're on Linux or a Mac, all you need to do is open a terminal and type this:

```
$ curl https://sh.rustup.rs -sSf | sh
```

This will download a script and start the installation. You may be prompted for your password. If it all goes well, you'll see this appear:

```
Rust is installed now. Great!
```

Of course, if you disapprove of the `curl | sh` pattern, you can download, inspect and run the script however you like.

The installation script automatically adds Rust to your system PATH after your next login. If you want to start using Rust right away, run the following command in your shell:

```
$ source $HOME/.cargo/env
```

Alternatively, add the following line to your `~/.bash_profile`:

```
$ export PATH="$HOME/.cargo/bin:$PATH"
```

Installing on Windows

On Windows, go to https://rustup.rs and follow the instructions to download rustup-init.exe. Run that and follow the rest of the instructions it gives you.

The rest of the Windows-specific commands in the book will assume that you are using `cmd` as your shell. If you use a different shell, you may be able to run the same commands that Linux and Mac users do. If neither work, consult the documentation for the shell you are using.

Custom installations

If you have reasons for preferring not to use rustup.rs, please see the Rust installation page for other options.

Updating

Once you have Rust installed, updating to the latest version is easy. From your shell, run the update script:

```
$ rustup update
```

Uninstalling

Uninstalling Rust is as easy as installing it. From your shell, run the uninstall script:

```
$ rustup self uninstall
```

Troubleshooting

If you’ve got Rust installed, you can open up a shell, and type this:

```
$ rustc --version
```

You should see the version number, commit hash, and commit date in a format similar to this for the latest stable version at the time you install:

```
rustc x.y.z (abcabcabc yyyy-mm-dd)
```

If you see this, Rust has been installed successfully! Congrats!

If you don’t and you’re on Windows, check that Rust is in your `%PATH%` system variable.

If it still isn’t working, there are a number of places where you can get help. The easiest is the #rust IRC channel on irc.mozilla.org, which you can access through Mibbit. Go to that address, and you’ll be chatting with other Rustaceans (a silly nickname we call ourselves) who can help you out. Other great resources include the Users forum and Stack Overflow.

Local documentation

The installer also includes a copy of the documentation locally, so you can read it offline. Run `rustup doc` to open the local documentation in your browser.

Any time there’s a type or function provided by the standard library and you’re not sure what it does, use the API documentation to find out!

Hello, World!

Now that you have Rust installed, let's write your first Rust program. It's traditional when learning a new language to write a little program to print the text "Hello, world!" to the screen, and in this section, we'll follow that tradition.

> Note: This book assumes basic familiarity with the command line. Rust itself makes no specific demands about your editing, tooling, or where your code lives, so if you prefer an IDE to the command line, feel free to use your favorite IDE.

Creating a Project Directory

First, make a directory to put your Rust code in. Rust doesn't care where your code lives, but for this book, we'd suggest making a *projects* directory in your home directory and keeping all your projects there. Open a terminal and enter the following commands to make a directory for this particular project:

Linux and Mac:

```
$ mkdir ~/projects
$ cd ~/projects
$ mkdir hello_world
$ cd hello_world
```

Windows CMD:

```
> mkdir %USERPROFILE%\projects
> cd %USERPROFILE%\projects
> mkdir hello_world
> cd hello_world
```

Windows PowerShell:

```
> mkdir $env:USERPROFILE\projects
> cd $env:USERPROFILE\projects
> mkdir hello_world
> cd hello_world
```

Writing and Running a Rust Program

Next, make a new source file and call it *main.rs*. Rust files always end with the *.rs* extension. If you're using more than one word in your filename, use an underscore to separate them. For example, you'd use *hello_world.rs* rather than *helloworld.rs*.

Now open the *main.rs* file you just created, and type the following code:

Filename: main.rs

```
fn main() {
    println!("Hello, world!");
}
```

Save the file, and go back to your terminal window. On Linux or OSX, enter the following commands:

```
$ rustc main.rs
$ ./main
Hello, world!
```

On Windows, run `.\main.exe` instead of `./main`. Regardless of your operating system, you should see the string `Hello, world!` print to the terminal. If you did, then congratulations! You've officially written a Rust program. That makes you a Rust programmer! Welcome!

Anatomy of a Rust Program

Now, let's go over what just happened in your "Hello, world!" program in detail. Here's the first piece of the puzzle:

```
fn main() {

}
```

These lines define a *function* in Rust. The `main` function is special: it's the first thing that is run for every executable Rust program. The first line says, "I'm declaring a function named `main` that has no parameters and returns nothing." If there were parameters, their names would go inside the parentheses, `(` and `)`.

Also note that the function body is wrapped in curly brackets, `{` and `}`. Rust requires these around all function bodies. It's considered good style to put the opening curly bracket on the same line as the function declaration, with one space in between.

Inside the `main` function:

```
    println!("Hello, world!");
```

This line does all of the work in this little program: it prints text to the screen. There are a number of details to notice here. The first is that Rust style is to indent with four spaces, not a tab.

The second important part is `println!`. This is calling a Rust *macro*, which is how metaprogramming is done in Rust. If it were calling a function instead, it would look like this: `println` (without the `!`). We'll discuss Rust macros in more detail in Appendix E, but for now you just need to know that when you see a `!` that means that you're calling a macro instead of a normal function.

Next is `"Hello, world!"` which is a *string*. We pass this string as an argument to `println!`, which prints the string to the screen. Easy enough!

The line ends with a semicolon (`;`). The `;` indicates that this expression is over, and the next one is ready to begin. Most lines of Rust code end with a `;`.

Compiling and Running Are Separate Steps

In "Writing and Running a Rust Program", we showed you how to run a newly created program. We'll break that process down and examine each step now.

Before running a Rust program, you have to compile it. You can use the Rust compiler by entering the `rustc` command and passing it the name of your source file, like this:

```
$ rustc main.rs
```

If you come from a C or C++ background, you'll notice that this is similar to `gcc` or `clang`. After compiling successfully, Rust should output a binary executable, which you can see on Linux or OSX by entering the `ls` command in your shell as follows:

```
$ ls
main  main.rs
```

On Windows, you'd enter:

```
> dir /B %= the /B option says to only show the file names =%
main.exe
main.rs
```

This shows we have two files: the source code, with the *.rs* extension, and the executable (*main.exe* on Windows, *main* everywhere else). All that's left to do from here is run the *main* or *main.exe* file, like this:

```
$ ./main  # or .\main.exe on Windows
```

If *main.rs* were your “Hello, world!” program, this would print `Hello, world!` to your terminal.

If you come from a dynamic language like Ruby, Python, or JavaScript, you may not be used to compiling and running a program being separate steps. Rust is an *ahead-of-time compiled* language, which means that you can compile a program, give it to someone else, and they can run it even without having Rust installed. If you give someone a `.rb`, `.py`, or `.js` file, on the other hand, they need to have a Ruby, Python, or JavaScript implementation installed (respectively), but you only need one command to both compile and run your program. Everything is a tradeoff in language design.

Just compiling with `rustc` is fine for simple programs, but as your project grows, you’ll want to be able to manage all of the options your project has and make it easy to share your code with other people and projects. Next, we’ll introduce you to a tool called Cargo, which will help you write real-world Rust programs.

Hello, Cargo!

Cargo is Rust’s build system and package manager, and Rustaceans use Cargo to manage their Rust projects because it makes a lot of tasks easier. For example, Cargo takes care of building your code, downloading the libraries your code depends on, and building those libraries. We call libraries your code needs *dependencies*.

The simplest Rust programs, like the one we’ve written so far, don’t have any dependencies, so right now, you’d only be using the part of Cargo that can take care of building your code. As you write more complex Rust programs, you’ll want to add dependencies, and if you start off using Cargo, that will be a lot easier to do.

As the vast, vast majority of Rust projects use Cargo, we will assume that you’re using it for the rest of the book. Cargo comes installed with Rust itself, if you used the official installers as covered in the Installation chapter. If you installed Rust through some other means, you can check if you have Cargo installed by typing the following into your terminal:

```
$ cargo --version
```

If you see a version number, great! If you see an error like `command not found`, then you should look at the documentation for your method of installation to determine how to install Cargo separately.

Creating a Project with Cargo

Let’s create a new project using Cargo and look at how it differs from our project in `hello_world`. Go back to your projects directory (or wherever you decided to put your code):

Linux and Mac:

```
$ cd ~/projects
```

Windows:

```
> cd %USERPROFILE%\projects
```

And then on any operating system run:

```
$ cargo new hello_cargo --bin
$ cd hello_cargo
```

We passed the `--bin` argument to `cargo new` because our goal is to make an executable application, as opposed to a library. Executables are binary executable files often called just *binaries*. We've given `hello_cargo` as the name for our project, and Cargo creates its files in a directory of the same name that we can then go into.

If we list the files in the *hello_cargo* directory, we can see that Cargo has generated two files and one directory for us: a *Cargo.toml* and a *src* directory with a *main.rs* file inside. It has also initialized a new git repository in the *hello_cargo* directory for us, along with a *.gitignore* file; you can change this to use a different version control system, or no version control system, by using the `--vcs` flag.

Open up *Cargo.toml* in your text editor of choice. It should look something like this:

Filename: Cargo.toml

```
[package]
name = "hello_cargo"
version = "0.1.0"
authors = ["Your Name <you@example.com>"]

[dependencies]
```

This file is in the *TOML* (Tom's Obvious, Minimal Language) format. TOML is similar to INI but has some extra goodies and is used as Cargo's configuration format.

The first line, `[package]`, is a section heading that indicates that the following statements are configuring a package. As we add more information to this file, we'll add other sections.

The next three lines set the three bits of configuration that Cargo needs to see in order to know that it should compile your program: its name, what version it is, and who wrote it. Cargo gets your name and email information from your environment. If it's not correct, go ahead and fix that and save the file.

The last line, `[dependencies]`, is the start of a section for you to list any *crates* (which is what we call packages of Rust code) that your project will depend on so that Cargo knows to download and compile those too. We won't need any other crates for this project, but we will in the guessing game tutorial in the next chapter.

Now let's look at *src/main.rs*:

Filename: src/main.rs

```
fn main() {
    println!("Hello, world!");
}
```

Cargo has generated a "Hello World!" for you, just like the one we wrote earlier! So that part is the same. The differences between our previous project and the project generated by Cargo that we've seen so far are:

- Our code goes in the *src* directory
- The top level contains a *Cargo.toml* configuration file

Cargo expects your source files to live inside the *src* directory so that the top-level project directory is just for READMEs, license information, configuration files, and anything else not related to your code. In this way, using Cargo helps you keep your projects nice and tidy. There's a place for everything, and everything is in its place.

If you started a project that doesn't use Cargo, as we did with our project in the *hello_world* directory, you can convert it to a project that does use Cargo by moving your code into the *src* directory and creating an appropriate *Cargo.toml*.

Building and Running a Cargo Project

Now let's look at what's different about building and running your Hello World program through Cargo! To do so, enter the following commands:

```
$ cargo build
   Compiling hello_cargo v0.1.0 (file:///projects/hello_cargo)
```

This should have created an executable file in *target/debug/hello_cargo* (or *target\debug\hello_cargo.exe* on Windows), which you can run with this command:

```
$ ./target/debug/hello_cargo # or .\target\debug\hello_cargo.exe on Windows
Hello, world!
```

Bam! If all goes well, `Hello, world!` should print to the terminal once more.

Running `cargo build` for the first time also causes Cargo to create a new file at the top level called *Cargo.lock*, which looks like this:

Filename: Cargo.lock

```
[root]
name = "hello_cargo"
version = "0.1.0"
```

Cargo uses the *Cargo.lock* to keep track of dependencies in your application. This project doesn't have dependencies, so the file is a bit sparse. Realistically, you won't ever need to touch this file yourself; just let Cargo handle it.

We just built a project with `cargo build` and ran it with `./target/debug/hello_cargo`, but we can also use `cargo run` to compile and then run:

```
$ cargo run
     Running `target/debug/hello_cargo`
Hello, world!
```

Notice that this time, we didn't see the output telling us that Cargo was compiling `hello_cargo`. Cargo figured out that the files haven't changed, so it just ran the binary. If you had modified your source code, Cargo would have rebuilt the project before running it, and you would have seen something like this:

```
$ cargo run
   Compiling hello_cargo v0.1.0 (file:///projects/hello_cargo)
     Running `target/debug/hello_cargo`
Hello, world!
```

So a few more differences we've now seen:

- Instead of using `rustc`, build a project using `cargo build` (or build and run it in one step with `cargo run`)
- Instead of the result of the build being put in the same directory as our code, Cargo will put it in the *target/debug* directory.

The other advantage of using Cargo is that the commands are the same no matter what operating system you're on, so at this point we will no longer be providing specific instructions for Linux and Mac versus Windows.

Building for Release

When your project is finally ready for release, you can use `cargo build --release` to compile your project with optimizations. This will create an executable in *target/release* instead of *target/debug*. These optimizations make your Rust code run faster, but turning them on makes your program take longer to compile. This is why there are two different profiles: one for development when you want to be able to rebuild quickly and often, and one for building the final program you'll give to a user that won't be rebuilt and that we want to run as fast as possible. If you're benchmarking the running time of your code, be sure to run `cargo build --release` and benchmark with the executable in *target/release*.

Cargo as Convention

With simple projects, Cargo doesn't provide a whole lot of value over just using `rustc`, but it will prove its worth as you continue. With complex projects composed of multiple crates, it's much easier to let Cargo coordinate the build. With Cargo, you can just run `cargo build`, and it should work the right way. Even though this project is simple, it now uses much of the real tooling you'll use for the rest of your Rust career. In fact, you can get started with virtually all Rust projects you want to work on with the following commands:

```
$ git clone someurl.com/someproject
$ cd someproject
$ cargo build
```

> Note: If you want to look at Cargo in more detail, check out the official Cargo guide, which covers all of its features.

Guessing Game

Let's jump into Rust by working through a hands-on project together! This chapter introduces you to a few common Rust concepts by showing you how to use them in a real program. You'll learn about `let`, `match`, methods, associated functions, using external crates, and more! The following chapters will explore these ideas in more detail. In this chapter, you'll practice the fundamentals.

We'll implement a classic beginner programming problem: a guessing game. Here's how it works: the program will generate a random integer between 1 and 100. It will then prompt the player to enter a guess. After entering a guess, it will indicate whether the guess is too low or too high. If the guess is correct, the game will print congratulations and exit.

Setting Up a New Project

To set up a new project, go to the *projects* directory that you created in Chapter 1, and make a new project using Cargo, like so:

```
$ cargo new guessing_game --bin
$ cd guessing_game
```

The first command, `cargo new`, takes the name of the project (`guessing_game`) as the first argument. The `--bin` flag tells Cargo to make a binary project, similar to the one in Chapter 1. The second command changes to the new project's directory.

Look at the generated *Cargo.toml* file:

Filename: Cargo.toml

```
[package]
name = "guessing_game"
version = "0.1.0"
authors = ["Your Name <you@example.com>"]

[dependencies]
```

If the author information that Cargo obtained from your environment is not correct, fix that in the file and save it again.

As you saw in Chapter 1, `cargo new` generates a "Hello, world!" program for you. Check out the *src/main.rs* file:

Filename: src/main.rs

```
fn main() {
    println!("Hello, world!");
}
```

Now let's compile this "Hello, world!" program and run it in the same step using the `cargo run` command:

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished dev [unoptimized + debuginfo] target(s) in 1.50 secs
     Running `target/debug/guessing_game`
Hello, world!
```

The `run` command comes in handy when you need to rapidly iterate on a project, and this game is such a project: we want to quickly test each iteration before moving on to the next one.

Reopen the *src/main.rs* file. You'll be writing all the code in this file.

Processing a Guess

The first part of the program will ask for user input, process that input, and check that the input is in the expected form. To start, we'll allow the player to input a guess. Enter the code in Listing 2-1 into *src/main.rs*.

Filename: src/main.rs

```
use std::io;

fn main() {
    println!("Guess the number!");

    println!("Please input your guess.");

    let mut guess = String::new();

    io::stdin().read_line(&mut guess)
        .expect("Failed to read line");

    println!("You guessed: {}", guess);
}
```

Listing 2-1: Code to get a guess from the user and print it out

This code contains a lot of information, so let's go over it bit by bit. To obtain user input and then print the result as output, we need to bring the `io` (input/output) library into scope. The `io` library comes from the standard library (which is known as `std`):

```
use std::io;
```

By default, Rust brings only a few types into the scope of every program in the *prelude*. If a type you want to use isn't in the prelude, you have to bring that type into scope explicitly with a `use` statement. Using the `std::io` library provides you with a number of useful `io`-related features, including the functionality to accept user input.

As you saw in Chapter 1, the `main` function is the entry point into the program:

```
fn main() {
```

The `fn` syntax declares a new function, the `()` indicate there are no parameters, and `{` starts the body of the function.

As you also learned in Chapter 1, `println!` is a macro that prints a string to the screen:

```
println!("Guess the number!");

println!("Please input your guess.");
```

This code is printing a prompt stating what the game is and requesting input from the user.

Storing Values with Variables

Next, we'll create a place to store the user input, like this:

```
let mut guess = String::new();
```

Now the program is getting interesting! There's a lot going on in this little line. Notice that this is a `let` statement, which is used to create *variables*. Here's another example:

```
let foo = bar;
```

This line will create a new variable named `foo` and bind it to the value `bar`. In Rust, variables are immutable by default. The following example shows how to use `mut` before the variable name to make a variable mutable:

```
let foo = 5; // immutable
let mut bar = 5; // mutable
```

> Note: The `//` syntax starts a comment that continues until the end of the line. Rust ignores everything in comments.

Now you know that `let mut guess` will introduce a mutable variable named `guess`. On the other side of the equal sign (`=`) is the value that `guess` is bound to, which is the result of calling `String::new`, a function that returns a new instance of a `String`. `String` is a string type provided by the standard library that is a growable, UTF-8 encoded bit of text.

The `::` syntax in the `::new` line indicates that `new` is an *associated function* of the `String` type. An associated function is implemented on a type, in this case `String`, rather than on a particular instance of a `String`. Some languages call this a *static method*.

This `new` function creates a new, empty `String`. You'll find a `new` function on many types, because it's a common name for a function that makes a new value of some kind.

To summarize, the `let mut guess = String::new();` line has created a mutable variable that is currently bound to a new, empty instance of a `String`. Whew!

Recall that we included the input/output functionality from the standard library with `use std::io;` on the first line of the program. Now we'll call an associated function, `stdin`, on `io`:

```
io::stdin().read_line(&mut guess)
    .expect("Failed to read line");
```

If we didn't have the `use std::io` line at the beginning of the program, we could have written this function call as `std::io::stdin`. The `stdin` function returns an instance of `std::io::Stdin`, which is a type that represents a handle to the standard input for your terminal.

The next part of the code, `.read_line(&mut guess)`, calls the `read_line` method on the standard input handle to get input from the user. We're also passing one argument to `read_line`: `&mut guess`.

The job of `read_line` is to take whatever the user types into standard input and place that into a string, so it takes that string as an argument. The string argument needs to be mutable so the method can change the string's content by adding the user input.

The `&` indicates that this argument is a *reference*, which gives you a way to let multiple parts of your code access one piece of data without needing to copy that data into memory multiple times. References are a complex feature, and one of Rust's major advantages is how safe and easy it is to use references. You don't need to know a lot of those details to finish this program: Chapter 4 will explain references more thoroughly. For now, all you need to know is that like variables, references are immutable by default. Hence, we need to write `&mut guess` rather than `&guess` to make it mutable.

We're not quite done with this line of code. Although it's a single line of text, it's only the first part of the single logical line of code. The second part is this method:

```
.expect("Failed to read line");
```

When you call a method with the `.foo()` syntax, it's often wise to introduce a newline and other whitespace to help break up long lines. We could have written this code as:

```
io::stdin().read_line(&mut guess).expect("Failed to read line");
```

However, one long line is difficult to read, so it's best to divide it, two lines for two method calls. Now let's discuss what this line does.

Handling Potential Failure with the `Result` Type

As mentioned earlier, `read_line` puts what the user types into the string we're passing it, but it also returns a value—in this case, an `io::Result`. Rust has a number of types named `Result` in its standard library: a generic `Result` as well as specific versions for submodules, such as `io::Result`.

The `Result` types are *enumerations*, often referred to as *enums*. An enumeration is a type that can have a fixed set of values, and those values are called the enum's *variants*. Chapter 6 will cover enums in more detail.

For `Result`, the variants are `Ok` or `Err`. `Ok` indicates the operation was successful, and inside the `Ok` variant is the successfully generated value. `Err` means the operation failed, and `Err` contains information about how or why the operation failed.

The purpose of these `Result` types is to encode error handling information. Values of the `Result` type, like any type, have methods defined on them. An instance of `io::Result` has an `expect` method that you can call. If this instance of `io::Result` is an `Err` value, `expect` will cause the program to crash and display the message that you passed as an argument to `expect`. If the `read_line` method returns an `Err`, it would likely be the result of an error coming from the underlying operating system. If this instance of `io::Result` is an `Ok` value, `expect` will take the return value that `Ok` is holding and return just that value to you so you could use it. In this case, that value is the number of bytes in what the user entered into standard input.

If we don't call `expect`, the program will compile, but we'll get a warning:

```
$ cargo build
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
warning: unused `std::result::Result` which must be used
  --> src/main.rs:10:5
   |
10 |     io::stdin().read_line(&mut guess);
   |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
   |
   = note: #[warn(unused_must_use)] on by default
```

Rust warns that we haven't used the `Result` value returned from `read_line`, indicating that the program hasn't handled a possible error. The right way to suppress the warning is to actually write error handling, but since we want to crash this program when a problem occurs, we can use `expect`. You'll learn about recovering from errors in Chapter 9.

Printing Values with `println!` Placeholders

Aside from the closing curly brackets, there's only one more line to discuss in the code added so far, which is the following:

```
println!("You guessed: {}", guess);
```

This line prints out the string we saved the user's input in. The set of `{}` is a placeholder that holds a value in place. You can print more than one value using `{}`: the first set of `{}` holds the first value listed after the format string, the second set holds the second value, and so on. Printing out multiple values in one call to `println!` would look like this:

```
let x = 5;
let y = 10;

println!("x = {} and y = {}", x, y);
```

This code would print out `x = 5 and y = 10`.

Testing the First Part

Let's test the first part of the guessing game. You can run it using `cargo run`:

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished dev [unoptimized + debuginfo] target(s) in 2.53 secs
     Running `target/debug/guessing_game`
Guess the number!
Please input your guess.
6
You guessed: 6
```

At this point, the first part of the game is done: we're getting input from the keyboard and then printing it.

Generating a Secret Number

Next, we need to generate a secret number that the user will try to guess. The secret number should be different every time so the game is fun to play more than once. Let's use a random number between 1 and 100 so the game isn't too difficult. Rust doesn't yet include random number functionality in its standard library. However, the Rust team does provide a `rand` crate.

Using a Crate to Get More Functionality

Remember that a *crate* is a package of Rust code. The project we've been building is a *binary crate*, which is an executable. The `rand` crate is a *library crate*, which contains code intended to be used in other programs.

Cargo's use of external crates is where it really shines. Before we can write code that uses `rand`, we need to modify the *Cargo.toml* file to include the `rand` crate as a dependency. Open that file now and add the following line to the bottom beneath the `[dependencies]` section header that Cargo created for you:

Filename: Cargo.toml

```
[dependencies]

rand = "0.3.14"
```

In the *Cargo.toml* file, everything that follows a header is part of a section that continues until another section starts. The `[dependencies]` section is where you tell Cargo which external crates your project depends on and which versions of those crates you require. In this case, we'll specify the `rand` crate with the semantic version specifier `0.3.14`. Cargo understands Semantic Versioning (sometimes called *SemVer*), which is a standard for writing version numbers. The number `0.3.14` is actually shorthand for `^0.3.14`, which means "any version that has a public API compatible with version 0.3.14."

Now, without changing any of the code, let's build the project, as shown in Listing 2-2:

```
$ cargo build
    Updating registry `https://github.com/rust-lang/crates.io-index`
 Downloading rand v0.3.14
 Downloading libc v0.2.14
   Compiling libc v0.2.14
   Compiling rand v0.3.14
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished dev [unoptimized + debuginfo] target(s) in 2.53 secs
```

Listing 2-2: The output from running `cargo build` after adding the rand crate as a dependency

You may see different version numbers (but they will all be compatible with the code, thanks to SemVer!), and the lines may be in a different order.

Now that we have an external dependency, Cargo fetches the latest versions of everything from the *registry*, which is a copy of data from Crates.io. Crates.io is where people in the Rust ecosystem post their open source Rust projects for others to use.

After updating the registry, Cargo checks the `[dependencies]` section and downloads any you don't have yet. In this case, although we only listed `rand` as a dependency, Cargo also grabbed a copy of `libc`, because `rand` depends on `libc` to work. After downloading them, Rust compiles them and then compiles the project with the dependencies available.

If you immediately run `cargo build` again without making any changes, you won't get any output. Cargo knows it has already downloaded and compiled the dependencies, and you haven't changed anything about them in your *Cargo.toml* file. Cargo also knows that you haven't changed anything about your code, so it doesn't recompile that either. With nothing to do, it simply exits. If you open up the *src/main.rs* file, make a trivial change, then save it and build again, you'll only see one line of output:

```
$ cargo build
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
```

This line shows Cargo only updates the build with your tiny change to the *src/main.rs* file. Your dependencies haven't changed, so Cargo knows it can reuse what it has already downloaded and compiled for those. It just rebuilds your part of the code.

The *Cargo.lock* File Ensures Reproducible Builds

Cargo has a mechanism that ensures you can rebuild the same artifact every time you or anyone else builds your code: Cargo will use only the versions of the dependencies you specified until you indicate otherwise. For example, what happens if next week version `v0.3.15` of the `rand` crate comes out and contains an important bug fix but also contains a regression that will break your code?

The answer to this problem is the *Cargo.lock* file, which was created the first time you ran `cargo build` and is now in your *guessing_game* directory. When you build a project for the first time, Cargo figures out all the versions of the dependencies that fit the criteria and then writes them to the *Cargo.lock* file. When you build your project in the future, Cargo will see that the *Cargo.lock* file exists and use the versions specified there rather than doing all the work of figuring out versions again. This lets you have a reproducible build automatically. In other words, your project will remain at `0.3.14` until you explicitly upgrade, thanks to the *Cargo.lock* file.

Updating a Crate to Get a New Version

When you *do* want to update a crate, Cargo provides another command, `update`, which will:

1. Ignore the *Cargo.lock* file and figure out all the latest versions that fit your specifications in *Cargo.toml*.
2. If that works, Cargo will write those versions to the *Cargo.lock* file.

But by default, Cargo will only look for versions larger than `0.3.0` and smaller than `0.4.0`. If the `rand` crate has released two new versions, `0.3.15` and `0.4.0`, you would see the following if you ran `cargo update`:

```
$ cargo update
    Updating registry `https://github.com/rust-lang/crates.io-index`
    Updating rand v0.3.14 -> v0.3.15
```

At this point, you would also notice a change in your *Cargo.lock* file noting that the version of the `rand` crate you are now using is `0.3.15`.

If you wanted to use `rand` version `0.4.0` or any version in the `0.4.x` series, you'd have to update the *Cargo.toml* file to look like this instead:

```
[dependencies]

rand = "0.4.0"
```

The next time you run `cargo build`, Cargo will update the registry of crates available and reevaluate your `rand` requirements according to the new version you specified.

There's a lot more to say about Cargo and its ecosystem that Chapter 14 will discuss, but for now, that's all you need to know. Cargo makes it very easy to reuse libraries, so Rustaceans are able to write smaller projects that are assembled from a number of packages.

Generating a Random Number

Let's start *using* `rand`. The next step is to update *src/main.rs*, as shown in Listing 2-3:

Filename: src/main.rs

```
extern crate rand;

use std::io;
use rand::Rng;

fn main() {
    println!("Guess the number!");

    let secret_number = rand::thread_rng().gen_range(1, 101);

    println!("The secret number is: {}", secret_number);

    println!("Please input your guess.");

    let mut guess = String::new();

    io::stdin().read_line(&mut guess)
        .expect("Failed to read line");

    println!("You guessed: {}", guess);
}
```

Listing 2-3: Code changes needed in order to generate a random number

We're adding a `extern crate rand;` line to the top that lets Rust know we'll be using that external dependency. This also does the equivalent of calling `use rand`, so now we can call anything in the `rand` crate by prefixing it with `rand::`.

Next, we're adding another `use` line: `use rand::Rng`. `Rng` is a trait that defines methods that random number generators implement, and this trait must be in scope for us to use those methods. Chapter 10 will cover traits in detail.

Also, we're adding two more lines in the middle. The `rand::thread_rng` function will give us the particular random number generator that we're going to use: one that is local to the current thread of execution and seeded by the operating system. Next, we call the `gen_range` method on the random number generator. This method is defined by the `Rng` trait that we brought into scope with the `use rand::Rng` statement. The `gen_range` method takes two numbers as arguments and generates a random number between them. It's inclusive on the lower bound but exclusive on the upper bound, so we need to specify `1` and `101` to request a number between 1 and 100.

Knowing which traits to use and which functions and methods to call from a crate isn't something that you'll just *know*. Instructions for using a crate are in each crate's documentation. Another neat feature of Cargo is that you can run the `cargo doc --open` command that will build documentation provided by all of your dependencies locally and open it in your browser. If you're interested in other functionality in the `rand` crate, for example, run `cargo doc --open` and click `rand` in the sidebar on the left.

The second line that we added to the code prints the secret number. This is useful while we're developing the program to be able to test it, but we'll delete it from the final version. It's not much of a game if the program prints the answer as soon as it starts!

Try running the program a few times:

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished dev [unoptimized + debuginfo] target(s) in 2.53 secs
     Running `target/debug/guessing_game`
Guess the number!
The secret number is: 7
Please input your guess.
4
You guessed: 4
$ cargo run
     Running `target/debug/guessing_game`
Guess the number!
The secret number is: 83
Please input your guess.
5
You guessed: 5
```

You should get different random numbers, and they should all be numbers between 1 and 100. Great job!

Comparing the Guess to the Secret Number

Now that we have user input and a random number, we can compare them. That step is shown in Listing 2-4:

Filename: src/main.rs

```
extern crate rand;

use std::io;
use std::cmp::Ordering;
use rand::Rng;

fn main() {
    println!("Guess the number!");

    let secret_number = rand::thread_rng().gen_range(1, 101);

    println!("The secret number is: {}", secret_number);

    println!("Please input your guess.");

    let mut guess = String::new();

    io::stdin().read_line(&mut guess)
        .expect("Failed to read line");

    println!("You guessed: {}", guess);

    match guess.cmp(&secret_number) {
        Ordering::Less    => println!("Too small!"),
        Ordering::Greater => println!("Too big!"),
        Ordering::Equal   => println!("You win!"),
    }
}
```

Listing 2-4: Handling the possible return values of comparing two numbers

The first new bit here is another `use`, bringing a type called `std::cmp::Ordering` into scope from the standard library. `Ordering` is another enum, like `Result`, but the variants for `Ordering` are `Less`, `Greater`, and `Equal`. These are the three outcomes that are possible when you compare two values.

Then we add five new lines at the bottom that use the `Ordering` type:

```
match guess.cmp(&secret_number) {
    Ordering::Less    => println!("Too small!"),
    Ordering::Greater => println!("Too big!"),
    Ordering::Equal   => println!("You win!"),
}
```

The `cmp` method compares two values and can be called on anything that can be compared. It takes a reference to whatever you want to compare with: here it's comparing the `guess` to the `secret_number`. `cmp` returns a variant of the `Ordering` enum we brought into scope with the `use` statement. We use a `match` expression to decide what to do next based on which variant of `Ordering` was returned from the call to `cmp` with the values in `guess` and `secret_number`.

A `match` expression is made up of *arms*. An arm consists of a *pattern* and the code that should be run if the value given to the beginning of the `match` expression fits that arm's pattern. Rust takes the value given to `match` and looks through each arm's pattern in turn. The `match` construct and patterns are powerful features in Rust that let you express a variety of situations your code might encounter and helps ensure that you handle them all. These features will be covered in detail in Chapter 6 and Chapter 18, respectively.

Let's walk through an example of what would happen with the `match` expression used here. Say that the user has guessed 50, and the randomly generated secret number this time is 38. When the code compares 50 to 38, the `cmp` method will return `Ordering::Greater`, because 50 is greater than 38. `Ordering::Greater` is the value that the `match` expression gets. It looks at the first arm's pattern, `Ordering::Less`, but the value `Ordering::Greater` does not match `Ordering::Less`, so it ignores the code in that arm and moves to the next arm. The next arm's pattern, `Ordering::Greater`, *does* match `Ordering::Greater`! The associated code in that arm will execute and print `Too big!` to the screen. The `match` expression ends because it has no need to look at the last arm in this particular scenario.

However, the code in Listing 2-4 won't compile yet. Let's try it:

```
$ cargo build
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
error[E0308]: mismatched types
  --> src/main.rs:23:21
   |
23 |     match guess.cmp(&secret_number) {
   |                     ^^^^^^^^^^^^^^ expected struct `std::string::String`,
found integral variable
   |
   = note: expected type `&std::string::String`
   = note:    found type `&{integer}`

error: aborting due to previous error
Could not compile `guessing_game`.
```

The core of the error states that there are *mismatched types*. Rust has a strong, static type system. However, it also has type inference. When we wrote `let guess = String::new()`, Rust was able to infer that `guess` should be a `String` and didn't make us write the type. The `secret_number`, on the other hand, is a number type. A few number types can have a value between 1 and 100: `i32`, a 32-bit number; `u32`, an unsigned 32-bit number; `i64`, a 64-bit number; as well as others. Rust defaults to an `i32`, which is the type of `secret_number` unless we add type information elsewhere that would cause Rust to infer a different numerical type. The reason for the error is that Rust will not compare a string and a number type.

Ultimately, we want to convert the `String` the program reads as input into a real number type so we can compare it to the guess numerically. We can do that by adding the following two lines to the `main` function body:

Filename: src/main.rs

```
extern crate rand;

use std::io;
use std::cmp::Ordering;
use rand::Rng;

fn main() {
    println!("Guess the number!");

    let secret_number = rand::thread_rng().gen_range(1, 101);

    println!("The secret number is: {}", secret_number);

    println!("Please input your guess.");

    let mut guess = String::new();

    io::stdin().read_line(&mut guess)
        .expect("Failed to read line");

    let guess: u32 = guess.trim().parse()
        .expect("Please type a number!");

    println!("You guessed: {}", guess);

    match guess.cmp(&secret_number) {
        Ordering::Less    => println!("Too small!"),
        Ordering::Greater => println!("Too big!"),
        Ordering::Equal   => println!("You win!"),
    }
}
```

The two new lines are:

```
let guess: u32 = guess.trim().parse()
    .expect("Please type a number!");
```

We create a variable named `guess`. But wait, doesn't the program already have a variable named `guess`? It does, but Rust allows us to *shadow* the previous value of `guess` with a new one. This feature is often used in similar situations in which you want to convert a value from one type to another type. Shadowing lets us reuse the `guess` variable name rather than forcing us to create two unique variables, like `guess_str` and `guess` for example. (Chapter 3 covers shadowing in more detail.)

We bind `guess` to the expression `guess.trim().parse()`. The `guess` in the expression refers to the original `guess` that was a `String` with the input in it. The `trim` method on a `String` instance will eliminate any whitespace at the beginning and end. `u32` can only contain numerical characters, but the user must press the ENTER key to satisfy `read_line`. When the user presses ENTER, a newline character is added to the string. For example, if the user types 5 and presses ENTER, `guess` looks like this: `5\n`. The `\n` represents "newline," the enter key. The `trim` method eliminates `\n`, resulting in just `5`.

The `parse` method on strings parses a string into some kind of number. Because this method can parse a variety of number types, we need to tell Rust the exact number type we want by using `let guess: u32`. The colon (`:`) after `guess` tells Rust we'll annotate the variable's type. Rust has a few built-in number types; the `u32` seen here is an unsigned, 32-bit integer. It's a good default choice for a small positive number. You'll learn about other number types in Chapter 3. Additionally, the `u32` annotation in this example program and the comparison with `secret_number` means that Rust will infer that `secret_number` should be a `u32` as well. So now the comparison will be between two values of the same type!

The call to `parse` could easily cause an error. If, for example, the string contained `A👍%`, there would be no way to convert that to a number. Because it might fail, the `parse` method returns a `Result` type, much like the `read_line` method does as discussed earlier in "Handling Potential Failure with the Result Type". We'll treat this `Result` the same way by using the `expect` method again. If `parse` returns an `Err` `Result` variant because it couldn't create a number from the string, the `expect` call will crash the game and print the message we give it. If `parse` can successfully convert the string to a number, it will return the `Ok` variant of `Result`, and `expect` will return the number that we want from the `Ok` value.

Let's run the program now!

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished dev [unoptimized + debuginfo] target(s) in 0.43 secs
     Running `target/guessing_game`
Guess the number!
The secret number is: 58
Please input your guess.
  76
You guessed: 76
Too big!
```

Nice! Even though spaces were added before the guess, the program still figured out that the user guessed 76. Run the program a few times to verify the different behavior with different kinds of input: guess the number correctly, guess a number that is too high, and guess a number that is too low.

We have most of the game working now, but the user can make only one guess. Let's change that by adding a loop!

Allowing Multiple Guesses with Looping

The `loop` keyword gives us an infinite loop. Add that now to give users more chances at guessing the number:

Filename: src/main.rs

```
extern crate rand;

use std::io;
use std::cmp::Ordering;
use rand::Rng;

fn main() {
    println!("Guess the number!");

    let secret_number = rand::thread_rng().gen_range(1, 101);

    println!("The secret number is: {}", secret_number);

    loop {
        println!("Please input your guess.");

        let mut guess = String::new();

        io::stdin().read_line(&mut guess)
            .expect("Failed to read line");

        let guess: u32 = guess.trim().parse()
            .expect("Please type a number!");

        println!("You guessed: {}", guess);

        match guess.cmp(&secret_number) {
            Ordering::Less    => println!("Too small!"),
            Ordering::Greater => println!("Too big!"),
            Ordering::Equal   => println!("You win!"),
        }
    }
}
```

As you can see, we've moved everything into a loop from the guess input prompt onward. Be sure to indent those lines another four spaces each, and run the program again. Notice that there is a new problem because the program is doing exactly what we told it to do: ask for another guess forever! It doesn't seem like the user can quit!

The user could always halt the program by using the keyboard shortcut CTRL-C. But there's another way to escape this insatiable monster that we mentioned in the `parse` discussion in "Comparing the Guess to the Secret Number": if the user enters a non-number answer, the program will crash. The user can take advantage of that in order to quit, as shown here:

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
     Running `target/guessing_game`
Guess the number!
The secret number is: 59
Please input your guess.
45
You guessed: 45
Too small!
Please input your guess.
60
You guessed: 60
Too big!
Please input your guess.
59
You guessed: 59
You win!
Please input your guess.
quit
thread 'main' panicked at 'Please type a number!: ParseIntError { kind:
InvalidDigit }', src/libcore/result.rs:785
note: Run with `RUST_BACKTRACE=1` for a backtrace.
error: Process didn't exit successfully: `target/debug/guess` (exit code: 101)
```

Typing `quit` actually quits the game, but so will any other non-number input. However, this is suboptimal to say the least. We want the game to automatically stop when the correct number is guessed.

Quitting After a Correct Guess

Let's program the game to quit when the user wins by adding a `break`:

Filename: src/main.rs

```
extern crate rand;

use std::io;
use std::cmp::Ordering;
use rand::Rng;

fn main() {
    println!("Guess the number!");

    let secret_number = rand::thread_rng().gen_range(1, 101);

    println!("The secret number is: {}", secret_number);

    loop {
        println!("Please input your guess.");

        let mut guess = String::new();

        io::stdin().read_line(&mut guess)
            .expect("Failed to read line");

        let guess: u32 = guess.trim().parse()
            .expect("Please type a number!");

        println!("You guessed: {}", guess);

        match guess.cmp(&secret_number) {
            Ordering::Less    => println!("Too small!"),
            Ordering::Greater => println!("Too big!"),
            Ordering::Equal   => {
                println!("You win!");
                break;
            }
        }
    }
}
```

By adding the `break` line after `You win!`, the program will exit the loop when the user guesses the secret number correctly. Exiting the loop also means exiting the program, because the loop is the last part of `main`.

Handling Invalid Input

To further refine the game's behavior, rather than crashing the program when the user inputs a non-number, let's make the game ignore a non-number so the user can continue guessing. We can do that by altering the line where `guess` is converted from a `String` to a `u32`:

```
let guess: u32 = match guess.trim().parse() {
    Ok(num) => num,
    Err(_) => continue,
};
```

Switching from an `expect` call to a `match` expression is how you generally move from crash on error to actually handling the error. Remember that `parse` returns a `Result` type, and `Result` is an enum that has the variants `Ok` or `Err`. We're using a `match` expression here, like we did with the `Ordering` result of the `cmp` method.

If `parse` is able to successfully turn the string into a number, it will return an `Ok` value that contains the resulting number. That `Ok` value will match the first arm's pattern, and the `match` expression will just return the `num` value that `parse` produced and put inside the `Ok` value. That number will end up right where we want it in the new `guess` variable we're creating.

If `parse` is *not* able to turn the string into a number, it will return an `Err` value that contains more information about the error. The `Err` value does not match the `Ok(num)` pattern in the first `match` arm, but it does match the `Err(_)` pattern in the second arm. The `_` is a catchall value; in this example, we're saying we want to match all `Err` values, no matter what information they have inside them. So the program will execute the second arm's code, `continue`, which means to go to the next iteration of the `loop` and ask for another guess. So effectively, the program ignores all errors that `parse` might encounter!

Now everything in the program should work as expected. Let's try it by running `cargo run`:

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
     Running `target/guessing_game`
Guess the number!
The secret number is: 61
Please input your guess.
10
You guessed: 10
Too small!
Please input your guess.
99
You guessed: 99
Too big!
Please input your guess.
foo
Please input your guess.
61
You guessed: 61
You win!
```

Awesome! With one tiny final tweak, we will finish the guessing game: recall that the program is still printing out the secret number. That worked well for testing, but it ruins the game. Let's delete the `println!` that outputs the secret number. Listing 2-5 shows the final code:

Filename: src/main.rs

```
extern crate rand;

use std::io;
use std::cmp::Ordering;
use rand::Rng;

fn main() {
    println!("Guess the number!");

    let secret_number = rand::thread_rng().gen_range(1, 101);

    loop {
        println!("Please input your guess.");

        let mut guess = String::new();

        io::stdin().read_line(&mut guess)
            .expect("Failed to read line");

        let guess: u32 = match guess.trim().parse() {
            Ok(num) => num,
            Err(_) => continue,
        };

        println!("You guessed: {}", guess);

        match guess.cmp(&secret_number) {
            Ordering::Less    => println!("Too small!"),
            Ordering::Greater => println!("Too big!"),
            Ordering::Equal   => {
                println!("You win!");
                break;
            }
        }
    }
}
```

Listing 2-5: Complete code of the guessing game

Summary

At this point, you've successfully built the guessing game! Congratulations!

This project was a hands-on way to introduce you to many new Rust concepts: `let`, `match`, methods, associated functions, using external crates, and more. In the next few chapters, you'll learn about these concepts in more detail. Chapter 3 covers concepts that most programming languages have, such as variables, data types, and functions, and shows how to use them in

Rust. Chapter 4 explores ownership, which is a Rust feature that is most different from other languages. Chapter 5 discusses structs and method syntax, and Chapter 6 endeavors to explain enums.

Common Programming Concepts

This chapter covers concepts that appear in almost every programming language and how they work in Rust. Many programming languages have much in common at their core. None of the concepts presented in this chapter are unique to Rust, but we'll discuss them in the context of Rust and explain their conventions.

Specifically, you'll learn about variables, basic types, functions, comments, and control flow. These foundations will be in every Rust program, and learning them early will give you a strong core to start from.

> ### Keywords
>
> The Rust language has a set of *keywords* that have been reserved for use by the language only, much like other languages do. Keep in mind that you cannot use these words as names of variables or functions. Most of the keywords have special meanings, and you'll be using them to do various tasks in your Rust programs; a few have no current functionality associated with them but have been reserved for functionality that might be added to Rust in the future. You can find a list of the keywords in Appendix A.

Variables and Mutability

As mentioned in Chapter 2, by default variables are *immutable*. This is one of many nudges in Rust that encourages you to write your code in a way that takes advantage of the safety and easy concurrency that Rust offers. However, you still have the option to make your variables mutable. Let's explore how and why Rust encourages you to favor immutability, and why you might want to opt out.

When a variable is immutable, that means once a value is bound to a name, you can't change that value. To illustrate, let's generate a new project called *variables* in your *projects* directory by using `cargo new --bin variables`.

Then, in your new *variables* directory, open *src/main.rs* and replace its code with the following:

Filename: src/main.rs

```
fn main() {
    let x = 5;
    println!("The value of x is: {}", x);
    x = 6;
    println!("The value of x is: {}", x);
}
```

Save and run the program using `cargo run`. You should receive an error message, as shown in this output:

```
error[E0384]: re-assignment of immutable variable `x`
 --> src/main.rs:4:5
  |
2 |     let x = 5;
  |         - first assignment to `x`
3 |     println!("The value of x is: {}", x);
4 |     x = 6;
  |     ^^^^^ re-assignment of immutable variable
```

This example shows how the compiler helps you find errors in your programs. Even though compiler errors can be frustrating, they only mean your program isn't safely doing what you want it to do yet; they do *not* mean that you're not a good programmer! Experienced Rustaceans still get compiler errors. The error indicates that the cause of the error is `re-assignment of immutable variable`, because we tried to assign a second value to the immutable `x` variable.

It's important that we get compile-time errors when we attempt to change a value that we previously designated as immutable because this very situation can lead to bugs. If one part of our code operates on the assumption that a value will never change and another part of our code changes that value, it's possible that the first part of the code won't do what it was designed to do. This cause of bugs can be difficult to track down after the fact, especially when the second piece of code changes the value only *sometimes*.

In Rust the compiler guarantees that when we state that a value won't change, it really won't change. That means that when you're reading and writing code, you don't have to keep track of how and where a value might change, which can make code easier to reason about.

But mutability can be very useful. Variables are immutable only by default; we can make them mutable by adding `mut` in front of the variable name. In addition to allowing this value to change, it conveys intent to future readers of the code by indicating that other parts of the code will be changing this variable value.

For example, change *src/main.rs* to the following:

Filename: src/main.rs

```
fn main() {
    let mut x = 5;
    println!("The value of x is: {}", x);
    x = 6;
    println!("The value of x is: {}", x);
}
```

When we run this program, we get the following:

```
$ cargo run
   Compiling variables v0.1.0 (file:///projects/variables)
    Finished dev [unoptimized + debuginfo] target(s) in 0.30 secs
     Running `target/debug/variables`
The value of x is: 5
The value of x is: 6
```

Using `mut`, we're allowed to change the value that `x` binds to from `5` to `6`. In some cases, you'll want to make a variable mutable because it makes the code more convenient to write than an implementation that only uses immutable variables.

There are multiple trade-offs to consider, in addition to the prevention of bugs. For example, in cases where you're using large data structures, mutating an instance in place may be faster than copying and returning newly allocated instances. With smaller data structures, creating new instances and writing in a more functional programming style may be easier to reason about, so the lower performance might be a worthwhile penalty for gaining that clarity.

Differences Between Variables and Constants

Being unable to change the value of a variable might have reminded you of another programming concept that most other languages have: *constants*. Like immutable variables, constants are also values that are bound to a name and are not allowed to change, but there are a few differences between constants and variables.

First, we aren't allowed to use `mut` with constants: constants aren't only immutable by default, they're always immutable.

We declare constants using the `const` keyword instead of the `let` keyword, and the type of the value *must* be annotated. We're about to cover types and type annotations in the next section, "Data Types," so don't worry about the details right now, just know that we must always annotate the type.

Constants can be declared in any scope, including the global scope, which makes them useful for values that many parts of code need to know about.

The last difference is that constants may only be set to a constant expression, not the result of a function call or any other value that could only be computed at runtime.

Here's an example of a constant declaration where the constant's name is `MAX_POINTS` and its value is set to 100,000. (Rust constant naming convention is to use all upper case with underscores between words):

```
const MAX_POINTS: u32 = 100_000;
```

Constants are valid for the entire time a program runs, within the scope they were declared in, making them a useful choice for values in your application domain that multiple parts of the program might need to know about, such as the maximum number of points any player of a game is allowed to earn or the speed of light.

Naming hardcoded values used throughout your program as constants is useful in conveying the meaning of that value to future maintainers of the code. It also helps to have only one place in your code you would need to change if the hardcoded value needed to be updated in the future.

Shadowing

As we saw in the guessing game tutorial in Chapter 2, we can declare a new variable with the same name as a previous variable, and the new variable *shadows* the previous variable. Rustaceans say that the first variable is *shadowed* by the second, which means that the second variable's value is what we'll see when we use the variable. We can shadow a variable by using the same variable's name and repeating the use of the `let` keyword as follows:

Filename: src/main.rs

```
fn main() {
    let x = 5;

    let x = x + 1;

    let x = x * 2;

    println!("The value of x is: {}", x);
}
```

This program first binds `x` to a value of `5`. Then it shadows `x` by repeating `let x =`, taking the original value and adding `1` so the value of `x` is then `6`. The third `let` statement also shadows `x`, taking the previous value and multiplying it by `2` to give `x` a final value of `12`. When you run this program, it will output the following:

```
$ cargo run
   Compiling variables v0.1.0 (file:///projects/variables)
    Finished dev [unoptimized + debuginfo] target(s) in 0.31 secs
     Running `target/debug/variables`
The value of x is: 12
```

This is different than marking a variable as `mut`, because unless we use the `let` keyword again, we'll get a compile-time error if we accidentally try to reassign to this variable. We can perform a few transformations on a value but have the variable be immutable after those transformations have been completed.

The other difference between `mut` and shadowing is that because we're effectively creating a new variable when we use the `let` keyword again, we can change the type of the value, but reuse the same name. For example, say our program asks a user to show how many spaces they want between some text by inputting space characters, but we really want to store that input as a number:

```
let spaces = "   ";
let spaces = spaces.len();
```

This construct is allowed because the first `spaces` variable is a string type, and the second `spaces` variable, which is a brand-new variable that happens to have the same name as the first one, is a number type. Shadowing thus spares us from having to come up with different names, like `spaces_str` and `spaces_num`; instead, we can reuse the simpler `spaces` name. However, if we try to use `mut` for this, as shown here:

```
let mut spaces = "   ";
spaces = spaces.len();
```

we'll get a compile-time error because we're not allowed to mutate a variable's type:

```
error[E0308]: mismatched types
 --> src/main.rs:3:14
  |
3 |     spaces = spaces.len();
  |              ^^^^^^^^^^^^ expected &str, found usize
  |
  = note: expected type `&str`
             found type `usize`
```

Now that we've explored how variables work, let's look at more data types they can have.

Data Types

Every value in Rust is of a certain *type*, which tells Rust what kind of data is being specified so it knows how to work with that data. In this section, we'll look at a number of types that are built into the language. We split the types into two subsets: scalar and compound.

Throughout this section, keep in mind that Rust is a *statically typed* language, which means that it must know the types of all variables at compile time. The compiler can usually infer what type we want to use based on the value and how we use it. In cases when many types are possible, such as when we converted a `String` to a numeric type using `parse` in Chapter 2, we must add a type annotation, like this:

```
let guess: u32 = "42".parse().expect("Not a number!");
```

If we don't add the type annotation here, Rust will display the following error, which means the compiler needs more information from us to know which possible type we want to use:

```
error[E0282]: type annotations needed
 --> src/main.rs:2:9
  |
2 |     let guess = "42".parse().expect("Not a number!");
  |         ^^^^^
  |         |
  |         cannot infer type for `_`
  |         consider giving `guess` a type
```

You'll see different type annotations as we discuss the various data types.

Scalar Types

A *scalar* type represents a single value. Rust has four primary scalar types: integers, floating-point numbers, booleans, and characters. You'll likely recognize these from other programming languages, but let's jump into how they work in Rust.

Integer Types

An *integer* is a number without a fractional component. We used one integer type earlier in this chapter, the `u32` type. This type declaration indicates that the value it's associated with should be an unsigned integer (signed integer types start with `i` instead of `u`) that takes up 32 bits of space. Table 3-1 shows the built-in integer types in Rust. Each variant in the Signed and Unsigned columns (for example, *i16*) can be used to declare the type of an integer value.

Table 3-1: Integer Types in Rust

Length	Signed	Unsigned

Length	Signed	Unsigned
8-bit	i8	u8
16-bit	i16	u16
32-bit	i32	u32
64-bit	i64	u64
arch	isize	usize

Each variant can be either signed or unsigned and has an explicit size. Signed and unsigned refers to whether it's possible for the number to be negative or positive; in other words, whether the number needs to have a sign with it (signed) or whether it will only ever be positive and can therefore be represented without a sign (unsigned). It's like writing numbers on paper: when the sign matters, a number is shown with a plus sign or a minus sign; however, when it's safe to assume the number is positive, it's shown with no sign. Signed numbers are stored using two's complement representation (if you're unsure what this is, you can search for it online; an explanation is outside the scope of this book).

Each signed variant can store numbers from $-(2^{n-1})$ to $2^{n-1} - 1$ inclusive, where `n` is the number of bits that variant uses. So an `i8` can store numbers from $-(2^7)$ to $2^7 - 1$, which equals -128 to 127. Unsigned variants can store numbers from 0 to $2^n - 1$, so a `u8` can store numbers from 0 to $2^8 - 1$, which equals 0 to 255.

Additionally, the `isize` and `usize` types depend on the kind of computer your program is running on: 64-bits if you're on a 64-bit architecture and 32-bits if you're on a 32-bit architecture.

You can write integer literals in any of the forms shown in Table 3-2. Note that all number literals except the byte literal allow a type suffix, such as `57u8`, and `_` as a visual separator, such as `1_000`.

Table 3-2: Integer Literals in Rust

Number literals	Example
Decimal	`98_222`
Hex	`0xff`
Octal	`0o77`
Binary	`0b1111_0000`
Byte (`u8` only)	`b'A'`

So how do you know which type of integer to use? If you're unsure, Rust's defaults are generally good choices, and integer types default to `i32`: it's generally the fastest, even on 64-bit systems. The primary situation in which you'd use `isize` or `usize` is when indexing some sort of collection.

Floating-Point Types

Rust also has two primitive types for *floating-point numbers*, which are numbers with decimal points. Rust's floating-point types are `f32` and `f64`, which are 32 bits and 64 bits in size, respectively. The default type is `f64` because on modern CPUs it's roughly the same speed as `f32` but is capable of more precision.

Here's an example that shows floating-point numbers in action:

Filename: src/main.rs

```
fn main() {
    let x = 2.0; // f64

    let y: f32 = 3.0; // f32
}
```

Floating-point numbers are represented according to the IEEE-754 standard. The `f32` type is a single-precision float, and `f64` has double precision.

Numeric Operations

Rust supports the usual basic mathematical operations you'd expect for all of the number types: addition, subtraction, multiplication, division, and remainder. The following code shows how you'd use each one in a `let` statement:

Filename: src/main.rs

```
fn main() {
    // addition
    let sum = 5 + 10;

    // subtraction
    let difference = 95.5 - 4.3;

    // multiplication
    let product = 4 * 30;

    // division
    let quotient = 56.7 / 32.2;

    // remainder
    let remainder = 43 % 5;
}
```

Each expression in these statements uses a mathematical operator and evaluates to a single value, which is then bound to a variable. Appendix B contains a list of all operators that Rust provides.

The Boolean Type

As in most other programming languages, a boolean type in Rust has two possible values: `true` and `false`. The boolean type in Rust is specified using `bool`. For example:

Filename: src/main.rs

```
fn main() {
    let t = true;

    let f: bool = false; // with explicit type annotation
}
```

The main way to consume boolean values is through conditionals, such as an `if` expression. We'll cover how `if` expressions work in Rust in the "Control Flow" section.

The Character Type

So far we've only worked with numbers, but Rust supports letters too. Rust's `char` type is the language's most primitive alphabetic type, and the following code shows one way to use it. Note that the `char` type is specified with single quotes, as opposed to strings that use double quotes:

Filename: src/main.rs

```
fn main() {
   let c = 'z';
   let z = 'ℤ';
   let heart_eyed_cat = '😻';
}
```

Rust's `char` type represents a Unicode Scalar Value, which means it can represent a lot more than just ASCII. Accented letters, Chinese/Japanese/Korean ideographs, emoji, and zero width spaces are all valid `char` types in Rust. Unicode Scalar Values range from `U+0000` to `U+D7FF` and `U+E000` to `U+10FFFF` inclusive. However, a "character" isn't really a concept in Unicode, so your human intuition for what a "character" is may not match up with what a `char` is in Rust. We'll discuss this topic in detail in the "Strings" section in Chapter 8.

Compound Types

Compound types can group multiple values of other types into one type. Rust has two primitive compound types: tuples and arrays.

Grouping Values into Tuples

A tuple is a general way of grouping together some number of other values with a variety of types into one compound type.

We create a tuple by writing a comma-separated list of values inside parentheses. Each position in the tuple has a type, and the types of the different values in the tuple don't have to be the same. We've added optional type annotations in this example:

Filename: src/main.rs

```
fn main() {
    let tup: (i32, f64, u8) = (500, 6.4, 1);
}
```

The variable `tup` binds to the entire tuple, since a tuple is considered a single compound element. To get the individual values out of a tuple, we can use pattern matching to destructure a tuple value, like this:

Filename: src/main.rs

```
fn main() {
    let tup = (500, 6.4, 1);

    let (x, y, z) = tup;

    println!("The value of y is: {}", y);
}
```

This program first creates a tuple and binds it to the variable `tup`. It then uses a pattern with `let` to take `tup` and turn it into three separate variables, `x`, `y`, and `z`. This is called *destructuring*, because it breaks the single tuple into three parts. Finally, the program prints the value of `y`, which is `6.4`.

In addition to destructuring through pattern matching, we can also access a tuple element directly by using a period (`.`) followed by the index of the value we want to access. For example:

Filename: src/main.rs

```
fn main() {
    let x: (i32, f64, u8) = (500, 6.4, 1);

    let five_hundred = x.0;

    let six_point_four = x.1;

    let one = x.2;
}
```

This program creates a tuple, `x`, and then makes new variables for each element by using their index. As with most programming languages, the first index in a tuple is 0.

Arrays

Another way to have a collection of multiple values is with an *array*. Unlike a tuple, every element of an array must have the same type. Arrays in Rust are different than arrays in some other languages because arrays in Rust have a fixed length: once declared, they cannot grow or shrink in size.

In Rust, the values going into an array are written as a comma-separated list inside square brackets:

Filename: src/main.rs

```
fn main() {
    let a = [1, 2, 3, 4, 5];
}
```

Arrays are useful when you want your data allocated on the stack rather than the heap (we will discuss the stack and the heap more in Chapter 4), or when you want to ensure you always have a fixed number of elements. They aren't as flexible as the vector type, though. The vector type is a similar collection type provided by the standard library that *is* allowed to grow or shrink in size. If you're unsure whether to use an array or a vector, you should probably use a vector: Chapter 8 discusses vectors in more detail.

An example of when you might want to use an array rather than a vector is in a program that needs to know the names of the months of the year. It's very unlikely that such a program will need to add or remove months, so you can use an array because you know it will always contain 12 items:

```
let months = ["January", "February", "March", "April", "May", "June", "July",
              "August", "September", "October", "November", "December"];
```

Accessing Array Elements

An array is a single chunk of memory allocated on the stack. We can access elements of an array using indexing, like this:

Filename: src/main.rs

```
fn main() {
    let a = [1, 2, 3, 4, 5];

    let first = a[0];
    let second = a[1];
}
```

In this example, the variable named `first` will get the value `1`, because that is the value at index `[0]` in the array. The variable named `second` will get the value `2` from index `[1]` in the array.

Invalid Array Element Access

What happens if we try to access an element of an array that is past the end of the array? Say we change the example to the following:

Filename: src/main.rs

```
fn main() {
    let a = [1, 2, 3, 4, 5];
    let index = 10;

    let element = a[index];

    println!("The value of element is: {}", element);
}
```

Running this code using `cargo run` produces the following result:

```
$ cargo run
   Compiling arrays v0.1.0 (file:///projects/arrays)
    Finished dev [unoptimized + debuginfo] target(s) in 0.31 secs
     Running `target/debug/arrays`
thread '<main>' panicked at 'index out of bounds: the len is 5 but the index is
 10', src/main.rs:6
note: Run with `RUST_BACKTRACE=1` for a backtrace.
```

The compilation didn't produce any errors, but the program results in a *runtime* error and didn't exit successfully. When you attempt to access an element using indexing, Rust will check that the index you've specified is less than the array length. If the index is greater than the length, Rust will *panic*, which is the term Rust uses when a program exits with an error.

This is the first example of Rust's safety principles in action. In many low-level languages, this kind of check is not done, and when you provide an incorrect index, invalid memory can be accessed. Rust protects you against this kind of error by immediately exiting instead of allowing the memory access and continuing. Chapter 9 discusses more of Rust's error handling.

How Functions Work

Functions are pervasive in Rust code. You've already seen one of the most important functions in the language: the `main` function, which is the entry point of many programs. You've also seen the `fn` keyword, which allows you to declare new functions.

Rust code uses *snake case* as the conventional style for function and variable names. In snake case, all letters are lowercase and underscores separate words. Here's a program that contains an example function definition:

Filename: src/main.rs

```
fn main() {
    println!("Hello, world!");

    another_function();
}

fn another_function() {
    println!("Another function.");
}
```

Function definitions in Rust start with `fn` and have a set of parentheses after the function name. The curly brackets tell the compiler where the function body begins and ends.

We can call any function we've defined by entering its name followed by a set of parentheses. Because `another_function` is defined in the program, it can be called from inside the `main` function. Note that we defined `another_function` *after* the `main` function in the source code; we could have defined it before as well. Rust doesn't care where you define your functions, only that they're defined somewhere.

Let's start a new binary project named *functions* to explore functions further. Place the `another_function` example in *src/main.rs* and run it. You should see the following output:

```
$ cargo run
   Compiling functions v0.1.0 (file:///projects/functions)
    Finished dev [unoptimized + debuginfo] target(s) in 0.28 secs
     Running `target/debug/functions`
Hello, world!
Another function.
```

The lines execute in the order in which they appear in the `main` function. First, the "Hello, world!" message prints, and then `another_function` is called and its message is printed.

Function Parameters

Functions can also be defined to have *parameters*, which are special variables that are part of a function's signature. When a function has parameters, we can provide it with concrete values for those parameters. Technically, the concrete values are called *arguments*, but in casual conversation people tend to use the words "parameter" and "argument" interchangeably for either the variables in a function's definition or the concrete values passed in when you call a function.

The following rewritten version of `another_function` shows what parameters look like in Rust:

Filename: src/main.rs

```
fn main() {
    another_function(5);
}

fn another_function(x: i32) {
    println!("The value of x is: {}", x);
}
```

Try running this program; you should get the following output:

```
$ cargo run
   Compiling functions v0.1.0 (file:///projects/functions)
    Finished dev [unoptimized + debuginfo] target(s) in 1.21 secs
     Running `target/debug/functions`
The value of x is: 5
```

The declaration of `another_function` has one parameter named `x`. The type of `x` is specified as `i32`. When `5` is passed to `another_function`, the `println!` macro puts `5` where the pair of curly brackets were in the format string.

In function signatures, you *must* declare the type of each parameter. This is a deliberate decision in Rust's design: requiring type annotations in function definitions means the compiler almost never needs you to use them elsewhere in the code to figure out what you mean.

When you want a function to have multiple parameters, separate the parameter declarations with commas, like this:

Filename: src/main.rs

```
fn main() {
    another_function(5, 6);
}

fn another_function(x: i32, y: i32) {
    println!("The value of x is: {}", x);
    println!("The value of y is: {}", y);
}
```

This example creates a function with two parameters, both of which are `i32` types. The function then prints out the values in both of its parameters. Note that function parameters don't all need to be the same type, they just happen to be in this example.

Let's try running this code. Replace the program currently in your *function* project's *src/main.rs* file with the preceding example, and run it using `cargo run`:

```
$ cargo run
   Compiling functions v0.1.0 (file:///projects/functions)
    Finished dev [unoptimized + debuginfo] target(s) in 0.31 secs
     Running `target/debug/functions`
The value of x is: 5
The value of y is: 6
```

Because we called the function with `5` as the value for `x` and `6` is passed as the value for `y`, the two strings are printed with these values.

Function Bodies

Function bodies are made up of a series of statements optionally ending in an expression. So far, we've only covered functions without an ending expression, but we have seen expressions as parts of statements. Because Rust is an expression-based language, this is an important distinction to understand. Other languages don't have the same distinctions, so let's look at what statements and expressions are and how their differences affect the bodies of functions.

Statements and Expressions

We've actually already used statements and expressions. *Statements* are instructions that perform some action and do not return a value. *Expressions* evaluate to a resulting value. Let's look at some examples.

Creating a variable and assigning a value to it with the `let` keyword is a statement. In Listing 3-3, `let y = 6;` is a statement:

Filename: src/main.rs

```
fn main() {
    let y = 6;
}
```

Listing 3-3: A `main` function declaration containing one statement.

Function definitions are also statements; the entire preceding example is a statement in itself.

Statements do not return values. Therefore, you can't assign a `let` statement to another variable, as the following code tries to do:

Filename: src/main.rs

```
fn main() {
    let x = (let y = 6);
}
```

When you run this program, you'll get an error like this:

```
$ cargo run
   Compiling functions v0.1.0 (file:///projects/functions)
error: expected expression, found statement (`let`)
 --> src/main.rs:2:14
  |
2 |     let x = (let y = 6);
  |              ^^^
  |
  = note: variable declaration using `let` is a statement
```

The `let y = 6` statement does not return a value, so there isn't anything for `x` to bind to. This is different than in other languages, such as C and Ruby, where the assignment returns the value of the assignment. In those languages, you can write `x = y = 6` and have both `x` and `y` have the value `6`; that is not the case in Rust.

Expressions evaluate to something and make up most of the rest of the code that you'll write in Rust. Consider a simple math operation, such as `5 + 6`, which is an expression that evaluates to the value `11`. Expressions can be part of statements: in Listing 3-3 that had the statement `let y = 6;`, `6` is an expression that evaluates to the value `6`. Calling a function is an expression. Calling a macro is an expression. The block that we use to create new scopes, `{}`, is an expression, for example:

Filename: src/main.rs

```
fn main() {
    let x = 5;

    let y = {
        let x = 3;
        x + 1
    };

    println!("The value of y is: {}", y);
}
```

This expression:

```
{
    let x = 3;
    x + 1
}
```

is a block that, in this case, evaluates to `4`. That value gets bound to `y` as part of the `let` statement. Note the `x + 1` line without a semicolon at the end, unlike most of the lines you've seen so far. Expressions do not include ending semicolons. If you add a semicolon to the end of an expression, you turn it into a statement, which will then not return a value. Keep this in mind as you explore function return values and expressions next.

Functions with Return Values

Functions can return values to the code that calls them. We don't name return values, but we do declare their type after an arrow (`->`). In Rust, the return value of the function is synonymous with the value of the final expression in the block of the body of a function. You can return early from a function by using the `return` keyword and specifying a value, but most functions return the last expression implicitly. Here's an example of a function that returns a value:

Filename: src/main.rs

```
fn five() -> i32 {
    5
}

fn main() {
    let x = five();

    println!("The value of x is: {}", x);
}
```

There are no function calls, macros, or even `let` statements in the `five` function—just the number `5` by itself. That's a perfectly valid function in Rust. Note that the function's return type is specified, too, as `-> i32`. Try running this code; the output should look like this:

```
$ cargo run
   Compiling functions v0.1.0 (file:///projects/functions)
    Finished dev [unoptimized + debuginfo] target(s) in 0.30 secs
     Running `target/debug/functions`
The value of x is: 5
```

The `5` in `five` is the function's return value, which is why the return type is `i32`. Let's examine this in more detail. There are two important bits: first, the line `let x = five();` shows that we're using the return value of a function to initialize a variable. Because the function `five` returns a `5`, that line is the same as the following:

```
let x = 5;
```

Second, the `five` function has no parameters and defines the type of the return value, but the body of the function is a lonely `5` with no semicolon because it's an expression whose value we want to return. Let's look at another example:

Filename: src/main.rs

```
fn main() {
    let x = plus_one(5);

    println!("The value of x is: {}", x);
}

fn plus_one(x: i32) -> i32 {
    x + 1
}
```

Running this code will print `The value of x is: 6`. What happens if we place a semicolon at the end of the line containing `x + 1`, changing it from an expression to a statement?

Filename: src/main.rs

```
fn main() {
    let x = plus_one(5);

    println!("The value of x is: {}", x);
}

fn plus_one(x: i32) -> i32 {
    x + 1;
}
```

Running this code produces an error, as follows:

```
error[E0308]: mismatched types
 --> src/main.rs:7:28
  |
7 |   fn plus_one(x: i32) -> i32 {
  |  ____________________________^
8 | |     x + 1;
  | |          - help: consider removing this semicolon
9 | | }
  | |_^ expected i32, found ()
  |
  = note: expected type `i32`
             found type `()`
```

The main error message, "mismatched types," reveals the core issue with this code. The definition of the function `plus_one` says that it will return an `i32`, but statements don't evaluate to a value, which is expressed by `()`, the empty tuple. Therefore, nothing is returned, which contradicts the function definition and results in an error. In this output, Rust provides a message to possibly help rectify this issue: it suggests removing the semicolon, which would fix the error.

Comments

All programmers strive to make their code easy to understand, but sometimes extra explanation is warranted. In these cases, programmers leave notes, or *comments*, in their source code that the compiler will ignore but people reading the source code may find useful.

Here's a simple comment:

```
// Hello, world.
```

In Rust, comments must start with two slashes and continue until the end of the line. For comments that extend beyond a single line, you'll need to include `//` on each line, like this:

```
// So we're doing something complicated here, long enough that we need
// multiple lines of comments to do it! Whew! Hopefully, this comment will
// explain what's going on.
```

Comments can also be placed at the end of lines containing code:

Filename: src/main.rs

```
fn main() {
    let lucky_number = 7; // I’m feeling lucky today.
}
```

But you’ll more often see them used in this format, with the comment on a separate line above the code it’s annotating:

Filename: src/main.rs

```
fn main() {
    // I’m feeling lucky today.
    let lucky_number = 7;
}
```

Rust also has another kind of comment, documentation comments, which we’ll discuss in Chapter 14.

Control Flow

Deciding whether or not to run some code depending on if a condition is true or deciding to run some code repeatedly while a condition is true are basic building blocks in most programming languages. The most common constructs that let you control the flow of execution of Rust code are `if` expressions and loops.

`if` Expressions

An `if` expression allows us to branch our code depending on conditions. We provide a condition and then state, “If this condition is met, run this block of code. If the condition is not met, do not run this block of code.”

Create a new project called *branches* in your *projects* directory to explore the `if` expression. In the *src/main.rs* file, input the following:

Filename: src/main.rs

```
fn main() {
    let number = 3;

    if number < 5 {
        println!("condition was true");
    } else {
        println!("condition was false");
    }
}
```

All `if` expressions start with the keyword `if`, which is followed by a condition. In this case, the condition checks whether or not the variable `number` has a value less than 5. The block of code we want to execute if the condition is true is placed immediately after the condition inside curly brackets. Blocks of code associated with the conditions in `if` expressions are sometimes called *arms*, just like the arms in `match` expressions that we discussed in the "Comparing the Guess to the Secret Number" section of Chapter 2. Optionally, we can also include an `else` expression, which we chose to do here, to give the program an alternative block of code to execute should the condition evaluate to false. If you don't provide an `else` expression and the condition is false, the program will just skip the `if` block and move on to the next bit of code.

Try running this code; you should see the following output:

```
$ cargo run
   Compiling branches v0.1.0 (file:///projects/branches)
    Finished dev [unoptimized + debuginfo] target(s) in 0.31 secs
     Running `target/debug/branches`
condition was true
```

Let's try changing the value of `number` to a value that makes the condition `false` to see what happens:

```
let number = 7;
```

Run the program again, and look at the output:

```
$ cargo run
   Compiling branches v0.1.0 (file:///projects/branches)
    Finished dev [unoptimized + debuginfo] target(s) in 0.31 secs
     Running `target/debug/branches`
condition was false
```

It's also worth noting that the condition in this code *must* be a `bool`. To see what happens if the condition isn't a `bool`, try running the following code:

Filename: src/main.rs

```
fn main() {
    let number = 3;

    if number {
        println!("number was three");
    }
}
```

The `if` condition evaluates to a value of `3` this time, and Rust throws an error:

```
error[E0308]: mismatched types
 --> src/main.rs:4:8
  |
4 |     if number {
  |        ^^^^^^ expected bool, found integral variable
  |
  = note: expected type `bool`
             found type `{integer}`
```

The error indicates that Rust expected a `bool` but got an integer. Rust will not automatically try to convert non-boolean types to a boolean, unlike languages such as Ruby and JavaScript. You must be explicit and always provide `if` with a `boolean` as its condition. If we want the `if` code block to run only when a number is not equal to `0`, for example, we can change the `if` expression to the following:

Filename: src/main.rs

```
fn main() {
    let number = 3;

    if number != 0 {
        println!("number was something other than zero");
    }
}
```

Running this code will print `number was something other than zero`.

Multiple Conditions with `else if`

We can have multiple conditions by combining `if` and `else` in an `else if` expression. For example:

Filename: src/main.rs

```
fn main() {
    let number = 6;

    if number % 4 == 0 {
        println!("number is divisible by 4");
    } else if number % 3 == 0 {
        println!("number is divisible by 3");
    } else if number % 2 == 0 {
        println!("number is divisible by 2");
    } else {
        println!("number is not divisible by 4, 3, or 2");
    }
}
```

This program has four possible paths it can take. After running it, you should see the following output:

```
$ cargo run
   Compiling branches v0.1.0 (file:///projects/branches)
    Finished dev [unoptimized + debuginfo] target(s) in 0.31 secs
     Running `target/debug/branches`
number is divisible by 3
```

When this program executes, it checks each `if` expression in turn and executes the first body for which the condition holds true. Note that even though 6 is divisible by 2, we don't see the output `number is divisible by 2`, nor do we see the `number is not divisible by 4, 3, or 2` text from the `else` block. The reason is that Rust will only execute the block for the first true condition, and once it finds one, it won't even check the rest.

Using too many `else if` expressions can clutter your code, so if you have more than one, you might want to refactor your code. Chapter 6 describes a powerful Rust branching construct called `match` for these cases.

Using `if` in a `let` statement

Because `if` is an expression, we can use it on the right side of a `let` statement, for instance in Listing 3-4:

Filename: src/main.rs

```
fn main() {
    let condition = true;
    let number = if condition {
        5
    } else {
        6
    };

    println!("The value of number is: {}", number);
}
```

Listing 3-4: Assigning the result of an `if` expression to a variable

The `number` variable will be bound to a value based on the outcome of the `if` expression. Run this code to see what happens:

```
$ cargo run
   Compiling branches v0.1.0 (file:///projects/branches)
    Finished dev [unoptimized + debuginfo] target(s) in 0.30 secs
     Running `target/debug/branches`
The value of number is: 5
```

Remember that blocks of code evaluate to the last expression in them, and numbers by themselves are also expressions. In this case, the value of the whole `if` expression depends on which block of code executes. This means the values that have the potential to be results from each arm of the `if` must be the same type; in Listing 3-4, the results of both the `if` arm and the `else` arm were `i32` integers. But what happens if the types are mismatched, as in the following example?

Filename: src/main.rs

```
fn main() {
    let condition = true;

    let number = if condition {
        5
    } else {
        "six"
    };

    println!("The value of number is: {}", number);
}
```

When we try to run this code, we'll get an error. The `if` and `else` arms have value types that are incompatible, and Rust indicates exactly where to find the problem in the program:

```
error[E0308]: if and else have incompatible types
 --> src/main.rs:4:18
  |
4 |       let number = if condition {
  |  __________________^
5 | |         5
6 | |     } else {
7 | |         "six"
8 | |     };
  | |_____^ expected integral variable, found reference
  |
  = note: expected type `{integer}`
             found type `&str`
```

The expression in the `if` block evaluates to an integer, and the expression in the `else` block evaluates to a string. This won't work because variables must have a single type. Rust needs to know at compile time what type the `number` variable is, definitively, so it can verify at compile time that its type is valid everywhere we use `number`. Rust wouldn't be able to do that if the type of `number` was only determined at runtime; the compiler would be more complex and would make fewer guarantees about the code if it had to keep track of multiple hypothetical types for any variable.

Repetition with Loops

It's often useful to execute a block of code more than once. For this task, Rust provides several *loops*. A loop runs through the code inside the loop body to the end and then starts immediately back at the beginning. To experiment with loops, let's make a new project called *loops*.

Rust has three kinds of loops: `loop`, `while`, and `for`. Let's try each one.

Repeating Code with `loop`

The `loop` keyword tells Rust to execute a block of code over and over again forever or until you explicitly tell it to stop.

As an example, change the *src/main.rs* file in your *loops* directory to look like this:

Filename: src/main.rs

```
fn main() {
    loop {
        println!("again!");
    }
}
```

When we run this program, we'll see `again!` printed over and over continuously until we stop the program manually. Most terminals support a keyboard shortcut, CTRL-C, to halt a program that is stuck in a continual loop. Give it a try:

```
$ cargo run
   Compiling loops v0.1.0 (file:///projects/loops)
    Finished dev [unoptimized + debuginfo] target(s) in 0.29 secs
     Running `target/debug/loops`
again!
again!
again!
again!
^Cagain!
```

The symbol `^C` represents where you pressed CTRL-C . You may or may not see the word `again!` printed after the `^C`, depending on where the code was in the loop when it received the halt signal.

Fortunately, Rust provides another, more reliable way to break out of a loop. You can place the `break` keyword within the loop to tell the program when to stop executing the loop. Recall that we did this in the guessing game in the "Quitting After a Correct Guess" section of Chapter 2 to exit the program when the user won the game by guessing the correct number.

Conditional Loops with `while`

It's often useful for a program to evaluate a condition within a loop. While the condition is true, the loop runs. When the condition ceases to be true, you call `break`, stopping the loop. This loop type could be implemented using a combination of `loop`, `if`, `else`, and `break`; you could try that now in a program, if you'd like.

However, this pattern is so common that Rust has a built-in language construct for it, and it's called a `while` loop. The following example uses `while`: the program loops three times, counting down each time. Then, after the loop, it prints another message and exits:

Filename: src/main.rs

```
fn main() {
    let mut number = 3;

    while number != 0 {
        println!("{}!", number);

        number = number - 1;
    }

    println!("LIFTOFF!!!");
}
```

This construct eliminates a lot of nesting that would be necessary if you used `loop`, `if`, `else`, and `break`, and it's clearer. While a condition holds true, the code runs; otherwise, it exits the loop.

Looping Through a Collection with `for`

You could use the `while` construct to loop over the elements of a collection, such as an array. For example, let's look at Listing 3-5:

Filename: src/main.rs

```
fn main() {
    let a = [10, 20, 30, 40, 50];
    let mut index = 0;

    while index < 5 {
        println!("the value is: {}", a[index]);

        index = index + 1;
    }
}
```

Listing 3-5: Looping through each element of a collection using a `while` loop

Here, the code counts up through the elements in the array. It starts at index `0`, and then loops until it reaches the final index in the array (that is, when `index < 5` is no longer true). Running this code will print out every element in the array:

```
$ cargo run
   Compiling loops v0.1.0 (file:///projects/loops)
    Finished dev [unoptimized + debuginfo] target(s) in 0.32 secs
     Running `target/debug/loops`
the value is: 10
the value is: 20
the value is: 30
the value is: 40
the value is: 50
```

All five array values appear in the terminal, as expected. Even though `index` will reach a value of `5` at some point, the loop stops executing before trying to fetch a sixth value from the array.

But this approach is error prone; we could cause the program to panic if the index length is incorrect. It's also slow, because the compiler adds runtime code to perform the conditional check on every element on every iteration through the loop.

As a more efficient alternative, you can use a `for` loop and execute some code for each item in a collection. A `for` loop looks like this code in Listing 3-6:

Filename: src/main.rs

```
fn main() {
    let a = [10, 20, 30, 40, 50];

    for element in a.iter() {
        println!("the value is: {}", element);
    }
}
```

Listing 3-6: Looping through each element of a collection using a `for` loop

When we run this code, we'll see the same output as in Listing 3-5. More importantly, we've now increased the safety of the code and eliminated the chance of bugs that might result from going beyond the end of the array or not going far enough and missing some items.

For example, in the code in Listing 3-5, if you removed an item from the `a` array but forgot to update the condition to `while index < 4`, the code would panic. Using the `for` loop, you don't need to remember to change any other code if you changed the number of values in the array.

The safety and conciseness of `for` loops make them the most commonly used loop construct in Rust. Even in situations in which you want to run some code a certain number of times, as in the countdown example that used a `while` loop in Listing 3-5, most Rustaceans would use a `for` loop. The way to do that would be to use a `Range`, which is a type provided by the standard library that generates all numbers in sequence starting from one number and ending before another number.

Here's what the countdown would look like using a `for` loop and another method we've not yet talked about, `rev`, to reverse the range:

Filename: src/main.rs

```
fn main() {
    for number in (1..4).rev() {
        println!("{}!", number);
    }
    println!("LIFTOFF!!!");
}
```

This code is a bit nicer, isn't it?

Summary

You made it! That was a sizable chapter: you learned about variables, scalar and `if` expressions, and loops! If you want to practice with the concepts discussed in this chapter, try building programs to do the following:

- Convert temperatures between Fahrenheit and Celsius.
- Generate the nth Fibonacci number.
- Print the lyrics to the Christmas carol "The Twelve Days of Christmas," taking advantage of the repetition in the song.

When you're ready to move on, we'll talk about a concept in Rust that *doesn't* commonly exist in other programming languages: ownership.

Understanding Ownership

Ownership is Rust's most unique feature, and it enables Rust to make memory safety guarantees without needing a garbage collector. Therefore, it's important to understand how ownership works in Rust. In this chapter we'll talk about ownership as well as several related features: borrowing, slices, and how Rust lays data out in memory.

What Is Ownership?

Rust's central feature is *ownership*. Although the feature is straightforward to explain, it has deep implications for the rest of the language.

All programs have to manage the way they use a computer's memory while running. Some languages have garbage collection that constantly looks for no longer used memory as the program runs; in other languages, the programmer must explicitly allocate and free the memory. Rust uses a third approach: memory is managed through a system of ownership with a set of rules that the compiler checks at compile time. No run-time costs are incurred for any of the ownership features.

Because ownership is a new concept for many programmers, it does take some time to get used to. The good news is that the more experienced you become with Rust and the rules of the ownership system, the more you'll be able to naturally develop code that is safe and efficient. Keep at it!

When you understand ownership, you'll have a solid foundation for understanding the features that make Rust unique. In this chapter, you'll learn ownership by working through some examples that focus on a very common data structure: strings.

The Stack and the Heap

In many programming languages, we don’t have to think about the stack and the heap very often. But in a systems programming language like Rust, whether a value is on the stack or the heap has more of an effect on how the language behaves and why we have to make certain decisions. We’ll describe parts of ownership in relation to the stack and the heap later in this chapter, so here is a brief explanation in preparation.

Both the stack and the heap are parts of memory that is available to your code to use at runtime, but they are structured in different ways. The stack stores values in the order it gets them and removes the values in the opposite order. This is referred to as *last in, first out*. Think of a stack of plates: when you add more plates, you put them on top of the pile, and when you need a plate, you take one off the top. Adding or removing plates from the middle or bottom wouldn’t work as well! Adding data is called *pushing onto the stack*, and removing data is called *popping off the stack*.

The stack is fast because of the way it accesses the data: it never has to search for a place to put new data or a place to get data from because that place is always the top. Another property that makes the stack fast is that all data on the stack must take up a known, fixed size.

For data with a size unknown to us at compile time or a size that might change, we can store data on the heap instead. The heap is less organized: when we put data on the heap, we ask for some amount of space. The operating system finds an empty spot somewhere in the heap that is big enough, marks it as being in use, and returns to us a pointer to that location. This process is called *allocating on the heap*, and sometimes we abbreviate the phrase as just “allocating.” Pushing values onto the stack is not considered allocating. Because the pointer is a known, fixed size, we can store the pointer on the stack, but when we want the actual data, we have to follow the pointer.

Think of being seated at a restaurant. When you enter, you state the number of people in your group, and the staff finds an empty table that fits everyone and leads you there. If someone in your group comes late, they can ask where you’ve been seated to find you.

Accessing data in the heap is slower than accessing data on the stack because we have to follow a pointer to get there. Contemporary processors are faster if they jump around less in memory. Continuing the analogy, consider a server at a restaurant taking orders from many tables. It’s most efficient to get all the orders at one table before moving on to the next table. Taking an order from table A, then an order from table B, then one from A again, and then one from B again would be a much slower process. By the same token, a processor can do its job better if it works on data that’s close to other data (as it is on the stack) rather than farther away (as it can be on the heap). Allocating a large amount of space on the heap can also take time.

When our code calls a function, the values passed into the function (including, potentially, pointers to data on the heap) and the function’s local variables get pushed onto the stack.

When the function is over, those values get popped off the stack.

Keeping track of what parts of code are using what data on the heap, minimizing the amount of duplicate data on the heap, and cleaning up unused data on the heap so we don’t run out of space are all problems that ownership addresses. Once you understand ownership, you won’t need to think about the stack and the heap very often, but knowing that managing heap data is why ownership exists can help explain why it works the way it does.

Ownership Rules

First, let’s take a look at the ownership rules. Keep these rules in mind as we work through the examples that illustrate the rules:

---

1. Each value in Rust has a variable that’s called its *owner*.
2. There can only be one owner at a time.
3. When the owner goes out of scope, the value will be dropped.

Variable Scope

We’ve walked through an example of a Rust program already in Chapter 2. Now that we’re past basic syntax, we won’t include all the `fn main() {` code in examples, so if you’re following along, you’ll have to put the following examples inside a `main` function manually. As a result, our examples will be a bit more concise, letting us focus on the actual details rather than boilerplate code.

As a first example of ownership, we’ll look at the *scope* of some variables. A scope is the range within a program for which an item is valid. Let’s say we have a variable that looks like this:

```rust
let s = "hello";
```

The variable `s` refers to a string literal, where the value of the string is hardcoded into the text of our program. The variable is valid from the point at which it’s declared until the end of the current *scope*. Listing 4-1 has comments annotating where the variable `s` is valid:

```
{                      // s is not valid here, it’s not yet declared
    let s = "hello";   // s is valid from this point forward

    // do stuff with s
}                      // this scope is now over, and s is no longer valid
```

Listing 4-1: A variable and the scope in which it is valid

In other words, there are two important points in time here:

1. When `s` comes *into scope*, it is valid.
2. It remains so until it goes *out of scope*.

At this point, the relationship between scopes and when variables are valid is similar to other programming languages. Now we’ll build on top of this understanding by introducing the `String` type.

The `String` Type

To illustrate the rules of ownership, we need a data type that is more complex than the ones we covered in Chapter 3. All the data types we’ve looked at previously are stored on the stack and popped off the stack when their scope is over, but we want to look at data that is stored on the heap and explore how Rust knows when to clean up that data.

We’ll use `String` as the example here and concentrate on the parts of `String` that relate to ownership. These aspects also apply to other complex data types provided by the standard library and that you create. We’ll discuss `String` in more depth in Chapter 8.

We’ve already seen string literals, where a string value is hardcoded into our program. String literals are convenient, but they aren’t always suitable for every situation in which you want to use text. One reason is that they’re immutable. Another is that not every string value can be known when we write our code: for example, what if we want to take user input and store it? For these situations, Rust has a second string type, `String`. This type is allocated on the heap and as such is able to store an amount of text that is unknown to us at compile time. You can create a `String` from a string literal using the `from` function, like so:

```
let s = String::from("hello");
```

The double colon (`::`) is an operator that allows us to namespace this particular `from` function under the `String` type rather than using some sort of name like `string_from`. We’ll discuss this syntax more in the “Method Syntax” section of Chapter 5 and when we talk about namespacing with modules in Chapter 7.

This kind of string *can* be mutated:

```
let mut s = String::from("hello");

s.push_str(", world!"); // push_str() appends a literal to a String

println!("{}", s); // This will print `hello, world!`
```

So, what's the difference here? Why can `String` be mutated but literals cannot? The difference is how these two types deal with memory.

Memory and Allocation

In the case of a string literal, we know the contents at compile time so the text is hardcoded directly into the final executable, making string literals fast and efficient. But these properties only come from its immutability. Unfortunately, we can't put a blob of memory into the binary for each piece of text whose size is unknown at compile time and whose size might change while running the program.

With the `String` type, in order to support a mutable, growable piece of text, we need to allocate an amount of memory on the heap, unknown at compile time, to hold the contents. This means:

1. The memory must be requested from the operating system at runtime.
2. We need a way of returning this memory to the operating system when we're done with our `String`.

That first part is done by us: when we call `String::from`, its implementation requests the memory it needs. This is pretty much universal in programming languages.

However, the second part is different. In languages with a *garbage collector (GC)*, the GC keeps track and cleans up memory that isn't being used anymore, and we, as the programmer, don't need to think about it. Without a GC, it's the programmer's responsibility to identify when memory is no longer being used and call code to explicitly return it, just as we did to request it. Doing this correctly has historically been a difficult programming problem. If we forget, we'll waste memory. If we do it too early, we'll have an invalid variable. If we do it twice, that's a bug too. We need to pair exactly one `allocate` with exactly one `free`.

Rust takes a different path: the memory is automatically returned once the variable that owns it goes out of scope. Here's a version of our scope example from Listing 4-1 using a `String` instead of a string literal:

```
{
    let s = String::from("hello"); // s is valid from this point forward

    // do stuff with s
}                                  // this scope is now over, and s is no
                                   // longer valid
```

There is a natural point at which we can return the memory our `String` needs to the operating system: when `s` goes out of scope. When a variable goes out of scope, Rust calls a special function for us. This function is called `drop`, and it's where the author of `String` can put the code to return the memory. Rust calls `drop` automatically at the closing `}`.

> Note: In C++, this pattern of deallocating resources at the end of an item's lifetime is sometimes called *Resource Acquisition Is Initialization (RAII)*. The `drop` function in Rust will be familiar to you if you've used RAII patterns.

This pattern has a profound impact on the way Rust code is written. It may seem simple right now, but the behavior of code can be unexpected in more complicated situations when we want to have multiple variables use the data we've allocated on the heap. Let's explore some of those situations now.

Ways Variables and Data Interact: Move

Multiple variables can interact with the same data in different ways in Rust. Let's look at an example using an integer in Listing 4-2:

```
let x = 5;
let y = x;
```

Listing 4-2: Assigning the integer value of variable `x` to `y`

We can probably guess what this is doing based on our experience with other languages: "Bind the value `5` to `x`; then make a copy of the value in `x` and bind it to `y`." We now have two variables, `x` and `y`, and both equal `5`. This is indeed what is happening because integers are simple values with a known, fixed size, and these two `5` values are pushed onto the stack.

Now let's look at the `String` version:

```
let s1 = String::from("hello");
let s2 = s1;
```

This looks very similar to the previous code, so we might assume that the way it works would be the same: that is, the second line would make a copy of the value in `s1` and bind it to `s2`. But this isn't quite what happens.

To explain this more thoroughly, let's look at what `String` looks like under the covers in Figure 4-3. A `String` is made up of three parts, shown on the left: a pointer to the memory that holds the contents of the string, a length, and a capacity. This group of data is stored on the stack. On the right is the memory on the heap that holds the contents.

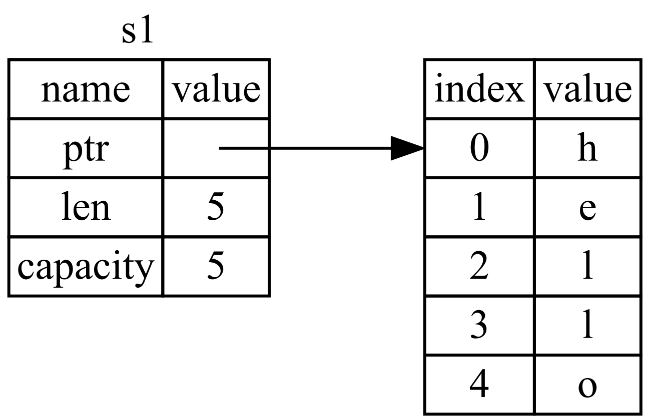


Figure 4-3: Representation in memory of a `String` holding the value `"hello"` bound to `s1`

The length is how much memory, in bytes, the contents of the `String` is currently using. The capacity is the total amount of memory, in bytes, that the `String` has received from the operating system. The difference between length and capacity matters, but not in this context, so for now, it's fine to ignore the capacity.

When we assign `s1` to `s2`, the `String` data is copied, meaning we copy the pointer, the length, and the capacity that are on the stack. We do not copy the data on the heap that the pointer refers to. In other words, the data representation in memory looks like Figure 4-4.

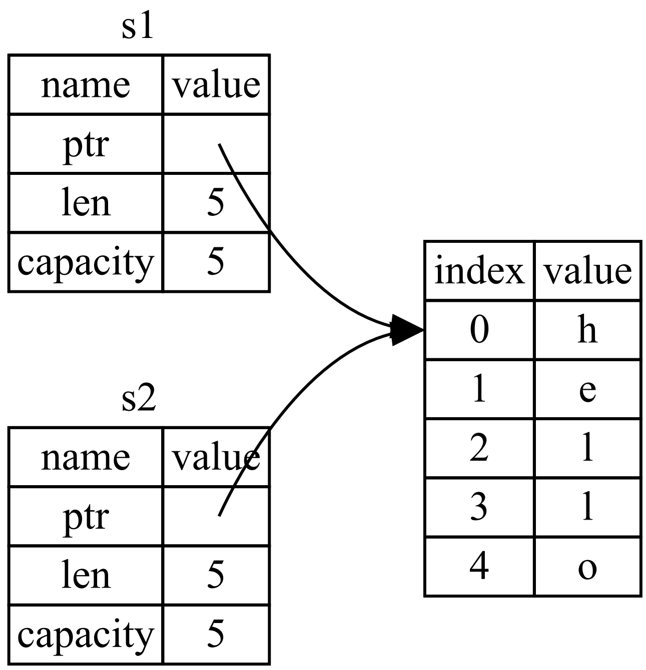


Figure 4-4: Representation in memory of the variable `s2` that has a copy of the pointer, length, and capacity of `s1`

The representation does *not* look like Figure 4-5, which is what memory would look like if Rust instead copied the heap data as well. If Rust did this, the operation `s2 = s1` could potentially be very expensive in terms of runtime performance if the data on the heap was large.

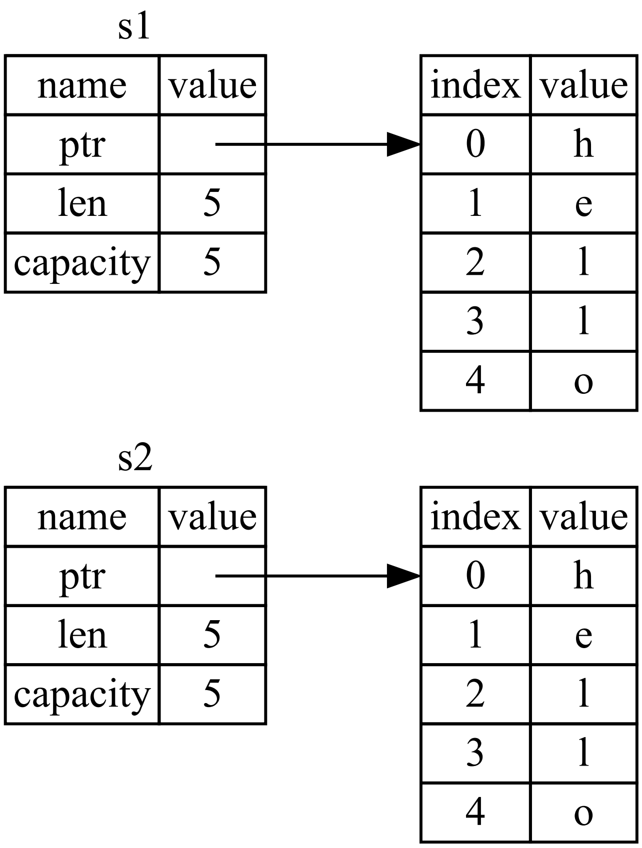


Figure 4-5: Another possibility of what `s2 = s1` might do if Rust copied the heap data as well

Earlier, we said that when a variable goes out of scope, Rust automatically calls the `drop` function and cleans up the heap memory for that variable. But Figure 4-4 shows both data pointers pointing to the same location. This is a problem: when `s2` and `s1` go out of scope, they will both try to free the same memory. This is known as a *double free* error and is one of the memory safety bugs we mentioned previously. Freeing memory twice can lead to memory corruption, which can potentially lead to security vulnerabilities.

To ensure memory safety, there's one more detail to what happens in this situation in Rust. Instead of trying to copy the allocated memory, Rust considers `s1` to no longer be valid and therefore, Rust doesn't need to free anything when `s1` goes out of scope. Check out what happens when you try to use `s1` after `s2` is created:

```
let s1 = String::from("hello");
let s2 = s1;

println!("{}, world!", s1);
```

You'll get an error like this because Rust prevents you from using the invalidated reference:

```
error[E0382]: use of moved value: `s1`
 --> src/main.rs:4:27
  |
3 |     let s2 = s1;
  |         -- value moved here
4 |     println!("{}, world!", s1);
  |                            ^^ value used here after move
  |
  = note: move occurs because `s1` has type `std::string::String`,
which does not implement the `Copy` trait
```

If you've heard the terms "shallow copy" and "deep copy" while working with other languages, the concept of copying the pointer, length, and capacity without copying the data probably sounds like a shallow copy. But because Rust also invalidates the first variable, instead of calling this a shallow copy, it's known as a *move*. Here we would read this by saying that `s1` was *moved* into `s2`. So what actually happens is shown in Figure 4-6.

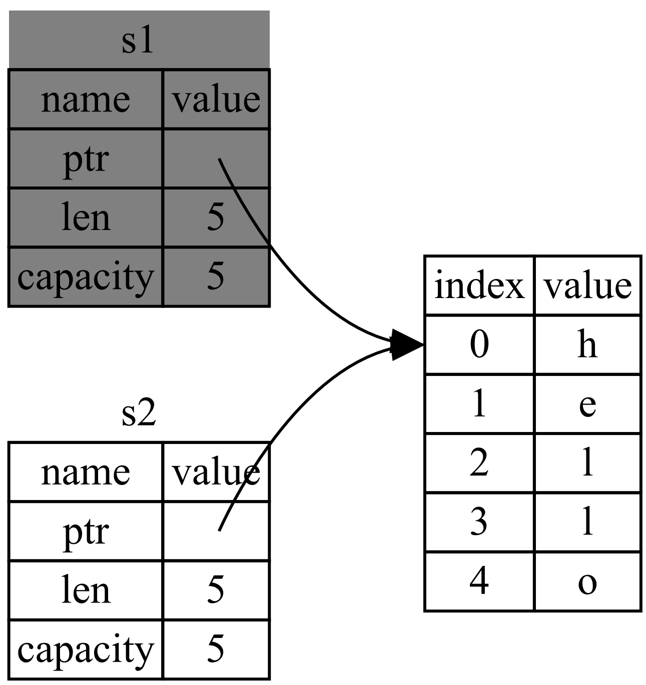


Figure 4-6: Representation in memory after `s1` has been invalidated

That solves our problem! With only `s2` valid, when it goes out of scope, it alone will free the memory, and we're done.

In addition, there's a design choice that's implied by this: Rust will never automatically create "deep" copies of your data. Therefore, any *automatic* copying can be assumed to be inexpensive in terms of runtime performance.

Ways Variables and Data Interact: Clone

If we *do* want to deeply copy the heap data of the `String`, not just the stack data, we can use a common method called `clone`. We'll discuss method syntax in Chapter 5, but because methods are a common feature in many programming languages, you've probably seen them before.

Here's an example of the `clone` method in action:

```
let s1 = String::from("hello");
let s2 = s1.clone();

println!("s1 = {}, s2 = {}", s1, s2);
```

This works just fine and is how you can explicitly produce the behavior shown in Figure 4-5, where the heap data *does* get copied.

When you see a call to `clone`, you know that some arbitrary code is being executed and that code may be expensive. It's a visual indicator that something different is going on.

Stack-Only Data: Copy

There's another wrinkle we haven't talked about yet. This code using integers, part of which was shown earlier in Listing 4-2, works and is valid:

```
let x = 5;
let y = x;

println!("x = {}, y = {}", x, y);
```

But this code seems to contradict what we just learned: we don't have a call to `clone`, but `x` is still valid and wasn't moved into `y`.

The reason is that types like integers that have a known size at compile time are stored entirely on the stack, so copies of the actual values are quick to make. That means there's no reason we would want to prevent `x` from being valid after we create the variable `y`. In other words, there's no difference between deep and shallow copying here, so calling `clone` wouldn't do anything differently from the usual shallow copying and we can leave it out.

Rust has a special annotation called the `Copy` trait that we can place on types like integers that are stored on the stack (we'll talk more about traits in Chapter 10). If a type has the `Copy` trait, an older variable is still usable after assignment. Rust won't let us annotate a type with the `Copy` trait if the type, or any of its parts, has implemented the `Drop` trait. If the type needs something special to happen when the value goes out of scope and we add the `Copy` annotation to that type, we'll get a compile time error. To learn about how to add the `Copy` annotation to your type, see Appendix C on Derivable Traits.

So what types are `Copy`? You can check the documentation for the given type to be sure, but as a general rule, any group of simple scalar values can be `Copy`, and nothing that requires allocation or is some form of resource is `Copy`. Here are some of the types that are `Copy`:

- All the integer types, like `u32`.
- The boolean type, `bool`, with values `true` and `false`.
- All the floating point types, like `f64`.
- Tuples, but only if they contain types that are also `Copy`. `(i32, i32)` is `Copy`, but `(i32, String)` is not.

Ownership and Functions

The semantics for passing a value to a function are similar to assigning a value to a variable. Passing a variable to a function will move or copy, just like assignment. Listing 4-7 has an example with some annotations showing where variables go into and out of scope:

Filename: src/main.rs

```
fn main() {
    let s = String::from("hello");  // s comes into scope.

    takes_ownership(s);             // s's value moves into the function...
                                    // ... and so is no longer valid here.
    let x = 5;                      // x comes into scope.

    makes_copy(x);                  // x would move into the function,
                                    // but i32 is Copy, so it’s okay to still
                                    // use x afterward.

} // Here, x goes out of scope, then s. But since s's value was moved, nothing
  // special happens.

fn takes_ownership(some_string: String) { // some_string comes into scope.
    println!("{}", some_string);
} // Here, some_string goes out of scope and `drop` is called. The backing
  // memory is freed.

fn makes_copy(some_integer: i32) { // some_integer comes into scope.
    println!("{}", some_integer);
} // Here, some_integer goes out of scope. Nothing special happens.
```

Listing 4-7: Functions with ownership and scope annotated

If we tried to use `s` after the call to `takes_ownership`, Rust would throw a compile time error. These static checks protect us from mistakes. Try adding code to `main` that uses `s` and `x` to see where you can use them and where the ownership rules prevent you from doing so.

Return Values and Scope

Returning values can also transfer ownership. Here's an example with similar annotations to those in Listing 4-7:

Filename: src/main.rs

```
fn main() {
    let s1 = gives_ownership();         // gives_ownership moves its return
                                        // value into s1.

    let s2 = String::from("hello");     // s2 comes into scope.

    let s3 = takes_and_gives_back(s2);  // s2 is moved into
                                        // takes_and_gives_back, which also
                                        // moves its return value into s3.
} // Here, s3 goes out of scope and is dropped. s2 goes out of scope but was
  // moved, so nothing happens. s1 goes out of scope and is dropped.

fn gives_ownership() -> String {             // gives_ownership will move its
                                             // return value into the function
                                             // that calls it.

    let some_string = String::from("hello"); // some_string comes into scope.

    some_string                              // some_string is returned and
                                             // moves out to the calling
                                             // function.
}

// takes_and_gives_back will take a String and return one.
fn takes_and_gives_back(a_string: String) -> String { // a_string comes into
                                                      // scope.

    a_string  // a_string is returned and moves out to the calling function.
}
```

The ownership of a variable follows the same pattern every time: assigning a value to another variable moves it. When a variable that includes data on the heap goes out of scope, the value will be cleaned up by `drop` unless the data has been moved to be owned by another variable.

Taking ownership and then returning ownership with every function is a bit tedious. What if we want to let a function use a value but not take ownership? It's quite annoying that anything we pass in also needs to be passed back if we want to use it again, in addition to any data resulting from the body of the function that we might want to return as well.

It's possible to return multiple values using a tuple, like this:

Filename: src/main.rs

```
fn main() {
    let s1 = String::from("hello");

    let (s2, len) = calculate_length(s1);

    println!("The length of '{}' is {}.", s2, len);
}

fn calculate_length(s: String) -> (String, usize) {
    let length = s.len(); // len() returns the length of a String.

    (s, length)
}
```

But this is too much ceremony and a lot of work for a concept that should be common. Luckily for us, Rust has a feature for this concept, and it's called *references*.

References and Borrowing

The issue with the tuple code at the end of the preceding section is that we have to return the `String` to the calling function so we can still use the `String` after the call to `calculate_length`, because the `String` was moved into `calculate_length`.

Here is how you would define and use a `calculate_length` function that has a *reference* to an object as a parameter instead of taking ownership of the value:

Filename: src/main.rs

```
fn main() {
    let s1 = String::from("hello");

    let len = calculate_length(&s1);

    println!("The length of '{}' is {}.", s1, len);
}

fn calculate_length(s: &String) -> usize {
    s.len()
}
```

First, notice that all the tuple code in the variable declaration and the function return value is gone. Second, note that we pass `&s1` into `calculate_length`, and in its definition, we take `&String` rather than `String`.

These ampersands are *references*, and they allow you to refer to some value without taking ownership of it. Figure 4-8 shows a diagram.

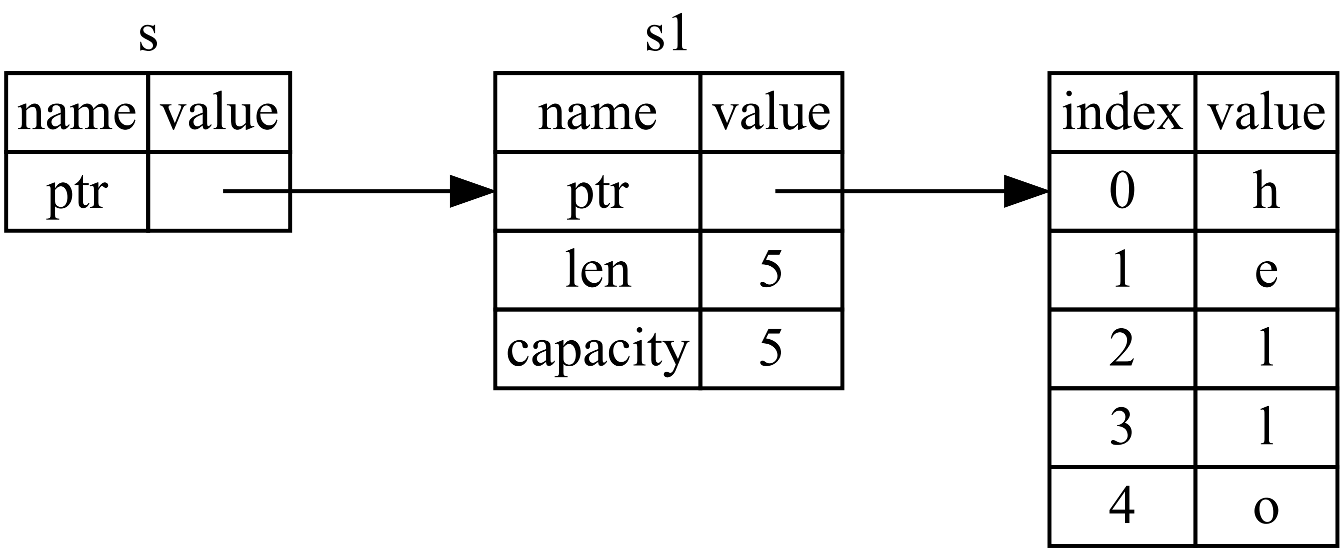


Figure 4-8: `&String s` pointing at `String s1`

Let's take a closer look at the function call here:

```
let s1 = String::from("hello");

let len = calculate_length(&s1);
```

The `&s1` syntax lets us create a reference that *refers* to the value of `s1` but does not own it. Because it does not own it, the value it points to will not be dropped when the reference goes out of scope.

Likewise, the signature of the function uses `&` to indicate that the type of the parameter `s` is a reference. Let's add some explanatory annotations:

```
fn calculate_length(s: &String) -> usize { // s is a reference to a String
    s.len()
} // Here, s goes out of scope. But because it does not have ownership of what
  // it refers to, nothing happens.
```

The scope in which the variable `s` is valid is the same as any function parameter's scope, but we don't drop what the reference points to when it goes out of scope because we don't have ownership. Functions that have references as parameters instead of the actual values mean we won't need to return the values in order to give back ownership, since we never had ownership.

We call having references as function parameters *borrowing*. As in real life, if a person owns something, you can borrow it from them. When you're done, you have to give it back.

So what happens if we try to modify something we're borrowing? Try the code in Listing 4-9. Spoiler alert: it doesn't work!

Filename: src/main.rs

```
fn main() {
    let s = String::from("hello");

    change(&s);
}

fn change(some_string: &String) {
    some_string.push_str(", world");
}
```

Listing 4-9: Attempting to modify a borrowed value

Here's the error:

```
error: cannot borrow immutable borrowed content `*some_string` as mutable
 --> error.rs:8:5
  |
8 |     some_string.push_str(", world");
  |     ^^^^^^^^^^^
```

Just as variables are immutable by default, so are references. We're not allowed to modify something we have a reference to.

Mutable References

We can fix the error in the code from Listing 4-9 with just a small tweak:

Filename: src/main.rs

```
fn main() {
    let mut s = String::from("hello");

    change(&mut s);
}

fn change(some_string: &mut String) {
    some_string.push_str(", world");
}
```

First, we had to change `s` to be `mut`. Then we had to create a mutable reference with `&mut s` and accept a mutable reference with `some_string: &mut String`.

But mutable references have one big restriction: you can only have one mutable reference to a particular piece of data in a particular scope. This code will fail:

Filename: src/main.rs

```
let mut s = String::from("hello");

let r1 = &mut s;
let r2 = &mut s;
```

Here's the error:

```
error[E0499]: cannot borrow `s` as mutable more than once at a time
 --> borrow_twice.rs:5:19
  |
4 |     let r1 = &mut s;
  |                   - first mutable borrow occurs here
5 |     let r2 = &mut s;
  |                   ^ second mutable borrow occurs here
6 | }
  | - first borrow ends here
```

This restriction allows for mutation but in a very controlled fashion. It's something that new Rustaceans struggle with, because most languages let you mutate whenever you'd like. The benefit of having this restriction is that Rust can prevent data races at compile time.

A *data race* is a particular type of race condition in which these three behaviors occur:

1. Two or more pointers access the same data at the same time.
2. At least one of the pointers is being used to write to the data.
3. There's no mechanism being used to synchronize access to the data.

Data races cause undefined behavior and can be difficult to diagnose and fix when you're trying to track them down at runtime; Rust prevents this problem from happening because it won't even compile code with data races!

As always, we can use curly brackets to create a new scope, allowing for multiple mutable references, just not *simultaneous* ones:

```
let mut s = String::from("hello");

{
    let r1 = &mut s;

} // r1 goes out of scope here, so we can make a new reference with no problems.

let r2 = &mut s;
```

A similar rule exists for combining mutable and immutable references. This code results in an error:

```
let mut s = String::from("hello");

let r1 = &s; // no problem
let r2 = &s; // no problem
let r3 = &mut s; // BIG PROBLEM
```

Here's the error:

```
error[E0502]: cannot borrow `s` as mutable because it is also borrowed as
immutable
 --> borrow_thrice.rs:6:19
  |
4 |     let r1 = &s; // no problem
  |               - immutable borrow occurs here
5 |     let r2 = &s; // no problem
6 |     let r3 = &mut s; // BIG PROBLEM
  |                   ^ mutable borrow occurs here
7 | }
  | - immutable borrow ends here
```

Whew! We *also* cannot have a mutable reference while we have an immutable one. Users of an immutable reference don't expect the values to suddenly change out from under them! However, multiple immutable references are okay because no one who is just reading the data has the ability to affect anyone else's reading of the data.

Even though these errors may be frustrating at times, remember that it's the Rust compiler pointing out a potential bug early (at compile time rather than at runtime) and showing you exactly where the problem is instead of you having to track down why sometimes your data isn't what you thought it should be.

Dangling References

In languages with pointers, it's easy to erroneously create a *dangling pointer*, a pointer that references a location in memory that may have been given to someone else, by freeing some memory while preserving a pointer to that memory. In Rust, by contrast, the compiler guarantees that references will never be dangling references: if we have a reference to some data, the compiler will ensure that the data will not go out of scope before the reference to the data does.

Let's try to create a dangling reference:

Filename: src/main.rs

```
fn main() {
    let reference_to_nothing = dangle();
}

fn dangle() -> &String {
    let s = String::from("hello");

    &s
}
```

Here's the error:

```
error[E0106]: missing lifetime specifier
 --> dangle.rs:5:16
  |
5 | fn dangle() -> &String {
  |                ^^^^^^^
  |
  = help: this function's return type contains a borrowed value, but there is no
    value for it to be borrowed from
  = help: consider giving it a 'static lifetime

error: aborting due to previous error
```

This error message refers to a feature we haven't covered yet: *lifetimes*. We'll discuss lifetimes in detail in Chapter 10. But, if you disregard the parts about lifetimes, the message does contain the key to why this code is a problem:

```
this function's return type contains a borrowed value, but there is no value
for it to be borrowed from.
```

Let's take a closer look at exactly what's happening at each stage of our `dangle` code:

```
fn dangle() -> &String { // dangle returns a reference to a String

    let s = String::from("hello"); // s is a new String

    &s // we return a reference to the String, s
} // Here, s goes out of scope, and is dropped. Its memory goes away.
  // Danger!
```

Because `s` is created inside `dangle`, when the code of `dangle` is finished, `s` will be deallocated. But we tried to return a reference to it. That means this reference would be pointing to an invalid `String`! That's no good. Rust won't let us do this.

The solution here is to return the `String` directly:

```
fn no_dangle() -> String {
    let s = String::from("hello");

    s
}
```

This works without any problems. Ownership is moved out, and nothing is deallocated.

The Rules of References

Let's recap what we've discussed about references:

1. At any given time, you can have *either* but not both of:

- One mutable reference.
- Any number of immutable references.

2. References must always be valid.

Next, we'll look at a different kind of reference: slices.

Slices

Another data type that does not have ownership is the *slice*. Slices let you reference a contiguous sequence of elements in a collection rather than the whole collection.

Here's a small programming problem: write a function that takes a string and returns the first word it finds in that string. If the function doesn't find a space in the string, it means the whole string is one word, so the entire string should be returned.

Let's think about the signature of this function:

```
fn first_word(s: &String) -> ?
```

This function, `first_word`, has a `&String` as a parameter. We don't want ownership, so this is fine. But what should we return? We don't really have a way to talk about *part* of a string. However, we could return the index of the end of the word. Let's try that as shown in Listing 4-10:

Filename: src/main.rs

```
fn first_word(s: &String) -> usize {
    let bytes = s.as_bytes();

    for (i, &item) in bytes.iter().enumerate() {
        if item == b' ' {
            return i;
        }
    }

    s.len()
}
```

Listing 4-10: The `first_word` function that returns a byte index value into the `String` parameter

Let's break down this code a bit. Because we need to go through the `String` element by element and check whether a value is a space, we'll convert our `String` to an array of bytes using the `as_bytes` method:

```
let bytes = s.as_bytes();
```

Next, we create an iterator over the array of bytes using the `iter` method :

```
for (i, &item) in bytes.iter().enumerate() {
```

We'll discuss iterators in more detail in Chapter 13. For now, know that `iter` is a method that returns each element in a collection, and `enumerate` wraps the result of `iter` and returns each element as part of a tuple instead. The first element of the returned tuple is the index, and the second element is a reference to the element. This is a bit more convenient than calculating the index ourselves.

Because the `enumerate` method returns a tuple, we can use patterns to destructure that tuple, just like everywhere else in Rust. So in the `for` loop, we specify a pattern that has `i` for the index in the tuple and `&item` for the single byte in the tuple. Because we get a reference to the element from `.iter().enumerate()`, we use `&` in the pattern.

We search for the byte that represents the space by using the byte literal syntax. If we find a space, we return the position. Otherwise, we return the length of the string by using `s.len()`:

```
    if item == b' ' {
        return i;
    }
}
s.len()
```

We now have a way to find out the index of the end of the first word in the string, but there's a problem. We're returning a `usize` on its own, but it's only a meaningful number in the context of the `&String`. In other words, because it's a separate value from the `String`, there's no guarantee that it will still be valid in the future. Consider the program in Listing 4-11 that uses the `first_word` function from Listing 4-10:

Filename: src/main.rs

```
fn main() {
    let mut s = String::from("hello world");

    let word = first_word(&s); // word will get the value 5.

    s.clear(); // This empties the String, making it equal to "".

    // word still has the value 5 here, but there's no more string that
    // we could meaningfully use the value 5 with. word is now totally invalid!
}
```

Listing 4-11: Storing the result from calling the `first_word` function then changing the `String` contents

This program compiles without any errors and also would if we used `word` after calling `s.clear()`. `word` isn't connected to the state of `s` at all, so `word` still contains the value `5`. We could use that value `5` with the variable `s` to try to extract the first word out, but this would be a bug because the contents of `s` have changed since we saved `5` in `word`.

Having to worry about the index in `word` getting out of sync with the data in `s` is tedious and error prone! Managing these indices is even more brittle if we write a `second_word` function. Its signature would have to look like this:

```
fn second_word(s: &String) -> (usize, usize) {
```

Now we're tracking a start *and* an ending index, and we have even more values that were calculated from data in a particular state but aren't tied to that state at all. We now have three unrelated variables floating around that need to be kept in sync.

Luckily, Rust has a solution to this problem: string slices.

String Slices

A *string slice* is a reference to part of a `String`, and looks like this:

```
let s = String::from("hello world");

let hello = &s[0..5];
let world = &s[6..11];
```

This is similar to taking a reference to the whole `String` but with the extra `[0..5]` bit. Rather than a reference to the entire `String`, it's a reference to a portion of the `String`. The `start..end` syntax is a range that begins at `start` and continues up to, but not including, `end`.

We can create slices using a range within brackets by specifying `[starting_index..ending_index]`, where `starting_index` is the first position included in the slice and `ending_index` is one more than the last position included in the slice. Internally, the slice data structure stores the starting position and the length of the slice, which corresponds to `ending_index` minus `starting_index`. So in the case of `let world = &s[6..11];`, `world` would be a slice that contains a pointer to the 6th byte of `s` and a length value of 5.

Figure 4-12 shows this in a diagram.

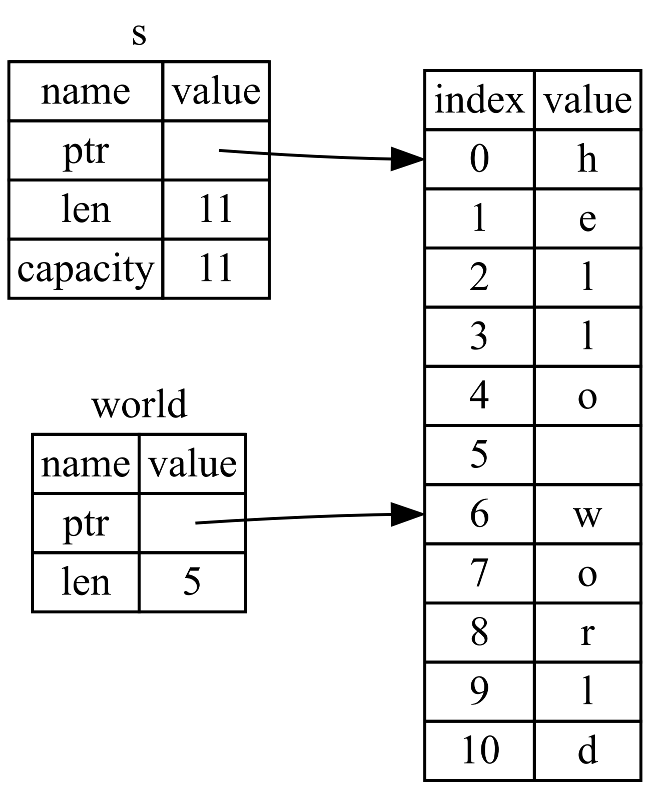


Figure 4-12: String slice referring to part of a `String`

With Rust's `..` range syntax, if you want to start at the first index (zero), you can drop the value before the two periods. In other words, these are equal:

```
let s = String::from("hello");

let slice = &s[0..2];
let slice = &s[..2];
```

By the same token, if your slice includes the last byte of the `String`, you can drop the trailing number. That means these are equal:

```
let s = String::from("hello");

let len = s.len();

let slice = &s[3..len];
let slice = &s[3..];
```

You can also drop both values to take a slice of the entire string. So these are equal:

```
let s = String::from("hello");

let len = s.len();

let slice = &s[0..len];
let slice = &s[..];
```

With all this information in mind, let's rewrite `first_word` to return a slice. The type that signifies "string slice" is written as `&str`:

Filename: src/main.rs

```
fn first_word(s: &String) -> &str {
    let bytes = s.as_bytes();

    for (i, &item) in bytes.iter().enumerate() {
        if item == b' ' {
            return &s[0..i];
        }
    }

    &s[..]
}
```

We get the index for the end of the word in the same way as we did in Listing 4-10, by looking for the first occurrence of a space. When we find a space, we return a string slice using the start of the string and the index of the space as the starting and ending indices.

Now when we call `first_word`, we get back a single value that is tied to the underlying data. The value is made up of a reference to the starting point of the slice and the number of elements in the slice.

Returning a slice would also work for a `second_word` function:

```
fn second_word(s: &String) -> &str {
```

We now have a straightforward API that's much harder to mess up, since the compiler will ensure the references into the `String` remain valid. Remember the bug in the program in Listing 4-11, when we got the index to the end of the first word but then cleared the string so our index was invalid? That code was logically incorrect but didn't show any immediate errors. The problems would show up later if we kept trying to use the first word index with an emptied string. Slices make this bug impossible and let us know we have a problem with our code much sooner. Using the slice version of `first_word` will throw a compile time error:

Filename: src/main.rs

```
fn main() {
    let mut s = String::from("hello world");

    let word = first_word(&s);

    s.clear(); // Error!
}
```

Here's the compiler error:

```
17:6 error: cannot borrow `s` as mutable because it is also borrowed as
            immutable [E0502]
    s.clear(); // Error!
    ^
15:29 note: previous borrow of `s` occurs here; the immutable borrow prevents
            subsequent moves or mutable borrows of `s` until the borrow ends
    let word = first_word(&s);
                           ^
18:2 note: previous borrow ends here
fn main() {

}
^
```

Recall from the borrowing rules that if we have an immutable reference to something, we cannot also take a mutable reference. Because `clear` needs to truncate the `String`, it tries to take a mutable reference, which fails. Not only has Rust made our API easier to use, but it has also eliminated an entire class of errors at compile time!

String Literals Are Slices

Recall that we talked about string literals being stored inside the binary. Now that we know about slices, we can properly understand string literals:

```
let s = "Hello, world!";
```

The type of `s` here is `&str`: it's a slice pointing to that specific point of the binary. This is also why string literals are immutable; `&str` is an immutable reference.

String Slices as Parameters

Knowing that you can take slices of literals and `String`s leads us to one more improvement on `first_word`, and that's its signature:

```
fn first_word(s: &String) -> &str {
```

A more experienced Rustacean would write the following line instead because it allows us to use the same function on both `String`s and `&str`s:

```
fn first_word(s: &str) -> &str {
```

If we have a string slice, we can pass that directly. If we have a `String`, we can pass a slice of the entire `String`. Defining a function to take a string slice instead of a reference to a String makes our API more general and useful without losing any functionality:

Filename: src/main.rs

```
fn main() {
    let my_string = String::from("hello world");

    // first_word works on slices of `String`s
    let word = first_word(&my_string[..]);

    let my_string_literal = "hello world";

    // first_word works on slices of string literals
    let word = first_word(&my_string_literal[..]);

    // since string literals *are* string slices already,
    // this works too, without the slice syntax!
    let word = first_word(my_string_literal);
}
```

Other Slices

String slices, as you might imagine, are specific to strings. But there's a more general slice type, too. Consider this array:

```
let a = [1, 2, 3, 4, 5];
```

Just like we might want to refer to a part of a string, we might want to refer to part of an array and would do so like this:

```
let a = [1, 2, 3, 4, 5];

let slice = &a[1..3];
```

This slice has the type `&[i32]`. It works the same way as string slices do, by storing a reference to the first element and a length. You'll use this kind of slice for all sorts of other collections. We'll discuss these collections in detail when we talk about vectors in Chapter 8.

Summary

The concepts of ownership, borrowing, and slices are what ensure memory safety in Rust programs at compile time. The Rust language gives you control over your memory usage like other systems programming languages, but having the owner of data automatically clean up that data when the owner goes out of scope means you don't have to write and debug extra code to get this control.

Ownership affects how lots of other parts of Rust work, so we'll talk about these concepts further throughout the rest of the book. Let's move on to the next chapter and look at grouping pieces of data together in a `struct`.

Using Structs to Structure Related Data

A *struct*, or *structure*, is a custom data type that lets us name and package together multiple related values that make up a meaningful group. If you're familiar with an object-oriented language, a *struct* is like an object's data attributes. In this chapter, we'll compare and contrast tuples with structs, demonstrate how to use structs, and discuss how to define methods and associated functions to specify behavior associated with a struct's data. The struct and *enum* (which is discussed in Chapter 6) concepts are the building blocks for creating new types in your program's domain to take full advantage of Rust's compile time type checking.

Defining and Instantiating Structs

Structs are similar to tuples, which were discussed in Chapter 3. Like tuples, the pieces of a struct can be different types. Unlike tuples, we name each piece of data so it's clear what the values mean. As a result of these names, structs are more flexible than tuples: we don't have to rely on the order of the data to specify or access the values of an instance.

To define a struct, we enter the keyword `struct` and name the entire struct. A struct's name should describe the significance of the pieces of data being grouped together. Then, inside curly brackets, we define the names and types of the pieces of data, which we call *fields*. For example, Listing 5-1 shows a struct to store information about a user account:

```rust
struct User {
    username: String,
    email: String,
    sign_in_count: u64,
    active: bool,
}
```

Listing 5-1: A `User` struct definition

To use a struct after we've defined it, we create an *instance* of that struct by specifying concrete values for each of the fields. We create an instance by stating the name of the struct, and then add curly brackets containing `key: value` pairs where the keys are the names of the fields and the values are the data we want to store in those fields. We don't have to specify the fields in the same order in which we declared them in the struct. In other words, the struct definition is like a general template for the type, and instances fill in that template with particular data to create values of the type. For example, we can declare a particular user as shown in Listing 5-2:

```rust
let user1 = User {
    email: String::from("someone@example.com"),
    username: String::from("someusername123"),
    active: true,
    sign_in_count: 1,
};
```

Listing 5-2: Creating an instance of the `User` struct

To get a specific value from a struct, we can use dot notation. If we wanted just this user's email address, we can use `user1.email` wherever we want to use this value. If the instance is mutable, we can change a value by using the dot notation and assigning into a particular field. Listing 5-3 shows how to change the value in the `email` field of a mutable `User` instance:

```
let mut user1 = User {
    email: String::from("someone@example.com"),
    username: String::from("someusername123"),
    active: true,
    sign_in_count: 1,
};

user1.email = String::from("anotheremail@example.com");
```

Listing 5-3: Changing the value in the `email` field of a `User` instance

Note that the entire instance must be mutable; Rust doesn't allow us to mark only certain fields as mutable. Also note that as with any expression, we can construct a new instance of the struct as the last expression in the function body to implicitly return that new instance.

Listing 5-4 shows a `build_user` function that returns a `User` instance with the given email and username. The `active` field gets the value of `true`, and the `sign_in_count` gets a value of `1`.

```
fn build_user(email: String, username: String) -> User {
    User {
        email: email,
        username: username,
        active: true,
        sign_in_count: 1,
    }
}
```

Listing 5-4: A `build_user` function that takes an email and username and returns a `User` instance

It makes sense to name the function arguments with the same name as the struct fields, but having to repeat the `email` and `username` field names and variables is a bit tedious. If the struct had more fields, repeating each name would get even more annoying. Luckily, there's a convenient shorthand!

Using the Field Init Shorthand when Variables and Fields Have the Same Name

Because the parameter names and the struct field names are exactly the same in Listing 5-4, we can use the *field init shorthand* syntax to rewrite `build_user` so that it behaves exactly the same but doesn't have the repetition of `email` and `username` in the way shown in Listing 5-5.

```
fn build_user(email: String, username: String) -> User {
    User {
        email,
        username,
        active: true,
        sign_in_count: 1,
    }
}
```

Listing 5-5: A `build_user` function that uses field init shorthand since the `email` and `username` parameters have the same name as struct fields

Here, we're creating a new instance of the `User` struct, which has a field named `email`. We want to set the `email` field's value to the value in the `email` parameter of the `build_user` function. Because the `email` field and the `email` parameter have the same name, we only need to write `email` rather than `email: email`.

Creating Instances From Other Instances With Struct Update Syntax

It's often useful to create a new instance of a struct that uses most of an old instance's values, but changes some. We do this using *struct update syntax*.

First, Listing 5-6 shows how we create a new `User` instance in `user2` without the update syntax. We set new values for `email` and `username`, but otherwise use the same values from `user1` that we created in Listing 5-2:

```
let user2 = User {
    email: String::from("another@example.com"),
    username: String::from("anotherusername567"),
    active: user1.active,
    sign_in_count: user1.sign_in_count,
};
```

Listing 5-6: Creating a new `User` instance using some of the values from `user1`

Using struct update syntax, we can achieve the same effect with less code, shown in Listing 5-7. The syntax `..` specifies that the remaining fields not explicitly set should have the same value as the fields in the given instance.

```
let user2 = User {
    email: String::from("another@example.com"),
    username: String::from("anotherusername567"),
    ..user1
};
```

Listing 5-7: Using struct update syntax to set a new `email` and `username` values for a `User` instance but use the rest of the values from the fields of the instance in the `user1` variable

The code in Listing 5-7 also creates an instance in `user2` that has a different value for `email` and `username` but has the same values for the `active` and `sign_in_count` fields from `user1`.

Tuple Structs without Named Fields to Create Different Types

We can also define structs that look similar to tuples, called *tuple structs*, that have the added meaning the struct name provides, but don't have names associated with their fields, just the types of the fields. Tuple structs are useful when you want to give the whole tuple a name and make the tuple be a different type than other tuples, but naming each field as in a regular struct would be verbose or redundant.

To define a tuple struct you start with the `struct` keyword and the struct name followed by the types in the tuple. For example, here are definitions and usages of two tuple structs named `Color` and `Point`:

```
struct Color(i32, i32, i32);
struct Point(i32, i32, i32);

let black = Color(0, 0, 0);
let origin = Point(0, 0, 0);
```

Note that the `black` and `origin` values are different types, since they're instances of different tuple structs. Each struct we define is its own type, even though the fields within the struct have the same types. For example, a function that takes a parameter of type `Color` cannot take a `Point` as an argument, even though both types are made up of three `i32` values. Otherwise, tuple struct instances behave like tuples, which we covered in Chapter 3: you can destructure them into their individual pieces, you can use a `.` followed by the index to access an individual value, and so on.

Unit-Like Structs without Any Fields

We can also define structs that don't have any fields! These are called *unit-like structs* since they behave similarly to `()`, the unit type. Unit-like structs can be useful in situations such as when you need to implement a trait on some type, but you don't have any data that you want to store in the type itself. We'll be discussing traits in Chapter 10.

Ownership of Struct Data

In the `User` struct definition in Listing 5-1, we used the owned `String` type rather than the `&str` string slice type. This is a deliberate choice because we want instances of this struct to own all of its data and for that data to be valid for as long as the entire struct is valid.

It's possible for structs to store references to data owned by something else, but to do so requires the use of *lifetimes*, a Rust feature that is discussed in Chapter 10. Lifetimes ensure that the data referenced by a struct is valid for as long as the struct is. Let's say you try to store a reference in a struct without specifying lifetimes, like this:

Filename: src/main.rs

```rust
struct User {
    username: &str,
    email: &str,
    sign_in_count: u64,
    active: bool,
}

fn main() {
    let user1 = User {
        email: "someone@example.com",
        username: "someusername123",
        active: true,
        sign_in_count: 1,
    };
}
```

The compiler will complain that it needs lifetime specifiers:

```
error[E0106]: missing lifetime specifier
 -->
  |
2 |     username: &str,
  |               ^ expected lifetime parameter

error[E0106]: missing lifetime specifier
 -->
  |
3 |     email: &str,
  |            ^ expected lifetime parameter
```

We'll discuss how to fix these errors so you can store references in structs in Chapter 10, but for now, we'll fix errors like these using owned types like `String` instead of references like `&str`.

An Example Program Using Structs

To understand when we might want to use structs, let's write a program that calculates the area of a rectangle. We'll start with single variables, and then refactor the program until we're using structs instead.

Let's make a new binary project with Cargo called *rectangles* that will take the width and height of a rectangle specified in pixels and will calculate the area of the rectangle. Listing 5-8 shows a short program with one way of doing just that in our project's *src/main.rs*:

Filename: src/main.rs

```
fn main() {
    let width1 = 30;
    let height1 = 50;

    println!(
        "The area of the rectangle is {} square pixels.",
        area(width1, height1)
    );
}

fn area(width: u32, height: u32) -> u32 {
    width * height
}
```

Listing 5-8: Calculating the area of a rectangle specified by its width and height in separate variables

Now, run this program using `cargo run`:

```
The area of the rectangle is 1500 square pixels.
```

Refactoring with Tuples

Even though Listing 5-8 works and figures out the area of the rectangle by calling the `area` function with each dimension, we can do better. The width and the height are related to each other because together they describe one rectangle.

The issue with this method is evident in the signature of `area`:

```
fn area(width: u32, height: u32) -> u32 {
```

The `area` function is supposed to calculate the area of one rectangle, but the function we wrote has two parameters. The parameters are related, but that's not expressed anywhere in our program. It would be more readable and more manageable to group width and height together. We've already discussed one way we might do that in the Grouping Values into Tuples section of Chapter 3 on page XX: by using tuples. Listing 5-9 shows another version of our program that uses tuples:

Filename: src/main.rs

```
fn main() {
    let rect1 = (30, 50);

    println!(
        "The area of the rectangle is {} square pixels.",
        area(rect1)
    );
}

fn area(dimensions: (u32, u32)) -> u32 {
    dimensions.0 * dimensions.1
}
```

Listing 5-8: Specifying the width and height of the rectangle with a tuple

In one way, this program is better. Tuples let us add a bit of structure, and we're now passing just one argument. But in another way this version is less clear: tuples don't name their elements, so our calculation has become more confusing because we have to index into the parts of the tuple.

It doesn't matter if we mix up width and height for the area calculation, but if we want to draw the rectangle on the screen, it would matter! We would have to keep in mind that `width` is the tuple index `0` and `height` is the tuple index `1`. If someone else worked on this code, they would have to figure this out and keep it in mind as well. It would be easy to forget or mix up these values and cause errors, because we haven't conveyed the meaning of our data in our code.

Refactoring with Structs: Adding More Meaning

We use structs to add meaning by labeling the data. We can transform the tuple we're using into a data type with a name for the whole as well as names for the parts, as shown in Listing 5-10:

Filename: src/main.rs

```
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
    let rect1 = Rectangle { width: 30, height: 50 };

    println!(
        "The area of the rectangle is {} square pixels.",
        area(&rect1)
    );
}

fn area(rectangle: &Rectangle) -> u32 {
    rectangle.width * rectangle.height
}
```

Listing 5-10: Defining a `Rectangle` struct

Here we've defined a struct and named it `Rectangle`. Inside the `{}` we defined the fields as `width` and `height`, both of which have type `u32`. Then in `main` we create a particular instance of a `Rectangle` that has a width of 30 and a height of 50.

Our `area` function is now defined with one parameter, which we've named `rectangle`, whose type is an immutable borrow of a struct `Rectangle` instance. As mentioned in Chapter 4, we want to borrow the struct rather than take ownership of it. This way, `main` retains its ownership and can continue using `rect1`, which is the reason we use the `&` in the function signature and where we call the function.

The `area` function accesses the `width` and `height` fields of the `Rectangle` instance. Our function signature for `area` now indicates exactly what we mean: calculate the area of a `Rectangle` using its `width` and `height` fields. This conveys that the width and height are related to each other, and gives descriptive names to the values rather than using the tuple index values of `0` and `1`—a win for clarity.

Adding Useful Functionality with Derived Traits

It would be helpful to be able to print out an instance of the `Rectangle` while we're debugging our program in order to see the values for all its fields. Listing 5-11 uses the `println!` macro as we have been in earlier chapters:

Filename: src/main.rs

```
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
    let rect1 = Rectangle { width: 30, height: 50 };

    println!("rect1 is {}", rect1);
}
```

Listing 5-11: Attempting to print a `Rectangle` instance

When we run this code, we get an error with this core message:

```
error[E0277]: the trait bound `Rectangle: std::fmt::Display` is not satisfied
```

The `println!` macro can do many kinds of formatting, and by default, `{}` tells `println!` to use formatting known as `Display`: output intended for direct end user consumption. The primitive types we've seen so far implement `Display` by default, because there's only one way you'd want to show a `1` or any other primitive type to a user. But with structs, the way `println!` should format the output is less clear because there are more display possibilities: do you want commas or not? Do you want to print the curly brackets? Should all the fields be shown? Due to this ambiguity, Rust doesn't try to guess what we want and structs don't have a provided implementation of `Display`.

If we continue reading the errors, we'll find this helpful note:

```
note: `Rectangle` cannot be formatted with the default formatter; try using
`:?` instead if you are using a format string
```

Let's try it! The `println!` macro call will now look like `println!("rect1 is {:?}", rect1);`. Putting the specifier `:?` inside the `{}` tells `println!` we want to use an output format called `Debug`. `Debug` is a trait that enables us to print out our struct in a way that is useful for developers so we can see its value while we're debugging our code.

Run the code with this change. Drat! We still get an error:

```
error: the trait bound `Rectangle: std::fmt::Debug` is not satisfied
```

But again, the compiler gives us a helpful note:

```
note: `Rectangle` cannot be formatted using `:?`; if it is defined in your
crate, add `#[derive(Debug)]` or manually implement it
```

Rust *does* include functionality to print out debugging information, but we have to explicitly opt-in to make that functionality available for our struct. To do that, we add the annotation

`#[derive(Debug)]` just before the struct definition, as shown in Listing 5-12:

Filename: src/main.rs

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
    let rect1 = Rectangle { width: 30, height: 50 };

    println!("rect1 is {:?}", rect1);
}
```

Listing 5-12: Adding the annotation to derive the `Debug` trait and printing the `Rectangle` instance using debug formatting

Now when we run the program, we won't get any errors and we'll see the following output:

```
rect1 is Rectangle { width: 30, height: 50 }
```

Nice! It's not the prettiest output, but it shows the values of all the fields for this instance, which would definitely help during debugging. When we have larger structs, it's useful to have output that's a bit easier to read; in those cases, we can use `{:#?}` instead of `{:?}` in the `println!` string. When we use the `{:#?}` style in the example, the output will look like this:

```
rect1 is Rectangle {
    width: 30,
    height: 50
}
```

Rust has provided a number of traits for us to use with the `derive` annotation that can add useful behavior to our custom types. Those traits and their behaviors are listed in Appendix C. We'll cover how to implement these traits with custom behavior as well as how to create your own traits in Chapter 10.

Our `area` function is very specific: it only computes the area of rectangles. It would be helpful to tie this behavior more closely to our `Rectangle` struct, because it won't work with any other type. Let's look at how we can continue to refactor this code by turning the `area` function into an `area` *method* defined on our `Rectangle` type.

Method Syntax

Methods are similar to functions: they're declared with the `fn` keyword and their name, they can have parameters and a return value, and they contain some code that is run when they're called from somewhere else. However, methods are different from functions in that they're defined within the context of a struct (or an enum or a trait object, which we cover in Chapters 6 and 17, respectively), and their first parameter is always `self`, which represents the instance of the struct the method is being called on.

Defining Methods

Let's change the `area` function that has a `Rectangle` instance as a parameter and instead make an `area` method defined on the `Rectangle` struct, as shown in Listing 5-13:

Filename: src/main.rs

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}

impl Rectangle {
    fn area(&self) -> u32 {
        self.width * self.height
    }
}

fn main() {
    let rect1 = Rectangle { width: 30, height: 50 };

    println!(
        "The area of the rectangle is {} square pixels.",
        rect1.area()
    );
}
```

Listing 5-13: Defining an `area` method on the `Rectangle` struct

To define the function within the context of `Rectangle`, we start an `impl` (*implementation*) block. Then we move the `area` function within the `impl` curly brackets and change the first (and in this case, only) parameter to be `self` in the signature and everywhere within the body. In `main` where we called the `area` function and passed `rect1` as an argument, we can instead use *method syntax* to call the `area` method on our `Rectangle` instance. The method syntax goes after an instance: we add a dot followed by the method name, parentheses, and any arguments.

In the signature for `area`, we use `&self` instead of `rectangle: &Rectangle` because Rust knows the type of `self` is `Rectangle` due to this method being inside the `impl Rectangle` context. Note that we still need to use the `&` before `self`, just like we did in `&Rectangle`. Methods can take ownership of `self`, borrow `self` immutably as we've done here, or borrow `self` mutably, just like any other parameter.

We've chosen `&self` here for the same reason we used `&Rectangle` in the function version: we don't want to take ownership, and we just want to read the data in the struct, not write to it. If we wanted to change the instance that we've called the method on as part of what the method does, we'd use `&mut self` as the first parameter. Having a method that takes ownership of the instance by using just `self` as the first parameter is rare; this technique is usually used when the method transforms `self` into something else and we want to prevent the caller from using the original instance after the transformation.

The main benefit of using methods instead of functions, in addition to using method syntax and not having to repeat the type of `self` in every method's signature, is for organization. We've put all the things we can do with an instance of a type in one `impl` block rather than making future users of our code search for capabilities of `Rectangle` in various places in the library we provide.

Where's the `->` Operator?

In languages like C++, two different operators are used for calling methods: you use `.` if you're calling a method on the object directly and `->` if you're calling the method on a pointer to the object and need to dereference the pointer first. In other words, if `object` is a pointer, `object->something()` is similar to `(*object).something()`.

Rust doesn't have an equivalent to the `->` operator; instead, Rust has a feature called *automatic referencing and dereferencing*. Calling methods is one of the few places in Rust that has this behavior.

Here's how it works: when you call a method with `object.something()`, Rust automatically adds in `&`, `&mut`, or `*` so `object` matches the signature of the method. In other words, the following are the same:

```
p1.distance(&p2);
(&p1).distance(&p2);
```

The first one looks much cleaner. This automatic referencing behavior works because methods have a clear receiver—the type of `self`. Given the receiver and name of a method, Rust can figure out definitively whether the method is reading (`&self`), mutating (`&mut self`), or consuming (`self`). The fact that Rust makes borrowing implicit for method receivers is a big part of making ownership ergonomic in practice.

Methods with More Parameters

Let's practice using methods by implementing a second method on the `Rectangle` struct. This time, we want an instance of `Rectangle` to take another instance of `Rectangle` and return `true` if the second `Rectangle` can fit completely within `self`; otherwise it should return `false`. That is, we want to be able to write the program shown in Listing 5-14, once we've defined the `can_hold` method:

Filename: src/main.rs

```
fn main() {
    let rect1 = Rectangle { width: 30, height: 50 };
    let rect2 = Rectangle { width: 10, height: 40 };
    let rect3 = Rectangle { width: 60, height: 45 };

    println!("Can rect1 hold rect2? {}", rect1.can_hold(&rect2));
    println!("Can rect1 hold rect3? {}", rect1.can_hold(&rect3));
}
```

Listing 5-14: Demonstration of using the as-yet-unwritten `can_hold` method

And the expected output would look like the following, because both dimensions of `rect2` are smaller than the dimensions of `rect1`, but `rect3` is wider than `rect1`:

```
Can rect1 hold rect2? true
Can rect1 hold rect3? false
```

We know we want to define a method, so it will be within the `impl Rectangle` block. The method name will be `can_hold`, and it will take an immutable borrow of another `Rectangle` as a parameter. We can tell what the type of the parameter will be by looking at the code that calls the method: `rect1.can_hold(&rect2)` passes in `&rect2`, which is an immutable borrow to `rect2`, an instance of `Rectangle`. This makes sense because we only need to read `rect2` (rather than write, which would mean we'd need a mutable borrow), and we want `main` to retain ownership of `rect2` so we can use it again after calling the `can_hold` method. The return value of `can_hold` will be a boolean, and the implementation will check whether the width and height of `self` are both greater than the width and height of the other `Rectangle`, respectively. Let's add the new `can_hold` method to the `impl` block from Listing 5-13, shown in Listing 5-15:

Filename: src/main.rs

```
impl Rectangle {
    fn area(&self) -> u32 {
        self.width * self.height
    }

    fn can_hold(&self, other: &Rectangle) -> bool {
        self.width > other.width && self.height > other.height
    }
}
```

Listing 5-15: Implementing the `can_hold` method on `Rectangle` that takes another `Rectangle` instance as a parameter

When we run this code with the `main` function in Listing 5-14, we'll get our desired output. Methods can take multiple parameters that we add to the signature after the `self` parameter, and those parameters work just like parameters in functions.

Associated Functions

Another useful feature of `impl` blocks is that we're allowed to define functions within `impl` blocks that *don't* take `self` as a parameter. These are called *associated functions* because they're associated with the struct. They're still functions, not methods, because they don't have an instance of the struct to work with. You've already used the `String::from` associated function.

Associated functions are often used for constructors that will return a new instance of the struct. For example, we could provide an associated function that would have one dimension parameter and use that as both width and height, thus making it easier to create a square `Rectangle` rather than having to specify the same value twice:

Filename: src/main.rs

```
impl Rectangle {
    fn square(size: u32) -> Rectangle {
        Rectangle { width: size, height: size }
    }
}
```

To call this associated function, we use the `::` syntax with the struct name, like `let sq = Rectangle::square(3);`, for example. This function is namespaced by the struct: the `::` syntax is used for both associated functions and namespaces created by modules, which we'll discuss in Chapter 7.

Multiple `impl` Blocks

Each struct is allowed to have multiple `impl` blocks. For example, Listing 5-15 is equivalent to the code shown in Listing 5-16, which has each method in its own `impl` block:

```
impl Rectangle {
    fn area(&self) -> u32 {
        self.width * self.height
    }
}

impl Rectangle {
    fn can_hold(&self, other: &Rectangle) -> bool {
        self.width > other.width && self.height > other.height
    }
}
```

Listing 5-16: Rewriting Listing 5-15 using multiple `impl` blocks

There's no reason to separate these methods into multiple `impl` blocks here, but it's valid syntax. We will see a case when multiple `impl` blocks are useful in Chapter 10 when we discuss generic types and traits.

Summary

Structs let us create custom types that are meaningful for our domain. By using structs, we can keep associated pieces of data connected to each other and name each piece to make our code clear. Methods let us specify the behavior that instances of our structs have, and associated functions let us namespace functionality that is particular to our struct without having an instance available.

But structs aren't the only way we can create custom types: let's turn to Rust's enum feature to add another tool to our toolbox.

Enums and Pattern Matching

In this chapter we'll look at *enumerations*, also referred to as *enums*. Enums allow you to define a type by enumerating its possible values. First, we'll define and use an enum to show how an enum can encode meaning along with data. Next, we'll explore a particularly useful enum, called `Option`, which expresses that a value can be either something or nothing. Then we'll look at how pattern matching in the `match` expression makes it easy to run different code for different values of an enum. Finally, we'll cover how the `if let` construct is another convenient and concise idiom available to you to handle enums in your code.

Enums are a feature in many languages, but their capabilities differ in each language. Rust's enums are most similar to *algebraic data types* in functional languages like F#, OCaml, and Haskell.

Defining an Enum

Let's look at a situation we might want to express in code and see why enums are useful and more appropriate than structs in this case. Say we need to work with IP addresses. Currently, two major standards are used for IP addresses: version four and version six. These are the only possibilities for an IP address that our program will come across: we can *enumerate* all possible values, which is where enumeration gets its name.

Any IP address can be either a version four or a version six address but not both at the same time. That property of IP addresses makes the enum data structure appropriate for this case, because enum values can only be one of the variants. Both version four and version six addresses are still fundamentally IP addresses, so they should be treated as the same type when the code is handling situations that apply to any kind of IP address.

We can express this concept in code by defining an `IpAddrKind` enumeration and listing the possible kinds an IP address can be, `V4` and `V6`. These are known as the *variants* of the enum:

```
enum IpAddrKind {
    V4,
    V6,
}
```

`IpAddrKind` is now a custom data type that we can use elsewhere in our code.

Enum Values

We can create instances of each of the two variants of `IpAddrKind` like this:

```
let four = IpAddrKind::V4;
let six = IpAddrKind::V6;
```

Note that the variants of the enum are namespaced under its identifier, and we use a double colon to separate the two. The reason this is useful is that now both values `IpAddrKind::V4` and `IpAddrKind::V6` are of the same type: `IpAddrKind`. We can then, for instance, define a function that takes any `IpAddrKind`:

```
fn route(ip_type: IpAddrKind) { }
```

And we can call this function with either variant:

```
route(IpAddrKind::V4);
route(IpAddrKind::V6);
```

Using enums has even more advantages. Thinking more about our IP address type, at the moment we don't have a way to store the actual IP address *data*; we only know what *kind* it is. Given that you just learned about structs in Chapter 5, you might tackle this problem as shown in Listing 6-1:

```
enum IpAddrKind {
    V4,
    V6,
}

struct IpAddr {
    kind: IpAddrKind,
    address: String,
}

let home = IpAddr {
    kind: IpAddrKind::V4,
    address: String::from("127.0.0.1"),
};

let loopback = IpAddr {
    kind: IpAddrKind::V6,
    address: String::from("::1"),
};
```

Listing 6-1: Storing the data and `IpAddrKind` variant of an IP address using a `struct`

Here, we've defined a struct `IpAddr` that has two fields: a `kind` field that is of type `IpAddrKind` (the enum we defined previously) and an `address` field of type `String`. We have two instances of this struct. The first, `home`, has the value `IpAddrKind::V4` as its `kind` with associated address data of `127.0.0.1`. The second instance, `loopback`, has the other variant of `IpAddrKind` as its `kind` value, `V6`, and has address `::1` associated with it. We've used a struct to bundle the `kind` and `address` values together, so now the variant is associated with the value.

We can represent the same concept in a more concise way using just an enum rather than an enum as part of a struct by putting data directly into each enum variant. This new definition of the `IpAddr` enum says that both `V4` and `V6` variants will have associated `String` values:

```
enum IpAddr {
    V4(String),
    V6(String),
}

let home = IpAddr::V4(String::from("127.0.0.1"));

let loopback = IpAddr::V6(String::from("::1"));
```

We attach data to each variant of the enum directly, so there is no need for an extra struct.

There's another advantage to using an enum rather than a struct: each variant can have different types and amounts of associated data. Version four type IP addresses will always have four numeric components that will have values between 0 and 255. If we wanted to store `V4` addresses as four `u8` values but still express `V6` addresses as one `String` value, we wouldn't be able to with a struct. Enums handle this case with ease:

```
enum IpAddr {
    V4(u8, u8, u8, u8),
    V6(String),
}

let home = IpAddr::V4(127, 0, 0, 1);

let loopback = IpAddr::V6(String::from("::1"));
```

We've shown several different possibilities that we could define in our code for storing IP addresses of the two different varieties using an enum. However, as it turns out, wanting to store IP addresses and encode which kind they are is so common that the standard library has a definition we can use! Let's look at how the standard library defines `IpAddr`: it has the exact enum and variants that we've defined and used, but it embeds the address data inside the variants in the form of two different structs, which are defined differently for each variant:

```rust
struct Ipv4Addr {
    // details elided
}

struct Ipv6Addr {
    // details elided
}

enum IpAddr {
    V4(Ipv4Addr),
    V6(Ipv6Addr),
}
```

This code illustrates that you can put any kind of data inside an enum variant: strings, numeric types, or structs, for example. You can even include another enum! Also, standard library types are often not much more complicated than what you might come up with.

Note that even though the standard library contains a definition for `IpAddr`, we can still create and use our own definition without conflict because we haven't brought the standard library's definition into our scope. We'll talk more about importing types in Chapter 7.

Let's look at another example of an enum in Listing 6-2: this one has a wide variety of types embedded in its variants:

```rust
enum Message {
    Quit,
    Move { x: i32, y: i32 },
    Write(String),
    ChangeColor(i32, i32, i32),
}
```

Listing 6-2: A `Message` enum whose variants each store different amounts and types of values

This enum has four variants with different types:

- `Quit` has no data associated with it at all.
- `Move` includes an anonymous struct inside it.
- `Write` includes a single `String`.
- `ChangeColor` includes three `i32`s.

Defining an enum with variants like the ones in Listing 6-2 is similar to defining different kinds of struct definitions except the enum doesn't use the `struct` keyword and all the variants are grouped together under the `Message` type. The following structs could hold the same data that the preceding enum variants hold:

```
struct QuitMessage; // unit struct
struct MoveMessage {
    x: i32,
    y: i32,
}
struct WriteMessage(String); // tuple struct
struct ChangeColorMessage(i32, i32, i32); // tuple struct
```

But if we used the different structs, which each have their own type, we wouldn't be able to as easily define a function that could take any of these kinds of messages as we could with the `Message` enum defined in Listing 6-2, which is a single type.

There is one more similarity between enums and structs: just as we're able to define methods on structs using `impl`, we're also able to define methods on enums. Here's a method named `call` that we could define on our `Message` enum:

```
impl Message {
    fn call(&self) {
        // method body would be defined here
    }
}

let m = Message::Write(String::from("hello"));
m.call();
```

The body of the method would use `self` to get the value that we called the method on. In this example, we've created a variable `m` that has the value `Message::Write(String::from("hello"))`, and that is what `self` will be in the body of the `call` method when `m.call()` runs.

Let's look at another enum in the standard library that is very common and useful: `Option`.

The `Option` Enum and Its Advantages Over Null Values

In the previous section, we looked at how the `IpAddr` enum let us use Rust's type system to encode more information than just the data into our program. This section explores a case study of `Option`, which is another enum defined by the standard library. The `Option` type is used in many places because it encodes the very common scenario in which a value could be something or it could be nothing. Expressing this concept in terms of the type system means the compiler can check that you've handled all the cases you should be handling, which can prevent bugs that are extremely common in other programming languages.

Programming language design is often thought of in terms of which features you include, but the features you exclude are important too. Rust doesn't have the null feature that many other languages have. *Null* is a value that means there is no value there. In languages with null, variables can always be in one of two states: null or not-null.

In “Null References: The Billion Dollar Mistake,” Tony Hoare, the inventor of null, has this to say:

> I call it my billion-dollar mistake. At that time, I was designing the first comprehensive type system for references in an object-oriented language. My goal was to ensure that all use of references should be absolutely safe, with checking performed automatically by the compiler. But I couldn’t resist the temptation to put in a null reference, simply because it was so easy to implement. This has led to innumerable errors, vulnerabilities, and system crashes, which have probably caused a billion dollars of pain and damage in the last forty years.

The problem with null values is that if you try to actually use a value that’s null as if it is a not-null value, you’ll get an error of some kind. Because this null or not-null property is pervasive, it’s extremely easy to make this kind of error.

However, the concept that null is trying to express is still a useful one: a null is a value that is currently invalid or absent for some reason.

The problem isn’t with the actual concept but with the particular implementation. As such, Rust does not have nulls, but it does have an enum that can encode the concept of a value being present or absent. This enum is `Option<T>`, and it is defined by the standard library as follows:

```
enum Option<T> {
    Some(T),
    None,
}
```

The `Option<T>` enum is so useful that it’s even included in the prelude; you don’t need to import it explicitly. In addition, so are its variants: you can use `Some` and `None` directly without prefixing them with `Option::`. `Option<T>` is still just a regular enum, and `Some(T)` and `None` are still variants of type `Option<T>`.

The `<T>` syntax is a feature of Rust we haven’t talked about yet. It’s a generic type parameter, and we’ll cover generics in more detail in Chapter 10. For now, all you need to know is that `<T>` means the `Some` variant of the `Option` enum can hold one piece of data of any type. Here are some examples of using `Option` values to hold number types and string types:

```
let some_number = Some(5);
let some_string = Some("a string");

let absent_number: Option<i32> = None;
```

If we use `None` rather than `Some`, we need to tell Rust what type of `Option<T>` we have, because the compiler can't infer the type that the `Some` variant will hold by looking only at a `None` value.

When we have a `Some` value, we know that a value is present, and the value is held within the `Some`. When we have a `None` value, in some sense, it means the same thing as null: we don't have a valid value. So why is having `Option<T>` any better than having null?

In short, because `Option<T>` and `T` (where `T` can be any type) are different types, the compiler won't let us use an `Option<T>` value as if it was definitely a valid value. For example, this code won't compile because it's trying to add an `i8` to an `Option<i8>`:

```
let x: i8 = 5;
let y: Option<i8> = Some(5);

let sum = x + y;
```

If we run this code, we get an error message like this:

```
error[E0277]: the trait bound `i8: std::ops::Add<std::option::Option<i8>>` is
not satisfied
 -->
  |
7 | let sum = x + y;
  |           ^^^^^
  |
```

Intense! In effect, this error message means that Rust doesn't understand how to add an `Option<i8>` and an `i8`, because they're different types. When we have a value of a type like `i8` in Rust, the compiler will ensure that we always have a valid value. We can proceed confidently without having to check for null before using that value. Only when we have an `Option<i8>` (or whatever type of value we're working with) do we have to worry about possibly not having a value, and the compiler will make sure we handle that case before using the value.

In other words, you have to convert an `Option<T>` to a `T` before you can perform `T` operations with it. Generally, this helps catch one of the most common issues with null: assuming that something isn't null when it actually is.

Not having to worry about missing an assumption of having a not-null value helps you to be more confident in your code. In order to have a value that can possibly be null, you must explicitly opt in by making the type of that value `Option<T>`. Then, when you use that value, you are required to explicitly handle the case when the value is null. Everywhere that a value has a type that isn't an `Option<T>`, you *can* safely assume that the value isn't null. This was a deliberate design decision for Rust to limit null's pervasiveness and increase the safety of Rust code.

So, how do you get the `T` value out of a `Some` variant when you have a value of type `Option<T>` so you can use that value? The `Option<T>` enum has a large number of methods that are useful in a variety of situations; you can check them out in its documentation. Becoming familiar with the methods on `Option<T>` will be extremely useful in your journey with Rust.

In general, in order to use an `Option<T>` value, we want to have code that will handle each variant. We want some code that will run only when we have a `Some(T)` value, and this code is allowed to use the inner `T`. We want some other code to run if we have a `None` value, and that code doesn't have a `T` value available. The `match` expression is a control flow construct that does just this when used with enums: it will run different code depending on which variant of the enum it has, and that code can use the data inside the matching value.

The `match` Control Flow Operator

Rust has an extremely powerful control-flow operator called `match` that allows us to compare a value against a series of patterns and then execute code based on which pattern matches. Patterns can be made up of literal values, variable names, wildcards, and many other things; Chapter 18 will cover all the different kinds of patterns and what they do. The power of `match` comes from the expressiveness of the patterns and the compiler checks that make sure all possible cases are handled.

Think of a `match` expression kind of like a coin sorting machine: coins slide down a track with variously sized holes along it, and each coin falls through the first hole it encounters that it fits into. In the same way, values go through each pattern in a `match`, and at the first pattern the value "fits," the value will fall into the associated code block to be used during execution.

Because we just mentioned coins, let's use them as an example using `match`! We can write a function that can take an unknown United States coin and, in a similar way as the counting machine, determine which coin it is and return its value in cents, as shown here in Listing 6-3:

```
enum Coin {
    Penny,
    Nickel,
    Dime,
    Quarter,
}

fn value_in_cents(coin: Coin) -> u32 {
    match coin {
        Coin::Penny => 1,
        Coin::Nickel => 5,
        Coin::Dime => 10,
        Coin::Quarter => 25,
    }
}
```

Listing 6-3: An enum and a `match` expression that has the variants of the enum as its patterns.

Let's break down the `match` in the `value_in_cents` function. First, we list the `match` keyword followed by an expression, which in this case is the value `coin`. This seems very similar to an expression used with `if`, but there's a big difference: with `if`, the expression needs to return a boolean value. Here, it can be any type. The type of `coin` in this example is the `Coin` enum that we defined in Listing 6-3.

Next are the `match` arms. An arm has two parts: a pattern and some code. The first arm here has a pattern that is the value `Coin::Penny` and then the `=>` operator that separates the pattern and the code to run. The code in this case is just the value `1`. Each arm is separated from the next with a comma.

When the `match` expression executes, it compares the resulting value against the pattern of each arm, in order. If a pattern matches the value, the code associated with that pattern is executed. If that pattern doesn't match the value, execution continues to the next arm, much like a coin sorting machine. We can have as many arms as we need: in Listing 6-3, our `match` has four arms.

The code associated with each arm is an expression, and the resulting value of the expression in the matching arm is the value that gets returned for the entire `match` expression.

Curly brackets typically aren't used if the match arm code is short, as it is in Listing 6-3 where each arm just returns a value. If you want to run multiple lines of code in a match arm, you can use curly brackets. For example, the following code would print out "Lucky penny!" every time the method was called with a `Coin::Penny` but would still return the last value of the block, `1`:

```
fn value_in_cents(coin: Coin) -> u32 {
    match coin {
        Coin::Penny => {
            println!("Lucky penny!");
            1
        },
        Coin::Nickel => 5,
        Coin::Dime => 10,
        Coin::Quarter => 25,
    }
}
```

Patterns that Bind to Values

Another useful feature of match arms is that they can bind to parts of the values that match the pattern. This is how we can extract values out of enum variants.

As an example, let's change one of our enum variants to hold data inside it. From 1999 through 2008, the United States minted quarters with different designs for each of the 50 states on one side. No other coins got state designs, so only quarters have this extra value. We can add this information to our `enum` by changing the `Quarter` variant to include a `UsState` value stored inside it, which we've done here in Listing 6-4:

```
#[derive(Debug)] // So we can inspect the state in a minute
enum UsState {
    Alabama,
    Alaska,
    // ... etc
}

enum Coin {
    Penny,
    Nickel,
    Dime,
    Quarter(UsState),
}
```

Listing 6-4: A `Coin` enum where the `Quarter` variant also holds a `UsState` value

Let's imagine that a friend of ours is trying to collect all 50 state quarters. While we sort our loose change by coin type, we'll also call out the name of the state associated with each quarter so if it's one our friend doesn't have, they can add it to their collection.

In the match expression for this code, we add a variable called `state` to the pattern that matches values of the variant `Coin::Quarter`. When a `Coin::Quarter` matches, the `state` variable will bind to the value of that quarter's state. Then we can use `state` in the code for that arm, like so:

```
fn value_in_cents(coin: Coin) -> u32 {
    match coin {
        Coin::Penny => 1,
        Coin::Nickel => 5,
        Coin::Dime => 10,
        Coin::Quarter(state) => {
            println!("State quarter from {:?}!", state);
            25
        },
    }
}
```

If we were to call `value_in_cents(Coin::Quarter(UsState::Alaska))`, `coin` would be `Coin::Quarter(UsState::Alaska)`. When we compare that value with each of the match arms, none of them match until we reach `Coin::Quarter(state)`. At that point, the binding for `state` will be the value `UsState::Alaska`. We can then use that binding in the `println!` expression, thus getting the inner state value out of the `Coin` enum variant for `Quarter`.

Matching with `Option<T>`

In the previous section we wanted to get the inner `T` value out of the `Some` case when using `Option<T>`; we can also handle `Option<T>` using `match` as we did with the `Coin` enum! Instead of comparing coins, we'll compare the variants of `Option<T>`, but the way that the `match` expression works remains the same.

Let's say we want to write a function that takes an `Option<i32>`, and if there's a value inside, adds one to that value. If there isn't a value inside, the function should return the `None` value and not attempt to perform any operations.

This function is very easy to write, thanks to `match`, and will look like Listing 6-5:

```
fn plus_one(x: Option<i32>) -> Option<i32> {
    match x {
        None => None,
        Some(i) => Some(i + 1),
    }
}

let five = Some(5);
let six = plus_one(five);
let none = plus_one(None);
```

Listing 6-5: A function that uses a `match` expression on an `Option<i32>`

Matching `Some(T)`

Let's examine the first execution of `plus_one` in more detail. When we call `plus_one(five)`, the variable `x` in the body of `plus_one` will have the value `Some(5)`. We then compare that against each match arm.

```
None => None,
```

The `Some(5)` value doesn't match the pattern `None`, so we continue to the next arm.

```
Some(i) => Some(i + 1),
```

Does `Some(5)` match `Some(i)`? Well yes it does! We have the same variant. The `i` binds to the value contained in `Some`, so `i` takes the value `5`. The code in the match arm is then executed, so we add one to the value of `i` and create a new `Some` value with our total `6` inside.

Matching `None`

Now let's consider the second call of `plus_one` in Listing 6-5 where `x` is `None`. We enter the `match` and compare to the first arm.

```
None => None,
```

It matches! There's no value to add to, so the program stops and returns the `None` value on the right side of `=>`. Because the first arm matched, no other arms are compared.

Combining `match` and enums is useful in many situations. You'll see this pattern a lot in Rust code: `match` against an enum, bind a variable to the data inside, and then execute code based on it. It's a bit tricky at first, but once you get used to it, you'll wish you had it in all languages. It's consistently a user favorite.

Matches Are Exhaustive

There's one other aspect of `match` we need to discuss. Consider this version of our `plus_one` function:

```
fn plus_one(x: Option<i32>) -> Option<i32> {
    match x {
        Some(i) => Some(i + 1),
    }
}
```

We didn't handle the `None` case, so this code will cause a bug. Luckily, it's a bug Rust knows how to catch. If we try to compile this code, we'll get this error:

```
error[E0004]: non-exhaustive patterns: `None` not covered
 -->
  |
6 |         match x {
  |               ^ pattern `None` not covered
```

Rust knows that we didn't cover every possible case and even knows which pattern we forgot! Matches in Rust are *exhaustive*: we must exhaust every last possibility in order for the code to be valid. Especially in the case of `Option<T>`, when Rust prevents us from forgetting to explicitly handle the `None` case, it protects us from assuming that we have a value when we might have null, thus making the billion dollar mistake discussed earlier.

The `_` Placeholder

Rust also has a pattern we can use in situations when we don't want to list all possible values. For example, a `u8` can have valid values of 0 through 255. If we only care about the values 1, 3, 5, and 7, we don't want to have to list out 0, 2, 4, 6, 8, 9 all the way up to 255. Fortunately, we don't have to: we can use the special pattern `_` instead:

```
let some_u8_value = 0u8;
match some_u8_value {
    1 => println!("one"),
    3 => println!("three"),
    5 => println!("five"),
    7 => println!("seven"),
    _ => (),
}
```

The `_` pattern will match any value. By putting it after our other arms, the `_` will match all the possible cases that aren't specified before it. The `()` is just the unit value, so nothing will happen in the `_` case. As a result, we can say that we want to do nothing for all the possible values that we don't list before the `_` placeholder.

However, the `match` expression can be a bit wordy in a situation in which we only care about *one* of the cases. For this situation, Rust provides `if let`.

Concise Control Flow with `if let`

The `if let` syntax lets you combine `if` and `let` into a less verbose way to handle values that match one pattern and ignore the rest. Consider the program in Listing 6-6 that matches on an `Option<u8>` value but only wants to execute code if the value is three:

```
let some_u8_value = Some(0u8);
match some_u8_value {
    Some(3) => println!("three"),
    _ => (),
}
```

Listing 6-6: A `match` that only cares about executing code when the value is `Some(3)`

We want to do something with the `Some(3)` match but do nothing with any other `Some<u8>` value or the `None` value. To satisfy the `match` expression, we have to add `_ => ()` after processing just one variant, which is a lot of boilerplate code to add.

Instead, we could write this in a shorter way using `if let`. The following code behaves the same as the `match` in Listing 6-6:

```
if let Some(3) = some_u8_value {
    println!("three");
}
```

`if let` takes a pattern and an expression separated by an `=`. It works the same way as a `match`, where the expression is given to the `match` and the pattern is its first arm.

Using `if let` means you have less to type, less indentation, and less boilerplate code. However, we've lost the exhaustive checking that `match` enforces. Choosing between `match` and `if let` depends on what you're doing in your particular situation and if gaining conciseness is an appropriate trade-off for losing exhaustive checking.

In other words, you can think of `if let` as syntax sugar for a `match` that runs code when the value matches one pattern and then ignores all other values.

We can include an `else` with an `if let`. The block of code that goes with the `else` is the same as the block of code that would go with the `_` case in the `match` expression that is equivalent to the `if let` and `else`. Recall the `Coin` enum definition in Listing 6-4, where the `Quarter` variant also held a `UsState` value. If we wanted to count all non-quarter coins we see while also announcing the state of the quarters, we could do that with a `match` expression like this:

```
let mut count = 0;
match coin {
    Coin::Quarter(state) => println!("State quarter from {:?}!", state),
    _ => count += 1,
}
```

Or we could use an `if let` and `else` expression like this:

```
let mut count = 0;
if let Coin::Quarter(state) = coin {
    println!("State quarter from {:?}!", state);
} else {
    count += 1;
}
```

If you have a situation in which your program has logic that is too verbose to express using a `match`, remember that `if let` is in your Rust toolbox as well.

Summary

We've now covered how to use enums to create custom types that can be one of a set of enumerated values. We've shown how the standard library's `Option<T>` type helps you use the type system to prevent errors. When enum values have data inside them, you can use `match` or `if let` to extract and use those values, depending on how many cases you need to handle.

Your Rust programs can now express concepts in your domain using structs and enums. Creating custom types to use in your API ensures type safety: the compiler will make certain your functions only get values of the type each function expects.

In order to provide a well-organized API to your users that is straightforward to use and only exposes exactly what your users will need, let's now turn to Rust's modules.

Using Modules to Reuse and Organize Code

When you start writing programs in Rust, your code might live solely in the `main` function. As your code grows, you'll eventually move functionality into other functions for reuse and better organization. By splitting your code into smaller chunks, each chunk is easier to understand on its own. But what happens if you have too many functions? Rust has a module system that enables the reuse of code in an organized fashion.

In the same way that you extract lines of code into a function, you can extract functions (and other code, like structs and enums) into different modules. A *module* is a namespace that contains definitions of functions or types, and you can choose whether those definitions are visible outside their module (public) or not (private). Here's an overview of how modules work:

- The `mod` keyword declares a new module. Code within the module appears either immediately following this declaration within curly brackets or in another file.
- By default, functions, types, constants, and modules are private. The `pub` keyword makes an item public and therefore visible outside its namespace.
- The `use` keyword brings modules, or the definitions inside modules, into scope so it's easier to refer to them.

We'll look at each of these parts to see how they fit into the whole.

`mod` and the Filesystem

We'll start our module example by making a new project with Cargo, but instead of creating a binary crate, we'll make a library crate: a project that other people can pull into their projects as a dependency. For example, the `rand` crate in Chapter 2 is a library crate that we used as a dependency in the guessing game project.

We'll create a skeleton of a library that provides some general networking functionality; we'll concentrate on the organization of the modules and functions but we won't worry about what code goes in the function bodies. We'll call our library `communicator`. By default, Cargo will create a library unless another type of project is specified: if we omit the `--bin` option that we've been using in all of the chapters preceding this one, our project will be a library:

```
$ cargo new communicator
$ cd communicator
```

Notice that Cargo generated *src/lib.rs* instead of *src/main.rs*. Inside *src/lib.rs* we'll find the following:

Filename: src/lib.rs

```rust
#[cfg(test)]
mod tests {
    #[test]
    fn it_works() {
    }
}
```

Cargo creates an empty test to help us get our library started, rather than the "Hello, world!" binary that we get when we use the `--bin` option. We'll look at the `#[]` and `mod tests` syntax in the "Using `super` to Access a Parent Module" section later in this chapter, but for now, leave this code at the bottom of *src/lib.rs*.

Because we don't have a *src/main.rs* file, there's nothing for Cargo to execute with the `cargo run` command. Therefore, we'll use the `cargo build` command to compile our library crate's code.

We'll look at different options for organizing your library's code that will be suitable in a variety of situations, depending on the intent of the code.

Module Definitions

For our `communicator` networking library, we'll first define a module named `network` that contains the definition of a function called `connect`. Every module definition in Rust starts with the `mod` keyword. Add this code to the beginning of the *src/lib.rs* file, above the test code:

Filename: src/lib.rs

```
mod network {
    fn connect() {
    }
}
```

After the `mod` keyword, we put the name of the module, `network`, and then a block of code in curly brackets. Everything inside this block is inside the namespace `network`. In this case, we have a single function, `connect`. If we wanted to call this function from a script outside the `network` module, we would need to specify the module and use the namespace syntax `::`, like so: `network::connect()` rather than just `connect()`.

We can also have multiple modules, side by side, in the same *src/lib.rs* file. For example, to also have a `client` module that has a function named `connect` as well, we can add it as shown in Listing 7-1:

Filename: src/lib.rs

```
mod network {
    fn connect() {
    }
}

mod client {
    fn connect() {
    }
}
```

Listing 7-1: The `network` module and the `client` module defined side by side in *src/lib.rs*

Now we have a `network::connect` function and a `client::connect` function. These can have completely different functionality, and the function names do not conflict with each other because they're in different modules.

In this case, because we're building a library, the file that serves as the entry point for building our library is *src/lib.rs*. However, in respect to creating modules, there's nothing special about *src/lib.rs*. We could also create modules in *src/main.rs* for a binary crate in the same way as we're creating modules in *src/lib.rs* for the library crate. In fact, we can put modules inside of modules, which can be useful as your modules grow to keep related functionality organized together and separate functionality apart. The choice of how you organize your code depends on how you think about the relationship between the parts of your code. For instance, the `client` code and its `connect` function might make more sense to users of our library if they were inside the `network` namespace instead, as in Listing 7-2:

Filename: src/lib.rs

```
mod network {
    fn connect() {
    }

    mod client {
        fn connect() {
        }
    }
}
```

Listing 7-2: Moving the `client` module inside the `network` module

In your *src/lib.rs* file, replace the existing `mod network` and `mod client` definitions with the ones in Listing 7-2, which have the `client` module as an inner module of `network`. Now we have the functions `network::connect` and `network::client::connect`: again, the two functions named `connect` don't conflict with each other because they're in different namespaces.

In this way, modules form a hierarchy. The contents of *src/lib.rs* are at the topmost level, and the submodules are at lower levels. Here's what the organization of our example in Listing 7-1 looks like when thought of as a hierarchy:

```
communicator
 ├── network
 └── client
```

And here's the hierarchy corresponding to the example in Listing 7-2:

```
communicator
 └── network
     └── client
```

The hierarchy shows that in Listing 7-2, `client` is a child of the `network` module rather than a sibling. More complicated projects can have many modules, and they'll need to be organized logically in order to keep track of them. What "logically" means in your project is up to you and depends on how you and your library's users think about your project's domain. Use the techniques shown here to create side-by-side modules and nested modules in whatever structure you would like.

Moving Modules to Other Files

Modules form a hierarchical structure, much like another structure in computing that you're used to: filesystems! We can use Rust's module system along with multiple files to split up Rust projects so not everything lives in *src/lib.rs* or *src/main.rs*. For this example, let's start with the code in Listing 7-3:

Filename: src/lib.rs

```rust
mod client {
    fn connect() {
    }
}

mod network {
    fn connect() {
    }

    mod server {
        fn connect() {
        }
    }
}
```

Listing 7-3: Three modules, `client`, `network`, and `network::server`, all defined in *src/lib.rs*

The file *src/lib.rs* has this module hierarchy:

```
communicator
 ├── client
 └── network
     └── server
```

If these modules had many functions, and those functions were becoming lengthy, it would be difficult to scroll through this file to find the code we wanted to work with. Because the functions are nested inside one or more mod blocks, the lines of code inside the functions will start getting lengthy as well. These would be good reasons to separate the `client`, `network`, and `server` modules from *src/lib.rs* and place them into their own files.

First, replace the `client` module code with only the declaration of the `client` module, so that your *src/lib.rs* looks like the following:

Filename: src/lib.rs

```
mod client;

mod network {
    fn connect() {
    }

    mod server {
        fn connect() {
        }
    }
}
```

We're still *declaring* the `client` module here, but by replacing the block with a semicolon, we're telling Rust to look in another location for the code defined within the scope of the `client` module. In other words, the line `mod client;` means:

```
mod client {
    // contents of client.rs
}
```

Now we need to create the external file with that module name. Create a *client.rs* file in your *src/* directory and open it. Then enter the following, which is the `connect` function in the `client` module that we removed in the previous step:

Filename: src/client.rs

```
fn connect() {
}
```

Note that we don't need a `mod` declaration in this file because we already declared the `client` module with `mod` in *src/lib.rs*. This file just provides the *contents* of the `client` module. If we put a `mod client` here, we'd be giving the `client` module its own submodule named `client`!

Rust only knows to look in *src/lib.rs* by default. If we want to add more files to our project, we need to tell Rust in *src/lib.rs* to look in other files; this is why `mod client` needs to be defined in *src/lib.rs* and can't be defined in *src/client.rs*.

Now the project should compile successfully, although you'll get a few warnings. Remember to use `cargo build` instead of `cargo run` because we have a library crate rather than a binary crate:

```
$ cargo build
   Compiling communicator v0.1.0 (file:///projects/communicator)

warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/client.rs:1:1
  |
1 | fn connect() {
  | ^

warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/lib.rs:4:5
  |
4 |     fn connect() {
  |     ^

warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/lib.rs:8:9
  |
8 |         fn connect() {
  |         ^
```

These warnings tell us that we have functions that are never used. Don't worry about these warnings for now; we'll address them in the "Controlling Visibility with `pub`" section later in this chapter. The good news is that they're just warnings; our project built successfully!

Next, let's extract the `network` module into its own file using the same pattern. In *src/lib.rs*, delete the body of the `network` module and add a semicolon to the declaration, like so:

Filename: src/lib.rs

```
mod client;

mod network;
```

Then create a new *src/network.rs* file and enter the following:

Filename: src/network.rs

```
fn connect() {
}

mod server {
    fn connect() {
    }
}
```

Notice that we still have a `mod` declaration within this module file; this is because we still want `server` to be a submodule of `network`.

Run `cargo build` again. Success! We have one more module to extract: `server`. Because it's a submodule—that is, a module within a module—our current tactic of extracting a module into a file named after that module won't work. We'll try anyway so you can see the error. First, change *src/network.rs* to have `mod server;` instead of the `server` module's contents:

Filename: src/network.rs

```
fn connect() {
}

mod server;
```

Then create a *src/server.rs* file and enter the contents of the `server` module that we extracted:

Filename: src/server.rs

```
fn connect() {
}
```

When we try to `cargo build`, we'll get the error shown in Listing 7-4:

```
$ cargo build
   Compiling communicator v0.1.0 (file:///projects/communicator)
error: cannot declare a new module at this location
 --> src/network.rs:4:5
  |
4 | mod server;
  |     ^^^^^^
  |
note: maybe move this module `network` to its own directory via `network/mod.rs`
 --> src/network.rs:4:5
  |
4 | mod server;
  |     ^^^^^^
note: ... or maybe `use` the module `server` instead of possibly redeclaring it
 --> src/network.rs:4:5
  |
4 | mod server;
  |     ^^^^^^
```

Listing 7-4: Error when trying to extract the `server` submodule into *src/server.rs*

The error says we `cannot declare a new module at this location` and is pointing to the `mod server;` line in *src/network.rs*. So *src/network.rs* is different than *src/lib.rs* somehow: keep reading to understand why.

The note in the middle of Listing 7-4 is actually very helpful because it points out something we haven't yet talked about doing:

```
note: maybe move this module `network` to its own directory via
`network/mod.rs`
```

Instead of continuing to follow the same file naming pattern we used previously, we can do what the note suggests:

1. Make a new *directory* named *network*, the parent module's name.
2. Move the *src/network.rs* file into the new *network* directory, and rename it to *src/network/mod.rs*.
3. Move the submodule file *src/server.rs* into the *network* directory.

Here are commands to carry out these steps:

```
$ mkdir src/network
$ mv src/network.rs src/network/mod.rs
$ mv src/server.rs src/network
```

Now when we try to run `cargo build`, compilation will work (we'll still have warnings though). Our module layout still looks like this, which is exactly the same as it did when we had all the code in *src/lib.rs* in Listing 7-3:

```
communicator
 ├── client
 └── network
     └── server
```

The corresponding file layout now looks like this:

```
├── src
│   ├── client.rs
│   ├── lib.rs
│   └── network
│       ├── mod.rs
│       └── server.rs
```

So when we wanted to extract the `network::server` module, why did we have to also change the *src/network.rs* file to the *src/network/mod.rs* file and put the code for `network::server` in the *network* directory in *src/network/server.rs* instead of just being able to extract the `network::server` module into *src/server.rs*? The reason is that Rust wouldn't be able to recognize that `server` was supposed to be a submodule of `network` if the *server.rs* file was in the *src* directory. To clarify Rust's behavior here, let's consider a different example with the following module hierarchy, where all the definitions are in *src/lib.rs*:

```
communicator
 ├── client
 └── network
     └── client
```

In this example, we have three modules again: `client`, `network`, and `network::client`. Following the same steps we did earlier for extracting modules into files, we would create *src/client.rs* for the `client` module. For the `network` module, we would create *src/network.rs*. But we wouldn't be able to extract the `network::client` module into a *src/client.rs* file because that already exists for the top-level `client` module! If we could put the code for *both* the `client` and `network::client` modules in the *src/client.rs* file, Rust wouldn't have any way to know whether the code was for `client` or for `network::client`.

Therefore, in order to extract a file for the `network::client` submodule of the `network` module, we needed to create a directory for the `network` module instead of a *src/network.rs* file. The code that is in the `network` module then goes into the *src/network/mod.rs* file, and the submodule `network::client` can have its own *src/network/client.rs* file. Now the top-level *src/client.rs* is unambiguously the code that belongs to the `client` module.

Rules of Module Filesystems

Let's summarize the rules of modules with regard to files:

- If a module named `foo` has no submodules, you should put the declarations for `foo` in a file named *foo.rs*.
- If a module named `foo` does have submodules, you should put the declarations for `foo` in a file named *foo/mod.rs*.

These rules apply recursively, so if a module named `foo` has a submodule named `bar` and `bar` does not have submodules, you should have the following files in your *src* directory:

```
├── foo
│   ├── bar.rs (contains the declarations in `foo::bar`)
│   └── mod.rs (contains the declarations in `foo`, including `mod bar`)
```

The modules should be declared in their parent module's file using the `mod` keyword.

Next, we'll talk about the `pub` keyword and get rid of those warnings!

Controlling Visibility with `pub`

We resolved the error messages shown in Listing 7-4 by moving the `network` and `network::server` code into the *src/network/mod.rs* and *src/network/server.rs* files, respectively. At that point, `cargo build` was able to build our project, but we still get warning messages about the `client::connect`, `network::connect`, and `network::server::connect` functions not being used:

```
warning: function is never used: `connect`, #[warn(dead_code)] on by default
src/client.rs:1:1
  |
1 | fn connect() {
  | ^

warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/network/mod.rs:1:1
  |
1 | fn connect() {
  | ^

warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/network/server.rs:1:1
  |
1 | fn connect() {
  | ^
```

So why are we receiving these warnings? After all, we're building a library with functions that are intended to be used by our *users*, not necessarily by us within our own project, so it shouldn't matter that these `connect` functions go unused. The point of creating them is that they will be used by another project, not our own.

To understand why this program invokes these warnings, let's try using the `connect` library from another project, calling it externally. To do that, we'll create a binary crate in the same directory as our library crate by making a *src/main.rs* file containing this code:

Filename: src/main.rs

```
extern crate communicator;

fn main() {
    communicator::client::connect();
}
```

We use the `extern crate` command to bring the `communicator` library crate into scope. Our package now contains *two* crates. Cargo treats *src/main.rs* as the root file of a binary crate, which is separate from the existing library crate whose root file is *src/lib.rs*. This pattern is quite common for executable projects: most functionality is in a library crate, and the binary crate uses that library crate. As a result, other programs can also use the library crate, and it's a nice separation of concerns.

From the point of view of a crate outside the `communicator` library looking in, all the modules we've been creating are within a module that has the same name as the crate, `communicator`. We call the top-level module of a crate the *root module*.

Also note that even if we're using an external crate within a submodule of our project, the `extern crate` should go in our root module (so in *src/main.rs* or *src/lib.rs*). Then, in our submodules, we can refer to items from external crates as if the items are top-level modules.

Right now, our binary crate just calls our library's `connect` function from the `client` module. However, invoking `cargo build` will now give us an error after the warnings:

```
error: module `client` is private
 --> src/main.rs:4:5
  |
4 |     communicator::client::connect();
  |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
```

Ah ha! This error tells us that the `client` module is private, which is the crux of the warnings. It's also the first time we've run into the concepts of *public* and *private* in the context of Rust. The default state of all code in Rust is private: no one else is allowed to use the code. If you don't use a private function within your program, because your program is the only code allowed to use that function, Rust will warn you that the function has gone unused.

After we specify that a function like `client::connect` is public, not only will our call to that function from our binary crate be allowed, but the warning that the function is unused will go away. Marking a function as public lets Rust know that the function will be used by code outside of our program. Rust considers the theoretical external usage that's now possible as the function "being used." Thus, when something is marked public, Rust will not require that it be used in our program and will stop warning that the item is unused.

Making a Function Public

To tell Rust to make something public, we add the `pub` keyword to the start of the declaration of the item we want to make public. We'll focus on fixing the warning that indicates `client::connect` has gone unused for now, as well as the ``module `client` is private`` error from our binary crate. Modify *src/lib.rs* to make the `client` module public, like so:

Filename: src/lib.rs

```
pub mod client;

mod network;
```

The `pub` keyword is placed right before `mod`. Let's try building again:

```
error: function `connect` is private
 --> src/main.rs:4:5
  |
4 |     communicator::client::connect();
  |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
```

Hooray! We have a different error! Yes, different error messages are a cause for celebration. The new error shows ``function `connect` is private``, so let's edit *src/client.rs* to make `client::connect` public too:

Filename: src/client.rs

```
pub fn connect() {
}
```

Now run `cargo build` again:

```
warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/network/mod.rs:1:1
  |
1 | fn connect() {
  | ^

warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/network/server.rs:1:1
  |
1 | fn connect() {
  | ^
```

The code compiled, and the warning about `client::connect` not being used is gone!

Unused code warnings don't always indicate that an item in your code needs to be made public: if you *didn't* want these functions to be part of your public API, unused code warnings could be alerting you to code you no longer need that you can safely delete. They could also be alerting you to a bug if you had just accidentally removed all places within your library where this function is called.

But in this case, we *do* want the other two functions to be part of our crate's public API, so let's mark them as `pub` as well to get rid of the remaining warnings. Modify *src/network/mod.rs* to look like the following:

Filename: src/network/mod.rs

```
pub fn connect() {
}

mod server;
```

Then compile the code:

```
warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/network/mod.rs:1:1
  |
1 | pub fn connect() {
  | ^

warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/network/server.rs:1:1
  |
1 | fn connect() {
  | ^
```

Hmmm, we're still getting an unused function warning, even though `network::connect` is set to `pub`. The reason is that the function is public within the module, but the `network` module that the function resides in is not public. We're working from the interior of the library out this time, whereas with `client::connect` we worked from the outside in. We need to change *src/lib.rs* to make `network` public too, like so:

Filename: src/lib.rs

```
pub mod client;

pub mod network;
```

Now when we compile, that warning is gone:

```
warning: function is never used: `connect`, #[warn(dead_code)] on by default
 --> src/network/server.rs:1:1
  |
1 | fn connect() {
  | ^
```

Only one warning is left! Try to fix this one on your own!

Privacy Rules

Overall, these are the rules for item visibility:

1. If an item is public, it can be accessed through any of its parent modules.
2. If an item is private, it can be accessed only by its immediate parent module and any of the parent's child modules.

Privacy Examples

Let's look at a few more privacy examples to get some practice. Create a new library project and enter the code in Listing 7-5 into your new project's *src/lib.rs*:

Filename: src/lib.rs

```
mod outermost {
    pub fn middle_function() {}

    fn middle_secret_function() {}

    mod inside {
        pub fn inner_function() {}

        fn secret_function() {}
    }
}

fn try_me() {
    outermost::middle_function();
    outermost::middle_secret_function();
    outermost::inside::inner_function();
    outermost::inside::secret_function();
}
```

Listing 7-5: Examples of private and public functions, some of which are incorrect

Before you try to compile this code, make a guess about which lines in the `try_me` function will have errors. Then, try compiling the code to see whether you were right, and read on for the discussion of the errors!

Looking at the Errors

The `try_me` function is in the root module of our project. The module named `outermost` is private, but the second privacy rule states that the `try_me` function is allowed to access the `outermost` module because `outermost` is in the current (root) module, as is `try_me`.

The call to `outermost::middle_function` will work because `middle_function` is public, and `try_me` is accessing `middle_function` through its parent module `outermost`. We determined in the previous paragraph that this module is accessible.

The call to `outermost::middle_secret_function` will cause a compilation error. `middle_secret_function` is private, so the second rule applies. The root module is neither the current module of `middle_secret_function` (`outermost` is), nor is it a child module of the current module of `middle_secret_function`.

The module named `inside` is private and has no child modules, so it can only be accessed by its current module `outermost`. That means the `try_me` function is not allowed to call `outermost::inside::inner_function` or `outermost::inside::secret_function`.

Fixing the Errors

Here are some suggestions for changing the code in an attempt to fix the errors. Before you try each one, make a guess as to whether it will fix the errors, and then compile the code to see whether or not you're right, using the privacy rules to understand why.

- What if the `inside` module was public?
- What if `outermost` was public and `inside` was private?
- What if, in the body of `inner_function`, you called `::outermost::middle_secret_function()`? (The two colons at the beginning mean that we want to refer to the modules starting from the root module.)

Feel free to design more experiments and try them out!

Next, let's talk about bringing items into scope with the `use` keyword.

Importing Names

We've covered how to call functions defined within a module using the module name as part of the call, as in the call to the `nested_modules` function shown here in Listing 7-6:

Filename: src/main.rs

```
pub mod a {
    pub mod series {
        pub mod of {
            pub fn nested_modules() {}
        }
    }
}

fn main() {
    a::series::of::nested_modules();
}
```

Listing 7-6: Calling a function by fully specifying its enclosing module's path

As you can see, referring to the fully qualified name can get quite lengthy. Fortunately, Rust has a keyword to make these calls more concise.

Concise Imports with `use`

Rust's `use` keyword shortens lengthy function calls by bringing the modules of the function you want to call into scope. Here's an example of bringing the `a::series::of` module into a binary crate's root scope:

Filename: src/main.rs

```
pub mod a {
    pub mod series {
        pub mod of {
            pub fn nested_modules() {}
        }
    }
}

use a::series::of;

fn main() {
    of::nested_modules();
}
```

The line `use a::series::of;` means that rather than using the full `a::series::of` path wherever we want to refer to the `of` module, we can use `of`.

The `use` keyword brings only what we've specified into scope: it does not bring children of modules into scope. That's why we still have to use `of::nested_modules` when we want to call the `nested_modules` function.

We could have chosen to bring the function into scope by instead specifying the function in the `use` as follows:

```
pub mod a {
    pub mod series {
        pub mod of {
            pub fn nested_modules() {}
        }
    }
}

use a::series::of::nested_modules;

fn main() {
    nested_modules();
}
```

Doing so allows us to exclude all the modules and reference the function directly.

Because enums also form a sort of namespace like modules, we can import an enum's variants with `use` as well. For any kind of `use` statement, if you're importing multiple items from one namespace, you can list them using curly brackets and commas in the last position, like so:

```
enum TrafficLight {
    Red,
    Yellow,
    Green,
}

use TrafficLight::{Red, Yellow};

fn main() {
    let red = Red;
    let yellow = Yellow;
    let green = TrafficLight::Green;
}
```

We're still specifying the `TrafficLight` namespace for the `Green` variant because we didn't include `Green` in the `use` statement.

Glob Imports with `*`

To import all the items in a namespace at once, we can use the `*` syntax. For example:

```
enum TrafficLight {
    Red,
    Yellow,
    Green,
}

use TrafficLight::*;

fn main() {
    let red = Red;
    let yellow = Yellow;
    let green = Green;
}
```

The `*` is called a *glob*, and it will import all items visible inside the namespace. You should use globs sparingly: they are convenient, but this might also pull in more items than you expected and cause naming conflicts.

Using `super` to Access a Parent Module

As we saw at the beginning of this chapter, when you create a library crate, Cargo makes a `tests` module for you. Let's go into more detail about that now. In your `communicator` project, open *src/lib.rs*:

Filename: src/lib.rs

```
pub mod client;

pub mod network;

#[cfg(test)]
mod tests {
    #[test]
    fn it_works() {
    }
}
```

Chapter 11 explains more about testing, but parts of this example should make sense now: we have a module named `tests` that lives next to our other modules and contains one function named `it_works`. Even though there are special annotations, the `tests` module is just another module! So our module hierarchy looks like this:

```
communicator
 ├── client
 ├── network
 |   └── client
 └── tests
```

Tests are for exercising the code within our library, so let's try to call our `client::connect` function from this `it_works` function, even though we won't be checking any functionality right now:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    #[test]
    fn it_works() {
        client::connect();
    }
}
```

Run the tests by invoking the `cargo test` command:

```
$ cargo test
   Compiling communicator v0.1.0 (file:///projects/communicator)
error[E0433]: failed to resolve. Use of undeclared type or module `client`
 --> src/lib.rs:9:9
  |
9 |         client::connect();
  |         ^^^^^^^^^^^^^^^ Use of undeclared type or module `client`
```

The compilation failed, but why? We don't need to place `communicator::` in front of the function like we did in *src/main.rs* because we are definitely within the `communicator` library crate here. The reason is that paths are always relative to the current module, which here is `tests`. The only exception is in a `use` statement, where paths are relative to the crate root by default. Our `tests` module needs the `client` module in its scope!

So how do we get back up one module in the module hierarchy to call the `client::connect` function in the `tests` module? In the `tests` module, we can either use leading colons to let Rust know that we want to start from the root and list the whole path, like this:

```
::client::connect();
```

Or, we can use `super` to move up one module in the hierarchy from our current module, like this:

```
super::client::connect();
```

These two options don't look that different in this example, but if you're deeper in a module hierarchy, starting from the root every time would make your code lengthy. In those cases, using `super` to get from the current module to sibling modules is a good shortcut. Plus, if you've specified the path from the root in many places in your code and then you rearrange your modules by moving a subtree to another place, you'd end up needing to update the path in several places, which would be tedious.

It would also be annoying to have to type `super::` in each test, but you've already seen the tool for that solution: `use`! The `super::` functionality changes the path you give to `use` so it is relative to the parent module instead of to the root module.

For these reasons, in the `tests` module especially, `use super::something` is usually the best solution. So now our test looks like this:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    use super::client;

    #[test]
    fn it_works() {
        client::connect();
    }
}
```

When we run `cargo test` again, the test will pass and the first part of the test result output will be the following:

```
$ cargo test
   Compiling communicator v0.1.0 (file:///projects/communicator)
     Running target/debug/communicator-92007ddb5330fa5a

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

Summary

Now you know some new techniques for organizing your code! Use these techniques to group related functionality together, keep files from becoming too long, and present a tidy public API to your library users.

Next, we'll look at some collection data structures in the standard library that you can use in your nice, neat code!

Common Collections

Rust's standard library includes a number of very useful data structures called *collections*. Most other data types represent one specific value, but collections can contain multiple values. Unlike the built-in array and tuple types, the data these collections point to is stored on the heap, which means the amount of data does not need to be known at compile time and can grow or shrink as the program runs. Each kind of collection has different capabilities and costs, and choosing an appropriate one for your current situation is a skill you'll develop over time. In this chapter, we'll discuss three collections that are used very often in Rust programs:

- A *vector* allows us to store a variable number of values next to each other.
- A *string* is a collection of characters. We've discussed the `String` type previously, but in this chapter we'll talk about it in depth.
- A *hash map* allows us to associate a value with a particular key. It's a particular implementation of the more general data structure called a *map*.

To learn about the other kinds of collections provided by the standard library, see the documentation.

We'll discuss how to create and update vectors, strings, and hash maps, as well as what makes each special.

Vectors

The first collection type we'll look at is `Vec<T>`, also known as a *vector*. Vectors allow us to store more than one value in a single data structure that puts all the values next to each other in memory. Vectors can only store values of the same type. They are useful in situations in which you have a list of items, such as the lines of text in a file or the prices of items in a shopping cart.

Creating a New Vector

To create a new, empty vector, we can call the `Vec::new` function as shown in Listing 8-1:

```
let v: Vec<i32> = Vec::new();
```

Listing 8-1: Creating a new, empty vector to hold values of type `i32`

Note that we added a type annotation here. Because we aren't inserting any values into this vector, Rust doesn't know what kind of elements we intend to store. This is an important point. Vectors are implemented using generics; we'll cover how to use generics with your own types in Chapter 10. For now, know that the `Vec<T>` type provided by the standard library can hold any type, and when a specific vector holds a specific type, the type is specified within angle brackets. In Listing 8-1, we've told Rust that the `Vec<T>` in `v` will hold elements of the `i32` type.

In more realistic code, Rust can often infer the type of value we want to store once we insert values, so you rarely need to do this type annotation. It's more common to create a `Vec<T>` that has initial values, and Rust provides the `vec!` macro for convenience. The macro will create a new vector that holds the values we give it. Listing 8-2 creates a new `Vec<i32>` that holds the values `1`, `2`, and `3`:

```
let v = vec![1, 2, 3];
```

Listing 8-2: Creating a new vector containing values

Because we've given initial `i32` values, Rust can infer that the type of `v` is `Vec<i32>`, and the type annotation isn't necessary. Next, we'll look at how to modify a vector.

Updating a Vector

To create a vector and then add elements to it, we can use the `push` method as shown in Listing 8-3:

```
let mut v = Vec::new();

v.push(5);
v.push(6);
v.push(7);
v.push(8);
```

Listing 8-3: Using the `push` method to add values to a vector

As with any variable, as discussed in Chapter 3, if we want to be able to change its value, we need to make it mutable using the `mut` keyword. The numbers we place inside are all of type `i32`, and Rust infers this from the data, so we don't need the `Vec<i32>` annotation.

Dropping a Vector Drops Its Elements

Like any other `struct`, a vector will be freed when it goes out of scope, as annotated in Listing 8-4:

```
{
    let v = vec![1, 2, 3, 4];

    // do stuff with v

} // <- v goes out of scope and is freed here
```

Listing 8-4: Showing where the vector and its elements are dropped

When the vector gets dropped, all of its contents will also be dropped, meaning those integers it holds will be cleaned up. This may seem like a straightforward point but can get a bit more complicated when we start to introduce references to the elements of the vector. Let's tackle that next!

Reading Elements of Vectors

Now that you know how to create, update, and destroy vectors, knowing how to read their contents is a good next step. There are two ways to reference a value stored in a vector. In the examples, we've annotated the types of the values that are returned from these functions for extra clarity.

Listing 8-5 shows both methods of accessing a value in a vector either with indexing syntax or the `get` method:

```
let v = vec![1, 2, 3, 4, 5];

let third: &i32 = &v[2];
let third: Option<&i32> = v.get(2);
```

Listing 8-5: Using indexing syntax or the `get` method to access an item in a vector

Note two details here. First, we use the index value of `2` to get the third element: vectors are indexed by number, starting at zero. Second, the two different ways to get the third element are by using `&` and `[]`, which gives us a reference, or by using the `get` method with the index passed as an argument, which gives us an `Option<&T>`.

The reason Rust has two ways to reference an element is so you can choose how the program behaves when you try to use an index value that the vector doesn't have an element for. As an example, what should a program do if it has a vector that holds five elements and then tries to access an element at index 100, as shown in Listing 8-6:

```
let v = vec![1, 2, 3, 4, 5];

let does_not_exist = &v[100];
let does_not_exist = v.get(100);
```

Listing 8-6: Attempting to access the element at index 100 in a vector containing 5 elements

When you run this code, the first `[]` method will cause a `panic!` because it references a nonexistent element. This method is best used when you want your program to consider an attempt to access an element past the end of the vector to be a fatal error that crashes the program.

When the `get` method is passed an index that is outside the vector, it returns `None` without panicking. You would use this method if accessing an element beyond the range of the vector happens occasionally under normal circumstances. Your code will then have logic to handle having either `Some(&element)` or `None`, as discussed in Chapter 6. For example, the index could be coming from a person entering a number. If they accidentally enter a number that's too large and the program gets a `None` value, you could tell the user how many items are in the current `Vec` and give them another chance to enter a valid value. That would be more user-friendly than crashing the program due to a typo!

Invalid References

When the program has a valid reference, the borrow checker enforces the ownership and borrowing rules (covered in Chapter 4) to ensure this reference and any other references to the contents of the vector remain valid. Recall the rule that states we can't have mutable and immutable references in the same scope. That rule applies in Listing 8-7 where we hold an immutable reference to the first element in a vector and try to add an element to the end:

```
let mut v = vec![1, 2, 3, 4, 5];

let first = &v[0];

v.push(6);
```

Listing 8-7: Attempting to add an element to a vector while holding a reference to an item

Compiling this code will result in this error:

```
error[E0502]: cannot borrow `v` as mutable because it is also borrowed as
immutable
  |
4 | let first = &v[0];
  |              - immutable borrow occurs here
5 |
6 | v.push(6);
  | ^ mutable borrow occurs here
7 | }
  | - immutable borrow ends here
```

The code in Listing 8-7 might look like it should work: why should a reference to the first element care about what changes at the end of the vector? The reason behind this error is due to the way vectors work: adding a new element onto the end of the vector might require allocating new memory and copying the old elements to the new space if there isn't enough room to put all the elements next to each other where the vector was. In that case, the reference to the first element would be pointing to deallocated memory. The borrowing rules prevent programs from ending up in that situation.

> Note: For more on the implementation details of the `Vec<T>` type, see "The Nomicon" at https://doc.rust-lang.org/stable/nomicon/vec.html.

Iterating Over the Values in a Vector

If we want to access each element in a vector in turn, rather than using indexing to access one element, we can iterate through all of the elements. Listing 8-8 shows how to use a `for` loop to get immutable references to each element in a vector of `i32` values and print them out:

```
let v = vec![100, 32, 57];
for i in &v {
    println!("{}", i);
}
```

Listing 8-8: Printing each element in a vector by iterating over the elements using a `for` loop

We can also iterate over mutable references to each element in a mutable vector if we want to make changes to all the elements. The `for` loop in Listing 8-9 will add `50` to each element:

```
let mut v = vec![100, 32, 57];
for i in &mut v {
    *i += 50;
}
```

Listing 8-9: Iterating over mutable references to elements in a vector

In order to change the value that the mutable reference refers to, before we can use the `+=` operator with `i`, we have to use the dereference operator (`*`) to get to the value.

Using an Enum to Store Multiple Types

At the beginning of this chapter, we said that vectors can only store values that are the same type. This can be inconvenient; there are definitely use cases for needing to store a list of items of different types. Fortunately, the variants of an enum are defined under the same enum type, so when we need to store elements of a different type in a vector, we can define and use an enum!

For example, let's say we want to get values from a row in a spreadsheet where some of the columns in the row contain integers, some floating-point numbers, and some strings. We can define an enum whose variants will hold the different value types, and then all the enum variants will be considered the same type, that of the enum. Then we can create a vector that holds that enum and so, ultimately, holds different types. We've demonstrated this in Listing 8-8:

```
enum SpreadsheetCell {
    Int(i32),
    Float(f64),
    Text(String),
}

let row = vec![
    SpreadsheetCell::Int(3),
    SpreadsheetCell::Text(String::from("blue")),
    SpreadsheetCell::Float(10.12),
];
```

Listing 8-8: Defining an `enum` to store values of different types in one vector

The reason Rust needs to know what types will be in the vector at compile time is so it knows exactly how much memory on the heap will be needed to store each element. A secondary advantage is that we can be explicit about what types are allowed in this vector. If Rust allowed a vector to hold any type, there would be a chance that one or more of the types would cause errors with the operations performed on the elements of the vector. Using an enum plus a `match` expression means that Rust will ensure at compile time that we always handle every possible case, as discussed in Chapter 6.

If you don't know when you're writing a program the exhaustive set of types the program will get at runtime to store in a vector, the enum technique won't work. Instead, you can use a trait object, which we'll cover in Chapter 17.

Now that we've discussed some of the most common ways to use vectors, be sure to review the API documentation for all the many useful methods defined on `Vec` by the standard library. For example, in addition to `push`, a `pop` method removes and returns the last element. Let's move on to the next collection type: `String`!

Strings

We talked about strings in Chapter 4, but we'll look at them in more depth now. New Rustaceans commonly get stuck on strings due to a combination of three concepts: Rust's propensity for exposing possible errors, strings being a more complicated data structure than many programmers give them credit for, and UTF-8. These concepts combine in a way that can seem difficult when you're coming from other programming languages.

This discussion of strings is in the collections chapter because strings are implemented as a collection of bytes plus some methods to provide useful functionality when those bytes are interpreted as text. In this section, we'll talk about the operations on `String` that every collection type has, such as creating, updating, and reading. We'll also discuss the ways in which `String` is different than the other collections, namely how indexing into a `String` is complicated by the differences between how people and computers interpret `String` data.

What Is a String?

We'll first define what we mean by the term *string*. Rust has only one string type in the core language, which is the string slice `str` that is usually seen in its borrowed form `&str`. In Chapter 4, we talked about *string slices*, which are references to some UTF-8 encoded string data stored elsewhere. String literals, for example, are stored in the binary output of the program and are therefore string slices.

The `String` type is provided in Rust's standard library rather than coded into the core language and is a growable, mutable, owned, UTF-8 encoded string type. When Rustaceans refer to "strings" in Rust, they usually mean the `String` and the string slice `&str` types, not just one of those types. Although this section is largely about `String`, both types are used heavily in Rust's standard library and both `String` and string slices are UTF-8 encoded.

Rust's standard library also includes a number of other string types, such as `OsString`, `OsStr`, `CString`, and `CStr`. Library crates can provide even more options for storing string data. Similar to the `*String`/`*Str` naming, they often provide an owned and borrowed variant, just like `String`/`&str`. These string types can store text in different encodings or be represented in memory in a different way, for example. We won't discuss these other string types in this chapter; see their API documentation for more about how to use them and when each is appropriate.

Creating a New String

Many of the same operations available with `Vec` are available with `String` as well, starting with the `new` function to create a string, shown in Listing 8-9:

```
let mut s = String::new();
```

Listing 8-9: Creating a new, empty `String`

This line creates a new empty string called `s` that we can then load data into. Often, we'll have some initial data that we want to start the string with. For that, we use the `to_string` method, which is available on any type that implements the `Display` trait, which string literals do. Listing 8-10 shows two examples:

```
let data = "initial contents";

let s = data.to_string();

// the method also works on a literal directly:
let s = "initial contents".to_string();
```

Listing 8-10: Using the `to_string` method to create a `String` from a string literal

This code creates a string containing `initial contents`.

We can also use the function `String::from` to create a `String` from a string literal. The code in Listing 8-11 is equivalent to the code from Listing 8-10 that uses `to_string`:

```
let s = String::from("initial contents");
```

Listing 8-11: Using the `String::from` function to create a `String` from a string literal

Because strings are used for so many things, we can use many different generic APIs for strings, providing us with a lot of options. Some of them can seem redundant, but they all have their place! In this case, `String::from` and `to_string` do the same thing, so which you choose is a matter of style.

Remember that strings are UTF-8 encoded, so we can include any properly encoded data in them, as shown in Listing 8-12:

```
let hello = String::from("السلام عليكم");
let hello = String::from("Dobrý den");
let hello = String::from("Hello");
let hello = String::from("שָׁלוֹם");
let hello = String::from("नमस्ते");
let hello = String::from("こんにちは");
let hello = String::from("안녕하세요");
let hello = String::from("你好");
let hello = String::from("Olá");
let hello = String::from("Здравствуйте");
let hello = String::from("Hola");
```

Listing 8-12: Storing greetings in different languages in strings

All of these are valid `String` values.

Updating a String

A `String` can grow in size and its contents can change, just like the contents of a `Vec`, by pushing more data into it. In addition, we can conveniently use the `+` operator or the `format!` macro to concatenate `String` values together.

Appending to a String with `push_str` and `push`

We can grow a `String` by using the `push_str` method to append a string slice, as shown in Listing 8-13:

```
let mut s = String::from("foo");
s.push_str("bar");
```

Listing 8-13: Appending a string slice to a `String` using the `push_str` method

After these two lines, `s` will contain `foobar`. The `push_str` method takes a string slice because we don't necessarily want to take ownership of the parameter. For example, the code in Listing 8-14 shows that it would be unfortunate if we weren't able to use `s2` after appending its contents to `s1`:

```
let mut s1 = String::from("foo");
let s2 = "bar";
s1.push_str(&s2);
println!("s2 is {}", s2);
```

Listing 8-14: Using a string slice after appending its contents to a `String`

If the `push_str` method took ownership of `s2`, we wouldn't be able to print out its value on the last line. However, this code works as we'd expect!

The `push` method takes a single character as a parameter and adds it to the `String`. Listing 8-15 shows code that adds an l to a `String` using the `push` method:

```
let mut s = String::from("lo");
s.push('l');
```

Listing 8-15: Adding one character to a `String` value using `push`

As a result of this code, `s` will contain `lol`.

Concatenation with the `+` Operator or the `format!` Macro

Often, we'll want to combine two existing strings. One way is to use the `+` operator, as shown in Listing 8-16:

```
let s1 = String::from("Hello, ");
let s2 = String::from("world!");
let s3 = s1 + &s2; // Note that s1 has been moved here and can no longer be used
```

Listing 8-16: Using the `+` operator to combine two `String` values into a new `String` value

As a result of this code, the string `s3` will contain `Hello, world!`. The reason `s1` is no longer valid after the addition and the reason we used a reference to `s2` has to do with the signature of the method that gets called when we use the `+` operator. The `+` operator uses the `add` method, whose signature looks something like this:

```
fn add(self, s: &str) -> String {
```

This isn't the exact signature that's in the standard library: in the standard library, `add` is defined using generics. Here, we're looking at the signature of `add` with concrete types substituted for the generic ones, which is what happens when we call this method with `String` values. We'll discuss generics in Chapter 10. This signature gives us the clues we need to understand the tricky bits of the `+` operator.

First, `s2` has an `&`, meaning that we're adding a *reference* of the second string to the first string because of the `s` parameter in the `add` function: we can only add a `&str` to a `String`; we can't add two `String` values together. But wait - the type of `&s2` is `&String`, not `&str`, as specified in the second parameter to `add`. Why does Listing 8-16 compile? We are able to use `&s2` in the call to `add` because the compiler can *coerce* the `&String` argument into a `&str`. When we call the `add` method, Rust uses something called a *deref coercion*, which you could think of here as turning `&s2` into `&s2[..]`. We'll discuss deref coercion in more depth in Chapter 15. Because `add` does not take ownership of the `s` parameter, `s2` will still be a valid `String` after this operation.

Second, we can see in the signature that `add` takes ownership of `self`, because `self` does *not* have an `&`. This means `s1` in Listing 8-16 will be moved into the `add` call and no longer be valid after that. So although `let s3 = s1 + &s2;` looks like it will copy both strings and create a new one, this statement actually takes ownership of `s1`, appends a copy of the contents of `s2`, and then returns ownership of the result. In other words, it looks like it's making a lot of copies but isn't: the implementation is more efficient than copying.

If we need to concatenate multiple strings, the behavior of `+` gets unwieldy:

```
let s1 = String::from("tic");
let s2 = String::from("tac");
let s3 = String::from("toe");

let s = s1 + "-" + &s2 + "-" + &s3;
```

At this point, `s` will be `tic-tac-toe`. With all of the `+` and `"` characters, it's difficult to see what's going on. For more complicated string combining, we can use the `format!` macro:

```
let s1 = String::from("tic");
let s2 = String::from("tac");
let s3 = String::from("toe");

let s = format!("{}-{}-{}", s1, s2, s3);
```

This code also sets `s` to `tic-tac-toe`. The `format!` macro works in the same way as `println!`, but instead of printing the output to the screen, it returns a `String` with the contents. The version of the code using `format!` is much easier to read and also doesn't take ownership of any of its parameters.

Indexing into Strings

In many other programming languages, accessing individual characters in a string by referencing them by index is a valid and common operation. However, if we try to access parts of a `String` using indexing syntax in Rust, we'll get an error. Consider the code in Listing 8-17:

```
let s1 = String::from("hello");
let h = s1[0];
```

Listing 8-17: Attempting to use indexing syntax with a String

This code will result in the following error:

```
error: the trait bound `std::string::String: std::ops::Index<_>` is not
satisfied [--explain E0277]
  |>
  |>     let h = s1[0];
  |>             ^^^^^
note: the type `std::string::String` cannot be indexed by `_`
```

The error and the note tell the story: Rust strings don't support indexing. But why not? To answer that question, we need to discuss how Rust stores strings in memory.

Internal Representation

A `String` is a wrapper over a `Vec<u8>`. Let's look at some of our properly encoded UTF-8 example strings from Listing 8-12. First, this one:

```
let len = String::from("Hola").len();
```

In this case, `len` will be four, which means the `Vec` storing the string "Hola" is four bytes long. Each of these letters takes one byte when encoded in UTF-8. But what about the following line?

```
let len = String::from("Здравствуйте").len();
```

Asked how long the string is, you might say 12. However, Rust's answer is 24: that's the number of bytes it takes to encode "Здравствуйте" in UTF-8, because each Unicode scalar value takes two bytes of storage. Therefore, an index into the string's bytes will not always correlate to a valid Unicode scalar value. To demonstrate, consider this invalid Rust code:

```
let hello = "Здравствуйте";
let answer = &hello[0];
```

What should the value of `answer` be? Should it be `З`, the first letter? When encoded in UTF-8, the first byte of `З` is `208`, and the second is `151`, so `answer` should in fact be `208`, but `208` is not a valid character on its own. Returning `208` is likely not what a user would want if they asked for the first letter of this string; however, that's the only data that Rust has at byte index 0. Returning the byte value is probably not what users want, even if the string contains only Latin letters: if `&"hello"[0]` was valid code that returned the byte value, it would return `104`, not `h`. To avoid returning an unexpected value and causing bugs that might not be discovered immediately, Rust doesn't compile this code at all and prevents misunderstandings earlier in the development process.

Bytes and Scalar Values and Grapheme Clusters! Oh My!

Another point about UTF-8 is that there are actually three relevant ways to look at strings from Rust's perspective: as bytes, scalar values, and grapheme clusters (the closest thing to what we would call *letters*).

If we look at the Hindi word "नमस्ते" written in the Devanagari script, it is ultimately stored as a `Vec` of `u8` values that looks like this:

```
[224, 164, 168, 224, 164, 174, 224, 164, 184, 224, 165, 141, 224, 164, 164,
224, 165, 135]
```

That's 18 bytes and is how computers ultimately store this data. If we look at them as Unicode scalar values, which are what Rust's `char` type is, those bytes look like this:

```
['न', 'म', 'स', '्', 'त', 'े']
```

There are six `char` values here, but the fourth and sixth are not letters: they're diacritics that don't make sense on their own. Finally, if we look at them as grapheme clusters, we'd get what a person would call the four letters that make up the Hindi word:

```
["न", "म", "स्", "ते"]
```

Rust provides different ways of interpreting the raw string data that computers store so that each program can choose the interpretation it needs, no matter what human language the data is in.

A final reason Rust doesn't allow us to index into a `String` to get a character is that indexing operations are expected to always take constant time (O(1)). But it isn't possible to guarantee that performance with a `String`, because Rust would have to walk through the contents from the beginning to the index to determine how many valid characters there were.

Slicing Strings

Indexing into a string is often a bad idea because it's not clear what the return type of the string indexing operation should be: a byte value, a character, a grapheme cluster, or a string slice. Therefore, Rust asks you to be more specific if you really need to use indices to create string slices. To be more specific in your indexing and indicate that you want a string slice, rather than indexing using `[]` with a single number, you can use `[]` with a range to create a string slice containing particular bytes:

```rust
let hello = "Здравствуйте";

let s = &hello[0..4];
```

Here, `s` will be a `&str` that contains the first four bytes of the string. Earlier, we mentioned that each of these characters was two bytes, which means `s` will be `Зд`.

What would happen if we used `&hello[0..1]`? The answer: Rust will panic at runtime in the same way that accessing an invalid index in a vector does:

```
thread 'main' panicked at 'index 0 and/or 1 in `Здравствуйте` do not lie on
character boundary', ../src/libcore/str/mod.rs:1694
```

You should use ranges to create string slices with caution, because it can crash your program.

Methods for Iterating Over Strings

Fortunately, we can access elements in a string in other ways.

If we need to perform operations on individual Unicode scalar values, the best way to do so is to use the `chars` method. Calling `chars` on “नमस्ते” separates out and returns six values of type `char`, and you can iterate over the result in order to access each element:

```
for c in "नमस्ते".chars() {
    println!("{}", c);
}
```

This code will print the following:

```
न
म
स
्
त
े
```

The `bytes` method returns each raw byte, which might be appropriate for your domain:

```
for b in "नमस्ते".bytes() {
    println!("{}", b);
}
```

This code will print the 18 bytes that make up this `String`, starting with:

```
224
164
168
224
// ... etc
```

But be sure to remember that valid Unicode scalar values may be made up of more than one byte.

Getting grapheme clusters from strings is complex, so this functionality is not provided by the standard library. Crates are available on crates.io if this is the functionality you need.

Strings Are Not So Simple

To summarize, strings are complicated. Different programming languages make different choices about how to present this complexity to the programmer. Rust has chosen to make the correct handling of `String` data the default behavior for all Rust programs, which means programmers have to put more thought into handling UTF-8 data upfront. This trade-off exposes more of the complexity of strings than other programming languages do but prevents you from having to handle errors involving non-ASCII characters later in your development life cycle.

Let's switch to something a bit less complex: hash maps!

Hash Maps

The last of our common collections is the *hash map*. The type `HashMap<K, V>` stores a mapping of keys of type `K` to values of type `V`. It does this via a *hashing function*, which determines how it places these keys and values into memory. Many different programming languages support this kind of data structure, but often use a different name, such as hash, map, object, hash table, or associative array, just to name a few.

Hash maps are useful for when you want to look up data not by an index, as you can with vectors, but by using a key that can be of any type. For example, in a game, you could keep track of each team's score in a hash map where each key is a team's name and the values are each team's score. Given a team name, you can retrieve its score.

We'll go over the basic API of hash maps in this section, but many more goodies are hiding in the functions defined on `HashMap<K, V>` by the standard library. As always, check the standard library documentation for more information.

Creating a New Hash Map

We can create an empty hash map with `new` and add elements with `insert`. In Listing 8-18, we're keeping track of the scores of two teams whose names are Blue and Yellow. The Blue team will start with 10 points, and the Yellow team starts with 50:

```
use std::collections::HashMap;

let mut scores = HashMap::new();

scores.insert(String::from("Blue"), 10);
scores.insert(String::from("Yellow"), 50);
```

Listing 8-18: Creating a new hash map and inserting some keys and values

Note that we need to first `use` the `HashMap` from the collections portion of the standard library. Of our three common collections, this one is the least often used, so it's not included in the features imported automatically in the prelude. Hash maps also have less support from the standard library; there's no built-in macro to construct them, for example.

Just like vectors, hash maps store their data on the heap. This `HashMap` has keys of type `String` and values of type `i32`. Like vectors, hash maps are homogeneous: all of the keys must have the same type, and all of the values must have the same type.

Another way of constructing a hash map is by using the `collect` method on a vector of tuples, where each tuple consists of a key and its value. The `collect` method gathers data into a number of collection types, including `HashMap`. For example, if we had the team names and initial scores in two separate vectors, we can use the `zip` method to create a vector of tuples where "Blue" is paired with 10, and so forth. Then we can use the `collect` method to turn that vector of tuples into a `HashMap` as shown in Listing 8-19:

```
use std::collections::HashMap;

let teams  = vec![String::from("Blue"), String::from("Yellow")];
let initial_scores = vec![10, 50];

let scores: HashMap<_, _> = teams.iter().zip(initial_scores.iter()).collect();
```

Listing 8-19: Creating a hash map from a list of teams and a list of scores

The type annotation `HashMap<_, _>` is needed here because it's possible to `collect` into many different data structures, and Rust doesn't know which you want unless you specify. For the type parameters for the key and value types, however, we use underscores, and Rust can infer the types that the hash map contains based on the types of the data in the vectors.

Hash Maps and Ownership

For types that implement the `Copy` trait, like `i32`, the values are copied into the hash map. For owned values like `String`, the values will be moved and the hash map will be the owner of those values as demonstrated in Listing 8-20:

```
use std::collections::HashMap;

let field_name = String::from("Favorite color");
let field_value = String::from("Blue");

let mut map = HashMap::new();
map.insert(field_name, field_value);
// field_name and field_value are invalid at this point, try using them and
// see what compiler error you get!
```

Listing 8-20: Showing that keys and values are owned by the hash map once they're inserted

We aren't able to use the variables `field_name` and `field_value` after they've been moved into the hash map with the call to `insert`.

If we insert references to values into the hash map, the values won't be moved into the hash map. The values that the references point to must be valid for at least as long as the hash map is valid. We'll talk more about these issues in the "Validating References with Lifetimes" section in Chapter 10.

Accessing Values in a Hash Map

We can get a value out of the hash map by providing its key to the `get` method as shown in Listing 8-21:

```
use std::collections::HashMap;

let mut scores = HashMap::new();

scores.insert(String::from("Blue"), 10);
scores.insert(String::from("Yellow"), 50);

let team_name = String::from("Blue");
let score = scores.get(&team_name);
```

Listing 8-21: Accessing the score for the Blue team stored in the hash map

Here, `score` will have the value that's associated with the Blue team, and the result will be `Some(&10)`. The result is wrapped in `Some` because `get` returns an `Option<&V>`; if there's no value for that key in the hash map, `get` will return `None`. The program will need to handle the `Option` in one of the ways that we covered in Chapter 6.

We can iterate over each key/value pair in a hash map in a similar manner as we do with vectors, using a `for` loop:

```
use std::collections::HashMap;

let mut scores = HashMap::new();

scores.insert(String::from("Blue"), 10);
scores.insert(String::from("Yellow"), 50);

for (key, value) in &scores {
    println!("{}: {}", key, value);
}
```

This code will print each pair in an arbitrary order:

```
Yellow: 50
Blue: 10
```

Updating a Hash Map

Although the number of keys and values is growable, each key can only have one value associated with it at a time. When we want to change the data in a hash map, we have to decide how to handle the case when a key already has a value assigned. We could replace the old value with the new value, completely disregarding the old value. We could keep the old value and ignore the new value, and only add the new value if the key *doesn't* already have a value. Or we could combine the old value and the new value. Let's look at how to do each of these!

Overwriting a Value

If we insert a key and a value into a hash map, and then insert that same key with a different value, the value associated with that key will be replaced. Even though the code in Listing 8-22 calls `insert` twice, the hash map will only contain one key/value pair because we're inserting the value for the Blue team's key both times:

```
use std::collections::HashMap;

let mut scores = HashMap::new();

scores.insert(String::from("Blue"), 10);
scores.insert(String::from("Blue"), 25);

println!("{:?}", scores);
```

Listing 8-22: Replacing a value stored with a particular key

This code will print `{"Blue": 25}`. The original value of `10` has been overwritten.

Only Insert If the Key Has No Value

It's common to check whether a particular key has a value, and if it doesn't, insert a value for it. Hash maps have a special API for this called `entry` that takes the key we want to check as a parameter. The return value of the `entry` function is an enum called `Entry` that represents a value that might or might not exist. Let's say we want to check whether the key for the Yellow team has a value associated with it. If it doesn't, we want to insert the value 50, and the same for the Blue team. Using the `entry` API, the code looks like Listing 8-23:

```rust
use std::collections::HashMap;

let mut scores = HashMap::new();
scores.insert(String::from("Blue"), 10);

scores.entry(String::from("Yellow")).or_insert(50);
scores.entry(String::from("Blue")).or_insert(50);

println!("{:?}", scores);
```

Listing 8-23: Using the `entry` method to only insert if the key does not already have a value

The `or_insert` method on `Entry` is defined to return the value for the corresponding `Entry` key if that key exists, and if not, inserts the parameter as the new value for this key and returns the modified `Entry`. This technique is much cleaner than writing the logic ourselves, and in addition, plays more nicely with the borrow checker.

Running the code in Listing 8-23 will print `{"Yellow": 50, "Blue": 10}`. The first call to `entry` will insert the key for the Yellow team with the value `50` because the Yellow team doesn't have a value already. The second call to `entry` will not change the hash map because the Blue team already has the value `10`.

Updating a Value Based on the Old Value

Another common use case for hash maps is to look up a key's value and then update it based on the old value. For instance, Listing 8-24 shows code that counts how many times each word appears in some text. We use a hash map with the words as keys and increment the value to keep track of how many times we've seen that word. If it's the first time we've seen a word, we'll first insert the value `0`:

```
use std::collections::HashMap;

let text = "hello world wonderful world";

let mut map = HashMap::new();

for word in text.split_whitespace() {
    let count = map.entry(word).or_insert(0);
    *count += 1;
}

println!("{:?}", map);
```

Listing 8-24: Counting occurrences of words using a hash map that stores words and counts

This code will print `{"world": 2, "hello": 1, "wonderful": 1}`. The `or_insert` method actually returns a mutable reference (`&mut V`) to the value for this key. Here we store that mutable reference in the `count` variable, so in order to assign to that value we must first dereference `count` using the asterisk (`*`). The mutable reference goes out of scope at the end of the `for` loop, so all of these changes are safe and allowed by the borrowing rules.

Hashing Function

By default, `HashMap` uses a cryptographically secure hashing function that can provide resistance to Denial of Service (DoS) attacks. This is not the fastest hashing algorithm available, but the trade-off for better security that comes with the drop in performance is worth it. If you profile your code and find that the default hash function is too slow for your purposes, you can switch to another function by specifying a different *hasher*. A hasher is a type that implements the `BuildHasher` trait. We'll talk about traits and how to implement them in Chapter 10. You don't necessarily have to implement your own hasher from scratch; crates.io has libraries shared by other Rust users that provide hashers implementing many common hashing algorithms.

Summary

Vectors, strings, and hash maps will provide a large amount of functionality that you need in programs where you need to store, access, and modify data. Here are some exercises you should now be equipped to solve:

- Given a list of integers, use a vector and return the mean (average), median (when sorted, the value in the middle position), and mode (the value that occurs most often; a hash map will be helpful here) of the list.

- Convert strings to pig latin. The first consonant of each word is moved to the end of the word and “ay” is added, so “first” becomes “irst-fay.” Words that start with a vowel have “hay” added to the end instead (“apple” becomes “apple-hay”). Keep in mind the details about UTF-8 encoding!
- Using a hash map and vectors, create a text interface to allow a user to add employee names to a department in a company. For example, “Add Sally to Engineering” or “Add Amir to Sales.” Then let the user retrieve a list of all people in a department or all people in the company by department, sorted alphabetically.

The standard library API documentation describes methods that vectors, strings, and hash maps have that will be helpful for these exercises!

We’re getting into more complex programs in which operations can fail; so, it’s a perfect time to discuss error handling next!

Error Handling

Rust’s commitment to reliability extends to error handling. Errors are a fact of life in software, so Rust has a number of features for handling situations in which something goes wrong. In many cases, Rust requires you to acknowledge the possibility of an error occurring and take some action before your code will compile. This requirement makes your program more robust by ensuring that you’ll discover errors and handle them appropriately before you’ve deployed your code to production!

Rust groups errors into two major categories: *recoverable* and *unrecoverable* errors. Recoverable errors are situations in which it’s reasonable to report the problem to the user and retry the operation, like a file not found error. Unrecoverable errors are always symptoms of bugs, like trying to access a location beyond the end of an array.

Most languages don’t distinguish between these two kinds of errors and handle both in the same way using mechanisms like exceptions. Rust doesn’t have exceptions. Instead, it has the value `Result<T, E>` for recoverable errors and the `panic!` macro that stops execution when it encounters unrecoverable errors. This chapter covers calling `panic!` first and then talks about returning `Result<T, E>` values. Additionally, we’ll explore considerations to take into account when deciding whether to try to recover from an error or to stop execution.

Unrecoverable Errors with `panic!`

Sometimes, bad things happen in your code, and there’s nothing you can do about it. In these cases, Rust has the `panic!` macro. When the `panic!` macro executes, your program will print a failure message, unwind and clean up the stack, and then quit. The most common situation this occurs in is when a bug of some kind has been detected, and it's not clear to the programmer how to handle the error.

Unwinding the Stack or Aborting in Response to a `panic!`

By default, when a `panic!` occurs, the program starts *unwinding*, which means Rust walks back up the stack and cleans up the data from each function it encounters. But this walking back and cleanup is a lot of work. The alternative is to immediately *abort*, which ends the program without cleaning up. Memory that the program was using will then need to be cleaned up by the operating system. If in your project you need to make the resulting binary as small as possible, you can switch from unwinding to aborting on panic by adding `panic = 'abort'` to the appropriate `[profile]` sections in your *Cargo.toml* file. For example, if you want to abort on panic in release mode, add this:

```
[profile.release]
panic = 'abort'
```

Let's try calling `panic!` in a simple program:

Filename: src/main.rs

```rust
fn main() {
    panic!("crash and burn");
}
```

When you run the program, you'll see something like this:

```
$ cargo run
   Compiling panic v0.1.0 (file:///projects/panic)
    Finished dev [unoptimized + debuginfo] target(s) in 0.25 secs
     Running `target/debug/panic`
thread 'main' panicked at 'crash and burn', src/main.rs:2
note: Run with `RUST_BACKTRACE=1` for a backtrace.
error: Process didn't exit successfully: `target/debug/panic` (exit code: 101)
```

The call to `panic!` causes the error message contained in the last three lines. The first line shows our panic message and the place in our source code where the panic occurred: *src/main.rs:2* indicates that it's the second line of our *src/main.rs* file.

In this case, the line indicated is part of our code, and if we go to that line, we see the `panic!` macro call. In other cases, the `panic!` call might be in code that our code calls. The filename and line number reported by the error message will be someone else's code where the `panic!` macro is called, not the line of our code that eventually led to the `panic!` call. We can use the backtrace of the functions the `panic!` call came from to figure out the part of our code that is causing the problem. We'll discuss what a backtrace is in more detail next.

Using a `panic!` Backtrace

Let's look at another example to see what it's like when a `panic!` call comes from a library because of a bug in our code instead of from our code calling the macro directly. Listing 9-1 has some code that attempts to access an element by index in a vector:

Filename: src/main.rs

```
fn main() {
    let v = vec![1, 2, 3];

    v[100];
}
```

Listing 9-1: Attempting to access an element beyond the end of a vector, which will cause a `panic!`

Here, we're attempting to access the hundredth element of our vector, but it has only three elements. In this situation, Rust will panic. Using `[]` is supposed to return an element, but if you pass an invalid index, there's no element that Rust could return here that would be correct.

Other languages, like C, will attempt to give you exactly what you asked for in this situation, even though it isn't what you want: you'll get whatever is at the location in memory that would correspond to that element in the vector, even though the memory doesn't belong to the vector. This is called a *buffer overread* and can lead to security vulnerabilities if an attacker is able to manipulate the index in such a way as to read data they shouldn't be allowed to that is stored after the array.

To protect your program from this sort of vulnerability, if you try to read an element at an index that doesn't exist, Rust will stop execution and refuse to continue. Let's try it and see:

```
$ cargo run
   Compiling panic v0.1.0 (file:///projects/panic)
    Finished dev [unoptimized + debuginfo] target(s) in 0.27 secs
     Running `target/debug/panic`
thread 'main' panicked at 'index out of bounds: the len is 3 but the index is
100', /stable-dist-rustc/build/src/libcollections/vec.rs:1362
note: Run with `RUST_BACKTRACE=1` for a backtrace.
error: Process didn't exit successfully: `target/debug/panic` (exit code: 101)
```

This error points at a file we didn't write, *libcollections/vec.rs*. That's the implementation of `Vec<T>` in the standard library. The code that gets run when we use `[]` on our vector `v` is in *libcollections/vec.rs*, and that is where the `panic!` is actually happening.

The next note line tells us that we can set the `RUST_BACKTRACE` environment variable to get a backtrace of exactly what happened to cause the error. A *backtrace* is a list of all the functions that have been called to get to this point. Backtraces in Rust work like they do in other languages: the key to reading the backtrace is to start from the top and read until you see files you wrote. That's the spot where the problem originated. The lines above the lines mentioning your files are code that your code called; the lines below are code that called your code. These lines might include core Rust code, standard library code, or crates that you're using. Let's try getting a backtrace: Listing 9-2 shows output similar to what you'll see:

```
$ RUST_BACKTRACE=1 cargo run
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/panic`
thread 'main' panicked at 'index out of bounds: the len is 3 but the index is
100', /stable-dist-rustc/build/src/libcollections/vec.rs:1392
stack backtrace:
   1:     0x560ed90ec04c -
std::sys::imp::backtrace::tracing::imp::write::hf33ae72d0baa11ed
                        at /stable-dist-
rustc/build/src/libstd/sys/unix/backtrace/tracing/gcc_s.rs:42
   2:     0x560ed90ee03e - std::panicking::default_hook::
{{closure}}::h59672b733cc6a455
                        at /stable-dist-rustc/build/src/libstd/panicking.rs:351
   3:     0x560ed90edc44 - std::panicking::default_hook::h1670459d2f3f8843
                        at /stable-dist-rustc/build/src/libstd/panicking.rs:367
   4:     0x560ed90ee41b - std::panicking::rust_panic_with_hook::hcf0ddb069e7abcd7
                        at /stable-dist-rustc/build/src/libstd/panicking.rs:555
   5:     0x560ed90ee2b4 - std::panicking::begin_panic::hd6eb68e27bdf6140
                        at /stable-dist-rustc/build/src/libstd/panicking.rs:517
   6:     0x560ed90ee1d9 - std::panicking::begin_panic_fmt::abcd5965948b877f8
                        at /stable-dist-rustc/build/src/libstd/panicking.rs:501
   7:     0x560ed90ee167 - rust_begin_unwind
                        at /stable-dist-rustc/build/src/libstd/panicking.rs:477
   8:     0x560ed911401d - core::panicking::panic_fmt::hc0f6d7b2c300cdd9
                        at /stable-dist-rustc/build/src/libcore/panicking.rs:69
   9:     0x560ed9113fc8 - core::panicking::panic_bounds_check::h02a4af86d01b3e96
                        at /stable-dist-rustc/build/src/libcore/panicking.rs:56
  10:     0x560ed90e71c5 - <collections::vec::Vec<T> as
core::ops::Index<usize>>::index::h98abcd4e2a74c41
                        at /stable-dist-rustc/build/src/libcollections/vec.rs:1392
  11:     0x560ed90e727a - panic::main::h5d6b77c20526bc35
                        at /home/you/projects/panic/src/main.rs:4
  12:     0x560ed90f5d6a - __rust_maybe_catch_panic
                        at /stable-dist-rustc/build/src/libpanic_unwind/lib.rs:98
  13:     0x560ed90ee926 - std::rt::lang_start::hd7c880a37a646e81
                        at /stable-dist-rustc/build/src/libstd/panicking.rs:436
                        at /stable-dist-rustc/build/src/libstd/panic.rs:361
                        at /stable-dist-rustc/build/src/libstd/rt.rs:57
  14:     0x560ed90e7302 - main
  15:     0x7f0d53f16400 - __libc_start_main
  16:     0x560ed90e6659 - _start
  17:                0x0 - <unknown>
```

Listing 9-2: The backtrace generated by a call to `panic!` displayed when the environment variable `RUST_BACKTRACE` is set

That's a lot of output! The exact output you see might be different depending on your operating system and Rust version. In order to get backtraces with this information, debug symbols must be enabled. Debug symbols are enabled by default when using cargo build or cargo run without the --release flag, as we have here.

In the output in Listing 9-2, line 11 of the backtrace points to the line in our project that's causing the problem: *src/main.rs* in line 4. If we don't want our program to panic, the location pointed to by the first line mentioning a file we wrote is where we should start investigating to figure out how we got to this location with values that caused the panic. In Listing 9-1 where we deliberately wrote code that would panic in order to demonstrate how to use backtraces, the way to fix the panic is to not request an element at index 100 from a vector that only contains three items. When your code panics in the future, you'll need to figure out what action the code is taking with what values that causes the panic and what the code should do instead.

We'll come back to `panic!` and when we should and should not use `panic!` to handle error conditions later in the chapter. Next, we'll look at how to recover from an error using `Result`.

Recoverable Errors with `Result`

Most errors aren't serious enough to require the program to stop entirely. Sometimes, when a function fails, it's for a reason that we can easily interpret and respond to. For example, if we try to open a file and that operation fails because the file doesn't exist, we might want to create the file instead of terminating the process.

Recall in Chapter 2 in the on "Handling Potential Failure with the `Result` Type" section that the `Result` enum is defined as having two variants, `Ok` and `Err`, as follows:

```rust
enum Result<T, E> {
    Ok(T),
    Err(E),
}
```

The `T` and `E` are generic type parameters: we'll discuss generics in more detail in Chapter 10. What you need to know right now is that `T` represents the type of the value that will be returned in a success case within the `Ok` variant, and `E` represents the type of the error that will be returned in a failure case within the `Err` variant. Because `Result` has these generic type parameters, we can use the `Result` type and the functions that the standard library has defined on it in many different situations where the successful value and error value we want to return may differ.

Let's call a function that returns a `Result` value because the function could fail: in Listing 9-3 we try to open a file:

Filename: src/main.rs

```
use std::fs::File;

fn main() {
    let f = File::open("hello.txt");
}
```

Listing 9-3: Opening a file

How do we know `File::open` returns a `Result`? We could look at the standard library API documentation, or we could ask the compiler! If we give `f` a type annotation of a type that we know the return type of the function is *not* and then we try to compile the code, the compiler will tell us that the types don't match. The error message will then tell us what the type of `f` *is*. Let's try it: we know that the return type of `File::open` isn't of type `u32`, so let's change the `let f` statement to this:

```
let f: u32 = File::open("hello.txt");
```

Attempting to compile now gives us the following output:

```
error[E0308]: mismatched types
 --> src/main.rs:4:18
  |
4 |     let f: u32 = File::open("hello.txt");
  |                  ^^^^^^^^^^^^^^^^^^^^^^^ expected u32, found enum
`std::result::Result`
  |
  = note: expected type `u32`
  = note:    found type `std::result::Result<std::fs::File, std::io::Error>`
```

This tells us the return type of the `File::open` function is a `Result<T, E>`. The generic parameter `T` has been filled in here with the type of the success value, `std::fs::File`, which is a file handle. The type of `E` used in the error value is `std::io::Error`.

This return type means the call to `File::open` might succeed and return to us a file handle that we can read from or write to. The function call also might fail: for example, the file might not exist or we might not have permission to access the file. The `File::open` function needs to have a way to tell us whether it succeeded or failed and at the same time give us either the file handle or error information. This information is exactly what the `Result` enum conveys.

In the case where `File::open` succeeds, the value we will have in the variable `f` will be an instance of `Ok` that contains a file handle. In the case where it fails, the value in `f` will be an instance of `Err` that contains more information about the kind of error that happened.

We need to add to the code in Listing 9-3 to take different actions depending on the value `File::open` returned. Listing 9-4 shows one way to handle the `Result` using a basic tool: the `match` expression that we discussed in Chapter 6.

Filename: src/main.rs

```
use std::fs::File;

fn main() {
    let f = File::open("hello.txt");

    let f = match f {
        Ok(file) => file,
        Err(error) => {
            panic!("There was a problem opening the file: {:?}", error)
        },
    };
}
```

Listing 9-4: Using a `match` expression to handle the `Result` variants we might have

Note that, like the `Option` enum, the `Result` enum and its variants have been imported in the prelude, so we don't need to specify `Result::` before the `Ok` and `Err` variants in the `match` arms.

Here we tell Rust that when the result is `Ok`, return the inner `file` value out of the `Ok` variant, and we then assign that file handle value to the variable `f`. After the `match`, we can then use the file handle for reading or writing.

The other arm of the `match` handles the case where we get an `Err` value from `File::open`. In this example, we've chosen to call the `panic!` macro. If there's no file named *hello.txt* in our current directory and we run this code, we'll see the following output from the `panic!` macro:

```
thread 'main' panicked at 'There was a problem opening the file: Error { repr:
Os { code: 2, message: "No such file or directory" } }', src/main.rs:8
```

As usual, this output tells us exactly what has gone wrong.

Matching on Different Errors

The code in Listing 9-4 will `panic!` no matter the reason that `File::open` failed. What we want to do instead is take different actions for different failure reasons: if `File::open` failed because the file doesn't exist, we want to create the file and return the handle to the new file. If `File::open` failed for any other reason, for example because we didn't have permission to open the file, we still want the code to `panic!` in the same way as it did in Listing 9-4. Look at Listing 9-5, which adds another arm to the `match`:

Filename: src/main.rs

```
use std::fs::File;
use std::io::ErrorKind;

fn main() {
    let f = File::open("hello.txt");

    let f = match f {
        Ok(file) => file,
        Err(ref error) if error.kind() == ErrorKind::NotFound => {
            match File::create("hello.txt") {
                Ok(fc) => fc,
                Err(e) => {
                    panic!(
                        "Tried to create file but there was a problem: {:?}",
                        e
                    )
                },
            }
        },
        Err(error) => {
            panic!(
                "There was a problem opening the file: {:?}",
                error
            )
        },
    };
}
```

Listing 9-5: Handling different kinds of errors in different ways

The type of the value that `File::open` returns inside the `Err` variant is `io::Error`, which is a struct provided by the standard library. This struct has a method `kind` that we can call to get an `io::ErrorKind` value. `io::ErrorKind` is an enum provided by the standard library that has variants representing the different kinds of errors that might result from an `io` operation. The variant we want to use is `ErrorKind::NotFound`, which indicates the file we're trying to open doesn't exist yet.

The condition `if error.kind() == ErrorKind::NotFound` is called a *match guard*: it's an extra condition on a `match` arm that further refines the arm's pattern. This condition must be true for that arm's code to be run; otherwise, the pattern matching will move on to consider the next arm in the `match`. The `ref` in the pattern is needed so `error` is not moved into the guard condition but is merely referenced by it. The reason `ref` is used to take a reference in a pattern instead of `&` will be covered in detail in Chapter 18. In short, in the context of a pattern, `&` matches a reference and gives us its value, but `ref` matches a value and gives us a reference to it.

The condition we want to check in the match guard is whether the value returned by `error.kind()` is the `NotFound` variant of the `ErrorKind` enum. If it is, we try to create the file with `File::create`. However, because `File::create` could also fail, we need to add an inner `match` statement as well. When the file can't be opened, a different error message will be printed. The last arm of the outer `match` stays the same so the program panics on any error besides the missing file error.

Shortcuts for Panic on Error: `unwrap` and `expect`

Using `match` works well enough, but it can be a bit verbose and doesn't always communicate intent well. The `Result<T, E>` type has many helper methods defined on it to do various tasks. One of those methods, called `unwrap`, is a shortcut method that is implemented just like the `match` statement we wrote in Listing 9-4. If the `Result` value is the `Ok` variant, `unwrap` will return the value inside the `Ok`. If the `Result` is the `Err` variant, `unwrap` will call the `panic!` macro for us. Here is an example of `unwrap` in action:

Filename: src/main.rs

```
use std::fs::File;

fn main() {
    let f = File::open("hello.txt").unwrap();
}
```

If we run this code without a *hello.txt* file, we'll see an error message from the `panic!` call that the `unwrap` method makes:

```
thread 'main' panicked at 'called `Result::unwrap()` on an `Err` value: Error {
repr: Os { code: 2, message: "No such file or directory" } }',
/stable-dist-rustc/build/src/libcore/result.rs:868
```

Another method, `expect`, which is similar to `unwrap`, lets us also choose the `panic!` error message. Using `expect` instead of `unwrap` and providing good error messages can convey your intent and make tracking down the source of a panic easier. The syntax of `expect` looks like this:

Filename: src/main.rs

```
use std::fs::File;

fn main() {
    let f = File::open("hello.txt").expect("Failed to open hello.txt");
}
```

We use `expect` in the same way as `unwrap`: to return the file handle or call the `panic!` macro. The error message used by `expect` in its call to `panic!` will be the parameter that we pass to `expect`, rather than the default `panic!` message that `unwrap` uses. Here's what it looks like:

```
thread 'main' panicked at 'Failed to open hello.txt: Error { repr: Os { code:
2, message: "No such file or directory" } }',
/stable-dist-rustc/build/src/libcore/result.rs:868
```

Because this error message starts with the text we specified, `Failed to open hello.txt`, it will be easier to find where in the code this error message is coming from. If we use `unwrap` in multiple places, it can take more time to figure out exactly which `unwrap` is causing the panic because all `unwrap` calls that panic print the same message.

Propagating Errors

When you're writing a function whose implementation calls something that might fail, instead of handling the error within this function, you can return the error to the calling code so that it can decide what to do. This is known as *propagating* the error and gives more control to the calling code where there might be more information or logic that dictates how the error should be handled than what you have available in the context of your code.

For example, Listing 9-6 shows a function that reads a username from a file. If the file doesn't exist or can't be read, this function will return those errors to the code that called this function:

Filename: src/main.rs

```rust
use std::io;
use std::io::Read;
use std::fs::File;

fn read_username_from_file() -> Result<String, io::Error> {
    let f = File::open("hello.txt");

    let mut f = match f {
        Ok(file) => file,
        Err(e) => return Err(e),
    };

    let mut s = String::new();

    match f.read_to_string(&mut s) {
        Ok(_) => Ok(s),
        Err(e) => Err(e),
    }
}
```

Listing 9-6: A function that returns errors to the calling code using `match`

Let's look at the return type of the function first: `Result<String, io::Error>`. This means the function is returning a value of the type `Result<T, E>` where the generic parameter `T` has been filled in with the concrete type `String`, and the generic type `E` has been filled in with the concrete type `io::Error`. If this function succeeds without any problems, the code that calls this function will receive an `Ok` value that holds a `String`—the username that this function read from the file. If this function encounters any problems, the code that calls this function will receive an `Err` value that holds an instance of `io::Error` that contains more information about what the problems were. We chose `io::Error` as the return type of this function because that happens to be the type of the error value returned from both of the operations we're calling in this function's body that might fail: the `File::open` function and the `read_to_string` method.

The body of the function starts by calling the `File::open` function. Then we handle the `Result` value returned with a `match` similar to the `match` in Listing 9-4, only instead of calling `panic!` in the `Err` case, we return early from this function and pass the error value from `File::open` back to the calling code as this function's error value. If `File::open` succeeds, we store the file handle in the variable `f` and continue.

Then we create a new `String` in variable `s` and call the `read_to_string` method on the file handle in `f` to read the contents of the file into `s`. The `read_to_string` method also returns a `Result` because it might fail, even though `File::open` succeeded. So we need another `match` to handle that `Result`: if `read_to_string` succeeds, then our function has succeeded, and we return the username from the file that's now in `s` wrapped in an `Ok`. If `read_to_string` fails, we return the error value in the same way that we returned the error value in the `match` that handled the return value of `File::open`. However, we don't need to explicitly say `return`, because this is the last expression in the function.

The code that calls this code will then handle getting either an `Ok` value that contains a username or an `Err` value that contains an `io::Error`. We don't know what the calling code will do with those values. If the calling code gets an `Err` value, it could call `panic!` and crash the program, use a default username, or look up the username from somewhere other than a file, for example. We don't have enough information on what the calling code is actually trying to do, so we propagate all the success or error information upwards for it to handle appropriately.

This pattern of propagating errors is so common in Rust that Rust provides the question mark operator `?` to make this easier.

A Shortcut for Propagating Errors: `?`

Listing 9-7 shows an implementation of `read_username_from_file` that has the same functionality as it had in Listing 9-6, but this implementation uses the question mark operator:

Filename: src/main.rs

```
use std::io;
use std::io::Read;
use std::fs::File;

fn read_username_from_file() -> Result<String, io::Error> {
    let mut f = File::open("hello.txt")?;
    let mut s = String::new();
    f.read_to_string(&mut s)?;
    Ok(s)
}
```

Listing 9-7: A function that returns errors to the calling code using `?`

The `?` placed after a `Result` value is defined to work in almost the same way as the `match` expressions we defined to handle the `Result` values in Listing 9-6. If the value of the `Result` is an `Ok`, the value inside the `Ok` will get returned from this expression and the program will continue. If the value is an `Err`, the value inside the `Err` will be returned from the whole function as if we had used the `return` keyword so the error value gets propagated to the calling code.

The one difference between the `match` expression from Listing 9-6 and what the question mark operator does is that when using the question mark operator, error values go through the `from` function defined in the `From` trait in the standard library. Many error types implement the `from` function to convert an error of one type into an error of another type. When used by the question mark operator, the call to the `from` function converts the error type that the question mark operator gets into the error type defined in the return type of the current function that we're using `?` in. This is useful when parts of a function might fail for many different reasons, but the function returns one error type that represents all the ways the function might fail. As long as each error type implements the `from` function to define how to convert itself to the returned error type, the question mark operator takes care of the conversion automatically.

In the context of Listing 9-7, the `?` at the end of the `File::open` call will return the value inside an `Ok` to the variable `f`. If an error occurs, `?` will return early out of the whole function and give any `Err` value to the calling code. The same thing applies to the `?` at the end of the `read_to_string` call.

The `?` eliminates a lot of boilerplate and makes this function's implementation simpler. We could even shorten this code further by chaining method calls immediately after the `?` as shown in Listing 9-8:

Filename: src/main.rs

```
use std::io;
use std::io::Read;
use std::fs::File;

fn read_username_from_file() -> Result<String, io::Error> {
    let mut s = String::new();

    File::open("hello.txt")?.read_to_string(&mut s)?;

    Ok(s)
}
```

Listing 9-8: Chaining method calls after the question mark operator

We've moved the creation of the new `String` in `s` to the beginning of the function; that part hasn't changed. Instead of creating a variable `f`, we've chained the call to `read_to_string` directly onto the result of `File::open("hello.txt")?`. We still have a `?` at the end of the `read_to_string` call, and we still return an `Ok` value containing the username in `s` when both `File::open` and `read_to_string` succeed rather than returning errors. The functionality is again the same as in Listing 9-6 and Listing 9-7; this is just a different, more ergonomic way to write it.

`?` Can Only Be Used in Functions That Return Result

The `?` can only be used in functions that have a return type of `Result`, because it is defined to work in the same way as the `match` expression we defined in Listing 9-6. The part of the `match` that requires a return type of `Result` is `return Err(e)`, so the return type of the function must be a `Result` to be compatible with this `return`.

Let's look at what happens if we use `?` in the `main` function, which you'll recall has a return type of `()`:

```
use std::fs::File;

fn main() {
    let f = File::open("hello.txt")?;
}
```

When we compile this code, we get the following error message:

```
error[E0277]: the `?` operator can only be used in a function that returns
`Result` (or another type that implements `std::ops::Try`)
 --> src/main.rs:4:13
  |
4 |     let f = File::open("hello.txt")?;
  |             ------------------------
  |             |
  |             cannot use the `?` operator in a function that returns `()`
  |             in this macro invocation
  |
  = help: the trait `std::ops::Try` is not implemented for `()`
  = note: required by `std::ops::Try::from_error`
```

This error points out that we're only allowed to use the question mark operator in a function that returns `Result`. In functions that don't return `Result`, when you call other functions that return `Result`, you'll need to use a `match` or one of the `Result` methods to handle it instead of using `?` to potentially propagate the error to the calling code.

Now that we've discussed the details of calling `panic!` or returning `Result`, let's return to the topic of how to decide which is appropriate to use in which cases.

To `panic!` or Not to `panic!`

So how do you decide when you should `panic!` and when you should return `Result`? When code panics, there's no way to recover. You could call `panic!` for any error situation, whether there's a possible way to recover or not, but then you're making the decision on behalf of the code calling your code that a situation is unrecoverable. When you choose to return a `Result` value, you give the calling code options rather than making the decision for it. The calling code could choose to attempt to recover in a way that's appropriate for its situation, or it could decide that an `Err` value in this case is unrecoverable, so it can call `panic!` and turn your recoverable error into an unrecoverable one. Therefore, returning `Result` is a good default choice when you're defining a function that might fail.

In a few situations it's more appropriate to write code that panics instead of returning a `Result`, but they are less common. Let's explore why it's appropriate to panic in examples, prototype code, and tests; then in situations where you as a human can know a method won't fail that the compiler can't reason about; and conclude with some general guidelines on how to decide whether to panic in library code.

Examples, Prototype Code, and Tests Are All Places it's Perfectly Fine to Panic

When you're writing an example to illustrate some concept, having robust error handling code in the example as well can make the example less clear. In examples, it's understood that a call to a method like `unwrap` that could `panic!` is meant as a placeholder for the way that you'd want your application to handle errors, which can differ based on what the rest of your code is doing.

Similarly, the `unwrap` and `expect` methods are very handy when prototyping, before you're ready to decide how to handle errors. They leave clear markers in your code for when you're ready to make your program more robust.

If a method call fails in a test, we'd want the whole test to fail, even if that method isn't the functionality under test. Because `panic!` is how a test is marked as a failure, calling `unwrap` or `expect` is exactly what should happen.

Cases When You Have More Information Than the Compiler

It would also be appropriate to call `unwrap` when you have some other logic that ensures the `Result` will have an `Ok` value, but the logic isn't something the compiler understands. You'll still have a `Result` value that you need to handle: whatever operation you're calling still has the possibility of failing in general, even though it's logically impossible in your particular situation. If you can ensure by manually inspecting the code that you'll never have an `Err` variant, it's perfectly acceptable to call `unwrap`. Here's an example:

```rust
use std::net::IpAddr;

let home = "127.0.0.1".parse::<IpAddr>().unwrap();
```

We're creating an `IpAddr` instance by parsing a hardcoded string. We can see that `127.0.0.1` is a valid IP address, so it's acceptable to use `unwrap` here. However, having a hardcoded, valid string doesn't change the return type of the `parse` method: we still get a `Result` value, and the compiler will still make us handle the `Result` as if the `Err` variant is still a possibility because the compiler isn't smart enough to see that this string is always a valid IP address. If the IP address string came from a user rather than being hardcoded into the program, and therefore *did* have a possibility of failure, we'd definitely want to handle the `Result` in a more robust way instead.

Guidelines for Error Handling

It's advisable to have your code `panic!` when it's possible that your code could end up in a bad state. In this context, bad state is when some assumption, guarantee, contract, or invariant has been broken, such as when invalid values, contradictory values, or missing values are passed to your code—plus one or more of the following:

- The bad state is not something that's *expected* to happen occasionally.
- Your code after this point needs to rely on not being in this bad state.
- There's not a good way to encode this information in the types you use.

If someone calls your code and passes in values that don't make sense, the best choice might be to `panic!` and alert the person using your library to the bug in their code so they can fix it during development. Similarly, `panic!` is often appropriate if you're calling external code that is out of your control, and it returns an invalid state that you have no way of fixing.

When a bad state is reached, but it's expected to happen no matter how well you write your code, it's still more appropriate to return a `Result` rather than making a `panic!` call. Examples of this include a parser being given malformed data or an HTTP request returning a status that indicates you have hit a rate limit. In these cases, you should indicate that failure is an expected possibility by returning a `Result` to propagate these bad states upwards so the calling code can decide how to handle the problem. To `panic!` wouldn't be the best way to handle these cases.

When your code performs operations on values, your code should verify the values are valid first, and `panic!` if the values aren't valid. This is mostly for safety reasons: attempting to operate on invalid data can expose your code to vulnerabilities. This is the main reason the standard library will `panic!` if you attempt an out-of-bounds memory access: trying to access memory that doesn't belong to the current data structure is a common security problem. Functions often have *contracts*: their behavior is only guaranteed if the inputs meet particular requirements. Panicking when the contract is violated makes sense because a contract violation always indicates a caller-side bug, and it's not a kind of error you want the calling code to have to explicitly handle. In fact, there's no reasonable way for calling code to recover: the calling *programmers* need to fix the code. Contracts for a function, especially when a violation will cause a panic, should be explained in the API documentation for the function.

However, having lots of error checks in all of your functions would be verbose and annoying. Fortunately, you can use Rust's type system (and thus the type checking the compiler does) to do many of the checks for you. If your function has a particular type as a parameter, you can proceed with your code's logic knowing that the compiler has already ensured you have a valid value. For example, if you have a type rather than an `Option`, your program expects to have *something* rather than *nothing*. Your code then doesn't have to handle two cases for the `Some` and `None` variants: it will only have one case for definitely having a value. Code trying to pass nothing to your function won't even compile, so your function doesn't have to check for that case at runtime. Another example is using an unsigned integer type like `u32`, which ensures the parameter is never negative.

Creating Custom Types for Validation

Let's take the idea of using Rust's type system to ensure we have a valid value one step further and look at creating a custom type for validation. Recall the guessing game in Chapter 2 where our code asked the user to guess a number between 1 and 100. We never validated that the user's guess was between those numbers before checking it against our secret number; we only validated that the guess was positive. In this case, the consequences were not very dire: our output of "Too high" or "Too low" would still be correct. It would be a useful enhancement to guide the user toward valid guesses and have different behavior when a user guesses a number that's out of range versus when a user types, for example, letters instead.

One way to do this would be to parse the guess as an `i32` instead of only a `u32` to allow potentially negative numbers, and then add a check for the number being in range, like so:

```
loop {
    // snip

    let guess: i32 = match guess.trim().parse() {
        Ok(num) => num,
        Err(_) => continue,
    };

    if guess < 1 || guess > 100 {
        println!("The secret number will be between 1 and 100.");
        continue;
    }

    match guess.cmp(&secret_number) {
    // snip
}
```

The `if` expression checks whether our value is out of range, tells the user about the problem, and calls `continue` to start the next iteration of the loop and ask for another guess. After the `if` expression, we can proceed with the comparisons between `guess` and the secret number knowing that `guess` is between 1 and 100.

However, this is not an ideal solution: if it was absolutely critical that the program only operated on values between 1 and 100, and it had many functions with this requirement, it would be tedious (and potentially impact performance) to have a check like this in every function.

Instead, we can make a new type and put the validations in a function to create an instance of the type rather than repeating the validations everywhere. That way, it's safe for functions to use the new type in their signatures and confidently use the values they receive. Listing 9-9 shows one way to define a `Guess` type that will only create an instance of `Guess` if the `new` function receives a value between 1 and 100:

```
pub struct Guess {
    value: u32,
}

impl Guess {
    pub fn new(value: u32) -> Guess {
        if value < 1 || value > 100 {
            panic!("Guess value must be between 1 and 100, got {}.", value);
        }

        Guess {
            value
        }
    }

    pub fn value(&self) -> u32 {
        self.value
    }
}
```

Listing 9-9: A `Guess` type that will only continue with values between 1 and 100

First, we define a struct named `Guess` that has a field named `value` that holds a `u32`. This is where the number will be stored.

Then we implement an associated function named `new` on `Guess` that creates instances of `Guess` values. The `new` function is defined to have one parameter named `value` of type `u32` and to return a `Guess`. The code in the body of the `new` function tests `value` to make sure it's between 1 and 100. If `value` doesn't pass this test, we make a `panic!` call, which will alert the programmer who is writing the calling code that they have a bug they need to fix, because creating a `Guess` with a `value` outside this range would violate the contract that `Guess::new` is relying on. The conditions in which `Guess::new` might panic should be discussed in its public-facing API documentation; we'll cover documentation conventions indicating the possibility of a `panic!` in the API documentation that you create in Chapter 14. If `value` does pass the test, we create a new `Guess` with its `value` field set to the `value` parameter and return the `Guess`.

Next, we implement a method named `value` that borrows `self`, doesn't have any other parameters, and returns a `u32`. This is a kind of method sometimes called a *getter*, because its purpose is to get some data from its fields and return it. This public method is necessary because the `value` field of the `Guess` struct is private. It's important that the `value` field is private so code using the `Guess` struct is not allowed to set `value` directly: code outside the module *must* use the `Guess::new` function to create an instance of `Guess`, which ensures there's no way for a `Guess` to have a `value` that hasn't been checked by the conditions in the `Guess::new` function.

A function that has a parameter or returns only numbers between 1 and 100 could then declare in its signature that it takes or returns a `Guess` rather than a `u32` and wouldn't need to do any additional checks in its body.

Summary

Rust's error handling features are designed to help you write more robust code. The `panic!` macro signals that your program is in a state it can't handle and lets you tell the process to stop instead of trying to proceed with invalid or incorrect values. The `Result` enum uses Rust's type system to indicate that operations might fail in a way that your code could recover from. You can use `Result` to tell code that calls your code that it needs to handle potential success or failure as well. Using `panic!` and `Result` in the appropriate situations will make your code more reliable in the face of inevitable problems.

Now that you've seen useful ways that the standard library uses generics with the `Option` and `Result` enums, we'll talk about how generics work and how you can use them in your code in the next chapter.

Generic Types, Traits, and Lifetimes

Every programming language has tools to deal effectively with duplication of concepts; in Rust, one of those tools is *generics*. Generics are abstract stand-ins for concrete types or other properties. When we're writing and compiling the code we can express properties of generics, such as their behavior or how they relate to other generics, without needing to know what will actually be in their place.

In the same way that a function takes parameters whose value we don't know in order to write code once that will be run on multiple concrete values, we can write functions that take parameters of some generic type instead of a concrete type like `i32` or `String`. We've already used generics in Chapter 6 with `Option<T>`, Chapter 8 with `Vec<T>` and `HashMap<K, V>`, and Chapter 9 with `Result<T, E>`. In this chapter, we'll explore how to define our own types, functions, and methods with generics!

First, we're going to review the mechanics of extracting a function that reduces code duplication. Then we'll use the same mechanics to make a generic function out of two functions that only differ in the types of their parameters. We'll go over using generic types in struct and enum definitions too.

After that, we'll discuss *traits*, which are a way to define behavior in a generic way. Traits can be combined with generic types in order to constrain a generic type to those types that have a particular behavior, rather than any type at all.

Finally, we'll discuss *lifetimes*, which are a kind of generic that let us give the compiler information about how references are related to each other. Lifetimes are the feature in Rust that allow us to borrow values in many situations and still have the compiler check that references will be valid.

Removing Duplication by Extracting a Function

Before getting into generics syntax, let's first review a technique for dealing with duplication that doesn't use generic types: extracting a function. Once that's fresh in our minds, we'll use the same mechanics with generics to extract a generic function! In the same way that you recognize duplicated code to extract into a function, you'll start to recognize duplicated code that can use generics.

Consider a small program that finds the largest number in a list, shown in Listing 10-1:

Filename: src/main.rs

```rust
fn main() {
    let number_list = vec![34, 50, 25, 100, 65];

    let mut largest = number_list[0];

    for number in number_list {
        if number > largest {
            largest = number;
        }
    }

    println!("The largest number is {}", largest);
}
```

Listing 10-1: Code to find the largest number in a list of numbers

This code takes a list of integers, stored here in the variable `number_list`. It puts the first item in the list in a variable named `largest`. Then it iterates through all the numbers in the list, and if the current value is greater than the number stored in `largest`, it replaces the value in `largest`. If the current value is smaller than the largest value seen so far, `largest` is not changed. When all the items in the list have been considered, `largest` will hold the largest value, which in this case is 100.

If we needed to find the largest number in two different lists of numbers, we could duplicate the code in Listing 10-1 and have the same logic exist in two places in the program, as in Listing 10-2:

Filename: src/main.rs

```
fn main() {
    let number_list = vec![34, 50, 25, 100, 65];

    let mut largest = number_list[0];

    for number in number_list {
        if number > largest {
            largest = number;
        }
    }

    println!("The largest number is {}", largest);

    let number_list = vec![102, 34, 6000, 89, 54, 2, 43, 8];

    let mut largest = number_list[0];

    for number in number_list {
        if number > largest {
            largest = number;
        }
    }

    println!("The largest number is {}", largest);
}
```

Listing 10-2: Code to find the largest number in *two* lists of numbers

While this code works, duplicating code is tedious and error-prone, and means we have multiple places to update the logic if we need to change it.

To eliminate this duplication, we can create an abstraction, which in this case will be in the form of a function that operates on any list of integers given to the function in a parameter. This will increase the clarity of our code and let us communicate and reason about the concept of finding the largest number in a list independently of the specific places this concept is used.

In the program in Listing 10-3, we've extracted the code that finds the largest number into a function named `largest`. This program can find the largest number in two different lists of numbers, but the code from Listing 10-1 only exists in one spot:

Filename: src/main.rs

```
fn largest(list: &[i32]) -> i32 {
    let mut largest = list[0];

    for &item in list.iter() {
        if item > largest {
            largest = item;
        }
    }

    largest
}

fn main() {
    let number_list = vec![34, 50, 25, 100, 65];

    let result = largest(&number_list);
    println!("The largest number is {}", result);

    let number_list = vec![102, 34, 6000, 89, 54, 2, 43, 8];

    let result = largest(&number_list);
    println!("The largest number is {}", result);
}
```

Listing 10-3: Abstracted code to find the largest number in two lists

The function has a parameter, `list`, which represents any concrete slice of `i32` values that we might pass into the function. The code in the function definition operates on the `list` representation of any `&[i32]`. When we call the `largest` function, the code actually runs on the specific values that we pass in.

The mechanics we went through to get from Listing 10-2 to Listing 10-3 were these steps:

1. We noticed there was duplicate code.
2. We extracted the duplicate code into the body of the function, and specified the inputs and return values of that code in the function signature.
3. We replaced the two concrete places that had the duplicated code to call the function instead.

We can use these same steps with generics to reduce code duplication in different ways in different scenarios. In the same way that the function body is now operating on an abstract `list` instead of concrete values, code using generics will operate on abstract types. The concepts powering generics are the same concepts you already know that power functions, just applied in different ways.

What if we had two functions, one that found the largest item in a slice of `i32` values and one that found the largest item in a slice of `char` values? How would we get rid of that duplication? Let's find out!

Generic Data Types

Using generics where we usually place types, like in function signatures or structs, lets us create definitions that we can use for many different concrete data types. Let's take a look at how to define functions, structs, enums, and methods using generics, and at the end of this section we'll discuss the performance of code using generics.

Using Generic Data Types in Function Definitions

We can define functions that use generics in the signature of the function where the data types of the parameters and return value go. In this way, the code we write can be more flexible and provide more functionality to callers of our function, while not introducing code duplication.

Continuing with our `largest` function, Listing 10-4 shows two functions providing the same functionality to find the largest value in a slice. The first function is the one we extracted in Listing 10-3 that finds the largest `i32` in a slice. The second function finds the largest `char` in a slice:

Filename: src/main.rs

```
fn largest_i32(list: &[i32]) -> i32 {
    let mut largest = list[0];

    for &item in list.iter() {
        if item > largest {
            largest = item;
        }
    }

    largest
}

fn largest_char(list: &[char]) -> char {
    let mut largest = list[0];

    for &item in list.iter() {
        if item > largest {
            largest = item;
        }
    }

    largest
}

fn main() {
    let number_list = vec![34, 50, 25, 100, 65];

    let result = largest_i32(&number_list);
    println!("The largest number is {}", result);

    let char_list = vec!['y', 'm', 'a', 'q'];

    let result = largest_char(&char_list);
    println!("The largest char is {}", result);
}
```

Listing 10-4: Two functions that differ only in their names and the types in their signatures

Here, the functions `largest_i32` and `largest_char` have the exact same body, so it would be nice if we could turn these two functions into one and get rid of the duplication. Luckily, we can do that by introducing a generic type parameter!

To parameterize the types in the signature of the one function we're going to define, we need to create a name for the type parameter, just like how we give names for the value parameters to a function. We're going to choose the name `T`. Any identifier can be used as a type parameter name, but we're choosing `T` because Rust's type naming convention is CamelCase. Generic type parameter names also tend to be short by convention, often just one letter. Short for "type", `T` is the default choice of most Rust programmers.

When we use a parameter in the body of the function, we have to declare the parameter in the signature so that the compiler knows what that name in the body means. Similarly, when we use a type parameter name in a function signature, we have to declare the type parameter name before we use it. Type name declarations go in angle brackets between the name of the function and the parameter list.

The function signature of the generic `largest` function we're going to define will look like this:

```
fn largest<T>(list: &[T]) -> T {
```

We would read this as: the function `largest` is generic over some type `T`. It has one parameter named `list`, and the type of `list` is a slice of values of type `T`. The `largest` function will return a value of the same type `T`.

Listing 10-5 shows the unified `largest` function definition using the generic data type in its signature, and shows how we'll be able to call `largest` with either a slice of `i32` values or `char` values. Note that this code won't compile yet!

Filename: src/main.rs

```
fn largest<T>(list: &[T]) -> T {
    let mut largest = list[0];

    for &item in list.iter() {
        if item > largest {
            largest = item;
        }
    }

    largest
}

fn main() {
    let number_list = vec![34, 50, 25, 100, 65];

    let result = largest(&number_list);
    println!("The largest number is {}", result);

    let char_list = vec!['y', 'm', 'a', 'q'];

    let result = largest(&char_list);
    println!("The largest char is {}", result);
}
```

Listing 10-5: A definition of the `largest` function that uses generic type parameters but doesn't compile yet

If we try to compile this code right now, we'll get this error:

```
error[E0369]: binary operation `>` cannot be applied to type `T`
  |
5 |         if item > largest {
  |            ^^^^
  |
note: an implementation of `std::cmp::PartialOrd` might be missing for `T`
```

The note mentions `std::cmp::PartialOrd`, which is a *trait*. We're going to talk about traits in the next section, but briefly, what this error is saying is that the body of `largest` won't work for all possible types that `T` could be; since we want to compare values of type `T` in the body, we can only use types that know how to be ordered. The standard library has defined the trait `std::cmp::PartialOrd` that types can implement to enable comparisons. We'll come back to traits and how to specify that a generic type has a particular trait in the next section, but let's set this example aside for a moment and explore other places we can use generic type parameters first.

Using Generic Data Types in Struct Definitions

We can define structs to use a generic type parameter in one or more of the struct's fields with the `<>` syntax too. Listing 10-6 shows the definition and use of a `Point` struct that can hold `x` and `y` coordinate values of any type:

Filename: src/main.rs

```
struct Point<T> {
    x: T,
    y: T,
}

fn main() {
    let integer = Point { x: 5, y: 10 };
    let float = Point { x: 1.0, y: 4.0 };
}
```

Listing 10-6: A `Point` struct that holds `x` and `y` values of type `T`

The syntax is similar to using generics in function definitions. First, we have to declare the name of the type parameter within angle brackets just after the name of the struct. Then we can use the generic type in the struct definition where we would specify concrete data types.

Note that because we've only used one generic type in the definition of `Point`, what we're saying is that the `Point` struct is generic over some type `T`, and the fields `x` and `y` are *both* that same type, whatever it ends up being. If we try to create an instance of a `Point` that has values of different types, as in Listing 10-7, our code won't compile:

Filename: src/main.rs

```
struct Point<T> {
    x: T,
    y: T,
}

fn main() {
    let wont_work = Point { x: 5, y: 4.0 };
}
```

Listing 10-7: The fields `x` and `y` must be the same type because both have the same generic data type `T`

If we try to compile this, we'll get the following error:

```
error[E0308]: mismatched types
 -->
  |
7 |     let wont_work = Point { x: 5, y: 4.0 };
  |                                      ^^^ expected integral variable, found
  floating-point variable
  |
  = note: expected type `{integer}`
  = note:    found type `{float}`
```

When we assigned the integer value 5 to `x`, the compiler then knows for this instance of `Point` that the generic type `T` will be an integer. Then when we specified 4.0 for `y`, which is defined to have the same type as `x`, we get a type mismatch error.

If we wanted to define a `Point` struct where `x` and `y` could have different types but still have those types be generic, we can use multiple generic type parameters. In listing 10-8, we've changed the definition of `Point` to be generic over types `T` and `U`. The field `x` is of type `T`, and the field `y` is of type `U`:

Filename: src/main.rs

```
struct Point<T, U> {
    x: T,
    y: U,
}

fn main() {
    let both_integer = Point { x: 5, y: 10 };
    let both_float = Point { x: 1.0, y: 4.0 };
    let integer_and_float = Point { x: 5, y: 4.0 };
}
```

Listing 10-8: A `Point` generic over two types so that `x` and `y` may be values of different types

Now all of these instances of `Point` are allowed! You can use as many generic type parameters in a definition as you want, but using more than a few gets hard to read and understand. If you get to a point of needing lots of generic types, it's probably a sign that your code could use some restructuring to be separated into smaller pieces.

Using Generic Data Types in Enum Definitions

Similarly to structs, enums can be defined to hold generic data types in their variants. We used the `Option<T>` enum provided by the standard library in Chapter 6, and now its definition should make more sense. Let's take another look:

```rust
enum Option<T> {
    Some(T),
    None,
}
```

In other words, `Option<T>` is an enum generic in type `T`. It has two variants: `Some`, which holds one value of type `T`, and a `None` variant that doesn't hold any value. The standard library only has to have this one definition to support the creation of values of this enum that have any concrete type. The idea of "an optional value" is a more abstract concept than one specific type, and Rust lets us express this abstract concept without lots of duplication.

Enums can use multiple generic types as well. The definition of the `Result` enum that we used in Chapter 9 is one example:

```rust
enum Result<T, E> {
    Ok(T),
    Err(E),
}
```

The `Result` enum is generic over two types, `T` and `E`. `Result` has two variants: `Ok`, which holds a value of type `T`, and `Err`, which holds a value of type `E`. This definition makes it convenient to use the `Result` enum anywhere we have an operation that might succeed (and return a value of some type `T`) or fail (and return an error of some type `E`). Recall Listing 9-2 when we opened a file: in that case, `T` was filled in with the type `std::fs::File` when the file was opened successfully and `E` was filled in with the type `std::io::Error` when there were problems opening the file.

When you recognize situations in your code with multiple struct or enum definitions that differ only in the types of the values they hold, you can remove the duplication by using the same process we used with the function definitions to introduce generic types instead.

Using Generic Data Types in Method Definitions

Like we did in Chapter 5, we can implement methods on structs and enums that have generic types in their definitions. Listing 10-9 shows the `Point<T>` struct we defined in Listing 10-6. We've then defined a method named `x` on `Point<T>` that returns a reference to the data in the field `x`:

Filename: src/main.rs

```
struct Point<T> {
    x: T,
    y: T,
}

impl<T> Point<T> {
    fn x(&self) -> &T {
        &self.x
    }
}

fn main() {
    let p = Point { x: 5, y: 10 };

    println!("p.x = {}", p.x());
}
```

Listing 10-9: Implementing a method named `x` on the `Point<T>` struct that will return a reference to the `x` field, which is of type `T`.

Note that we have to declare `T` just after `impl` in order to use `T` in the type `Point<T>`. Declaring `T` as a generic type after the `impl` is how Rust knows the type in the angle brackets in `Point` is a generic type rather than a concrete type. For example, we could choose to implement methods on `Point<f32>` instances rather than `Point` instances with any generic type. Listing 10-10 shows that we don't declare anything after the `impl` in this case, since we're using a concrete type, `f32`:

```
impl Point<f32> {
    fn distance_from_origin(&self) -> f32 {
        (self.x.powi(2) + self.y.powi(2)).sqrt()
    }
}
```

Listing 10-10: Building an `impl` block which only applies to a struct with a specific type is used for the generic type parameter `T`

This code means the type `Point<f32>` will have a method named `distance_from_origin`, and other instances of `Point<T>` where `T` is not of type `f32` will not have this method defined.

This method measures how far our point is from the point of coordinates (0.0, 0.0) and uses mathematical operations which are only available for floating-point types.

Generic type parameters in a struct definition aren't always the same generic type parameters you want to use in that struct's method signatures. Listing 10-11 defines a method `mixup` on the `Point<T, U>` struct from Listing 10-8. The method takes another `Point` as a parameter, which might have different types than the `self` `Point` that we're calling `mixup` on. The method creates a new `Point` instance that has the `x` value from the `self` `Point` (which is of type `T`) and the `y` value from the passed-in `Point` (which is of type `W`):

Filename: src/main.rs

```
struct Point<T, U> {
    x: T,
    y: U,
}

impl<T, U> Point<T, U> {
    fn mixup<V, W>(self, other: Point<V, W>) -> Point<T, W> {
        Point {
            x: self.x,
            y: other.y,
        }
    }
}

fn main() {
    let p1 = Point { x: 5, y: 10.4 };
    let p2 = Point { x: "Hello", y: 'c'};

    let p3 = p1.mixup(p2);

    println!("p3.x = {}, p3.y = {}", p3.x, p3.y);
}
```

Listing 10-11: Methods that use different generic types than their struct's definition

In `main`, we've defined a `Point` that has an `i32` for `x` (with value `5`) and an `f64` for `y` (with value `10.4`). `p2` is a `Point` that has a string slice for `x` (with value `"Hello"`) and a `char` for `y` (with value `c`). Calling `mixup` on `p1` with the argument `p2` gives us `p3`, which will have an `i32` for `x`, since `x` came from `p1`. `p3` will have a `char` for `y`, since `y` came from `p2`. The `println!` will print `p3.x = 5, p3.y = c`.

Note that the generic parameters `T` and `U` are declared after `impl`, since they go with the struct definition. The generic parameters `V` and `W` are declared after `fn mixup`, since they are only relevant to the method.

Performance of Code Using Generics

You may have been reading this section and wondering if there's a run-time cost to using generic type parameters. Good news: the way that Rust has implemented generics means that your code will not run any slower than if you had specified concrete types instead of generic type parameters!

Rust accomplishes this by performing *monomorphization* of code using generics at compile time. Monomorphization is the process of turning generic code into specific code with the concrete types that are actually used filled in.

What the compiler does is the opposite of the steps that we performed to create the generic function in Listing 10-5. The compiler looks at all the places that generic code is called and generates code for the concrete types that the generic code is called with.

Let's work through an example that uses the standard library's `Option` enum:

```
let integer = Some(5);
let float = Some(5.0);
```

When Rust compiles this code, it will perform monomorphization. The compiler will read the values that have been passed to `Option` and see that we have two kinds of `Option<T>`: one is `i32`, and one is `f64`. As such, it will expand the generic definition of `Option<T>` into `Option_i32` and `Option_f64`, thereby replacing the generic definition with the specific ones.

The monomorphized version of our code that the compiler generates looks like this, with the uses of the generic `Option` replaced with the specific definitions created by the compiler:

Filename: src/main.rs

```
enum Option_i32 {
    Some(i32),
    None,
}

enum Option_f64 {
    Some(f64),
    None,
}

fn main() {
    let integer = Option_i32::Some(5);
    let float = Option_f64::Some(5.0);
}
```

We can write the non-duplicated code using generics, and Rust will compile that into code that specifies the type in each instance. That means we pay no runtime cost for using generics;

when the code runs, it performs just like it would if we had duplicated each particular definition by hand. The process of monomorphization is what makes Rust's generics extremely efficient at runtime.

Traits: Defining Shared Behavior

Traits allow us to use another kind of abstraction: they let us abstract over behavior that types can have in common. A *trait* tells the Rust compiler about functionality a particular type has and might share with other types. In situations where we use generic type parameters, we can use *trait bounds* to specify, at compile time, that the generic type may be any type that implements a trait and therefore has the behavior we want to use in that situation.

> Note: *Traits* are similar to a feature often called 'interfaces' in other languages, though with some differences.

Defining a Trait

The behavior of a type consists of the methods we can call on that type. Different types share the same behavior if we can call the same methods on all of those types. Trait definitions are a way to group method signatures together in order to define a set of behaviors necessary to accomplish some purpose.

For example, say we have multiple structs that hold various kinds and amounts of text: a `NewsArticle` struct that holds a news story filed in a particular place in the world, and a `Tweet` that can have at most 140 characters in its content along with metadata like whether it was a retweet or a reply to another tweet.

We want to make a media aggregator library that can display summaries of data that might be stored in a `NewsArticle` or `Tweet` instance. The behavior we need each struct to have is that it's able to be summarized, and that we can ask for that summary by calling a `summary` method on an instance. Listing 10-12 shows the definition of a `Summarizable` trait that expresses this concept:

Filename: lib.rs

```
pub trait Summarizable {
    fn summary(&self) -> String;
}
```

Listing 10-12: Definition of a `Summarizable` trait that consists of the behavior provided by a `summary` method

We declare a trait with the `trait` keyword, then the trait's name, in this case `Summarizable`. Inside curly brackets we declare the method signatures that describe the behaviors that types that implement this trait will need to have, in this case `fn summary(&self) -> String`. After the method signature, instead of providing an implementation within curly brackets, we put a semicolon. Each type that implements this trait must then provide its own custom behavior for the body of the method, but the compiler will enforce that any type that has the `Summarizable` trait will have the method `summary` defined for it with this signature exactly.

A trait can have multiple methods in its body, with the method signatures listed one per line and each line ending in a semicolon.

Implementing a Trait on a Type

Now that we've defined the `Summarizable` trait, we can implement it on the types in our media aggregator that we want to have this behavior. Listing 10-13 shows an implementation of the `Summarizable` trait on the `NewsArticle` struct that uses the headline, the author, and the location to create the return value of `summary`. For the `Tweet` struct, we've chosen to define `summary` as the username followed by the whole text of the tweet, assuming that tweet content is already limited to 140 characters.

Filename: lib.rs

```
pub struct NewsArticle {
    pub headline: String,
    pub location: String,
    pub author: String,
    pub content: String,
}

impl Summarizable for NewsArticle {
    fn summary(&self) -> String {
        format!("{}, by {} ({})", self.headline, self.author, self.location)
    }
}

pub struct Tweet {
    pub username: String,
    pub content: String,
    pub reply: bool,
    pub retweet: bool,
}

impl Summarizable for Tweet {
    fn summary(&self) -> String {
        format!("{}: {}", self.username, self.content)
    }
}
```

Listing 10-13: Implementing the `Summarizable` trait on the `NewsArticle` and `Tweet` types

Implementing a trait on a type is similar to implementing methods that aren't related to a trait. The difference is after `impl`, we put the trait name that we want to implement, then say `for` and the name of the type that we want to implement the trait for. Within the `impl` block, we put the method signatures that the trait definition has defined, but instead of putting a semicolon after each signature, we put curly brackets and fill in the method body with the specific behavior that we want the methods of the trait to have for the particular type.

Once we've implemented the trait, we can call the methods on instances of `NewsArticle` and `Tweet` in the same manner that we call methods that aren't part of a trait:

```
let tweet = Tweet {
    username: String::from("horse_ebooks"),
    content: String::from("of course, as you probably already know, people"),
    reply: false,
    retweet: false,
};

println!("1 new tweet: {}", tweet.summary());
```

This will print `1 new tweet: horse_ebooks: of course, as you probably already know, people`.

Note that because we've defined the `Summarizable` trait and the `NewsArticle` and `Tweet` types all in the same `lib.rs` in Listing 10-13, they're all in the same scope. If this `lib.rs` is for a crate we've called `aggregator`, and someone else wants to use our crate's functionality plus implement the `Summarizable` trait on their `WeatherForecast` struct, their code would need to import the `Summarizable` trait into their scope first before they could implement it, like in Listing 10-14:

Filename: lib.rs

```
extern crate aggregator;

use aggregator::Summarizable;

struct WeatherForecast {
    high_temp: f64,
    low_temp: f64,
    chance_of_precipitation: f64,
}

impl Summarizable for WeatherForecast {
    fn summary(&self) -> String {
        format!("The high will be {}, and the low will be {}. The chance of
        precipitation is {}%.", self.high_temp, self.low_temp,
        self.chance_of_precipitation)
    }
}
```

Listing 10-14: Bringing the `Summarizable` trait from our `aggregator` crate into scope in another crate

This code also assumes `Summarizable` is a public trait, which it is because we put the `pub` keyword before `trait` in Listing 10-12.

One restriction to note with trait implementations: we may implement a trait on a type as long as either the trait or the type are local to our crate. In other words, we aren't allowed to implement external traits on external types. We can't implement the `Display` trait on `Vec`, for example, since both `Display` and `Vec` are defined in the standard library. We are allowed to implement standard library traits like `Display` on a custom type like `Tweet` as part of our `aggregator` crate functionality. We could also implement `Summarizable` on `Vec` in our `aggregator` crate, since we've defined `Summarizable` there. This restriction is part of what's called the *orphan rule*, which you can look up if you're interested in type theory. Briefly, it's called the orphan rule because the parent type is not present. Without this rule, two crates could implement the same trait for the same type, and the two implementations would conflict: Rust wouldn't know which implementation to use. Because Rust enforces the orphan rule, other people's code can't break your code and vice versa.

Default Implementations

Sometimes it's useful to have default behavior for some or all of the methods in a trait, instead of making every implementation on every type define custom behavior. When we implement the trait on a particular type, we can choose to keep or override each method's default behavior.

Listing 10-15 shows how we could have chosen to specify a default string for the `summary` method of the `Summarize` trait instead of choosing to only define the method signature like we did in Listing 10-12:

Filename: lib.rs

```
pub trait Summarizable {
    fn summary(&self) -> String {
        String::from("(Read more...)")
    }
}
```

Listing 10-15: Definition of a `Summarizable` trait with a default implementation of the `summary` method

If we wanted to use this default implementation to summarize instances of `NewsArticle` instead of defining a custom implementation like we did in Listing 10-13, we would specify an empty `impl` block:

```
impl Summarizable for NewsArticle {}
```

Even though we're no longer choosing to define the `summary` method on `NewsArticle` directly, since the `summary` method has a default implementation and we specified that `NewsArticle` implements the `Summarizable` trait, we can still call the `summary` method on an instance of `NewsArticle`:

```
let article = NewsArticle {
    headline: String::from("Penguins win the Stanley Cup Championship!"),
    location: String::from("Pittsburgh, PA, USA"),
    author: String::from("Iceburgh"),
    content: String::from("The Pittsburgh Penguins once again are the best
    hockey team in the NHL."),
};

println!("New article available! {}", article.summary());
```

This code prints `New article available! (Read more...)`.

Changing the `Summarizable` trait to have a default implementation for `summary` does not require us to change anything about the implementations of `Summarizable` on `Tweet` in Listing 10-13 or `WeatherForecast` in Listing 10-14: the syntax for overriding a default implementation is exactly the same as the syntax for implementing a trait method that doesn't have a default implementation.

Default implementations are allowed to call the other methods in the same trait, even if those other methods don't have a default implementation. In this way, a trait can provide a lot of useful functionality and only require implementors to specify a small part of it. We could choose to have the `Summarizable` trait also have an `author_summary` method whose implementation is required, then a `summary` method that has a default implementation that calls the `author_summary` method:

```
pub trait Summarizable {
    fn author_summary(&self) -> String;

    fn summary(&self) -> String {
        format!("(Read more from {}...)", self.author_summary())
    }
}
```

In order to use this version of `Summarizable`, we're only required to define `author_summary` when we implement the trait on a type:

```
impl Summarizable for Tweet {
    fn author_summary(&self) -> String {
        format!("@{}", self.username)
    }
}
```

Once we define `author_summary`, we can call `summary` on instances of the `Tweet` struct, and the default implementation of `summary` will call the definition of `author_summary` that we've provided.

```
let tweet = Tweet {
    username: String::from("horse_ebooks"),
    content: String::from("of course, as you probably already know, people"),
    reply: false,
    retweet: false,
};

println!("1 new tweet: {}", tweet.summary());
```

This will print `1 new tweet: (Read more from @horse_ebooks...)`.

Note that it is not possible to call the default implementation from an overriding implementation.

Trait Bounds

Now that we've defined traits and implemented those traits on types, we can use traits with generic type parameters. We can constrain generic types so that rather than being any type, the compiler will ensure that the type will be limited to those types that implement a particular trait and thus have the behavior that we need the types to have. This is called specifying *trait bounds* on a generic type.

For example, in Listing 10-13, we implemented the `Summarizable` trait on the types `NewsArticle` and `Tweet`. We can define a function `notify` that calls the `summary` method on its parameter `item`, which is of the generic type `T`. To be able to call `summary` on `item` without getting an error, we can use trait bounds on `T` to specify that `item` must be of a type that implements the `Summarizable` trait:

```
pub fn notify<T: Summarizable>(item: T) {
    println!("Breaking news! {}", item.summary());
}
```

Trait bounds go with the declaration of the generic type parameter, after a colon and within the angle brackets. Because of the trait bound on `T`, we can call `notify` and pass in any instance of `NewsArticle` or `Tweet`. The external code from Listing 10-14 that's using our `aggregator` crate can call our `notify` function and pass in an instance of `WeatherForecast`, since `Summarizable` is implemented for `WeatherForecast` as well. Code that calls `notify` with any other type, like a `String` or an `i32`, won't compile, since those types do not implement `Summarizable`.

We can specify multiple trait bounds on a generic type by using `+`. If we needed to be able to use display formatting on the type `T` in a function as well as the `summary` method, we can use the trait bounds `T: Summarizable + Display`. This means `T` can be any type that implements both `Summarizable` and `Display`.

For functions that have multiple generic type parameters, each generic has its own trait bounds. Specifying lots of trait bound information in the angle brackets between a function's name and its parameter list can get hard to read, so there's an alternate syntax for specifying trait bounds that lets us move them to a `where` clause after the function signature. So instead of:

```
fn some_function<T: Display + Clone, U: Clone + Debug>(t: T, u: U) -> i32 {
```

We can write this instead with a `where` clause:

```
fn some_function<T, U>(t: T, u: U) -> i32
    where T: Display + Clone,
          U: Clone + Debug
{
```

This is less cluttered and makes this function's signature look more similar to a function without lots of trait bounds, in that the function name, parameter list, and return type are close together.

Fixing the `largest` Function with Trait Bounds

So any time you want to use behavior defined by a trait on a generic, you need to specify that trait in the generic type parameter's type bounds. We can now fix the definition of the `largest` function that uses a generic type parameter from Listing 10-5! When we set that code aside, we were getting this error:

```
error[E0369]: binary operation `>` cannot be applied to type `T`
  |
5 |         if item > largest {
  |            ^^^^
  |
note: an implementation of `std::cmp::PartialOrd` might be missing for `T`
```

In the body of `largest` we wanted to be able to compare two values of type `T` using the greater-than operator. That operator is defined as a default method on the standard library trait `std::cmp::PartialOrd`. So in order to be able to use the greater-than operator, we need to specify `PartialOrd` in the trait bounds for `T` so that the `largest` function will work on slices of any type that can be compared. We don't need to bring `PartialOrd` into scope because it's in the prelude.

```
fn largest<T: PartialOrd>(list: &[T]) -> T {
```

If we try to compile this, we'll get different errors:

```
error[E0508]: cannot move out of type `[T]`, a non-copy array
 --> src/main.rs:4:23
  |
4 |     let mut largest = list[0];
  |         -----------   ^^^^^^^ cannot move out of here
  |         |
  |         hint: to prevent move, use `ref largest` or `ref mut largest`

error[E0507]: cannot move out of borrowed content
 --> src/main.rs:6:9
  |
6 |     for &item in list.iter() {
  |         ^----
  |         ||
  |         |hint: to prevent move, use `ref item` or `ref mut item`
  |         cannot move out of borrowed content
```

The key to this error is `cannot move out of type [T], a non-copy array`. With our non-generic versions of the `largest` function, we were only trying to find the largest `i32` or `char`. As we discussed in Chapter 4, types like `i32` and `char` that have a known size can be stored on the stack, so they implement the `Copy` trait. When we changed the `largest` function to be generic, it's now possible that the `list` parameter could have types in it that don't implement the `Copy` trait, which means we wouldn't be able to move the value out of `list[0]` and into the `largest` variable.

If we only want to be able to call this code with types that are `Copy`, we can add `Copy` to the trait bounds of `T`! Listing 10-16 shows the complete code of a generic `largest` function that will compile as long as the types of the values in the slice that we pass into `largest` implement both the `PartialOrd` and `Copy` traits, like `i32` and `char`:

Filename: src/main.rs

```
use std::cmp::PartialOrd;

fn largest<T: PartialOrd + Copy>(list: &[T]) -> T {
    let mut largest = list[0];

    for &item in list.iter() {
        if item > largest {
            largest = item;
        }
    }

    largest
}

fn main() {
    let number_list = vec![34, 50, 25, 100, 65];

    let result = largest(&number_list);
    println!("The largest number is {}", result);

    let char_list = vec!['y', 'm', 'a', 'q'];

    let result = largest(&char_list);
    println!("The largest char is {}", result);
}
```

Listing 10-16: A working definition of the `largest` function that works on any generic type that implements the `PartialOrd` and `Copy` traits

If we don't want to restrict our `largest` function to only types that implement the `Copy` trait, we could specify that `T` has the trait bound `Clone` instead of `Copy` and clone each value in the slice when we want the `largest` function to have ownership. Using the `clone` function means we're potentially making more heap allocations, though, and heap allocations can be slow if we're working with large amounts of data. Another way we could implement `largest` is for the function to return a reference to a `T` value in the slice. If we change the return type to be `&T` instead of `T` and change the body of the function to return a reference, we wouldn't need either the `Clone` or `Copy` trait bounds and we wouldn't be doing any heap allocations. Try implementing these alternate solutions on your own!

Using Trait Bounds to Conditionally Implement Methods

By using a trait bound with an `impl` block that uses generic type parameters, we can conditionally implement methods only for types that implement the specified traits. For example, the type `Pair<T>` in listing 10-17 always implements the `new` method, but `Pair<T>` only implements the `cmp_display` if its inner type `T` implements the `PartialOrd` trait that enables comparison and the `Display` trait that enables printing:

```rust
use std::fmt::Display;

struct Pair<T> {
    x: T,
    y: T,
}

impl<T> Pair<T> {
    fn new(x: T, y: T) -> Self {
        Self {
            x,
            y,
        }
    }
}

impl<T: Display + PartialOrd> Pair<T> {
    fn cmp_display(&self) {
        if self.x >= self.y {
            println!("The largest member is x = {}", self.x);
        } else {
            println!("The largest member is y = {}", self.y);
        }
    }
}
```

Listing 10-17: Conditionally implement methods on a generic type depending on trait bounds

We can also conditionally implement a trait for any type that implements a trait. Implementations of a trait on any type that satisfies the trait bounds are called *blanket implementations*, and are extensively used in the Rust standard library. For example, the standard library implements the `ToString` trait on any type that implements the `Display` trait. This `impl` block looks similar to this code:

```
impl<T: Display> ToString for T {
    // ...snip...
}
```

Because the standard library has this blanket implementation, we can call the `to_string` method defined by the `ToString` type on any type that implements the `Display` trait. For example, we can turn integers into their corresponding `String` values like this since integers implement `Display`:

```
let s = 3.to_string();
```

Blanket implementations appear in the documentation for the trait in the "Implementors" section.

Traits and trait bounds let us write code that uses generic type parameters in order to reduce duplication, but still specify to the compiler exactly what behavior our code needs the generic type to have. Because we've given the trait bound information to the compiler, it can check that all the concrete types used with our code provide the right behavior. In dynamically typed languages, if we tried to call a method on a type that the type didn't implement, we'd get an error at runtime. Rust moves these errors to compile time so that we're forced to fix the problems before our code is even able to run. Additionally, we don't have to write code that checks for behavior at runtime since we've already checked at compile time, which improves performance compared to other languages without having to give up the flexibility of generics.

There's another kind of generics that we've been using without even realizing it called *lifetimes*. Rather than helping us ensure that a type has the behavior we need it to have, lifetimes help us ensure that references are valid as long as we need them to be. Let's learn how lifetimes do that.

Validating References with Lifetimes

When we talked about references in Chapter 4, we left out an important detail: every reference in Rust has a *lifetime*, which is the scope for which that reference is valid. Most of the time lifetimes are implicit and inferred, just like most of the time types are inferred. Similarly to when we have to annotate types because multiple types are possible, there are cases where the lifetimes of references could be related in a few different ways, so Rust needs us to annotate the relationships using generic lifetime parameters so that it can make sure the actual references used at runtime will definitely be valid.

Yes, it's a bit unusual, and will be different to tools you've used in other programming languages. Lifetimes are, in some ways, Rust's most distinctive feature.

Lifetimes are a big topic that can't be covered in entirety in this chapter, so we'll cover common ways you might encounter lifetime syntax in this chapter to get you familiar with the concepts. Chapter 19 will contain more advanced information about everything lifetimes can do.

Lifetimes Prevent Dangling References

The main aim of lifetimes is to prevent dangling references, which will cause a program to reference data other than the data we're intending to reference. Consider the program in Listing 10-18, with an outer scope and an inner scope. The outer scope declares a variable named `r` with no initial value, and the inner scope declares a variable named `x` with the initial value of 5. Inside the inner scope, we attempt to set the value of `r` as a reference to `x`. Then the inner scope ends, and we attempt to print out the value in `r`:

```
{
    let r;

    {
        let x = 5;
        r = &x;
    }

    println!("r: {}", r);
}
```

Listing 10-18: An attempt to use a reference whose value has gone out of scope

---

Uninitialized Variables Cannot Be Used

The next few examples declare variables without giving them an initial value, so that the variable name exists in the outer scope. This might appear to be in conflict with Rust not having null. However, if we try to use a variable before giving it a value, we'll get a compile-time error. Try it out!

When we compile this code, we'll get an error:

```
error: `x` does not live long enough
   |
6  |         r = &x;
   |              - borrow occurs here
7  |     }
   |     ^ `x` dropped here while still borrowed
...
10 | }
   | - borrowed value needs to live until here
```

The variable `x` doesn't "live long enough." Why not? Well, `x` is going to go out of scope when we hit the closing curly bracket on line 7, ending the inner scope. But `r` is valid for the outer scope; its scope is larger and we say that it "lives longer." If Rust allowed this code to work, `r` would be referencing memory that was deallocated when `x` went out of scope, and anything we tried to do with `r` wouldn't work correctly. So how does Rust determine that this code should not be allowed?

The Borrow Checker

The part of the compiler called the *borrow checker* compares scopes to determine that all borrows are valid. Listing 10-19 shows the same example from Listing 10-18 with annotations showing the lifetimes of the variables:

```
{
    let r;         // -------+-- 'a
                   //        |
    {              //        |
        let x = 5; // -+-----+-- 'b
        r = &x;    //  |     |
    }              // -+     |
                   //        |
    println!("r: {}", r); // |
                   //        |
                   // -------+
}
```

Listing 10-19: Annotations of the lifetimes of `r` and `x`, named `'a` and `'b` respectively

We've annotated the lifetime of `r` with `'a` and the lifetime of `x` with `'b`. As you can see, the inner `'b` block is much smaller than the outer `'a` lifetime block. At compile time, Rust compares the size of the two lifetimes and sees that `r` has a lifetime of `'a`, but that it refers to an object with a lifetime of `'b`. The program is rejected because the lifetime `'b` is shorter than the lifetime of `'a`: the subject of the reference does not live as long as the reference.

Let's look at an example in Listing 10-20 that doesn't try to make a dangling reference and compiles without any errors:

```
{
    let x = 5;            // -----+-- 'b
                          //      |
    let r = &x;           // --+--+-- 'a
                          //   |  |
    println!("r: {}", r); //   |  |
                          // --+  |
}                         // -----+
```

Listing 10-20: A valid reference because the data has a longer lifetime than the reference

Here, `x` has the lifetime `'b`, which in this case is larger than `'a`. This means `r` can reference `x`: Rust knows that the reference in `r` will always be valid while `x` is valid.

Now that we've shown where the lifetimes of references are in a concrete example and discussed how Rust analyzes lifetimes to ensure references will always be valid, let's talk about generic lifetimes of parameters and return values in the context of functions.

Generic Lifetimes in Functions

Let's write a function that will return the longest of two string slices. We want to be able to call this function by passing it two string slices, and we want to get back a string slice. The code in Listing 10-21 should print `The longest string is abcd` once we've implemented the `longest` function:

Filename: src/main.rs

```
fn main() {
    let string1 = String::from("abcd");
    let string2 = "xyz";

    let result = longest(string1.as_str(), string2);
    println!("The longest string is {}", result);
}
```

Listing 10-21: A `main` function that calls the `longest` function to find the longest of two string slices

Note that we want the function to take string slices (which are references, as we talked about in Chapter 4) since we don't want the `longest` function to take ownership of its arguments. We want the function to be able to accept slices of a `String` (which is the type of the variable `string1`) as well as string literals (which is what variable `string2` contains).

Refer back to the "String Slices as Parameters" section of Chapter 4 for more discussion about why these are the arguments we want.

If we try to implement the `longest` function as shown in Listing 10-22, it won't compile:

Filename: src/main.rs

```
fn longest(x: &str, y: &str) -> &str {
    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```

Listing 10-22: An implementation of the `longest` function that returns the longest of two string slices, but does not yet compile

Instead we get the following error that talks about lifetimes:

```
error[E0106]: missing lifetime specifier
   |
1  | fn longest(x: &str, y: &str) -> &str {
   |                                 ^ expected lifetime parameter
   |
   = help: this function's return type contains a borrowed value, but the
   signature does not say whether it is borrowed from `x` or `y`
```

The help text is telling us that the return type needs a generic lifetime parameter on it because Rust can't tell if the reference being returned refers to `x` or `y`. Actually, we don't know either, since the `if` block in the body of this function returns a reference to `x` and the `else` block returns a reference to `y`!

As we're defining this function, we don't know the concrete values that will be passed into this function, so we don't know whether the `if` case or the `else` case will execute. We also don't know the concrete lifetimes of the references that will be passed in, so we can't look at the scopes like we did in Listings 10-19 and 10-20 in order to determine that the reference we return will always be valid. The borrow checker can't determine this either, because it doesn't know how the lifetimes of `x` and `y` relate to the lifetime of the return value. We're going to add generic lifetime parameters that will define the relationship between the references so that the borrow checker can perform its analysis.

Lifetime Annotation Syntax

Lifetime annotations don't change how long any of the references involved live. In the same way that functions can accept any type when the signature specifies a generic type parameter, functions can accept references with any lifetime when the signature specifies a generic lifetime parameter. What lifetime annotations do is relate the lifetimes of multiple references to each other.

Lifetime annotations have a slightly unusual syntax: the names of lifetime parameters must start with an apostrophe `'`. The names of lifetime parameters are usually all lowercase, and like generic types, their names are usually very short. `'a` is the name most people use as a default. Lifetime parameter annotations go after the `&` of a reference, and a space separates the lifetime annotation from the reference's type.

Here's some examples: we've got a reference to an `i32` without a lifetime parameter, a reference to an `i32` that has a lifetime parameter named `'a`, and a mutable reference to an `i32` that also has the lifetime `'a`:

```
&i32        // a reference
&'a i32     // a reference with an explicit lifetime
&'a mut i32 // a mutable reference with an explicit lifetime
```

One lifetime annotation by itself doesn't have much meaning: lifetime annotations tell Rust how the generic lifetime parameters of multiple references relate to each other. If we have a function with the parameter `first` that is a reference to an `i32` that has the lifetime `'a`, and the function has another parameter named `second` that is another reference to an `i32` that also has the lifetime `'a`, these two lifetime annotations that have the same name indicate that the references `first` and `second` must both live as long as the same generic lifetime.

Lifetime Annotations in Function Signatures

Let's look at lifetime annotations in the context of the `longest` function we're working on. Just like generic type parameters, generic lifetime parameters need to be declared within angle brackets between the function name and the parameter list. The constraint we want to tell Rust about for the references in the parameters and the return value is that they all must have the same lifetime, which we'll name `'a` and add to each reference as shown in Listing 10-23:

Filename: src/main.rs

```
fn longest<'a>(x: &'a str, y: &'a str) -> &'a str {
    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```

Listing 10-23: The `longest` function definition that specifies all the references in the signature must have the same lifetime, `'a`

This will compile and will produce the result we want when used with the `main` function in Listing 10-21.

The function signature now says that for some lifetime `'a`, the function will get two parameters, both of which are string slices that live at least as long as the lifetime `'a`. The function will return a string slice that also will last at least as long as the lifetime `'a`. This is the contract we are telling Rust we want it to enforce.

By specifying the lifetime parameters in this function signature, we are not changing the lifetimes of any values passed in or returned, but we are saying that any values that do not adhere to this contract should be rejected by the borrow checker. This function does not know (or need to know) exactly how long `x` and `y` will live, but only needs to know that there is some scope that can be substituted for `'a` that will satisfy this signature.

When annotating lifetimes in functions, the annotations go on the function signature, and not in any of the code in the function body. This is because Rust is able to analyze the code within the function without any help, but when a function has references to or from code outside that function, the lifetimes of the arguments or return values will potentially be different each time the function is called. This would be incredibly costly and often impossible for Rust to figure out. In this case, we need to annotate the lifetimes ourselves.

When concrete references are passed to `longest`, the concrete lifetime that gets substituted for `'a` is the part of the scope of `x` that overlaps with the scope of `y`. Since scopes always nest, another way to say this is that the generic lifetime `'a` will get the concrete lifetime equal to the smaller of the lifetimes of `x` and `y`. Because we've annotated the returned reference with the same lifetime parameter `'a`, the returned reference will therefore be guaranteed to be valid as long as the shorter of the lifetimes of `x` and `y`.

Let's see how this restricts the usage of the `longest` function by passing in references that have different concrete lifetimes. Listing 10-24 is a straightforward example that should match your intuition from any language: `string1` is valid until the end of the outer scope, `string2` is valid until the end of the inner scope, and `result` references something that is valid until the end of the inner scope. The borrow checker approves of this code; it will compile and print `The longest string is long string is long` when run:

Filename: src/main.rs

```
fn main() {
    let string1 = String::from("long string is long");

    {
        let string2 = String::from("xyz");
        let result = longest(string1.as_str(), string2.as_str());
        println!("The longest string is {}", result);
    }
}
```

Listing 10-24: Using the `longest` function with references to `String` values that have different concrete lifetimes

Next, let's try an example that will show that the lifetime of the reference in `result` must be the smaller lifetime of the two arguments. We'll move the declaration of the `result` variable outside the inner scope, but leave the assignment of the value to the `result` variable inside the scope with `string2`. Next, we'll move the `println!` that uses `result` outside of the inner scope, after it has ended. The code in Listing 10-25 will not compile:

Filename: src/main.rs

```
fn main() {
    let string1 = String::from("long string is long");
    let result;
    {
        let string2 = String::from("xyz");
        result = longest(string1.as_str(), string2.as_str());
    }
    println!("The longest string is {}", result);
}
```

Listing 10-25: Attempting to use `result` after `string2` has gone out of scope won't compile

If we try to compile this, we'll get this error:

```
error: `string2` does not live long enough
   |
6  |         result = longest(string1.as_str(), string2.as_str());
   |                                            ------- borrow occurs here
7  |     }
   |     ^ `string2` dropped here while still borrowed
8  |     println!("The longest string is {}", result);
9  | }
   | - borrowed value needs to live until here
```

The error is saying that in order for `result` to be valid for the `println!`, `string2` would need to be valid until the end of the outer scope. Rust knows this because we annotated the lifetimes of the function parameters and return values with the same lifetime parameter, `'a`.

We can look at this code as humans and see that `string1` is longer, and therefore `result` will contain a reference to `string1`. Because `string1` has not gone out of scope yet, a reference to `string1` will still be valid for the `println!`. However, what we've told Rust with the lifetime parameters is that the lifetime of the reference returned by the `longest` function is the same as the smaller of the lifetimes of the references passed in. Therefore, the borrow checker disallows the code in Listing 10-25 as possibly having an invalid reference.

Try designing some more experiments that vary the values and lifetimes of the references passed in to the `longest` function and how the returned reference is used. Make hypotheses about whether your experiments will pass the borrow checker or not before you compile, then check to see if you're right!

Thinking in Terms of Lifetimes

The exact way to specify lifetime parameters depends on what your function is doing. For example, if we changed the implementation of the `longest` function to always return the first argument rather than the longest string slice, we wouldn't need to specify a lifetime on the `y` parameter. This code compiles:

Filename: src/main.rs

```
fn longest<'a>(x: &'a str, y: &str) -> &'a str {
    x
}
```

In this example, we've specified a lifetime parameter `'a` for the parameter `x` and the return type, but not for the parameter `y`, since the lifetime of `y` does not have any relationship with the lifetime of `x` or the return value.

When returning a reference from a function, the lifetime parameter for the return type needs to match the lifetime parameter of one of the arguments. If the reference returned does *not* refer to one of the arguments, the only other possibility is that it refers to a value created within this function, which would be a dangling reference since the value will go out of scope at the end of the function. Consider this attempted implementation of the `longest` function that won't compile:

Filename: src/main.rs

```
fn longest<'a>(x: &str, y: &str) -> &'a str {
    let result = String::from("really long string");
    result.as_str()
}
```

Even though we've specified a lifetime parameter `'a` for the return type, this implementation fails to compile because the return value lifetime is not related to the lifetime of the parameters at all. Here's the error message we get:

```
error: `result` does not live long enough
  |
3 |     result.as_str()
  |     ^^^^^^ does not live long enough
4 | }
  | - borrowed value only lives until here
  |
note: borrowed value must be valid for the lifetime 'a as defined on the block
at 1:44...
  |
1 | fn longest<'a>(x: &str, y: &str) -> &'a str {
  |                                             ^
```

The problem is that `result` will go out of scope and get cleaned up at the end of the `longest` function, and we're trying to return a reference to `result` from the function. There's no way we can specify lifetime parameters that would change the dangling reference, and Rust won't let us create a dangling reference. In this case, the best fix would be to return an owned data type rather than a reference so that the calling function is then responsible for cleaning up the value.

Ultimately, lifetime syntax is about connecting the lifetimes of various arguments and return values of functions. Once they're connected, Rust has enough information to allow memory-safe operations and disallow operations that would create dangling pointers or otherwise violate memory safety.

Lifetime Annotations in Struct Definitions

Up until now, we've only defined structs to hold owned types. It is possible for structs to hold references, but we need to add a lifetime annotation on every reference in the struct's definition. Listing 10-26 has a struct named `ImportantExcerpt` that holds a string slice:

Filename: src/main.rs

```
struct ImportantExcerpt<'a> {
    part: &'a str,
}

fn main() {
    let novel = String::from("Call me Ishmael. Some years ago...");
    let first_sentence = novel.split('.')
        .next()
        .expect("Could not find a '.'");
    let i = ImportantExcerpt { part: first_sentence };
}
```

Listing 10-26: A struct that holds a reference, so its definition needs a lifetime annotation

This struct has one field, `part`, that holds a string slice, which is a reference. Just like with generic data types, we have to declare the name of the generic lifetime parameter inside angle brackets after the name of the struct so that we can use the lifetime parameter in the body of the struct definition.

The `main` function here creates an instance of the `ImportantExcerpt` struct that holds a reference to the first sentence of the `String` owned by the variable `novel`.

Lifetime Elision

In this section, we've learned that every reference has a lifetime, and we need to specify lifetime parameters for functions or structs that use references. However, in Chapter 4 we had a function in the "String Slices" section, shown again in Listing 10-27, that compiled without lifetime annotations:

Filename: src/lib.rs

```
fn first_word(s: &str) -> &str {
    let bytes = s.as_bytes();

    for (i, &item) in bytes.iter().enumerate() {
        if item == b' ' {
            return &s[0..i];
        }
    }

    &s[..]
}
```

Listing 10-27: A function we defined in Chapter 4 that compiled without lifetime annotations, even though the parameter and return type are references

The reason this function compiles without lifetime annotations is historical: in early versions of pre-1.0 Rust, this indeed wouldn't have compiled. Every reference needed an explicit lifetime. At that time, the function signature would have been written like this:

```
fn first_word<'a>(s: &'a str) -> &'a str {
```

After writing a lot of Rust code, the Rust team found that Rust programmers were typing the same lifetime annotations over and over in particular situations. These situations were predictable and followed a few deterministic patterns. The Rust team then programmed these patterns into the Rust compiler's code so that the borrow checker can infer the lifetimes in these situations without forcing the programmer to explicitly add the annotations.

We mention this piece of Rust history because it's entirely possible that more deterministic patterns will emerge and be added to the compiler. In the future, even fewer lifetime annotations might be required.

The patterns programmed into Rust's analysis of references are called the *lifetime elision rules*. These aren't rules for programmers to follow; the rules are a set of particular cases that the compiler will consider, and if your code fits these cases, you don't need to write the lifetimes explicitly.

The elision rules don't provide full inference: if Rust deterministically applies the rules but there's still ambiguity as to what lifetimes the references have, it won't guess what the lifetime of the remaining references should be. In this case, the compiler will give you an error that can be resolved by adding the lifetime annotations that correspond to your intentions for how the references relate to each other.

First, some definitions: Lifetimes on function or method parameters are called *input lifetimes*, and lifetimes on return values are called *output lifetimes*.

Now, on to the rules that the compiler uses to figure out what lifetimes references have when there aren't explicit annotations. The first rule applies to input lifetimes, and the second two rules apply to output lifetimes. If the compiler gets to the end of the three rules and there are still references that it can't figure out lifetimes for, the compiler will stop with an error.

1. Each parameter that is a reference gets its own lifetime parameter. In other words, a function with one parameter gets one lifetime parameter: `fn foo<'a>(x: &'a i32)`, a function with two arguments gets two separate lifetime parameters: `fn foo<'a, 'b>(x: &'a i32, y: &'b i32)`, and so on.

2. If there is exactly one input lifetime parameter, that lifetime is assigned to all output lifetime parameters: `fn foo<'a>(x: &'a i32) -> &'a i32`.

3. If there are multiple input lifetime parameters, but one of them is `&self` or `&mut self` because this is a method, then the lifetime of `self` is assigned to all output lifetime parameters. This makes writing methods much nicer.

Let's pretend we're the compiler and apply these rules to figure out what the lifetimes of the references in the signature of the `first_word` function in Listing 10-27 are. The signature starts without any lifetimes associated with the references:

```
fn first_word(s: &str) -> &str {
```

Then we (as the compiler) apply the first rule, which says each parameter gets its own lifetime. We're going to call it `'a` as usual, so now the signature is:

```
fn first_word<'a>(s: &'a str) -> &str {
```

On to the second rule, which applies because there is exactly one input lifetime. The second rule says the lifetime of the one input parameter gets assigned to the output lifetime, so now the signature is:

```
fn first_word<'a>(s: &'a str) -> &'a str {
```

Now all the references in this function signature have lifetimes, and the compiler can continue its analysis without needing the programmer to annotate the lifetimes in this function signature.

Let's do another example, this time with the `longest` function that had no lifetime parameters when we started working with in Listing 10-22:

```
fn longest(x: &str, y: &str) -> &str {
```

Pretending we're the compiler again, let's apply the first rule: each parameter gets its own lifetime. This time we have two parameters, so we have two lifetimes:

```
fn longest<'a, 'b>(x: &'a str, y: &'b str) -> &str {
```

Looking at the second rule, it doesn't apply since there is more than one input lifetime. Looking at the third rule, this also does not apply because this is a function rather than a method, so none of the parameters are `self`. So we're out of rules, but we haven't figured out what the return type's lifetime is. This is why we got an error trying to compile the code from Listing 10-22: the compiler worked through the lifetime elision rules it knows, but still can't figure out all the lifetimes of the references in the signature.

Because the third rule only really applies in method signatures, let's look at lifetimes in that context now, and see why the third rule means we don't have to annotate lifetimes in method signatures very often.

Lifetime Annotations in Method Definitions

When we implement methods on a struct with lifetimes, the syntax is again the same as that of generic type parameters that we showed in Listing 10-11: the place that lifetime parameters are declared and used depends on whether the lifetime parameter is related to the struct fields or the method arguments and return values.

Lifetime names for struct fields always need to be declared after the `impl` keyword and then used after the struct's name, since those lifetimes are part of the struct's type.

In method signatures inside the `impl` block, references might be tied to the lifetime of references in the struct's fields, or they might be independent. In addition, the lifetime elision rules often make it so that lifetime annotations aren't necessary in method signatures. Let's look at some examples using the struct named `ImportantExcerpt` that we defined in Listing 10-26.

First, here's a method named `level`. The only parameter is a reference to `self`, and the return value is just an `i32`, not a reference to anything:

```
impl<'a> ImportantExcerpt<'a> {
    fn level(&self) -> i32 {
        3
    }
}
```

The lifetime parameter declaration after `impl` and use after the type name is required, but we're not required to annotate the lifetime of the reference to `self` because of the first elision rule.

Here's an example where the third lifetime elision rule applies:

```
impl<'a> ImportantExcerpt<'a> {
    fn announce_and_return_part(&self, announcement: &str) -> &str {
        println!("Attention please: {}", announcement);
        self.part
    }
}
```

There are two input lifetimes, so Rust applies the first lifetime elision rule and gives both `&self` and `announcement` their own lifetimes. Then, because one of the parameters is `&self`, the return type gets the lifetime of `&self`, and all lifetimes have been accounted for.

The Static Lifetime

There is *one* special lifetime we need to discuss: `'static`. The `'static` lifetime is the entire duration of the program. All string literals have the `'static` lifetime, which we can choose to annotate as follows:

```
let s: &'static str = "I have a static lifetime.";
```

The text of this string is stored directly in the binary of your program and the binary of your program is always available. Therefore, the lifetime of all string literals is `'static`.

You may see suggestions to use the `'static` lifetime in error message help text, but before specifying `'static` as the lifetime for a reference, think about whether the reference you have is one that actually lives the entire lifetime of your program or not (or even if you want it to live that long, if it could). Most of the time, the problem in the code is an attempt to create a dangling reference or a mismatch of the available lifetimes, and the solution is fixing those problems, not specifying the `'static` lifetime.

Generic Type Parameters, Trait Bounds, and Lifetimes Together

Let's briefly look at the syntax of specifying generic type parameters, trait bounds, and lifetimes all in one function!

```
use std::fmt::Display;

fn longest_with_an_announcement<'a, T>(x: &'a str, y: &'a str, ann: T) -> &'a str
    where T: Display
{
    println!("Announcement! {}", ann);
    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```

This is the `longest` function from Listing 10-23 that returns the longest of two string slices, but with an extra argument named `ann`. The type of `ann` is the generic type `T`, which may be filled in by any type that implements the `Display` trait as specified by the `where` clause. This extra argument will be printed out before the function compares the lengths of the string slices, which is why the `Display` trait bound is necessary. Because lifetimes are a type of generic, the declarations of both the lifetime parameter `'a` and the generic type parameter `T` go in the same list within the angle brackets after the function name.

Summary

We covered a lot in this chapter! Now that you know about generic type parameters, traits and trait bounds, and generic lifetime parameters, you're ready to write code that isn't duplicated but can be used in many different situations. Generic type parameters mean the code can be applied to different types. Traits and trait bounds ensure that even though the types are generic, those types will have the behavior the code needs. Relationships between the lifetimes of references specified by lifetime annotations ensure that this flexible code won't have any dangling references. And all of this happens at compile time so that run-time performance isn't affected!

Believe it or not, there's even more to learn in these areas: Chapter 17 will discuss trait objects, which are another way to use traits. Chapter 19 will be covering more complex scenarios involving lifetime annotations. Chapter 20 will get to some advanced type system features. Up next, though, let's talk about how to write tests in Rust so that we can make sure our code using all these features is working the way we want it to!

Writing Automated Tests

> Program testing can be a very effective way to show the presence of bugs, but it is hopelessly inadequate for showing their absence. Edsger W. Dijkstra, “The Humble Programmer” (1972)

Correctness in our programs means that our code does what we intend for it to do. Rust is a programming language that cares a lot about correctness, but correctness is a complex topic and isn’t easy to prove. Rust’s type system shoulders a huge part of this burden, but the type system cannot catch every kind of incorrectness. As such, Rust includes support for writing software tests within the language itself.

As an example, say we write a function called `add_two` that adds two to whatever number is passed to it. This function’s signature accepts an integer as a parameter and returns an integer as a result. When we implement and compile that function, Rust will do all the type checking and borrow checking that we’ve seen so far to make sure that, for instance, we aren’t passing a `String` value or an invalid reference to this function. What Rust *can’t* check is that this function will do precisely what we intend: return the parameter plus two, rather than, say, the parameter plus 10 or the parameter minus 50! That’s where tests come in.

We can write tests that assert, for example, that when we pass `3` to the `add_two` function, we get `5` back. We can run these tests whenever we make changes to our code to make sure any existing correct behavior has not changed.

Testing is a complex skill, and we cannot hope to cover everything about how to write good tests in one chapter of a book, so here we’ll just discuss the mechanics of Rust’s testing facilities. We’ll talk about the annotations and macros available to you when writing your tests, the default behavior and options provided for running your tests, and how to organize tests into unit tests and integration tests.

How to Write Tests

Tests are Rust functions that verify that the non-test code is functioning in the expected manner. The bodies of test functions typically perform some setup, run the code we want to test, then assert whether the results are what we expect. Let’s look at the features Rust provides specifically for writing tests: the `test` attribute, a few macros, and the `should_panic` attribute.

The Anatomy of a Test Function

At its simplest, a test in Rust is a function that’s annotated with the `test` attribute. Attributes are metadata about pieces of Rust code: the `derive` attribute that we used with structs in

Chapter 5 is one example. To make a function into a test function, we add `#[test]` on the line before `fn`. When we run our tests with the `cargo test` command, Rust will build a test runner binary that runs the functions annotated with the `test` attribute and reports on whether each test function passes or fails.

We saw in Chapter 7 that when you make a new library project with Cargo, a test module with a test function in it is automatically generated for us. This is to help us get started writing our tests so we don't have to go look up the exact structure and syntax of test functions every time we start a new project. We can add as many additional test functions and as many test modules as we want, though!

We're going to explore some aspects of how tests work by experimenting with the template test generated for us, without actually testing any code. Then we'll write some real-world tests that call some code that we've written and assert that its behavior is correct.

Let's create a new library project called `adder`:

```
$ cargo new adder
     Created library `adder` project
$ cd adder
```

The contents of the `src/lib.rs` file in your adder library should be as follows:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    #[test]
    fn it_works() {
    }
}
```

Listing 11-1: The test module and function generated automatically for us by `cargo new`

For now, let's ignore the top two lines and focus on the function to see how it works. Note the `#[test]` annotation before the `fn` line: this attribute indicates this is a test function, so that the test runner knows to treat this function as a test. We could also have non-test functions in the `tests` module to help set up common scenarios or perform common operations, so we need to indicate which functions are tests with the `#[test]` attribute.

The function currently has no body, which means there is no code to fail the test; an empty test is a passing test! Let's run it and see that this test passes.

The `cargo test` command runs all tests we have in our project, as shown in Listing 11-2:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished dev [unoptimized + debuginfo] target(s) in 0.22 secs
     Running target/debug/deps/adder-ce99bcc2479f4607

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

Listing 11-2: The output from running the one automatically generated test

Cargo compiled and ran our test. After the `Compiling`, `Finished`, and `Running` lines, we see the line `running 1 test`. The next line shows the name of the generated test function, called `it_works`, and the result of running that test, `ok`. Then we see the overall summary of running the tests: `test result: ok.` means all the tests passed. `1 passed; 0 failed` adds up the number of tests that passed or failed.

We don't have any tests we've marked as ignored, so the summary says `0 ignored`. We're going to talk about ignoring tests in the next section on different ways to run tests. The `0 measured` statistic is for benchmark tests that measure performance. Benchmark tests are, as of this writing, only available in nightly Rust. See Appendix D for more information about nightly Rust.

The next part of the test output that starts with `Doc-tests adder` is for the results of any documentation tests. We don't have any documentation tests yet, but Rust can compile any code examples that appear in our API documentation. This feature helps us keep our docs and our code in sync! We'll be talking about how to write documentation tests in the "Documentation Comments" section of Chapter 14. We're going to ignore the `Doc-tests` output for now.

Let's change the name of our test and see how that changes the test output. Give the `it_works` function a different name, such as `exploration`, like so:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    #[test]
    fn exploration() {
    }
}
```

And run `cargo test` again. In the output, we'll now see `exploration` instead of `it_works`:

```
running 1 test
test tests::exploration ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

Let's add another test, but this time we'll make a test that fails! Tests fail when something in the test function panics. Each test is run in a new thread, and when the main thread sees that a test thread has died, the test is marked as failed. We talked about the simplest way to cause a panic in Chapter 9: call the `panic!` macro! Type in the new test so that your `src/lib.rs` now looks like Listing 11-3:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    #[test]
    fn exploration() {
    }

    #[test]
    fn another() {
        panic!("Make this test fail");
    }
}
```

Listing 11-3: Adding a second test; one that will fail since we call the `panic!` macro

And run the tests again with `cargo test`. The output should look like Listing 11-4, which shows that our `exploration` test passed and `another` failed:

```
running 2 tests
test tests::exploration ... ok
test tests::another ... FAILED

failures:

---- tests::another stdout ----
    thread 'tests::another' panicked at 'Make this test fail', src/lib.rs:9
note: Run with `RUST_BACKTRACE=1` for a backtrace.

failures:
    tests::another

test result: FAILED. 1 passed; 1 failed; 0 ignored; 0 measured

error: test failed
```

Listing 11-4: Test results when one test passes and one test fails

Instead of `ok`, the line `test tests::another` says `FAILED`. We have two new sections between the individual results and the summary: the first section displays the detailed reason for the test failures. In this case, `another` failed because it `panicked at 'Make this test fail'`, which happened on *src/lib.rs* line 9. The next section lists just the names of all the failing tests, which is useful when there are lots of tests and lots of detailed failing test output. We can use the name of a failing test to run just that test in order to more easily debug it; we'll talk more about ways to run tests in the next section.

Finally, we have the summary line: overall, our test result is `FAILED`. We had 1 test pass and 1 test fail.

Now that we've seen what the test results look like in different scenarios, let's look at some macros other than `panic!` that are useful in tests.

Checking Results with the `assert!` Macro

The `assert!` macro, provided by the standard library, is useful when you want to ensure that some condition in a test evaluates to `true`. We give the `assert!` macro an argument that evaluates to a boolean. If the value is `true`, `assert!` does nothing and the test passes. If the value is `false`, `assert!` calls the `panic!` macro, which causes the test to fail. This is one macro that helps us check that our code is functioning in the way we intend.

Remember all the way back in Chapter 5, Listing 5-9, where we had a `Rectangle` struct and a `can_hold` method, repeated here in Listing 11-5. Let's put this code in *src/lib.rs* and write some tests for it using the `assert!` macro.

Filename: src/lib.rs

```
#[derive(Debug)]
pub struct Rectangle {
    length: u32,
    width: u32,
}

impl Rectangle {
    pub fn can_hold(&self, other: &Rectangle) -> bool {
        self.length > other.length && self.width > other.width
    }
}
```

Listing 11-5: The `Rectangle` struct and its `can_hold` method from Chapter 5

The `can_hold` method returns a boolean, which means it's a perfect use case for the `assert!` macro. In Listing 11-6, let's write a test that exercises the `can_hold` method by creating a `Rectangle` instance that has a length of 8 and a width of 7, and asserting that it can hold another `Rectangle` instance that has a length of 5 and a width of 1:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn larger_can_hold_smaller() {
        let larger = Rectangle { length: 8, width: 7 };
        let smaller = Rectangle { length: 5, width: 1 };

        assert!(larger.can_hold(&smaller));
    }
}
```

Listing 11-6: A test for `can_hold` that checks that a larger rectangle indeed holds a smaller rectangle

Note that we've added a new line inside the `tests` module: `use super::*;`. The `tests` module is a regular module that follows the usual visibility rules we covered in Chapter 7. Because we're in an inner module, we need to bring the code under test in the outer module into the scope of the inner module. We've chosen to use a glob here so that anything we define in the outer module is available to this `tests` module.

We've named our test `larger_can_hold_smaller`, and we've created the two `Rectangle` instances that we need. Then we called the `assert!` macro and passed it the result of calling `larger.can_hold(&smaller)`. This expression is supposed to return `true`, so our test should pass. Let's find out!

```
running 1 test
test tests::larger_can_hold_smaller ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

It does pass! Let's add another test, this time asserting that a smaller rectangle cannot hold a larger rectangle:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn larger_can_hold_smaller() {
        let larger = Rectangle { length: 8, width: 7 };
        let smaller = Rectangle { length: 5, width: 1 };

        assert!(larger.can_hold(&smaller));
    }

    #[test]
    fn smaller_cannot_hold_larger() {
        let larger = Rectangle { length: 8, width: 7 };
        let smaller = Rectangle { length: 5, width: 1 };

        assert!(!smaller.can_hold(&larger));
    }
}
```

Because the correct result of the `can_hold` function in this case is `false`, we need to negate that result before we pass it to the `assert!` macro. This way, our test will pass if `can_hold` returns `false`:

```
running 2 tests
test tests::smaller_cannot_hold_larger ... ok
test tests::larger_can_hold_smaller ... ok

test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured
```

Two passing tests! Now let's see what happens to our test results if we introduce a bug in our code. Let's change the implementation of the `can_hold` method to have a less-than sign when it compares the lengths where it's supposed to have a greater-than sign:

```
#[derive(Debug)]
pub struct Rectangle {
    length: u32,
    width: u32,
}

impl Rectangle {
    pub fn can_hold(&self, other: &Rectangle) -> bool {
        self.length < other.length && self.width > other.width
    }
}
```

Running the tests now produces:

```
running 2 tests
test tests::smaller_cannot_hold_larger ... ok
test tests::larger_can_hold_smaller ... FAILED

failures:

---- tests::larger_can_hold_smaller stdout ----
    thread 'tests::larger_can_hold_smaller' panicked at 'assertion failed:
    larger.can_hold(&smaller)', src/lib.rs:22
note: Run with `RUST_BACKTRACE=1` for a backtrace.

failures:
    tests::larger_can_hold_smaller

test result: FAILED. 1 passed; 1 failed; 0 ignored; 0 measured
```

Our tests caught the bug! Since `larger.length` is 8 and `smaller.length` is 5, the comparison of the lengths in `can_hold` now returns `false` since 8 is not less than 5.

Testing Equality with the `assert_eq!` and `assert_ne!` Macros

A common way to test functionality is to take the result of the code under test and the value we expect the code to return and check that they're equal. We could do this using the `assert!` macro and passing it an expression using the `==` operator. However, this is such a common test that the standard library provides a pair of macros to perform this test more conveniently: `assert_eq!` and `assert_ne!`. These macros compare two arguments for equality or inequality, respectively. They'll also print out the two values if the assertion fails, so that it's easier to see *why* the test failed, while the `assert!` macro only tells us that it got a `false` value for the `==` expression, not the values that lead to the `false` value.

In Listing 11-7, let's write a function named `add_two` that adds two to its parameter and returns the result. Then let's test this function using the `assert_eq!` macro:

Filename: src/lib.rs

```
pub fn add_two(a: i32) -> i32 {
    a + 2
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_adds_two() {
        assert_eq!(4, add_two(2));
    }
}
```

Listing 11-7: Testing the function `add_two` using the `assert_eq!` macro

Let's check that it passes!

```
running 1 test
test tests::it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

The first argument we gave to the `assert_eq!` macro, 4, is equal to the result of calling `add_two(2)`. We see a line for this test that says `test tests::it_adds_two ... ok`, and the `ok` text indicates that our test passed!

Let's introduce a bug into our code to see what it looks like when a test that uses `assert_eq!` fails. Change the implementation of the `add_two` function to instead add 3:

```
pub fn add_two(a: i32) -> i32 {
    a + 3
}
```

And run the tests again:

```
running 1 test
test tests::it_adds_two ... FAILED

failures:

---- tests::it_adds_two stdout ----
    thread 'tests::it_adds_two' panicked at 'assertion failed: `(left ==
    right)` (left: `4`, right: `5`)', src/lib.rs:11
note: Run with `RUST_BACKTRACE=1` for a backtrace.

failures:
    tests::it_adds_two

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured
```

Our test caught the bug! The `it_adds_two` test failed with the message `` assertion failed: `(left == right)` (left: `4`, right: `5`) ``. This message is useful and helps us get started debugging: it says the `left` argument to `assert_eq!` was 4, but the `right` argument, where we had `add_two(2)`, was 5.

Note that in some languages and test frameworks, the parameters to the functions that assert two values are equal are called `expected` and `actual` and the order in which we specify the arguments matters. However, in Rust, they're called `left` and `right` instead, and the order in which we specify the value we expect and the value that the code under test produces doesn't matter. We could write the assertion in this test as `assert_eq!(add_two(2), 4)`, which would result in a failure message that says `` assertion failed: `(left == right)` (left: `5`, right: `4`) ``.

The `assert_ne!` macro will pass if the two values we give to it are not equal and fail if they are equal. This macro is most useful for cases when we're not sure exactly what a value *will* be, but we know what the value definitely *won't* be, if our code is functioning as we intend. For example, if we have a function that is guaranteed to change its input in some way, but the way in which the input is changed depends on the day of the week that we run our tests, the best thing to assert might be that the output of the function is not equal to the input.

Under the surface, the `assert_eq!` and `assert_ne!` macros use the operators `==` and `!=`, respectively. When the assertions fail, these macros print their arguments using debug formatting, which means the values being compared must implement the `PartialEq` and `Debug` traits. All of the primitive types and most of the standard library types implement these traits. For structs and enums that you define, you'll need to implement `PartialEq` in order to be able to assert that values of those types are equal or not equal. You'll need to implement `Debug` in order to be able to print out the values in the case that the assertion fails. Because both of these traits are derivable traits, as we mentioned in Chapter 5, this is usually as straightforward as adding the `#[derive(PartialEq, Debug)]` annotation to your struct or enum definition. See Appendix C for more details about these and other derivable traits.

Custom Failure Messages

We can also add a custom message to be printed with the failure message as optional arguments to `assert!`, `assert_eq!`, and `assert_ne!`. Any arguments specified after the one required argument to `assert!` or the two required arguments to `assert_eq!` and `assert_ne!` are passed along to the `format!` macro that we talked about in Chapter 8, so you can pass a format string that contains `{}` placeholders and values to go in the placeholders. Custom messages are useful in order to document what an assertion means, so that when the test fails, we have a better idea of what the problem is with the code.

For example, let's say we have a function that greets people by name, and we want to test that the name we pass into the function appears in the output:

Filename: src/lib.rs

```
pub fn greeting(name: &str) -> String {
    format!("Hello {}!", name)
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn greeting_contains_name() {
        let result = greeting("Carol");
        assert!(result.contains("Carol"));
    }
}
```

The requirements for this program haven't been agreed upon yet, and we're pretty sure the `Hello` text at the beginning of the greeting will change. We decided we don't want to have to update the test for the name when that happens, so instead of checking for exact equality to the value returned from the `greeting` function, we're just going to assert that the output contains the text of the input parameter.

Let's introduce a bug into this code to see what this test failure looks like, by changing `greeting` to not include `name`:

```
pub fn greeting(name: &str) -> String {
    String::from("Hello!")
}
```

Running this test produces:

```
running 1 test
test tests::greeting_contains_name ... FAILED

failures:

---- tests::greeting_contains_name stdout ----
    thread 'tests::greeting_contains_name' panicked at 'assertion failed:
    result.contains("Carol")', src/lib.rs:12
note: Run with `RUST_BACKTRACE=1` for a backtrace.

failures:
    tests::greeting_contains_name
```

This just tells us that the assertion failed and which line the assertion is on. A more useful failure message in this case would print the value we did get from the `greeting` function. Let's change the test function to have a custom failure message made from a format string with a placeholder filled in with the actual value we got from the `greeting` function:

```
#[test]
fn greeting_contains_name() {
    let result = greeting("Carol");
    assert!(
        result.contains("Carol"),
        "Greeting did not contain name, value was `{}`", result
    );
}
```

Now if we run the test again, we'll get a much more informative error message:

```
---- tests::greeting_contains_name stdout ----
    thread 'tests::greeting_contains_name' panicked at 'Greeting did not contain
    name, value was `Hello`', src/lib.rs:12
note: Run with `RUST_BACKTRACE=1` for a backtrace.
```

We can see the value we actually got in the test output, which would help us debug what happened instead of what we were expecting to happen.

Checking for Panics with `should_panic`

In addition to checking that our code returns the correct values we expect, it's also important to check that our code handles error conditions as we expect. For example, consider the `Guess` type that we created in Chapter 9 in Listing 9-8. Other code that uses `Guess` is depending on the guarantee that `Guess` instances will only contain values between 1 and 100. We can write a test that ensures that attempting to create a `Guess` instance with a value outside that range panics.

We can do this by adding another attribute, `should_panic`, to our test function. This attribute makes a test pass if the code inside the function panics, and the test will fail if the code inside the function doesn't panic.

Listing 11-8 shows how we'd write a test that checks the error conditions of `Guess::new` happen when we expect:

Filename: src/lib.rs

```
pub struct Guess {
    value: u32,
}

impl Guess {
    pub fn new(value: u32) -> Guess {
        if value < 1 || value > 100 {
            panic!("Guess value must be between 1 and 100, got {}.", value);
        }

        Guess {
            value
        }
    }
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    #[should_panic]
    fn greater_than_100() {
        Guess::new(200);
    }
}
```

Listing 11-8: Testing that a condition will cause a `panic!`

The `#[should_panic]` attribute goes after the `#[test]` attribute and before the test function it applies to. Let's see what it looks like when this test passes:

```
running 1 test
test tests::greater_than_100 ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

Looks good! Now let's introduce a bug in our code, by removing the condition that the `new` function will panic if the value is greater than 100:

```
impl Guess {
    pub fn new(value: u32) -> Guess {
        if value < 1  {
            panic!("Guess value must be between 1 and 100, got {}.", value);
        }

        Guess {
            value
        }
    }
}
```

If we run the test from Listing 11-8, it will fail:

```
running 1 test
test tests::greater_than_100 ... FAILED

failures:

failures:
    tests::greater_than_100

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured
```

We don't get a very helpful message in this case, but once we look at the test function, we can see that it's annotated with `#[should_panic]`. The failure we got means that the code in the function, `Guess::new(200)`, did not cause a panic.

`should_panic` tests can be imprecise, however, because they only tell us that the code has caused some panic. A `should_panic` test would pass even if the test panics for a different reason than the one we were expecting to happen. To make `should_panic` tests more precise, we can add an optional `expected` parameter to the `should_panic` attribute. The test harness will make sure that the failure message contains the provided text. For example, consider the modified code for `Guess` in Listing 11-9 where the `new` function panics with different messages depending on whether the value was too small or too large:

Filename: src/lib.rs

```
pub struct Guess {
    value: u32,
}

impl Guess {
    pub fn new(value: u32) -> Guess {
        if value < 1 {
            panic!("Guess value must be greater than or equal to 1, got {}.",
                   value);
        } else if value > 100 {
            panic!("Guess value must be less than or equal to 100, got {}.",
                   value);
        }

        Guess {
            value
        }
    }
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    #[should_panic(expected = "Guess value must be less than or equal to 100")]
    fn greater_than_100() {
        Guess::new(200);
    }
}
```

Listing 11-9: Testing that a condition will cause a `panic!` with a particular panic message

This test will pass, because the value we put in the `expected` parameter of the `should_panic` attribute is a substring of the message that the `Guess::new` function panics with. We could have specified the whole panic message that we expect, which in this case would be `Guess value must be less than or equal to 100, got 200.` It depends on how much of the panic message is unique or dynamic and how precise you want your test to be. In this case, a substring of the panic message is enough to ensure that the code in the function that gets run is the `else if value > 100` case.

To see what happens when a `should_panic` test with an `expected` message fails, let's again introduce a bug into our code by swapping the bodies of the `if value < 1` and the `else if value > 100` blocks:

```
if value < 1 {
    panic!("Guess value must be less than or equal to 100, got {}.", value);
} else if value > 100 {
    panic!("Guess value must be greater than or equal to 1, got {}.", value);
}
```

This time when we run the `should_panic` test, it will fail:

```
running 1 test
test tests::greater_than_100 ... FAILED

failures:

---- tests::greater_than_100 stdout ----
    thread 'tests::greater_than_100' panicked at 'Guess value must be greater
    than or equal to 1, got 200.', src/lib.rs:10
note: Run with `RUST_BACKTRACE=1` for a backtrace.
note: Panic did not include expected string 'Guess value must be less than or
equal to 100'

failures:
    tests::greater_than_100

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured
```

The failure message indicates that this test did indeed panic as we expected, but the panic message did not include expected string `'Guess value must be less than or equal to 100'` . We can see the panic message that we did get, which in this case was `Guess value must be greater than or equal to 1, got` We could then start figuring out where our bug was!

Now that we've gone over ways to write tests, let's look at what is happening when we run our tests and talk about the different options we can use with `cargo test`.

Controlling How Tests are Run

Just as `cargo run` compiles your code and then runs the resulting binary, `cargo test` compiles your code in test mode and runs the resulting test binary. There are options you can use to change the default behavior of `cargo test`. For example, the default behavior of the binary produced by `cargo test` is to run all the tests in parallel and capture output generated during test runs, preventing it from being displayed to make it easier to read the output related to the test results. You can change this default behavior by specifying command line options.

Some command line options can be passed to `cargo test`, and some need to be passed instead to the resulting test binary. To separate these two types of arguments, you list the arguments that go to `cargo test`, then the separator `--`, and then the arguments that go to the test binary. Running `cargo test --help` will tell you about the options that go with `cargo test`, and running `cargo test -- --help` will tell you about the options that go after the separator `--`.

Running Tests in Parallel or Consecutively

When multiple tests are run, by default they run in parallel using threads. This means the tests will finish running faster, so that we can get faster feedback on whether or not our code is working. Since the tests are running at the same time, you should take care that your tests do not depend on each other or on any shared state, including a shared environment such as the current working directory or environment variables.

For example, say each of your tests runs some code that creates a file on disk named `test-output.txt` and writes some data to that file. Then each test reads the data in that file and asserts that the file contains a particular value, which is different in each test. Because the tests are all run at the same time, one test might overwrite the file between when another test writes and reads the file. The second test will then fail, not because the code is incorrect, but because the tests have interfered with each other while running in parallel. One solution would be to make sure each test writes to a different file; another solution is to run the tests one at a time.

If you don't want to run the tests in parallel, or if you want more fine-grained control over the number of threads used, you can send the `--test-threads` flag and the number of threads you want to use to the test binary. For example:

```
$ cargo test -- --test-threads=1
```

We set the number of test threads to 1, telling the program not to use any parallelism. This will take longer than running them in parallel, but the tests won't be potentially interfering with each other if they share state.

Showing Function Output

By default, if a test passes, Rust's test library captures anything printed to standard output. For example, if we call `println!` in a test and the test passes, we won't see the `println!` output in the terminal: we'll only see the line that says the test passed. If a test fails, we'll see whatever was printed to standard output with the rest of the failure message.

For example, Listing 11-10 has a silly function that prints out the value of its parameter and then returns 10. We then have a test that passes and a test that fails:

Filename: src/lib.rs

```
fn prints_and_returns_10(a: i32) -> i32 {
    println!("I got the value {}", a);
    10
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn this_test_will_pass() {
        let value = prints_and_returns_10(4);
        assert_eq!(10, value);
    }

    #[test]
    fn this_test_will_fail() {
        let value = prints_and_returns_10(8);
        assert_eq!(5, value);
    }
}
```

Listing 11-10: Tests for a function that calls `println!`

The output we'll see when we run these tests with `cargo test` is:

```
running 2 tests
test tests::this_test_will_pass ... ok
test tests::this_test_will_fail ... FAILED

failures:

---- tests::this_test_will_fail stdout ----
    I got the value 8
thread 'tests::this_test_will_fail' panicked at 'assertion failed: `(left ==
right)` (left: `5`, right: `10`)', src/lib.rs:19
note: Run with `RUST_BACKTRACE=1` for a backtrace.

failures:
    tests::this_test_will_fail

test result: FAILED. 1 passed; 1 failed; 0 ignored; 0 measured
```

Note that nowhere in this output do we see `I got the value 4`, which is what gets printed when the test that passes runs. That output has been captured. The output from the test that failed, `I got the value 8`, appears in the section of the test summary output that also shows the cause of the test failure.

If we want to be able to see printed values for passing tests as well, the output capture behavior can be disabled by using the `--nocapture` flag:

```
$ cargo test -- --nocapture
```

Running the tests from Listing 11-10 again with the `--nocapture` flag now shows:

```
running 2 tests
I got the value 4
I got the value 8
test tests::this_test_will_pass ... ok
thread 'tests::this_test_will_fail' panicked at 'assertion failed: `(left ==
right)` (left: `5`, right: `10`)', src/lib.rs:19
note: Run with `RUST_BACKTRACE=1` for a backtrace.
test tests::this_test_will_fail ... FAILED

failures:

failures:
    tests::this_test_will_fail

test result: FAILED. 1 passed; 1 failed; 0 ignored; 0 measured
```

Note that the output for the tests and the test results is interleaved; this is because the tests are running in parallel as we talked about in the previous section. Try using both the `--test-threads=1` option and the `--nocapture` flag and see what the output looks like then!

Running a Subset of Tests by Name

Sometimes, running a full test suite can take a long time. If you're working on code in a particular area, you might want to run only the tests pertaining to that code. You can choose which tests to run by passing `cargo test` the name or names of the test(s) you want to run as an argument.

To demonstrate how to run a subset of tests, we'll create three tests for our `add_two` function as shown in Listing 11-11 and choose which ones to run:

Filename: src/lib.rs

```
pub fn add_two(a: i32) -> i32 {
    a + 2
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn add_two_and_two() {
        assert_eq!(4, add_two(2));
    }

    #[test]
    fn add_three_and_two() {
        assert_eq!(5, add_two(3));
    }

    #[test]
    fn one_hundred() {
        assert_eq!(102, add_two(100));
    }
}
```

Listing 11-11: Three tests with a variety of names

If we run the tests without passing any arguments, as we've already seen, all the tests will run in parallel:

```
running 3 tests
test tests::add_two_and_two ... ok
test tests::add_three_and_two ... ok
test tests::one_hundred ... ok

test result: ok. 3 passed; 0 failed; 0 ignored; 0 measured
```

Running Single Tests

We can pass the name of any test function to `cargo test` to run only that test:

```
$ cargo test one_hundred
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running target/debug/deps/adder-06a75b4a1f2515e9

running 1 test
test tests::one_hundred ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

We can't specify the names of multiple tests in this way, only the first value given to `cargo test` will be used.

Filtering to Run Multiple Tests

However, we can specify part of a test name, and any test whose name matches that value will get run. For example, since two of our tests' names contain `add`, we can run those two by running `cargo test add`:

```
$ cargo test add
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running target/debug/deps/adder-06a75b4a1f2515e9

running 2 tests
test tests::add_two_and_two ... ok
test tests::add_three_and_two ... ok

test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured
```

This ran all tests with `add` in the name. Also note that the module in which tests appear becomes part of the test's name, so we can run all the tests in a module by filtering on the module's name.

Ignore Some Tests Unless Specifically Requested

Sometimes a few specific tests can be very time-consuming to execute, so you might want to exclude them during most runs of `cargo test`. Rather than listing as arguments all tests you do want to run, we can instead annotate the time consuming tests with the `ignore` attribute to exclude them:

Filename: src/lib.rs

```rust
#[test]
fn it_works() {
    assert!(true);
}

#[test]
#[ignore]
fn expensive_test() {
    // code that takes an hour to run
}
```

We add the `#[ignore]` line to the test we want to exclude, after `#[test]`. Now if we run our tests, we'll see `it_works` runs, but `expensive_test` does not:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished dev [unoptimized + debuginfo] target(s) in 0.24 secs
     Running target/debug/deps/adder-ce99bcc2479f4607

running 2 tests
test expensive_test ... ignored
test it_works ... ok

test result: ok. 1 passed; 0 failed; 1 ignored; 0 measured

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

`expensive_test` is listed as `ignored`. If we want to run only the ignored tests, we can ask for them to be run with `cargo test -- --ignored`:

```
$ cargo test -- --ignored
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running target/debug/deps/adder-ce99bcc2479f4607

running 1 test
test expensive_test ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

By controlling which tests run, you can make sure your `cargo test` results will be fast. When you're at a point that it makes sense to check the results of the `ignored` tests and you have time to wait for the results, you can choose to run `cargo test -- --ignored` instead.

Test Organization

As mentioned at the start of the chapter, testing is a large discipline, and different people use different terminology and organization. The Rust community tends to think about tests in terms of two main categories: *unit tests* and *integration tests*. Unit tests are smaller and more focused, testing one module in isolation at a time, and can test private interfaces. Integration tests are entirely external to your library, and use your code in the same way any other external code would, using only the public interface and exercising multiple modules per test.

Writing both kinds of tests is important to ensure that the pieces of your library are doing what you expect them to separately and together.

Unit Tests

The purpose of unit tests is to test each unit of code in isolation from the rest of the code, in order to be able to quickly pinpoint where code is and is not working as expected. We put unit tests in the *src* directory, in each file with the code that they're testing. The convention is that we create a module named `tests` in each file to contain the test functions, and we annotate the module with `cfg(test)`.

The Tests Module and `#[cfg(test)]`

The `#[cfg(test)]` annotation on the tests module tells Rust to compile and run the test code only when we run `cargo test`, and not when we run `cargo build`. This saves compile time when we only want to build the library, and saves space in the resulting compiled artifact since the tests are not included. We'll see that since integration tests go in a different directory, they don't need the `#[cfg(test)]` annotation. Because unit tests go in the same files as the code, though, we use `#[cfg(test)]` to specify that they should not be included in the compiled result.

Remember that when we generated the new `adder` project in the first section of this chapter, Cargo generated this code for us:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    #[test]
    fn it_works() {
    }
}
```

This is the automatically generated test module. The attribute `cfg` stands for *configuration*, and tells Rust that the following item should only be included given a certain configuration option. In this case, the configuration option is `test`, provided by Rust for compiling and running tests. By using this attribute, Cargo only compiles our test code if we actively run the tests with `cargo test`. This includes any helper functions that might be within this module, in addition to the functions annotated with `#[test]`.

Testing Private Functions

There's debate within the testing community about whether private functions should be tested directly or not, and other languages make it difficult or impossible to test private functions. Regardless of which testing ideology you adhere to, Rust's privacy rules do allow you to test private functions. Consider the code in Listing 11-12 with the private function `internal_adder`:

Filename: src/lib.rs

```
pub fn add_two(a: i32) -> i32 {
    internal_adder(a, 2)
}

fn internal_adder(a: i32, b: i32) -> i32 {
    a + b
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn internal() {
        assert_eq!(4, internal_adder(2, 2));
    }
}
```

Listing 11-12: Testing a private function

Note that the `internal_adder` function is not marked as `pub`, but because tests are just Rust code and the `tests` module is just another module, we can import and call `internal_adder` in a test just fine. If you don't think private functions should be tested, there's nothing in Rust that will compel you to do so.

Integration Tests

In Rust, integration tests are entirely external to your library. They use your library in the same way any other code would, which means they can only call functions that are part of your library's public API. Their purpose is to test that many parts of your library work correctly together. Units of code that work correctly by themselves could have problems when integrated, so test coverage of the integrated code is important as well. To create integration tests, you first need a *tests* directory.

The *tests* Directory

To write integration tests for our code, we need to make a *tests* directory at the top level of our project directory, next to *src*. Cargo knows to look for integration test files in this directory. We can then make as many test files as we'd like in this directory, and Cargo will compile each of the files as an individual crate.

Let's give it a try! Keep the code from Listing 11-12 in *src/lib.rs*. Make a *tests* directory, then make a new file named *tests/integration_test.rs*, and enter the code in Listing 11-13.

Filename: tests/integration_test.rs

```
extern crate adder;

#[test]
fn it_adds_two() {
    assert_eq!(4, adder::add_two(2));
}
```

Listing 11-13: An integration test of a function in the `adder` crate

We've added `extern crate adder` at the top, which we didn't need in the unit tests. This is because each test in the `tests` directory is an entirely separate crate, so we need to import our library into each of them. Integration tests use the library like any other consumer of it would, by importing the crate and using only the public API.

We don't need to annotate any code in *tests/integration_test.rs* with `#[cfg(test)]`. Cargo treats the `tests` directory specially and will only compile files in this directory if we run `cargo test`. Let's try running `cargo test` now:

```
cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished dev [unoptimized + debuginfo] target(s) in 0.31 secs
     Running target/debug/deps/adder-abcabcabc

running 1 test
test tests::internal ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

     Running target/debug/deps/integration_test-ce99bcc2479f4607

running 1 test
test it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

Now we have three sections of output: the unit tests, the integration test, and the doc tests. The first section for the unit tests is the same as we have been seeing: one line for each unit test (we have one named `internal` that we added in Listing 11-12), then a summary line for the unit tests.

The integration tests section starts with the line that says `Running target/debug/deps/integration-test-ce99bcc2479f4607` (the hash at the end of your output will be different). Then there's a line for each test function in that integration test, and a summary line for the results of the integration test just before the `Doc-tests adder` section starts.

Note that adding more unit test functions in any *src* file will add more test result lines to the unit tests section. Adding more test functions to the integration test file we created will add more lines to the integration test section. Each integration test file gets its own section, so if we add more files in the *tests* directory, there will be more integration test sections.

We can still run a particular integration test function by specifying the test function's name as an argument to `cargo test`. To run all of the tests in a particular integration test file, use the `--test` argument of `cargo test` followed by the name of the file:

```
$ cargo test --test integration_test
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running target/debug/integration_test-952a27e0126bb565

running 1 test
test it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

This tests only the file that we specified from the *tests* directory.

Submodules in Integration Tests

As you add more integration tests, you may want to make more than one file in the *tests* directory to help organize them; for example, to group the test functions by the functionality they're testing. As we mentioned, each file in the *tests* directory is compiled as its own separate crate.

Treating each integration test file as its own crate is useful to create separate scopes that are more like the way end users will be using your crate. However, this means files in the *tests* directory don't share the same behavior as files in *src* do that we learned about in Chapter 7 regarding how to separate code into modules and files.

The different behavior of files in the *tests* directory is usually most noticeable if you have a set of helper functions that would be useful in multiple integration test files, and you try to follow the steps from Chapter 7 to extract them into a common module. For example, if we create *tests/common.rs* and place this function named `setup` in it, where we could put some code that we want to be able to call from multiple test functions in multiple test files:

Filename: tests/common.rs

```
pub fn setup() {
    // setup code specific to your library's tests would go here
}
```

If we run the tests again, we'll see a new section in the test output for the *common.rs* file, even though this file doesn't contain any test functions, nor are we calling the `setup` function from anywhere:

```
running 1 test
test tests::internal ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

     Running target/debug/deps/common-b8b07b6f1be2db70

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured

     Running target/debug/deps/integration_test-d993c68b431d39df

running 1 test
test it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

Having `common` show up in the test results with `running 0 tests` displayed for it is not what we wanted; we just wanted to be able to share some code with the other integration test files.

In order to not have `common` show up in the test output, we need to use the other method of extracting code into a file that we learned about in Chapter 7: instead of creating *tests/common.rs*, we'll create *tests/common/mod.rs*. When we move the `setup` function code into *tests/common/mod.rs* and get rid of the *tests/common.rs* file, the section in the test output will no longer show up. Files in subdirectories of the *tests* directory do not get compiled as separate crates or have sections in the test output.

Once we have *tests/common/mod.rs*, we can use it from any of the integration test files as a module. Here's an example of calling the `setup` function from the `it_adds_two` test in *tests/integration_test.rs*:

Filename: tests/integration_test.rs

```
extern crate adder;

mod common;

#[test]
fn it_adds_two() {
    common::setup();
    assert_eq!(4, adder::add_two(2));
}
```

Note the `mod common;` declaration is the same as the module declarations we did in Chapter 7. Then in the test function, we can call the `common::setup()` function.

Integration Tests for Binary Crates

If our project is a binary crate that only contains a *src/main.rs* and does not have a *src/lib.rs*, we aren't able to create integration tests in the *tests* directory and use `extern crate` to import functions defined in *src/main.rs*. Only library crates expose functions that other crates are able to call and use; binary crates are meant to be run on their own.

This is one of the reasons Rust projects that provide a binary have a straightforward *src/main.rs* that calls logic that lives in *src/lib.rs*. With that structure, integration tests *can* test the library crate by using `extern crate` to cover the important functionality. If the important functionality works, the small amount of code in *src/main.rs* will work as well, and that small amount of code does not need to be tested.

Summary

Rust's testing features provide a way to specify how code should function to ensure it continues to work as we expect even as we make changes. Unit tests exercise different parts of a library separately and can test private implementation details. Integration tests cover the use of many parts of the library working together, and they use the library's public API to test the code in the same way external code will use it. Even though Rust's type system and ownership rules help prevent some kinds of bugs, tests are still important to help reduce logic bugs having to do with how your code is expected to behave.

Let's put together the knowledge from this chapter and other previous chapters and work on a project in the next chapter!

An I/O Project: Building a Command Line Program

This chapter is both a recap of the many skills you've learned so far and an exploration of a few more standard library features. We're going to build a command line tool that interacts with file and command line input/output to practice some of the Rust you now have under your belt.

Rust's speed, safety, *single binary* output, and cross-platform support make it a good language for creating command line tools, so for our project we'll make our own version of the classic command line tool `grep`. Grep is an acronym for "**G**lobally search a **R**egular **E**xpression and **P**rint." In the simplest use case, `grep` searches a specified file for a specified string. To do so, `grep` takes a filename and a string as its arguments, then reads the file and finds lines in that file that contain the string argument. It'll then print out those lines.

Along the way, we'll show how to make our command line tool use features of the terminal that many command line tools use. We'll read the value of an environment variable in order to allow the user to configure the behavior of our tool. We'll print to the standard error console stream (`stderr`) instead of standard output (`stdout`) so that, for example, the user can choose to redirect successful output to a file while still seeing error messages on the screen.

One Rust community member, Andrew Gallant, has already created a fully-featured, very fast version of `grep`, called `ripgrep`. By comparison, our version of `grep` will be fairly simple, but this chapter will give you some of the background knowledge to help you understand a real-world project like `ripgrep`.

This project will bring together a number of concepts you've learned so far:

- Organizing code (using what we learned in modules, Chapter 7)
- Using vectors and strings (collections, Chapter 8)
- Handling errors (Chapter 9)
- Using traits and lifetimes where appropriate (Chapter 10)
- Writing tests (Chapter 11)

We'll also briefly introduce closures, iterators, and trait objects, which Chapters 13 and 17 will cover in detail.

Accepting Command Line Arguments

Let's create a new project with, as always, `cargo new`. We're calling our project `minigrep` to distinguish from the `grep` tool that you may already have on your system:

```
$ cargo new --bin minigrep
     Created binary (application) `minigrep` project
$ cd minigrep
```

Our first task is to make `minigrep` able to accept its two command line arguments: the filename and a string to search for. That is, we want to be able to run our program with `cargo run`, a string to search for, and a path to a file to search in, like so:

```
$ cargo run searchstring example-filename.txt
```

Right now, the program generated by `cargo new` cannot process arguments we give it. There are some existing libraries on crates.io that can help us accept command line arguments, but since you're learning, let's implement this ourselves.

Reading the Argument Values

We first need to make sure our program is able to get the values of command line arguments we pass to it, for which we'll need a function provided in Rust's standard library: `std::env::args`. This function returns an *iterator* of the command line arguments that were given to our program. We haven't discussed iterators yet, and we'll cover them fully in Chapter 13, but for our purposes now we only need to know two things about iterators: Iterators produce a series of values, and we can call the `collect` function on an iterator to turn it into a collection, such as a vector, containing all of the elements the iterator produces.

Let's give it a try: use the code in Listing 12-1 to allow your `minigrep` program to read any command line arguments passed it and then collect the values into a vector.

Filename: src/main.rs

```rust
use std::env;

fn main() {
    let args: Vec<String> = env::args().collect();
    println!("{:?}", args);
}
```

Listing 12-1: Collect the command line arguments into a vector and print them out

First, we bring the `std::env` module into scope with a `use` statement so that we can use its `args` function. Notice the `std::env::args` function is nested in two levels of modules. As we talked about in Chapter 7, in cases where the desired function is nested in more than one module, it's conventional to bring the parent module into scope, rather than the function itself. This lets us easily use other functions from `std::env`. It's also less ambiguous than adding `use std::env::args;` then calling the function with just `args`; that might easily be mistaken for a function that's defined in the current module.

The `args` Function and Invalid Unicode

> Note that `std::env::args` will panic if any argument contains invalid Unicode. If you need to accept arguments containing invalid Unicode, use `std::env::args_os` instead. That function returns `OsString` values instead of `String` values. We've chosen to use `std::env::args` here for simplicity because `OsString` values differ per-platform and are more complex to work with than `String` values.

On the first line of `main`, we call `env::args`, and immediately use `collect` to turn the iterator into a vector containing all of the values produced by the iterator. The `collect` function can be used to create many kinds of collections, so we explicitly annotate the type of `args` to specify that we want a vector of strings. Though we very rarely need to annotate types in Rust, `collect` is one function you do often need to annotate because Rust isn't able to infer what kind of collection you want.

Finally, we print out the vector with the debug formatter, `:?`. Let's try running our code with no arguments, and then with two arguments:

```
$ cargo run
["target/debug/minigrep"]

$ cargo run needle haystack
...snip...
["target/debug/minigrep", "needle", "haystack"]
```

You may notice that the first value in the vector is `"target/debug/minigrep"`, which is the name of our binary. This matches the behavior of the arguments list in C, and lets programs use the name by which they were invoked in their execution. It's convenient to have access to the program name in case we want to print it in messages or change behavior of the program based on what command line alias was used to invoke the program, but for the purposes of this chapter we're going to ignore it and only save the two arguments we need.

Saving the Argument Values in Variables

Printing out the value of the vector of arguments has illustrated that the program is able to access the values specified as command line arguments. Now we need to save the values of the two arguments in variables so that we can use the values throughout the rest of the program. Let's do that as shown in Listing 12-2:

Filename: src/main.rs

```
use std::env;

fn main() {
    let args: Vec<String> = env::args().collect();

    let query = &args[1];
    let filename = &args[2];

    println!("Searching for {}", query);
    println!("In file {}", filename);
}
```

Listing 12-2: Create variables to hold the query argument and filename argument

As we saw when we printed out the vector, the program's name takes up the first value in the vector at `args[0]`, so that we're starting at index `1`. The first argument `minigrep` takes is the string we're searching for, so we put a reference to the first argument in the variable `query`. The second argument will be the filename, so we put a reference to the second argument in the variable `filename`.

We're temporarily printing out the values of these variables, again to prove to ourselves that our code is working as we intend. Let's try running this program again with the arguments `test` and `sample.txt`:

```
$ cargo run test sample.txt
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep test sample.txt`
Searching for test
In file sample.txt
```

Great, it's working! The values of the arguments we need are being saved into the right variables. Later we'll add some error handling to deal with certain potential erroneous situations, such as when the user provides no arguments, but for now we'll ignore that and work on adding file reading capabilities instead.

Reading a File

Next, we're going to add functionality to read the file that specified in the `filename` command line argument. First, we need a sample file to test it with—the best kind of file to use to make sure that `minigrep` is working is one with a small amount of text over multiple lines with some repeated words. Listing 12-3 has an Emily Dickinson poem that will work well! Create a file called `poem.txt` at the root level of your project, and enter the poem "I'm nobody! Who are you?":

Filename: poem.txt

```
I’m nobody! Who are you?
Are you nobody, too?
Then there’s a pair of us — don’t tell!
They’d banish us, you know.

How dreary to be somebody!
How public, like a frog
To tell your name the livelong day
To an admiring bog!
```

Listing 12-3: The poem “I’m nobody! Who are you?” by Emily Dickinson that will make a good test case

With that in place, edit *src/main.rs* and add code to open the file as shown in Listing 12-4:

Filename: src/main.rs

```
use std::env;
use std::fs::File;
use std::io::prelude::*;

fn main() {
    // ...snip...
    println!("In file {}", filename);

    let mut f = File::open(filename).expect("file not found");

    let mut contents = String::new();
    f.read_to_string(&mut contents)
        .expect("something went wrong reading the file");

    println!("With text:\n{}", contents);
}
```

Listing 12-4: Reading the contents of the file specified by the second argument

First, we add some more `use` statements to bring in relevant parts of the standard library: we need `std::fs::File` for dealing with files, and `std::io::prelude::*` contains various traits that are useful when doing I/O, including file I/O. In the same way that Rust has a general prelude that brings certain things into scope automatically, the `std::io` module has its own prelude of common things you’ll need when working with I/O. Unlike the default prelude, we must explicitly `use` the prelude from `std::io`.

In `main`, we’ve added three things: first, we get a mutable handle to the file by calling the `File::open` function and passing it the value of the `filename` variable. Second, we create a variable called `contents` and set it to a mutable, empty `String`. This will hold the content of the file after we read it in. Third, we call `read_to_string` on our file handle and pass a mutable reference to `contents` as an argument.

After those lines, we've again added a temporary `println!` statement that prints out the value of `contents` after the file is read, so that we can check that our program is working so far.

Let's try running this code with any string as the first command line argument (since we haven't implemented the searching part yet) and our *poem.txt* file as the second argument:

```
$ cargo run the poem.txt
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep the poem.txt`
Searching for the
In file poem.txt
With text:
I'm nobody! Who are you?
Are you nobody, too?
Then there's a pair of us — don't tell!
They'd banish us, you know.

How dreary to be somebody!
How public, like a frog
To tell your name the livelong day
To an admiring bog!
```

Great! Our code read in and printed out the content of the file. We've got a few flaws though. The `main` function has multiple responsibilities; generally functions are clearer and easier to maintain if each function is responsible for only one idea. The other problem is that we're not handling errors as well as we could be. While our program is still small, these flaws aren't a big problem, but as our program grows, it will be harder to fix them cleanly. It's good practice to begin refactoring early on when developing a program, as it's much easier to refactor smaller amounts of code, so we'll do that now.

Refactoring to Improve Modularity and Error Handling

There are four problems that we'd like to fix to improve our program, and they have to do with the way the program is structured and how it's handling potential errors.

First, our `main` function now performs two tasks: it parses arguments and opens up files. For such a small function, this isn't a huge problem. However, if we keep growing our program inside of `main`, the number of separate tasks the `main` function handles will grow. As a function gains responsibilities, it gets harder to reason about, harder to test, and harder to change without breaking one of its parts. It's better to separate out functionality so that each function is responsible for one task.

This also ties into our second problem: while `query` and `filename` are configuration variables to our program, variables like `f` and `contents` are used to perform our program's logic. The longer `main` gets, the more variables we're going to need to bring into scope; the more variables we have in scope, the harder it is to keep track of the purpose of each. It's better to group the configuration variables into one structure to make their purpose clear.

The third problem is that we've used `expect` to print out an error message when opening the file fails, but the error message only says `file not found`. There are a number of ways that opening a file can fail besides the file being missing: for example, the file might exist, but we might not have permission to open it. Right now, if we're in that situation, we'd print the `file not found` error message that would give the user the wrong advice!

Fourth, we use `expect` repeatedly to deal with different errors, and if the user runs our programs without specifying enough arguments, they'll get an "index out of bounds" error from Rust that doesn't clearly explain the problem. It would be better if all our error handling code was in one place so that future maintainers only have one place to consult in the code if the error handling logic needs to change. Having all the error handling code in one place will also help us to ensure that we're printing messages that will be meaningful to our end users.

Let's address these problems by refactoring our project.

Separation of Concerns for Binary Projects

The organizational problem of allocating responsibility for multiple tasks to the `main` function responsible is common to many binary projects, so the Rust community has developed a kind of guideline process for splitting up the separate concerns of a binary program when `main` starts getting large. The process has the following steps:

- Split your program into both a *main.rs* and a *lib.rs* and move your program's logic into *lib.rs*.
- While your command line parsing logic is small, it can remain in *main.rs*.
- When the command line parsing logic starts getting complicated, extract it from *main.rs* into *lib.rs* as well.
- The responsibilities that remain in the `main` function after this process should be limited to:
  - Calling the command line parsing logic with the argument values
  - Setting up any other configuration
  - Calling a `run` function in *lib.rs*
  - If `run` returns an error, handling that error

This pattern is all about separating concerns: *main.rs* handles running the program, and *lib.rs* handles all of the logic of the task at hand. Because we can't test the `main` function directly, this structure lets us test all of our program's logic by moving it into functions in *lib.rs*. The only code that remains in *main.rs* will be small enough to verify its correctness by reading it. Let's re-work our program by following this process.

Extracting the Argument Parser

First, we'll extract the functionality for parsing arguments into a function that `main` will call to prepare for moving the command line parsing logic to *src/lib.rs*. Listing 12-5 shows the new start of `main` that calls a new function `parse_config`, which we're still going to define in *src/main.rs* for the moment:

Filename: src/main.rs

```
fn main() {
    let args: Vec<String> = env::args().collect();

    let (query, filename) = parse_config(&args);

    // ...snip...
}

fn parse_config(args: &[String]) -> (&str, &str) {
    let query = &args[1];
    let filename = &args[2];

    (query, filename)
}
```

Listing 12-5: Extract a `parse_config` function from `main`

We're still collecting the command line arguments into a vector, but instead of assigning the argument value at index `1` to the variable `query` and the argument value at index `2` to the variable `filename` within the `main` function, we pass the whole vector to the `parse_config` function. The `parse_config` function then holds the logic that determines which argument goes in which variable, and passes the values back to `main`. We still create the `query` and `filename` variables in `main`, but `main` no longer has the responsibility of determining how the command line arguments and variables correspond.

This may seem like overkill for our small program, but we're refactoring in small, incremental steps. After making this change, run the program again to verify that the argument parsing still works. It's good to check your progress often, as that will help you identify the cause of problems when they occur.

Grouping Configuration Values

We can take another small step to improve this function further. At the moment, we're returning a tuple, but then we immediately break that tuple up into individual parts again. This is a sign that perhaps we don't have the right abstraction yet.

Another indicator that there's room for improvement is the `config` part of `parse_config`, which implies that the two values we return are related and are both part of one configuration value. We're not currently conveying this meaning in the structure of the data other than grouping the two values into a tuple: we could put the two values into one struct and give each of the struct fields a meaningful name. This will make it easier for future maintainers of this code to understand how the different values relate to each other and what their purpose is.

> Note: some people call this anti-pattern of using primitive values when a complex type would be more appropriate *primitive obsession*.

Listing 12-6 shows the addition of a struct named `Config` defined to have fields named `query` and `filename`. We've also changed the `parse_config` function to return an instance of the `Config` struct, and updated `main` to use the struct fields rather than having separate variables:

Filename: src/main.rs

```
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = parse_config(&args);

    println!("Searching for {}", config.query);
    println!("In file {}", config.filename);

    let mut f = File::open(config.filename).expect("file not found");

    // ...snip...
}

struct Config {
    query: String,
    filename: String,
}

fn parse_config(args: &[String]) -> Config {
    let query = args[1].clone();
    let filename = args[2].clone();

    Config { query, filename }
}
```

Listing 12-6: Refactoring `parse_config` to return an instance of a `Config` struct

The signature of `parse_config` now indicates that it returns a `Config` value. In the body of `parse_config`, where we used to return string slices that reference `String` values in `args`, we've now chosen to define `Config` to contain owned `String` values. The `args` variable in `main` is the owner of the argument values and is only letting the `parse_config` function borrow them, though, which means we'd violate Rust's borrowing rules if `Config` tried to take ownership of the values in `args`.

There are a number of different ways we could manage the `String` data, and the easiest, though somewhat inefficient, route is to call the `clone` method on the values. This will make a full copy of the data for the `Config` instance to own, which does take more time and memory than storing a reference to the string data. However, cloning the data also makes our code very straightforward since we don't have to manage the lifetimes of the references, so in this circumstance giving up a little performance to gain simplicity is a worthwhile trade-off.

> ### The Tradeoffs of Using `clone`
>
> There's a tendency among many Rustaceans to avoid using `clone` to fix ownership problems because of its runtime cost. In Chapter 13 on iterators, you'll learn how to use more efficient methods in this kind of situation, but for now, it's okay to copy a few strings to keep making progress since we'll only make these copies once, and our filename and query string are both very small. It's better to have a working program that's a bit inefficient than try to hyper-optimize code on your first pass. As you get more experienced with Rust, it'll be easier to go straight to the desirable method, but for now it's perfectly acceptable to call `clone`.

We've updated `main` so that it places the instance of `Config` returned by `parse_config` into a variable named `config`, and updated the code that previously used the separate `query` and `filename` variables so that it now uses the fields on the `Config` struct instead.

Our code now more clearly conveys that `query` and `filename` are related and their purpose is to configure how the program will work. Any code that uses these values knows to find them in the `config` instance in the fields named for their purpose.

Creating a Constructor for `Config`

So far, we've extracted the logic responsible for parsing the command line arguments from `main` into the `parse_config` function, which helped us to see that the `query` and `filename` values were related and that relationship should be conveyed in our code. We then added a `Config` struct to name the related purpose of `query` and `filename`, and to be able to return the values' names as struct field names from the `parse_config` function.

So now that the purpose of the `parse_config` function is to create a `Config` instance, we can change `parse_config` from being a plain function into a function named `new` that is associated with the `Config` struct. Making this change will make our code more idiomatic: we can create instances of types in the standard library like `String` by calling `String::new`, and by changing `parse_config` into a `new` function associated with `Config`, we'll be able to create instances of `Config` by calling `Config::new`. Listing 12-7 shows the changes we'll need to make:

Filename: src/main.rs

```
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::new(&args);

    // ...snip...
}

// ...snip...

impl Config {
    fn new(args: &[String]) -> Config {
        let query = args[1].clone();
        let filename = args[2].clone();

        Config { query, filename }
    }
}
```

Listing 12-7: Changing `parse_config` into `Config::new`

We've updated `main` where we were calling `parse_config` to instead call `Config::new`. We've changed the name of `parse_config` to `new` and moved it within an `impl` block, which makes the `new` function associated with `Config`. Try compiling this again to make sure it works.

Fixing the Error Handling

Now we'll work on fixing our error handling. Recall that we mentioned that attempting to access the values in the `args` vector at index `1` or index `2` will cause the program to panic if the vector contains fewer than 3 items. Try running the program without any arguments; it will look like this:

```
$ cargo run
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep`
thread 'main' panicked at 'index out of bounds: the len is 1
but the index is 1', /stable-dist-rustc/build/src/libcollections/vec.rs:1307
note: Run with `RUST_BACKTRACE=1` for a backtrace.
```

The line that states `index out of bounds: the len is 1 but the index is 1` is an error message intended for programmers, and won't really help our end users understand what happened and what they should do instead. Let's fix that now.

Improving the Error Message

In Listing 12-8, we're adding a check in the `new` function that will check that the slice is long enough before accessing index `1` and `2`. If the slice isn't long enough, the program panics, with a better error message than the `index out of bounds` message:

Filename: src/main.rs

```
// ...snip...
fn new(args: &[String]) -> Config {
    if args.len() < 3 {
        panic!("not enough arguments");
    }
    // ...snip...
```

Listing 12-8: Adding a check for the number of arguments

This is similar to the `Guess::new` function we wrote in Listing 9-8, where `panic!` was called when the `value` argument was out of the range of valid values. Instead of checking for a range of values here, we're checking that the length of `args` is at least 3, and the rest of the function can operate under the assumption that this condition has been met. If `args` has fewer than 3 items, this condition will be true, and we call the `panic!` macro to end the program immediately.

With these extra few lines of code in `new`, let's try running our program without any arguments again and see what the error looks like now:

```
$ cargo run
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep`
thread 'main' panicked at 'not enough arguments', src/main.rs:29
note: Run with `RUST_BACKTRACE=1` for a backtrace.
```

This output is better, we now have a reasonable error message. However, we also have a bunch of extra information we don't want to give to our users. So perhaps using the technique we used in Listing 9-8 isn't the best to use here; a call to `panic!` is more appropriate for a programming problem rather than a usage problem, as we discussed in Chapter 9. Instead, we can use the other technique you also learned about in Chapter 9: returning a `Result` that can indicate either success or an error.

Returning a `Result` from `new` Instead of Calling `panic!`

We can choose to instead return a `Result` value that will contain a `Config` instance in the successful case, and will describe the problem in the error case. When `Config::new` is communicating to `main`, we can use the `Result` type to signal that there was a problem. Then we can change `main` to convert an `Err` variant into a more practical error for our users, without the surrounding text about `thread 'main'` and `RUST_BACKTRACE` that a call to `panic!` causes.

Listing 12-9 shows the changes you need to make to the return value of `Config::new` and the body of the function needed to return a `Result`:

Filename: src/main.rs

```
impl Config {
    fn new(args: &[String]) -> Result<Config, &'static str> {
        if args.len() < 3 {
            return Err("not enough arguments");
        }

        let query = args[1].clone();
        let filename = args[2].clone();

        Ok(Config { query, filename })
    }
}
```

Listing 12-9: Return a `Result` from `Config::new`

Our `new` function now returns a `Result`, with a `Config` instance in the success case and a `&'static str` in the error case. Recall from "The Static Lifetime" section in Chapter 10 that `&'static str` is the type of string literals, which is our error message type for now.

We've made two changes in the body of the `new` function: instead of calling `panic!` when the user doesn't pass enough arguments, we now return an `Err` value, and we've wrapped the `Config` return value in an `Ok`. These changes make the function conform to its new type signature.

Returning an `Err` value from `Config::new` allows the `main` function to handle the `Result` value returned from the `new` function and exit the process more cleanly in the error case.

Calling `Config::new` and Handling Errors

In order to handle the error case and print a user-friendly message, we need to update `main` to handle the `Result` being returned by `Config::new`, as shown in Listing 12-10. We're also going to take the responsibility of exiting the command line tool with a nonzero error code from `panic!` and implement it by hand. A nonzero exit status is a convention to signal to the process that called our program that our program exited with an error state.

Filename: src/main.rs

```
use std::process;

fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::new(&args).unwrap_or_else(|err| {
        println!("Problem parsing arguments: {}", err);
        process::exit(1);
    });

    // ...snip...
```

Listing 12-10: Exiting with an error code if creating a new `Config` fails

In this listing, we're using a method we haven't covered before: `unwrap_or_else`, which is defined on `Result<T, E>` by the standard library. Using `unwrap_or_else` allows us to define some custom, non-`panic!` error handling. If the `Result` is an `Ok` value, this method's behavior is similar to `unwrap`: it returns the inner value `Ok` is wrapping. However, if the value is an `Err` value, this method calls the code in the *closure*, which is an anonymous function we define and pass as an argument to `unwrap_or_else`. We'll be covering closures in more detail in Chapter 13. What you need to know for now is that `unwrap_or_else` will pass the inner value of the `Err`, which in this case is the static string `not enough arguments` that we added in Listing 12-9, to our closure in the argument `err` that appears between the vertical pipes. The code in the closure can then use the `err` value when it runs.

We've added a new `use` line to import `process` from the standard library. The code in the closure that will get run in the error case is only two lines: we print out the `err` value, then call `process::exit`. The `process::exit` function will stop the program immediately and return the number that was passed as the exit status code. This is similar to the `panic!`-based handling we used in Listing 12-8, but we no longer get all the extra output. Let's try it:

```
$ cargo run
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished dev [unoptimized + debuginfo] target(s) in 0.48 secs
     Running `target/debug/minigrep`
Problem parsing arguments: not enough arguments
```

Great! This output is much friendlier for our users.

Extracting Logic from `main`

Now we're done refactoring our configuration parsing; let's turn to our program's logic. As we laid out in the "Separation of Concerns for Binary Projects" section, we're going to extract a function named `run` that will hold all of the logic currently in the `main` function not involved with setting up configuration or handling errors. Once we're done, `main` will be concise and easy to verify by inspection, and we'll be able to write tests for all of the other logic.

Listing 12-11 shows the extracted `run` function. For now, we're making only the small, incremental improvement of extracting the function. We're still defining the function in *src/main.rs*:

Filename: src/main.rs

```
fn main() {
    // ...snip...

    println!("Searching for {}", config.query);
    println!("In file {}", config.filename);

    run(config);
}

fn run(config: Config) {
    let mut f = File::open(config.filename).expect("file not found");

    let mut contents = String::new();
    f.read_to_string(&mut contents)
        .expect("something went wrong reading the file");

    println!("With text:\n{}", contents);
}

// ...snip...
```

Listing 12-11: Extracting a `run` function containing the rest of the program logic

The `run` function now contains all the remaining logic from `main` starting from reading the file. The `run` function takes the `Config` instance as an argument.

Returning Errors from the `run` Function

With the remaining program logic separated into the `run` function, we can improve the error handling like we did with `Config::new` in Listing 12-9. Instead of allowing the program to panic by calling `expect`, the `run` function will return a `Result<T, E>` when something goes wrong. This will let us further consolidate into `main` the logic around handling errors in a user-friendly way. Listing 12-12 shows the changes you need to make to the signature and body of `run`:

Filename: src/main.rs

```
use std::error::Error;

// ...snip...

fn run(config: Config) -> Result<(), Box<Error>> {
    let mut f = File::open(config.filename)?;

    let mut contents = String::new();
    f.read_to_string(&mut contents)?;

    println!("With text:\n{}", contents);

    Ok(())
}
```

Listing 12-12: Changing the `run` function to return `Result`

We've made three big changes here. First, we're changing the return type of the `run` function to `Result<(), Box<Error>>`. This function previously returned the unit type, `()`, and we keep that as the value returned in the `Ok` case.

For our error type, we're using the *trait object* `Box<Error>` (and we've brought `std::error::Error` into scope with a `use` statement at the top). We'll be covering trait objects in Chapter 17. For now, just know that `Box<Error>` means the function will return a type that implements the `Error` trait, but we don't have to specify what particular type the return value will be. This gives us flexibility to return error values that may be of different types in different error cases.

The second change we're making is removing the calls to `expect` in favor of `?`, like we talked about in Chapter 9. Rather than `panic!` on an error, this will return the error value from the current function for the caller to handle.

Thirdly, this function now returns an `Ok` value in the success case. We've declared the `run` function's success type as `()` in the signature, which means we need to wrap the unit type value in the `Ok` value. This `Ok(())` syntax may look a bit strange at first, but using `()` like this is the idiomatic way to indicate that we're calling `run` for its side effects only; it doesn't return a value we need.

When you run this, it will compile, but with a warning:

```
warning: unused result which must be used, #[warn(unused_must_use)] on by
default
  --> src/main.rs:39:5
   |
39 |     run(config);
   |     ^^^^^^^^^^^^
```

Rust is telling us that our code ignores the `Result` value, which might be indicating that there was an error. We're not checking to see if there was an error or not, though, and the compiler is reminding us that we probably meant to have some error handling code here! Let's rectify that now.

Handling Errors Returned from `run` in `main`

We'll check for errors and handle them using a technique similar to the way we handled errors with `Config::new` in Listing 12-10, but with a slight difference:

Filename: src/main.rs

```
fn main() {
    // ...snip...

    println!("Searching for {}", config.query);
    println!("In file {}", config.filename);

    if let Err(e) = run(config) {
        println!("Application error: {}", e);

        process::exit(1);
    }
}
```

We use `if let` to check whether `run` returns an `Err` value, rather than `unwrap_or_else`, and call `process::exit(1)` if it does. `run` doesn't return a value that we want to `unwrap` like `Config::new` returns the `Config` instance. Because `run` returns a `()` in the success case, we only care about detecting an error, so we don't need `unwrap_or_else` to return the unwrapped value as it would only be `()`.

The bodies of the `if let` and the `unwrap_or_else` functions are the same in both cases though: we print out the error and exit.

Splitting Code into a Library Crate

This is looking pretty good so far! Now we're going to split the *src/main.rs* file up and put some code into *src/lib.rs* so that we can test it and have a *src/main.rs* file with fewer responsibilities.

Let's move everything that isn't the `main` function from *src/main.rs* to a new file, *src/lib.rs*:

- The `run` function definition
- The relevant `use` statements
- The definition of `Config`
- The `Config::new` function definition

The contents of *src/lib.rs* should have the signatures shown in Listing 12-13 (we've omitted the bodies of the functions for brevity):

Filename: src/lib.rs

```
use std::error::Error;
use std::fs::File;
use std::io::prelude::*;

pub struct Config {
    pub query: String,
    pub filename: String,
}

impl Config {
    pub fn new(args: &[String]) -> Result<Config, &'static str> {
        // ...snip...
    }
}

pub fn run(config: Config) -> Result<(), Box<Error>> {
    // ...snip...
}
```

Listing 12-13: Moving `Config` and `run` into *src/lib.rs*

We've made liberal use of `pub` here: on `Config`, its fields and its `new` method, and on the `run` function. We now have a library crate that has a public API that we can test!

Now we need to bring the code we moved to *src/lib.rs* into the scope of the binary crate in *src/main.rs* by using `extern crate minigrep`. Then we'll add a `use minigrep::Config` line to bring the `Config` type into scope, and prefix the `run` function with our crate name as shown in Listing 12-14:

Filename: src/main.rs

```
extern crate minigrep;

use std::env;
use std::process;

use minigrep::Config;

fn main() {
    // ...snip...
    if let Err(e) = minigrep::run(config) {
        // ...snip...
    }
}
```

Listing 12-14: Bringing the `minigrep` crate into the scope of *src/main.rs*

To bring the library crate into the binary crate, we use `extern crate minigrep`. Then we'll add a `use minigrep::Config` line to bring the `Config` type into scope, and we'll prefix the `run` function with our crate name. With that, all the functionality should be connected and should work. Give it a `cargo run` and make sure everything is wired up correctly.

Whew! That was a lot of work, but we've set ourselves up for success in the future. Now it's much easier to handle errors, and we've made our code more modular. Almost all of our work will be done in *src/lib.rs* from here on out.

Let's take advantage of this newfound modularity by doing something that would have been hard with our old code, but is easy with our new code: write some tests!

Developing the Library's Functionality with Test Driven Development

Now that we've extracted the logic into *src/lib.rs* and left the argument collecting and error handling in *src/main.rs*, it's much easier for us to write tests for the core functionality of our code. We can call our functions directly with various arguments and check return values without having to call our binary from the command line. Feel free to write some tests for the functionality in the `Config::new` and `run` functions on your own if you'd like.

In this section, we're going to move on to adding the searching logic of `minigrep` by following the Test Driven Development (TDD) process. This is a software development technique that follows this set of steps:

- Write a test that fails, and run it to make sure it fails for the reason you expected.
- Write or modify just enough code to make the new test pass.
- Refactor the code you just added or changed, and make sure the tests continue to pass.
- Repeat!

This is just one of many ways to write software, but TDD can help drive the design of code. Writing the test before you write the code that makes the test pass helps to maintain high test coverage throughout the process.

We're going to test drive the implementation of the functionality that will actually do the searching for the query string in the file contents and produce a list of lines that match the query. We're going to add this functionality in a function called `search`.

Writing a Failing Test

First, since we don't really need them any more, let's remove the `println!` statements from both *src/lib.rs* and *src/main.rs*. Then we'll add a `test` module with a test function like we did in Chapter 11. The test function specifies the behavior we'd like the `search` function to have: it will take a query and the text to search for the query in, and will return only the lines from the text that contain the query. Listing 12-15 shows this test:

Filename: src/lib.rs

```
#[cfg(test)]
mod test {
    use super::*;

    #[test]
    fn one_result() {
        let query = "duct";
        let contents = "\
Rust:
safe, fast, productive.
Pick three.";

        assert_eq!(
            vec!["safe, fast, productive."],
            search(query, contents)
        );
    }
}
```

Listing 12-15: Creating a failing test for the `search` function we wish we had

The string we are searching for is "duct" in this test. The text we're searching is three lines, only one of which contains "duct". We assert that the value returned from the `search` function contains only the line we expect.

We aren't able to run this test and watch it fail though, since this test doesn't even compile–the search function doesn't exist yet! So now we'll add just enough code to get the tests to compile and run: a definition of the `search` function that always returns an empty vector, as shown in Listing 12-16. Once we have this, the test should compile and fail because an empty vector doesn't match a vector containing the line `"safe, fast, productive."`.

Filename: src/lib.rs

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a str> {
    vec![]
}
```

Listing 12-16: Defining just enough of the `search` function so that our test will compile

Notice that we need an explicit lifetime `'a` defined in the signature of `search` and used with the `contents` argument and the return value. Remember from Chapter 10 that the lifetime parameters specify which argument lifetime is connected to the lifetime of the return value. In this case, we're indicating that the returned vector should contain string slices that reference slices of the argument `contents` (rather than the argument `query`).

In other words, we're telling Rust that the data returned by the `search` function will live as long as the data passed into the `search` function in the `contents` argument. This is important! The data referenced *by* a slice needs to be valid in order for the reference to be valid; if the compiler assumed we were making string slices of `query` rather than `contents`, it would do its safety checking incorrectly.

If we tried to compile this function without lifetimes, we would get this error:

```
error[E0106]: missing lifetime specifier
 --> src/lib.rs:5:47
  |
5 | fn search(query: &str, contents: &str) -> Vec<&str> {
  |                                               ^ expected lifetime parameter
  |
  = help: this function's return type contains a borrowed value, but the
  signature does not say whether it is borrowed from `query` or `contents`
```

Rust can't possibly know which of the two arguments we need, so we need to tell it. Because `contents` is the argument that contains all of our text and we want to return the parts of that text that match, we know `contents` is the argument that should be connected to the return value using the lifetime syntax.

Other programming languages don't require you to connect arguments to return values in the signature, so this may still feel strange, but will get easier over time. You may want to compare this example with the Lifetime Syntax section in Chapter 10.

Now let's try running our test:

```
$ cargo test
...warnings...
    Finished dev [unoptimized + debuginfo] target(s) in 0.43 secs
     Running target/debug/deps/minigrep-abcabcabc

running 1 test
test test::one_result ... FAILED

failures:

---- test::one_result stdout ----
    thread 'test::one_result' panicked at 'assertion failed: `(left == right)`
(left: `["safe, fast, productive."]`, right: `[]`)', src/lib.rs:16
note: Run with `RUST_BACKTRACE=1` for a backtrace.


failures:
    test::one_result

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured

error: test failed
```

Great, our test fails, exactly as we expected. Let's get the test to pass!

Writing Code to Pass the Test

Currently, our test is failing because we always return an empty vector. To fix that and implement `search`, our program needs to follow these steps:

- Iterate through each line of the contents.
- Check if the line contains our query string.
- If it does, add it to the list of values we're returning.
- If it doesn't, do nothing.
- Return the list of results that match.

Let's take each step at a time, starting with iterating through lines.

Iterating Through Lines with the `lines` Method

Rust has a helpful method to handle line-by-line iteration of strings, conveniently named `lines`, that works as shown in Listing 12-17:

Filename: src/lib.rs

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a str> {
    for line in contents.lines() {
        // do something with line
    }
}
```

Listing 12-17: Iterating through each line in `contents`

The `lines` method returns an iterator. We'll be talking about iterators in depth in Chapter 13, but we've already seen this way of using an iterator in Listing 3-6, where we used a `for` loop with an iterator to run some code on each item in a collection.

Searching Each Line for the Query

Next, we'll add functionality to check if the current line contains the query string. Luckily, strings have another helpful method named `contains` that does this for us! Add a call to the `contains` method in the `search` function as shown in Listing 12-18:

Filename: src/lib.rs

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a str> {
    for line in contents.lines() {
        if line.contains(query) {
            // do something with line
        }
    }
}
```

Listing 12-18: Adding functionality to see if the line contains the string in `query`

Storing Matching Lines

Finally, we need a way to store the lines that contain our query string. For that, we can make a mutable vector before the `for` loop and call the `push` method to store a `line` in the vector. After the `for` loop, we return the vector, as shown in Listing 12-19:

Filename: src/lib.rs

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a str> {
    let mut results = Vec::new();

    for line in contents.lines() {
        if line.contains(query) {
            results.push(line);
        }
    }

    results
}
```

Listing 12-19: Storing the lines that match so that we can return them

Now the `search` function should be returning only the lines that contain `query`, and our test should pass. Let's run the tests:

```
$ cargo test
running 1 test
test test::one_result ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

Our test passed, great, it works!

Now that our test is passing, we could consider opportunities for refactoring the implementation of the `search` function while keeping the code that passes the tests, in order to maintain the same functionality. The code in the `search` function isn't too bad, but it isn't taking advantage of some useful features of iterators. We'll be coming back to this example in Chapter 13 where we'll explore iterators in detail and see how to improve it.

Using the `search` Function in the `run` Function

Now that we have the `search` function working and tested, we need to actually call `search` from our `run` function. We need to pass the `config.query` value and the `contents` that `run` read from the file to the `search` function. Then `run` will print out each line returned from `search`:

Filename: src/lib.rs

```
pub fn run(config: Config) -> Result<(), Box<Error>> {
    let mut f = File::open(config.filename)?;

    let mut contents = String::new();
    f.read_to_string(&mut contents)?;

    for line in search(&config.query, &contents) {
        println!("{}", line);
    }

    Ok(())
}
```

We're still using a `for` loop to get each line returned from `search` and print it out.

Now our whole program should be working! Let's try it out, first with a word that should return exactly one line from the Emily Dickinson poem, "frog":

```
$ cargo run frog poem.txt
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished dev [unoptimized + debuginfo] target(s) in 0.38 secs
     Running `target/debug/minigrep frog poem.txt`
How public, like a frog
```

Cool! Next, how about a word that will match multiple lines, like "the":

```
$ cargo run the poem.txt
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep the poem.txt`
Then there's a pair of us — don't tell!
To tell your name the livelong day
```

And finally, let's make sure that we don't get any lines when we search for a word that isn't anywhere in the poem, like "monomorphization":

```
$ cargo run monomorphization poem.txt
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep monomorphization poem.txt`
```

Excellent! We've built our own mini version of a classic tool, and learned a lot about how to structure applications. We've also learned a bit about file input and output, lifetimes, testing, and command line parsing.

To round out this project chapter, we're going to briefly demonstrate how to work with environment variables and how to print to standard error, both of which are useful when writing command line programs. Feel free to move on to Chapter 13 if you'd like at this point.

Working with Environment Variables

We're going to improve our tool with an extra feature: an option for case insensitive searching that the user can turn on via an environment variable. We could make this a command line option and require that users enter it each time they want it to apply, but instead we're going to use an environment variable. This allows our users to set the environment variable once and have all their searches be case insensitive in that terminal session.

Writing a Failing Test for the Case-Insensitive `search` Function

We want to add a new `search_case_insensitive` function that we will call when the environment variable is on.

We're going to continue following the TDD process, so the first step is again to write a failing test. We'll add a new test for the new case-insensitive search function, and rename our old test from `one_result` to `case_sensitive` to be clearer about the differences between the two tests, as shown in Listing 12-20:

Filename: src/lib.rs

```
#[cfg(test)]
mod test {
    use super::*;

    #[test]
    fn case_sensitive() {
        let query = "duct";
        let contents = "\
Rust:
safe, fast, productive.
Pick three.
Duct tape.";

        assert_eq!(
            vec!["safe, fast, productive."],
            search(query, contents)
        );
    }

    #[test]
    fn case_insensitive() {
        let query = "rUsT";
        let contents = "\
Rust:
safe, fast, productive.
Pick three.
Trust me.";

        assert_eq!(
            vec!["Rust:", "Trust me."],
            search_case_insensitive(query, contents)
        );
    }
}
```

Listing 12-20: Adding a new failing test for the case insensitive function we're about to add

Note that we've edited the old test's `contents` too. We've added a new line with the text "Duct tape", with a capital D, that shouldn't match the query "duct" when we're searching in a case sensitive manner. Changing the old test in this way helps ensure that we don't accidentally break the case sensitive search functionality that we've already implemented; this test should pass now and should continue to pass as we work on the case insensitive search.

The new test for the case *insensitive* search uses "rUsT" as its query. In the `search_case_insensitive` function we're going to add, the query "rUsT" should match both the line containing "Rust:" with a capital R and also the line "Trust me." even though both of those have different casing than the query. This is our failing test, and it will fail to compile because we haven't yet defined the `search_case_insensitive` function. Feel free to add a skeleton implementation that always returns an empty vector in the same way that we did for the `search` function in Listing 12-16 in order to see the test compile and fail.

Implementing the `search_case_insensitive` Function

The `search_case_insensitive` function, shown in Listing 12-21, will be almost the same as the `search` function. The only difference is that we'll lowercase the `query` and each `line` so that whatever the case of the input arguments, they will be the same case when we check whether the line contains the query.

Filename: src/lib.rs

```
fn search_case_insensitive<'a>(query: &str, contents: &'a str) -> Vec<&'a str> {
    let query = query.to_lowercase();
    let mut results = Vec::new();

    for line in contents.lines() {
        if line.to_lowercase().contains(&query) {
            results.push(line);
        }
    }

    results
}
```

Listing 12-21: Defining the `search_case_insensitive` function to lowercase both the query and the line before comparing them

First, we lowercase the `query` string, and store it in a shadowed variable with the same name. Calling `to_lowercase` on the query is necessary so that no matter if the user's query is "rust", "RUST", "Rust", or "rUsT", we'll treat the query as if it was "rust" and be insensitive to the case.

Note that `query` is now a `String` rather than a string slice, because calling `to_lowercase` creates new data rather than referencing existing data. Say the query is "rUsT", as an example: that string slice does not contain a lowercase "u" or "t" for us to use, so we have to allocate a new `String` containing "rust". When we pass `query` as an argument to the `contains` method now, we need to add an ampersand because the signature of `contains` is defined to take a string slice.

Next, we add a call to `to_lowercase` on each `line` before we check if it contains `query` to lowercase all characters. Now that we've converted both `line` and `query` to lowercase, we'll find matches no matter what the case of the query.

Let's see if this implementation passes the tests:

```
running 2 tests
test test::case_insensitive ... ok
test test::case_sensitive ... ok

test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured
```

Great! Now, let's actually call the new `search_case_insensitive` function from the `run` function. First, we're going to add a configuration option for switching between case sensitive and case insensitive search to the `Config` struct:

Filename: src/lib.rs

```rust
pub struct Config {
    pub query: String,
    pub filename: String,
    pub case_sensitive: bool,
}
```

We add the `case_sensitive` field that holds a boolean. Then we need our `run` function to check the `case_sensitive` field's value and use that to decide whether to call the `search` function or the `search_case_insensitive` function as shown in Listing 12-22:

Filename: src/lib.rs

```rust
pub fn run(config: Config) -> Result<(), Box<Error>>{
    let mut f = File::open(config.filename)?;

    let mut contents = String::new();
    f.read_to_string(&mut contents)?;

    let results = if config.case_sensitive {
        search(&config.query, &contents)
    } else {
        search_case_insensitive(&config.query, &contents)
    };

    for line in results {
        println!("{}", line);
    }

    Ok(())
}
```

Listing 12-22: Calling either `search` or `search_case_insensitive` based on the value in `config.case_sensitive`

Finally, we need to actually check for the environment variable. The functions for working with environment variables are in the `env` module in the standard library, so we want to bring that module into scope with a `use std::env;` line at the top of *src/lib.rs*. Then we're going to use the `var` method from the `env` module to check for an environment variable named `CASE_INSENSITIVE`, as shown in Listing 12-23:

Filename: src/lib.rs

```
use std::env;

// ...snip...

impl Config {
    pub fn new(args: &[String]) -> Result<Config, &'static str> {
        if args.len() < 3 {
            return Err("not enough arguments");
        }

        let query = args[1].clone();
        let filename = args[2].clone();

        let case_sensitive = env::var("CASE_INSENSITIVE").is_err();

        Ok(Config { query, filename, case_sensitive })
    }
}
```

Listing 12-23: Checking for an environment variable named `CASE_INSENSITIVE`

Here, we create a new variable `case_sensitive`. In order to set its value, we call the `env::var` function and pass it the name of the `CASE_INSENSITIVE` environment variable. The `env::var` method returns a `Result` that will be the successful `Ok` variant that contains the value of the environment variable if the environment variable is set. It will return the `Err` variant if the environment variable is not set.

We're using the `is_err` method on the `Result` to check to see if it's an error, and therefore unset, which means it *should* do a case sensitive search. If the `CASE_INSENSITIVE` environment variable is set to anything, `is_err` will return false and it will perform a case insensitive search. We don't care about the *value* of the environment variable, just whether it's set or unset, so we're checking `is_err` rather than `unwrap`, `expect`, or any of the other methods we've seen on `Result`.

We pass the value in the `case_sensitive` variable to the `Config` instance so that the `run` function can read that value and decide whether to call `search` or `search_case_insensitive` as we implemented in Listing 12-22.

Let's give it a try! First, we'll run our program without the environment variable set and with the query "to", which should match any line that contains the word "to" in all lowercase:

```
$ cargo run to poem.txt
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep to poem.txt`
Are you nobody, too?
How dreary to be somebody!
```

Looks like that still works! Now, let's run the program with `CASE_INSENSITIVE` set to 1 but with the same query "to", and we should get lines that contain "to" that might have uppercase letters:

```
$ CASE_INSENSITIVE=1 cargo run to poem.txt
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/minigrep to poem.txt`
Are you nobody, too?
How dreary to be somebody!
To tell your name the livelong day
To an admiring bog!
```

Excellent, we also got lines containing "To"! Our `minigrep` program can now do case insensitive searching, controlled by an environment variable. Now you know how to manage options set using either command line arguments or environment variables!

Some programs allow both arguments *and* environment variables for the same configuration. In those cases, the programs decide that one or the other takes precedence. For another exercise on your own, try controlling case insensitivity through either a command line argument or an environment variable. Decide whether the command line argument or the environment variable should take precedence if the program is run with one set to case sensitive and one set to case insensitive.

The `std::env` module contains many more useful features for dealing with environment variables; check out its documentation to see what's available.

Writing Error Messages to Standard Error Instead of Standard Output

At the moment we're writing all of our output to the terminal with the `println!` function. Most terminals provide two kinds of output: *standard output* for general information (sometimes abbreviated as `stdout` in code), and *standard error* for error messages (`stderr`). This distinction enables users to choose to direct the successful output of a program to a file but still print error messages to the screen.

The `println!` function is only capable of printing to standard output, though, so we have to use something else in order to print to standard error.

Checking Where Errors are Written to

First, let's observe how all content printed by `minigrep` is currently being written to standard output, including error messages that we want to write to standard error instead. We'll do that by redirecting the standard output stream to a file while we also intentionally cause an error. We won't redirect the standard error stream, so any content sent to standard error will continue to display on the screen. Command line programs are expected to send error messages to the standard error stream so that we can still see error messages on the screen even if we choose to redirect the standard output stream to a file. Our program is not currently well-behaved; we're about to see that it saves the error message output to the file instead!

The way to demonstrate this behavior is by running the program with `>` and the filename, *output.txt*, that we want to redirect the standard output stream to. We're not going to pass any arguments, which should cause an error:

```
$ cargo run > output.txt
```

The `>` syntax tells the shell to write the contents of standard output to *output.txt* instead of the screen. We didn't see the error message we were expecting printed on the screen, so that means it must have ended up in the file. Let's see what *output.txt* contains:

```
Problem parsing arguments: not enough arguments
```

Yup, our error message is being printed to standard output. It's much more useful for error messages like this to be printed to standard error, and have only data from a successful run end up in the file when we redirect standard output in this way. We'll change that.

Printing Errors to Standard Error

Let's change how error messages are printed using the code in Listing 12-24. Because of the refactoring we did earlier in this chapter, all the code that prints error messages is in one function, in `main`. The standard library provides the `eprintln!` macro that prints to the standard error stream, so let's change the two places we were calling `println!` to print errors so that these spots use `eprintln!` instead:

Filename: src/main.rs

```
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::new(&args).unwrap_or_else(|err| {
        eprintln!("Problem parsing arguments: {}", err);
        process::exit(1);
    });

    if let Err(e) = minigrep::run(config) {
        eprintln!("Application error: {}", e);

        process::exit(1);
    }
}
```

Listing 12-24: Writing error messages to standard error instead of standard output using `eprintln!`

After changing `println!` to `eprintln!`, let's try running the program again in the same way, without any arguments and redirecting standard output with `>`:

```
$ cargo run > output.txt
Problem parsing arguments: not enough arguments
```

Now we see our error on the screen and `output.txt` contains nothing, which is the behavior expected of command line programs.

If we run the program again with arguments that don't cause an error, but still redirect standard output to a file:

```
$ cargo run to poem.txt > output.txt
```

We won't see any output to our terminal, and `output.txt` will contain our results:

Filename: output.txt

```
Are you nobody, too?
How dreary to be somebody!
```

This demonstrates that we're now using standard output for successful output and standard error for error output as appropriate.

Summary

In this chapter, we've recapped on some of the major concepts so far and covered how to do common I/O operations in a Rust context. By using command line arguments, files, environment variables, and the `eprintln!` macro for printing errors, you're now prepared to write command line applications. By using the concepts from previous chapters, your code will be well-organized, be able to store data effectively in the appropriate data structures, handle errors nicely, and be well tested.

Next, let's explore some functional-language influenced Rust features: closures and iterators.

Functional Language features in Rust: Iterators and Closures

Rust's design has taken inspiration from a lot of existing languages and techniques, and one significant influence is *functional programming*. Programming in a functional style often includes using functions as values, by passing them in arguments, returning them from other functions, assigning them to variables for later execution, and so forth. We won't debate here the issue of what, exactly, functional programming is or is not, but will instead show off some features of Rust that are similar to features in many languages often referred to as functional.

More specifically, we're going to cover:

- *Closures*: a function-like construct you can store in a variable.
- *Iterators*: a way of processing a series of elements.
- How to use these features to improve on the I/O project from Chapter 12.
- The performance of these features. Spoiler alert: they're faster than you might think!

There are other Rust features influenced by the functional style, like pattern matching and enums, that we've covered in other chapters as well. Mastering closures and iterators is an important part of writing idiomatic, fast Rust code, so we're devoting an entire chapter to them here.

Closures: Anonymous Functions that can Capture their Environment

Rust's *closures* are anonymous functions you can save in a variable or pass as arguments to other functions. You can create the closure in one place, and then call the closure to evaluate it in a different context. Unlike functions, closures are able to capture values from the scope in which they are called. We're going to demonstrate how these features of closures allow for code reuse and customization of behavior.

Creating an Abstraction of Behavior Using a Closure

Let's work on an example of a situation in which it's useful to store a closure to be executed at a later time. We'll talk about the syntax of closures, type inference, and traits along the way.

The hypothetical situation is this: we work at a startup that's making an app to generate custom exercise workout plans. The backend is written in Rust, and the algorithm that generates the workout plan takes into account many different factors, like the app user's age, Body Mass Index, preferences, recent workouts, and an intensity number they specify. The actual algorithm used isn't important in this example; what's important is that this calculation takes a few seconds. We only want to call this algorithm when we need to, and only call it once, so we aren't making the user wait more than necessary.

We'll simulate calling this hypothetical algorithm with the `simulated_expensive_calculation` function shown in Listing 13-1, which will print `calculating slowly...`, wait for two seconds, and then return whatever number we passed in:

Filename: src/main.rs

```
use std::thread;
use std::time::Duration;

fn simulated_expensive_calculation(intensity: u32) -> u32 {
    println!("calculating slowly...");
    thread::sleep(Duration::from_secs(2));
    intensity
}
```

Listing 13-1: A function to stand in for a hypothetical calculation that takes about two seconds to run

Next, we have a `main` function that contains the parts of the workout app important for this example. This represents the code that the app would call when a user asks for a workout plan. Because the interaction with the app's frontend isn't relevant to the use of closures, we're going to hardcode values representing inputs to our program and print the outputs.

The required inputs are:

- **An intensity number from the user**, specified when they request a workout to indicate whether they'd like a low intensity workout or a high intensity workout
- **A random number** that will generate some variety in the workout plans

The output will be the recommended workout plan.

Listing 13-2 shows the `main` function we're going to use.

Filename: src/main.rs

```
fn main() {
    let simulated_user_specified_value = 10;
    let simulated_random_number = 7;

    generate_workout(
        simulated_user_specified_value,
        simulated_random_number
    );
}
```

Listing 13-2: A `main` function with hardcoded values to simulate user input and random number generation

We've hardcoded the variable `simulated_user_specified_value` to 10 and the variable `simulated_random_number` to 7 for simplicity's sake; in an actual program we'd get the intensity number from the app frontend and we'd use the `rand` crate to generate a random number like we did in the Guessing Game example in Chapter 2. The `main` function calls a `generate_workout` function with the simulated input values.

There's the context, so let's get to the algorithm. The `generate_workout` function in Listing 13-3 contains the business logic of the app that we're most concerned with in this example. The rest of the code changes in this example will be made to this function:

Filename: src/main.rs

```
fn generate_workout(intensity: u32, random_number: u32) {
    if intensity < 25 {
        println!(
            "Today, do {} pushups!",
            simulated_expensive_calculation(intensity)
        );
        println!(
            "Next, do {} situps!",
            simulated_expensive_calculation(intensity)
        );
    } else {
        if random_number == 3 {
            println!("Take a break today! Remember to stay hydrated!");
        } else {
            println!(
                "Today, run for {} minutes!",
                simulated_expensive_calculation(intensity)
            );
        }
    }
}
```

Listing 13-3: The business logic that prints the workout plans based on the inputs and calls to the `simulated_expensive_calculation` function

The code in Listing 13-3 has multiple calls to the slow calculation function. The first `if` block calls `simulated_expensive_calculation` twice, the `if` inside the outer `else` doesn't call it at all, and the code inside the second `else` case calls it once.

The desired behavior of the `generate_workout` function is to first check if the user wants a low intensity workout (indicated by a number less than 25) or a high intensity workout (25 or more).

Low intensity workout plans will recommend a number of pushups and situps based on the complex algorithm we're simulating.

If the user wants a high intensity workout, there's some additional logic: if the value of the random number generated by the app happens to be 3, the app will recommend a break and hydration. If not, the user will get a number of minutes of running based on the complex algorithm.

The data science team has let us know that we'll have to make some changes to the way we call the algorithm in the future. To simplify the update when those changes happen, we want to refactor this code so it only calls the `simulated_expensive_calculation` function once. We also want to cut the place where we're currently calling the function twice unnecessarily without adding any other calls to that function in the process. That is, we don't want to call it if the result isn't needed, and we still want to call it only once.

Refactoring Using Functions

There are many ways we could restructure this program. First we'll try extracting the duplicated call to the expensive calculation function into a variable, as shown in Listing 13-4:

Filename: src/main.rs

```
fn generate_workout(intensity: u32, random_number: u32) {
    let expensive_result =
        simulated_expensive_calculation(intensity);

    if intensity < 25 {
        println!(
            "Today, do {} pushups!",
            expensive_result
        );
        println!(
            "Next, do {} situps!",
            expensive_result
        );
    } else {
        if random_number == 3 {
            println!("Take a break today! Remember to stay hydrated!");
        } else {
            println!(
                "Today, run for {} minutes!",
                expensive_result
            );
        }
    }
}
```

Listing 13-4: Extracting the calls to `simulated_expensive_calculation` to one place and storing the result in the `expensive_result` variable

This change unifies all the calls to `simulated_expensive_calculation` and solves the problem of the first `if` block calling the function twice unnecessarily. Unfortunately, we're now calling this function and waiting for the result in all cases, which includes the inner `if` block that doesn't use the result value at all.

We want to define code in one place in our program, but only *execute* that code where we actually need the result. This is a use case for closures!

Refactoring with Closures to Store Code for Later Execution

Instead of always calling the `simulated_expensive_calculation` function before the `if` blocks, we can define a closure and store the *closure* in a variable rather than storing the result, as shown in Listing 13-5. We can actually move the whole body of `simulated_expensive_calculation` within the closure we're introducing here:

Filename: src/main.rs

```
let expensive_closure = |num| {
    println!("calculating slowly...");
    thread::sleep(Duration::from_secs(2));
    num
};
```

Listing 13-5: Defining a closure and storing it in the `expensive_closure` variable

The closure definition comes after the `=` to assign it to the variable `expensive_closure`. To define a closure, we start with a pair of vertical pipes (`|`), inside which we specify the parameters to the closure; this syntax was chosen because of its similarity to closure definitions in Smalltalk and Ruby. This closure has one parameter named `num`; if we had more than one parameter, we would separate them with commas, like `|param1, param2|`.

After the parameters, we place curly brackets that hold the body of the closure—these are optional if the closure body is a single expression. The end of the closure, after the curly brackets, needs a semicolon to complete the `let` statement. The value returned from the last line in the closure body (`num`) will be the value returned from the closure when it's called, since that line doesn't end in a semicolon; just like in function bodies.

Note that this `let` statement means `expensive_closure` contains the *definition* of an anonymous function, not the *resulting value* of calling the anonymous function. Recall that we're using a closure because we want to define the code to call at one point, store that code, and actually call it at a later point; the code we want to call is now stored in `expensive_closure`.

Now that we have the closure defined, we can change the code in the `if` blocks to call the closure, in order to execute the code and get the resulting value. We call a closure like we do a function: we specify the variable name that holds the closure definition and follow it with parentheses containing the argument values we want to use, as shown in Listing 13-6:

Filename: src/main.rs

```
fn generate_workout(intensity: u32, random_number: u32) {
    let expensive_closure = |num| {
        println!("calculating slowly...");
        thread::sleep(Duration::from_secs(2));
        num
    };

    if intensity < 25 {
        println!(
            "Today, do {} pushups!",
            expensive_closure(intensity)
        );
        println!(
            "Next, do {} situps!",
            expensive_closure(intensity)
        );
    } else {
        if random_number == 3 {
            println!("Take a break today! Remember to stay hydrated!");
        } else {
            println!(
                "Today, run for {} minutes!",
                expensive_closure(intensity)
            );
        }
    }
}
```

Listing 13-6: Calling the `expensive_closure` we've defined

Now the expensive calculation is called in only one place, and we're only executing that code where we need the results.

We have, however, reintroduced one of the problems from Listing 13-3: we're still calling the closure twice in the first `if` block, which will call the expensive code twice and make the user wait twice as long as they need to. We could fix this problem by creating a variable local to that `if` block to hold the result of calling the closure, but closures provide us with another solution. We'll get back to that solution in a bit; let's first talk about why there aren't type annotations in the closure definition and the traits involved with closures.

Closure Type Inference and Annotation

Closures differ from functions defined with the `fn` keyword in a few ways. The first is that closures don't require you to annotate the types of the parameters or the return value like `fn` functions do.

Type annotations are required on functions because they are part of an explicit interface exposed to your users. Defining this interface rigidly is important for ensuring that everyone agrees on what types of values a function uses and returns. Closures aren't used in an exposed interface like this, though: they're stored in variables and used without naming them and exposing them to users of our library.

Additionally, closures are usually short and only relevant within a narrow context rather than in any arbitrary scenario. Within these limited contexts, the compiler is reliably able to infer the types of the parameters and return type, similar to how it's able to infer the types of most variables.

Making programmers annotate the types in these small, anonymous functions would be annoying and largely redundant with the information the compiler already has available.

Like variables, we can choose to add type annotations if we want to increase explicitness and clarity at the cost of being more verbose than is strictly necessary; annotating the types for the closure we defined in Listing 13-4 would look like the definition shown in Listing 13-7:

Filename: src/main.rs

```
let expensive_closure = |num: u32| -> u32 {
    println!("calculating slowly...");
    thread::sleep(Duration::from_secs(2));
    num
};
```

Listing 13-7: Adding optional type annotations of the parameter and return value types in the closure

The syntax of closures and functions looks more similar with type annotations. Here's a vertical comparison of the syntax for the definition of a function that adds one to its parameter, and a closure that has the same behavior. We've added some spaces here to line up the relevant parts). This illustrates how closure syntax is similar to function syntax, except for the use of pipes and the amount of syntax that is optional:

```
fn  add_one_v1   (x: u32) -> u32 { x + 1 }
let add_one_v2 = |x: u32| -> u32 { x + 1 };
let add_one_v3 = |x|             { x + 1 };
let add_one_v4 = |x|               x + 1  ;
```

The first line shows a function definition, and the second line shows a fully annotated closure definition. The third line removes the type annotations from the closure definition, and the fourth line removes the brackets that are optional, since the closure body only has one expression. These are all valid definitions that will produce the same behavior when they're called.

Closure definitions will have one concrete type inferred for each of their parameters and for their return value. For instance, Listing 13-8 shows the definition of a short closure that just returns the value it receives as a parameter.

This closure isn't very useful except for the purposes of this example. Note that we haven't added any type annotations to the definition: if we then try to call the closure twice, using a `String` as an argument the first time and an `u32` the second time, we'll get an error:

Filename: src/main.rs

```
let example_closure = |x| x;

let s = example_closure(String::from("hello"));
let n = example_closure(5);
```

Listing 13-8: Attempting to call a closure whose types are inferred with two different types

The compiler gives us this error:

```
error[E0308]: mismatched types
 --> src/main.rs
  |
  | let n = example_closure(5);
  |                         ^ expected struct `std::string::String`, found
  integral variable
  |
  = note: expected type `std::string::String`
             found type `{integer}`
```

The first time we call `example_closure` with the `String` value, the compiler infers the type of `x` and the return type of the closure to be `String`. Those types are then locked in to the closure in `example_closure`, and we get a type error if we try to use a different type with the same closure.

Storing Closures Using Generic Parameters and the `Fn` Traits

Returning to our workout generation app, in Listing 13-6 we left our code still calling the expensive calculation closure more times than it needs to. One option to solve this issue is to save the result of the expensive closure in a variable for reuse and use the variable instead in each place we need the result instead of calling the closure again. This method, though, could result in a lot of repeated code.

Fortunately, we have another solution available to us. We can create a struct that will hold the closure and the resulting value of calling the closure. The struct will only execute the closure if we need the resulting value, and it will cache the resulting value so that the rest of our code doesn't have to be responsible for saving and reusing the result. You may know this pattern as *memoization* or *lazy evaluation*.

In order to make a struct that holds a closure, we need to be able to specify the type of the closure, because a struct definition needs to know the types of each of its fields. Each closure instance has its own unique anonymous type: that is, even if two closures have the same signature, their types are still considered different. In order to define structs, enums, or function parameters that use closures, we use generics and trait bounds like we discussed in Chapter 10.

The `Fn` traits are provided by the standard library. All closures implement one of the traits `Fn`, `FnMut`, or `FnOnce`. We'll discuss the difference between these traits in the next section on capturing the environment; in this example, we can use the `Fn` trait.

We add types to the `Fn` trait bound to represent the types of the parameters and return values the closures must have in order to match this trait bound. In this case, our closure has a parameter of type `u32` and returns an `u32`, so the trait bound we specify is `Fn(u32) -> u32`.

Listing 13-9 shows the definition of the `Cacher` struct that holds a closure and an optional result value:

Filename: src/main.rs

```
struct Cacher<T>
    where T: Fn(u32) -> u32
{
    calculation: T,
    value: Option<u32>,
}
```

Listing 13-9: Defining a `Cacher` struct that holds a closure in `calculation` and an optional result in `value`

The `Cacher` struct has a `calculation` field of the generic type `T`. The trait bounds on `T` specify that it's a closure by using the `Fn` trait. Any closure we want to store in the `calculation` field must have one `u32` parameter (specified within the parentheses after `Fn`) and must return an `u32` (specified after the `->`).

> Note: Functions implement all three of the `Fn` traits too. If what we want to do doesn't require capturing a value from the environment, we can use a function rather than a closure where we need something that implements an `Fn` trait.

The `value` field is of type `Option<u32>`. Before we execute the closure, `value` will be `None`. When code using a `Cacher` asks for the *result* of the closure, the `Cacher` will execute the closure at that time and store the result within a `Some` variant in the `value` field. Then if the code asks for the result of the closure again, instead of executing the closure again, the `Cacher` will return the result held in the `Some` variant.

The logic around the `value` field we've just described is defined in Listing 13-10:

Filename: src/main.rs

```
impl<T> Cacher<T>
    where T: Fn(u32) -> u32
{
    fn new(calculation: T) -> Cacher<T> {
        Cacher {
            calculation,
            value: None,
        }
    }

    fn value(&mut self, arg: u32) -> u32 {
        match self.value {
            Some(v) => v,
            None => {
                let v = (self.calculation)(arg);
                self.value = Some(v);
                v
            },
        }
    }
}
```

Listing 13-10: The caching logic of `Cacher`

We want `Cacher` to manage the struct fields' values, rather than letting the calling code potentially change the values in these fields directly, so these fields are private.

The `Cacher::new` function takes a generic parameter `T`, which we've defined as having the same trait bound as the `Cacher` struct. Then `Cacher::new` returns a `Cacher` instance that holds the closure specified in the `calculation` field and a `None` value in the `value` field, since we haven't executed the closure yet.

When the calling code wants the result of evaluating the closure, instead of calling the closure directly, it will call the `value` method. This method checks to see if we already have a resulting value in `self.value` in a `Some`; if we do, it returns the value within the `Some` without executing the closure again.

If `self.value` is `None`, we call the closure stored in `self.calculation`, save the result in `self.value` for future use, and return the value as well.

Listing 13-11 shows how we can use this `Cacher` struct in the `generate_workout` function from Listing 13-6:

Filename: src/main.rs

```
fn generate_workout(intensity: u32, random_number: u32) {
    let mut expensive_result = Cacher::new(|num| {
        println!("calculating slowly...");
        thread::sleep(Duration::from_secs(2));
        num
    });

    if intensity < 25 {
        println!(
            "Today, do {} pushups!",
            expensive_result.value(intensity)
        );
        println!(
            "Next, do {} situps!",
            expensive_result.value(intensity)
        );
    } else {
        if random_number == 3 {
            println!("Take a break today! Remember to stay hydrated!");
        } else {
            println!(
                "Today, run for {} minutes!",
                expensive_result.value(intensity)
            );
        }
    }
}
```

Listing 13-11: Using `Cacher` in the `generate_workout` function to abstract away the caching logic

Instead of saving the closure in a variable directly, we save a new instance of `Cacher` that holds the closure. Then, in each place we want the result, we call the `value` method on the `Cacher` instance. We can call the `value` method as many times as we want, or not call it at all, and the expensive calculation will be run a maximum of once.

Try running this program with the `main` function from Listing 13-2. Change the values in the `simulated_user_specified_value` and `simulated_random_number` variables to verify that in all of the cases in the various `if` and `else` blocks, `calculating slowly...` only shows up once and only when needed. The `Cacher` takes care of the logic necessary to ensure we aren't calling the expensive calculation more than we need to, so that `generate_workout` can focus on the business logic.

Limitations of the `Cacher` Implementation

Caching values is a generally useful behavior that we might want to use in other parts of our code with different closures. However, there are a few problems with the current implementation of `Cacher` that would make reusing it in different contexts difficult.

The first problem is a `Cacher` instance assumes it will always get the same value for the parameter `arg` to the `value` method. That is, this test of `Cacher` will fail:

```
#[test]
fn call_with_different_values() {
    let mut c = Cacher::new(|a| a);

    let v1 = c.value(1);
    let v2 = c.value(2);

    assert_eq!(v2, 2);
}
```

This test creates a new `Cacher` instance with a closure that returns the value passed into it. We call the `value` method on this `Cacher` instance with an `arg` value of 1 and then an `arg` value of 2, and we expect that the call to `value` with the `arg` value of 2 should return 2.

Run this with the `Cacher` implementation from Listing 13-9 and Listing 13-10 and the test will fail on the `assert_eq!` with this message:

```
thread 'call_with_different_arg_values' panicked at 'assertion failed:
`(left == right)` (left: `1`, right: `2`)', src/main.rs
```

The problem is that the first time we called `c.value` with 1, the `Cacher` instance saved `Some(1)` in `self.value`. After that, no matter what we pass in to the `value` method, it will always return 1.

Try modifying `Cacher` to hold a hash map rather than a single value. The keys of the hash map will be the `arg` values that are passed in, and the values of the hash map will be the result of calling the closure on that key. Instead of looking at whether `self.value` directly has a `Some` or a `None` value, the `value` function will look up the `arg` in the hash map and return the value, if it's present. If it's not present, the `Cacher` will call the closure and save the resulting value in the hash map associated with its `arg` value.

Another problem with the current `Cacher` implementation is that it only accepts closures that take one parameter of type `u32` and return an `u32`. We might want to cache the results of closures that take a string slice and return `usize` values, for example. To fix this issue, try introducing more generic parameters to increase the flexibility of the `Cacher` functionality.

Closures Can Capture Their Environment

In the workout generator example, we only used closures as inline anonymous functions. Closures have an additional ability that functions don't have, however: they can capture their environment and access variables from the scope in which they're defined.

Listing 13-12 has an example of a closure stored in the variable `equal_to_x` that uses the variable `x` from the closure's surrounding environment:

Filename: src/main.rs

```
fn main() {
    let x = 4;

    let equal_to_x = |z| z == x;

    let y = 4;

    assert!(equal_to_x(y));
}
```

Listing 13-12: Example of a closure that refers to a variable in its enclosing scope

Here, even though `x` is not one of the parameters of `equal_to_x`, the `equal_to_x` closure is allowed to use the `x` variable that's defined in the same scope that `equal_to_x` is defined in.

We can't do the same with functions; let's see what happens if we try:

Filename: src/main.rs

```
fn main() {
    let x = 4;

    fn equal_to_x(z: i32) -> bool { z == x }

    let y = 4;

    assert!(equal_to_x(y));
}
```

We get an error:

```
error[E0434]: can't capture dynamic environment in a fn item; use the || { ... }
closure form instead
 -->
  |
4 |     fn equal_to_x(z: i32) -> bool { z == x }
  |                                          ^
```

The compiler even reminds us that this only works with closures!

When a closure captures a value from its environment, it uses memory to store the values for use in the closure body. This use of memory is overhead that we don't want to pay in more common cases, where we want to execute code that doesn't capture its environment. Because functions are never allowed to capture their environment, defining and using functions will never incur this overhead.

Closures can capture values from their environment in three ways, which directly map to the three ways a function can take a parameter: taking ownership, borrowing immutably, and borrowing mutably. These are encoded in the three `Fn` traits as follows:

- `FnOnce` consumes the variables it captures from its enclosing scope, known as the closure's *environment*. In order to consume the captured variables, the closure must take ownership of these variables and move them into the closure when it is defined. The `Once` part of the name is because the closure can't take ownership of the same variables more than once, so it can only be called one time.
- `Fn` borrows values from the environment immutably.
- `FnMut` can change the environment since it mutably borrows values.

When we create a closure, Rust infers which to use based on how the closure uses the values from the environment. In Listing 13-12, the `equal_to_x` closure borrows `x` immutably (so `equal_to_x` has the `Fn` trait) since the body of the closure only needs to read the value in `x`.

If we want to force the closure to take ownership of the values it uses in the environment, we can use the `move` keyword before the parameter list. This is mostly useful when passing a closure to a new thread in order to move the data so that it's owned by the new thread.

We'll have more examples of `move` closures in Chapter 16 when we talk about concurrency, but for now here's the code from Listing 13-12 with the `move` keyword added to the closure definition and using vectors instead of integers, since integers can be copied rather than moved:

Filename: src/main.rs

```
fn main() {
    let x = vec![1, 2, 3];

    let equal_to_x = move |z| z == x;

    println!("can't use x here: {:?}", x);

    let y = vec![1, 2, 3];

    assert!(equal_to_x(y));
}
```

This example doesn't compile:

```
error[E0382]: use of moved value: `x`
 --> src/main.rs:6:40
  |
4 |     let equal_to_x = move |z| z == x;
  |                      -------- value moved (into closure) here
5 |
6 |     println!("can't use x here: {:?}", x);
  |                                        ^ value used here after move
  |
  = note: move occurs because `x` has type `std::vec::Vec<i32>`, which does not
    implement the `Copy` trait
```

The `x` value is moved into the closure when the closure is defined, because we added the `move` keyword. The closure then has ownership of `x`, and `main` isn't allowed to use `x` anymore in the `println!` statement. Removing `println!` will fix this example.

Most of the time when specifying one of the `Fn` trait bounds, you can start with `Fn` and the compiler will tell you if you need `FnMut` or `FnOnce` based on what happens in the closure body.

To illustrate situations where closures that can capture their environment are useful as function parameters, let's move on to our next topic: iterators.

Processing a Series of Items with Iterators

The iterator pattern allows you to perform some task on a sequence of items in turn. An *iterator* is responsible for the logic of iterating over each item and determining when the sequence has finished. When we use iterators, we don't have to reimplement that logic ourselves.

In Rust, iterators are *lazy*, meaning they have no effect until we call methods that consume the iterator to use it up. For example, the code in Listing 13-13 creates an iterator over the items in the vector `v1` by calling the `iter` method defined on `Vec`. This code by itself doesn't do anything useful:

```rust
let v1 = vec![1, 2, 3];

let v1_iter = v1.iter();
```

Listing 13-13: Creating an iterator

Once we've created an iterator, we can choose to use it in a variety of ways. In Listing 3-6 from Chapter 3, we actually used iterators with `for` loops to execute some code on each item, though we glossed over what the call to `iter` did until now.

The example in Listing 13-14 separates the creation of the iterator from the use of the iterator in the `for` loop. The iterator is stored in the `v1_iter` variable, and no iteration takes place at that time. Once the `for` loop is called using the iterator in `v1_iter`, then each element in the iterator is used in one iteration of the loop, which prints out each value:

```
let v1 = vec![1, 2, 3];

let v1_iter = v1.iter();

for val in v1_iter {
    println!("Got: {}", val);
}
```

Listing 13-14: Making use of an iterator in a `for` loop

In languages that don't have iterators provided by their standard libraries, we would likely write this same functionality by starting a variable at index 0, using that variable to index into the vector to get a value, and incrementing the variable value in a loop until it gets to the total number of items in the vector.

Iterators take care of all of that logic for us, cutting down on repetitive code we could potentially mess up. Iterators give us more flexibility to use the same logic with many different kinds of sequences, not just data structures we can index into like vectors. Let's see how iterators do that.

The `Iterator` trait and the `next` method

Iterators all implement a trait named `Iterator` that is defined in the standard library. The definition of the trait looks like this:

```
trait Iterator {
    type Item;

    fn next(&mut self) -> Option<Self::Item>;

    // methods with default implementations elided
}
```

You'll notice some new syntax that we haven't covered yet: `type Item` and `Self::Item`, which are defining an *associated type* with this trait. We'll talk about associated types in depth in

Chapter 19, but for now, all you need to know is that this code says implementing the `Iterator` trait requires that you also define an `Item` type, and this `Item` type is used in the return type of the `next` method. In other words, the `Item` type will be the type returned from the iterator.

The `Iterator` trait only requires implementors to define one method: the `next` method, which returns one item of the iterator at a time wrapped in `Some` and, when iteration is over, it returns `None`.

We can call the `next` method on iterators directly; Listing 13-15 demonstrates what values are returned from repeated calls to `next` on the iterator created from the vector:

Filename: src/lib.rs

```
#[test]
fn iterator_demonstration() {
    let v1 = vec![1, 2, 3];

    let mut v1_iter = v1.iter();

    assert_eq!(v1_iter.next(), Some(&1));
    assert_eq!(v1_iter.next(), Some(&2));
    assert_eq!(v1_iter.next(), Some(&3));
    assert_eq!(v1_iter.next(), None);
}
```

Listing 13-15: Calling the `next` method on an iterator

Note that we needed to make `v1_iter` mutable: calling the `next` method on an iterator changes state that keeps track of where it is in the sequence. Put another way, this code *consumes*, or uses up, the iterator. Each call to `next` eats up an item from the iterator. We didn't need to make `v1_iter` mutable when we used a `for` loop because the loop took ownership of `v1_iter` and made it mutable behind the scenes.

Also note that the values we get from the calls to `next` are immutable references to the values in the vector. The `iter` method produces an iterator over immutable references. If we want to create an iterator that takes ownership of `v1` and returns owned values, we can call `into_iter` instead of `iter`. Similarly, if we want to iterate over mutable references, we can call `iter_mut` instead of `iter`.

Methods in the `Iterator` Trait that Consume the Iterator

The `Iterator` trait has a number of different methods with default implementations provided for us by the standard library; you can find out all about these methods by looking in the standard library API documentation for the `Iterator` trait. Some of these methods call the `next` method in their definition, which is why we're required to implement the `next` method when implementing the `Iterator` trait.

Methods that call `next` are called *consuming adaptors*, because calling them uses up the iterator. One example is the `sum` method, which takes ownership of the iterator and iterates through the items by repeatedly calling `next`, thus consuming the iterator. As it iterates through, it adds each item to a running total and returns the total when iteration is complete. Listing 13-16 has a test illustrating a use of the `sum` method:

Filename: src/lib.rs

```
#[test]
fn iterator_sum() {
    let v1 = vec![1, 2, 3];

    let v1_iter = v1.iter();

    let total: i32 = v1_iter.sum();

    assert_eq!(total, 6);
}
```

Listing 13-16: Calling the `sum` method to get the total of all items in the iterator

We aren't allowed to use `v1_iter` after the call to `sum` since `sum` takes ownership of the iterator we call it on.

Methods in the `Iterator` Trait that Produce Other Iterators

Other methods defined on the `Iterator` trait, known as *iterator adaptors*, allow us to change iterators into different kind of iterators. We can chain multiple calls to iterator adaptors to perform complex actions in a readable way. Because all iterators are lazy, however, we have to call one of the consuming adaptor methods in order to get results from calls to iterator adaptors.

Listing 13-17 shows an example of calling the iterator adaptor method `map` which takes a closure to call on each item in order to produce a new iterator. The closure here creates a new iterator in which each item from the vector has been incremented by 1. This code produces a warning, though:

Filename: src/main.rs

```
let v1: Vec<i32> = vec![1, 2, 3];

v1.iter().map(|x| x + 1);
```

Listing 13-17: Calling the iterator adapter `map` to create a new iterator

The warning we get is:

```
warning: unused result which must be used: iterator adaptors are lazy and do
nothing unless consumed
 --> src/main.rs:4:1
  |
4 | v1.iter().map(|x| x + 1);
  | ^^^^^^^^^^^^^^^^^^^^^^^^^
  |
  = note: #[warn(unused_must_use)] on by default
```

The code in Listing 13-17 isn't actually doing anything; the closure we've specified never gets called. The warning reminds us why: iterator adaptors are lazy, and we need to consume the iterator here.

To fix this and consume the iterator, we're going to use the `collect` method, which we saw briefly in Chapter 12. This method consumes the iterator and collects the resulting values into a collection data type.

In Listing 13-18, we collect the results of iterating over the iterator that's returned from the call to `map` into a vector. This vector will end up containing each item from the original vector incremented by 1:

Filename: src/main.rs

```
let v1: Vec<i32> = vec![1, 2, 3];

let v2: Vec<_> = v1.iter().map(|x| x + 1).collect();

assert_eq!(v2, vec![2, 3, 4]);
```

Listing 13-18: Calling the `map` method to create a new iterator, then calling the `collect` method to consume the new iterator and create a vector

Because `map` takes a closure, we can specify any operation we want to perform on each item. This is a great example of how closures let us customize some behavior while reusing the iteration behavior that the `Iterator` trait provides.

Using Closures that Capture their Environment with Iterators

Now that we've introduced iterators, we can demonstrate a common use of closures that capture their environment by using the `filter` iterator adapter. The `filter` method on an iterator takes a closure that takes each item from the iterator and returns a boolean. If the closure returns `true`, the value will be included in the iterator produced by `filter`. If the closure returns `false`, the value won't be included in the resulting iterator.

In Listing 13-19 we use `filter` with a closure that captures the `shoe_size` variable from its environment, in order to iterate over a collection of `Shoe` struct instances. It will return only shoes that are the specified size:

Filename: src/lib.rs

```
#[derive(PartialEq, Debug)]
struct Shoe {
    size: u32,
    style: String,
}

fn shoes_in_my_size(shoes: Vec<Shoe>, shoe_size: u32) -> Vec<Shoe> {
    shoes.into_iter()
        .filter(|s| s.size == shoe_size)
        .collect()
}

#[test]
fn filters_by_size() {
    let shoes = vec![
        Shoe { size: 10, style: String::from("sneaker") },
        Shoe { size: 13, style: String::from("sandal") },
        Shoe { size: 10, style: String::from("boot") },
    ];

    let in_my_size = shoes_in_my_size(shoes, 10);

    assert_eq!(
        in_my_size,
        vec![
            Shoe { size: 10, style: String::from("sneaker") },
            Shoe { size: 10, style: String::from("boot") },
        ]
    );
}
```

Listing 13-19: Using the `filter` method with a closure that captures `shoe_size`

The `shoes_in_my_size` function takes ownership of a vector of shoes and a shoe size as parameters. It returns a vector containing only shoes of the specified size.

In the body of `shoes_in_my_size`, we call `into_iter` to create an iterator that takes ownership of the vector. Then we call `filter` to adapt that iterator into a new iterator that only contains elements for which the closure returns `true`.

The closure captures the `shoe_size` parameter from the environment and compares the value with each shoe's size, keeping only shoes of the size specified. Finally, calling `collect` gathers the values returned by the adapted iterator into a vector that's returned by the function.

The test shows that when we call `shoes_in_my_size`, we only get back shoes that have the same size as the value we specified.

Implementing the `Iterator` Trait to Create Our Own Iterators

We've shown that we can create an iterator by calling `iter`, `into_iter`, or `iter_mut` on a vector. We can create iterators from the other collection types in the standard library, such as hash map. We can also create iterators that do anything we want by implementing the `Iterator` trait on our own types. As previously mentioned, the only method we're required to provide a definition for is the `next` method. Once we've done that, we can use all other methods that have default implementations provided by the `Iterator` trait!

To demonstrate, let's create an iterator that will only ever count from 1 to 5. First, we'll create a struct to hold some values, and then we'll make this struct into an iterator by implementing the `Iterator` trait and use the values in that implementation.

Listing 13-20 has the definition of the `Counter` struct and an associated `new` function to create instances of `Counter`:

Filename: src/lib.rs

```
struct Counter {
    count: u32,
}

impl Counter {
    fn new() -> Counter {
        Counter { count: 0 }
    }
}
```

Listing 13-20: Defining the `Counter` struct and a `new` function that creates instances of `Counter` with an initial value of 0 for `count`

The `Counter` struct has one field named `count`. This holds a `u32` value that will keep track of where we are in the process of iterating from 1 to 5. The `count` field is private since we want the implementation of `Counter` to manage its value. The `new` function enforces the behavior of always starting new instances with a value of 0 in the `count` field.

Next, we're going to implement the `Iterator` trait for our `Counter` type by defining the body of the `next` method, to specify what we want to happen when this iterator is used, as shown in Listing 13-21:

Filename: src/lib.rs

```
impl Iterator for Counter {
    type Item = u32;

    fn next(&mut self) -> Option<Self::Item> {
        self.count += 1;

        if self.count < 6 {
            Some(self.count)
        } else {
            None
        }
    }
}
```

Listing 13-21: Implementing the `Iterator` trait on our `Counter` struct

We set the associated `Item` type for our iterator to `u32`, meaning the iterator will return `u32` values. Again, don't worry about associated types yet, we'll be covering them in Chapter 19.

We want our iterator to add one to the current state, so we initialized `count` to 0 so it would return one first. If the value of `count` is less than six, `next` will return the current value wrapped in `Some`, but if `count` is six or higher, our iterator will return `None`.

Using Our `Counter` Iterator's `next` Method

Once we've implemented the `Iterator` trait, we have an iterator! Listing 13-22 shows a test demonstrating that we can use the iterator functionality of our `Counter` struct by calling the `next` method on it directly, just like we did with the iterator created from a vector in Listing 13-15:

Filename: src/lib.rs

```
#[test]
fn calling_next_directly() {
    let mut counter = Counter::new();

    assert_eq!(counter.next(), Some(1));
    assert_eq!(counter.next(), Some(2));
    assert_eq!(counter.next(), Some(3));
    assert_eq!(counter.next(), Some(4));
    assert_eq!(counter.next(), Some(5));
    assert_eq!(counter.next(), None);
}
```

Listing 13-22: Testing the functionality of the `next` method implementation

This test creates a new `Counter` instance in the `counter` variable and then calls `next` repeatedly, verifying that we have implemented the behavior we want this iterator to have: returning the values from 1 to 5.

Using Other `Iterator` Trait Methods on Our Iterator

Because we implemented the `Iterator` trait by defining the `next` method, we can now use any `Iterator` trait method's default implementations as defined in the standard library, since they all use the `next` method's functionality.

For example, if for some reason we wanted to take the values produced by an instance of `Counter`, pair them with values produced by another `Counter` instance after skipping the first value, multiply each pair together, keep only those results that are divisible by three, and add all the resulting values together, we could do so as shown in the test in Listing 13-23:

Filename: src/lib.rs

```
#[test]
fn using_other_iterator_trait_methods() {
    let sum: u32 = Counter::new().zip(Counter::new().skip(1))
                                 .map(|(a, b)| a * b)
                                 .filter(|x| x % 3 == 0)
                                 .sum();
    assert_eq!(18, sum);
}
```

Listing 13-23: Using a variety of `Iterator` trait methods on our `Counter` iterator

Note that `zip` produces only four pairs; the theoretical fifth pair `(5, None)` is never produced because `zip` returns `None` when either of its input iterators return `None`.

All of these method calls are possible because we specified how the `next` method works, and the standard library provides default implementations for other methods that call `next`.

Improving our I/O Project

With this new knowledge, we can improve the I/O project in Chapter 12 by using iterators to make places in the code clearer and more concise. Let's take a look at how iterators can improve our implementation of both the `Config::new` function and the `search` function.

Removing a `clone` Using an Iterator

In Listing 12-6, we added code that took a slice of `String` values and created an instance of the `Config` struct by indexing into the slice and cloning the values, allowing the `Config` struct to own those values. We've reproduced the implementation of the `Config::new` function as it was at the end of Chapter 12 in Listing 13-24:

Filename: src/lib.rs

```
impl Config {
    pub fn new(args: &[String]) -> Result<Config, &'static str> {
        if args.len() < 3 {
            return Err("not enough arguments");
        }

        let query = args[1].clone();
        let filename = args[2].clone();

        let case_sensitive = env::var("CASE_INSENSITIVE").is_err();

        Ok(Config { query, filename, case_sensitive })
    }
}
```

Listing 13-24: Reproduction of the `Config::new` function from the end of Chapter 12

At the time, we said not to worry about the inefficient `clone` calls here because we would remove them in the future. Well, that time is now!

We needed `clone` here because we have a slice with `String` elements in the parameter `args`, but the `new` function doesn't own `args`. In order to be able to return ownership of a `Config` instance, we had to clone the values from the `query` and `filename` fields of `Config`, so that the `Config` instance can own its values.

With our new knowledge about iterators, we can change the `new` function to take ownership of an iterator as its argument instead of borrowing a slice. We'll use the iterator functionality instead of the code that checks the length of the slice and indexes into specific locations. This will clear up what the `Config::new` function is doing since the iterator will take care of accessing the values.

Once `Config::new` takes ownership of the iterator and stops using indexing operations that borrow, we can move the `String` values from the iterator into `Config` rather than calling `clone` and making a new allocation.

Using the Iterator Returned by `env::args` Directly

Open your I/O project's *src/main.rs*, and we'll change the start of the `main` function that we had at the end of Chapter 12:

Filename: src/main.rs

```
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::new(&args).unwrap_or_else(|err| {
        eprintln!("Problem parsing arguments: {}", err);
        process::exit(1);
    });

    // ...snip...
}
```

To the code in Listing 13-25:

Filename: src/main.rs

```
fn main() {
    let config = Config::new(env::args()).unwrap_or_else(|err| {
        eprintln!("Problem parsing arguments: {}", err);
        process::exit(1);
    });

    // ...snip...
}
```

Listing 13-25: Passing the return value of `env::args` to `Config::new`

The `env::args` function returns an iterator! Rather than collecting the iterator values into a vector and then passing a slice to `Config::new`, now we're passing ownership of the iterator returned from `env::args` to `Config::new` directly.

Next, we need to update the definition of `Config::new`. In your I/O project's *src/lib.rs*, let's change the signature of `Config::new` to look like Listing 13-26:

Filename: src/lib.rs

```
impl Config {
    pub fn new(mut args: std::env::Args) -> Result<Config, &'static str> {
        // ...snip...
```

Listing 13-26: Updating the signature of `Config::new` to expect an iterator

The standard library documentation for the `env::args` function shows that the type of the iterator it returns is `std::env::Args`. We've updated the signature of the `Config::new` function so that the parameter `args` has the type `std::env::Args` instead of `&[String]`. Because we're taking ownership of `args`, and we're going to be mutating `args` by iterating over it, we can add the `mut` keyword into the specification of the `args` parameter to make it mutable.

Using `Iterator` Trait Methods Instead of Indexing

Next, we'll fix the body of `Config::new`. The standard library documentation also mentions that `std::env::Args` implements the `Iterator` trait, so we know we can call the `next` method on it! Listing 13-27 has updated the code from Listing 12-23 to use the `next` method:

Filename: src/lib.rs

```
impl Config {
    pub fn new(mut args: std::env::Args) -> Result<Config, &'static str> {
        args.next();

        let query = match args.next() {
            Some(arg) => arg,
            None => return Err("Didn't get a query string"),
        };

        let filename = match args.next() {
            Some(arg) => arg,
            None => return Err("Didn't get a file name"),
        };

        let case_sensitive = env::var("CASE_INSENSITIVE").is_err();

        Ok(Config { query, filename, case_sensitive })
    }
}
```

Listing 13-27: Changing the body of `Config::new` to use iterator methods

Remember that the first value in the return value of `env::args` is the name of the program. We want to ignore that and get to the next value, so first we call `next` and do nothing with the return value. Second, we call `next` on the value we want to put in the `query` field of `Config`. If `next` returns a `Some`, we use a `match` to extract the value. If it returns `None`, it means not enough arguments were given and we return early with an `Err` value. We do the same thing for the `filename` value.

Making Code Clearer with Iterator Adaptors

The other place in our I/O project we could take advantage of iterators is in the `search` function, reproduced here in Listing 13-28 as it was at the end of Chapter 12:

Filename: src/lib.rs

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a str> {
    let mut results = Vec::new();

    for line in contents.lines() {
        if line.contains(query) {
            results.push(line);
        }
    }

    results
}
```

Listing 13-28: The implementation of the `search` function from Chapter 12

We can write this code in a much more concise way using iterator adaptor methods. This also lets us avoid having a mutable intermediate `results` vector. The functional programming style prefers to minimize the amount of mutable state to make code clearer. Removing the mutable state might make it easier for us to make a future enhancement to make searching happen in parallel, since we wouldn't have to manage concurrent access to the `results` vector. Listing 13-29 shows this change:

Filename: src/lib.rs

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a str> {
    contents.lines()
        .filter(|line| line.contains(query))
        .collect()
}
```

Listing 13-29: Using iterator adaptor methods in the implementation of the `search` function

Recall that the purpose of the `search` function is to return all lines in `contents` that contain the `query`. Similar to the `filter` example in Listing 13-19, we can use the `filter` adaptor to keep only the lines that `line.contains(query)` returns true for. We then collect the matching lines up into another vector with `collect`. Much simpler! Feel free to make the same change to use iterator methods in the `search_case_insensitive` function as well.

The next logical question is which style you should choose in your own code and why: the original implementation in Listing 13-28, or the version using iterators in Listing 13-29. Most Rust programmers prefer to use the iterator style. It's a bit tougher to get the hang of at first, but once you get a feel for the various iterator adaptors and what they do, iterators can be easier to understand. Instead of fiddling with the various bits of looping and building new vectors, the code focuses on the high-level objective of the loop. This abstracts away some of the commonplace code so that it's easier to see the concepts that are unique to this code, like the filtering condition each element in the iterator must pass.

But are the two implementations truly equivalent? The intuitive assumption might be that the more low-level loop will be faster. Let's talk about performance.

Comparing Performance: Loops versus Iterators

To determine which to use, we need to know which version of our `search` functions is faster: the version with an explicit `for` loop or the version with iterators.

We ran a benchmark by loading the entire contents of "The Adventures of Sherlock Holmes" by Sir Arthur Conan Doyle into a `String` and looking for the word "the" in the contents. Here were the results of the benchmark on the version of `search` using the `for` loop and the version using iterators:

```
test bench_search_for  ... bench:  19,620,300 ns/iter (+/- 915,700)
test bench_search_iter ... bench:  19,234,900 ns/iter (+/- 657,200)
```

The iterator version ended up slightly faster! We're not going to go through the benchmark code here, as the point is not to prove that they're exactly equivalent, but to get a general sense of how these two implementations compare performance-wise.

For a more comprehensive benchmark, you'd want to check various texts of various sizes, different words, words of different lengths, and all kinds of other variations. The point is this: iterators, while a high-level abstraction, get compiled down to roughly the same code as if you'd written the lower-level code yourself. Iterators are one of Rust's *zero-cost abstractions*, by which we mean using the abstraction imposes no additional runtime overhead, in the same way that Bjarne Stroustrup, the original designer and implementor of C++, defines *zero-overhead*:

> In general, C++ implementations obey the zero-overhead principle: What you don't use, you don't pay for. And further: What you do use, you couldn't hand code any better.
>
> - Bjarne Stroustrup "Foundations of C++"

As another example, here is some code taken from an audio decoder. The decoding algorithm uses the linear prediction mathematical operation to estimate future values based on a linear function of the previous samples.

This code uses an iterator chain to do some math on three variables in scope: a `buffer` slice of data, an array of 12 `coefficients`, and an amount by which to shift data in `qlp_shift`. We've declared the variables within this example but not given them any values; while this code doesn't have much meaning outside of its context, it's still a concise, real-world example of how Rust translates high-level ideas to low-level code:

```
let buffer: &mut [i32];
let coefficients: [i64; 12];
let qlp_shift: i16;

for i in 12..buffer.len() {
    let prediction = coefficients.iter()
                                 .zip(&buffer[i - 12..i])
                                 .map(|(&c, &s)| c * s as i64)
                                 .sum::<i64>() >> qlp_shift;
    let delta = buffer[i];
    buffer[i] = prediction as i32 + delta;
}
```

In order to calculate the value of `prediction`, this code iterates through each of the 12 values in `coefficients` and uses the `zip` method to pair the coefficient values with the previous 12 values in `buffer`. Then, for each pair, we multiply the values together, sum all the results, and shift the bits in the sum `qlp_shift` bits to the right.

Calculations in applications like audio decoders often prioritize performance most highly. Here, we're creating an iterator, using two adaptors, then consuming the value. What assembly code would this Rust code compile to? Well, as of this writing, it compiles down to the same assembly you'd write by hand. There's no loop at all corresponding to the iteration over the values in `coefficients`: Rust knows that there are twelve iterations, so it "unrolls" the loop. *Unrolling* is an optimization that removes the overhead of the loop controlling code and instead generates repetitive code for each iteration of the loop.

All of the coefficients get stored in registers, which means it's very fast to access the values. There are no bounds checks on the array access at runtime. All these optimizations Rust is able to apply make the resulting code extremely efficient.

Now that you know this, go use iterators and closures without fear! They make code feel higher-level, but don't impose a runtime performance penalty for doing so.

Summary

Closures and iterators are Rust features inspired by functional programming language ideas. They contribute to Rust's ability to clearly express high-level ideas, at low level performance. The implementations of closures and iterators are such that runtime performance is not affected. This is part of Rust's goal to strive to provide zero-cost abstractions.

Now that we've improved the expressiveness of our I/O project, let's look at some more features of `cargo` that would help us get ready to share the project with the world.

More about Cargo and Crates.io

So far we've used only the most basic features of Cargo to build, run, and test our code, but it can do a lot more. Here we'll go over some of its other, more advanced features to show you how to:

- Customize your build through release profiles
- Publish libraries on crates.io
- Organize larger projects with workspaces
- Install binaries from crates.io
- Extend Cargo with your own custom commands

Cargo can do even more than what we can cover in this chapter too, so for a full explanation, see its documentation.

Customizing Builds with Release Profiles

In Rust *release profiles* are pre-defined, and customizable, profiles with different configurations, to allow the programmer more control over various options for compiling your code. Each profile is configured independently of the others.

Cargo has two main profiles you should know about: the `dev` profile Cargo uses when you run `cargo build`, and the `release` profile Cargo uses when you run `cargo build --release`. The `dev` profile is defined with good defaults for developing, and likewise the `release` profile has good defaults for release builds.

These names may be familiar from the output of your builds, which shows the profile used in the build:

```
$ cargo build
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
$ cargo build --release
    Finished release [optimized] target(s) in 0.0 secs
```

The “dev” and “release” notifications here indicate that the compiler is using different profiles.

Customizing Release Profiles

Cargo has default settings for each of the profiles that apply when there aren’t any `[profile.*]` sections in the project’s *Cargo.toml* file. By adding `[profile.*]` sections for any profile we want to customize, we can choose to override any subset of the default settings. For example, here are the default values for the `opt-level` setting for the `dev` and `release` profiles:

Filename: Cargo.toml

```
[profile.dev]
opt-level = 0

[profile.release]
opt-level = 3
```

The `opt-level` setting controls how many optimizations Rust will apply to your code, with a range of zero to three. Applying more optimizations makes compilation take longer, so if you’re in development and compiling very often, you’d want compiling to be fast at the expense of the resulting code running slower. That’s why the default `opt-level` for `dev` is `0`. When you’re ready to release, it’s better to spend more time compiling. You’ll only be compiling in release mode once, and running the compiled program many times, so release mode trades longer compile time for code that runs faster. That’s why the default `opt-level` for the `release` profile is `3`.

We can choose to override any default setting by adding a different value for them in *Cargo.toml*. If we wanted to use optimization level 1 in the development profile, for example, we can add these two lines to our project’s *Cargo.toml*:

Filename: Cargo.toml

```
[profile.dev]
opt-level = 1
```

This overrides the default setting of `0`. Now when we run `cargo build`, Cargo will use the defaults for the `dev` profile plus our customization to `opt-level`. Because we set `opt-level` to `1`, Cargo will apply more optimizations than the default, but not as many as a release build.

For the full list of configuration options and defaults for each profile, see Cargo's documentation.

Publishing a Crate to Crates.io

We've used packages from crates.io as dependencies of our project, but you can also share your code for other people to use by publishing your own packages. Crates.io distributes the source code of your packages, so it primarily hosts code that's open source.

Rust and Cargo have features that help make your published package easier for people to find and use. We'll talk about some of those features, then cover how to publish a package.

Making Useful Documentation Comments

Accurately documenting your packages will help other users know how and when to use them, so it's worth spending some time to write documentation. In Chapter 3, we discussed how to comment Rust code with `//`. Rust also has particular kind of comment for documentation, known conveniently as *documentation comments*, that will generate HTML documentation. The HTML displays the contents of documentation comments for public API items, intended for programmers interested in knowing how to *use* your crate, as opposed to how your crate is *implemented*.

Documentation comments use `///` instead of `//` and support Markdown notation for formatting the text if you'd like. You place documentation comments just before the item they are documenting. Listing 14-1 shows documentation comments for an `add_one` function in a crate named `my_crate`:

Filename: src/lib.rs

```
/// Adds one to the number given.
///
/// # Examples
///
/// ```
/// let five = 5;
///
/// assert_eq!(6, my_crate::add_one(5));
/// ```
pub fn add_one(x: i32) -> i32 {
    x + 1
}
```

Listing 14-1: A documentation comment for a function

Here, we give a description of what the `add_one` function does, then start a section with the heading "Examples", and code that demonstrates how to use the `add_one` function. We can generate the HTML documentation from this documentation comment by running `cargo doc`. This command runs the `rustdoc` tool distributed with Rust and puts the generated HTML documentation in the *target/doc* directory.

For convenience, running `cargo doc --open` will build the HTML for your current crate's documentation (as well as the documentation for all of your crate's dependencies) and open the result in a web browser. Navigate to the `add_one` function and you'll see how the text in the documentation comments gets rendered, shown here in Figure 14-2:

Figure 14-2: HTML documentation for the `add_one` function

Commonly Used Sections

We used the `# Examples` markdown heading in Listing 14-1 to create a section in the HTML with the title "Examples". Some other sections that crate authors commonly use in their documentation include:

- **Panics**: The scenarios in which this function could `panic!`. Callers of this function who don't want their programs to panic should make sure that they don't call this function in these situations.
- **Errors**: If this function returns a `Result`, describing the kinds of errors that might occur and what conditions might cause those errors to be returned can be helpful to callers so that they can write code to handle the different kinds of errors in different ways.
- **Safety**: If this function is `unsafe` to call (we will discuss unsafety in Chapter 19), there should be a section explaining why the function is unsafe and covering the invariants that this function expects callers to uphold.

Most documentation comment sections don't need all of these sections, but this is a good list to check to remind you of the kinds of things that people calling your code will be interested in knowing about.

Documentation Comments as Tests

Adding examples in code blocks in your documentation comments is a way to clearly demonstrate how to use your library, but it has an additional bonus: running `cargo test` will run the code examples in your documentation as tests! Nothing is better than documentation with examples. Nothing is worse than examples that don't actually work because the code has changed since the documentation has been written. Try running `cargo test` with the documentation for the `add_one` function like in Listing 14-1; you should see a section in the test results like this:

```
   Doc-tests my_crate

running 1 test
test src/lib.rs - add_one (line 5) ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

Now try changing either the function or the example so that the `assert_eq!` in the example will panic. Run `cargo test` again, and you'll see that the doc tests catch that the example and the code are out of sync from one another!

Commenting Contained Items

There's another style of doc comment, `//!`, that adds documentation to the item that contains the comments, rather than adding documentation to the items following the comments. These are typically used inside the crate root file (*src/lib.rs* by convention) or inside a module to document the crate or the module as a whole.

For example, if we wanted to add documentation that described the purpose of the `my_crate` crate that contains the `add_one` function, we can add documentation comments that start with `//!` to the beginning of *src/lib.rs* as shown in Listing 14-3:

Filename: src/lib.rs

```
//! # My Crate
//!
//! `my_crate` is a collection of utilities to make performing certain
//! calculations more convenient.

/// Adds one to the number given.
// ...snip...
```

Listing 14-3: Documentation for the `my_crate` crate as a whole

Notice there isn't any code after the last line that begins with `//!`. Because we started the comments with `//!` instead of `///`, we're documenting the item that contains this comment rather than an item that follows this comment. In this case, the item that contains this comment is the *src/lib.rs* file, which is the crate root. These comments describe the entire crate.

If we run `cargo doc --open`, we'll see these comments displayed on the front page of the documentation for `my_crate` above the list of public items in the crate, as shown in Figure 14-4:

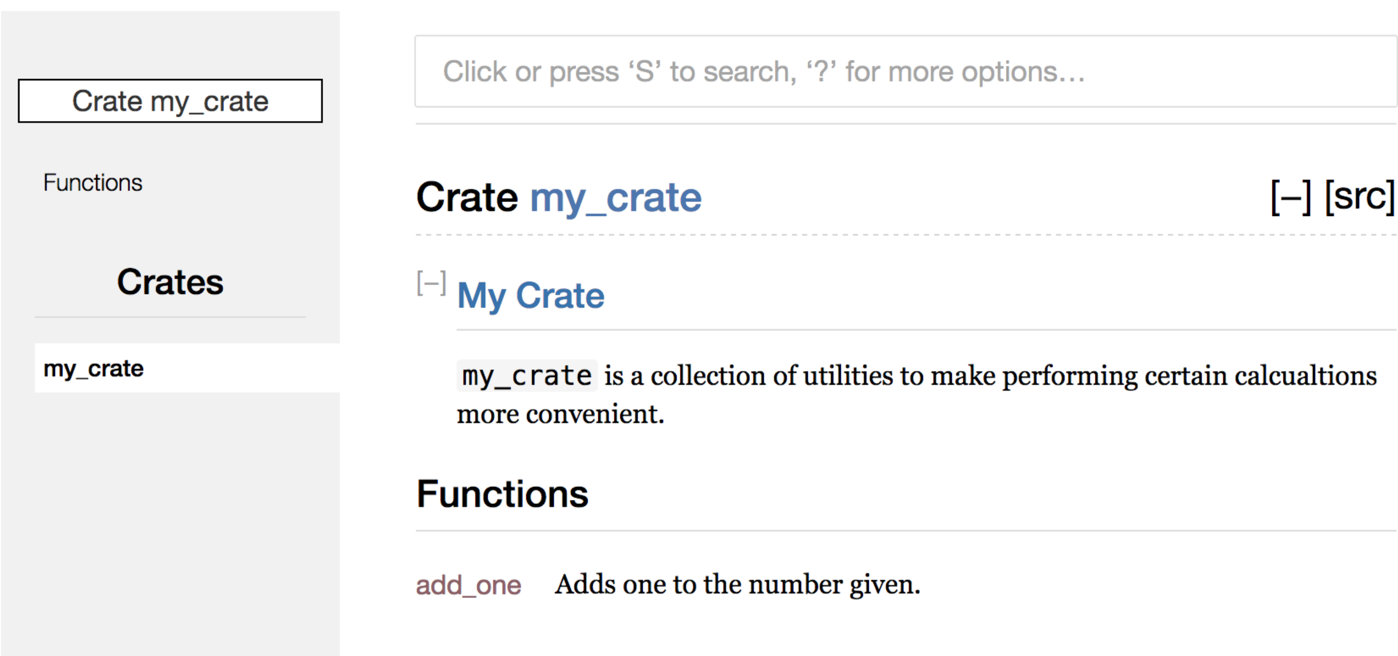


Figure 14-4: Rendered documentation for `my_crate` including the comment describing the crate as a whole

Documentation comments within items are useful for describing crates and modules especially. Use them to talk about the purpose of the container overall to help users of your crate understand your organization.

Exporting a Convenient Public API with `pub use`

In Chapter 7, we covered how to organize our code into modules with the `mod` keyword, how to make items public with the `pub` keyword, and how to bring items into a scope with the `use` keyword. The structure that makes sense to you while you're developing a crate may not be very convenient for your users, however. You may wish to organize your structs in a hierarchy containing multiple levels, but people that want to use a type you've defined deep in the hierarchy might have trouble finding out that those types exist. They might also be annoyed at having to type `use my_crate::some_module::another_module::UsefulType;` rather than `use my_crate::UsefulType;`.

The structure of your public API is a major consideration when publishing a crate. People who use your crate are less familiar with the structure than you are, and might have trouble finding the pieces they want to use if the module hierarchy is large.

The good news is that, if the structure *isn't* convenient for others to use from another library, you don't have to rearrange your internal organization: you can choose to re-export items to make a public structure that's different to your private structure, using `pub use`. Re-exporting takes a public item in one location and makes it public in another location as if it was defined in the other location instead.

For example, say we made a library named `art` for modeling artistic concepts. Within this library is a `kinds` module containing two enums named `PrimaryColor` and `SecondaryColor` and a `utils` module containing a function named `mix` as shown in Listing 14-5:

Filename: src/lib.rs

```rust
//! # Art
//!
//! A library for modeling artistic concepts.

pub mod kinds {
    /// The primary colors according to the RYB color model.
    pub enum PrimaryColor {
        Red,
        Yellow,
        Blue,
    }

    /// The secondary colors according to the RYB color model.
    pub enum SecondaryColor {
        Orange,
        Green,
        Purple,
    }
}

pub mod utils {
    use kinds::*;

    /// Combines two primary colors in equal amounts to create
    /// a secondary color.
    pub fn mix(c1: PrimaryColor, c2: PrimaryColor) -> SecondaryColor {
        // ...snip...
    }
}
```

Listing 14-5: An `art` library with items organized into `kinds` and `utils` modules

The front page of the documentation for this crate generated by `cargo doc` would look like Figure 14-6:

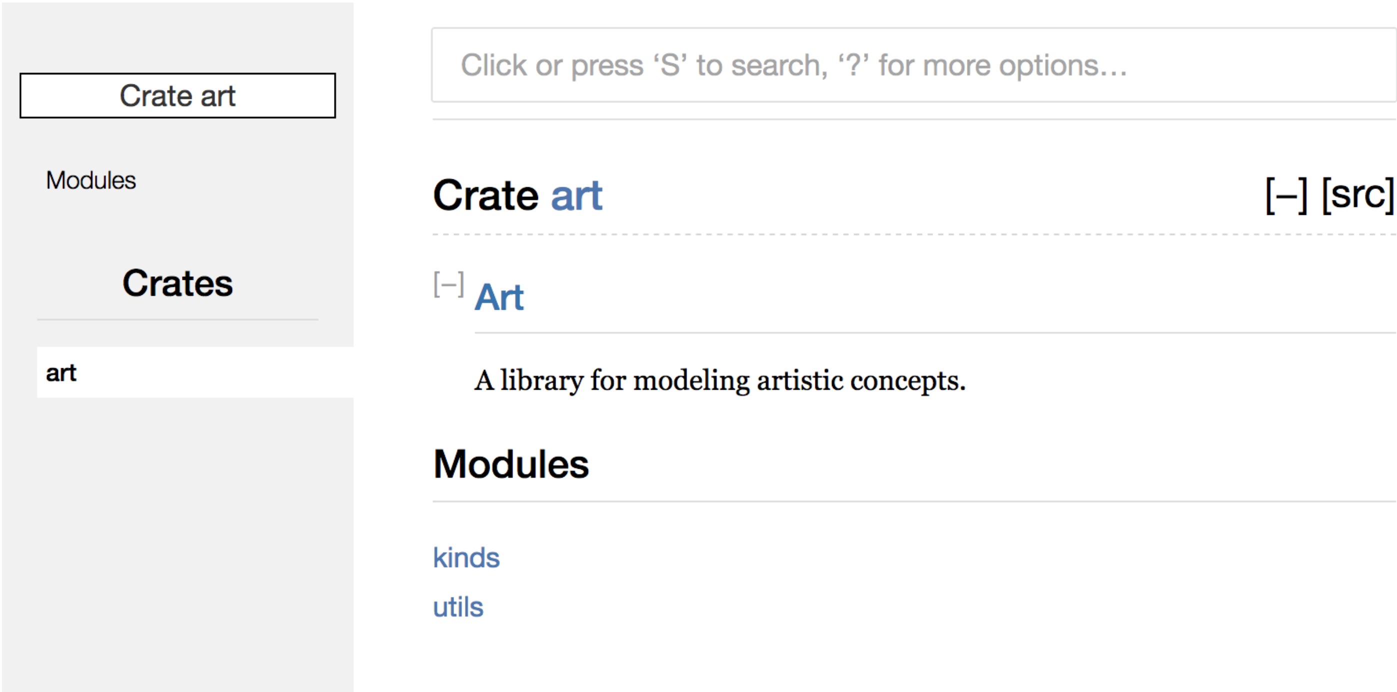


Figure 14-6: Front page of the documentation for `art` that lists the `kinds` and `utils` modules

Note that the `PrimaryColor` and `SecondaryColor` types aren't listed on the front page, nor is the `mix` function. We have to click on `kinds` and `utils` in order to see them.

Another crate depending on this library would need `use` statements that import the items from `art` including specifying the module structure that's currently defined. Listing 14-7 shows an example of a crate that uses the `PrimaryColor` and `mix` items from the `art` crate:

Filename: src/main.rs

```
extern crate art;

use art::kinds::PrimaryColor;
use art::utils::mix;

fn main() {
    let red = PrimaryColor::Red;
    let yellow = PrimaryColor::Yellow;
    mix(red, yellow);
}
```

Listing 14-7: A crate using the `art` crate's items with its internal structure exported

The author of the code in Listing 14-7 that uses the `art` crate had to figure out that `PrimaryColor` is in the `kinds` module and `mix` is in the `utils` module. The module structure of the `art` crate is more relevant to developers working on the `art` crate than developers using the `art` crate. The internal structure that organizes parts of the crate into the `kinds` module and the `utils` module doesn't add any useful information to someone trying to understand how to use the `art` crate. The `art` crate's module structure adds confusion in having to figure out where to look and inconvenience in having to specify the module names in the `use` statements.

To remove the internal organization from the public API, we can take the `art` crate code from Listing 14-5 and add `pub use` statements to re-export the items at the top level, as shown in Listing 14-8:

Filename: src/lib.rs

```
//! # Art
//!
//! A library for modeling artistic concepts.

pub use kinds::PrimaryColor;
pub use kinds::SecondaryColor;
pub use utils::mix;

pub mod kinds {
    // ...snip...
}

pub mod utils {
    // ...snip...
}
```

Listing 14-8: Adding `pub use` statements to re-export items

The API documentation generated with `cargo doc` for this crate will now list and link re-exports on the front page as shown in Figure 14-9, which makes these types easier to find.

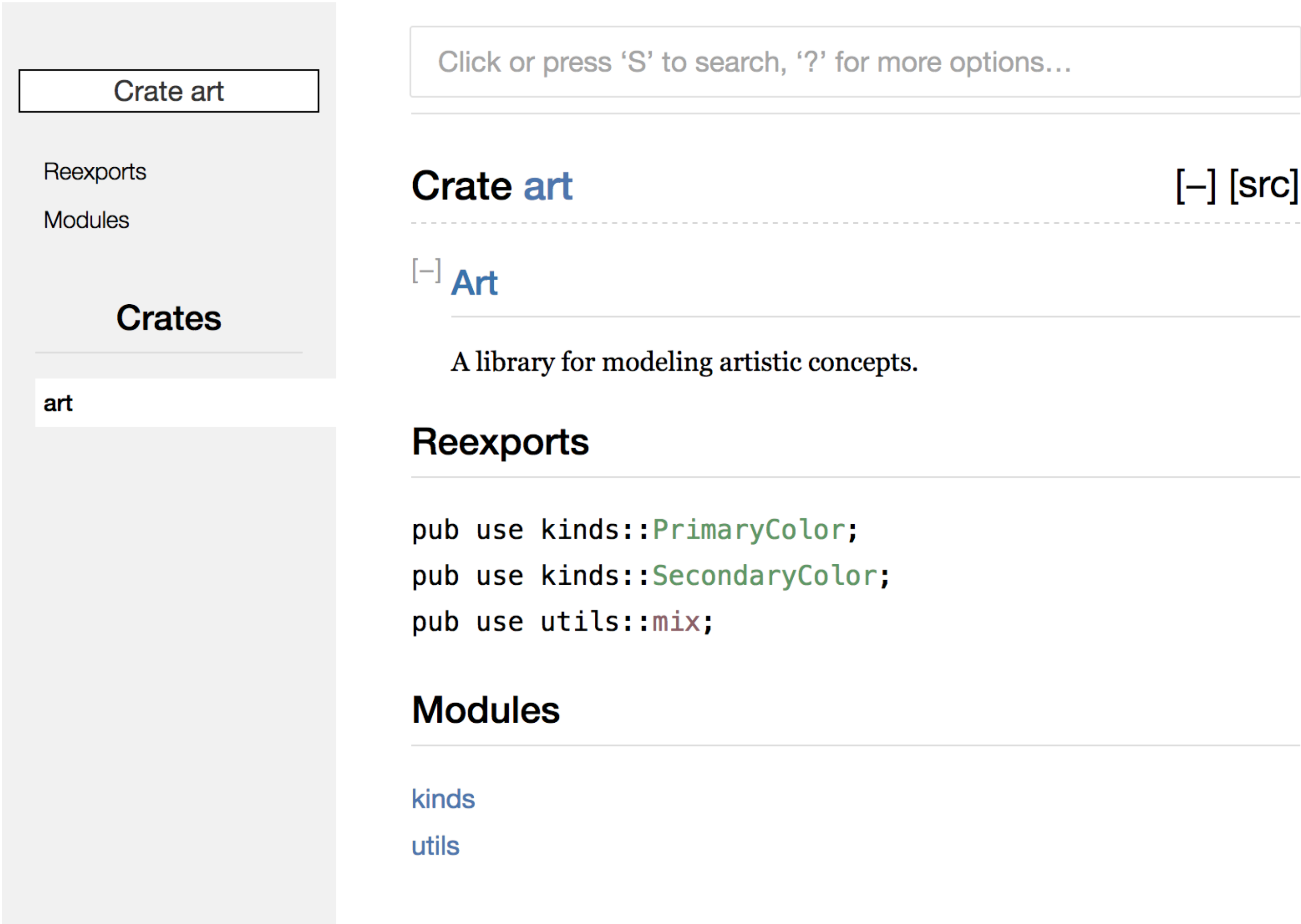


Figure 14-9: Front page of the documentation for `art` that lists the re-exports

Users of the `art` crate can still see and choose to use the internal structure as in Listing 14-7, or they can use the more convenient structure from Listing 14-8, as shown in Listing 14-10:

Filename: src/main.rs

```
extern crate art;

use art::PrimaryColor;
use art::mix;

fn main() {
    // ...snip...
}
```

Listing 14-10: A program using the re-exported items from the `art` crate

In cases where there are many nested modules, re-exporting the types at the top level with `pub use` can make a big difference in the experience of people who use the crate.

Creating a useful public API structure is more of an art than a science, and you can iterate to find the API that works best for your users. Choosing `pub use` gives you flexibility in how you structure your crate internally, and decouples that internal structure with what you present to your users. Take a look at some of the code of crates you've installed to see if their internal structure differs from their public API.

Setting up a Crates.io Account

Before you can publish any crates, you need to create an account on crates.io and get an API token. To do so, visit the home page at *https://crates.io* and log in via a GitHub account—the GitHub account is a requirement for now, but the site may support other ways of creating an account in the future. Once you're logged in, visit your account settings at *https://crates.io/me* and retrieve your API key. Then run the `cargo login` command with your API key, like this:

```
$ cargo login abcdefghijklmnopqrstuvwxyz012345
```

This command will inform Cargo of your API token and store it locally in *~/.cargo/credentials*. Note that this token is a *secret* and should not be shared with anyone else. If it is shared with anyone for any reason, you should revoke it and generate a new token on Crates.io.

Before Publishing a New Crate

Now you have an account, and let's say you already have a crate you want to publish. Before publishing, you'll need to add some metadata to your crate by adding it to the `[package]` section of the crate's *Cargo.toml*.

Your crate will first need a unique name. While you're working on a crate locally, you may name a crate whatever you'd like. However, crate names on Crates.io are allocated on a first-come-first-serve basis. Once a crate name is taken, no one else may publish a crate with that name. Search for the name you'd like to use on the site to find out if it has been taken. If it hasn't, edit the name in *Cargo.toml* under `[package]` to have the name you want to use for publishing like so:

Filename: Cargo.toml

```
[package]
name = "guessing_game"
```

Even if you've chosen a unique name, if you try to run `cargo publish` to publish the crate at this point, you'll get a warning and then an error:

```
$ cargo publish
    Updating registry `https://github.com/rust-lang/crates.io-index`
warning: manifest has no description, license, license-file, documentation,
homepage or repository.
...snip...
error: api errors: missing or empty metadata fields: description, license.
```

This is because we're missing some crucial information: a description and license are required so that people will know what your crate does and under what terms they may use it. To rectify this error, we need to include this information in *Cargo.toml*.

Make a description that's just a sentence or two, as it will appear with your crate in search results and on your crate's page. For the `license` field, you need to give a *license identifier value*. The Linux Foundation's Software Package Data Exchange (SPDX) at *http://spdx.org/licenses/* lists the identifiers you can use for this value. For example, to specify that you've licensed your crate using the MIT License, add the `MIT` identifier:

Filename: Cargo.toml

```
[package]
name = "guessing_game"
license = "MIT"
```

If you want to use a license that doesn't appear in the SPDX, you need to place the text of that license in a file, include the file in your project, then use `license-file` to specify the name of that file instead of using the `license` key.

Guidance on which license is right for your project is out of scope for this book. Many people in the Rust community choose to license their projects in the same way as Rust itself, with a dual license of `MIT/Apache-2.0`—this demonstrates that you can also specify multiple license identifiers separated by a slash.

So, with a unique name, the version, and author details that `cargo new` added when you created the crate, your description, and the license you chose added, the *Cargo.toml* for a project that's ready to publish might look like this:

Filename: Cargo.toml

```
[package]
name = "guessing_game"
version = "0.1.0"
authors = ["Your Name <you@example.com>"]
description = "A fun game where you guess what number the computer has chosen."
license = "MIT/Apache-2.0"

[dependencies]
```

Cargo's documentation describes other metadata you can specify to ensure your crate can be discovered and used more easily!

Publishing to Crates.io

Now that you've created an account, saved your API token, chosen a name for your crate, and specified the required metadata, you're ready to publish! Publishing a crate uploads a specific version to crates.io for others to use.

Take care when publishing a crate, because a publish is *permanent*. The version can never be overwritten, and the code cannot be deleted. One major goal of Crates.io is to act as a permanent archive of code so that builds of all projects that depend on crates from Crates.io will continue to work. Allowing deletion of versions would make fulfilling that goal impossible. However, there is no limit to the number of versions of a crate you can publish.

Let's run the `cargo publish` command again. It should succeed now:

```
$ cargo publish
 Updating registry `https://github.com/rust-lang/crates.io-index`
Packaging guessing_game v0.1.0 (file:///projects/guessing_game)
Verifying guessing_game v0.1.0 (file:///projects/guessing_game)
Compiling guessing_game v0.1.0
(file:///projects/guessing_game/target/package/guessing_game-0.1.0)
 Finished dev [unoptimized + debuginfo] target(s) in 0.19 secs
Uploading guessing_game v0.1.0 (file:///projects/guessing_game)
```

Congratulations! You've now shared your code with the Rust community, and anyone can easily add your crate as a dependency of their project.

Publishing a New Version of an Existing Crate

When you've made changes to your crate and are ready to release a new version, you change the `version` value specified in your *Cargo.toml* and republish. Use the Semantic Versioning rules to decide what an appropriate next version number is based on the kinds of changes you've made. Then run `cargo publish` to upload the new version.

Removing Versions from Crates.io with `cargo yank`

While you can't remove previous versions of a crate, you can prevent any future projects from adding them as a new dependency. This is useful when a version of a crate ends up being broken for one reason or another. For situations such as this, Cargo supports *yanking* a version of a crate.

Yanking a version prevents new projects from starting to depend on that version while allowing all existing projects that depend on it to continue to download and depend on that version. Essentially, a yank means that all projects with a *Cargo.lock* will not break, while any future *Cargo.lock* files generated will not use the yanked version.

To yank a version of a crate, run `cargo yank` and specify which version you want to yank:

```
$ cargo yank --vers 1.0.1
```

You can also undo a yank, and allow projects to start depending on a version again, by adding `--undo` to the command:

```
$ cargo yank --vers 1.0.1 --undo
```

A yank *does not* delete any code. The yank feature is not intended for deleting accidentally uploaded secrets, for example. If that happens, you must reset those secrets immediately.

Cargo Workspaces

In Chapter 12, we built a package that included both a binary crate and a library crate. You may find, as your project develops, that the library crate continues to get bigger and you want to split your package up further into multiple library crates. In this situation, Cargo has a feature called *workspaces* that can help manage multiple related packages that are developed in tandem.

A *workspace* is a set of packages that will all share the same *Cargo.lock* and output directory. Let's make a project using a workspace, using trivial code so we can concentrate on the structure of a workspace. We'll have a binary that uses two libraries: one library that will provide an `add_one` function and a second library that will provide an `add_two` function. These three crates will all be part of the same workspace. We'll start by creating a new crate for the binary:

```
$ cargo new --bin adder
     Created binary (application) `adder` project
$ cd adder
```

We need to modify the binary package's *Cargo.toml* and add a `[workspace]` section to tell Cargo the `adder` package is a workspace. Add this at the bottom of the file:

Filename: Cargo.toml

```
[workspace]
```

Like many Cargo features, workspaces support convention over configuration: we don't need to add anything more than this to *Cargo.toml* to define our workspace as long as we follow the convention.

Specifying Workspace Dependencies

By default, Cargo will include all transitive path dependencies. A *path dependency* is when any crate, whether in a workspace or not, specifies that it has a dependency on a crate in a local directory by using the `path` attribute on the dependency specification in *Cargo.toml*. If a crate has the `[workspace]` key, or if the crate is itself part of a workspace, and we specify path dependencies where the paths are subdirectories of the crate's directory, those dependent crates will be considered part of the workspace. Let's specify in the *Cargo.toml* for the top-level `adder` crate that it will have a dependency on an `add-one` crate that will be in the `add-one` subdirectory, by changing *Cargo.toml* to look like this:

Filename: Cargo.toml

```
[dependencies]
add-one = { path = "add-one" }
```

If we add dependencies to *Cargo.toml* that don't have a `path` specified, those dependencies will be normal dependencies that aren't in this workspace and are assumed to come from Crates.io.

Creating the Second Crate in the Workspace

Next, while in the `adder` directory, generate an `add-one` crate:

```
$ cargo new add-one
     Created library `add-one` project
```

Your `adder` directory should now have these directories and files:

```
├── Cargo.toml
├── add-one
│   ├── Cargo.toml
│   └── src
│       └── lib.rs
└── src
    └── main.rs
```

In *add-one/src/lib.rs*, let's add an `add_one` function:

Filename: add-one/src/lib.rs

```
pub fn add_one(x: i32) -> i32 {
    x + 1
}
```

Open up *src/main.rs* for `adder` and add an `extern crate` line at the top of the file to bring the new `add-one` library crate into scope. Then change the `main` function to call the `add_one` function, as in Listing 14-11:

Filename: src/main.rs

```
extern crate add_one;

fn main() {
    let num = 10;
    println!("Hello, world! {} plus one is {}!", num, add_one::add_one(num));
}
```

Listing 14-11: Using the `add-one` library crate from the `adder` crate

Let's build the `adder` crate by running `cargo build` in the *adder* directory!

```
$ cargo build
   Compiling add-one v0.1.0 (file:///projects/adder/add-one)
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished dev [unoptimized + debuginfo] target(s) in 0.68 secs
```

Note that this builds both the `adder` crate and the `add-one` crate in *adder/add-one*. Now your *adder* directory should have these files:

```
├── Cargo.lock
├── Cargo.toml
├── add-one
│   ├── Cargo.toml
│   └── src
│       └── lib.rs
├── src
│   └── main.rs
└── target
```

The workspace has one *target* directory at the top level; *add-one* doesn't have its own *target* directory. Even if we go into the `add-one` directory and run `cargo build`, the compiled artifacts end up in *adder/target* rather than *adder/add-one/target*. The crates in a workspace depend on each other. If each crate had its own *target* directory, each crate in the workspace would have to recompile each other crate in the workspace in order to have the artifacts in its own *target* directory. By sharing one *target* directory, the crates in the workspace can avoid rebuilding the other crates in the workspace more than necessary.

Depending on an External Crate in a Workspace

Also notice the workspace only has one *Cargo.lock*, rather than having a top-level *Cargo.lock* and *add-one/Cargo.lock*. This ensures that all crates are using the same version of all dependencies. If we add the `rand` crate to both *Cargo.toml* and *add-one/Cargo.toml*, Cargo will resolve both of those to one version of `rand` and record that in the one *Cargo.lock*. Making all crates in the workspace use the same dependencies means the crates in the workspace will always be compatible with each other. Let's try this out now.

Let's add the `rand` crate to the `[dependencies]` section in *add-one/Cargo.toml* in order to be able to use the `rand` crate in the `add-one` crate:

Filename: add-one/Cargo.toml

```
[dependencies]

rand = "0.3.14"
```

We can now add `extern crate rand;` to *add-one/src/lib.rs*, and building the whole workspace by running `cargo build` in the *adder* directory will bring in and compile the `rand` crate:

```
$ cargo build
    Updating registry `https://github.com/rust-lang/crates.io-index`
 Downloading rand v0.3.14
   ...snip...
   Compiling rand v0.3.14
   Compiling add-one v0.1.0 (file:///projects/adder/add-one)
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished dev [unoptimized + debuginfo] target(s) in 10.18 secs
```

The top level *Cargo.lock* now contains information about `add-one`'s dependency on `rand`. However, even though `rand` is used somewhere in the workspace, we can't use it in other crates in the workspace unless we add `rand` to their *Cargo.toml* as well. If we add `extern crate rand;` to *src/main.rs* for the top level `adder` crate, for example, we'll get an error:

```
$ cargo build
   Compiling adder v0.1.0 (file:///projects/adder)
error[E0463]: can't find crate for `rand`
 --> src/main.rs:1:1
  |
1 | extern crate rand;
  | ^^^^^^^^^^^^^^^^^^ can't find crate
```

To fix this, edit *Cargo.toml* for the top level `adder` crate and indicate that `rand` is a dependency for that crate as well. Building the `adder` crate will add `rand` to the list of dependencies for `adder` in *Cargo.lock*, but no additional copies of `rand` will be downloaded. Cargo has ensured for us that any crate in the workspace using the `rand` crate will be using the same version. Using the same version of `rand` across the workspace saves space since we won't have multiple copies and ensures that the crates in the workspace will be compatible with each other.

Adding a Test to a Workspace

For another enhancement, let's add a test of the `add_one::add_one` function within the `add_one` crate:

Filename: add-one/src/lib.rs

```
pub fn add_one(x: i32) -> i32 {
    x + 1
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_works() {
        assert_eq!(3, add_one(2));
    }
}
```

Now run `cargo test` in the top-level *adder* directory:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished dev [unoptimized + debuginfo] target(s) in 0.27 secs
     Running target/debug/adder-f0253159197f7841

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

Wait a second, zero tests? We just added one! If we look at the output, we can see that `cargo test` in a workspace only runs tests for the top level crate. To run tests for all of the crates in the workspace, we need to pass the `--all` flag:

```
$ cargo test --all
    Finished dev [unoptimized + debuginfo] target(s) in 0.37 secs
     Running target/debug/deps/add_one-abcabcabc

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out

     Running target/debug/deps/adder-abcabcabc

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out

   Doc-tests add-one

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out
```

When passing `--all`, `cargo test` will run the tests for all of the crates in the workspace. We can also choose to run tests for one particular crate in a workspace from the top level directory by using the `-p` flag and specifying the name of the crate we want to test:

```
$ cargo test -p add-one
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running target/debug/deps/add_one-b3235fea9a156f74

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out

   Doc-tests add-one

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out
```

This output shows `cargo test` only ran the tests for the `add-one` crate and didn't run the `adder` crate tests.

If you choose to publish the crates in the workspace to crates.io, each crate in the workspace will get published separately. The `cargo publish` command does not have an `--all` flag or a `-p` flag, so it is necessary to change to each crate's directory and run `cargo publish` on each crate in the workspace in order to publish them.

Now try adding an `add-two` crate to this workspace in a similar way as the `add-one` crate for some more practice!

As your project grows, consider using a workspace: smaller components are easier to understand individually than one big blob of code. Keeping the crates in a workspace can make coordination among them easier if they work together and are often changed at the same time.

Installing Binaries from Crates.io with `cargo install`

The `cargo install` command allows you to install and use binary crates locally. This isn't intended to replace system packages; it's meant to be a convenient way for Rust developers to install tools that others have shared on crates.io. Only packages that have binary targets can be installed. A binary target is the runnable program that gets created if the crate has a *src/main.rs* or another file specified as a binary, as opposed to a library target that isn't runnable on its own but is suitable for including within other programs. Usually, crates have information in the *README* file about whether a crate is a library, has a binary target, or both.

All binaries from `cargo install` are put into the installation root's *bin* folder. If you installed Rust using *rustup.rs* and don't have any custom configurations, this will be `$HOME/.cargo/bin`. Ensure that directory is in your `$PATH` to be able to run programs you've gotten through `cargo install`.

For example, we mentioned in Chapter 12 that there's a Rust implementation of the `grep` tool for searching files called `ripgrep`. If we want to install `ripgrep`, we can run:

```
$ cargo install ripgrep
Updating registry `https://github.com/rust-lang/crates.io-index`
 Downloading ripgrep v0.3.2
 ...snip...
   Compiling ripgrep v0.3.2
    Finished release [optimized + debuginfo] target(s) in 97.91 secs
  Installing ~/.cargo/bin/rg
```

The last line of the output shows the location and the name of the installed binary, which in the case of `ripgrep` is `rg`. As long as the installation directory is in your `$PATH` as mentioned above, you can then run `rg --help` and start using a faster, rustier tool for searching files!

Extending Cargo with Custom Commands

Cargo is designed so you can extend it with new subcommands without having to modify Cargo itself. If a binary in your `$PATH` is named `cargo-something`, you can run it as if it were a Cargo subcommand by running `cargo something`. Custom commands like this are also listed when you run `cargo --list`. Being able to `cargo install` extensions and then run them just like the built-in Cargo tools is a super convenient benefit of Cargo's design!

Summary

Sharing code with Cargo and crates.io is part of what makes the Rust ecosystem useful for many different tasks. Rust's standard library is small and stable, but crates are easy to share, use, and improve on a timeline different from the language itself. Don't be shy about sharing code that's useful to you on Crates.io; it's likely that it will be useful to someone else as well!

Smart Pointers

A *pointer* is a general concept for a variable that contains an address in memory. This address refers to, or "points at", some other data. The most common kind of pointer in Rust is a *reference*, which we learned about in Chapter 4. References are indicated by the `&` symbol and borrow the value that they point to. They don't have any special abilities other than referring to data. They also don't have any overhead, so they're used the most often.

Smart pointers, on the other hand, are data structures that act like a pointer, but they also have additional metadata and capabilities. The concept of smart pointers isn't unique to Rust; it originated in C++ and exists in other languages as well. The different smart pointers defined in Rust's standard library provide extra functionality beyond what references provide. One example that we'll explore in this chapter is the *reference counting* smart pointer type, which enables you to have multiple owners of data. The reference counting smart pointer keeps track of how many owners there are, and when there aren't any remaining, the smart pointer takes care of cleaning up the data.

In Rust, where we have the concept of ownership and borrowing, an additional difference between references and smart pointers is that references are a kind of pointer that only borrow data; by contrast, in many cases, smart pointers *own* the data that they point to.

We've actually already encountered a few smart pointers in this book, such as `String` and `Vec<T>` from Chapter 8, though we didn't call them smart pointers at the time. Both these types count as smart pointers because they own some memory and allow you to manipulate it. They also have metadata (such as their capacity) and extra capabilities or guarantees (such as `String` ensuring its data will always be valid UTF-8).

Smart pointers are usually implemented using structs. The characteristics that distinguish a smart pointer from an ordinary struct are that smart pointers implement the `Deref` and `Drop` traits. The `Deref` trait allows an instance of the smart pointer struct to behave like a reference so that we can write code that works with either references or smart pointers. The `Drop` trait allows us to customize the code that gets run when an instance of the smart pointer goes out of scope. In this chapter, we'll be discussing both of those traits and demonstrating why they're important to smart pointers.

Given that the smart pointer pattern is a general design pattern used frequently in Rust, this chapter won't cover every smart pointer that exists. Many libraries have their own smart pointers and you can even write some yourself. We'll just cover the most common smart pointers from the standard library:

- `Box<T>` for allocating values on the heap
- `Rc<T>`, a reference counted type that enables multiple ownership
- `Ref<T>` and `RefMut<T>`, accessed through `RefCell<T>`, a type that enforces the borrowing rules at runtime instead of compile time

Along the way, we'll cover the *interior mutability* pattern where an immutable type exposes an API for mutating an interior value. We'll also discuss *reference cycles*, how they can leak memory, and how to prevent them.

Let's dive in!

`Box<T>` Points to Data on the Heap and Has a Known Size

The most straightforward smart pointer is a *box*, whose type is written `Box<T>`. Boxes allow you to store data on the heap rather than the stack. What remains on the stack is the pointer to the heap data. Refer back to Chapter 4 if you'd like to review the difference between the stack and the heap.

Boxes don't have performance overhead other than their data being on the heap instead of on the stack, but they don't have a lot of extra abilities either. They're most often used in these situations:

- When you have a type whose size can't be known at compile time, and you want to use a value of that type in a context that needs to know an exact size
- When you have a large amount of data and you want to transfer ownership but ensure the data won't be copied when you do so
- When you want to own a value and only care that it's a type that implements a particular trait rather than knowing the concrete type itself

We're going to demonstrate the first case in the rest of this section. To elaborate on the other two situations a bit more: in the second case, transferring ownership of a large amount of data can take a long time because the data gets copied around on the stack. To improve performance in this situation, we can store the large amount of data on the heap in a box. Then, only the small amount of pointer data is copied around on the stack, and the data stays in one place on the heap. The third case is known as a *trait object*, and Chapter 17 has an entire section devoted just to that topic. So know that what you learn here will be applied again in Chapter 17!

Using a `Box<T>` to Store Data on the Heap

Before we get into a use case for `Box<T>`, let's get familiar with the syntax and how to interact with values stored within a `Box<T>`.

Listing 15-1 shows how to use a box to store an `i32` on the heap:

Filename: src/main.rs

```
fn main() {
    let b = Box::new(5);
    println!("b = {}", b);
}
```

Listing 15-1: Storing an `i32` value on the heap using a box

We define the variable `b` to have the value of a `Box` that points to the value `5`, which is allocated on the heap. This program will print `b = 5`; in this case, we can access the data in the box in a similar way as we would if this data was on the stack. Just like any value that has ownership of data, when a box goes out of scope like `b` does at the end of `main`, it will be deallocated. The deallocation happens for both the box (stored on the stack) and the data it points to (stored on the heap).

Putting a single value on the heap isn't very useful, so you won't use boxes by themselves in the way that Listing 15-1 does very often. Having values like a single `i32` on the stack, where they're stored by default is more appropriate in the majority of cases. Let's get into a case where boxes allow us to define types that we wouldn't be allowed to if we didn't have boxes.

Boxes Enable Recursive Types

Rust needs to know at compile time how much space a type takes up. One kind of type whose size can't be known at compile time is a *recursive type* where a value can have as part of itself another value of the same type. This nesting of values could theoretically continue infinitely, so Rust doesn't know how much space a value of a recursive type needs. Boxes have a known size, however, so by inserting a box in a recursive type definition, we are allowed to have recursive types.

Let's explore the *cons list*, a data type common in functional programming languages, to illustrate this concept. The cons list type we're going to define is straightforward except for the recursion, so the concepts in this example will be useful any time you get into more complex situations involving recursive types.

A cons list is a list where each item in the list contains two things: the value of the current item and the next item. The last item in the list contains only a value called `Nil` without a next item.

> ### More Information About the Cons List
>
> A *cons list* is a data structure that comes from the Lisp programming language and its dialects. In Lisp, the `cons` function (short for "construct function") constructs a new list from its two arguments, which usually are a single value and another list.
>
> The cons function concept has made its way into more general functional programming jargon; "to cons x onto y" informally means to construct a new container instance by putting the element x at the start of this new container, followed by the container y.
>
> A cons list is produced by recursively calling the `cons` function. The canonical name to denote the base case of the recursion is `Nil`, which announces the end of the list. Note that this is not the same as the "null" or "nil" concept from Chapter 6, which is an invalid or absent value.

Note that while functional programming languages use cons lists frequently, this isn't a commonly used data structure in Rust. Most of the time when you have a list of items in Rust, `Vec<T>` is a better choice. Other, more complex recursive data types *are* useful in various situations in Rust, but by starting with the cons list, we can explore how boxes let us define a recursive data type without much distraction.

Listing 15-2 contains an enum definition for a cons list. Note that this won't compile quite yet because this is type doesn't have a known size, which we'll demonstrate:

Filename: src/main.rs

```
enum List {
    Cons(i32, List),
    Nil,
}
```

Listing 15-2: The first attempt of defining an enum to represent a cons list data structure of `i32` values

---

> Note: We're choosing to implement a cons list that only holds `i32` values for the purposes of this example. We could have implemented it using generics, as we discussed in Chapter 10, in order to define a cons list type that could store values of any type.

Using our cons list type to store the list `1, 2, 3` would look like the code in Listing 15-3:

Filename: src/main.rs

```
use List::{Cons, Nil};

fn main() {
    let list = Cons(1, Cons(2, Cons(3, Nil)));
}
```

Listing 15-3: Using the `List` enum to store the list `1, 2, 3`

The first `Cons` value holds `1` and another `List` value. This `List` value is another `Cons` value that holds `2` and another `List` value. This is one more `Cons` value that holds `3` and a `List` value, which is finally `Nil`, the non-recursive variant that signals the end of the list.

If we try to compile the above code, we get the error shown in Listing 15-4:

```
error[E0072]: recursive type `List` has infinite size
 -->
  |
1 | enum List {
  | ^^^^^^^^^ recursive type has infinite size
2 |     Cons(i32, List),
  |     --------------- recursive without indirection
  |
  = help: insert indirection (e.g., a `Box`, `Rc`, or `&`) at some point to
  make `List` representable
```

Listing 15-4: The error we get when attempting to define a recursive enum

The error says this type 'has infinite size'. The reason is the way we've defined `List` is with a variant that is recursive: it holds another value of itself directly. This means Rust can't figure out how much space it needs in order to store a `List` value. Let's break this down a bit: first let's look at how Rust decides how much space it needs to store a value of a non-recursive type.

Computing the Size of a Non-Recursive Type

Recall the `Message` enum we defined in Listing 6-2 when we discussed enum definitions in Chapter 6:

```
enum Message {
    Quit,
    Move { x: i32, y: i32 },
    Write(String),
    ChangeColor(i32, i32, i32),
}
```

To determine how much space to allocate for a `Message` value, Rust goes through each of the variants to see which variant needs the most space. Rust sees that `Message::Quit` doesn't need any space, `Message::Move` needs enough space to store two `i32` values, and so forth. Since only one variant will end up being used, the most space a `Message` value will need is the space it would take to store the largest of its variants.

Contrast this to what happens when Rust tries to determine how much space a recursive type like the `List` enum in Listing 15-2 needs. The compiler starts by looking at the `Cons` variant, which holds a value of type `i32` and a value of type `List`. Therefore, `Cons` needs an amount of space equal to the size of an `i32` plus the size of a `List`. To figure out how much memory the `List` type needs, the compiler looks at the variants, starting with the `Cons` variant. The `Cons` variant holds a value of type `i32` and a value of type `List`, and this continues infinitely, as shown in Figure 15-5.

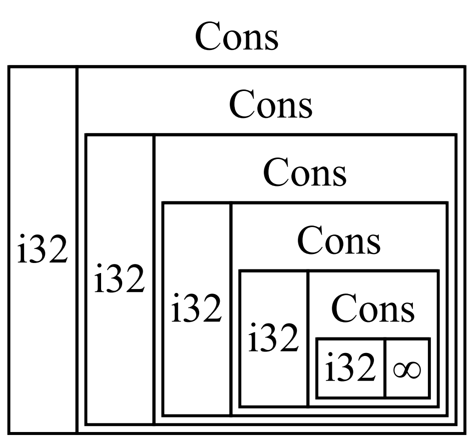


Figure 15-5: An infinite `List` consisting of infinite `Cons` variants

Using `Box<T>` to Get a Recursive Type with a Known Size

Rust can't figure out how much space to allocate for recursively defined types, so the compiler gives the error in Listing 15-4. The error does include this helpful suggestion:

```
= help: insert indirection (e.g., a `Box`, `Rc`, or `&`) at some point to
        make `List` representable
```

In this suggestion, "indirection" means that instead of storing a value directly, we're going to store the value indirectly by storing a pointer to the value instead.

Because a `Box<T>` is a pointer, Rust always knows how much space a `Box<T>` needs: a pointer's size doesn't change based on the amount of data it's pointing to.

So we can put a `Box` inside the `Cons` variant instead of another `List` value directly. The `Box` will point to the next `List` value that will be on the heap, rather than inside the `Cons` variant. Conceptually, we still have a list created by lists "holding" other lists, but the way this concept is implemented is now more like the items being next to one another rather than inside one another.

We can change the definition of the `List` enum from Listing 15-2 and the usage of the `List` from Listing 15-3 to the code in Listing 15-6, which will compile:

Filename: src/main.rs

```
enum List {
    Cons(i32, Box<List>),
    Nil,
}

use List::{Cons, Nil};

fn main() {
    let list = Cons(1,
        Box::new(Cons(2,
            Box::new(Cons(3,
                Box::new(Nil))))));
}
```

Listing 15-6: Definition of `List` that uses `Box<T>` in order to have a known size

The `Cons` variant will need the size of an `i32` plus the space to store the box's pointer data. The `Nil` variant stores no values, so it needs less space than the `Cons` variant. We now know that any `List` value will take up the size of an `i32` plus the size of a box's pointer data. By using a box, we've broken the infinite, recursive chain so the compiler is able to figure out the size it needs to store a `List` value. Figure 15-7 shows what the `Cons` variant looks like now:

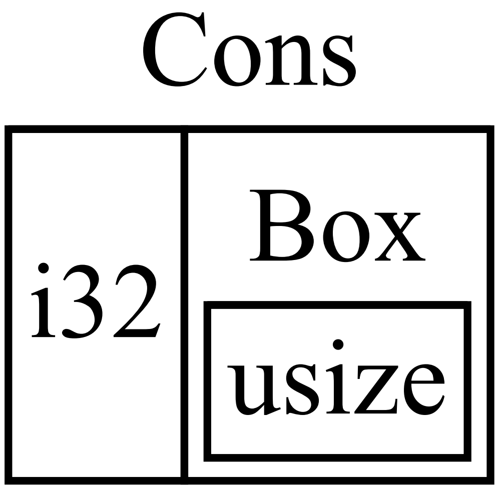


Figure 15-7: A `List` that is not infinitely sized since `Cons` holds a `Box`

Boxes only provide the indirection and heap allocation; they don't have any other special abilities like those we'll see with the other smart pointer types. They also don't have any performance overhead that these special abilities incur, so they can be useful in cases like the cons list where the indirection is the only feature we need. We'll look at more use cases for boxes in Chapter 17, too.

The `Box<T>` type is a smart pointer because it implements the `Deref` trait, which allows `Box<T>` values to be treated like references. When a `Box<T>` value goes out of scope, the heap data that the box is pointing to is cleaned up as well because of the `Box<T>` type's `Drop` trait implementation. Let's explore these two types in more detail; these traits are going to be even more important to the functionality provided by the other smart pointer types we'll be discussing in the rest of this chapter.

Treating Smart Pointers like Regular References with the `Deref` Trait

Implementing `Deref` trait allows us to customize the behavior of the *dereference operator* `*`(as opposed to the multiplication or glob operator). By implementing `Deref` in such a way that a smart pointer can be treated like a regular reference, we can write code that operates on references and use that code with smart pointers too.

Let's first take a look at how `*` works with regular references, then try and define our own type like `Box<T>` and see why `*` doesn't work like a reference. We'll explore how implementing the `Deref` trait makes it possible for smart pointers to work in a similar way as references. Finally, we'll look at the *deref coercion* feature of Rust and how that lets us work with either references or smart pointers.

Following the Pointer to the Value with `*`

A regular reference is a type of pointer, and one way to think of a pointer is that it's an arrow to a value stored somewhere else. In Listing 15-8, let's create a reference to an `i32` value then use the dereference operator to follow the reference to the data:

Filename: src/main.rs

```
fn main() {
    let x = 5;
    let y = &x;

    assert_eq!(5, x);
    assert_eq!(5, *y);
}
```

Listing 15-8: Using the dereference operator to follow a reference to an `i32` value

The variable `x` holds an `i32` value, `5`. We set `y` equal to a reference to `x`. We can assert that `x` is equal to `5`. However, if we want to make an assertion about the value in `y`, we have to use `*y` to follow the reference to the value that the reference is pointing to (hence *de-reference*). Once we de-reference `y`, we have access to the integer value `y` is pointing to that we can compare with `5`.

If we try to write `assert_eq!(5, y);` instead, we'll get this compilation error:

```
error[E0277]: the trait bound `{integer}: std::cmp::PartialEq<&{integer}>` is
not satisfied
 --> <assert_eq macros>:5:19
  |
5 | if ! ( * left_val == * right_val ) {
  |                   ^^ can't compare `{integer}` with `&{integer}`
  |
  = help: the trait `std::cmp::PartialEq<&{integer}>` is not implemented for
  `{integer}`
```

Comparing a reference to a number with a number isn't allowed because they're different types. We have to use `*` to follow the reference to the value it's pointing to.

Using `Box<T>` Like a Reference

We can rewrite the code in Listing 15-8 to use a `Box<T>` instead of a reference, and the dereference operator will work the same way as shown in Listing 15-9:

Filename: src/main.rs

```
fn main() {
    let x = 5;
    let y = Box::new(x);

    assert_eq!(5, x);
    assert_eq!(5, *y);
}
```

Listing 15-9: Using the dereference operator on a `Box<i32>`

The only part of Listing 15-8 that we changed was to set `y` to be an instance of a box pointing to the value in `x` rather than a reference pointing to the value of `x`. In the last assertion, we can use the dereference operator to follow the box's pointer in the same way that we did when `y` was a reference. Let's explore what is special about `Box<T>` that enables us to do this by defining our own box type.

Defining Our Own Smart Pointer

Let's build a smart pointer similar to the `Box<T>` type that the standard library has provided for us, in order to experience that smart pointers don't behave like references by default. Then we'll learn about how to add the ability to use the dereference operator.

`Box<T>` is ultimately defined as a tuple struct with one element, so Listing 15-10 defines a `MyBox<T>` type in the same way. We'll also define a `new` function to match the `new` function defined on `Box<T>`:

Filename: src/main.rs

```
struct MyBox<T>(T);

impl<T> MyBox<T> {
    fn new(x: T) -> MyBox<T> {
        MyBox(x)
    }
}
```

Listing 15-10: Defining a `MyBox<T>` type

We define a struct named `MyBox` and declare a generic parameter `T`, since we want our type to be able to hold values of any type. `MyBox` is a tuple struct with one element of type `T`. The

`MyBox::new` function takes one parameter of type `T` and returns a `MyBox` instance that holds the value passed in.

Let's try adding the code from Listing 15-9 to the code in Listing 15-10 and changing `main` to use the `MyBox<T>` type we've defined instead of `Box<T>`. The code in Listing 15-11 won't compile because Rust doesn't know how to dereference `MyBox`:

Filename: src/main.rs

```
fn main() {
    let x = 5;
    let y = MyBox::new(x);

    assert_eq!(5, x);
    assert_eq!(5, *y);
}
```

Listing 15-11: Attempting to use `MyBox<T>` in the same way we were able to use references and `Box<T>`

The compilation error we get is:

```
error: type `MyBox<{integer}>` cannot be dereferenced
  --> src/main.rs:14:19
   |
14 |     assert_eq!(5, *y);
   |                   ^^
```

Our `MyBox<T>` type can't be dereferenced because we haven't implemented that ability on our type. To enable dereferencing with the `*` operator, we can implement the `Deref` trait.

Implementing the `Deref` Trait Defines How To Treat a Type Like a Reference

As we discussed in Chapter 10, in order to implement a trait, we need to provide implementations for the trait's required methods. The `Deref` trait, provided by the standard library, requires implementing one method named `deref` that borrows `self` and returns a reference to the inner data. Listing 15-12 contains an implementation of `Deref` to add to the definition of `MyBox`:

Filename: src/main.rs

```
use std::ops::Deref;

impl<T> Deref for MyBox<T> {
    type Target = T;

    fn deref(&self) -> &T {
        &self.0
    }
}
```

Listing 15-12: Implementing `Deref` on `MyBox<T>`

The `type Target = T;` syntax defines an associated type for this trait to use. Associated types are a slightly different way of declaring a generic parameter that you don't need to worry about too much for now; we'll cover it in more detail in Chapter 19.

We filled in the body of the `deref` method with `&self.0` so that `deref` returns a reference to the value we want to access with the `*` operator. The `main` function from Listing 15-11 that calls `*` on the `MyBox<T>` value now compiles and the assertions pass!

Without the `Deref` trait, the compiler can only dereference `&` references. The `Deref` trait's `deref` method gives the compiler the ability to take a value of any type that implements `Deref` and call the `deref` method in order to get a `&` reference that it knows how to dereference.

When we typed `*y` in Listing 15-11, what Rust actually ran behind the scenes was this code:

```
*(y.deref())
```

Rust substitutes the `*` operator with a call to the `deref` method and then a plain dereference so that we don't have to think about when we have to call the `deref` method or not. This feature of Rust lets us write code that functions identically whether we have a regular reference or a type that implements `Deref`.

The reason the `deref` method returns a reference to a value, and why the plain dereference outside the parentheses in `*(y.deref())` is still necessary, is because of ownership. If the `deref` method returned the value directly instead of a reference to the value, the value would be moved out of `self`. We don't want to take ownership of the inner value inside `MyBox<T>` in this case and in most cases where we use the dereference operator.

Note that replacing `*` with a call to the `deref` method and then a call to `*` happens once, each time we type a `*` in our code. The substitution of `*` does not recurse infinitely. That's how we end up with data of type `i32`, which matches the `5` in the `assert_eq!` in Listing 15-11.

Implicit Deref Coercions with Functions and Methods

Deref coercion is a convenience that Rust performs on arguments to functions and methods. Deref coercion converts a reference to a type that implements `Deref` into a reference to a type that `Deref` can convert the original type into. Deref coercion happens automatically when we pass a reference to a value of a particular type as an argument to a function or method that doesn't match the type of the parameter in the function or method definition, and there's a sequence of calls to the `deref` method that will convert the type we provided into the type that the parameter needs.

Deref coercion was added to Rust so that programmers writing function and method calls don't need to add as many explicit references and dereferences with `&` and `*`. This feature also lets us write more code that can work for either references or smart pointers.

To illustrate deref coercion in action, let's use the `MyBox<T>` type we defined in Listing 15-10 as well as the implementation of `Deref` that we added in Listing 15-12. Listing 15-13 shows the definition of a function that has a string slice parameter:

Filename: src/main.rs

```
fn hello(name: &str) {
    println!("Hello, {}!", name);
}
```

Listing 15-13: A `hello` function that has the parameter `name` of type `&str`

We can call the `hello` function with a string slice as an argument, like `hello("Rust");` for example. Deref coercion makes it possible for us to call `hello` with a reference to a value of type `MyBox<String>`, as shown in Listing 15-14:

Filename: src/main.rs

```
fn main() {
    let m = MyBox::new(String::from("Rust"));
    hello(&m);
}
```

Listing 15-14: Calling `hello` with a reference to a `MyBox<String>`, which works because of deref coercion

Here we're calling the `hello` function with the argument `&m`, which is a reference to a `MyBox<String>` value. Because we implemented the `Deref` trait on `MyBox<T>` in Listing 15-12, Rust can turn `&MyBox<String>` into `&String` by calling `deref`. The standard library provides an implementation of `Deref` on `String` that returns a string slice, which we can see in the API documentation for `Deref`. Rust calls `deref` again to turn the `&String` into `&str`, which matches the `hello` function's definition.

If Rust didn't implement deref coercion, in order to call `hello` with a value of type `&MyBox<String>`, we'd have to write the code in Listing 15-15 instead of the code in Listing 15-14:

Filename: src/main.rs

```
fn main() {
    let m = MyBox::new(String::from("Rust"));
    hello(&(*m)[..]);
}
```

Listing 15-15: The code we'd have to write if Rust didn't have deref coercion

The `(*m)` is dereferencing the `MyBox<String>` into a `String`. Then the `&` and `[..]` are taking a string slice of the `String` that is equal to the whole string to match the signature of `hello`. The code without deref coercions is harder to read, write, and understand with all of these symbols involved. Deref coercion makes it so that Rust takes care of these conversions for us automatically.

When the `Deref` trait is defined for the types involved, Rust will analyze the types and use `Deref::deref` as many times as it needs in order to get a reference to match the parameter's type. This is resolved at compile time, so there is no run-time penalty for taking advantage of deref coercion!

How Deref Coercion Interacts with Mutability

Similar to how we use the `Deref` trait to override `*` on immutable references, Rust provides a `DerefMut` trait for overriding `*` on mutable references.

Rust does deref coercion when it finds types and trait implementations in three cases:

- From `&T` to `&U` when `T: Deref<Target=U>`.
- From `&mut T` to `&mut U` when `T: DerefMut<Target=U>`.
- From `&mut T` to `&U` when `T: Deref<Target=U>`.

The first two cases are the same except for mutability. The first case says that if you have a `&T`, and `T` implements `Deref` to some type `U`, you can get a `&U` transparently. The second case states that the same deref coercion happens for mutable references.

The last case is trickier: Rust will also coerce a mutable reference to an immutable one. The reverse is *not* possible though: immutable references will never coerce to mutable ones. Because of the borrowing rules, if you have a mutable reference, that mutable reference must be the only reference to that data (otherwise, the program wouldn't compile). Converting one mutable reference to one immutable reference will never break the borrowing rules. Converting an immutable reference to a mutable reference would require that there was only one immutable reference to that data, and the borrowing rules don't guarantee that. Therefore, Rust can't make the assumption that converting an immutable reference to a mutable reference is possible.

The `Drop` Trait Runs Code on Cleanup

The second trait important to the smart pointer pattern is `Drop`, which lets us customize what happens when a value is about to go out of scope. We can provide an implementation for the `Drop` trait on any type, and the code we specify can be used to release resources like files or network connections. We're introducing `Drop` in the context of smart pointers because the functionality of the `Drop` trait is almost always used when implementing a smart pointer. For example, `Box<T>` customizes `Drop` in order to deallocate the space on the heap that the box points to.

In some languages, the programmer must call code to free memory or resources every time they finish using an instance of a smart pointer. If they forget, the system might become overloaded and crash. In Rust, we can specify that a particular bit of code should be run whenever a value goes out of scope, and the compiler will insert this code automatically.

This means we don't need to be careful about placing clean up code everywhere in a program that an instance of a particular type is finished with, but we still won't leak resources!

We specify the code to run when a value goes out of scope by implementing the `Drop` trait. The `Drop` trait requires us to implement one method named `drop` that takes a mutable reference to `self`. In order to be able to see when Rust calls `drop`, let's implement `drop` with `println!` statements for now.

Listing 15-8 shows a `CustomSmartPointer` struct whose only custom functionality is that it will print out `Dropping CustomSmartPointer!` when the instance goes out of scope. This will demonstrate when Rust runs the `drop` function:

Filename: src/main.rs

```
struct CustomSmartPointer {
    data: String,
}

impl Drop for CustomSmartPointer {
    fn drop(&mut self) {
        println!("Dropping CustomSmartPointer with data `{}`!", self.data);
    }
}

fn main() {
    let c = CustomSmartPointer { data: String::from("my stuff") };
    let d = CustomSmartPointer { data: String::from("other stuff") };
    println!("CustomSmartPointers created.");
}
```

Listing 15-8: A `CustomSmartPointer` struct that implements the `Drop` trait, where we would put our clean up code.

The `Drop` trait is included in the prelude, so we don't need to import it. We implement the `Drop` trait on `CustomSmartPointer`, and provide an implementation for the `drop` method that calls `println!`. The body of the `drop` function is where you'd put any logic that you wanted to run when an instance of your type goes out of scope. We're choosing to print out some text here in order to demonstrate when Rust will call `drop`.

In `main`, we create a new instance of `CustomSmartPointer` and then print out `CustomSmartPointer created.`. At the end of `main`, our instance of `CustomSmartPointer` will go out of scope, and Rust will call the code we put in the `drop` method, printing our final message. Note that we didn't need to call the `drop` method explicitly.

When we run this program, we'll see the following output:

```
CustomSmartPointers created.
Dropping CustomSmartPointer with data `other stuff`!
Dropping CustomSmartPointer with data `my stuff`!
```

Rust automatically called `drop` for us when our instance went out of scope, calling the code we specified. Variables are dropped in the reverse order of the order in which they were created, so `d` was dropped before `c`. This is just to give you a visual guide to how the drop method works, but usually you would specify the cleanup code that your type needs to run rather than a print message.

Dropping a Value Early with `std::mem::drop`

Rust inserts the call to `drop` automatically when a value goes out of scope, and it's not straightforward to disable this functionality. Disabling `drop` isn't usually necessary; the whole point of the `Drop` trait is that it's taken care of automatically for us. Occasionally you may find that you want to clean up a value early. One example is when using smart pointers that manage locks; you may want to force the `drop` method that releases the lock to run so that other code in the same scope can acquire the lock. First, let's see what happens if we try to call the `Drop` trait's `drop` method ourselves by modifying the `main` function from Listing 15-8 as shown in Listing 15-9:

Filename: src/main.rs

```
fn main() {
    let c = CustomSmartPointer { data: String::from("some data") };
    println!("CustomSmartPointer created.");
    c.drop();
    println!("CustomSmartPointer dropped before the end of main.");
}
```

Listing 15-9: Attempting to call the `drop` method from the `Drop` trait manually to clean up early

If we try to compile this, we'll get this error:

```
error[E0040]: explicit use of destructor method
  --> src/main.rs:15:7
   |
15 |     c.drop();
   |       ^^^^ explicit destructor calls not allowed
```

This error message says we're not allowed to explicitly call `drop`. The error message uses the term *destructor*, which is the general programming term for a function that cleans up an instance. A *destructor* is analogous to a *constructor* that creates an instance. The `drop` function in Rust is one particular destructor.

Rust doesn't let us call `drop` explicitly because Rust would still automatically call `drop` on the value at the end of `main`, and this would be a *double free* error since Rust would be trying to clean up the same value twice.

Because we can't disable the automatic insertion of `drop` when a value goes out of scope, and we can't call the `drop` method explicitly, if we need to force a value to be cleaned up early, we can use the `std::mem::drop` function.

The `std::mem::drop` function is different than the `drop` method in the `Drop` trait. We call it by passing the value we want to force to be dropped early as an argument. `std::mem::drop` is in the prelude, so we can modify `main` from Listing 15-8 to call the `drop` function as shown in Listing 15-10:

Filename: src/main.rs

```
fn main() {
    let c = CustomSmartPointer { data: String::from("some data") };
    println!("CustomSmartPointer created.");
    drop(c);
    println!("CustomSmartPointer dropped before the end of main.");
}
```

Listing 15-10: Calling `std::mem::drop` to explicitly drop a value before it goes out of scope

Running this code will print the following:

```
CustomSmartPointer created.
Dropping CustomSmartPointer!
CustomSmartPointer dropped before the end of main.
```

The `Dropping CustomSmartPointer!` is printed between `CustomSmartPointer created.` and `CustomSmartPointer dropped before the end of main.`, showing that the `drop` method code is called to drop `c` at that point.

Code specified in a `Drop` trait implementation can be used in many ways to make cleanup convenient and safe: we could use it to create our own memory allocator, for instance! With the `Drop` trait and Rust's ownership system, you don't have to remember to clean up after yourself, Rust takes care of it automatically.

We also don't have to worry about accidentally cleaning up values still in use because that would cause a compiler error: the ownership system that makes sure references are always valid will also make sure that `drop` only gets called once when the value is no longer being used.

Now that we've gone over `Box<T>` and some of the characteristics of smart pointers, let's talk about a few other smart pointers defined in the standard library.

`Rc<T>`, the Reference Counted Smart Pointer

In the majority of cases, ownership is clear: you know exactly which variable owns a given value. However, there are cases when a single value may have multiple owners. For example, in graph data structures, multiple edges may point to the same node, and that node is conceptually owned by all of the edges that point to it. A node shouldn't be cleaned up unless it doesn't have any edges pointing to it.

In order to enable multiple ownership, Rust has a type called `Rc<T>`. Its name is an abbreviation for reference counting. *Reference counting* means keeping track of the number of references to a value in order to know if a value is still in use or not. If there are zero references to a value, the value can be cleaned up without any references becoming invalid.

Imagine it like a TV in a family room. When one person enters to watch TV, they turn it on. Others can come into the room and watch the TV. When the last person leaves the room, they turn the TV off because it's no longer being used. If someone turns the TV off while others are still watching it, there'd be uproar from the remaining TV watchers!

`Rc<T>` is used when we want to allocate some data on the heap for multiple parts of our program to read, and we can't determine at compile time which part will finish using the data last. If we did know which part would finish last, we could just make that the owner of the data and the normal ownership rules enforced at compile time would kick in.

Note that `Rc<T>` is only for use in single-threaded scenarios; Chapter 16 on concurrency will cover how to do reference counting in multithreaded programs.

Using `Rc<T>` to Share Data

Let's return to our cons list example from Listing 15-6, as we defined it using `Box<T>`. This time, we want to create two lists that both share ownership of a third list, which conceptually will look something like Figure 15-11:

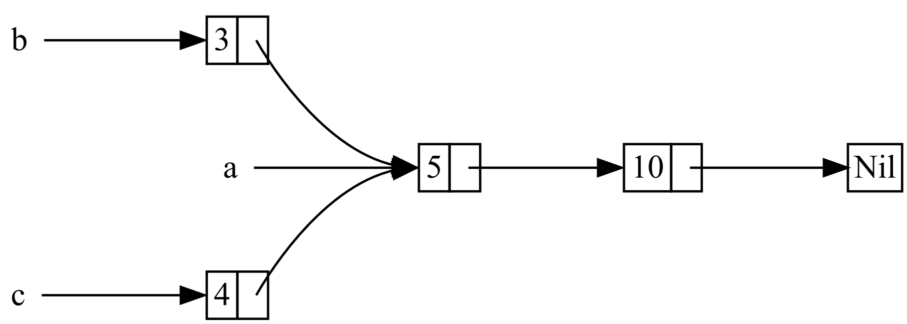


Figure 15-11: Two lists, `b` and `c`, sharing ownership of a third list, `a`

We'll create list `a` that contains 5 and then 10, then make two more lists: `b` that starts with 3 and `c` that starts with 4. Both `b` and `c` lists will then continue on to the first `a` list containing 5 and 10. In other words, both lists will try to share the first list containing 5 and 10.

Trying to implement this using our definition of `List` with `Box<T>` won't work, as shown in Listing 15-12:

Filename: src/main.rs

```
enum List {
    Cons(i32, Box<List>),
    Nil,
}

use List::{Cons, Nil};

fn main() {
    let a = Cons(5,
        Box::new(Cons(10,
            Box::new(Nil))));
    let b = Cons(3, Box::new(a));
    let c = Cons(4, Box::new(a));
}
```

Listing 15-12: Demonstrating we're not allowed to have two lists using `Box<T>` that try to share ownership of a third list

If we compile this, we get this error:

```
error[E0382]: use of moved value: `a`
  --> src/main.rs:13:30
   |
12 |     let b = Cons(3, Box::new(a));
   |                              - value moved here
13 |     let c = Cons(4, Box::new(a));
   |                              ^ value used here after move
   |
   = note: move occurs because `a` has type `List`, which does not
   implement the `Copy` trait
```

The `Cons` variants own the data they hold, so when we create the `b` list, `a` is moved into `b` and `b` owns `a`. Then, when we try to use `a` again when creating `c`, we're not allowed to because `a` has been moved.

We could change the definition of `Cons` to hold references instead, but then we'd have to specify lifetime parameters. By specifying lifetime parameters, we'd be specifying that every element in the list will live at least as long as the list itself. The borrow checker wouldn't let us compile `let a = Cons(10, &Nil);` for example, since the temporary `Nil` value would be dropped before `a` could take a reference to it.

Instead, we'll change our definition of `List` to use `Rc<T>` in place of `Box<T>` as shown here in Listing 15-13. Each `Cons` variant now holds a value and an `Rc` pointing to a `List`. When we create `b`, instead of taking ownership of `a`, we clone the `Rc` that `a` is holding, which increases the number of references from 1 to 2 and lets `a` and `b` share ownership of the data in that `Rc`. We also clone `a` when creating `c`, which increases the number of references from 2 to 3. Every time we call `Rc::clone`, the reference count to the data within the `Rc` is increased, and the data won't be cleaned up unless there are zero references to it:

Filename: src/main.rs

```
enum List {
    Cons(i32, Rc<List>),
    Nil,
}

use List::{Cons, Nil};
use std::rc::Rc;

fn main() {
    let a = Rc::new(Cons(5, Rc::new(Cons(10, Rc::new(Nil)))));
    let b = Cons(3, Rc::clone(&a));
    let c = Cons(4, Rc::clone(&a));
}
```

Listing 15-13: A definition of `List` that uses `Rc<T>`

We need to add a `use` statement to bring `Rc` into scope because it's not in the prelude. In `main`, we create the list holding 5 and 10 and store it in a new `Rc` in `a`. Then when we create `b` and `c`, we call the `Rc::clone` function and pass a reference to the `Rc` in `a` as an argument.

We could have called `a.clone()` rather than `Rc::clone(&a)`, but Rust convention is to use `Rc::clone` in this case. The implementation of `Rc::clone` doesn't make a deep copy of all the data like most types' implementations of `clone` do. `Rc::clone` only increments the reference count, which doesn't take very much time. Deep copies of data can take a lot of time, so by using `Rc::clone` for reference counting, we can visually distinguish between the deep copy kinds of clones that might have a large impact on runtime performance and memory usage and the types of clones that increase the reference count that have a comparatively small impact on runtime performance and don't allocate new memory.

Cloning an `Rc<T>` Increases the Reference Count

Let's change our working example from Listing 15-13 so that we can see the reference counts changing as we create and drop references to the `Rc` in `a`.

In Listing 15-14, we'll change `main` so that it has an inner scope around list `c`, so that we can see how the reference count changes when `c` goes out of scope. At each point in the program where the reference count changes, we'll print out the reference count, which we can get by calling the `Rc::strong_count` function. We'll talk about why this function is named `strong_count` rather than `count` in the section later in this chapter about preventing reference cycles.

Filename: src/main.rs

```
fn main() {
    let a = Rc::new(Cons(5, Rc::new(Cons(10, Rc::new(Nil)))));
    println!("count after creating a = {}", Rc::strong_count(&a));
    let b = Cons(3, Rc::clone(&a));
    println!("count after creating b = {}", Rc::strong_count(&a));
    {
        let c = Cons(4, Rc::clone(&a));
        println!("count after creating c = {}", Rc::strong_count(&a));
    }
    println!("count after c goes out of scope = {}", Rc::strong_count(&a));
}
```

Listing 15-14: Printing out the reference count

This will print out:

```
count after creating a = 1
count after creating b = 2
count after creating c = 3
count after c goes out of scope = 2
```

We're able to see that the `Rc` in `a` has an initial reference count of one, then each time we call `clone`, the count goes up by one. When `c` goes out of scope, the count goes down by one. We don't have to call a function to decrease the reference count like we have to call `Rc::clone` to increase the reference count; the implementation of the `Drop` trait decreases the reference count automatically when an `Rc` value goes out of scope.

What we can't see from this example is that when `b` and then `a` go out of scope at the end of `main`, the count is then 0, and the `Rc` is cleaned up completely at that point. Using `Rc` allows a single value to have multiple owners, and the count will ensure that the value remains valid as long as any of the owners still exist.

`Rc<T>` allows us to share data between multiple parts of our program for reading only, via immutable references. If `Rc<T>` allowed us to have multiple mutable references too, we'd be able to violate one of the the borrowing rules that we discussed in Chapter 4: multiple mutable borrows to the same place can cause data races and inconsistencies. But being able to mutate data is very useful! In the next section, we'll discuss the interior mutability pattern and the `RefCell<T>` type that we can use in conjunction with an `Rc<T>` to work with this restriction on immutability.

`RefCell<T>` and the Interior Mutability Pattern

Interior mutability is a design pattern in Rust for allowing you to mutate data even when there are immutable references to that data, normally disallowed by the borrowing rules. To do so, the pattern uses `unsafe` code inside a data structure to bend Rust's usual rules around mutation and borrowing. We haven't yet covered unsafe code; we will in Chapter 19. We can choose to use types that make use of the interior mutability pattern when we can ensure that the borrowing rules will be followed at runtime, even though the compiler can't ensure that. The `unsafe` code involved is then wrapped in a safe API, and the outer type is still immutable.

Let's explore this by looking at the `RefCell<T>` type that follows the interior mutability pattern.

Enforcing Borrowing Rules at Runtime with `RefCell<T>`

Unlike `Rc<T>`, the `RefCell<T>` type represents single ownership over the data it holds. So, what makes `RefCell<T>` different than a type like `Box<T>`? Let's recall the borrowing rules we learned in Chapter 4:

1. At any given time, you can have *either* but not both of:

- One mutable reference.
- Any number of immutable references.

2. References must always be valid.

With references and `Box<T>`, the borrowing rules' invariants are enforced at compile time. With `RefCell<T>`, these invariants are enforced *at runtime*. With references, if you break these rules, you'll get a compiler error. With `RefCell<T>`, if you break these rules, you'll get a `panic!` .

The advantages to checking the borrowing rules at compile time are that errors will be caught sooner in the development process and there is no impact on runtime performance since all the analysis is completed beforehand. For those reasons, checking the borrowing rules at compile time is the best choice for the majority of cases, which is why this is Rust's default.

The advantage to checking the borrowing rules at runtime instead is that certain memory safe scenarios are then allowed, whereas they are disallowed by the compile time checks. Static analysis, like the Rust compiler, is inherently conservative. Some properties of code are impossible to detect by analyzing the code: the most famous example is the Halting Problem, which is out of scope of this book but an interesting topic to research if you're interested.

Because some analysis is impossible, if the Rust compiler can't be sure the code complies with the ownership rules, it may reject a correct program; in this way, it is conservative. If Rust were to accept an incorrect program, users would not be able to trust in the guarantees Rust makes. However, if Rust rejects a correct program, the programmer will be inconvenienced, but nothing catastrophic can occur. `RefCell<T>` is useful when you yourself are sure that your code follows the borrowing rules, but the compiler is not able to understand and guarantee that.

Similarly to `Rc<T>`, `RefCell<T>` is only for use in single-threaded scenarios and will give you a compile time error if you try in a multithreaded context. We'll talk about how to get the functionality of `RefCell<T>` in a multithreaded program in Chapter 16.

To recap the reasons to choose `Box<T>`, `Rc<T>`, or `RefCell<T>`:

- `Rc<T>` enables multiple owners of the same data; `Box<T>` and `RefCell<T>` have single owners.
- `Box<T>` allows immutable or mutable borrows checked at compile time; `Rc<T>` only allows immutable borrows checked at compile time; `RefCell<T>` allows immutable or mutable borrows checked at runtime.
- Because `RefCell<T>` allows mutable borrows checked at runtime, we can mutate the value inside the `RefCell<T>` even when the `RefCell<T>` is itself immutable.

The last reason is the *interior mutability* pattern. Let's look at a case when interior mutability is useful and discuss how this is possible.

Interior Mutability: A Mutable Borrow to an Immutable Value

A consequence of the borrowing rules is that when we have an immutable value, we can't borrow it mutably. For example, this code won't compile:

```
fn main() {
    let x = 5;
    let y = &mut x;
}
```

If we try to compile this, we'll get this error:

```
error[E0596]: cannot borrow immutable local variable `x` as mutable
 --> src/main.rs:3:18
  |
2 |     let x = 5;
  |         - consider changing this to `mut x`
3 |     let y = &mut x;
  |                  ^ cannot borrow mutably
```

However, there are situations where it would be useful for a value to be able to mutate itself in its methods, but to other code, the value would appear to be immutable. Code outside the value's methods would not be able to mutate the value. `RefCell<T>` is one way to get the ability to have interior mutability. `RefCell<T>` isn't getting around the borrowing rules completely, but the borrow checker in the compiler allows this interior mutability and the borrowing rules are checked at runtime instead. If we violate the rules, we'll get a `panic!` instead of a compiler error.

Let's work through a practical example where we can use `RefCell<T>` to make it possible to mutate an immutable value and see why that's useful.

A Use Case for Interior Mutability: Mock Objects

A *test double* is the general programming concept for a type that stands in the place of another type during testing. *Mock objects* are specific types of test doubles that record what happens during a test so that we can assert that the correct actions took place.

While Rust doesn't have objects in the exact same sense that other languages have objects, and Rust doesn't have mock object functionality built into the standard library like some other languages do, we can definitely create a struct that will serve the same purposes as a mock object.

Here's the scenario we'd like to test: we're creating a library that tracks a value against a maximum value, and sends messages based on how close to the maximum value the current value is. This could be used for keeping track of a user's quota for the number of API calls they're allowed to make, for example.

Our library is only going to provide the functionality of tracking how close to the maximum a value is, and what the messages should be at what times. Applications that use our library will be expected to provide the actual mechanism for sending the messages: the application could choose to put a message in the application, send an email, send a text message, or something else. Our library doesn't need to know about that detail; all it needs is something that implements a trait we'll provide called `Messenger`. Listing 15-15 shows our library code:

Filename: src/lib.rs

```
pub trait Messenger {
    fn send(&self, msg: &str);
}

pub struct LimitTracker<'a, T: 'a + Messenger> {
    messenger: &'a T,
    value: usize,
    max: usize,
}

impl<'a, T> LimitTracker<'a, T>
    where T: Messenger {
    pub fn new(messenger: &T, max: usize) -> LimitTracker<T> {
        LimitTracker {
            messenger,
            value: 0,
            max,
        }
    }

    pub fn set_value(&mut self, value: usize) {
        self.value = value;

        let percentage_of_max = self.value as f64 / self.max as f64;

        if percentage_of_max >= 0.75 && percentage_of_max < 0.9 {
            self.messenger.send("Warning: You've used up over 75% of your
quota!");
        } else if percentage_of_max >= 0.9 && percentage_of_max < 1.0 {
            self.messenger.send("Urgent warning: You've used up over 90% of your
quota!");
        } else if percentage_of_max >= 1.0 {
            self.messenger.send("Error: You are over your quota!");
        }
    }
}
```

Listing 15-15: A library to keep track of how close to a maximum value a value is, and warn when the value is at certain levels

One important part of this code is that the `Messenger` trait has one method, `send`, that takes an immutable reference to `self` and text of the message. This is the interface our mock object will need to have. The other important part is that we want to test the behavior of the `set_value` method on the `LimitTracker`. We can change what we pass in for the `value` parameter, but `set_value` doesn't return anything for us to make assertions on. What we want to be able to say is that if we create a `LimitTracker` with something that implements the `Messenger` trait and a particular value for `max`, when we pass different numbers for `value`, the messenger gets told to send the appropriate messages.

What we need is a mock object that, instead of actually sending an email or text message when we call `send`, will only keep track of the messages it's told to send. We can create a new instance of the mock object, create a `LimitTracker` that uses the mock object, call the `set_value` method on `LimitTracker`, then check that the mock object has the messages we expect. Listing 15-16 shows an attempt of implementing a mock object to do just that, but that the borrow checker won't allow:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    use super::*;

    struct MockMessenger {
        sent_messages: Vec<String>,
    }

    impl MockMessenger {
        fn new() -> MockMessenger {
            MockMessenger { sent_messages: vec![] }
        }
    }

    impl Messenger for MockMessenger {
        fn send(&self, message: &str) {
            self.sent_messages.push(String::from(message));
        }
    }

    #[test]
    fn it_sends_an_over_75_percent_warning_message() {
        let mock_messenger = MockMessenger::new();
        let mut limit_tracker = LimitTracker::new(&mock_messenger, 100);

        limit_tracker.set_value(80);

        assert_eq!(mock_messenger.sent_messages.len(), 1);
    }
}
```

Listing 15-16: An attempt to implement a `MockMessenger` that isn't allowed by the borrow checker

This test code defines a `MockMessenger` struct that has a `sent_messages` field with a `Vec` of `String` values to keep track of the messages it's told to send. We also defined an associated function `new` to make it convenient to create new `MockMessenger` values that start with an empty list of messages. We then implement the `Messenger` trait for `MockMessenger` so that we can give a `MockMessenger` to a `LimitTracker`. In the definition of the `send` method, we take the message passed in as a parameter and store it in the `MockMessenger` list of `sent_messages`.

In the test, we're testing what happens when the `LimitTracker` is told to set `value` to something that's over 75% of the `max` value. First, we create a new `MockMessenger`, which will start with an empty list of messages. Then we create a new `LimitTracker` and give it a reference to the new `MockMessenger` and a `max` value of 100. We call the `set_value` method on the `LimitTracker` with a value of 80, which is more than 75% of 100. Then we assert that the list of messages that the `MockMessenger` is keeping track of should now have one message in it.

There's one problem with this test, however:

```
error[E0596]: cannot borrow immutable field `self.sent_messages` as mutable
  --> src/lib.rs:46:13
   |
45 |         fn send(&self, message: &str) {
   |                 ----- use `&mut self` here to make mutable
46 |             self.sent_messages.push(String::from(message));
   |             ^^^^^^^^^^^^^^^^^^ cannot mutably borrow immutable field
```

We can't modify the `MockMessenger` to keep track of the messages because the `send` method takes an immutable reference to `self`. We also can't take the suggestion from the error text to use `&mut self` instead because then the signature of `send` wouldn't match the signature in the `Messenger` trait definition (feel free to try and see what error message you get).

This is where interior mutability can help! We're going to store the `sent_messages` within a `RefCell`, and then the `send` message will be able to modify `sent_messages` to store the messages we've seen. Listing 15-17 shows what that looks like:

Filename: src/lib.rs

```
#[cfg(test)]
mod tests {
    use super::*;
    use std::cell::RefCell;

    struct MockMessenger {
        sent_messages: RefCell<Vec<String>>,
    }

    impl MockMessenger {
        fn new() -> MockMessenger {
            MockMessenger { sent_messages: RefCell::new(vec![]) }
        }
    }

    impl Messenger for MockMessenger {
        fn send(&self, message: &str) {
            self.sent_messages.borrow_mut().push(String::from(message));
        }
    }

    #[test]
    fn it_sends_an_over_75_percent_warning_message() {
        // ...snip...

        assert_eq!(mock_messenger.sent_messages.borrow().len(), 1);
    }
}
```

Listing 15-17: Using `RefCell<T>` to be able to mutate an inner value while the outer value is considered immutable

The `sent_messages` field is now of type `RefCell<Vec<String>>` instead of `Vec<String>`. In the `new` function, we create a new `RefCell` instance around the empty vector.

For the implementation of the `send` method, the first parameter is still an immutable borrow of `self`, which matches the trait definition. We call `borrow_mut` on the `RefCell` in `self.sent_messages` to get a mutable reference to the value inside the `RefCell`, which is the vector. Then we can call `push` on the mutable reference to the vector in order to keep track of the messages seen during the test.

The last change we have to make is in the assertion: in order to see how many items are in the inner vector, we call `borrow` on the `RefCell` to get an immutable reference to the vector.

Now that we've seen how to use `RefCell<T>`, let's dig into how it works!

`RefCell<T>` Keeps Track of Borrows at Runtime

When creating immutable and mutable references we use the `&` and `&mut` syntax, respectively. With `RefCell<T>`, we use the `borrow` and `borrow_mut` methods, which are part of the safe API that belongs to `RefCell<T>`. The `borrow` method returns the smart pointer type `Ref`, and `borrow_mut` returns the smart pointer type `RefMut`. Both types implement `Deref` so we can treat them like regular references.

The `RefCell<T>` keeps track of how many `Ref` and `RefMut` smart pointers are currently active. Every time we call `borrow`, the `RefCell<T>` increases its count of how many immutable borrows are active. When a `Ref` value goes out of scope, the count of immutable borrows goes down by one. Just like the compile time borrowing rules, `RefCell<T>` lets us have many immutable borrows or one mutable borrow at any point in time.

If we try to violate these rules, rather than getting a compiler error like we would with references, the implementation of `RefCell<T>` will `panic!` at runtime. Listing 15-18 shows a modification to the implementation of `send` from Listing 15-17 where we're deliberately trying to create two mutable borrows active for the same scope in order to illustrate that `RefCell<T>` prevents us from doing this at runtime:

Filename: src/lib.rs

```
impl Messenger for MockMessenger {
    fn send(&self, message: &str) {
        let mut one_borrow = self.sent_messages.borrow_mut();
        let mut two_borrow = self.sent_messages.borrow_mut();

        one_borrow.push(String::from(message));
        two_borrow.push(String::from(message));
    }
}
```

Listing 15-18: Creating two mutable references in the same scope to see that `RefCell<T>` will panic

We create a variable `one_borrow` for the `RefMut` smart pointer returned from `borrow_mut`. Then we create another mutable borrow in the same way in the variable `two_borrow`. This makes two mutable references in the same scope, which isn't allowed. If we run the tests for our library, this code will compile without any errors, but the test will fail:

```
---- tests::it_sends_an_over_75_percent_warning_message stdout ----
    thread 'tests::it_sends_an_over_75_percent_warning_message' panicked at
    'already borrowed: BorrowMutError', src/libcore/result.rs:906:4
note: Run with `RUST_BACKTRACE=1` for a backtrace.
```

We can see that the code panicked with the message `already borrowed: BorrowMutError`. This is how `RefCell<T>` handles violations of the borrowing rules at runtime.

Catching borrowing errors at runtime rather than compile time means that we'd find out that we made a mistake in our code later in the development process-- and possibly not even until our code was deployed to production. There's also a small runtime performance penalty our code will incur as a result of keeping track of the borrows at runtime rather than compile time. However, using `RefCell` made it possible for us to write a mock object that can modify itself to keep track of the messages it has seen while we're using it in a context where only immutable values are allowed. We can choose to use `RefCell<T>` despite its tradeoffs to get more abilities than regular references give us.

Having Multiple Owners of Mutable Data by Combining `Rc<T>` and `RefCell<T>`

A common way to use `RefCell<T>` is in combination with `Rc<T>`. Recall that `Rc<T>` lets us have multiple owners of some data, but it only gives us immutable access to that data. If we have an `Rc<T>` that holds a `RefCell<T>`, then we can get a value that can have multiple owners *and* that we can mutate!

For example, recall the cons list example from Listing 15-13 where we used `Rc<T>` to let us have multiple lists share ownership of another list. Because `Rc<T>` only holds immutable values, we aren't able to change any of the values in the list once we've created them. Let's add in `RefCell<T>` to get the ability to change the values in the lists. Listing 15-19 shows that by using a `RefCell<T>` in the `Cons` definition, we're allowed to modify the value stored in all the lists:

Filename: src/main.rs

```
#[derive(Debug)]
enum List {
    Cons(Rc<RefCell<i32>>, Rc<List>),
    Nil,
}

use List::{Cons, Nil};
use std::rc::Rc;
use std::cell::RefCell;

fn main() {
    let value = Rc::new(RefCell::new(5));

    let a = Rc::new(Cons(Rc::clone(&value), Rc::new(Nil)));

    let b = Cons(Rc::new(RefCell::new(6)), Rc::clone(&a));
    let c = Cons(Rc::new(RefCell::new(10)), Rc::clone(&a));

    *value.borrow_mut() += 10;

    println!("a after = {:?}", a);
    println!("b after = {:?}", b);
    println!("c after = {:?}", c);
}
```

Listing 15-19: Using `Rc<RefCell<i32>>` to create a `List` that we can mutate

We create a value that's an instance of `Rc<RefCell<i32>` and store it in a variable named `value` so we can access it directly later. Then we create a `List` in `a` with a `Cons` variant that holds `value`. We need to clone `value` so that both `a` and `value` have ownership of the inner `5` value, rather than transferring ownership from `value` to `a` or having `a` borrow from `value`.

We wrap the list `a` in an `Rc<T>` so that when we create lists `b` and `c`, they can both refer to `a`, the same as we did in Listing 15-13.

Once we have the lists in `a`, `b`, and `c` created, we add 10 to the value in `value`. We do this by calling `borrow_mut` on `value`, which uses the automatic dereferencing feature we discussed in Chapter 5 ("Where's the `->` Operator?") to dereference the `Rc<T>` to the inner `RefCell<T>` value. The `borrow_mut` method returns a `RefMut<T>` smart pointer, and we use the dereference operator on it and change the inner value.

When we print out `a`, `b`, and `c`, we can see that they all have the modified value of 15 rather than 5:

```
a after = Cons(RefCell { value: 15 }, Nil)
b after = Cons(RefCell { value: 6 }, Cons(RefCell { value: 15 }, Nil))
c after = Cons(RefCell { value: 10 }, Cons(RefCell { value: 15 }, Nil))
```

This is pretty neat! By using `RefCell<T>`, we have an outwardly immutable `List`, but we can use the methods on `RefCell<T>` that provide access to its interior mutability so we can modify our data when we need to. The runtime checks of the borrowing rules protect us from data races, and it's sometimes worth trading a bit of speed for this flexibility in our data structures.

The standard library has other types that provide interior mutability, too, like `Cell<T>`, which is similar except that instead of giving references to the inner value, the value is copied in and out of the `Cell<T>`. There's also `Mutex<T>`, which offers interior mutability that's safe to use across threads, and we'll be discussing its use in the next chapter on concurrency. Check out the standard library docs for more details on the differences between these types.

Reference Cycles Can Leak Memory

Rust's memory safety guarantees make it *difficult* to accidentally create memory that's never cleaned up, known as a *memory leak*, but not impossible. Entirely preventing memory leaks is not one of Rust's guarantees in the same way that disallowing data races at compile time is, meaning memory leaks are memory safe in Rust. We can see this with `Rc<T>` and `RefCell<T>`: it's possible to create references where items refer to each other in a cycle. This creates memory leaks because the reference count of each item in the cycle will never reach 0, and the values will never be dropped.

Creating a Reference Cycle

Let's take a look at how a reference cycle might happen and how to prevent it, starting with the definition of the `List` enum and a `tail` method in Listing 15-20:

Filename: src/main.rs

```
use std::rc::Rc;
use std::cell::RefCell;
use List::{Cons, Nil};

#[derive(Debug)]
enum List {
    Cons(i32, RefCell<Rc<List>>),
    Nil,
}

impl List {
    fn tail(&self) -> Option<&RefCell<Rc<List>>> {
        match *self {
            Cons(_, ref item) => Some(item),
            Nil => None,
        }
    }
}
```

Listing 15-20: A cons list definition that holds a `RefCell` so that we can modify what a `Cons` variant is referring to

We're using another variation of the `List` definition from Listing 15-6. The second element in the `Cons` variant is now `RefCell<Rc<List>>`, meaning that instead of having the ability to modify the `i32` value like we did in Listing 15-19, we want to be able to modify which `List` a `Cons` variant is pointing to. We've also added a `tail` method to make it convenient for us to access the second item, if we have a `Cons` variant.

In listing 15-21, we're adding a `main` function that uses the definitions from Listing 15-20. This code creates a list in `a`, a list in `b` that points to the list in `a`, and then modifies the list in `a` to point to `b`, which creates a reference cycle. There are `println!` statements along the way to show what the reference counts are at various points in this process.

Filename: src/main.rs

```rust
fn main() {
    let a = Rc::new(Cons(5, RefCell::new(Rc::new(Nil))));

    println!("a initial rc count = {}", Rc::strong_count(&a));
    println!("a next item = {:?}", a.tail());

    let b = Rc::new(Cons(10, RefCell::new(Rc::clone(&a))));

    println!("a rc count after b creation = {}", Rc::strong_count(&a));
    println!("b initial rc count = {}", Rc::strong_count(&b));
    println!("b next item = {:?}", b.tail());

    if let Some(ref link) = a.tail() {
        *link.borrow_mut() = Rc::clone(&b);
    }

    println!("b rc count after changing a = {}", Rc::strong_count(&b));
    println!("a rc count after changing a = {}", Rc::strong_count(&a));

    // Uncomment the next line to see that we have a cycle; it will
    // overflow the stack
    // println!("a next item = {:?}", a.tail());
}
```

Listing 15-21: Creating a reference cycle of two `List` values pointing to each other

We create an `Rc` instance holding a `List` value in the variable `a` with an initial list of `5, Nil`. We then create an `Rc` instance holding another `List` value in the variable `b` that contains the value 10, then points to the list in `a`.

Finally, we modify `a` so that it points to `b` instead of `Nil`, which creates a cycle. We do that by using the `tail` method to get a reference to the `RefCell` in `a`, which we put in the variable `link`. Then we use the `borrow_mut` method on the `RefCell` to change the value inside from an `Rc` that holds a `Nil` value to the `Rc` in `b`.

If we run this code, keeping the last `println!` commented out for the moment, we'll get this output:

```
a initial rc count = 1
a next item = Some(RefCell { value: Nil })
a rc count after b creation = 2
b initial rc count = 1
b next item = Some(RefCell { value: Cons(5, RefCell { value: Nil }) })
b rc count after changing a = 2
a rc count after changing a = 2
```

We can see that the reference count of the `Rc` instances in both `a` and `b` are 2 after we change the list in `a` to point to `b`. At the end of `main`, Rust will try and drop `b` first, which will decrease the count in each of the `Rc` instances in `a` and `b` by one.

However, because `a` is still referencing the `Rc` that was in `b`, that `Rc` has a count of 1 rather than 0, so the memory the `Rc` has on the heap won't be dropped. The memory will just sit there with a count of one, forever.

To visualize this, we've created a reference cycle that looks like Figure 15-22:

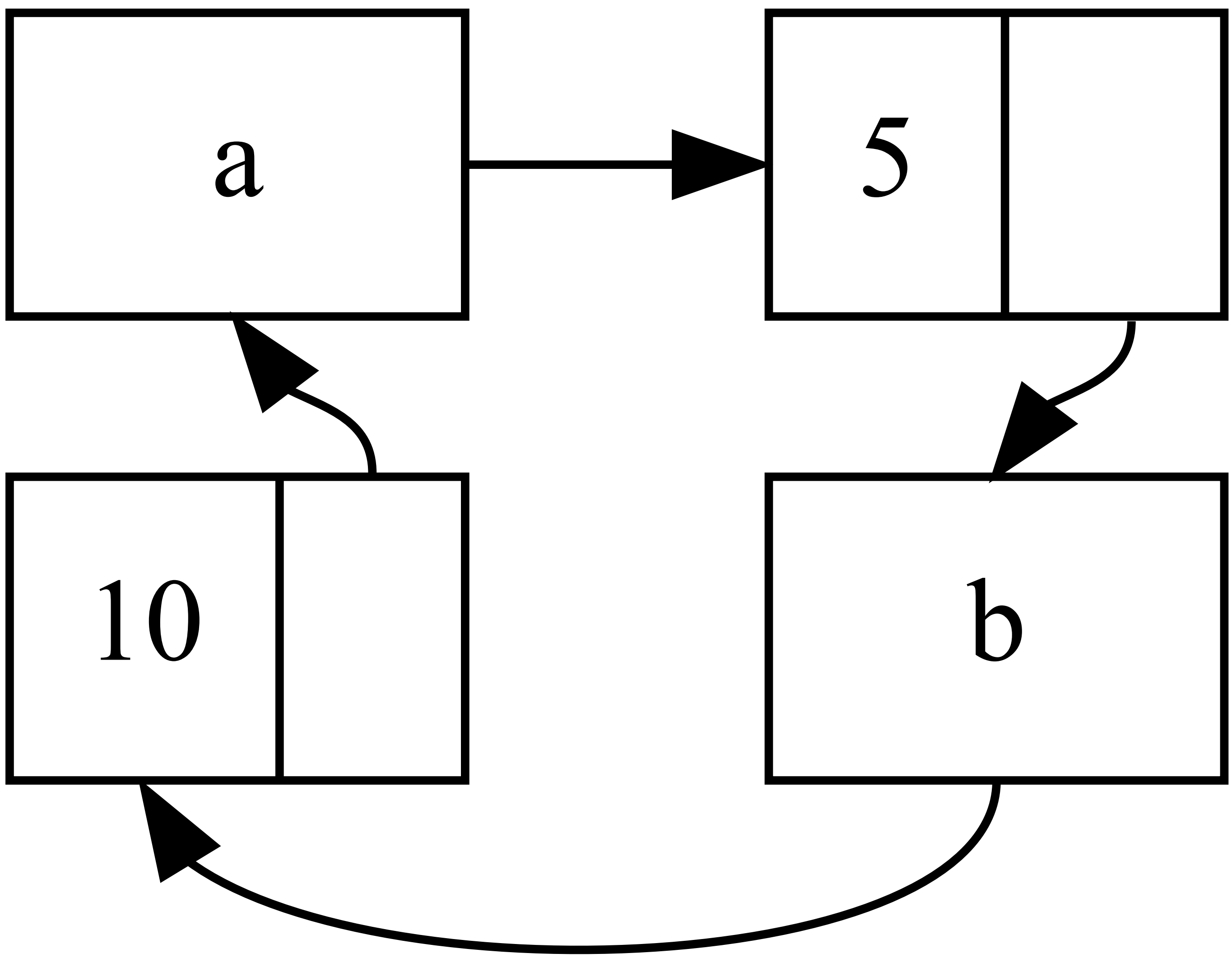


Figure 15-22: A reference cycle of lists `a` and `b` pointing to each other

If you uncomment the last `println!` and run the program, Rust will try and print this cycle out with `a` pointing to `b` pointing to `a` and so forth until it overflows the stack.

In this specific case, right after we create the reference cycle, the program ends. The consequences of this cycle aren't so dire. If a more complex program allocates lots of memory in a cycle and holds onto it for a long time, the program would be using more memory than it needs, and might overwhelm the system and cause it to run out of available memory.

Creating reference cycles is not easily done, but it's not impossible either. If you have `RefCell<T>` values that contain `Rc<T>` values or similar nested combinations of types with interior mutability and reference counting, be aware that you have to ensure you don't create cycles yourself; you can't rely on Rust to catch them. Creating a reference cycle would be a logic bug in your program that you should use automated tests, code reviews, and other software development practices to minimize.

Another solution is reorganizing your data structures so that some references express ownership and some references don't. In this way, we can have cycles made up of some ownership relationships and some non-ownership relationships, and only the ownership relationships affect whether a value may be dropped or not. In Listing 15-20, we always want `Cons` variants to own their list, so reorganizing the data structure isn't possible. Let's look at an example using graphs made up of parent nodes and child nodes to see when non-ownership relationships are an appropriate way to prevent reference cycles.

Preventing Reference Cycles: Turn an `Rc<T>` into a `Weak<T>`

So far, we've shown how calling `Rc::clone` increases the `strong_count` of an `Rc` instance, and that an `Rc` instance is only cleaned up if its `strong_count` is 0. We can also create a *weak reference* to the value within an `Rc` instance by calling `Rc::downgrade` and passing a reference to the `Rc`. When we call `Rc::downgrade`, we get a smart pointer of type `Weak<T>`. Instead of increasing the `strong_count` in the `Rc` instance by one, calling `Rc::downgrade` increases the `weak_count` by one. The `Rc` type uses `weak_count` to keep track of how many `Weak<T>` references exist, similarly to `strong_count`. The difference is the `weak_count` does not need to be 0 in order for the `Rc` instance to be cleaned up.

Strong references are how we can share ownership of an `Rc` instance. Weak references don't express an ownership relationship. They won't cause a reference cycle since any cycle involving some weak references will be broken once the strong reference count of values involved is 0.

Because the value that `Weak<T>` references might have been dropped, in order to do anything with the value that a `Weak<T>` is pointing to, we have to check to make sure the value is still around. We do this by calling the `upgrade` method on a `Weak<T>` instance, which will return an `Option<Rc<T>>`. We'll get a result of `Some` if the `Rc` value has not been dropped yet, and `None` if the `Rc` value has been dropped. Because `upgrade` returns an `Option`, we can be sure that Rust will handle both the `Some` case and the `None` case, and there won't be an invalid pointer.

As an example, rather than using a list whose items know only about the next item, we'll create a tree whose items know about their children items *and* their parent items.

Creating a Tree Data Structure: a `Node` with Child Nodes

To start building this tree, we'll create a struct named `Node` that holds its own `i32` value as well as references to its children `Node` values:

Filename: src/main.rs

```
use std::rc::Rc;
use std::cell::RefCell;

#[derive(Debug)]
struct Node {
    value: i32,
    children: RefCell<Vec<Rc<Node>>>,
}
```

We want a `Node` to own its children, and we want to be able to share that ownership with variables so we can access each `Node` in the tree directly. To do this, we define the `Vec` items to be values of type `Rc<Node>`. We also want to be able to modify which nodes are children of another node, so we have a `RefCell` in `children` around the `Vec`.

Next, let's use our struct definition and create one `Node` instance named `leaf` with the value 3 and no children, and another instance named `branch` with the value 5 and `leaf` as one of its children, as shown in Listing 15-23:

Filename: src/main.rs

```
fn main() {
    let leaf = Rc::new(Node {
        value: 3,
        children: RefCell::new(vec![]),
    });

    let branch = Rc::new(Node {
        value: 5,
        children: RefCell::new(vec![Rc::clone(&leaf)]),
    });
}
```

Listing 15-23: Creating a `leaf` node with no children and a `branch` node with `leaf` as one of its children

We clone the `Rc` in `leaf` and store that in `branch`, meaning the `Node` in `leaf` now has two owners: `leaf` and `branch`. We can get from `branch` to `leaf` through `branch.children`, but there's no way to get from `leaf` to `branch`. `leaf` has no reference to `branch` and doesn't know they are related. We'd like `leaf` to know that `branch` is its parent.

Adding a Reference from a Child to its Parent

To make the child node aware of its parent, we need to add a `parent` field to our `Node` struct definition. The trouble is in deciding what the type of `parent` should be. We know it can't contain an `Rc<T>` because that would create a reference cycle, with `leaf.parent` pointing to `branch` and `branch.children` pointing to `leaf`, which would cause their `strong_count` values to never be zero.

Thinking about the relationships another way, a parent node should own its children: if a parent node is dropped, its child nodes should be dropped as well. However, a child should not own its parent: if we drop a child node, the parent should still exist. This is a case for weak references!

So instead of `Rc`, we'll make the type of `parent` use `Weak<T>`, specifically a `RefCell<Weak<Node>>`. Now our `Node` struct definition looks like this:

Filename: src/main.rs

```
use std::rc::{Rc, Weak};
use std::cell::RefCell;

#[derive(Debug)]
struct Node {
    value: i32,
    parent: RefCell<Weak<Node>>,
    children: RefCell<Vec<Rc<Node>>>,
}
```

This way, a node will be able to refer to its parent node, but does not own its parent. In Listing 15-24, let's update `main` to use this new definition so that the `leaf` node will have a way to refer to its parent, `branch`:

Filename: src/main.rs

```
fn main() {
    let leaf = Rc::new(Node {
        value: 3,
        parent: RefCell::new(Weak::new()),
        children: RefCell::new(vec![]),
    });

    println!("leaf parent = {:?}", leaf.parent.borrow().upgrade());

    let branch = Rc::new(Node {
        value: 5,
        parent: RefCell::new(Weak::new()),
        children: RefCell::new(vec![Rc::clone(&leaf)]),
    });

    *leaf.parent.borrow_mut() = Rc::downgrade(&branch);

    println!("leaf parent = {:?}", leaf.parent.borrow().upgrade());
}
```

Listing 15-24: A `leaf` node with a `Weak` reference to its parent node, `branch`

Creating the `leaf` node looks similar to how creating the `leaf` node looked in Listing 15-23, with the exception of the `parent` field: `leaf` starts out without a parent, so we create a new, empty `Weak` reference instance.

At this point, when we try to get a reference to the parent of `leaf` by using the `upgrade` method, we get a `None` value. We see this in the output from the first `println!`:

```
leaf parent = None
```

When we create the `branch` node, it will also have a new `Weak` reference, since `branch` does not have a parent node. We still have `leaf` as one of the children of `branch`. Once we have the `Node` instance in `branch`, we can modify `leaf` to give it a `Weak` reference to its parent. We use the `borrow_mut` method on the `RefCell` in the `parent` field of `leaf`, then we use the `Rc::downgrade` function to create a `Weak` reference to `branch` from the `Rc` in `branch.`

When we print out the parent of `leaf` again, this time we'll get a `Some` variant holding `branch`: `leaf` can now access its parent! When we print out `leaf`, we also avoid the cycle that eventually ended in a stack overflow like we had in Listing 15-21: the `Weak` references are printed as `(Weak)`:

```
leaf parent = Some(Node { value: 5, parent: RefCell { value: (Weak) },
children: RefCell { value: [Node { value: 3, parent: RefCell { value: (Weak) },
children: RefCell { value: [] } }] } })
```

The lack of infinite output indicates that this code didn't create a reference cycle. We can also tell this by looking at the values we get from calling `Rc::strong_count` and `Rc::weak_count`.

Visualizing Changes to `strong_count` and `weak_count`

Let's look at how the `strong_count` and `weak_count` values of the `Rc` instances change by creating a new inner scope and moving the creation of `branch` into that scope. This will let us see what happens when `branch` is created and then dropped when it goes out of scope. The modifications are shown in Listing 15-25:

Filename: src/main.rs

```
fn main() {
    let leaf = Rc::new(Node {
        value: 3,
        parent: RefCell::new(Weak::new()),
        children: RefCell::new(vec![]),
    });

    println!(
        "leaf strong = {}, weak = {}",
        Rc::strong_count(&leaf),
        Rc::weak_count(&leaf),
    );

    {
        let branch = Rc::new(Node {
            value: 5,
            parent: RefCell::new(Weak::new()),
            children: RefCell::new(vec![Rc::clone(&leaf)]),
        });
        *leaf.parent.borrow_mut() = Rc::downgrade(&branch);

        println!(
            "branch strong = {}, weak = {}",
            Rc::strong_count(&branch),
            Rc::weak_count(&branch),
        );

        println!(
            "leaf strong = {}, weak = {}",
            Rc::strong_count(&leaf),
            Rc::weak_count(&leaf),
        );
    }

    println!("leaf parent = {:?}", leaf.parent.borrow().upgrade());
    println!(
        "leaf strong = {}, weak = {}",
        Rc::strong_count(&leaf),
        Rc::weak_count(&leaf),
    );
}
```

Listing 15-25: Creating `branch` in an inner scope and examining strong and weak reference counts

Once `leaf` is created, its `Rc` has a strong count of 1 and a weak count of 0. In the inner scope we create `branch` and associate it with `leaf`, at which point the `Rc` in `branch` will have a strong count of 1 and a weak count of 1 (for `leaf.parent` pointing to `branch` with a `Weak<T>`). Here `leaf` will have a strong count of 2, because `branch` now has a clone of the `Rc` of `leaf` stored in `branch.children`, but will still have a weak count of 0.

When the inner scope ends, `branch` goes out of scope and the strong count of the `Rc` decreases to 0, so its `Node` gets dropped. The weak count of 1 from `leaf.parent` has no bearing on whether `Node` is dropped or not, so we don't get any memory leaks!

If we try to access the parent of `leaf` after the end of the scope, we'll get `None` again. At the end of the program, the `Rc` in `leaf` has a strong count of 1 and a weak count of 0, because the variable `leaf` is now the only reference to the `Rc` again.

All of the logic that manages the counts and value dropping is built in to `Rc` and `Weak` and their implementations of the `Drop` trait. By specifying that the relationship from a child to its parent should be a `Weak<T>` reference in the definition of `Node`, we're able to have parent nodes point to child nodes and vice versa without creating a reference cycle and memory leaks.

Summary

This chapter covered how you can use smart pointers to make different guarantees and tradeoffs than those Rust makes by default with regular references. `Box<T>` has a known size and points to data allocated on the heap. `Rc<T>` keeps track of the number of references to data on the heap so that data can have multiple owners. `RefCell<T>` with its interior mutability gives us a type that can be used when we need an immutable type but need the ability to change an inner value of that type, and enforces the borrowing rules at runtime instead of at compile time.

We also discussed the `Deref` and `Drop` traits that enable a lot of the functionality of smart pointers. We explored reference cycles that can cause memory leaks, and how to prevent them using `Weak<T>`.

If this chapter has piqued your interest and you want to implement your own smart pointers, check out "The Nomicon" for even more useful information.

Next, let's talk about concurrency in Rust. We'll even learn about a few new smart pointers.

Fearless Concurrency

Handling concurrent programming safely and efficiently is another of Rust's major goals. *Concurrent programming*, where different parts of a program execute independently, and *parallel programming*, where different parts of a program are executing at the same time, are becoming increasingly important as more computers have multiple processors to take advantage of. Historically, programming in these contexts has been difficult and error prone: Rust hopes to change that.

Initially, the Rust team thought that ensuring memory safety and preventing concurrency problems were two separate challenges to be solved with different methods. Over time, they discovered that the ownership and type systems are a powerful set of tools to help in dealing with both memory safety *and* concurrency problems! By leveraging ownership and type checking, many concurrency errors are *compile time* errors in Rust, rather than runtime errors. Rather than spending lots of time trying to reproduce the exact circumstances under which a runtime concurrency bug occurs, incorrect code will refuse to compile with an error explaining the problem. This lets you fix your code while you're working on it, rather than potentially after it's been shipped to production. We've nicknamed this aspect of Rust *fearless concurrency*. Fearless concurrency allows you to write code that's free of subtle bugs and is easy to refactor without introducing new bugs.

> Note: we'll be referring to many of the problems here as *concurrent* rather than being more precise by saying *concurrent and/or parallel*, for simplicity's sake. If this were a book specifically about concurrency and/or parallelism, we'd be sure to be more specific. For this chapter, please mentally substitute *concurrent and/or parallel* whenever we say *concurrent*.

Many languages are strongly opinionated about the solutions they offer for dealing with concurrent problems. For example, Erlang has elegant functionality for message passing concurrency, but only obscure ways to share state between threads. Only supporting a subset of possible solutions is a reasonable strategy for higher-level languages to take, because a higher-level language promises benefits from giving up some control in order to gain abstractions. However, lower-level languages are expected to provide the solution with the best performance in any given situation, and have fewer abstractions over the hardware. Rust, therefore, gives us a variety of tools for modeling your problems in whatever way is appropriate for your situation and requirements.

Here's what we'll cover in this chapter:

- How to create threads to run multiple pieces of code at the same time
- *Message passing* concurrency, where channels are used to send messages between threads.
- *Shared state* concurrency, where multiple threads have access to some piece of data.
- The `Sync` and `Send` traits, which extend Rust's concurrency guarantees to user-defined types as well as types provided by the standard library.

Using Threads to Run Code Simultaneously

In most operating systems today, an executed program's code is run in a *process*, and the operating system manages multiple process at once. Within your program, you can also have independent parts that run simultaneously. The feature that runs these independent parts is called *threads*.

Splitting the computation in your program up into multiple threads can improve performance, since the program will be doing multiple things at the same time, but it also adds complexity. Because threads may run simultaneously, there's no inherent guarantee about the order in which parts of your code on different threads will run. This can lead to problems such as:

- Race conditions, where threads are accessing data or resources in an inconsistent order
- Deadlocks, where two threads are waiting for each other to finish using a resource the other thread has, which prevents both threads from continuing
- Bugs that only happen in certain situations and are hard to reproduce and fix reliably

Rust attempts to mitigate negative effects of using threads. Programming in a multithreaded context still takes careful thought and requires a code structure that's different from programs that run in a single thread.

Programming languages implement threads in a few different ways. Many operating systems provide an API for creating new threads. This model where a language calls the operating system APIs to create threads is sometimes called *1:1*, one OS thread per one language thread.

Many programming languages provide their own special implementation of threads. Programming language-provided threads are known as *green* threads, and languages that use these green threads will execute them in the context of a different number of operating system threads. For this reason, the green threaded model is called the *M:N* model, `M` green threads per `N` OS threads, where `M` and `N` are not necessarily the same number.

Each model has its own advantages and tradeoffs, and the tradeoff most important to Rust is runtime support. *Runtime* is a confusing term and can have different meanings in different contexts.

In this context, by runtime we mean code that's included by the language in every binary. This code can be large or small depending on the language, but every non-assembly language will have some amount of runtime code. For that reason, colloquially when people say a language has "no runtime" they often mean "small runtime." Smaller runtimes have fewer features but have the advantage of resulting in smaller binaries, which make it easier to combine the language with other languages in more contexts. While many languages are okay with increasing the runtime size in exchange for more features, Rust needs to have nearly no runtime, and cannot compromise on being able to call into C in order to maintain performance.

The green threading M:N model requires a larger language runtime to manage threads. As such, the Rust standard library only provides an implementation of 1:1 threading. Because Rust is such a low-level language, there are crates that implement M:N threading if you would rather trade overhead for aspects such as more control over which threads run when and lower costs of context switching, for example.

Now that we've defined threads in Rust, let's explore how to use the thread-related API provided by the standard library.

Creating a New Thread with `spawn`

To create a new thread, we call the `thread::spawn` function, and pass it a closure (we talked about closures in Chapter 13) containing the code we want to run in the new thread. The example in Listing 16-1 prints some text from a main thread and other text from a new thread:

Filename: src/main.rs

```
use std::thread;

fn main() {
    thread::spawn(|| {
        for i in 1..10 {
            println!("hi number {} from the spawned thread!", i);
        }
    });

    for i in 1..5 {
        println!("hi number {} from the main thread!", i);
    }
}
```

Listing 16-1: Creating a new thread to print one thing while the main thread prints something else

Note that with this function, the new thread will be stopped when the main thread ends, whether it has finished running or not. The output from this program might be a little different every time, but it will look similar to this:

```
hi number 1 from the main thread!
hi number 1 from the spawned thread!
hi number 2 from the main thread!
hi number 2 from the spawned thread!
hi number 3 from the main thread!
hi number 3 from the spawned thread!
hi number 4 from the main thread!
hi number 4 from the spawned thread!
hi number 5 from the spawned thread!
```

The threads will probably take turns, but that's not guaranteed: it depends on how your operating system schedules the threads. In this run, the main thread printed first, even though the print statement from the spawned thread appears first in the code. And even though we told the spawned thread to print until `i` is 9, it only got to 5 before the main thread shut down.

If you run this code and only see one thread, or don't see any overlap, try increasing the numbers in the ranges to create more opportunities for a thread to take a break and give the other thread a turn.

Waiting for All Threads to Finish Using `join` Handles

The code in Listing 16-1 not only stops the spawned thread prematurely most of the time, because the main thread ends before the spawned thread is done, there's actually no guarantee that the spawned thread will get to run at all, because there's no guarantee on the order in which threads run!

We can fix this by saving the return value of `thread::spawn` in a variable. The return type of `thread::spawn` is `JoinHandle`. A `JoinHandle` is an owned value that, when we call the `join` method on it, will wait for its thread to finish. Listing 16-2 shows how to use the `JoinHandle` of the thread we created in Listing 16-1 and call `join` in order to make sure the spawned thread finishes before the `main` exits:

Filename: src/main.rs

```
use std::thread;

fn main() {
    let handle = thread::spawn(|| {
        for i in 1..10 {
            println!("hi number {} from the spawned thread!", i);
        }
    });

    for i in 1..5 {
        println!("hi number {} from the main thread!", i);
    }

    handle.join();
}
```

Listing 16-2: Saving a `JoinHandle` from `thread::spawn` to guarantee the thread is run to completion

Calling `join` on the handle blocks the thread currently running until the thread represented by the handle terminates. *Blocking* a thread means that thread is prevented from performing work or exiting. Because we've put the call to `join` after the main thread's `for` loop, running this example should produce output that looks something like this:

```
hi number 1 from the main thread!
hi number 2 from the main thread!
hi number 1 from the spawned thread!
hi number 3 from the main thread!
hi number 2 from the spawned thread!
hi number 4 from the main thread!
hi number 3 from the spawned thread!
hi number 4 from the spawned thread!
hi number 5 from the spawned thread!
hi number 6 from the spawned thread!
hi number 7 from the spawned thread!
hi number 8 from the spawned thread!
hi number 9 from the spawned thread!
```

The two threads are still alternating, but the main thread waits because of the call to `handle.join()` and does not end until the spawned thread is finished.

If we instead move `handle.join()` before the `for` loop in main, like this:

Filename: src/main.rs

```rust
use std::thread;

fn main() {
    let handle = thread::spawn(|| {
        for i in 1..10 {
            println!("hi number {} from the spawned thread!", i);
        }
    });

    handle.join();

    for i in 1..5 {
        println!("hi number {} from the main thread!", i);
    }
}
```

The main thread will wait for the spawned thread to finish and then run its `for` loop, so the output won't be interleaved anymore:

```
hi number 1 from the spawned thread!
hi number 2 from the spawned thread!
hi number 3 from the spawned thread!
hi number 4 from the spawned thread!
hi number 5 from the spawned thread!
hi number 6 from the spawned thread!
hi number 7 from the spawned thread!
hi number 8 from the spawned thread!
hi number 9 from the spawned thread!
hi number 1 from the main thread!
hi number 2 from the main thread!
hi number 3 from the main thread!
hi number 4 from the main thread!
```

Thinking about a small thing such as where to call `join` can affect whether your threads are actually running at the same time or not.

Using `move` Closures with Threads

The `move` closure, which we didn't cover in Chapter 13, is often used alongside `thread::spawn`, as it allows us to use data from one thread in another thread.

In Chapter 13, we said that "Creating closures that capture values from their environment is mostly used in the context of starting new threads."

Now we're creating new threads, so let's talk about capturing values in closures!

Notice in Listing 16-1 that the closure we pass to `thread::spawn` takes no arguments: we're not using any data from the main thread in the spawned thread's code. In order to do so, the spawned thread's closure must capture the values it needs. Listing 16-3 shows an attempt to create a vector in the main thread and use it in the spawned thread. However, this won't yet work, as you'll see in a moment:

Filename: src/main.rs

```rust
use std::thread;

fn main() {
    let v = vec![1, 2, 3];

    let handle = thread::spawn(|| {
        println!("Here's a vector: {:?}", v);
    });

    handle.join();
}
```

Listing 16-3: Attempting to use a vector created by the main thread in another thread

The closure uses `v`, so will capture `v` and make it part of the closure's environment. Because `thread::spawn` runs this closure in a new thread, we should be able to access `v` inside that new thread.

When we compile this example, however, we'll get the following error:

```
error[E0373]: closure may outlive the current function, but it borrows `v`,
which is owned by the current function
 -->
  |
6 |     let handle = thread::spawn(|| {
  |                                ^^ may outlive borrowed value `v`
7 |         println!("Here's a vector: {:?}", v);
  |                                           - `v` is borrowed here
  |
help: to force the closure to take ownership of `v` (and any other referenced
variables), use the `move` keyword, as shown:
  |     let handle = thread::spawn(move || {
```

Rust *infers* how to capture `v`, and since `println!` only needs a reference to `v`, the closure tries to borrow `v`. There's a problem, though: Rust can't tell how long the spawned thread will run, so doesn't know if the reference to `v` will always be valid.

Let's look at a scenario that's more likely to have a reference to `v` that won't be valid, shown Listing 16-4:

Filename: src/main.rs

```rust
use std::thread;

fn main() {
    let v = vec![1, 2, 3];

    let handle = thread::spawn(|| {
        println!("Here's a vector: {:?}", v);
    });

    drop(v); // oh no!

    handle.join();
}
```

Listing 16-4: A thread with a closure that attempts to capture a reference to `v` from a main thread that drops `v`

If we run this code, there's a possibility the spawned thread will be immediately put in the background without getting a chance to run at all. The spawned thread has a reference to `v` inside, but the main thread immediately drops `v`, using the `drop` function we discussed in

Chapter 15. Then, when the spawned thread starts to execute, `v` is no longer valid, so a reference to it is also invalid. Oh no!

To fix the problem in Listing 16-3, we can listen to the advice of the error message:

```
help: to force the closure to take ownership of `v` (and any other referenced
variables), use the `move` keyword, as shown:
  |     let handle = thread::spawn(move || {
```

By adding the `move` keyword before the closure, we force the closure to take ownership of the values it's using, rather than allowing Rust to infer that it should borrow. The modification to Listing 16-3 shown in Listing 16-5 will compile and run as we intend:

Filename: src/main.rs

```
use std::thread;

fn main() {
    let v = vec![1, 2, 3];

    let handle = thread::spawn(move || {
        println!("Here's a vector: {:?}", v);
    });

    handle.join();
}
```

Listing 16-5: Using the `move` keyword to force a closure to take ownership of the values it uses

What would happen to the code in Listing 16-4 where the main thread called `drop` if we use a `move` closure? Would `move` fix that case? Nope, we get a different error, because what Listing 16-4 is trying to do isn't allowed for a different reason! If we add `move` to the closure, we'd move `v` into the closure's environment, and we could no longer call `drop` on it in the main thread. We would get this compiler error instead:

```
error[E0382]: use of moved value: `v`
  -->
   |
6  |     let handle = thread::spawn(move || {
   |                                ------- value moved (into closure) here
...
10 |     drop(v); // oh no!
   |          ^ value used here after move
   |
   = note: move occurs because `v` has type `std::vec::Vec<i32>`, which does
   not implement the `Copy` trait
```

Rust's ownership rules have saved us again! We got an error from the code in Listing 16-3 because Rust was being conservative and only borrowing `v` for the thread, which meant the main thread could theoretically invalidate the spawned thread's reference. By telling Rust to move ownership of `v` to the spawned thread, we're guaranteeing to Rust that the main thread won't use `v` anymore. If we change Listing 16-4 in the same way, we're then violating the ownership rules when we try to use `v` in the main thread. The `move` keyword overrides Rust's conservative default of borrowing; it doesn't let us violate the ownership rules.

Now that we have a basic understanding of threads and the thread API, let's talk about what we can actually *do* with threads.

Message Passing to Transfer Data Between Threads

One increasingly popular approach to ensuring safe concurrency is *message passing*, where threads or actors communicate by sending each other messages containing data. Here's the idea in slogan form from the Go language documentation:

> Do not communicate by sharing memory; instead, share memory by communicating.
>
> --Effective Go

One major tool Rust has for accomplishing message sending concurrency is the *channel*, a programming concept that Rust's standard library provides an implementation of. You can imagine a channel in programming like a channel of water, such as a stream or a river. If you put something like a rubber duck or a boat into a stream, it will travel downstream to the end of the river.

A channel in programming has two halves: a transmitter and a receiver. The transmitter half is like the upstream location where we put rubber ducks into the river, and the receiver half is the downstream place where the rubber duck ends up. One part of our code calls methods on the transmitter with the data we want to send, and another part checks the receiving end for arriving messages.

Here we'll work up to a program that has one thread to generate values and send them down a channel, and another thread that will receive the values and print them out. We're going to be sending simple values between threads using a channel for the purposes of illustration. Once you're familiar with the technique, you could use channels to implement a chat system, or a system where many threads perform parts of a calculation and send the parts to one thread that aggregates the results.

First, we'll create a channel but not do anything with it in Listing 16-6:

Filename: src/main.rs

```
use std::sync::mpsc;

fn main() {
    let (tx, rx) = mpsc::channel();
}
```

Listing 16-6: Creating a channel and assigning the two halves to `tx` and `rx`

We create a new channel using the `mpsc::channel` function; `mpsc` stands for *multiple producer, single consumer*. In short, the way Rust's standard library has implemented channels is such that a channel can have multiple *sending* ends that produce values, but only one *receiving* end that consumes those values. Imagine multiple rivers and streams flowing together into one big river: everything sent down any of the streams will end up in one river at the end. We're going to start with a single producer for now, but we'll add multiple producers once we get this example working.

The `mpsc::channel` function returns a tuple, the first element of which is the sending end and the second element the receiving end. The abbreviations `tx` and `rx` are traditionally used in many fields for *transmitter* and *receiver* respectively, so we give our variables those names to indicate each end. We're using a `let` statement with a pattern that destructures the tuples; we'll be discussing the use of patterns in `let` statements and destructuring in Chapter

18. Using a `let` statement in this way is a convenient way to extract the pieces of the tuple returned by `mpsc::channel`.

Let's move the transmitting end into a spawned thread and have it send one string so that the spawned thread is communicating with the main thread, shown in Listing 16-7. This is like putting a rubber duck in the river upstream or sending a chat message from one thread to another:

Filename: src/main.rs

```
use std::thread;
use std::sync::mpsc;

fn main() {
    let (tx, rx) = mpsc::channel();

    thread::spawn(move || {
        let val = String::from("hi");
        tx.send(val).unwrap();
    });
}
```

Listing 16-7: Moving `tx` to a spawned thread and sending "hi"

We're again using `thread::spawn` to create a new thread, and then use `move` to move `tx` into the closure so the spawned thread owns `tx`. The spawned thread needs to own the transmitting end of the channel in order to be able to send messages through the channel.

The transmitting end has a `send` method that takes the value we want to send. The `send` method returns a `Result<T, E>` type, so that if the receiving end has already been dropped and there's nowhere to send a value, the send operation will error. In this example, we're simply calling `unwrap` to panic in case of error, but for a real application, we'd handle it properly--return to Chapter 9 to review strategies for proper error handling.

In Listing 16-8, we'll get the value from the receiving end of the channel in the main thread. This is like retrieving the rubber duck from the water at the end of the river, or like getting a chat message:

Filename: src/main.rs

```
use std::thread;
use std::sync::mpsc;

fn main() {
    let (tx, rx) = mpsc::channel();

    thread::spawn(move || {
        let val = String::from("hi");
        tx.send(val).unwrap();
    });

    let received = rx.recv().unwrap();
    println!("Got: {}", received);
}
```

Listing 16-8: Receiving the value "hi" in the main thread and printing it out

The receiving end of a channel has two useful methods: `recv` and `try_recv`. We're using `recv`, short for *receive*, which will block the main thread's execution and wait until a value is sent down the channel. Once a value is sent, `recv` will return it in a `Result<T, E>`. When the sending end of the channel closes, `recv` will return an error to signal that no more values will be coming.

The `try_recv` method doesn't block, but will instead return a `Result<T, E>` immediately: an `Ok` value holding a message if one is available, and an `Err` value if there aren't any messages this time. Using `try_recv` is useful if this thread has other work to do while waiting for messages: we could write a loop that calls `try_recv` every so often, handles a message if one is available, and otherwise does other work for a little while until checking again.

We've chosen to use `recv` in this example for simplicity; we don't have any other work for the main thread to do other than wait for messages, so blocking the main thread is appropriate.

If we run the code in Listing 16-8, we'll see the value printed out from the main thread:

```
Got: hi
```

Perfect!

Channels and Ownership Transference

The ownership rules play a vital role in message sending as far as helping us write safe, concurrent code. Preventing errors in concurrent programming is the advantage we get by making the tradeoff of having to think about ownership throughout our Rust programs. Let's do an experiment to show how channels and ownership work together to prevent problems: we'll try to use a `val` value in the spawned thread *after* we've sent it down the channel. Try compiling the code in Listing 16-9:

Filename: src/main.rs

```
use std::thread;
use std::sync::mpsc;

fn main() {
    let (tx, rx) = mpsc::channel();

    thread::spawn(move || {
        let val = String::from("hi");
        tx.send(val).unwrap();
        println!("val is {}", val);
    });

    let received = rx.recv().unwrap();
    println!("Got: {}", received);
}
```

Listing 16-9: Attempting to use `val` after we have sent it down the channel

Here, we try to print out `val` after we've sent it down the channel via `tx.send`. Allowing this would be a bad idea: once the value has been sent to another thread, that thread could modify or drop it before we try to use the value again, which would potentially cause errors or unexpected results due to inconsistent or nonexistent data.

However, Rust gives us an error if we try to compile this code:

```
error[E0382]: use of moved value: `val`
  --> src/main.rs:10:31
   |
9  |         tx.send(val).unwrap();
   |                 --- value moved here
10 |         println!("val is {}", val);
   |                               ^^^ value used here after move
   |
   = note: move occurs because `val` has type `std::string::String`, which does
   not implement the `Copy` trait
```

Our concurrency mistake has caused a compile-time error! The `send` function takes ownership of its parameter, and when the value is moved the receiver takes ownership of it. This stops us from accidentally use the value again after sending it; the ownership system checks that everything is okay.

Sending Multiple Values and Seeing the Receiver Waiting

The code in Listing 16-8 compiled and ran, but doesn't show us very clearly that two separate threads are talking to each other over the channel. In Listing 16-10 we've made some modifications that will prove this code is running concurrently: the spawned thread will now send multiple messages and pause for a second between each message.

Filename: src/main.rs

```
use std::thread;
use std::sync::mpsc;
use std::time::Duration;

fn main() {
    let (tx, rx) = mpsc::channel();

    thread::spawn(move || {
        let vals = vec![
            String::from("hi"),
            String::from("from"),
            String::from("the"),
            String::from("thread"),
        ];

        for val in vals {
            tx.send(val).unwrap();
            thread::sleep(Duration::from_secs(1));
        }
    });

    for received in rx {
        println!("Got: {}", received);
    }
}
```

Listing 16-10: Sending multiple messages and pausing between each one

This time, the spawned thread has a vector of strings that we want to send to the main thread. We iterate over them, sending each individually, and pause between each by calling the `thread::sleep` function with a `Duration` value of one second.

In the main thread, we're not calling the `recv` function explicitly anymore: instead we're treating `rx` as an iterator. For each value received, we're printing it out. When the channel is closed, iteration will end.

When running the code in Listing 16-10, you should see the following output, with a one second pause in between each line:

```
Got: hi
Got: from
Got: the
Got: thread
```

Because we don't have any code that pauses or delays in the `for` loop in the main thread, we can tell that the main thread is waiting to receive values from the spawned thread.

Creating Multiple Producers by Cloning the Transmitter

Near the start of this section, we mentioned that `mpsc` stood for *multiple producer, single consumer*. Let's put that ability to use and expand the code from Listing 16-10 to create multiple threads that all send values to the same receiver. We can do that by cloning the transmitting half of the channel, as shown in Listing 16-11:

Filename: src/main.rs

```
// ...snip...
let (tx, rx) = mpsc::channel();

let tx1 = mpsc::Sender::clone(&tx);
thread::spawn(move || {
    let vals = vec![
        String::from("hi"),
        String::from("from"),
        String::from("the"),
        String::from("thread"),
    ];

    for val in vals {
        tx1.send(val).unwrap();
        thread::sleep(Duration::from_secs(1));
    }
});

thread::spawn(move || {
    let vals = vec![
        String::from("more"),
        String::from("messages"),
        String::from("for"),
        String::from("you"),
    ];

    for val in vals {
        tx.send(val).unwrap();
        thread::sleep(Duration::from_secs(1));
    }
});
// ...snip...
```

Listing 16-11: Sending multiple messages and pausing between each one

This time, before we create the first spawned thread, we call `clone` on the sending end of the channel. This will give us a new sending handle we can pass to the first spawned thread. We pass the original sending end of the channel to a second spawned thread. This gives us two threads, each sending different messages to the receiving end of the channel.

If you run this, you'll *probably* see output like this:

```
Got: hi
Got: more
Got: from
Got: messages
Got: for
Got: the
Got: thread
Got: you
```

You might see the values in a different order, it depends on your system! This is what makes concurrency interesting as well as difficult. If you play around with `thread::sleep`, giving it different values in the different threads, each run will be more non-deterministic and create different output each time.

Now that we've seen how channels work, let's look at a different method of concurrency.

Shared State Concurrency

Message passing is a fine way of dealing with concurrency, but it's not the only one. Consider this slogan again:

> Do not communicate by sharing memory; instead, share memory by communicating.

What would "communicate by sharing memory" look like? And moreover, why would message passing enthusiasts choose not to use it and do the opposite instead?

In a way, channels in any programming language are sort of like single ownership, because once you transfer a value down a channel, you shouldn't use that value any longer. Shared memory concurrency is sort of like multiple ownership: multiple threads can access the same memory location at the same time. As we saw in Chapter 15 where multiple ownership was made possible by smart pointers, multiple ownership can add additional complexity because these different owners need managing.

Rust's type system and ownership rules assist a lot in getting this management correct, though. For an example, let's look at one of the more common concurrency primitives for shared memory: mutexes.

Mutexes Allow Access to Data from One Thread at a Time

A *mutex* is a concurrency primitive for sharing memory. It's short for "mutual exclusion", as in, it only allows one thread to access some data at any given time. In order to access the data in a mutex, a thread must first signal that it wants access by asking to acquire the mutex's *lock*. The lock is a data structure that is part of the mutex that keeps track of who currently has exclusive access to the data. We therefore describe the mutex as *guarding* the data it holds via the locking system.

Mutexes have a reputation for being hard to use because there are some rules you have to remember:

1. You must attempt to acquire the lock before using the data.
2. Once you're done with the data that's guarded by the mutex, you must unlock the data so other threads can acquire the lock.

For a real-world metaphor of a mutex, imagine a panel discussion at a conference with only one microphone. Before a panelist may speak, they have to ask or signal that they would like to use the microphone. Once they get the microphone, they may talk for as long as they would like, then hand the microphone to the next panelist who requests to speak. If a panelist forgets to hand the microphone off when they're finished with it, no one else is able to speak. If management of the shared microphone goes wrong, the panel would not work as planned!

Management of mutexes can be incredibly tricky to get right, and that's why so many people are enthusiastic about channels. However, thanks to Rust's type system and ownership rules, we can't get locking and unlocking wrong.

The API of `Mutex<T>`

Let's start simply with an example of using a mutex in a single-threaded context, shown in Listing 16-12:

Filename: src/main.rs

```rust
use std::sync::Mutex;

fn main() {
    let m = Mutex::new(5);

    {
        let mut num = m.lock().unwrap();
        *num = 6;
    }

    println!("m = {:?}", m);
}
```

Listing 16-12: Exploring the API of `Mutex<T>` in a single threaded context for simplicity

As with many types, we create a `Mutex<T>` using the associated function `new`. To access the data inside the mutex, we use the `lock` method to acquire the lock. This call will block the current thread so that it can't do any work until it's our turn to have the lock.

The call to `lock` would fail if another thread holding the lock panicked. In that case, no one would ever be able to get the lock, so we've chosen to `unwrap` and have this thread panic if we're in that situation.

Once we've acquired the lock, we can treat the return value, named `num` in this case, as a mutable reference to the data inside. The type system ensures that we acquire a lock before using this value: `Mutex<i32>` is not an `i32`, so we *must* acquire the lock in order to be able to use the `i32` value. We can't forget; the type system won't let us do it otherwise.

As you may suspect, `Mutex<T>` is a smart pointer. More accurately, the call to `lock` *returns* a smart pointer called `MutexGuard`. This smart pointer implements `Deref` to point at our inner data, and also has a `Drop` implementation that releases the lock automatically when `MutexGuard` goes out of scope, which happens at the end of the inner scope in Listing 16-12. This way, we don't risk forgetting to release the lock and blocking it from use by other threads, because it happens automatically.

After dropping the lock, we can print out the mutex value and see that we were able to change the inner `i32` to 6.

Sharing a `Mutex<T>` Between Multiple Threads

Let's now try to share a value between multiple threads using `Mutex<T>`. We'll spin up ten threads, and have them each increment a counter value by 1 so that the counter goes from 0 to 10. Note that the next few examples will have compiler errors, and we're going to use those errors to learn more about using `Mutex<T>` and how Rust helps us use it correctly. Listing 16-13 has our starting example:

Filename: src/main.rs

```
use std::sync::Mutex;
use std::thread;

fn main() {
    let counter = Mutex::new(0);
    let mut handles = vec![];

    for _ in 0..10 {
        let handle = thread::spawn(move || {
            let mut num = counter.lock().unwrap();

            *num += 1;
        });
        handles.push(handle);
    }

    for handle in handles {
        handle.join().unwrap();
    }

    println!("Result: {}", *counter.lock().unwrap());
}
```

Listing 16-13: Ten threads each increment a counter guarded by a `Mutex<T>`

We're creating a `counter` variable to hold an `i32` inside a `Mutex<T>`, like we did in Listing 16-12. Next, we're creating 10 threads by mapping over a range of numbers. We use `thread::spawn` and give all the threads the same closure, one that moves the counter into the thread, acquires a lock on the `Mutex<T>` by calling the `lock` method, and then adds 1 to the value in the mutex. When a thread finishes running its closure, `num` will go out of scope and release the lock so another thread can acquire it.

In the main thread, we collect all the join handles like we did in Listing 16-2, and then call `join` on each to make sure all the threads finish. At that point, the main thread will acquire the lock and print out the result of this program.

We hinted that this example won't compile, now let's find out why!

```
error[E0382]: capture of moved value: `counter`
  -->
   |
9  |         let handle = thread::spawn(move || {
   |                                    ------- value moved (into closure) here
10 |             let mut num = counter.lock().unwrap();
   |                           ^^^^^^^ value captured here after move
   |
   = note: move occurs because `counter` has type `std::sync::Mutex<i32>`,
   which does not implement the `Copy` trait

error[E0382]: use of moved value: `counter`
  -->
   |
9  |         let handle = thread::spawn(move || {
   |                                    ------- value moved (into closure) here
...
21 |     println!("Result: {}", *counter.lock().unwrap());
   |                             ^^^^^^^ value used here after move
   |
   = note: move occurs because `counter` has type `std::sync::Mutex<i32>`,
   which does not implement the `Copy` trait

error: aborting due to 2 previous errors
```

The error message is saying that the `counter` value is moved into the closure, then is captured when we call `lock`. That sounds like what we wanted, but it's not allowed!

Let's reason this out by simplifying the program. Instead of making 10 threads in a `for` loop, let's just make two threads without a loop and see what happens then. Replace the first `for` loop in Listing 16-13 with this code instead:

```rust
let handle = thread::spawn(move || {
    let mut num = counter.lock().unwrap();

    *num += 1;
});
handles.push(handle);

let handle2 = thread::spawn(move || {
    let mut num2 = counter.lock().unwrap();

    *num2 += 1;
});
handles.push(handle2);
```

We make two threads and change the variable names used with the second thread to `handle2` and `num2`. When we run this time, compiling gives us:

```
error[E0382]: capture of moved value: `counter`
  -->
   |
8  |     let handle = thread::spawn(move || {
   |                                -------- value moved (into closure) here
...
16 |         let mut num2 = counter.lock().unwrap();
   |                        ^^^^^^^ value captured here after move
   |
   = note: move occurs because `counter` has type `std::sync::Mutex<i32>`,
   which does not implement the `Copy` trait

error[E0382]: use of moved value: `counter`
  -->
   |
8  |     let handle = thread::spawn(move || {
   |                                -------- value moved (into closure) here
...
26 |     println!("Result: {}", *counter.lock().unwrap());
   |                             ^^^^^^^ value used here after move
   |
   = note: move occurs because `counter` has type `std::sync::Mutex<i32>`,
   which does not implement the `Copy` trait

error: aborting due to 2 previous errors
```

Aha! The first error message tells us that `counter` is moved into the closure for the thread associated with `handle`. That move is preventing us from capturing `counter` when we try to call `lock` on it and store the result in `num2` in the second thread! So Rust is telling us that we can't move ownership of `counter` into multiple threads. This was hard to see before because our threads were in a loop, and Rust can't point to different threads in different iterations of the loop. Let's try to fix this with a multiple-ownership method we saw in Chapter 15.

Multiple Ownership with Multiple Threads

In Chapter 15, we were able to give a value multiple owners by using the smart pointer `Rc<T>` to create a reference-counted value. Let's try to do the same here and see what happens. We'll wrap the `Mutex<T>` in `Rc<T>` in Listing 16-14, and clone the `Rc<T>` before moving ownership to the thread. Now we've seen the errors, we'll also switch back to using the `for` loop, and we'll keep the `move` keyword with the closure:

Filename: src/main.rs

```
use std::rc::Rc;
use std::sync::Mutex;
use std::thread;

fn main() {
    let counter = Rc::new(Mutex::new(0));
    let mut handles = vec![];

    for _ in 0..10 {
        let counter = Rc::clone(&counter);
        let handle = thread::spawn(move || {
            let mut num = counter.lock().unwrap();

            *num += 1;
        });
        handles.push(handle);
    }

    for handle in handles {
        handle.join().unwrap();
    }

    println!("Result: {}", *counter.lock().unwrap());
}
```

Listing 16-14: Attempting to use `Rc<T>` to allow multiple threads to own the `Mutex<T>`

Once again, we compile and get... different errors! The compiler is teaching us a lot!

```
error[E0277]: the trait bound `std::rc::Rc<std::sync::Mutex<i32>>:
std::marker::Send` is not satisfied
  -->
   |
11 |         let handle = thread::spawn(move || {
   |                      ^^^^^^^^^^^^^ the trait `std::marker::Send` is not
   implemented for `std::rc::Rc<std::sync::Mutex<i32>>`
   |
   = note: `std::rc::Rc<std::sync::Mutex<i32>>` cannot be sent between threads
   safely
   = note: required because it appears within the type
   `[closure@src/main.rs:11:36: 15:10
   counter:std::rc::Rc<std::sync::Mutex<i32>>]`
   = note: required by `std::thread::spawn`
```

Wow, that's quite wordy! Here are some important parts to pick out: the first note says `Rc<Mutex<i32>> cannot be sent between threads safely`. The reason for this is in the error message, which, once distilled, says `the trait bound Send is not satisfied`. We're going to talk about `Send` in the next section; it's one of the traits that ensures the types we use with threads are meant for use in concurrent situations.

Unfortunately, `Rc<T>` is not safe to share across threads. When `Rc<T>` manages the reference count, it adds to the count for each call to `clone` and subtracts from the count when each clone is dropped, but it doesn't use any concurrency primitives to make sure that changes to the count can't be interrupted by another thread. This could lead to wrong counts: subtle bugs that could in turn lead to memory leaks or a value being dropped before we're done with it. What we need is a type exactly like `Rc<T>`, but that makes changes to the reference count in a thread-safe way.

Atomic Reference Counting with `Arc<T>`

Luckily for us, there *is* a type like `Rc<T>` that's safe to use in concurrent situations: `Arc<T>`. The 'a' stands for *atomic*, meaning it's an *atomically reference counted* type. Atomics are an additional kind of concurrency primitive that we won't cover in detail here; see the standard library documentation for `std::sync::atomic` for more details. What you need to know here is that atomics work like primitive types, but are safe to share across threads.

You might then wonder why all primitive types aren't atomic, and why standard library types aren't implemented to use `Arc<T>` by default. The reason is that thread safety comes with a performance penalty that you only want to pay when you really need to. If you're only doing operations on values within a single thread, your code can run faster if it doesn't have to enforce the guarantees atomics provide.

Back to our example: `Arc<T>` and `Rc<T>` have the same API, so we fix our program by changing the `use` line and the call to `new`. The code in Listing 16-15 will finally compile and run:

Filename: src/main.rs

```
use std::sync::{Mutex, Arc};
use std::thread;

fn main() {
    let counter = Arc::new(Mutex::new(0));
    let mut handles = vec![];

    for _ in 0..10 {
        let counter = Arc::clone(&counter);
        let handle = thread::spawn(move || {
            let mut num = counter.lock().unwrap();

            *num += 1;
        });
        handles.push(handle);
    }

    for handle in handles {
        handle.join().unwrap();
    }

    println!("Result: {}", *counter.lock().unwrap());
}
```

Listing 16-15: Using an `Arc<T>` to wrap the `Mutex<T>` to be able to share ownership across multiple threads

This will print:

```
Result: 10
```

We did it! We counted from 0 to 10, which may not seem very impressive, but it did teach us a lot about `Mutex<T>` and thread safety! This structure could also be used to do more complicated operations than just incrementing a counter: these methods allow us to divide calculations up into independent parts, which we could split across threads, and then we can use a `Mutex<T>` to have each thread update the final result with its part.

Similarities between `RefCell<T>` / `Rc<T>` and `Mutex<T>` / `Arc<T>`

You may have noticed that `counter` is immutable but we could get a mutable reference to the value inside it; this means `Mutex<T>` provides interior mutability, like the `Cell` family does. In the same way we used `RefCell<T>` in Chapter 15 to allow us to mutate contents inside an `Rc<T>`, we use `Mutex<T>` to mutate contents inside of an `Arc<T>`.

Another thing to note is that Rust can't prevent us from all kinds of logic errors when using `Mutex<T>`. Recall from Chapter 15 that using `Rc<T>` came with the risk of creating reference cycles, where two `Rc<T>` values refer to each other, causing memory leaks. Similarly, `Mutex<T>` comes the risk of *deadlocks*. These occur when an operation needs to lock two resources and two threads have each acquired one of the locks, causing them to wait for each other forever. If you're interested in this topic, try creating a Rust program that has a deadlock, then research deadlock mitigation strategies for mutexes in any language, and have a go at implementing them in Rust. The standard library API documentation for `Mutex<T>` and `MutexGuard` will have useful information.

Let's round out this chapter by talking about the `Send` and `Sync` traits and how we could use them with custom types.

Extensible Concurrency with the `Sync` and `Send` Traits

Interestingly, the Rust language itself knows *very* little about concurrency. Almost everything we've talked about so far in this chapter has been part of the standard library, not the language. Our concurrency options are not limited to the language or the standard library, meaning we can write our own concurrency options or use ones others have written.

There *are* two concurrency concepts embedded in the language, however: the `std::marker` traits `Sync` and `Send`.

Allowing Transference of Ownership Between Threads with `Send`

The `Send` marker trait indicates that ownership of the type implementing `Send` may be transferred between threads. Almost every Rust type is `Send`, but there are some exceptions, including `Rc<T>`: this cannot be `Send` because if we cloned an `Rc<T>` value and tried to transfer ownership of the clone to another thread, both threads might update the reference count at the same time. For this reason, `Rc<T>` is implemented for use in single-threaded situations where you don't want to pay the threadsafe performance penalty.

In this way Rust's type system and trait bounds ensure we can never accidentally send an `Rc<T>` value across threads unsafely. When we tried to do this in Listing 16-14, we got an error that said `the trait Send is not implemented for Rc<Mutex<i32>>`. When we switched to `Arc<T>`, which is `Send`, the code compiled.

Any type composed entirely of `Send` types is automatically marked as `Send` as well. Almost all primitive types are `Send`, aside from raw pointers, which we'll discuss in Chapter 19.

Allowing Access from Multiple Threads with `Sync`

The `Sync` marker trait indicates that it is safe for the type implementing `Sync` to be referenced from multiple threads. Another way to say this is that any type `T` is `Sync` if `&T` (a reference to `T`) is `Send`, meaning the reference can be sent safely to another thread. In a similar manner as `Send`, primitive types are `Sync` and types composed entirely of types that are `Sync` are also `Sync`.

`Rc<T>` is also not `Sync`, for the same reasons that it's not `Send`. `RefCell<T>` (which we talked about in Chapter 15) and the family of related `Cell<T>` types are not `Sync`. The implementation of borrow checking that `RefCell<T>` does at runtime is not threadsafe. `Mutex<T>` is `Sync`, and can be used to share access with multiple threads as we saw in the previous section.

Implementing `Send` and `Sync` Manually is Unsafe

Because types that are made up of `Send` and `Sync` traits are automatically also `Send` and `Sync`, we don't have to implement those traits ourselves. As marker traits, they don't even have any methods to implement. They're just useful for enforcing concurrency-related invariants.

Manually implementing these traits involves implementing unsafe Rust code. We're going to be talking about using unsafe Rust code in Chapter 19; for now, the important information is that building new concurrent types not made up of `Send` and `Sync` parts requires careful thought, in order to uphold the safety guarantees. The Nomicon has more information about these guarantees and how to uphold them.

Summary

This isn't the last we'll see of concurrency in this book; the project in Chapter 20 will use these concepts in a more realistic situation than the smaller examples discussed here.

As we mentioned, since very little of how Rust deals with concurrency is part of the language, many concurrency solutions are implemented as crates. These evolve more quickly than the standard library; search online for the current state-of-the-art crates to use in multithreaded situations.

Rust provides channels for message passing and smart pointer types like `Mutex<T>` and `Arc<T>` that are safe to use in concurrent contexts. The type system and the borrow checker will make sure the code using these solutions won't end up with data races or invalid references. Once we get our code compiling, we can rest assured that it will happily run on multiple threads without the kinds of hard-to-track-down bugs common in other languages.

Concurrent programming is no longer something to be afraid of: go forth and make your programs concurrent, fearlessly!

Next, let's talk about idiomatic ways to model problems and structure solutions as your Rust programs get bigger, and how Rust's idioms relate to those you might be familiar with from Object Oriented Programming.

Is Rust an Object-Oriented Programming Language?

Object-Oriented Programming is a way of modeling programs that originated with Simula in the 1960s and became popular with C++ in the 1990s. There are many competing definitions for what OOP is: under some definitions, Rust is object-oriented; under other definitions, Rust is not. In this chapter, we'll explore some characteristics that are commonly considered to be object-oriented and how those characteristics translate to idiomatic Rust.

What Does Object-Oriented Mean?

There isn't consensus in the programming community about the features a language needs to have in order to be called object-oriented. Rust is influenced by many different programming paradigms; we explored the features it has that come from functional programming in Chapter 13. Some of the characteristics that object-oriented programming languages tend to share are objects, encapsulation, and inheritance. Let's take a look at what each of those mean and whether Rust supports them.

Objects Contain Data and Behavior

The book "Design Patterns: Elements of Reusable Object-Oriented Software," colloquially referred to as "The Gang of Four book," is a catalog of object-oriented design patterns. It defines object-oriented programming in this way:

> Object-oriented programs are made up of objects. An *object* packages both data and the procedures that operate on that data. The procedures are typically called *methods* or *operations*.

Under this definition, then, Rust is object-oriented: structs and enums have data and `impl` blocks provide methods on structs and enums. Even though structs and enums with methods aren't *called* objects, they provide the same functionality that objects do, using the Gang of Four's definition of objects.

Encapsulation that Hides Implementation Details

Another aspect commonly associated with object-oriented programming is the idea of *encapsulation*: the implementation details of an object aren't accessible to code using that object. The only way to interact with an object is through the public API the object offers; code using the object should not be able to reach into the object's internals and change data or behavior directly. Encapsulation enables changing and refactoring an object's internals without needing to change the code that uses the object.

As we discussed in Chapter 7, we can use the `pub` keyword to decide what modules, types, functions, and methods in our code should be public, and by default, everything is private. For example, we can define a struct `AveragedCollection` that has a field containing a vector of `i32` values. The struct can also have a field that knows the average of the values in the vector so that whenever anyone wants to know the average of the values that the struct has in its vector, we don't have to compute it on-demand. `AveragedCollection` will cache the calculated average for us. Listing 17-1 has the definition of the `AveragedCollection` struct:

Filename: src/lib.rs

```rust
pub struct AveragedCollection {
    list: Vec<i32>,
    average: f64,
}
```

Listing 17-1: An `AveragedCollection` struct that maintains a list of integers and the average of the items in the collection.

Note that the struct itself is marked `pub` so that other code may use this struct, but the fields within the struct remain private. This is important in this case because we want to ensure that whenever a value is added or removed from the list, we also update the average. We do this by implementing `add`, `remove`, and `average` methods on the struct as shown in Listing 17-2:

Filename: src/lib.rs

```rust
impl AveragedCollection {
    pub fn add(&mut self, value: i32) {
        self.list.push(value);
        self.update_average();
    }

    pub fn remove(&mut self) -> Option<i32> {
        let result = self.list.pop();
        match result {
            Some(value) => {
                self.update_average();
                Some(value)
            },
            None => None,
        }
    }

    pub fn average(&self) -> f64 {
        self.average
    }

    fn update_average(&mut self) {
        let total: i32 = self.list.iter().sum();
        self.average = total as f64 / self.list.len() as f64;
    }
}
```

Listing 17-2: Implementations of the public methods `add`, `remove`, and `average` on `AveragedCollection`

The public methods `add`, `remove`, and `average` are the only way to modify an instance of a `AveragedCollection`. When an item is added to `list` using the `add` method or removed using the `remove` method, the implementations of those methods call the private `update_average` method that takes care of updating the `average` field as well. Because the `list` and `average` fields are private, there's no way for external code to add or remove items to the `list` field directly, which could cause the `average` field to get out of sync. The `average` method returns the value in the `average` field, which allows external code to read the `average` but not modify it.

Because we've encapsulated the implementation details of `AveragedCollection`, we can easily change aspects like the data structure in the future. For instance, we could use a `HashSet` instead of a `Vec` for the `list` field. As long as the signatures of the `add`, `remove`, and `average` public methods stay the same, code using `AveragedCollection` wouldn't need to change. This wouldn't necessarily be the case if we exposed `list` to external code: `HashSet` and `Vec` have different methods for adding and removing items, so the external code would likely have to change if it was modifying `list` directly.

If encapsulation is a required aspect for a language to be considered object-oriented, then Rust meets that requirement. Using `pub` or not for different parts of code enables encapsulation of implementation details.

Inheritance as a Type System and as Code Sharing

Inheritance is a mechanism that some programming languages provide whereby an object can be defined to inherit from another object's definition, thus gaining the parent object's data and behavior without having to define those again. Inheritance is a characteristic that is part of some people's definitions of what an OOP language is.

If a language must have inheritance to be an object-oriented language, then Rust is not object-oriented. There is not a way to define a struct that inherits from another struct in order to gain the parent struct's fields and method implementations. However, if you're used to having inheritance in your programming toolbox, there are other solutions in Rust depending on the reason you want to use inheritance.

There are two main reasons to reach for inheritance. The first is to be able to re-use code: once a particular behavior is implemented for one type, inheritance can enable re-using that implementation for a different type. Rust code can be shared using default trait method implementations instead, which we saw in Listing 10-15 when we added a default implementation of the `summary` method on the `Summarizable` trait. Any type implementing the `Summarizable` trait would have the `summary` method available on it without any further code. This is similar to a parent class having an implementation of a method, and a child class inheriting from the parent class also having the implementation of the method due to the inheritance. We can also choose to override the default implementation of the `summary` method when we implement the `Summarizable` trait, which is similar to a child class overriding the implementation of a method inherited from a parent class.

The second reason to use inheritance is with the type system: to express that a child type can be used in the same places that the parent type can be used. This is also called *polymorphism*, which means that multiple objects can be substituted for each other at runtime if they have the same shape.

> While many people use "polymorphism" to describe inheritance, it's actually a specific kind of polymorphism, called "sub-type polymorphism." There are other forms as well; a generic parameter with a trait bound in Rust is also polymorphism, more specifically "parametric polymorphism." The exact details between the different kinds of polymorphism aren't crucial here, so don't worry too much about the details: just know that Rust has multiple polymorphism-related features, unlike many OOP languages.

To support this sort of pattern, Rust has *trait objects* so that we can specify that we would like values of any type, as long as the values implement a particular trait.

Inheritance has recently fallen out of favor as a programming design solution in many programming languages. Using inheritance to re-use some code can require more code to be shared than you actually need. Subclasses shouldn't always share all characteristics of their parent class, but inheritance means the subclass gets all of its parent's data and behavior. This can make a program's design less flexible, and creates the possibility of calling methods on subclasses that don't make sense or cause errors since the methods don't apply to the subclass but must be inherited from the parent class. In addition, some languages only allow a subclass to inherit from one class, further restricting the flexibility of a program's design.

For these reasons, Rust chose to take a different approach with trait objects instead of inheritance. Let's take a look at how trait objects enable polymorphism in Rust.

Trait Objects for Using Values of Different Types

In Chapter 8, we said that a limitation of vectors is that vectors can only store elements of one type. We had an example in Listing 8-1 where we defined a `SpreadsheetCell` enum that had variants to hold integers, floats, and text so that we could store different types of data in each cell and still have a vector represent a row of cells. This works for cases in which the kinds of things we want to be able to treat interchangeably are a fixed set of types that we know when our code gets compiled.

Sometimes we want the set of types that we use to be extensible by the programmers who use our library. For example, many Graphical User Interface tools have a concept of a list of items that get drawn on the screen by iterating through the list and calling a `draw` method on each of the items. We're going to create a library crate containing the structure of a GUI library called `rust_gui`. Our GUI library could include some types for people to use, such as `Button` or `TextField`. Programmers that use `rust_gui` will want to create more types that can be drawn on the screen: one programmer might add an `Image`, while another might add a `SelectBox`. We're not going to implement a fully-fledged GUI library in this chapter, but we will show how the pieces would fit together.

When we're writing the `rust_gui` library, we don't know all the types that other programmers will want to create, so we can't define an `enum` containing all the types. What we do know is that `rust_gui` needs to be able to keep track of a bunch of values of all these different types, and it needs to be able to call a `draw` method on each of these values. Our GUI library doesn't need to know what will happen exactly when we call the `draw` method, just that the value will have that method available for us to call.

In a language with inheritance, we might define a class named `Component` that has a method named `draw` on it. The other classes like `Button`, `Image`, and `SelectBox` would inherit from

`Component` and thus inherit the `draw` method. They could each override the `draw` method to define their custom behavior, but the framework could treat all of the types as if they were `Component` instances and call `draw` on them.

Defining a Trait for the Common Behavior

In Rust, though, we can define a trait that we'll name `Draw` and that will have one method named `draw`. Then we can define a vector that takes a *trait object*, which is a trait behind some sort of pointer, such as a `&` reference or a `Box<T>` smart pointer. We'll talk about the reason trait objects have to be behind a pointer in Chapter 19.

We mentioned that we don't call structs and enums "objects" to distinguish structs and enums from other languages' objects. The data in the struct or enum fields and the behavior in `impl` blocks is separated, as opposed to other languages that have data and behavior combined into one concept called an object. Trait objects *are* more like objects in other languages, in the sense that they combine the data made up of the pointer to a concrete object with the behavior of the methods defined in the trait. However, trait objects are different from objects in other languages because we can't add data to a trait object. Trait objects aren't as generally useful as objects in other languages: their purpose is to allow abstraction across common behavior.

A trait defines behavior that we need in a given situation. We can then use a trait as a trait object in places where we would use a concrete type or a generic type. Rust's type system will ensure that any value we substitute in for the trait object will implement the methods of the trait. Then we don't need to know all the possible types at compile time, and we can treat all the instances the same way. Listing 17-3 shows how to define a trait named `Draw` with one method named `draw`:

Filename: src/lib.rs

```rust
pub trait Draw {
    fn draw(&self);
}
```

Listing 17-3: Definition of the `Draw` trait

This should look familiar since we talked about how to define traits in Chapter 10. Next comes something new: Listing 17-4 has the definition of a struct named `Screen` that holds a vector named `components` that are of type `Box<Draw>`. That `Box<Draw>` is a trait object: it's a stand-in for any type inside a `Box` that implements the `Draw` trait.

Filename: src/lib.rs

```
pub struct Screen {
    pub components: Vec<Box<Draw>>,
}
```

Listing 17-4: Definition of the `Screen` struct with a `components` field that holds a vector of trait objects that implement the `Draw` trait

On the `Screen` struct, we'll define a method named `run`, which will call the `draw` method on each of its `components` as shown in Listing 17-5:

Filename: src/lib.rs

```
impl Screen {
    pub fn run(&self) {
        for component in self.components.iter() {
            component.draw();
        }
    }
}
```

Listing 17-5: Implementing a `run` method on `Screen` that calls the `draw` method on each component

This is different than defining a struct that uses a generic type parameter with trait bounds. A generic type parameter can only be substituted with one concrete type at a time, while trait objects allow for multiple concrete types to fill in for the trait object at runtime. For example, we could have defined the `Screen` struct using a generic type and a trait bound as in Listing 17-6:

Filename: src/lib.rs

```
pub struct Screen<T: Draw> {
    pub components: Vec<T>,
}

impl<T> Screen<T>
    where T: Draw {
    pub fn run(&self) {
        for component in self.components.iter() {
            component.draw();
        }
    }
}
```

Listing 17-6: An alternate implementation of the `Screen` struct and its `run` method using generics and trait bounds

This only lets us have a `Screen` instance that has a list of components that are all of type `Button` or all of type `TextField`. If you'll only ever have homogeneous collections, using generics and trait bounds is preferable since the definitions will be monomorphized at compile time to use the concrete types.

With the definition of `Screen` that holds a component list of trait objects in `Vec<Box<Draw>>` instead, one `Screen` instance can hold a `Vec` that contains a `Box<Button>` as well as a `Box<TextField>`. Let's see how that works, and then talk about the runtime performance implications.

Implementations of the Trait from Us or Library Users

Now to add some types that implement the `Draw` trait. We're going to provide the `Button` type, and again, actually implementing a GUI library is out of scope of this book, so the `draw` method won't have any useful implementation in its body. To imagine what the implementation might look like, a `Button` struct might have fields for `width`, `height`, and `label`, as shown in Listing 17-7:

Filename: src/lib.rs

```
pub struct Button {
    pub width: u32,
    pub height: u32,
    pub label: String,
}

impl Draw for Button {
    fn draw(&self) {
        // Code to actually draw a button
    }
}
```

Listing 17-7: A `Button` struct that implements the `Draw` trait

The `width`, `height`, and `label` fields on `Button` will differ from other components, such as a `TextField` type that might have `width`, `height`, `label`, and `placeholder` fields instead. Each of the types that we want to be able to draw on the screen will implement the `Draw` trait with different code in the `draw` method that defines how to draw that type like `Button` has here (without any actual GUI code that's out of scope of this chapter). In addition to implementing the `Draw` trait, `Button` might also have another `impl` block containing methods having to do with what happens if the button is clicked. These kinds of methods won't apply to types like `TextField`.

Someone using our library has decided to implement a `SelectBox` struct that has `width`, `height`, and `options` fields. They implement the `Draw` trait on the `SelectBox` type as well, as shown in Listing 17-8:

Filename: src/main.rs

```
extern crate rust_gui;
use rust_gui::Draw;

struct SelectBox {
    width: u32,
    height: u32,
    options: Vec<String>,
}

impl Draw for SelectBox {
    fn draw(&self) {
        // Code to actually draw a select box
    }
}
```

Listing 17-8: Another crate using `rust_gui` and implementing the `Draw` trait on a `SelectBox` struct

The user of our library can now write their `main` function to create a `Screen` instance and add a `SelectBox` and a `Button` to the screen by putting each in a `Box<T>` to become a trait object. They can then call the `run` method on the `Screen` instance, which will call `draw` on each of the components. Listing 17-9 shows this implementation:

Filename: src/main.rs

```
use rust_gui::{Screen, Button};

fn main() {
    let screen = Screen {
        components: vec![
            Box::new(SelectBox {
                width: 75,
                height: 10,
                options: vec![
                    String::from("Yes"),
                    String::from("Maybe"),
                    String::from("No")
                ],
            }),
            Box::new(Button {
                width: 50,
                height: 10,
                label: String::from("OK"),
            }),
        ],
    };

    screen.run();
}
```

Listing 17-9: Using trait objects to store values of different types that implement the same trait

Even though we didn't know that someone would add the `SelectBox` type someday, our `Screen` implementation was able to operate on the `SelectBox` and draw it because `SelectBox` implements the `Draw` type, which means it implements the `draw` method.

Only being concerned with the messages a value responds to, rather than the value's concrete type, is similar to a concept called *duck typing* in dynamically typed languages: if it walks like a duck, and quacks like a duck, then it must be a duck! In the implementation of `run` on `Screen` in Listing 17-5, `run` doesn't need to know what the concrete type of each component is. It doesn't check to see if a component is an instance of a `Button` or a `SelectBox`, it just calls the `draw` method on the component. By specifying `Box<Draw>` as the type of the values in the `components` vector, we've defined that `Screen` needs values that we can call the `draw` method on.

The advantage with using trait objects and Rust's type system to do duck typing is that we never have to check that a value implements a particular method at runtime or worry about getting errors if a value doesn't implement a method but we call it. Rust won't compile our code if the values don't implement the traits that the trait objects need.

For example, Listing 17-10 shows what happens if we try to create a `Screen` with a `String` as a component:

Filename: src/main.rs

```
extern crate rust_gui;
use rust_gui::Draw;

fn main() {
    let screen = Screen {
        components: vec![
            Box::new(String::from("Hi")),
        ],
    };

    screen.run();
}
```

Listing 17-10: Attempting to use a type that doesn't implement the trait object's trait

We'll get this error because `String` doesn't implement the `Draw` trait:

```
error[E0277]: the trait bound `std::string::String: Draw` is not satisfied
  -->
   |
 4 |             Box::new(String::from("Hi")),
   |             ^^^^^^^^^^^^^^^^^^^^^^^^^^^^ the trait `Draw` is not
   implemented for `std::string::String`
   |
   = note: required for the cast to the object type `Draw`
```

This lets us know that either we're passing something we didn't mean to pass to `Screen` and we should pass a different type, or we should implement `Draw` on `String` so that `Screen` is able to call `draw` on it.

Trait Objects Perform Dynamic Dispatch

Recall in Chapter 10 when we discussed the process of monomorphization that the compiler performs when we use trait bounds on generics: the compiler generates non-generic implementations of functions and methods for each concrete type that we use in place of a generic type parameter. The code that results from monomorphization is doing *static dispatch*: when the method is called, the code that goes with that method call has been determined at compile time, and looking up that code is very fast.

When we use trait objects, the compiler can't perform monomorphization because we don't know all the types that might be used with the code. Instead, Rust keeps track of the code that might be used when a method is called and figures out at runtime which code needs to be used for a particular method call. This is known as *dynamic dispatch*, and there's a runtime cost when this lookup happens. Dynamic dispatch also prevents the compiler from choosing to inline a method's code, which prevents some optimizations. We did get extra flexibility in the code that we wrote and were able to support, though, so it's a tradeoff to consider.

Object Safety is Required for Trait Objects

Not all traits can be made into trait objects; only *object safe* traits can. A trait is object safe as long as both of the following are true:

- The trait does not require `Self` to be `Sized`
- All of the trait's methods are object safe.

`Self` is a keyword that is an alias for the type that we're implementing traits or methods on. `Sized` is a marker trait like the `Send` and `Sync` traits that we talked about in Chapter 16. `Sized` is automatically implemented on types that have a known size at compile time, such as `i32` and references. Types that do not have a known size include slices (`[T]`) and trait objects.

`Sized` is an implicit trait bound on all generic type parameters by default. Most useful operations in Rust require a type to be `Sized`, so making `Sized` a default requirement on trait bounds means we don't have to write `T: Sized` with most every use of generics. If we want to be able to use a trait on slices, however, we need to opt out of the `Sized` trait bound, and we can do that by specifying `T: ?Sized` as a trait bound.

Traits have a default bound of `Self: ?Sized`, which means that they can be implemented on types that may or may not be `Sized`. If we create a trait `Foo` that opts out of the `Self: ?Sized` bound, that would look like the following:

```
trait Foo: Sized {
    fn some_method(&self);
}
```

The trait `Sized` is now a *supertrait* of trait `Foo`, which means trait `Foo` requires types that implement `Foo` (that is, `Self`) to be `Sized`. We're going to talk about supertraits in more detail in Chapter 19.

`Foo` requires `Self` to be `Sized`, and therefore is not allowed to be used in a trait object like `Box<Foo>`. This is because it would be impossible to implement the trait `Foo` for a trait object like `Box<Foo>`: trait objects aren't sized, but `Foo` requires `Self` to be `Sized`. A type can't be both sized and unsized at the same time!

For the second object safety requirement that says all of a trait's methods must be object safe, a method is object safe if either:

- It requires `Self` to be `Sized` or
- It meets all three of the following:
  - It must not have any generic type parameters
  - Its first argument must be of type `Self` or a type that dereferences to the Self type (that is, it must be a method rather than an associated function and have `self`, `&self`, or `&mut self` as the first argument)

- It must not use `Self` anywhere else in the signature except for the first argument

Those rules are a bit formal, but think of it this way: if your method requires the concrete `Self` type somewhere in its signature, but an object forgets the exact type that it is, there's no way that the method can use the original concrete type that it's forgotten. Same with generic type parameters that are filled in with concrete type parameters when the trait is used: the concrete types become part of the type that implements the trait. When the type is erased by the use of a trait object, there's no way to know what types to fill in the generic type parameters with.

An example of a trait whose methods are not object safe is the standard library's `Clone` trait. The signature for the `clone` method in the `Clone` trait looks like this:

```
pub trait Clone {
    fn clone(&self) -> Self;
}
```

`String` implements the `Clone` trait, and when we call the `clone` method on an instance of `String` we get back an instance of `String`. Similarly, if we call `clone` on an instance of `Vec`, we get back an instance of `Vec`. The signature of `clone` needs to know what type will stand in for `Self`, since that's the return type.

If we try to implement `Clone` on a trait like the `Draw` trait from Listing 17-3, we wouldn't know whether `Self` would end up being a `Button`, a `SelectBox`, or some other type that will implement the `Draw` trait in the future.

The compiler will tell you if you're trying to do something that violates the rules of object safety in regards to trait objects. For example, if we had tried to implement the `Screen` struct in Listing 17-4 to hold types that implement the `Clone` trait instead of the `Draw` trait, like this:

```
pub struct Screen {
    pub components: Vec<Box<Clone>>,
}
```

We'll get this error:

```
error[E0038]: the trait `std::clone::Clone` cannot be made into an object
 -->
  |
2 |     pub components: Vec<Box<Clone>>,
  |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ the trait `std::clone::Clone` cannot be
  made into an object
  |
  = note: the trait cannot require that `Self : Sized`
```

Object-Oriented Design Pattern Implementation

Let's look at an example of the state design pattern and how to use it in Rust. The *state pattern* is when a value has some internal state, and the value's behavior changes based on the internal state. The internal state is represented by a set of objects that inherit shared functionality (we'll use structs and traits since Rust doesn't have objects and inheritance). Each state object is responsible for its own behavior and the rules for when it should change into another state. The value that holds one of these state objects doesn't know anything about the different behavior of the states or when to transition between states. In the future when requirements change, we won't need to change the code of the value holding the state or the code that uses the value. We'll only need to update the code inside one of the state objects to change its rules, or perhaps add more state objects.

In order to explore this idea, we're going to implement a blog post workflow in an incremental way. The workflow that we want our blog posts to follow, once we're done with the implementation, is:

1. A blog post starts as an empty draft.
2. Once the draft is done, we request a review of the post.
3. Once the post is approved, it gets published.
4. Only published blog posts return content to print so that we can't accidentally print the text of a post that hasn't been approved.

Any other changes attempted on a post should have no effect. For example, if we try to approve a draft blog post before we've requested a review, the post should stay an unpublished draft.

Listing 17-11 shows this workflow in code form. This is an example usage of the API we're going to implement in a library crate named `blog`:

Filename: src/main.rs

```
extern crate blog;
use blog::Post;

fn main() {
    let mut post = Post::new();

    post.add_text("I ate a salad for lunch today");
    assert_eq!("", post.content());

    post.request_review();
    assert_eq!("", post.content());

    post.approve();
    assert_eq!("I ate a salad for lunch today", post.content());
}
```

Listing 17-11: Code that demonstrates the desired behavior we want our `blog` crate to have

We want to be able to create a new draft blog post with `Post::new`. Then, we want to add some text to the blog post while we're in the draft state. If we try to print out the post's content immediately, though, we shouldn't get any text, since the post is still a draft. We've added an `assert_eq!` here for demonstration purposes. Asserting that a draft blog post returns an empty string from the `content` method would make an excellent unit test in our library, but we're not going to write tests for this example.

Next, we want to be able to request a review of our post, and `content` should still return an empty string while waiting for a review. Lastly, when we approve the blog post, it should get published, which means the text we added will be returned when we call `content`.

Notice that the only type we're interacting with from the crate is the `Post` type. The various states a post can be in (draft, waiting for review, published) are managed internally to the `Post` type. The states change due to the methods we call on the `Post` instance, but we don't have to manage the state changes directly. This also means we won't make a mistake with the states, like forgetting to request a review before publishing.

Defining `Post` and Creating a New Instance in the Draft State

Let's get started on the implementation of the library! We know we want to have a public `Post` struct that holds some content, so let's start with the definition of the struct and an associated public `new` function to create an instance of `Post` as shown in Listing 17-12. We're also going to have a private trait `State`. `Post` will hold a trait object of `Box<State>` inside an `Option` in a private field named `state`. We'll see why the `Option` is necessary in a bit. The `State` trait defines all the behavior different post states share, and the `Draft`, `PendingReview`, and `Published` states will all implement the `State` trait. For now, the trait does not have any methods, and we're going to start by defining just the `Draft` state since that's the state we want to start in:

Filename: src/lib.rs

```
pub struct Post {
    state: Option<Box<State>>,
    content: String,
}

impl Post {
    pub fn new() -> Post {
        Post {
            state: Some(Box::new(Draft {})),
            content: String::new(),
        }
    }
}

trait State {}

struct Draft {}

impl State for Draft {}
```

Listing 17-12: Definition of a `Post` struct and a `new` function that creates a new `Post` instance, a `State` trait, and a `Draft` struct that implements `State`

When we create a new `Post`, we set its `state` field to a `Some` value holding a `Box` pointing to a new instance of the `Draft` struct. This ensures whenever we create a new instance of `Post`, it'll start out as a draft. Because the `state` field of `Post` is private, there's no way to create a `Post` in any other state!

Storing the Text of the Post Content

In the `Post::new` function, we set the `content` field to a new, empty `String`. In Listing 17-11, we showed that we want to be able to call a method named `add_text` and pass a `&str` to it to add that text to the content of the blog post. We're choosing to implement this as a method rather than exposing the `content` field as `pub` because we want to be able to control how the `content` field's data is read by implementing a method later. The `add_text` method is pretty straightforward though, let's add the implementation in Listing 17-13 to the `impl Post` block:

Filename: src/lib.rs

```
impl Post {
    // ...snip...
    pub fn add_text(&mut self, text: &str) {
        self.content.push_str(text);
    }
}
```

Listing 17-13: Implementing the `add_text` method to add text to a post's `content`

`add_text` takes a mutable reference to `self`, since we're changing the `Post` instance that we're calling `add_text` on. We then call `push_str` on the `String` in `content` and pass the `text` argument to add to the saved `content`. This isn't part of the state pattern since its behavior doesn't depend on the state that the post is in. The `add_text` method doesn't interact with the `state` field at all, but it is part of the behavior we want to support.

Content of a Draft Post is Empty

After we've called `add_text` and added some content to our post, we still want the `content` method to return an empty string slice since the post is still in the draft state, as shown on line 8 of Listing 17-11. For now, let's implement the `content` method with the simplest thing that will fulfill this requirement: always returning an empty string slice. We're going to change this later once we implement the ability to change a post's state to be published. With what we have so far, though, posts can only be in the draft state, which means the post content should always be empty. Listing 17-14 shows this placeholder implementation:

Filename: src/lib.rs

```
impl Post {
    // ...snip...
    pub fn content(&self) -> &str {
        ""
    }
}
```

Listing 17-14: Adding a placeholder implementation for the `content` method on `Post` that always returns an empty string slice

With this added `content` method, everything in Listing 17-11 up to line 8 works as we intend.

Requesting a Review of the Post Changes its State

Next up is requesting a review of a post, which should change its state from `Draft` to `PendingReview`. We want `Post` to have a public method named `request_review` that will take a mutable reference to `self`. Then we're going to call an internal `request_review` method on the state that we're holding, and this second `request_review` method will consume the current state and return a new state. In order to be able to consume the old state, the second `request_review` method needs to take ownership of the state value. This is where the `Option` comes in: we're going to `take` the `Some` value out of the `state` field and leave a `None` in its place since Rust doesn't let us have unpopulated fields in structs. Then we'll set the post's `state` value to the result of this operation. Listing 17-15 shows this code:

Filename: src/lib.rs

```
impl Post {
    // ...snip...
    pub fn request_review(&mut self) {
        if let Some(s) = self.state.take() {
            self.state = Some(s.request_review())
        }
    }
}

trait State {
    fn request_review(self: Box<Self>) -> Box<State>;
}

struct Draft {}

impl State for Draft {
    fn request_review(self: Box<Self>) -> Box<State> {
        Box::new(PendingReview {})
    }
}

struct PendingReview {}

impl State for PendingReview {
    fn request_review(self: Box<Self>) -> Box<State> {
        self
    }
}
```

Listing 17-15: Implementing `request_review` methods on `Post` and the `State` trait

We've added the `request_review` method to the `State` trait; all types that implement the trait will now need to implement the `request_review` method. Note that rather than having `self`, `&self`, or `&mut self` as the first parameter of the method, we have `self: Box<Self>`. This syntax means the method is only valid when called on a `Box` holding the type. This syntax takes ownership of `Box<Self>`, which is what we want because we're transforming the old state into a new state, and we want the old state to no longer be valid.

The implementation for the `request_review` method on `Draft` is to return a new, boxed instance of the `PendingReview` struct, which is a new type we've introduced that represents the state when a post is waiting for a review. The `PendingReview` struct also implements the `request_review` method, but it doesn't do any transformations. It returns itself since requesting a review on a post that's already in the `PendingReview` state should stay in the `PendingReview` state.

Now we can start seeing the advantages of the state pattern: the `request_review` method on `Post` is the same no matter what its `state` value is. Each state is responsible for its own rules.

We're going to leave the `content` method on `Post` as it is, returning an empty string slice. We can now have a `Post` in the `PendingReview` state, not just the `Draft` state, but we want the same behavior in the `PendingReview` state. Listing 17-11 now works up until line 11!

Approving a Post Changes the Behavior of `content`

The `approve` method on `Post` will be similar to that of the `request_review` method: it will set the `state` to the value that the current state says it should have when that state is approved. We'll need to add the `approve` method to the `State` trait, and we'll add a new struct that implements `State`, the `Published` state. Listing 17-16 shows the new code:

Filename: src/lib.rs

```
impl Post {
    // ...snip...
    pub fn approve(&mut self) {
        if let Some(s) = self.state.take() {
            self.state = Some(s.approve())
        }
    }
}

trait State {
    fn request_review(self: Box<Self>) -> Box<State>;
    fn approve(self: Box<Self>) -> Box<State>;
}

struct Draft {}

impl State for Draft {
    // ...snip...
    fn approve(self: Box<Self>) -> Box<State> {
        self
    }
}

struct PendingReview {}

impl State for PendingReview {
    // ...snip...
    fn approve(self: Box<Self>) -> Box<State> {
        Box::new(Published {})
    }
}

struct Published {}

impl State for Published {
    fn request_review(self: Box<Self>) -> Box<State> {
        self
    }

    fn approve(self: Box<Self>) -> Box<State> {
        self
    }
}
```

Listing 17-16: Implementing the `approve` method on `Post` and the `State` trait

Similarly to `request_review`, if we call the `approve` method on a `Draft`, it will have no effect since it will return `self`. When we call `approve` on `PendingReview`, it returns a new, boxed instance of the `Published` struct. The `Published` struct implements the `State` trait, and for both the `request_review` method and the `approve` method, it returns itself since the post should stay in the `Published` state in those cases.

Now for updating the `content` method on `Post`: we want to return the value in the post's `content` field if its state is `Published`, otherwise we want to return an empty string slice. Because the goal is to keep all the rules like this in the structs that implement `State`, we're going to call a `content` method on the value in `state` and pass the post instance (that is, `self`) as an argument. Then we'll return the value returned from the `content` method on the `state` value as shown in Listing 17-17:

Filename: src/lib.rs

```
impl Post {
    // ...snip...
    pub fn content(&self) -> &str {
        self.state.as_ref().unwrap().content(&self)
    }
    // ...snip...
}
```

Listing 17-17: Updating the `content` method on `Post` to delegate to a `content` method on `State`

We're calling the `as_ref` method on the `Option` because we want a reference to the value inside the `Option`. We're then calling the `unwrap` method, which we know will never panic because all the methods on `Post` ensure that the `state` value will have a `Some` value in it when those methods are done. This is one of the cases we talked about in Chapter 12 where we know that a `None` value is never possible even though the compiler isn't able to understand that.

The `content` method on the `State` trait is where the logic for what content to return will be. We're going to add a default implementation for the `content` method that returns an empty string slice. That lets us not need to implement `content` on the `Draft` and `PendingReview` structs. The `Published` struct will override the `content` method and will return the value in `post.content`, as shown in Listing 17-18:

Filename: src/lib.rs

```
trait State {
    // ...snip...
    fn content<'a>(&self, post: &'a Post) -> &'a str {
        ""
    }
}

// ...snip...
struct Published {}

impl State for Published {
    // ...snip...
    fn content<'a>(&self, post: &'a Post) -> &'a str {
        &post.content
    }
}
```

Listing 17-18: Adding the `content` method to the `State` trait

Note that we need lifetime annotations on this method, like we discussed in Chapter 10. We're taking a reference to a `post` as an argument, and we're returning a reference to a part of that `post`, so the lifetime of the returned reference is related to the lifetime of the `post` argument.

Tradeoffs of the State Pattern

We've shown that Rust is capable of implementing the object-oriented state pattern in order to encapsulate the different kinds of behavior that a post should have that depends on the state that the post is in. The methods on `Post` don't know anything about the different kinds of behavior. The way this code is organized, we have one place to look in order to find out all the different ways that a published post behaves: the implementation of the `State` trait on the `Published` struct.

An alternative implementation that didn't use the state pattern might have `match` statements in the methods on `Post` or even in the code that uses `Post` (`main` in our case) that checks what the state of the post is and changes behavior in those places instead. That would mean we'd have a lot of places to look in order to understand all the implications of a post being in the published state! This would get worse the more states we added: each of those `match` statements would need another arm. With the state pattern, the `Post` methods and the places we use `Post` don't need `match` statements and adding a new state only involves adding a new `struct` and implementing the trait methods on that one struct.

This implementation is easy to extend to add more functionality. Here are some changes you can try making to the code in this section to see for yourself what it's like to maintain code using this pattern over time:

- Only allow adding text content when a post is in the `Draft` state
- Add a `reject` method that changes the post's state from `PendingReview` back to `Draft`
- Require two calls to `approve` before changing the state to `Published`

A downside of the state pattern is that since the states implement the transitions between the states, some of the states are coupled to each other. If we add another state between `PendingReview` and `Published`, such as `Scheduled`, we would have to change the code in `PendingReview` to transition to `Scheduled` instead. It would be nicer if `PendingReview` wouldn't need to change because of the addition of a new state, but that would mean switching to another design pattern.

There are a few bits of duplicated logic that are a downside of this implementation in Rust. It would be nice if we could make default implementations for the `request_review` and `approve` methods on the `State` trait that return `self`, but this would violate object safety since the trait doesn't know what the concrete `self` will be exactly. We want to be able to use `State` as a trait object, so we need its methods to be object safe.

The other duplication that would be nice to get rid of is the similar implementations of the `request_review` and `approve` methods on `Post`. They both delegate to the implementation of the same method on the value in the `Option` in the `state` field, and set the new value of the `state` field to the result. If we had a lot of methods on `Post` that followed this pattern, we might consider defining a macro to eliminate the repetition (see Appendix E on macros).

A downside of implementing this object-oriented pattern exactly as it's defined for object-oriented languages is that we're not taking advantage of Rust's strengths as much as we could be. Let's take a look at some changes we can make to this code that can make invalid states and transitions into compile time errors.

Encoding States and Behavior as Types

We're going to show how to rethink the state pattern a bit in order to get a different set of tradeoffs. Rather than encapsulating the states and transitions completely so that outside code has no knowledge of them, we're going to encode the states into different types. When the states are types, Rust's type checking will make any attempt to use a draft post where we should only use published posts into a compiler error.

Let's consider the first part of `main` from Listing 17-11:

Filename: src/main.rs

```
fn main() {
    let mut post = Post::new();

    post.add_text("I ate a salad for lunch today");
    assert_eq!("", post.content());
}
```

We still want to create a new post in the draft state using `Post::new`, and we still want to be able to add text to the post's content. But instead of having a `content` method on a draft post that returns an empty string, we're going to make it so that draft posts don't have the `content` method at all. That way, if we try to get a draft post's content, we'll get a compiler error that the method doesn't exist. This will make it impossible for us to accidentally display draft post content in production, since that code won't even compile. Listing 17-19 shows the definition of a `Post` struct, a `DraftPost` struct, and methods on each:

Filename: src/lib.rs

```
pub struct Post {
    content: String,
}

pub struct DraftPost {
    content: String,
}

impl Post {
    pub fn new() -> DraftPost {
        DraftPost {
            content: String::new(),
        }
    }

    pub fn content(&self) -> &str {
       &self.content
    }
}

impl DraftPost {
    pub fn add_text(&mut self, text: &str) {
        self.content.push_str(text);
    }
}
```

Listing 17-19: A `Post` with a `content` method and a `DraftPost` without a `content` method

Both the `Post` and `DraftPost` structs have a private `content` field that stores the blog post text. The structs no longer have the `state` field since we're moving the encoding of the state to the types of the structs. `Post` will represent a published post, and it has a `content` method that returns the `content`.

We still have a `Post::new` function, but instead of returning an instance of `Post`, it returns an instance of `DraftPost`. It's not possible to create an instance of `Post` right now since `content` is private and there aren't any functions that return `Post`. `DraftPost` has an `add_text` method defined on it so that we can add text to `content` as before, but note that `DraftPost` does not have a `content` method defined! So we've enforced that all posts start as draft posts, and draft posts don't have their content available for display. Any attempt to get around these constraints will be a compiler error.

Implementing Transitions as Transformations into Different Types

So how do we get a published post then? The rule we want to enforce is that a draft post has to be reviewed and approved before it can be published. A post in the pending review state should still not display any content. Let's implement these constraints by adding another struct, `PendingReviewPost`, defining the `request_review` method on `DraftPost` to return a `PendingReviewPost`, and defining an `approve` method on `PendingReviewPost` to return a `Post` as shown in Listing 17-20:

Filename: src/lib.rs

```
impl DraftPost {
    // ...snip...

    pub fn request_review(self) -> PendingReviewPost {
        PendingReviewPost {
            content: self.content,
        }
    }
}

pub struct PendingReviewPost {
    content: String,
}

impl PendingReviewPost {
    pub fn approve(self) -> Post {
        Post {
            content: self.content,
        }
    }
}
```

Listing 17-20: A `PendingReviewPost` that gets created by calling `request_review` on `DraftPost`, and an `approve` method that turns a `PendingReviewPost` into a published `Post`

The `request_review` and `approve` methods take ownership of `self`, thus consuming the `DraftPost` and `PendingReviewPost` instances and transforming them into a

`PendingReviewPost` and a published `Post`, respectively. This way, we won't have any `DraftPost` instances lingering around after we've called `request_review` on them, and so forth. `PendingReviewPost` doesn't have a `content` method defined on it, so attempting to read its content is a compiler error like it is with `DraftPost`. Because the only way to get a published `Post` instance that does have a `content` method defined is to call the `approve` method on a `PendingReviewPost`, and the only way to get a `PendingReviewPost` is to call the `request_review` method on a `DraftPost`, we've now encoded the blog post workflow into the type system.

This does mean we have to make some small changes to `main`. Because `request_review` and `approve` return new instances rather than modifying the struct they're called on, we need to add more `let post =` shadowing assignments to save the returned instances. We also can't have the assertions about the draft and pending review post's contents being empty string anymore, nor do we need them: we can't compile code that tries to use the content of posts in those states any longer. The updated code in `main` is shown in Listing 17-21:

Filename: src/main.rs

```
extern crate blog;
use blog::Post;

fn main() {
    let mut post = Post::new();

    post.add_text("I ate a salad for lunch today");

    let post = post.request_review();

    let post = post.approve();

    assert_eq!("I ate a salad for lunch today", post.content());
}
```

Listing 17-21: Modifications to `main` to use the new implementation of the blog post workflow

Having to change `main` to reassign `post` is what makes this implementation not quite following the object-oriented state pattern anymore: the transformations between the states are no longer encapsulated entirely within the `Post` implementation. However, we've gained the property of having invalid states be impossible because of the type system and type checking that happens at compile time! This ensures that certain bugs, such as displaying the content of an unpublished post, will be discovered before they make it to production.

Try the tasks suggested that add additional requirements that we mentioned at the start of this section to see how working with this version of the code feels.

Even though Rust is capable of implementing object-oriented design patterns, there are other patterns like encoding state into the type system that are available in Rust. These patterns have different tradeoffs than the object-oriented patterns do. While you may be very familiar with object-oriented patterns, rethinking the problem in order to take advantage of Rust's features can give benefits like preventing some bugs at compile-time. Object-oriented patterns won't always be the best solution in Rust, since Rust has features like ownership that object-oriented languages don't have.

Summary

No matter whether you think Rust is an object-oriented language or not after reading this chapter, you've now seen that trait objects are a way to get some object-oriented features in Rust. Dynamic dispatch can give your code some flexibility in exchange for a bit of runtime performance. This flexibility can be used to implement object-oriented patterns that can help with the maintainability of your code. Rust also has different features, like ownership, than object-oriented languages. An object-oriented pattern won't always be the best way to take advantage of Rust's strengths.

Next, let's look at another feature of Rust that enables lots of flexibility: patterns. We've looked at them briefly throughout the book, but haven't seen everything they're capable of yet. Let's go!

Patterns Match the Structure of Values

Patterns are a special syntax within Rust for matching against the structure of our types, complex or simple. A pattern is made up of some combination of literals; destructured arrays, enums, structs, or tuples; variables, wildcards, and placeholders. These pieces describe the "shape" of the data we're working with.

We use a pattern by taking some value and comparing it against the pattern. If the pattern matches our value, we do something with the value parts. Recall in Chapter 6 when we discussed the `match` expression that uses patterns like a coin sorting machine. We can name pieces within the shape, like we named the state that appeared on quarters in Chapter 6, and if the data fits the shape, we can use the named pieces.

This chapter is a reference on all things related to patterns. We'll cover the valid places to use patterns, the difference between *refutable* and *irrefutable* patterns, and the different kinds of pattern syntax that you might see.

All the Places Patterns May be Used

Patterns pop up in a number of places in Rust. You've been using them a lot without realizing it! This section is a reference to all the places where patterns are valid.

`match` Arms

As we discussed in Chapter 6, a common place patterns are used is in the arms of `match` expressions. Formally, `match` expressions are defined as the keyword `match`, a value to match on, and one or more match arms that consist of a pattern and an expression to run if the value matches that arm's pattern:

```
match VALUE {
    PATTERN => EXPRESSION,
    PATTERN => EXPRESSION,
    PATTERN => EXPRESSION,
}
```

Exhaustiveness and the Default Pattern `_`

`match` expressions are required to be exhaustive. When we put all of the patterns in the arms together, all possibilities for the value in the `match` expression must be accounted for. One way to ensure you have every possibility covered is to have a catch-all pattern for the last arm, like a variable name. A name matching any value can never fail and thus covers every case remaining after the previous arms' patterns.

There's an additional pattern that's often used in the last match arm: `_`. It matches anything, but it never binds any variables. This can be useful when you only want to run code for some patterns but ignore any other value, for example.

`if let` Expressions

We discussed `if let` expressions in Chapter 6, and how they're mostly a shorter way to write the equivalent of a `match` that only cares about matching one case. `if let` can optionally have a corresponding `else` with code to run if the pattern in the `if let` doesn't match.

Listing 18-1 shows that it's even possible to mix and match `if let`, `else if`, and `else if let`. This code shows a series of checks of a bunch of different conditions to decide what the background color should be. For the purposes of the example, we've created variables with hardcoded values that a real program might get by asking the user. If the user has specified a favorite color, we'll use that as the background color. If today is Tuesday, the background color will be green. If the user has specified their age as a string and we can parse it as a number successfully, we'll use either purple or orange depending on the value of the parsed number. Finally, if none of these conditions apply, the background color will be blue:

Filename: src/main.rs

```
fn main() {
    let favorite_color: Option<&str> = None;
    let is_tuesday = false;
    let age: Result<u8, _> = "34".parse();

    if let Some(color) = favorite_color {
        println!("Using your favorite color, {}, as the background", color);
    } else if is_tuesday {
        println!("Tuesday is green day!");
    } else if let Ok(age) = age {
        if age > 30 {
            println!("Using purple as the background color");
        } else {
            println!("Using orange as the background color");
        }
    } else {
        println!("Using blue as the background color");
    }
}
```

Listing 18-1: Mixing `if let`, `else if`, `else if let`, and `else`

This conditional structure lets us support complex requirements. With the hardcoded values we have here, this example will print `Using purple as the background color`.

Note that `if let` can also introduce shadowed variables like `match` arms can: `if let Ok(age) = age` introduces a new shadowed `age` variable that contains the value inside the `Ok` variant. This also means the `if age > 30` condition needs to go within the block; we aren't able to combine these two conditions into `if let Ok(age) = age && age > 30` since the shadowed `age` that we want to compare to 30 isn't valid until the new scope starts with the curly bracket.

Also note that conditionals with many cases like these are not as powerful as `match` expression since exhaustiveness is not checked by the compiler. If we leave off the last `else` block and miss handling some cases, the compiler will not error. This example might be too complex to rewrite as a readable `match`, so we should take extra care to check that we're handling all the cases since the compiler is not checking exhaustiveness for us.

`while let`

A similar construction to `if let` is `while let`: this allows you to do a `while` loop as long as a pattern continues to match. Listing 18-2 shows an example using a `while let` loop to use a vector as a stack and print out the values in the vector in the opposite order that we pushed the values in:

```
let mut stack = Vec::new();

stack.push(1);
stack.push(2);
stack.push(3);

while let Some(top) = stack.pop() {
    println!("{}", top);
}
```

Listing 18-2: Using a `while let` loop to print out values as long as `stack.pop()` returns `Some`

This example will print 3, 2, then 1. The `pop` method takes the last element out of the vector and returns `Some(value)`. If the vector is empty, it returns `None`. The `while` loop will continue running the code in its block as long as `pop` is returning `Some`. Once it returns `None`, the `while` loop stops. We can use `while let` to pop every element off our stack.

`for` loops

Looping with `for`, as we discussed in Chapter 3, is the most common loop construction in Rust code. What we didn't talk about in that chapter was that `for` takes a pattern. In Listing 18-3, we're demonstrating how we can use a pattern in a `for` loop to destructure a tuple. The `enumerate` method adapts an iterator to produce a value and the index of the value in the iterator in a tuple:

```
let v = vec![1, 2, 3];

for (index, value) in v.iter().enumerate() {
    println!("{} is at index {}", value, index);
}
```

Listing 18-3: Using a pattern in a `for` loop to destructure the tuple returned from `enumerate` into its pieces

This will print:

```
1 is at index 0
2 is at index 1
3 is at index 2
```

The first call to `enumerate` produces the tuple `(0, 1)`. When this value is matched to the pattern `(index, value)`, `index` will be 0 and `value` will be 1.

`let` Statements

`match` and `if let` are the places we've explicitly discussed using patterns earlier in the book, but they aren't the only places we've *used* patterns. For example, consider this straightforward variable assignment with `let`:

```
let x = 5;
```

We've done this hundreds of times throughout this book. You may not have realized it, but you were using patterns! A `let` statement looks like this, more formally:

```
let PATTERN = EXPRESSION;
```

We've seen statements like `let x = 5;` with a variable name in the `PATTERN` slot; a variable name is just a particularly humble form of pattern.

With `let`, we compare the expression against the pattern, and assign any names we find. So for example, in our `let x = 5;` case, `x` is a pattern that says "bind what matches here to the variable `x`." And since the name `x` is the whole pattern, this pattern effectively means "bind everything to the variable `x`, whatever the value is."

To see the pattern matching aspect of `let` a bit more clearly, consider Listing 18-4 where we're using a pattern with `let` to destructuring a tuple:

```
let (x, y, z) = (1, 2, 3);
```

Listing 18-4: Using a pattern to destructure a tuple and create 3 variables at once

Here, we have a tuple that we're matching against a pattern. Rust will compare the value `(1, 2, 3)` to the pattern `(x, y, z)` and see that the value matches the pattern. In this case, it will bind `1` to `x`, `2` to `y`, and `3` to `z`. You can think of this tuple pattern as nesting three individual variable patterns inside of it.

We saw another example of destructuring a tuple in Chapter 16, Listing 16-6, where we destructured the return value of `mpsc::channel()` into the `tx` (transmitter) and `rx` (receiver) parts.

Function Parameters

Similarly to `let`, function parameters can also be patterns. The code in Listing 18-5 declaring a function named `foo` that takes one parameter named `x` of type `i32` should look familiar:

```
fn foo(x: i32) {
    // code goes here
}
```

Listing 18-5: A function signature uses patterns in the parameters

The `x` part is a pattern! In a similar way as we did with `let`, we could match a tuple in a function's arguments. Listing 18-6 shows how we could split apart the values in a tuple as part of passing the tuple to a function:

Filename: src/main.rs

```
fn print_coordinates(&(x, y): &(i32, i32)) {
    println!("Current location: ({}, {})", x, y);
}

fn main() {
    let point = (3, 5);
    print_coordinates(&point);
}
```

Listing 18-6: A function with parameters that destructure a tuple

This will print `Current location: (3, 5)`. When we pass the value `&(3, 5)` to `print_coordinates`, the values match the pattern `&(x, y)`. `x` gets the value 3, and `y` gets the value 5.

Because closures are similar to functions, as we discussed in Chapter 13, we can use patterns in closure parameter lists as well.

One difference between the places we can use patterns is that with `for` loops, `let`, and in function parameters, the patterns must be *irrefutable*. Let's discuss that next.

Refutability: Whether a Pattern Might Fail to Match

Patterns come in two forms: refutable and irrefutable. Patterns which cannot fail to match for any possible value are said to be *irrefutable*, and patterns which can fail to match for some possible value are said to be *refutable*. `let` statements, function parameters, and `for` loops are restricted to only accept irrefutable patterns, since there's nothing correct the program could do if the pattern fails to match. `if let`, and `while let` expressions are restricted to only accept refutable patterns, since they're made to handle possible failure and we wouldn't need their functionality if the pattern could never fail.

In general, you shouldn't have to worry about the distinction between refutable and irrefutable patterns; just be familiar with the concept of refutability when you see it mentioned in an error message. When you get an error message involving refutability, you'll need to change either the pattern or the construct you're using the pattern with, depending on your intentions for the behavior of the code.

Let's look at some examples. Earlier in this chapter, we had `let x = 5;`. `x` is indeed an irrefutable pattern we're allowed to use: since it matches anything, it can't fail to match. In contrast, consider trying to match one variant of an enum with `let`, such as matching only a `Some<T>` value from the `Option<T>` enum as shown in Listing 18-7:

```
let Some(x) = some_option_value;
```

Listing 18-7: Attempting to use a refutable pattern with `let`

If `some_option_value` was a `None` value, `some_option_value` would not match the pattern `Some(x)`. The pattern `Some(x)` is refutable since there exists a case in which it would fail to match a value. There's nothing valid that our code could do with this `let` statement if `some_option_value` was the `None` value. Therefore, Rust will complain at compile time that we've tried to use a refutable pattern where an irrefutable pattern is required:

```
error[E0005]: refutable pattern in local binding: `None` not covered
 --> <anon>:3:5
  |
3 | let Some(x) = some_option_value;
  |     ^^^^^^^ pattern `None` not covered
```

We didn't cover (and couldn't cover!) every valid value with the pattern `Some(x)`, so Rust will rightfully complain.

If we have a refutable pattern, instead of using `let`, we can use `if let`. That way, if the pattern doesn't match, the code inside the curly brackets won't execute. That code will only make sense and run if the value matches the pattern. Listing 18-8 shows how to fix the code in Listing 18-7 with `Some(x)` matching `some_option_value`. Using the refutable pattern `Some(x)` is allowed, since this example uses `if let`:

```
if let Some(x) = some_option_value {
    println!("{}", x);
}
```

Listing 18-8: Using `if let` and a block with refutable patterns instead of `let`

Consequently, if we give `if let` an irrefutable pattern that will always match, such as `x` as shown in Listing 18-9:

```
if let x = 5 {
    println!("{}", x);
};
```

Listing 18-9: Attempting to use an irrefutable pattern with `if let`

Rust will complain that it doesn't make sense to use `if let` with an irrefutable pattern:

```
error[E0162]: irrefutable if-let pattern
 --> <anon>:2:8
  |
2 | if let x = 5 {
  |        ^ irrefutable pattern
```

Generally, match arms use refutable patterns, except for the last arm that might match any remaining values with an irrefutable pattern. A `match` with only one arm whose pattern is irrefutable is allowed, but it's not particularly useful and could be replaced with a simpler `let` statement. Both the expressions associated with a `let` statement and a single arm irrefutable match will unconditionally be run, so the end result is the same if their expressions are.

Now that we've discussed all the places that patterns can be used and the difference between refutable and irrefutable patterns, let's go over all the syntax we can use to create patterns.

All the Pattern Syntax

We've seen some examples of different kinds of patterns throughout the book. This section lists all the syntax valid in patterns and why you might want to use each of them.

Literals

As we saw in Chapter 6, you can match against literals directly:

```
let x = 1;

match x {
    1 => println!("one"),
    2 => println!("two"),
    3 => println!("three"),
    _ => println!("anything"),
}
```

This prints `one` since the value in `x` is 1.

Named Variables

Named variables are irrefutable patterns that match any value.

As with all variables, variables declared as part of a pattern will shadow variables with the same name outside of the `match` construct since a `match` starts a new scope. In Listing 18-10, we declare a variable named `x` with the value `Some(5)` and a variable `y` with the value `10`. Then we have a `match` expression on the value `x`. Take a look at the patterns in the match arms and the `println!` at the end, and make a guess about what will be printed before running this code or reading further:

Filename: src/main.rs

```
fn main() {
    let x = Some(5);
    let y = 10;

    match x {
        Some(50) => println!("Got 50"),
        Some(y) => println!("Matched, y = {:?}", y),
        _ => println!("Default case, x = {:?}", x),
    }

    println!("at the end: x = {:?}, y = {:?}", x, y);
}
```

Listing 18-10: A `match` statement with an arm that introduces a shadowed variable `y`

Let's walk through what happens when the `match` statement runs. The first match arm has the pattern `Some(50)`, and the value in `x` (`Some(5)`) does not match `Some(50)`, so we continue. In the second match arm, the pattern `Some(y)` introduces a new variable name `y` that will match any value inside a `Some` value. Because we're in a new scope inside the `match` expression, this is a new variable, not the `y` we declared at the beginning that has the value 10. The new `y` binding will match any value inside a `Some`, which is what we have in `x`, so we execute the expression for that arm and print `Matched, y = 5` since this `y` binds to the inner value of the `Some` in `x`, which is 5.

If `x` had been a `None` value instead of `Some(5)`, we would have matched the underscore since the other two arms' patterns would not have matched. In the expression for that match arm, since we did not introduce an `x` variable in the pattern of the arm, this `x` is still the outer `x` that has not been shadowed. In this hypothetical case, the `match` would print `Default case, x = None`.

Once the `match` expression is over, its scope ends, and so does the scope of the inner `y`. The last `println!` produces `at the end: x = Some(5), y = 10`.

In order to make a `match` expression that compares the values of the outer `x` and `y` rather than introducing a shadowed variable, we would need to use a match guard conditional instead. We'll be talking about match guards later in this section.

Multiple patterns

In `match` expressions only, you can match multiple patterns with `|`, which means *or*:

```
let x = 1;

match x {
    1 | 2 => println!("one or two"),
    3 => println!("three"),
    _ => println!("anything"),
}
```

This prints `one or two`.

Matching Ranges of Values with `...`

You can match an inclusive range of values with `...`:

```
let x = 5;

match x {
    1 ... 5 => println!("one through five"),
    _ => println!("something else"),
}
```

If `x` is 1, 2, 3, 4, or 5, the first arm will match.

Ranges are only allowed with numeric values or `char` values. Here's an example using ranges of `char` values:

```
let x = 'c';

match x {
    'a' ... 'j' => println!("early ASCII letter"),
    'k' ... 'z' => println!("late ASCII letter"),
    _ => println!("something else"),
}
```

This will print `early ASCII letter`.

Destructuring to Break Apart Values

Patterns can be used to *destructure* structs, enums, tuples, and references. Destructuring means to break a value up into its component pieces. Listing 18-11 shows a `Point` struct with two fields, `x` and `y`, that we can break apart by using a pattern with a `let` statement:

Filename: src/main.rs

```
struct Point {
    x: i32,
    y: i32,
}

fn main() {
    let p = Point { x: 0, y: 7 };

    let Point { x, y } = p;
    assert_eq!(0, x);
    assert_eq!(7, y);
}
```

Listing 18-11: Destructuring using struct field shorthand

This creates the variables `x` and `y` that match the `x` and `y` of `p`. The names of the variables must match the names of the fields to use this shorthand. If we wanted to use names different than the variable names, we can specify `field_name: variable_name` in the pattern. In Listing 18-12, `a` will have the value in the `Point` instance's `x` field and `b` will have the value in the `y` field:

Filename: src/main.rs

```
struct Point {
    x: i32,
    y: i32,
}

fn main() {
    let p = Point { x: 0, y: 7 };

    let Point { x: a, y: b } = p;
    assert_eq!(0, a);
    assert_eq!(7, b);
}
```

Listing 18-12: Destructuring struct fields into variables with different names than the fields

We can also use destructuring with literal values in order to test and use inner parts of a value. Listing 18-13 shows a `match` statement that determines whether a point lies directly on the `x` axis (which is true when `y = 0`), on the `y` axis (`x = 0`), or neither:

```
fn main() {
    let p = Point { x: 0, y: 7 };

    match p {
        Point { x, y: 0 } => println!("On the x axis at {}", x),
        Point { x: 0, y } => println!("On the y axis at {}", y),
        Point { x, y } => println!("On neither axis: ({}, {})", x, y),
    }
}
```

Listing 18-13: Destructuring and matching literal values in one pattern

This will print `On the y axis at 7` since the value `p` matches the second arm by virtue of `x` having the value 0.

We used destructuring on enums in Chapter 6, such as in Listing 6-5 where we destructured an `Option<i32>` using a `match` expression and added one to the inner value of the `Some` variant.

When the value we're matching against a pattern contains a reference, we can specify a `&` in the pattern in order to separate the reference and the value. This is especially useful in closures used with iterators that iterate over references to values when we want to use the values in the closure rather than the references. Listing 18-14 shows how to iterate over references to `Point` instances in a vector, and destructure both the reference and the struct in order to be able to perform calculations on the `x` and `y` values easily:

```
let points = vec![
    Point { x: 0, y: 0 },
    Point { x: 1, y: 5 },
    Point { x: 10, y: -3 },
];
let sum_of_squares: i32 = points
    .iter()
    .map(|&Point {x, y}| x * x + y * y)
    .sum();
```

Listing 18-14: Destructuring a reference to a struct into the struct field values

Because `iter` iterates over references to the items in the vector, if we forgot the `&` in the closure arguments in the `map`, we'd get a type mismatch error like this:

```
error[E0308]: mismatched types
  -->
   |
14 |         .map(|Point {x, y}| x * x + y * y)
   |               ^^^^^^^^^^^^ expected &Point, found struct `Point`
   |
   = note: expected type `&Point`
              found type `Point`
```

This says Rust was expecting our closure to match `&Point`, but we tried to match the value with a pattern that was a `Point` value, not a reference to a `Point`.

We can mix, match, and nest destructuring patterns in even more complex ways: we can do something complicated like this example where we nest structs and tuples inside of a tuple and destructure all the primitive values out:

```
let ((feet, inches), Point {x, y}) = ((3, 10), Point { x: 3, y: -10 });
```

This lets us break complex types into their component parts.

Ignoring Values in a Pattern

There are a few ways to ignore entire values or parts of values: using the `_` pattern, using the `_` pattern within another pattern, using a name that starts with an underscore, or using `..` to ignore all remaining parts of a value. Let's explore how and why to do each of these.

Ignoring an Entire Value with `_`

We've seen the use of underscore as a wildcard pattern that will match any value but not bind to the value. While the underscore pattern is especially useful as the last arm in a `match` expression, we can use it in any pattern, such as function arguments as shown in Listing 18-15:

```
fn foo(_: i32) {
    // code goes here
}
```

Listing 18-15: Using `_` in a function signature

Normally, you would change the signature to not have the unused parameter. In cases such as implementing a trait, where you need a certain type signature, using an underscore lets you ignore a parameter, and the compiler won't warn about unused function parameters like it would if we had used a name instead.

Ignoring Parts of a Value with a Nested `_`

We can also use `_` inside of another pattern to ignore just part of a value. In Listing 18-16, the first `match` arm's pattern matches a `Some` value but ignores the value inside of the `Some` variant as specified by the underscore:

```
let x = Some(5);

match x {
    Some(_) => println!("got a Some and I don't care what's inside"),
    None => (),
}
```

Listing 18-16: Ignoring the value inside of the `Some` variant by using a nested underscore

This is useful when the code associated with the `match` arm doesn't use the nested part of the variable at all.

We can also use underscores in multiple places within one pattern, as shown in Listing 18-17 where we're ignoring the second and fourth values in a tuple of five items:

```
let numbers = (2, 4, 8, 16, 32);

match numbers {
    (first, _, third, _, fifth) => {
        println!("Some numbers: {}, {}, {}", first, third, fifth)
    },
}
```

Listing 18-17: Ignoring multiple parts of a tuple

This will print `Some numbers: 2, 8, 32`, and the values 4 and 16 will be ignored.

Ignoring an Unused Variable by Starting its Name with an Underscore

Usually, Rust will warn you if you create a variable but don't use it anywhere, since that could be a bug. If you're prototyping or just starting a project, though, you might create a variable that you'll use eventually, but temporarily it will be unused. If you're in this situation and would like to tell Rust not to warn you about the unused variable, you can start the name of the variable with an underscore. This works just like a variable name in any pattern, only Rust won't warn you if the variable goes unused. In Listing 18-18, we do get a warning about not using the variable `y`, but we don't get a warning about not using the variable `_x`:

```
fn main() {
    let _x = 5;
    let y = 10;
}
```

Listing 18-18: Starting a variable name with an underscore in order to not get unused variable warnings

Note that there is a subtle difference between using only `_` and using a name that starts with an underscore like `_x`: `_x` still binds the value to the variable, but `_` doesn't bind at all.

Listing 18-19 shows a case where this distinction matters: `s` will still be moved into `_s`, which prevents us from using `s` again:

```
let s = Some(String::from("Hello!"));

if let Some(_s) = s {
    println!("found a string");
}

println!("{:?}", s);
```

Listing 18-19: An unused variable starting with an underscore still binds the value, which may take ownership of the value

Using underscore by itself, however, doesn't ever bind to the value. Listing 18-20 will compile without any errors since `s` does not get moved into `_`:

```
let s = Some(String::from("Hello!"));

if let Some(_) = s {
    println!("found a string");
}

println!("{:?}", s);
```

Listing 18-20: Using underscore does not bind the value

This works just fine. Because we never bind `s` to anything, it's not moved.

Ignoring Remaining Parts of a Value with `..`

With values that have many parts, we can extract only a few parts and avoid having to list underscores for each remaining part by instead using `..`. The `..` pattern will ignore any parts of a value that we haven't explicitly matched in the rest of the pattern. In Listing 18-21, we have a `Point` struct that holds a coordinate in three dimensional space. In the `match` expression, we only want to operate on the `x` coordinate and ignore the values in the `y` and `z` fields:

```
struct Point {
    x: i32,
    y: i32,
    z: i32,
}

let origin = Point { x: 0, y: 0, z: 0 };

match origin {
    Point { x, .. } => println!("x is {}", x),
}
```

Listing 18-21: Ignoring all fields of a `Point` except for `x` by using `..`

Using `..` is shorter to type than having to list out `y: _` and `z: _`. The `..` pattern is especially useful when working with structs that have lots of fields in situations where only one or two fields are relevant.

`..` will expand to as many values as it needs to be. Listing 18-22 shows a use of `..` with a tuple:

```
fn main() {
    let numbers = (2, 4, 8, 16, 32);

    match numbers {
        (first, .., last) => {
            println!("Some numbers: {}, {}", first, last);
        },
    }
}
```

Listing 18-22: Matching only the first and last values in a tuple and ignoring all other values with `..`

Here, we have the first and last value matched, with `first` and `last`. The `..` will match and ignore all of the things in the middle.

Using `..` must be unambiguous, however. Listing 18-23 shows an example where it's not clear to Rust which values we want to match and which values we want to ignore:

```
fn main() {
    let numbers = (2, 4, 8, 16, 32);

    match numbers {
        (.., second, ..) => {
            println!("Some numbers: {}", second)
        },
    }
}
```

Listing 18-23: An attempt to use `..` in a way that is ambiguous

If we compile this example, we get this error:

```
error: `..` can only be used once per tuple or tuple struct pattern
 --> src/main.rs:5:22
  |
5 |         (.., second, ..) => {
  |                      ^^
```

It's not possible to determine how many values in the tuple should be ignored before one value is matched with `second`, and then how many further values are ignored after that. We could mean that we want to ignore 2, bind `second` to 4, then ignore 8, 16, and 32, or we could mean that we want to ignore 2 and 4, bind `second` to 8, then ignore 16 and 32, and so forth. The variable name `second` doesn't mean anything special to Rust, so we get a compiler error since using `..` in two places like this is ambiguous.

`ref` and `ref mut` to Create References in Patterns

Usually, when you match against a pattern, the variables that the pattern introduces are bound to a value. This means you'll end up moving the value into the `match` (or wherever you're using the pattern) since the ownership rules apply. Listing 18-24 shows an example:

```rust
let robot_name = Some(String::from("Bors"));

match robot_name {
    Some(name) => println!("Found a name: {}", name),
    None => (),
}

println!("robot_name is: {:?}", robot_name);
```

Listing 18-24: Creating a variable in a match arm pattern takes ownership of the value

This example will fail to compile since the value inside the `Some` value in `robot_name` is moved within the `match` when `name` binds to that value.

Using `&` in a pattern matches an existing reference in the value, as we saw in the "Destructuring to Break Apart Values" section. If you want to create a reference instead in order to borrow the value in a pattern variable, use the `ref` keyword before the new variable, as shown in Listing 18-25:

```
let robot_name = Some(String::from("Bors"));

match robot_name {
    Some(ref name) => println!("Found a name: {}", name),
    None => (),
}

println!("robot_name is: {:?}", robot_name);
```

Listing 18-25: Creating a reference so that a pattern variable does not take ownership of a value

This example will compile because the value in the `Some` variant in `robot_name` is not moved into the `Some(ref name)` arm of the match; the match only took a reference to the data in `robot_name` rather than moving it.

To create a mutable reference, use `ref mut` for the same reason as shown in Listing 18-26:

```
let mut robot_name = Some(String::from("Bors"));

match robot_name {
    Some(ref mut name) => *name = String::from("Another name"),
    None => (),
}

println!("robot_name is: {:?}", robot_name);
```

Listing 18-26: Creating a mutable reference to a value as part of a pattern using `ref mut`

This example will compile and print `robot_name is: Some("Another name")`. Since `name` is a mutable reference, within the match arm code, we need to dereference using the `*` operator in order to be able to mutate the value.

Extra Conditionals with Match Guards

You can introduce *match guards* as part of a match arm by specifying an additional `if` conditional after the pattern. The conditional can use variables created in the pattern. Listing 18-27 has a `match` expression with a match guard in the first arm:

```
let num = Some(4);

match num {
    Some(x) if x < 5 => println!("less than five: {}", x),
    Some(x) => println!("{}", x),
    None => (),
}
```

Listing 18-27: Adding a match guard to a pattern

This example will print `less than five: 4`. If `num` was instead `Some(7)`, this example would print `7`. Match guards allow you to express more complexity than patterns alone give you.

In Listing 18-10, we saw that since patterns shadow variables, we weren't able to specify a pattern to express the case when a value was equal to a variable outside the `match`. Listing 18-28 shows how we can use a match guard to accomplish this:

```
fn main() {
    let x = Some(5);
    let y = 10;

    match x {
        Some(50) => println!("Got 50"),
        Some(n) if n == y => println!("Matched, n = {:?}", n),
        _ => println!("Default case, x = {:?}", x),
    }

    println!("at the end: x = {:?}, y = {:?}", x, y);
}
```

Listing 18-28: Using a match guard to test for equality with an outer variable

This will now print `Default case, x = Some(5)`. Because the second match arm is not introducing a new variable `y` that shadows the outer `y` in the pattern, we can use `y` in the match guard. We're still destructuring `x` to get the inner value `n`, and then we can compare `n` and `y` in the match guard.

If you're using a match guard with multiple patterns specified by `|`, the match guard condition applies to all of the patterns. Listing 18-29 shows a match guard that applies to the value matched by all three patterns in the first arm:

```
let x = 4;
let y = false;

match x {
    4 | 5 | 6 if y => println!("yes"),
    _ => println!("no"),
}
```

Listing 18-29: Combining multiple patterns with a match guard

This prints `no` since the `if` condition applies to the whole pattern `4 | 5 | 6`, not only to the last value `6`. In other words, the precedence of a match guard in relation to a pattern behaves like this:

```
(4 | 5 | 6) if y => ...
```

rather than this:

```
4 | 5 | (6 if y) => ...
```

`@` Bindings

In order to test a value in a pattern but also be able to create a variable bound to the value, we can use `@`. Listing 18-30 shows an example where we want to test that a `Message::Hello` `id` field is within the range `3...7` but also be able to bind to the value so that we can use it in the code associated with the arm:

```
enum Message {
    Hello { id: i32 },
}

let msg = Message::Hello { id: 5 };

match msg {
    Message::Hello { id: id @ 3...7 } => {
        println!("Found an id in range: {}", id)
    },
    Message::Hello { id: 10...12 } => {
        println!("Found an id in another range")
    },
    Message::Hello { id } => {
        println!("Found some other id: {}", id)
    },
}
```

Listing 18-30: Using `@` to bind to a value in a pattern while also testing it

This example will print `Found an id in range: 5`. By specifying `id @` before the range, we're capturing whatever value matched the range while also testing it. In the second arm where we only have a range specified in the pattern, the code associated with the arm doesn't know if `id` is 10, 11, or 12, since we haven't saved the `id` value in a variable: we only know that the value matched something in that range if that arm's code is executed. In the last arm where we've specified a variable without a range, we do have the value available to use in the arm's code, but we haven't applied any other test to the value. Using `@` lets us test a value and save it in a variable within one pattern.

Summary

Patterns are a useful feature of Rust that help to distinguish between different kinds of data. When used in `match` statements, Rust makes sure that your patterns cover every possible value. Patterns in `let` statements and function parameters make those constructs more powerful, enabling the destructuring of values into smaller parts at the same time as assigning to variables.

Now, for the penultimate chapter of the book, let's take a look at some advanced parts of a variety of Rust's features.

Advanced Features

We've come a long way! By now, we've learned 99% of the things you'll need to know when writing Rust. Before we do one more project in Chapter 20, let's talk about a few things that you may run into that last 1% of the time. Feel free to skip this chapter and come back to it once you run into these things in the wild; the features we'll learn to use here are useful in very specific situations. We don't want to leave these features out, but you won't find yourself reaching for them often.

In this chapter, we're going to cover:

- Unsafe Rust: for when you need to opt out of some of Rust's guarantees and tell the compiler that you will be responsible for upholding the guarantees instead
- Advanced Lifetimes: Additional lifetime syntax for complex situations
- Advanced Traits: Associated Types, default type parameters, fully qualified syntax, supertraits, and the newtype pattern in relation to traits
- Advanced Types: some more about the newtype pattern, type aliases, the "never" type, and dynamically sized types
- Advanced Functions and Closures: function pointers and returning closures

It's a panoply of Rust features with something for everyone! Let's dive in!

Unsafe Rust

In all of the previous chapters in this book, we've been discussing code written in Rust that has memory safety guarantees enforced at compile time. However, Rust has a second language hiding out inside of it, unsafe Rust, which does not enforce these memory safety guarantees. Unsafe Rust works just like regular Rust does, but it gives you extra superpowers not available in safe Rust code.

Unsafe Rust exists because, by nature, static analysis is conservative. When trying to determine if code upholds some guarantees or not, it's better to reject some programs that are valid than it is to accept some programs that are invalid. There are some times when your code might be okay, but Rust thinks it's not! In these cases, you can use unsafe code to tell the compiler, "trust me, I know what I'm doing." The downside is that you're on your own; if you get unsafe code wrong, problems due to memory unsafety like null pointer dereferencing can occur.

There's another reason that Rust needs to have unsafe code: the underlying hardware of computers is inherently not safe. If Rust didn't let you do unsafe operations, there would be some tasks that you simply could not do. But Rust needs to be able to let you do low-level systems programming like directly interacting with your operating system, or even writing your own operating system! That's part of the goals of the language. We need some way to do these kinds of things.

Unsafe Superpowers

We switch into unsafe Rust by using the `unsafe` keyword and starting a new block that holds the unsafe code. There are four actions that you can take in unsafe Rust that you can't in safe Rust. We call these the "unsafe superpowers." We haven't seen most of these features yet since they're only usable with `unsafe`!

1. Dereferencing a raw pointer
2. Calling an unsafe function or method
3. Accessing or modifying a mutable static variable
4. Implementing an unsafe trait

It's important to understand that `unsafe` doesn't turn off the borrow checker or disable any other of Rust's safety checks: if you use a reference in unsafe code, it will still be checked. The only thing the `unsafe` keyword does is give you access to these four features that aren't checked by the compiler for memory safety. You still get some degree of safety inside of an unsafe block! Furthermore, `unsafe` does not mean the code inside the block is dangerous or definitely will have memory safety problems: the intent is that you as the programmer will ensure that the code inside an `unsafe` block will have valid memory, since you've turned off the compiler checks.

People are fallible, however, and mistakes will happen. By requiring these four unsafe operations to be inside blocks annotated with `unsafe`, if you make a mistake and get an error related to memory safety, you'll know that it has to be related to one of the places that you opted into this unsafety. That makes the cause of memory safety bugs much easier to find, since we know Rust is checking all of the other code for us. To get this benefit of only having a few places to investigate memory safety bugs, it's important to contain your unsafe code to as small of an area as possible. Any code inside of an `unsafe` block is suspect when debugging a memory problem: keep `unsafe` blocks small and you'll thank yourself later since you'll have less code to investigate.

In order to isolate unsafe code as much as possible, it's a good idea to enclose unsafe code within a safe abstraction and provide a safe API, which we'll be discussing once we get into unsafe functions and methods. Parts of the standard library are implemented as safe abstractions over unsafe code that has been audited. This prevents uses of `unsafe` from leaking out into all the places that you or your users might want to make use of the functionality implemented with `unsafe` code, since using a safe abstraction is safe.

Let's talk about each of the four unsafe superpowers in turn, and along the way we'll look at some abstractions that provide a safe interface to unsafe code.

Dereferencing a Raw Pointer

Way back in Chapter 4, we first learned about references. We also learned that the compiler ensures that references are always valid. Unsafe Rust has two new types similar to references called *raw pointers*. Just like references, we can have an immutable raw pointer and a mutable raw pointer, written as `*const T` and `*mut T`, respectively. In the context of raw pointers, "immutable" means that the pointer can't be directly assigned to after being dereferenced.

Raw pointers are different than references and smart pointers in a few ways. Raw pointers:

- Are allowed to ignore the borrowing rules and have both immutable and a mutable pointer or multiple mutable pointers to the same location
- Aren't guaranteed to point to valid memory
- Are allowed to be null
- Don't implement any automatic clean-up

Listing 19-1 shows how to create raw pointers from references:

```
let mut num = 5;

let r1 = &num as *const i32;
let r2 = &mut num as *mut i32;
```

Listing 19-1: Creating raw pointers from references

The `*const T` type is an immutable raw pointer, and `*mut T` is a mutable raw pointer. We've created raw pointers by using `as` to cast an immutable and a mutable reference into their corresponding raw pointer types. These particular raw pointers will be valid since we created them directly from references that are guaranteed to be valid, but we can't make that assumption about any raw pointer.

Listing 19-2 shows how to create a raw pointer to an arbitrary location in memory. Trying to use arbitrary memory is undefined: there may be data at that address, there may not be any data at that address, the compiler might optimize the code so that there is no memory access, or your program might segfault. There's not usually a good reason to be writing code like this, but it is possible:

```
let address = 0x012345usize;
let r = address as *const i32;
```

Listing 19-2: Creating a raw pointer to an arbitrary memory address

Note there's no `unsafe` block in either Listing 19-1 or 19-2. You can *create* raw pointers in safe code, but you can't *dereference* raw pointers and read the data being pointed to. Using the dereference operator, `*`, on a raw pointer requires an `unsafe` block, as shown in Listing 19-3:

```
let mut num = 5;

let r1 = &num as *const i32;
let r2 = &mut num as *mut i32;

unsafe {
    println!("r1 is: {}", *r1);
    println!("r2 is: {}", *r2);
}
```

Listing 19-3: Dereferencing raw pointers within an `unsafe` block

Creating a pointer can't do any harm; it's only when accessing the value that it points at that you might end up dealing with an invalid value.

Note also that in Listing 19-1 and 19-3 we created a `*const i32` and a `*mut i32` that both pointed to the same memory location, that of `num`. If we had tried to create an immutable and a mutable reference to `num` instead of raw pointers, this would not have compiled due to the rule that says we can't have a mutable reference at the same time as any immutable references. With raw pointers, we are able to create a mutable pointer and an immutable pointer to the same location, and change data through the mutable pointer, potentially creating a data race. Be careful!

With all of these dangers, why would we ever use raw pointers? One major use case is interfacing with C code, as we'll see in the next section on unsafe functions. Another case is to build up safe abstractions that the borrow checker doesn't understand. Let's introduce unsafe functions then look at an example of a safe abstraction that uses unsafe code.

Calling an Unsafe Function or Method

The second operation that requires an unsafe block is calling an unsafe function. Unsafe functions and methods look exactly like regular functions and methods, but they have an extra `unsafe` out front. Bodies of unsafe functions are effectively `unsafe` blocks. Here's an unsafe function named `dangerous`:

```rust
unsafe fn dangerous() {}

unsafe {
    dangerous();
}
```

If we try to call `dangerous` without the `unsafe` block, we'll get an error:

```
error[E0133]: call to unsafe function requires unsafe function or block
 --> <anon>:4:5
  |
4 |     dangerous();
  |     ^^^^^^^^^^^ call to unsafe function
```

By inserting the `unsafe` block around our call to `dangerous`, we're asserting to Rust that we've read the documentation for this function, we understand how to use it properly, and we've verified that everything is correct.

Creating a Safe Abstraction Over Unsafe Code

As an example, let's check out some functionality from the standard library, `split_at_mut`, and explore how we might implement it ourselves. This safe method is defined on mutable slices, and it takes one slice and makes it into two by splitting the slice at the index given as an argument, as demonstrated in Listing 19-4:

```
let mut v = vec![1, 2, 3, 4, 5, 6];

let r = &mut v[..];

let (a, b) = r.split_at_mut(3);

assert_eq!(a, &mut [1, 2, 3]);
assert_eq!(b, &mut [4, 5, 6]);
```

Listing 19-4: Using the safe `split_at_mut` function

This function can’t be implemented using only safe Rust. An attempt might look like Listing 19-5. For simplicity, we’re implementing `split_at_mut` as a function rather than a method, and only for slices of `i32` values rather than for a generic type `T`:

```
fn split_at_mut(slice: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]) {
    let len = slice.len();

    assert!(mid <= len);

    (&mut slice[..mid],
     &mut slice[mid..])
}
```

Listing 19-5: An attempted implementation of `split_at_mut` using only safe Rust

This function first gets the total length of the slice, then asserts that the index given as a parameter is within the slice by checking that the parameter is less than or equal to the length. The assertion means that if we pass an index that’s greater than the length of the slice to split at, the function will panic before it attempts to use that index.

Then we return two mutable slices in a tuple: one from the start of the initial slice to the `mid` index, and another from `mid` to the end of the slice.

If we try to compile this, we’ll get an error:

```
error[E0499]: cannot borrow `*slice` as mutable more than once at a time
 --> <anon>:6:11
  |
5 |     (&mut slice[..mid],
  |           ----- first mutable borrow occurs here
6 |      &mut slice[mid..])
  |           ^^^^^ second mutable borrow occurs here
7 | }
  | - first borrow ends here
```

Rust’s borrow checker can’t understand that we’re borrowing different parts of the slice; it only knows that we’re borrowing from the same slice twice. Borrowing different parts of a slice is fundamentally okay; our two `&mut [i32]` slices aren't overlapping. However, Rust isn't smart enough to know this. When we know something is okay, but Rust doesn't, it's time to reach for unsafe code.

Listing 19-6 shows how to use an `unsafe` block, a raw pointer, and some calls to unsafe functions to make the implementation of `split_at_mut` work:

```
use std::slice;

fn split_at_mut(slice: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]) {
    let len = slice.len();
    let ptr = slice.as_mut_ptr();

    assert!(mid <= len);

    unsafe {
        (slice::from_raw_parts_mut(ptr, mid),
         slice::from_raw_parts_mut(ptr.offset(mid as isize), len - mid))
    }
}
```

Listing 19-6: Using unsafe code in the implementation of the `split_at_mut` function

Recall from Chapter 4 that slices are a pointer to some data and the length of the slice. We've often used the `len` method to get the length of a slice; we can use the `as_mut_ptr` method to get access to the raw pointer of a slice. In this case, since we have a mutable slice to `i32` values, `as_mut_ptr` returns a raw pointer with the type `*mut i32`, which we've stored in the variable `ptr`.

The assertion that the `mid` index is within the slice stays the same. Then, the `slice::from_raw_parts_mut` function does the reverse from the `as_mut_ptr` and `len` methods: it takes a raw pointer and a length and creates a slice. We call `slice::from_raw_parts_mut` to create a slice that starts from `ptr` and is `mid` items long. Then we call the `offset` method on `ptr` with `mid` as an argument to get a raw pointer that starts at `mid`, and we create a slice using that pointer and the remaining number of items after `mid` as the length.

Because slices are checked, they're safe to use once we've created them. The function `slice::from_raw_parts_mut` is an unsafe function because it takes a raw pointer and trusts that this pointer is valid. The `offset` method on raw pointers is also unsafe, since it trusts that the location some offset after a raw pointer is also a valid pointer. We've put an `unsafe` block around our calls to `slice::from_raw_parts_mut` and `offset` to be allowed to call them, and we can tell by looking at the code and by adding the assertion that `mid` must be less than or equal to `len` that all the raw pointers used within the `unsafe` block will be valid pointers to data within the slice. This is an acceptable and appropriate use of `unsafe`.

Note that the resulting `split_at_mut` function is safe: we didn't have to add the `unsafe` keyword in front of it, and we can call this function from safe Rust. We've created a safe abstraction to the unsafe code by writing an implementation of the function that uses `unsafe` code in a safe way by only creating valid pointers from the data this function has access to.

In contrast, the use of `slice::from_raw_parts_mut` in Listing 19-7 would likely crash when the slice is used. This code takes an arbitrary memory location and creates a slice ten thousand items long:

```
use std::slice;

let address = 0x012345usize;
let r = address as *mut i32;

let slice = unsafe {
    slice::from_raw_parts_mut(r, 10000)
};
```

Listing 19-7: Creating a slice from an arbitrary memory location

We don't own the memory at this arbitrary location, and there's no guarantee that the slice this code creates contains valid `i32` values. Attempting to use `slice` as if it was a valid slice would be undefined behavior.

`extern` Functions for Calling External Code are Unsafe

Sometimes, your Rust code may need to interact with code written in another language. To do this, Rust has a keyword, `extern`, that facilitates creating and using a *Foreign Function Interface* (FFI). Listing 19-8 demonstrates how to set up an integration with the `abs` function defined in the C standard library. Functions declared within `extern` blocks are always unsafe to call from Rust code:

Filename: src/main.rs

```
extern "C" {
    fn abs(input: i32) -> i32;
}

fn main() {
    unsafe {
        println!("Absolute value of -3 according to C: {}", abs(-3));
    }
}
```

Listing 19-8: Declaring and calling an `extern` function defined in another language

Within the `extern "C"` block, we list the names and signatures of functions defined in a library written in another language that we want to be able to call. `"C"` defines which *application binary interface* (ABI) the external function uses. The ABI defines how to call the function at the assembly level. The `"C"` ABI is the most common, and follows the C programming language's ABI.

Calling an external function is always unsafe. If we're calling into some other language, that language does not enforce Rust's safety guarantees. Since Rust can't check that the external code is safe, we are responsible for checking the safety of the external code and indicating we have done so by using an `unsafe` block to call external functions.

Calling Rust Functions from Other Languages

The `extern` keyword is also used for creating an interface that allows other languages to call Rust functions. Instead of an `extern` block, we can add the `extern` keyword and specifying the ABI to use just before the `fn` keyword. We also add the `#[no_mangle]` annotation to tell the Rust compiler not to mangle the name of this function. The `call_from_c` function in this example would be accessible from C code, once we've compiled to a shared library and linked from C:

```
#[no_mangle]
pub extern "C" fn call_from_c() {
    println!("Just called a Rust function from C!");
}
```

This usage of `extern` does not require `unsafe`

Accessing or Modifying a Mutable Static Variable

We've gone this entire book without talking about *global variables*. Many programming languages support them, and so does Rust. However, global variables can be problematic: for example, if you have two threads accessing the same mutable global variable, a data race can happen.

Global variables are called *static* in Rust. Listing 19-9 shows an example declaration and use of a static variable with a string slice as a value:

Filename: src/main.rs

```
static HELLO_WORLD: &str = "Hello, world!";

fn main() {
    println!("name is: {}", HELLO_WORLD);
}
```

Listing 19-9: Defining and using an immutable static variable

`static` variables are similar to constants: their names are also in `SCREAMING_SNAKE_CASE` by convention, and we *must* annotate the variable's type, which is `&'static str` in this case. Only references with the `'static` lifetime may be stored in a static variable. Because of this, the Rust compiler can figure out the lifetime by itself and we don't need to annotate it explicitly.

Accessing immutable static variables is safe. Values in a static variable have a fixed address in memory, and using the value will always access the same data. Constants, on the other hand, are allowed to duplicate their data whenever they are used.

Another way in which static variables are different from constants is that static variables can be mutable. Both accessing and modifying mutable static variables is unsafe. Listing 19-10 shows how to declare, access, and modify a mutable static variable named `COUNTER`:

Filename: src/main.rs

```
static mut COUNTER: u32 = 0;

fn add_to_count(inc: u32) {
    unsafe {
        COUNTER += inc;
    }
}

fn main() {
    add_to_count(3);

    unsafe {
        println!("COUNTER: {}", COUNTER);
    }
}
```

Listing 19-10: Reading from or writing to a mutable static variable is unsafe

Just like with regular variables, we specify that a static variable should be mutable using the `mut` keyword. Any time that we read or write from `COUNTER` has to be within an `unsafe` block. This code compiles and prints `COUNTER: 3` as we would expect since it's single threaded, but having multiple threads accessing `COUNTER` would likely result in data races.

Mutable data that is globally accessible is difficult to manage and ensure that there are no data races, which is why Rust considers mutable static variables to be unsafe. If possible, prefer using the concurrency techniques and threadsafe smart pointers we discussed in Chapter 16 to have the compiler check that data accessed from different threads is done safely.

Implementing an Unsafe Trait

Finally, the last action we're only allowed to take when we use the `unsafe` keyword is implementing an unsafe trait. We can declare that a trait is `unsafe` by adding the `unsafe` keyword before `trait`, and then implementing the trait must be marked as `unsafe` too, as shown in Listing 19-11:

```rust
unsafe trait Foo {
    // methods go here
}

unsafe impl Foo for i32 {
    // method implementations go here
}
```

Listing 19-11: Defining and implementing an unsafe trait

Like unsafe functions, methods in an unsafe trait have some invariant that the compiler cannot verify. By using `unsafe impl`, we're promising that we'll uphold these invariants.

As an example, recall the `Sync` and `Send` marker traits from Chapter 16, and that the compiler implements these automatically if our types are composed entirely of `Send` and `Sync` types. If we implement a type that contains something that's not `Send` or `Sync` such as raw pointers, and we want to mark our type as `Send` or `Sync`, that requires using `unsafe`. Rust can't verify that our type upholds the guarantees that a type can be safely sent across threads or accessed from multiple threads, so we need to do those checks ourselves and indicate as such with `unsafe`.

Using `unsafe` to take one of these four actions isn't wrong or frowned upon, but it is trickier to get `unsafe` code correct since the compiler isn't able to help uphold memory safety. When you have a reason to use `unsafe` code, however, it's possible to do so, and having the explicit `unsafe` annotation makes it easier to track down the source of problems if they occur.

Advanced Lifetimes

Back in Chapter 10, we learned how to annotate references with lifetime parameters to help Rust understand how the lifetimes of different references relate. We saw how most of the time, Rust will let you elide lifetimes, but every reference has a lifetime. There are three advanced features of lifetimes that we haven't covered though: *lifetime subtyping*, *lifetime bounds*, and *trait object lifetimes*.

Lifetime Subtyping

Imagine that we want to write a parser. To do this, we'll have a structure that holds a reference to the string that we're parsing, and we'll call that struct `Context`. We'll write a parser that will parse this string and return success or failure. The parser will need to borrow the context to do the parsing. Implementing this would look like the code in Listing 19-12, which won't compile because we've left off the lifetime annotations for now:

```
struct Context(&str);

struct Parser {
    context: &Context,
}

impl Parser {
    fn parse(&self) -> Result<(), &str> {
        Err(&self.context.0[1..])
    }
}
```

Listing 19-12: Defining a `Context` struct that holds a string slice, a `Parser` struct that holds a reference to a `Context` instance, and a `parse` method that always returns an error referencing the string slice

For simplicity's sake, our `parse` function returns a `Result<(), &str>`. That is, we don't do anything on success, and on failure we return the part of the string slice that didn't parse correctly. A real implementation would have more error information than that, and would actually return something created when parsing succeeds, but we're leaving those parts of the implementation off since they aren't relevant to the lifetimes part of this example. We're also defining `parse` to always produce an error after the first byte. Note that this may panic if the first byte is not on a valid character boundary; again, we're simplifying the example in order to concentrate on the lifetimes involved.

So how do we fill in the lifetime parameters for the string slice in `Context` and the reference to the `Context` in `Parser`? The most straightforward thing to do is to use the same lifetime everywhere, as shown in Listing 19-13:

```
struct Context<'a>(&'a str);

struct Parser<'a> {
    context: &'a Context<'a>,
}

impl<'a> Parser<'a> {
    fn parse(&self) -> Result<(), &str> {
        Err(&self.context.0[1..])
    }
}
```

Listing 19-13: Annotating all references in `Context` and `Parser` with the same lifetime parameter

This compiles fine. Next, in Listing 19-14, let's write a function that takes an instance of `Context`, uses a `Parser` to parse that context, and returns what `parse` returns. This won't quite work:

```
fn parse_context(context: Context) -> Result<(), &str> {
    Parser { context: &context }.parse()
}
```

Listing 19-14: An attempt to add a `parse_context` function that takes a `Context` and uses a `Parser`

We get two quite verbose errors when we try to compile the code with the addition of the `parse_context` function:

```
error: borrowed value does not live long enough
  --> <anon>:16:5
   |
16 |     Parser { context: &context }.parse()
   |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^ does not live long enough
17 | }
   | - temporary value only lives until here
   |
note: borrowed value must be valid for the anonymous lifetime #1 defined on the
body at 15:55...
  --> <anon>:15:56
   |
15 |   fn parse_context(context: Context) -> Result<(), &str> {
   |  ________________________________________________________^
16 | |     Parser { context: &context }.parse()
17 | | }
   | |_^

error: `context` does not live long enough
  --> <anon>:16:24
   |
16 |     Parser { context: &context }.parse()
   |                        ^^^^^^^ does not live long enough
17 | }
   | - borrowed value only lives until here
   |
note: borrowed value must be valid for the anonymous lifetime #1 defined on the
body at 15:55...
  --> <anon>:15:56
   |
15 |   fn parse_context(context: Context) -> Result<(), &str> {
   |  ________________________________________________________^
16 | |     Parser { context: &context }.parse()
17 | | }
   | |_^
```

These errors are saying that both the `Parser` instance we're creating and the `context` parameter live from the line that the `Parser` is created until the end of the `parse_context` function, but they both need to live for the entire lifetime of the function.

In other words, `Parser` and `context` need to *outlive* the entire function and be valid before the function starts as well as after it ends in order for all the references in this code to always be valid. Both the `Parser` we're creating and the `context` parameter go out of scope at the end of the function, though (since `parse_context` takes ownership of `context`).

Let's look at the definitions in Listing 19-13 again, especially the signature of the `parse` method:

```
    fn parse(&self) -> Result<(), &str> {
```

Remember the elision rules? If we annotate the lifetimes of the references, the signature would be:

```
    fn parse<'a>(&'a self) -> Result<(), &'a str> {
```

That is, the error part of the return value of `parse` has a lifetime that is tied to the `Parser` instance's lifetime (that of `&self` in the `parse` method signature). That makes sense, as the returned string slice references the string slice in the `Context` instance that the `Parser` holds, and we've specified in the definition of the `Parser` struct that the lifetime of the reference to `Context` that `Parser` holds and the lifetime of the string slice that `Context` holds should be the same.

The problem is that the `parse_context` function returns the value returned from `parse`, so the lifetime of the return value of `parse_context` is tied to the lifetime of the `Parser` as well. But the `Parser` instance created in the `parse_context` function won't live past the end of the function (it's temporary), and the `context` will go out of scope at the end of the function (`parse_context` takes ownership of it).

We're not allowed to return a reference to a value that goes out of scope at the end of the function. Rust thinks that's what we're trying to do because we annotated all the lifetimes with the same lifetime parameter. That told Rust the lifetime of the string slice that `Context` holds is the same as that of the lifetime of the reference to `Context` that `Parser` holds.

The `parse_context` function can't see that within the `parse` function, the string slice returned will outlive both `Context` and `Parser`, and that the reference `parse_context` returns refers to the string slice, not to `Context` or `Parser`.

By knowing what the implementation of `parse` does, we know that the only reason that the return value of `parse` is tied to the `Parser` is because it's referencing the `Parser`'s `Context`, which is referencing the string slice, so it's really the lifetime of the string slice that `parse_context` needs to care about. We need a way to tell Rust that the string slice in `Context` and the reference to the `Context` in `Parser` have different lifetimes and that the return value of `parse_context` is tied to the lifetime of the string slice in `Context`.

We could try only giving `Parser` and `Context` different lifetime parameters as shown in Listing 19-15. We've chosen the lifetime parameter names `'s` and `'c` here to be clearer about which lifetime goes with the string slice in `Context` and which goes with the reference to `Context` in `Parser`. Note that this won't completely fix the problem, but it's a start and we'll look at why this isn't sufficient when we try to compile.

```
struct Context<'s>(&'s str);

struct Parser<'c, 's> {
    context: &'c Context<'s>,
}

impl<'c, 's> Parser<'c, 's> {
    fn parse(&self) -> Result<(), &'s str> {
        Err(&self.context.0[1..])
    }
}

fn parse_context(context: Context) -> Result<(), &str> {
    Parser { context: &context }.parse()
}
```

Listing 19-15: Specifying different lifetime parameters for the references to the string slice and to `Context`

We've annotated the lifetimes of the references in all the same places that we annotated them in Listing 19-13, but used different parameters depending on whether the reference goes with the string slice or with `Context`. We've also added an annotation to the string slice part of the return value of `parse` to indicate that it goes with the lifetime of the string slice in `Context`.

Here's the error we get now:

```
error[E0491]: in type `&'c Context<'s>`, reference has a longer lifetime than the
data it references
 --> src/main.rs:4:5
  |
4 |     context: &'c Context<'s>,
  |     ^^^^^^^^^^^^^^^^^^^^^^^^
  |
note: the pointer is valid for the lifetime 'c as defined on the struct at 3:0
 --> src/main.rs:3:1
  |
3 | / struct Parser<'c, 's> {
4 | |     context: &'c Context<'s>,
5 | | }
  | |_^
note: but the referenced data is only valid for the lifetime 's as defined on the
struct at 3:0
 --> src/main.rs:3:1
  |
3 | / struct Parser<'c, 's> {
4 | |     context: &'c Context<'s>,
5 | | }
  | |_^
```

Rust doesn't know of any relationship between `'c` and `'s`. In order to be valid, the referenced data in `Context` with lifetime `'s` needs to be constrained to guarantee that it lives longer than the reference to `Context` that has lifetime `'c`. If `'s` is not longer than `'c`, then the reference to `Context` might not be valid.

Which gets us to the point of this section: Rust has a feature called *lifetime subtyping*, which is a way to specify that one lifetime parameter lives at least as long as another one. In the angle brackets where we declare lifetime parameters, we can declare a lifetime `'a` as usual, and declare a lifetime `'b` that lives at least as long as `'a` by declaring `'b` with the syntax `'b: 'a`.

In our definition of `Parser`, in order to say that `'s` (the lifetime of the string slice) is guaranteed to live at least as long as `'c` (the lifetime of the reference to `Context`), we change the lifetime declarations to look like this:

```
struct Parser<'c, 's: 'c> {
    context: &'c Context<'s>,
}
```

Now, the reference to `Context` in the `Parser` and the reference to the string slice in the `Context` have different lifetimes, and we've ensured that the lifetime of the string slice is longer than the reference to the `Context`.

That was a very long-winded example, but as we mentioned at the start of this chapter, these features are pretty niche. You won't often need this syntax, but it can come up in situations like this one, where you need to refer to something you have a reference to.

Lifetime Bounds

In Chapter 10, we discussed how to use trait bounds on generic types. We can also add lifetime parameters as constraints on generic types, which are called *lifetime bounds*. For example, consider a type that is a wrapper over references. Recall the `RefCell<T>` type from Chapter 15: its `borrow` and `borrow_mut` methods return the types `Ref` and `RefMut`, respectively. These types are wrappers over references that keep track of the borrowing rules at runtime. The definition of the `Ref` struct is shown in Listing 19-16, without lifetime bounds for now:

```
struct Ref<'a, T>(&'a T);
```

Listing 19-16: Defining a struct to wrap a reference to a generic type; without lifetime bounds to start

Without constraining the lifetime `'a` in relation to the generic parameter `T`, we get an error because Rust doesn't know how long the generic type `T` will live:

```
error[E0309]: the parameter type `T` may not live long enough
 --> <anon>:1:19
  |
1 | struct Ref<'a, T>(&'a T);
  |                   ^^^^^^
  |
  = help: consider adding an explicit lifetime bound `T: 'a`...
note: ...so that the reference type `&'a T` does not outlive the data it points at
 --> <anon>:1:19
  |
1 | struct Ref<'a, T>(&'a T);
  |                   ^^^^^^
```

Since `T` can be any type, `T` could itself be a reference or a type that holds one or more references, each of which could have their own lifetimes. Rust can't be sure `T` will live as long as `'a`.

Fortunately, Rust gave us helpful advice on how to specify the lifetime bound in this case:

```
consider adding an explicit lifetime bound `T: 'a` so that the reference type
`&'a T` does not outlive the data it points at.
```

Listing 19-17 shows how to apply this advice by specifying the lifetime bound when we declare the generic type `T`. This code now compiles because the `T: 'a` syntax specifies that `T` can be any type, but if it contains any references, the references must live at least as long as `'a`:

```rust
struct Ref<'a, T: 'a>(&'a T);
```

Listing 19-17: Adding lifetime bounds on `T` to specify that any references in `T` live at least as long as `'a`

We could choose to solve this in a different way, shown in the definition of a `StaticRef` struct in Listing 19-18, by adding the `'static` lifetime bound on `T`. This means if `T` contains any references, they must have the `'static` lifetime:

```rust
struct StaticRef<T: 'static>(&'static T);
```

Listing 19-18: Adding a `'static` lifetime bound to `T` to constrain `T` to types that have only `'static` references or no references

Types without any references count as `T: 'static`. Because `'static` means the reference must live as long as the entire program, a type that contains no references meets the criteria of all references living as long as the entire program (since there are no references). Think of it this way: if the borrow checker is concerned about references living long enough, then there's no real distinction between a type that has no references and a type that has references that live forever; both of them are the same for the purpose of determining whether or not a reference has a shorter lifetime than what it refers to.

Trait Object Lifetimes

In Chapter 17, we learned about trait objects that consist of putting a trait behind a reference in order to use dynamic dispatch. However, we didn’t discuss what happens if the type implementing the trait used in the trait object has a lifetime. Consider Listing 19-19, where we have a trait `Foo` and a struct `Bar` that holds a reference (and thus has a lifetime parameter) that implements trait `Foo`, and we want to use an instance of `Bar` as the trait object `Box<Foo>`:

```
trait Foo { }

struct Bar<'a> {
    x: &'a i32,
}

impl<'a> Foo for Bar<'a> { }

let num = 5;

let obj = Box::new(Bar { x: &num }) as Box<Foo>;
```

Listing 19-19: Using a type that has a lifetime parameter with a trait object

This code compiles without any errors, even though we haven’t said anything about the lifetimes involved in `obj`. This works because there are rules having to do with lifetimes and trait objects:

- The default lifetime of a trait object is `'static`.
- If we have `&'a X` or `&'a mut X`, then the default is `'a`.
- If we have a single `T: 'a` clause, then the default is `'a`.
- If we have multiple `T: 'a`-like clauses, then there is no default; we must be explicit.

When we must be explicit, we can add a lifetime bound on a trait object like `Box<Foo>` with the syntax `Box<Foo + 'a>` or `Box<Foo + 'static>`, depending on what’s needed. Just as with the other bounds, this means that any implementor of the `Foo` trait that has any references inside must have the lifetime specified in the trait object bounds as those references.

Next, let’s take a look at some other advanced features dealing with traits!

Advanced Traits

We covered traits in Chapter 10, but like lifetimes, we didn't get to all the details. Now that we know more Rust, we can get into the nitty-gritty.

Associated Types

Associated types are a way of associating a type placeholder with a trait such that the trait method definitions can use these placeholder types in their signatures. The implementor of a trait will specify the concrete type to be used in this type's place for the particular implementation.

We've described most of the things in this chapter as being very rare. Associated types are somewhere in the middle; they're more rare than the rest of the book, but more common than many of the things in this chapter.

An example of a trait with an associated type is the `Iterator` trait provided by the standard library. It has an associated type named `Item` that stands in for the type of the values that we're iterating over. We mentioned in Chapter 13 that the definition of the `Iterator` trait is as shown in Listing 19-20:

```
pub trait Iterator {
    type Item;
    fn next(&mut self) -> Option<Self::Item>;
}
```

Listing 19-20: The definition of the `Iterator` trait that has an associated type `Item`

This says that the `Iterator` trait has an associated type named `Item`. `Item` is a placeholder type, and the return value of the `next` method will return values of type `Option<Self::Item>`. Implementors of this trait will specify the concrete type for `Item`, and the `next` method will return an `Option` containing a value of whatever type the implementor has specified.

Associated Types Versus Generics

When we implemented the `Iterator` trait on the `Counter` struct in Listing 13-6, we specified that the `Item` type was `u32`:

```
impl Iterator for Counter {
    type Item = u32;

    fn next(&mut self) -> Option<Self::Item> {
```

This feels similar to generics. So why isn't the `Iterator` trait defined as shown in Listing 19-21?

```
pub trait Iterator<T> {
    fn next(&mut self) -> Option<T>;
}
```

Listing 19-21: A hypothetical definition of the `Iterator` trait using generics

The difference is that with the definition in Listing 19-21, we could also implement `Iterator<String> for Counter`, or any other type as well, so that we'd have multiple implementations of `Iterator` for `Counter`. In other words, when a trait has a generic parameter, we can implement that trait for a type multiple times, changing the generic type parameters' concrete types each time. Then when we use the `next` method on `Counter`, we'd have to provide type annotations to indicate which implementation of `Iterator` we wanted to use.

With associated types, we can't implement a trait on a type multiple times. Using the actual definition of `Iterator` from Listing 19-20, we can only choose once what the type of `Item` will be, since there can only be one `impl Iterator for Counter`. We don't have to specify that we want an iterator of `u32` values everywhere that we call `next` on `Counter`.

The benefit of not having to specify generic type parameters when a trait uses associated types shows up in another way as well. Consider the two traits defined in Listing 19-22. Both are defining a trait having to do with a graph structure that contains nodes of some type and edges of some type. `GGraph` is defined using generics, and `AGraph` is defined using associated types:

```
trait GGraph<Node, Edge> {
    // methods would go here
}

trait AGraph {
    type Node;
    type Edge;

    // methods would go here
}
```

Listing 19-22: Two graph trait definitions, `GGraph` using generics and `AGraph` using associated types for `Node` and `Edge`

Let's say we wanted to implement a function that computes the distance between two nodes in any types that implement the graph trait. With the `GGraph` trait defined using generics, our `distance` function signature would have to look like Listing 19-23:

```rust
fn distance<N, E, G: GGraph<N, E>>(graph: &G, start: &N, end: &N) -> u32 {
    // ...snip...
}
```

Listing 19-23: The signature of a `distance` function that uses the trait `GGraph` and has to specify all the generic parameters

Our function would need to specify the generic type parameters `N`, `E`, and `G`, where `G` is bound by the trait `GGraph` that has type `N` as its `Node` type and type `E` as its `Edge` type. Even though `distance` doesn't need to know the types of the edges, we're forced to declare an `E` parameter, because we need to to use the `GGraph` trait and that requires specifying the type for `Edge`.

Contrast with the definition of `distance` in Listing 19-24 that uses the `AGraph` trait from Listing 19-22 with associated types:

```rust
fn distance<G: AGraph>(graph: &G, start: &G::Node, end: &G::Node) -> u32 {
    // ...snip...
}
```

Listing 19-24: The signature of a `distance` function that uses the trait `AGraph` and the associated type `Node`

This is much cleaner. We only need to have one generic type parameter, `G`, with the trait bound `AGraph`. Since `distance` doesn't use the `Edge` type at all, it doesn't need to be specified anywhere. To use the `Node` type associated with `AGraph`, we can specify `G::Node`.

Trait Objects with Associated Types

You may have been wondering why we didn't use a trait object in the `distance` functions in Listing 19-23 and Listing 19-24. The signature for the `distance` function using the generic `GGraph` trait does get a bit more concise using a trait object:

```rust
fn distance<N, E>(graph: &GGraph<N, E>, start: &N, end: &N) -> u32 {
    // ...snip...
}
```

This might be a more fair comparison to Listing 19-24. Specifying the `Edge` type is still required, though, which means Listing 19-24 is still preferable since we don't have to specify something we don't use.

It's not possible to change Listing 19-24 to use a trait object for the graph, since then there would be no way to refer to the `AGraph` trait's associated type.

It is possible in general to use trait objects of traits that have associated types, though; Listing 19-25 shows a function named `traverse` that doesn't need to use the trait's associated types in other arguments. We do, however, have to specify the concrete types for the associated types in this case. Here, we've chosen to accept types that implement the `AGraph` trait with the concrete type of `usize` as their `Node` type and a tuple of two `usize` values for their `Edge` type:

```
fn traverse(graph: &AGraph<Node=usize, Edge=(usize, usize)>) {
    // ...snip...
}
```

While trait objects mean that we don't need to know the concrete type of the `graph` parameter at compile time, we do need to constrain the use of the `AGraph` trait in the `traverse` function by the concrete types of the associated types. If we didn't provide this constraint, Rust wouldn't be able to figure out which `impl` to match this trait object to.

Operator Overloading and Default Type Parameters

The `<PlaceholderType=ConcreteType>` syntax is used in another way as well: to specify the default type for a generic type. A great example of a situation where this is useful is operator overloading.

Rust does not allow you to create your own operators or overload arbitrary operators, but the operations and corresponding traits listed in `std::ops` can be overloaded by implementing the traits associated with the operator. For example, Listing 19-25 shows how to overload the `+` operator by implementing the `Add` trait on a `Point` struct so that we can add two `Point` instances together:

Filename: src/main.rs

```rust
use std::ops::Add;

#[derive(Debug,PartialEq)]
struct Point {
    x: i32,
    y: i32,
}

impl Add for Point {
    type Output = Point;

    fn add(self, other: Point) -> Point {
        Point {
            x: self.x + other.x,
            y: self.y + other.y,
        }
    }
}

fn main() {
    assert_eq!(Point { x: 1, y: 0 } + Point { x: 2, y: 3 },
               Point { x: 3, y: 3 });
}
```

Listing 19-25: Implementing the `Add` trait to overload the `+` operator for `Point` instances

We've implemented the `add` method to add the `x` values of two `Point` instances together and the `y` values of two `Point` instances together to create a new `Point`. The `Add` trait has an associated type named `Output` that's used to determine the type returned from the `add` method.

Let's look at the `Add` trait in a bit more detail. Here's its definition:

```rust
trait Add<RHS=Self> {
    type Output;

    fn add(self, rhs: RHS) -> Self::Output;
}
```

This should look familiar; it's a trait with one method and an associated type. The new part is the `RHS=Self` in the angle brackets: this syntax is called *default type parameters*. `RHS` is a generic type parameter (short for "right hand side") that's used for the type of the `rhs` parameter in the `add` method. If we don't specify a concrete type for `RHS` when we implement the `Add` trait, the type of `RHS` will default to the type of `Self` (the type that we're implementing `Add` on).

Let's look at another example of implementing the `Add` trait. Imagine we have two structs holding values in different units, `Millimeters` and `Meters`. We can implement `Add` for

`Millimeters` in different ways as shown in Listing 19-26:

```
use std::ops::Add;

struct Millimeters(u32);
struct Meters(u32);

impl Add for Millimeters {
    type Output = Millimeters;

    fn add(self, other: Millimeters) -> Millimeters {
        Millimeters(self.0 + other.0)
    }
}

impl Add<Meters> for Millimeters {
    type Output = Millimeters;

    fn add(self, other: Meters) -> Millimeters {
        Millimeters(self.0 + (other.0 * 1000))
    }
}
```

Listing 19-26: Implementing the `Add` trait on `Millimeters` to be able to add `Millimeters` to `Millimeters` and `Millimeters` to `Meters`

If we're adding `Millimeters` to other `Millimeters`, we don't need to parameterize the `RHS` type for `Add` since the default `Self` type is what we want. If we want to implement adding `Millimeters` and `Meters`, then we need to say `impl Add<Meters>` to set the value of the `RHS` type parameter.

Default type parameters are used in two main ways:

1. To extend a type without breaking existing code.
2. To allow customization in a way most users don't want.

The `Add` trait is an example of the second purpose: most of the time, you're adding two like types together. Using a default type parameter in the `Add` trait definition makes it easier to implement the trait since you don't have to specify the extra parameter most of the time. In other words, we've removed a little bit of implementation boilerplate.

The first purpose is similar, but in reverse: since existing implementations of a trait won't have specified a type parameter, if we want to add a type parameter to an existing trait, giving it a default will let us extend the functionality of the trait without breaking the existing implementation code.

Fully Qualified Syntax for Disambiguation

Rust cannot prevent a trait from having a method with the same name as another trait's method, nor can it prevent us from implementing both of these traits on one type. We can also have a method implemented directly on the type with the same name as well! In order to be able to call each of the methods with the same name, then, we need to tell Rust which one we want to use.

Consider the code in Listing 19-27 where we've defined two traits, `Pilot` and `Wizard`, that both have a method called `fly`. We then implement both traits on a type `Human` that itself already has a method named `fly` implemented on it. Each `fly` method does something different:

Filename: src/main.rs

```
trait Pilot {
    fn fly(&self);
}

trait Wizard {
    fn fly(&self);
}

struct Human;

impl Pilot for Human {
    fn fly(&self) {
        println!("This is your captain speaking.");
    }
}

impl Wizard for Human {
    fn fly(&self) {
        println!("Up!");
    }
}

impl Human {
    fn fly(&self) {
        println!("*waving arms furiously*");
    }
}
```

Listing 19-27: Two traits defined to have a `fly` method, and implementations of those traits on the `Human` type in addition to a `fly` method on `Human` directly

When we call `fly` on an instance of `Human`, the compiler defaults to calling the method that is directly implemented on the type, as shown in Listing 19-28:

Filename: src/main.rs

```
fn main() {
    let person = Human;
    person.fly();
}
```

Listing 19-28: Calling `fly` on an instance of `Human`

Running this will print out `*waving arms furiously*`, which shows that Rust called the `fly` method implemented on `Human` directly.

In order to call the `fly` methods from either the `Pilot` trait or the `Wizard` trait, we need to use more explicit syntax in order to specify which `fly` method we mean. This syntax is demonstrated in Listing 19-29:

Filename: src/main.rs

```
fn main() {
    let person = Human;
    Pilot::fly(&person);
    Wizard::fly(&person);
    person.fly();
}
```

Listing 19-29: Specifying which trait's `fly` method we want to call

Specifying the trait name before the method name clarifies to Rust which implementation of `fly` we want to call. We could also choose to write `Human::fly(&person)`, which is equivalent to `person.fly()` that we had in Listing 19-28, but is a bit longer to write if we don't need to disambiguate.

Running this code will print:

```
This is your captain speaking.
Up!
*waving arms furiously*
```

Because the `fly` method takes a `self` parameter, if we had two *types* that both implement one *trait*, Rust can figure out which implementation of a trait to use based on the type of `self`.

However, associated functions that are part of traits don't have a `self` parameter. When two types in the same scope implement that trait, Rust can't figure out which type we mean unless we use *fully qualified syntax*. For example, take the `Animal` trait in Listing 19-30 that has the associated function `baby_name`, the implementation of `Animal` for the struct `Dog`, and the associated function `baby_name` defined on `Dog` directly:

Filename: src/main.rs

```
trait Animal {
    fn baby_name() -> String;
}

struct Dog;

impl Dog {
    fn baby_name() -> String {
        String::from("Spot")
    }
}

impl Animal for Dog {
    fn baby_name() -> String {
        String::from("puppy")
    }
}

fn main() {
    println!("A baby dog is called a {}", Dog::baby_name());
}
```

Listing 19-30: A trait with an associated function and a type that has an associated function with the same name that also implements the trait

This code is for an animal shelter where they want to give all puppies the name Spot, which is implemented in the `baby_name` associated function that is defined on `Dog`. The `Dog` type also implements the trait `Animal`, which describes characteristics that all animals have. Baby dogs are called puppies, and that is expressed in the implementation of the `Animal` trait on `Dog` in the `baby_name` function associated with the `Animal` trait.

In `main`, we're calling the `Dog::baby_name` function, which calls the associated function defined on `Dog` directly. This code prints:

```
A baby dog is called a Spot
```

This isn't really what we wanted, in this case we want to call the `baby_name` function that's part of the `Animal` trait that we implemented on `Dog`, so that we can print `A baby dog is called a puppy`. The technique we used in Listing 19-29 doesn't help here; if we change `main` to be the code in Listing 19-31:

Filename: src/main.rs

```
fn main() {
    println!("A baby dog is called a {}", Animal::baby_name());
}
```

Listing 19-31: Attempting to call the `baby_name` function from the `Animal` trait, but Rust doesn't know which implementation to use

Because `Animal::baby_name` is an associated function rather than a method, and thus doesn't have a `self` parameter, Rust has no way to figure out which implementation of `Animal::baby_name` we want. We'll get this compiler error:

```
error[E0283]: type annotations required: cannot resolve `_: Animal`
  --> src/main.rs
   |
20 |     println!("A baby dog is called a {}", Animal::baby_name());
   |                                           ^^^^^^^^^^^^^^^^^
   |
   = note: required by `Animal::baby_name`
```

In order to tell Rust that we want to use the implementation of `Animal` for `Dog`, we need to use *fully qualified syntax*, which is the most specific we can be when calling a function. Listing 19-32 demonstrates how to use fully qualified syntax in this case:

Filename: src/main.rs

```rust
fn main() {
    println!("A baby dog is called a {}", <Dog as Animal>::baby_name());
}
```

Listing 19-32: Using fully qualified syntax to specify that we want to call the `baby_name` function from the `Animal` trait as implemented on `Dog`

We're providing Rust with a type annotation within the angle brackets, and we're specifying that we want to call the `baby_name` method from the `Animal` trait as implemented on `Dog` by saying that we want to treat the `Dog` type as an `Animal` for this function call. This code will now print what we want:

```
A baby dog is called a puppy
```

In general, fully qualified syntax is defined as:

```rust
<Type as Trait>::function(receiver_if_method, next_arg, ...);
```

For associated functions, there would not be a `receiver`, there would only be the list of other arguments. We could choose to use fully qualified syntax everywhere that we call functions or methods. However, we're allowed to leave out any part of this syntax that Rust is able to figure out from other information in the program. We only need to use this more verbose syntax in cases where there are multiple implementations that use the same name and Rust needs help in order to know which implementation we want to call.

Supertraits to Use One Trait's Functionality Within Another Trait

Sometimes, we may want a trait to be able to rely on another trait also being implemented wherever our trait is implemented, so that our trait can use the other trait's functionality. The required trait is a *supertrait* of the trait we're implementing.

For example, let's say we want to make an `OutlinePrint` trait with an `outline_print` method that will print out a value outlined in asterisks. That is, if our `Point` struct implements `Display` to result in `(x, y)`, calling `outline_print` on a `Point` instance that has 1 for `x` and 3 for `y` would look like:

```
**********
*        *
* (1, 3) *
*        *
**********
```

In the implementation of `outline_print`, since we want to be able to use the `Display` trait's functionality, we need to be able to say that the `OutlinePrint` trait will only work for types that also implement `Display` and provide the functionality that `OutlinePrint` needs. We can do that in the trait definition by specifying `OutlinePrint: Display`. It's like adding a trait bound to the trait. Listing 19-33 shows an implementation of the `OutlinePrint` trait:

```rust
use std::fmt;

trait OutlinePrint: fmt::Display {
    fn outline_print(&self) {
        let output = self.to_string();
        let len = output.len();
        println!("{}", "*".repeat(len + 4));
        println!("*{}*", " ".repeat(len + 2));
        println!("* {} *", output);
        println!("*{}*", " ".repeat(len + 2));
        println!("{}", "*".repeat(len + 4));
    }
}
```

Listing 19-33: Implementing the `OutlinePrint` trait that requires the functionality from `Display`

Because we've specified that `OutlinePrint` requires the `Display` trait, we can use `to_string` in `outline_print` (`to_string` is automatically implemented for any type that implements `Display`). If we hadn't added the `: Display` after the trait name and we tried to use `to_string` in `outline_print`, we'd get an error that no method named `to_string` was found for the type `&Self` in the current scope.

If we try to implement `OutlinePrint` on a type that doesn't implement `Display`, such as the `Point` struct:

```
struct Point {
    x: i32,
    y: i32,
}

impl OutlinePrint for Point {}
```

We'll get an error that `Display` isn't implemented and that `Display` is required by `OutlinePrint`:

```
error[E0277]: the trait bound `Point: std::fmt::Display` is not satisfied
  --> src/main.rs:20:6
   |
20 | impl OutlinePrint for Point {}
   |      ^^^^^^^^^^^^ the trait `std::fmt::Display` is not implemented for
   `Point`
   |
   = note: `Point` cannot be formatted with the default formatter; try using
   `:?` instead if you are using a format string
   = note: required by `OutlinePrint`
```

Once we implement `Display` on `Point` and satisfy the constraint that `OutlinePrint` requires, like so:

```
use std::fmt;

impl fmt::Display for Point {
    fn fmt(&self, f: &mut fmt::Formatter) -> fmt::Result {
        write!(f, "({}, {})", self.x, self.y)
    }
}
```

then implementing the `OutlinePrint` trait on `Point` will compile successfully and we can call `outline_print` on a `Point` instance to display it within an outline of asterisks.

The Newtype Pattern to Implement External Traits on External Types

In Chapter 10, we mentioned the orphan rule, which says we're allowed to implement a trait on a type as long as either the trait or the type are local to our crate. One way to get around this restriction is to use the *newtype pattern*, which involves creating a new type using a tuple struct with one field as a thin wrapper around the type we want to implement a trait for. Then the wrapper type is local to our crate, and we can implement the trait on the wrapper. "Newtype" is a term originating from the Haskell programming language. There's no runtime performance penalty for using this pattern. The wrapper type is elided at compile time.

For example, if we wanted to implement `Display` on `Vec`, we can make a `Wrapper` struct that holds an instance of `Vec`. Then we can implement `Display` on `Wrapper` and use the `Vec` value as shown in Listing 19-34:

Filename: src/main.rs

```
use std::fmt;

struct Wrapper(Vec<String>);

impl fmt::Display for Wrapper {
    fn fmt(&self, f: &mut fmt::Formatter) -> fmt::Result {
        write!(f, "[{}]", self.0.join(", "))
    }
}

fn main() {
    let w = Wrapper(vec![String::from("hello"), String::from("world")]);
    println!("w = {}", w);
}
```

Listing 19-34: Creating a `Wrapper` type around `Vec<String>` to be able to implement `Display`

The implementation of `Display` uses `self.0` to access the inner `Vec`, and then we can use the functionality of the `Display` type on `Wrapper`.

The downside is that since `Wrapper` is a new type, it doesn't have the methods of the value it's holding; we'd have to implement all the methods of `Vec` like `push`, `pop`, and all the rest directly on `Wrapper` to delegate to `self.0` in order to be able to treat `Wrapper` exactly like a `Vec`. If we wanted the new type to have every single method that the inner type has, implementing the `Deref` trait that we discussed in Chapter 15 on the wrapper to return the inner type can be a solution. If we don't want the wrapper type to have all the methods of the inner type, in order to restrict the wrapper type's behavior for example, we'd have to implement just the methods we do want ourselves.

That's how the newtype pattern is used in relation to traits; it's also a useful pattern without having traits involved. Let's switch focus now to talk about some advanced ways to interact with Rust's type system.

Advanced Types

The Rust type system has some features that we've mentioned or used without discussing. We started talking about the newtype pattern in regards to traits; we'll start with a more general discussion about why newtypes are useful as types. We'll then move to type aliases, a feature that is similar to newtypes but has slightly different semantics. We'll also discuss the `!` type and dynamically sized types.

Using the Newtype Pattern for Type Safety and Abstraction

The newtype pattern that we started discussing at the end of the "Advanced Traits" section, where we create a new type as a tuple struct with one field that wraps a type can also be useful for statically enforcing that values are never confused, and is often used to indicate the units of a value. We actually had an example of this in Listing 19-26: the `Millimeters` and `Meters` structs both wrap `u32` values in a new type. If we write a function with a parameter of type `Millimeters`, we won't be able to compile a program that accidentally tries to call that function with a value of type `Meters` or a plain `u32`.

Another reason to use the newtype pattern is to abstract away some implementation details of a type: the wrapper type can expose a different public API than the private inner type would if we used it directly in order to restrict the functionality that is available, for example. New types can also hide internal generic types. For example, we could provide a `People` type that wraps a `HashMap<i32, String>` that stores a person's ID associated with their name. Code using `People` would only interact with the public API we provide, such as a method to add a name string to the `People` collection, and that code wouldn't need to know that we assign an `i32` ID to names internally. The newtype pattern is a lightweight way to achieve encapsulation to hide implementation details that we discussed in Chapter 17.

Type Aliases Create Type Synonyms

The newtype pattern involves creating a new struct to be a new, separate type. Rust also provides the ability to declare a *type alias* with the `type` keyword to give an existing type another name. For example, we can create the alias `Kilometers` to `i32` like so:

```rust
type Kilometers = i32;
```

This means `Kilometers` is a *synonym* for `i32`; unlike the `Millimeters` and `Meters` types we created in Listing 19-26, `Kilometers` is not a separate, new type. Values that have the type `Kilometers` will be treated exactly the same as values of type `i32`:

```
type Kilometers = i32;

let x: i32 = 5;
let y: Kilometers = 5;

println!("x + y = {}", x + y);
```

Since `Kilometers` is an alias for `i32`, they're the same type. We can add values of type `i32` and `Kilometers` together, and we can pass `Kilometers` values to functions that take `i32` parameters. We don't get the type checking benefits that we get from the newtype pattern that we discussed in the previous section.

The main use case for type synonyms is to reduce repetition. For example, we may have a lengthy type like this:

```
Box<Fn() + Send + 'static>
```

Writing this out in function signatures and as type annotations all over the place can be tiresome and error-prone. Imagine having a project full of code like that in Listing 19-35:

```
let f: Box<Fn() + Send + 'static> = Box::new(|| println!("hi"));

fn takes_long_type(f: Box<Fn() + Send + 'static>) {
    // ...snip...
}

fn returns_long_type() -> Box<Fn() + Send + 'static> {
    // ...snip...
}
```

Listing 19-35: Using a long type in many places

A type alias makes this code more manageable by reducing the amount of repetition this project has. Here, we've introduced an alias named `Thunk` for the verbose type, and we can replace all uses of the type with the shorter `Thunk` as shown in Listing 19-36:

```
type Thunk = Box<Fn() + Send + 'static>;

let f: Thunk = Box::new(|| println!("hi"));

fn takes_long_type(f: Thunk) {
    // ...snip...
}

fn returns_long_type() -> Thunk {
    // ...snip...
}
```

Listing 19-36: Introducing a type alias `Thunk` to reduce repetition

Much easier to read and write! Choosing a good name for a type alias can help communicate your intent as well (*thunk* is a word for code to be evaluated at a later time, so it's an appropriate name for a closure that gets stored).

Another common use of type aliases is with the `Result<T, E>` type. Consider the `std::io` module in the standard library. I/O operations often return a `Result<T, E>`, since their operations may fail to work. There's a `std::io::Error` struct that represents all of the possible I/O errors. Many of the functions in `std::io` will be returning `Result<T, E>` where the `E` is `std::io::Error`, such as these functions in the `Write` trait:

```
use std::io::Error;
use std::fmt;

pub trait Write {
    fn write(&mut self, buf: &[u8]) -> Result<usize, Error>;
    fn flush(&mut self) -> Result<(), Error>;

    fn write_all(&mut self, buf: &[u8]) -> Result<(), Error>;
    fn write_fmt(&mut self, fmt: fmt::Arguments) -> Result<(), Error>;
}
```

We're writing `Result<..., Error>` a lot. As such, `std::io` has this type alias declaration:

```
type Result<T> = Result<T, std::io::Error>;
```

Because this is in the `std::io` module, the fully qualified alias that we can use is `std::io::Result<T>`; that is, a `Result<T, E>` with the `E` filled in as `std::io::Error`. The `Write` trait function signatures end up looking like this:

```
pub trait Write {
    fn write(&mut self, buf: &[u8]) -> Result<usize>;
    fn flush(&mut self) -> Result<()>;

    fn write_all(&mut self, buf: &[u8]) -> Result<()>;
    fn write_fmt(&mut self, fmt: Arguments) -> Result<()>;
}
```

The type alias helps in two ways: this is easier to write *and* it gives us a consistent interface across all of `std::io`. Because it's an alias, it is just another `Result<T, E>`, which means we can use any methods that work on `Result<T, E>` with it, and special syntax like `?`.

The Never Type, `!`, that Never Returns

Rust has a special type named `!`. In type theory lingo, it's called the *empty type*, because it has no values. We prefer to call it the *never type*. The name describes what it does: it stands in the place of the return type when a function will never return. For example:

```
fn bar() -> ! {
    // ...snip...
}
```

This is read as "the function `bar` returns never," and functions that return never are called *diverging functions*. We can't create values of the type `!`, so `bar` can never possibly return. What use is a type you can never create values for? If you think all the way back to Chapter 2, we had some code that looked like this, reproduced here in Listing 19-37:

```
let guess: u32 = match guess.trim().parse() {
    Ok(num) => num,
    Err(_) => continue,
};
```

Listing 19-37: A `match` with an arm that ends in `continue`

At the time, we skipped over some details in this code. In Chapter 6, we learned that `match` arms must return the same type. This doesn't work:

```
let guess = match guess.trim().parse()  {
    Ok(_) => 5,
    Err(_) => "hello",
}
```

What would the type of `guess` be here? It'd have to be both an integer and a string, and Rust requires that `guess` can only have one type. So what does `continue` return? Why are we allowed to return a `u32` from one arm in Listing 19-37 and have another arm that ends with `continue`?

As you may have guessed, `continue` has a value of `!`. That is, when Rust goes to compute the type of `guess`, it looks at both of the match arms. The former has a value of `u32`, and the latter has a value of `!`. Since `!` can never have a value, Rust is okay with this, and decides that the type of `guess` is `u32`. The formal way of describing this behavior of `!` is that the never type unifies with all other types. We're allowed to end this `match` arm with `continue` because `continue` doesn't actually return a value; it instead moves control back to the top of the loop, so in the `Err` case, we never actually assign a value to `guess`.

Another use of the never type is `panic!`. Remember the `unwrap` function that we call on `Option<T>` values to produce a value or panic? Here's its definition:

```
impl<T> Option<T> {
    pub fn unwrap(self) -> T {
        match self {
            Some(val) => val,
            None => panic!("called `Option::unwrap()` on a `None` value"),
        }
    }
}
```

Here, the same thing happens as in the `match` in Listing 19-33: we know that `val` has the type `T`, and `panic!` has the type `!`, so the result of the overall `match` expression is `T`. This works because `panic!` doesn't produce a value; it ends the program. In the `None` case, we won't be returning a value from `unwrap`, so this code is valid.

One final expression that has the type `!` is a `loop`:

```
print!("forever ");

loop {
    print!("and ever ");
}
```

Here, the loop never ends, so the value of the expression is `!`. This wouldn't be true if we included a `break`, however, as the loop would terminate when it gets to the `break`.

Dynamically Sized Types & `Sized`

Because Rust needs to know things like memory layout, there's a particular corner of its type system that can be confusing, and that's the concept of *dynamically sized types*. Sometimes referred to as 'DSTs' or 'unsized types', these types let us talk about types whose size we can only know at runtime.

Let's dig into the details of a dynamically sized type that we've been using this whole book: `str`. That's right, not `&str`, but `str` on its own. `str` is a DST; we can't know how long the string is until runtime. Since we can't know that, we can't create a variable of type `str`, nor can we take an argument of type `str`. Consider this code, which does not work:

```
let s1: str = "Hello there!";
let s2: str = "How's it going?";
```

These two `str` values would need to have the exact same memory layout, but they have different lengths: `s1` needs 12 bytes of storage, and `s2` needs 15. This is why it's not possible to create a variable holding a dynamically sized type.

So what to do? Well, you already know the answer in this case: the types of `s1` and `s2` are `&str` rather than `str`. If you think back to Chapter 4, we said this about `&str`:

> ... it's a reference to an internal position in the String and the number of elements that it refers to.

So while a `&T` is a single value that stores the memory address of where the `T` is located, a `&str` is *two* values: the address of the `str` and how long it is. As such, a `&str` has a size we can know at compile time: it's two times the size of a `usize` in length. That is, we always know the size of a `&str`, no matter how long the string it refers to is. This is the general way in which dynamically sized types are used in Rust; they have an extra bit of metadata that stores the size of the dynamic information. This leads us to the golden rule of dynamically sized types: we must always put values of dynamically sized types behind a pointer of some kind.

While we've talked a lot about `&str`, we can combine `str` with all kinds of pointers: `Box<str>`, for example, or `Rc<str>`. In fact, you've already seen this before, but with a different dynamically sized type: traits. Every trait is a dynamically sized type we can refer to by using the name of the trait. In Chapter 17, we mentioned that in order to use traits as trait objects, we have to put them behind a pointer like `&Trait` or `Box<Trait>` (`Rc<Trait>` would work too). Traits being dynamically sized is the reason we have to do that!

The `Sized` Trait

To work with DSTs, Rust has a trait that determines if a type's size is known at compile time or not, which is `Sized`. This trait is automatically implemented for everything the compiler knows the size of at compile time. In addition, Rust implicitly adds a bound on `Sized` to every generic function. That is, a generic function definition like this:

```
fn generic<T>(t: T) {
    // ...snip...
}
```

is actually treated as if we had written this:

```
fn generic<T: Sized>(t: T) {
    // ...snip...
}
```

By default, generic functions will only work on types that have a known size at compile time. There is, however, special syntax you can use to relax this restriction:

```
fn generic<T: ?Sized>(t: &T) {
    // ...snip...
}
```

A trait bound on `?Sized` is the opposite of a trait bound on `Sized`; that is, we would read this as "`T` may or may not be `Sized`". This syntax is only available for `Sized`, no other traits.

Also note we switched the type of the `t` parameter from `T` to `&T`: since the type might not be `Sized`, we need to use it behind some kind of pointer. In this case, we've chosen a reference.

Next let's talk about functions and closures!

Advanced Functions & Closures

Finally, let's discuss some advanced features having to do with functions and closures: function pointers, diverging functions, and returning closures.

Function pointers

We've talked about how to pass closures to functions, but you can pass regular functions to functions too! Functions coerce to the type `fn`, with a lower case 'f' not to be confused with the `Fn` closure trait. `fn` is called a *function pointer*. The syntax for specifying that a parameter is a function pointer is similar to that of closures, as shown in Listing 19-38:

Filename: src/main.rs

```
fn add_one(x: i32) -> i32 {
    x + 1
}

fn do_twice(f: fn(i32) -> i32, arg: i32) -> i32 {
    f(arg) + f(arg)
}

fn main() {
    let answer = do_twice(add_one, 5);

    println!("The answer is: {}", answer);
}
```

Listing 19-38: Using the `fn` type to accept a function pointer as an argument

This prints `The answer is: 12`. We specify that the parameter `f` in `do_twice` is an `fn` that takes one parameter of type `i32` and returns an `i32`. We can then call `f` in the body of `do_twice`. In `main`, we can pass the function name `add_one` as the first argument to `do_twice`.

Unlike closures, `fn` is a type rather than a trait, so we specify `fn` as the parameter type directly rather than declaring a generic type parameter with one of the `Fn` traits as a trait bound.

Function pointers implement all three of the closure traits (`Fn`, `FnMut`, and `FnOnce`), so we can always pass a function pointer as an argument when calling a function that expects a closure. Prefer to write functions using a generic type and one of the closure traits, so that your functions can accept either functions or closures. An example of a case where you'd only want to accept `fn` is when interfacing with external code that doesn't have closures: C functions can accept functions as arguments, but C doesn't have closures.

For example, if we wanted to use the `map` function to turn a vector of numbers into a vector of strings, we could use a closure:

```
let list_of_numbers = vec![1, 2, 3];
let list_of_strings: Vec<String> = list_of_numbers
    .iter()
    .map(|i| i.to_string())
    .collect();
```

Or we could name a function as the argument to `map` instead of the closure:

```
let list_of_numbers = vec![1, 2, 3];
let list_of_strings: Vec<String> = list_of_numbers
    .iter()
    .map(ToString::to_string)
    .collect();
```

Note that we do have to use the fully qualified syntax that we talked about in the “Advanced Traits” section because there are multiple functions available named `to_string`; here, we’re using the `to_string` function defined in the `ToString` trait, which the standard library has implemented for any type that implements `Display`.

Some people prefer this style, some people prefer the closure. They end up with the same code, so use whichever feels more clear to you.

Returning Closures

Because closures are represented by traits, returning closures is a little tricky; we can’t do it directly. In most cases where we may want to return a trait, we can instead use the concrete type that implements the trait of what we’re returning as the return value of the function. We can’t do that with closures, though. They don’t have a concrete type that’s returnable; we’re not allowed to use the function pointer `fn` as a return type, for example.

This code that tries to return a closure directly won’t compile:

```
fn returns_closure() -> Fn(i32) -> i32 {
    |x| x + 1
}
```

The compiler error is:

```
error[E0277]: the trait bound `std::ops::Fn(i32) -> i32 + 'static:
std::marker::Sized` is not satisfied
 --> <anon>:2:25
  |
2 | fn returns_closure() -> Fn(i32) -> i32 {
  |                         ^^^^^^^^^^^^^^ the trait `std::marker::Sized` is
  not implemented for `std::ops::Fn(i32) -> i32 + 'static`
  |
  = note: `std::ops::Fn(i32) -> i32 + 'static` does not have a constant size
  known at compile-time
  = note: the return type of a function must have a statically known size
```

The `Sized` trait again! Rust doesn’t know how much space it’ll need to store the closure. We saw a solution to this in the previous section, though: we can use a trait object:

```
fn returns_closure() -> Box<Fn(i32) -> i32> {
    Box::new(|x| x + 1)
}
```

For more about trait objects, refer back to Chapter 18.

Summary

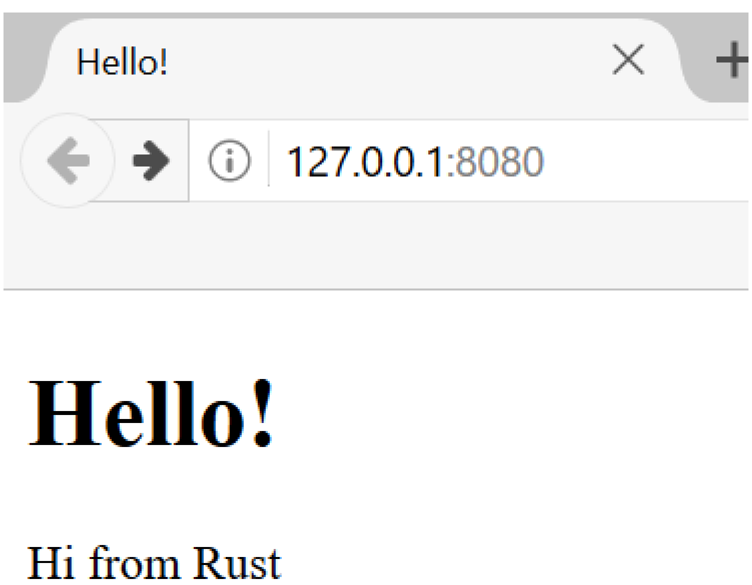
Whew! Now we've gone over features of Rust that aren't used very often, but are available if you need them. We've introduced a lot of complex topics so that when you encounter them in error message suggestions or when reading others' code, you'll at least have seen these concepts and syntax once before.

Now, let's put everything we've learned throughout the book into practice with one more project!

Final Project: Building a Multithreaded Web Server

It's been a long journey, but here we are! It's the end of the book. Parting is such sweet sorrow. But before we go, let's build one more project together, to show off some of the things we learned in these final chapters, as well as re-cap some of the earlier ones.

Here's what we're going to make: a web server that says hello:



To do this, we will:

1. Learn a little bit about TCP and HTTP
2. Listen for TCP connections on a socket
3. Parse a tiny number of HTTP requests
4. Create a proper HTTP response
5. Improve the throughput of our server with a thread pool

Before we get started, however, there's one thing we should mention: if you were writing this code in production, there are a lot of better ways to write it. Specifically, there are a number of robust crates on crates.io that provide much more complete web server and thread pool implementations than we are going to build.

However, for this chapter, our intention is to learn, not to take the easy route. Since Rust is a systems programming language, we're able to choose what level of abstraction we want to work with. We're able to go to a lower level than is possible or practical in other languages if we so choose. So we'll be writing a basic HTTP server and thread pool ourselves in order to learn the general ideas and techniques behind the crates we might use in the future.

A Single Threaded Web Server

First, let's get a single threaded web server working. We're going to work with the raw bytes of TCP and HTTP requests and responses to send HTML from our server to a web browser. Let's start with a quick overview of the protocols involved.

The *Hypertext Transfer Protocol* (*HTTP*) that powers the web is built on top of the *Transmission Control Protocol* (*TCP*). We won't get into the details too much, but here's a short overview: TCP is a low-level protocol, and HTTP builds a higher-level protocol on top of TCP. Both protocols are what's called a *request-response protocol*, that is, there is a *client* that initiates requests, and a *server* that listens to requests and provides a response to the client. The contents of those requests and responses are defined by the protocols themselves.

TCP describes the low-level details of how information gets from one server to another, but doesn't specify what that information is; it's just a bunch of ones and zeroes. HTTP builds on top of TCP by defining what the content of the requests and responses should be. As such, it's technically possible to use HTTP with other protocols, but in the vast majority of cases, HTTP sends its data over TCP.

So the first thing we need to build for our web server is to be able to listen to a TCP connection. The standard library has a `std::net` module that lets us do this. Let's make a new project:

```
$ cargo new hello --bin
     Created binary (application) `hello` project
$ cd hello
```

And put the code in Listing 20-1 in `src/main.rs` to start. This code will listen at the address `127.0.0.1:8080` for incoming TCP streams. When it gets an incoming stream, it will print `Connection established!`:

Filename: src/main.rs

```
use std::net::TcpListener;

fn main() {
    let listener = TcpListener::bind("127.0.0.1:8080").unwrap();

    for stream in listener.incoming() {
        let stream = stream.unwrap();

        println!("Connection established!");
    }
}
```

Listing 20-1: Listening for incoming streams and printing a message when we receive a stream

A `TcpListener` allows us to listen for TCP connections. We've chosen to listen to the address `127.0.0.1:8080`. The part before the colon is an IP address representing our own computer, and `8080` is the port. We've chosen this port because HTTP is normally accepted on port 80, but connecting to port 80 requires administrator privileges. Regular users can listen on ports higher than 1024; 8080 is easy to remember since it's the HTTP port 80 repeated.

The `bind` function is sort of like `new` in that it returns a new `TcpListener` instance, but `bind` is a more descriptive name that fits with the domain terminology. In networking, people will often talk about "binding to a port", so the function that the standard library defined to create a new `TcpListener` is called `bind`.

The `bind` function returns a `Result<T, E>`. Binding may fail, for example, if we had tried to connect to port 80 without being an administrator. Another example of a case when binding would fail is if we tried to have two programs listening to the same port, which would happen if we ran two instances of our program. Since we're writing a basic server here, we're not going to worry about handling these kinds of errors, and `unwrap` lets us just stop the program if they happen.

The `incoming` method on `TcpListener` returns an iterator that gives us a sequence of streams (more specifically, streams of type `TcpStream`). A *stream* represents an open connection between the client and the server. A *connection* is the name for the full request/response process when a client connects to the server, the server generates a response, and the server closes the connection. As such, the `TcpStream` will let us read from itself to see what the client sent, and we can write our response to it. So this `for` loop will process each connection in turn and produce a series of streams for us to handle.

For now, handling a stream means calling `unwrap` to terminate our program if the stream has any errors, then printing a message. Errors can happen because we're not actually iterating over connections, we're iterating over *connection attempts*. The connection might not work for a number of reasons, many of them operating-system specific. For example, many operating systems have a limit to the number of simultaneous open connections; new connection attempts will then produce an error until some of the open connections are closed.

Let's try this code out! First invoke `cargo run` in the terminal, then load up `127.0.0.1:8080` in a web browser. The browser will show an error message that will say something similar to "Connection reset", since we're not currently sending any data back. If we look at our terminal, though, we'll see a bunch of messages that were printed when the browser connected to the server!

```
     Running `target/debug/hello`
Connection established!
Connection established!
Connection established!
```

We got multiple messages printed out for one browser request; these connections might be the browser making a request for the page and a request for a `favicon.ico` icon that appears in the browser tab, or the browser might be retrying the connection. Our browser is expecting to speak HTTP, but we aren't replying with anything, just closing the connection by moving on to the next loop iteration. When `stream` goes out of scope and dropped at the end of the loop, its connection gets closed as part of the `drop` implementation for `TcpStream`. Browsers sometimes deal with closed connections by retrying, since the problem might be temporary. The important thing is that we've successfully gotten a handle on a TCP connection!

Remember to stop the program with CTRL-C when you're done running a particular version of the code, and restart `cargo run` after you've made each set of code changes in order to be running the newest code.

Reading the Request

Let's read in the request from our browser! Since we're adding more functionality that has the purpose of handling the connection, let's start a new function to have a nice separation of the concerns around setting up the server and connections versus processing each connection. In this new `handle_connection` function, we'll read data from the `stream` and print it out in order to see the data that the browser is sending us. Change the code to look like Listing 20-2:

Filename: src/main.rs

```
use std::io::prelude::*;
use std::net::TcpListener;
use std::net::TcpStream;

fn main() {
    let listener = TcpListener::bind("127.0.0.1:8080").unwrap();

    for stream in listener.incoming() {
        let stream = stream.unwrap();

        handle_connection(stream);
    }
}

fn handle_connection(mut stream: TcpStream) {
    let mut buffer = [0; 512];

    stream.read(&mut buffer).unwrap();

    println!("Request: {}", String::from_utf8_lossy(&buffer[..]));
}
```

Listing 20-2: Reading from the `TcpStream` and printing out the data

We added `std::io::prelude` to the beginning in order to bring traits into scope that let us read from and write to the stream. Instead of printing a message that we got a connection in the `for` loop in `main`, we're calling the new `handle_connection` function and passing the `stream` to it.

In `handle_connection`, we made the `stream` parameter mutable with the `mut` keyword. As we read from a stream, the `TcpStream` instance might read more than what we ask for into a buffer. Internally, it keeps track of what data it has returned to us. It needs to be `mut` because of that state changing, so even though we usually think of "reading" as not needing mutation, in this case, we do need to use the `mut` keyword.

Next, we need to actually read from the stream. We do this in two steps: first, we declare a `buffer` on the stack to hold the data that we read in. We've made the buffer 512 bytes in size, which is big enough to hold the data of a basic request. That's sufficient for our purposes in this chapter. If we wanted to handle requests of an arbitrary size, managing the buffer would need to be more complicated, but we're keeping it simple for now. We then pass the buffer to `stream.read`, which will read bytes from the `TcpStream` and put them in the buffer.

Then we convert the bytes in the buffer to a string and print out that string. The `String::from_utf8_lossy` function takes a `&[u8]` and produces a `String`. The 'lossy' part of the name comes from the behavior when this function sees invalid UTF-8 sequences: it replaces the invalid sequences with �, `U+FFFD REPLACEMENT CHARACTER`. You might see the replacement characters for remaining characters in the buffer that aren't filled by request data.

Let's give this a try! Start up the program and make a request in a web browser again. Note that we'll still get an error page in the browser, but the output of our program in the terminal will now look similar to this:

```
$ cargo run
   Compiling hello v0.1.0 (file:///projects/hello)
    Finished dev [unoptimized + debuginfo] target(s) in 0.42 secs
     Running `target/debug/hello`
Request: GET / HTTP/1.1
Host: 127.0.0.1:8080
User-Agent: Mozilla/5.0 (Windows NT 10.0; WOW64; rv:52.0) Gecko/20100101
Firefox/52.0
Accept: text/html,application/xhtml+xml,application/xml;q=0.9,*/*;q=0.8
Accept-Language: en-US,en;q=0.5
Accept-Encoding: gzip, deflate
Connection: keep-alive
Upgrade-Insecure-Requests: 1
������������������������������������
```

You'll probably get slightly different output depending on your browser. You also might see this request repeated again. Now that we're printing out the request data, we can see why we're getting multiple connections from one browser request by looking at the path after `Request: GET`. If the repeated connections are all requesting `/`, we know the browser is trying to fetch `/` repeatedly since it's not getting a response from us.

Let's break down this request data to understand what the browser is asking of us. HTTP is a text-based protocol, and a request takes this format:

```
Method Request-URI HTTP-Version CRLF
headers CRLF
message-body
```

The first line is called the *request line*, and it holds information about what the client is requesting. The first part of the request line is a *method*, like `GET` or `POST`, that describes how the client is making this request.

Then comes the request's *URI*, which stands for *Uniform Resource Identifier*. URIs are almost, but not quite the same as URLs (*Uniform Resource Locators*), which is what we typically call the addresses that we enter into a web browser. The HTTP spec uses the term URI, and the difference between URIs and URLs isn't important for our purposes of this chapter, so we can just mentally substitute URL for URI here.

Next, we have the HTTP version that the client used, and then the request line ends in a CRLF sequence. The CRLF sequence can also be written as `\r\n`: `\r` is a *carriage return* and `\n` is a *line feed*. These terms come from the typewriter days! The CRLF sequence separates the request line from the rest of the request data.

Taking a look at the request line data we saw printed out by our code:

```
GET / HTTP/1.1
```

`GET` is the method, `/` is the Request URI, and `HTTP/1.1` is the version.

The remaining lines starting from `Host:` onward are headers; `GET` requests have no body.

Try making a request from a different browser, or asking for a different address like `127.0.0.1:8080/test` to see how the request data changes, if you'd like.

Now that we know what the browser is asking for, let's send some data back!

Writing a Response

Let's send data back to our browser in response to its request. Responses have this format:

```
HTTP-Version Status-Code Reason-Phrase CRLF
headers CRLF
message-body
```

The first line is called a *status line* and contains the HTTP version used in the response, a numeric status code that summarizes the result of the request, and a reason phrase that provides a text description of the status code. After the CRLF sequence comes any headers, another CRLF sequence, and the body of the response.

Here's an example response that uses version 1.1 of HTTP, has a status code of `200`, a reason phrase of `OK`, no headers, and no body:

```
HTTP/1.1 200 OK\r\n\r\n
```

This text is a tiny successful HTTP response. Let's write this to the stream! Remove the `println!` that was printing the request data, and add the code in Listing 20-3 in its place:

Filename: src/main.rs

```
fn handle_connection(mut stream: TcpStream) {
    let mut buffer = [0; 512];

    stream.read(&mut buffer).unwrap();

    let response = "HTTP/1.1 200 OK\r\n\r\n";

    stream.write(response.as_bytes()).unwrap();
    stream.flush().unwrap();
}
```

Listing 20-3: Writing a tiny successful HTTP response to the stream

The first new line defines the `response` variable that holds the data of the tiny success response we're sending back. Then, we call `as_bytes` on our `response` because the `write` method on `stream` takes a `&[u8]` and sends those bytes directly down the connection.

The `write` operation could fail, so `write` returns a `Result<T, E>`; we're continuing to use `unwrap` to make progress on the core ideas in this chapter rather than error handling. Finally, `flush` will wait until all of the bytes are written to the connection; `TcpStream` contains an internal buffer to minimize calls into the underlying operating system.

With these changes, let's run our code and make a request! We're no longer printing any data to the terminal, so we won't see any output there other than the output from Cargo. When we load `127.0.0.1:8080` in a web browser, though, we get a blank page instead of an error. How exciting! You've just hand-coded an HTTP request and response.

Returning Real HTML

Let's return more than a blank page. Create a new file, *hello.html*, in the root of your project directory, that is, not in the `src` directory. You can put any HTML you want in it; Listing 20-4 shows what the authors used for theirs:

Filename: hello.html

```
<!DOCTYPE html>
<html lang="en">
  <head>
    <meta charset="utf-8">
    <title>Hello!</title>
  </head>
  <body>
    <h1>Hello!</h1>
    <p>Hi from Rust</p>
  </body>
</html>
```

Listing 20-4: A sample HTML file to return in a response

This is a minimal HTML 5 document with a heading and a little paragraph. Let's modify `handle_connection` as shown in Listing 20-5 to read the HTML file, add it to the response as a body, and send it:

Filename: src/main.rs

```
use std::fs::File;

// ...snip...

fn handle_connection(mut stream: TcpStream) {
    let mut buffer = [0; 512];
    stream.read(&mut buffer).unwrap();

    let mut file = File::open("hello.html").unwrap();

    let mut contents = String::new();
    file.read_to_string(&mut contents).unwrap();

    let response = format!("HTTP/1.1 200 OK\r\n\r\n{}", contents);

    stream.write(response.as_bytes()).unwrap();
    stream.flush().unwrap();
}
```

Listing 20-5: Sending the contents of *hello.html* as the body of the response

We've added a line at the top to bring the standard library's `File` into scope, and the file opening and reading code should look familiar since we had similar code in Chapter 12 when we read the contents of a file for our I/O project in Listing 12-4.

Next, we're using `format!` to add the file's contents as the body of the success response that we write to the stream.

Run it with `cargo run`, load up `127.0.0.1:8080` in your browser, and you should see your HTML rendered!

Note that we're currently ignoring the request data in `buffer` and sending back the contents of the HTML file unconditionally. Try requesting `127.0.0.1:8080/something-else` in your browser and you'll get back your HTML for that request too. Sending back the same response for all requests is pretty limited and not what most web servers do; let's examine the request and only send back the HTML file for a well-formed request to `/`.

Validating the Request and Selectively Responding

Right now, our web server will return the HTML in the file no matter what the client requested. Let's check that the browser is requesting `/`, and instead return an error if the browser requests anything else. Let's modify `handle_connection` as shown in Listing 20-6, which adds part of the code we'll need. This part checks the content of the request we received against what we know a request for `/` looks like and adds `if` and `else` blocks where we'll add code to treat requests differently:

Filename: src/main.rs

```
// ...snip...

fn handle_connection(mut stream: TcpStream) {
    let mut buffer = [0; 512];
    stream.read(&mut buffer).unwrap();

    let get = b"GET / HTTP/1.1\r\n";

    if buffer.starts_with(get) {
        let mut file = File::open("hello.html").unwrap();

        let mut contents = String::new();
        file.read_to_string(&mut contents).unwrap();

        let response = format!("HTTP/1.1 200 OK\r\n\r\n{}", contents);

        stream.write(response.as_bytes()).unwrap();
        stream.flush().unwrap();
    } else {
        // some other request
    };
}
```

Listing 20-6: Matching the request against the content we expect for a request to `/` and setting up conditionally handling requests to `/` differently than other requests

Here, we hardcoded the data corresponding to the request that we're looking for in the variable `get`. Because we're reading raw bytes into the buffer, we use a byte string, created with `b""`, to make `get` a byte string too. Then, we check to see if `buffer` starts with the bytes in `get`. If it does, we've gotten a well-formed request to `/`, which is the success case that we want to handle in the `if` block. The `if` block contains the code we added in Listing 20-5 that returns the contents of our HTML file.

If `buffer` does not start with the bytes in `get`, we've gotten some other request. We'll respond to all other requests using the code we're about to add in the `else` block.

If you run this code and request `127.0.0.1:8080`, you'll get the HTML that's in *hello.html*. If you make any other request, such as `127.0.0.1:8080/something-else`, you'll get a connection error like we saw when running the code in Listing 20-1 and Listing 20-2.

Let's add code to the `else` block as shown in Listing 20-7 to return a response with the status code `404`, which signals that the content for the request was not found. We'll also return HTML for a page to render in the browser indicating as such to the end user:

Filename: src/main.rs

```
// ...snip...

} else {
    let status_line = "HTTP/1.1 404 NOT FOUND\r\n\r\n";
    let mut file = File::open("404.html").unwrap();
    let mut contents = String::new();

    file.read_to_string(&mut contents).unwrap();

    let response = format!("{}{}", status_line, contents);

    stream.write(response.as_bytes()).unwrap();
    stream.flush().unwrap();
}
```

Listing 20-7: Responding with status code `404` and an error page if anything other than `/` was requested

Here, our response has a status line with status code `404` and the reason phrase `NOT FOUND`. We still aren't returning any headers, and the body of the response will be the HTML in the file *404.html*. Also create a *404.html* file next to *hello.html* for the error page; again feel free to use any HTML you'd like or use the example HTML in Listing 20-8:

Filename: 404.html

```
<!DOCTYPE html>
<html lang="en">
  <head>
    <meta charset="utf-8">
    <title>Hello!</title>
  </head>
  <body>
    <h1>Oops!</h1>
    <p>Sorry, I don't know what you're asking for.</p>
  </body>
</html>
```

Listing 20-8: Sample content for the page to send back with any `404` response

With these changes, try running your server again. Requesting `127.0.0.1:8080` should return the contents of *hello.html*, and any other request, like `127.0.0.1:8080/foo`, should return the error HTML from *404.html*!

There's a lot of repetition between the code in the `if` and the `else` blocks: they're both reading files and writing the contents of the files to the stream. The only differences between the two cases are the status line and the filename. Let's pull those differences out into an `if` and `else` of one line each that will assign the values of the status line and the filename to variables; we can then use those variables unconditionally in the code to read the file and write the response. The resulting code after this refactoring is shown in Listing 20-9:

Filename: src/main.rs

```
// ...snip...

fn handle_connection(mut stream: TcpStream) {
    // ...snip...

    let (status_line, filename) = if buffer.starts_with(get) {
        ("HTTP/1.1 200 OK\r\n\r\n", "hello.html")
    } else {
        ("HTTP/1.1 404 NOT FOUND\r\n\r\n", "404.html")
    };

    let mut file = File::open(filename).unwrap();
    let mut contents = String::new();

    file.read_to_string(&mut contents).unwrap();

    let response = format!("{}{}", status_line, contents);

    stream.write(response.as_bytes()).unwrap();
    stream.flush().unwrap();
}
```

Listing 20-9: Refactoring so that the `if` and `else` blocks only contain the code that differs between the two cases

Here, the only thing the `if` and `else` blocks do is return the appropriate values for the status line and filename in a tuple; we then use destructuring to assign these two values to `status_line` and `filename` using a pattern in the `let` statement like we discussed in Chapter 18.

The duplicated code to read the file and write the response is now outside the `if` and `else` blocks, and uses the `status_line` and `filename` variables. This makes it easier to see exactly what's different between the two cases, and makes it so that we only have one place to update the code if we want to change how the file reading and response writing works. The behavior of the code in Listing 20-9 will be exactly the same as that in Listing 20-8.

Awesome! We have a simple little web server in about 40 lines of Rust code that responds to one request with a page of content and responds to all other requests with a `404` response.

Since this server runs in a single thread, though, it can only serve one request at a time. Let's see how that can be a problem by simulating some slow requests.

How Slow Requests Affect Throughput

Right now, the server will process each request in turn. That works for services like ours that aren't expected to get very many requests, but as applications get more complex, this sort of serial execution isn't optimal.

Because our current program processes connections sequentially, it won't process a second connection until it's completed processing the first. If we get one request that takes a long time to process, requests coming in during that time will have to wait until the long request is finished, even if the new requests can be processed quickly. Let's see this in action.

Simulating a Slow Request in the Current Server Implementation

Let's see the effect of a request that takes a long time to process on requests made to our current server implementation. Listing 20-10 shows the code to respond to another request, `/sleep`, that will cause the server to sleep for five seconds before responding. This will simulate a slow request so that we can see that our server processes requests serially.

Filename: src/main.rs

```
use std::thread;
use std::time::Duration;
// ...snip...

fn handle_connection(mut stream: TcpStream) {
    // ...snip...

    let get = b"GET / HTTP/1.1\r\n";
    let sleep = b"GET /sleep HTTP/1.1\r\n";

    let (status_line, filename) = if buffer.starts_with(get) {
        ("HTTP/1.1 200 OK\r\n\r\n", "hello.html")
    } else if buffer.starts_with(sleep) {
        thread::sleep(Duration::from_secs(5));
        ("HTTP/1.1 200 OK\r\n\r\n", "hello.html")
    } else {
        ("HTTP/1.1 404 NOT FOUND\r\n\r\n", "404.html")
    };

    // ...snip...
}
```

Listing 20-10: Simulating a slow request by recognizing `/sleep` and sleeping for 5 seconds

This code is a bit messy, but it's good enough for our simulation purposes! We created a second request `sleep`, whose data we'll recognize. We added an `else if` after the `if` block to check for the request to `/sleep`, and when we see that request, we'll sleep for five seconds before rendering the hello page.

You can really see how primitive our server is here; real libraries would handle the recognition of multiple requests in a less verbose way!

Start the server with `cargo run`, and then open up two browser windows: one for `http://localhost:8080/` and one for `http://localhost:8080/sleep`. If you hit `/` a few times, as before, you'll see it respond quickly. But if you hit `/sleep`, and then load up `/`, you'll see that `/` waits until `sleep` has slept for its full five seconds before going on.

There are multiple ways we could change how our web server works in order to avoid having all requests back up behind a slow request; the one we're going to implement is a thread pool.

Improving Throughput with a Thread Pool

A *thread pool* is a group of spawned threads that are ready to handle some task. When the program receives a new task, one of the threads in the pool will be assigned the task and will go off and process it. The remaining threads in the pool are available to handle any other tasks that come in while the first thread is processing. When the first thread is done processing its task, it gets returned to the pool of idle threads ready to handle a new task.

A thread pool will allow us to process connections concurrently: we can start processing a new connection before an older connection is finished. This increases the throughput of our server.

Here's what we're going to implement: instead of waiting for each request to process before starting on the next one, we'll send the processing of each connection to a different thread. The threads will come from a pool of four threads that we'll spawn when we start our program. The reason we're limiting the number of threads to a small number is that if we created a new thread for each request as the requests come in, someone making ten million requests to our server could create havoc by using up all of our server's resources and grinding the processing of all requests to a halt.

Rather than spawning unlimited threads, we'll have a fixed number of threads waiting in the pool. As requests come in, we'll send the requests to the pool for processing. The pool will maintain a queue of incoming requests. Each of the threads in the pool will pop a request off of this queue, handle the request, and then ask the queue for another request. With this design, we can process `N` requests concurrently, where `N` is the number of threads. This still means that `N` long-running requests can cause requests to back up in the queue, but we've increased the number of long-running requests we can handle before that point from one to `N`.

This design is one of many ways to improve the throughput of our web server. This isn't a book about web servers, though, so it's the one we're going to cover. Other options are the fork/join model and the single threaded async I/O model. If you're interested in this topic, you may want to read more about other solutions and try to implement them in Rust; with a low-level language like Rust, all of these options are possible.

Designing the Thread Pool Interface

Let's talk about what using the pool should look like. The authors often find that when trying to design some code, writing the client interface first can really help guide your design. Write the API of the code to be structured in the way you'd want to call it, then implement the functionality within that structure rather than implementing the functionality then designing the public API.

Similar to how we used Test Driven Development in the project in Chapter 12, we're going to use Compiler Driven Development here. We're going to write the code that calls the functions we wish we had, then we'll lean on the compiler to tell us what we should change next. The compiler error messages will guide our implementation.

Code Structure if We Could Use `thread::spawn`

First, let's explore what the code to create a new thread for every connection could look like. This isn't our final plan due to the problems with potentially spawning an unlimited number of threads that we talked about earlier, but it's a start. Listing 20-11 shows the changes to `main` to spawn a new thread to handle each stream within the `for` loop:

Filename: src/main.rs

```
fn main() {
    let listener = TcpListener::bind("127.0.0.1:8080").unwrap();

    for stream in listener.incoming() {
        let stream = stream.unwrap();

        thread::spawn(|| {
            handle_connection(stream);
        });
    }
}
```

Listing 20-11: Spawning a new thread for each stream

As we learned in Chapter 16, `thread::spawn` will create a new thread and then run the code in the closure in it. If you run this code and load `/sleep` and then `/` in two browser tabs, you'll indeed see the request to `/` doesn't have to wait for `/sleep` to finish. But as we mentioned, this will eventually overwhelm the system since we're making new threads without any limit.

Creating a Similar Interface for `ThreadPool`

We want our thread pool to work in a similar, familiar way so that switching from threads to a thread pool doesn't require large changes to the code we want to run in the pool. Listing 20-12 shows the hypothetical interface for a `ThreadPool` struct we'd like to use instead of `thread::spawn`:

Filename: src/main.rs

```
fn main() {
    let listener = TcpListener::bind("127.0.0.1:8080").unwrap();
    let pool = ThreadPool::new(4);

    for stream in listener.incoming() {
        let stream = stream.unwrap();

        pool.execute(|| {
            handle_connection(stream);
        });
    }
}
```

Listing 20-12: How we want to be able to use the `ThreadPool` we're going to implement

We use `ThreadPool::new` to create a new thread pool with a configurable number of threads, in this case four. Then, in the `for` loop, `pool.execute` will work in a similar way to `thread::spawn`.

Compiler Driven Development to Get the API Compiling

Go ahead and make the changes in Listing 20-12 to *src/main.rs*, and let's use the compiler errors to drive our development. Here's the first error we get:

```
$ cargo check
   Compiling hello v0.1.0 (file:///projects/hello)
error[E0433]: failed to resolve. Use of undeclared type or module `ThreadPool`
  --> src\main.rs:10:16
   |
10 |     let pool = ThreadPool::new(4);
   |                ^^^^^^^^^^^^^^^ Use of undeclared type or module
   `ThreadPool`

error: aborting due to previous error
```

Great, we need a `ThreadPool`. Let's switch the `hello` crate from a binary crate to a library crate to hold our `ThreadPool` implementation, since the thread pool implementation will be independent of the particular kind of work that we're doing in our web server. Once we've got the thread pool library written, we could use that functionality to do whatever work we want to do, not just serve web requests.

So create *src/lib.rs* that contains the simplest definition of a `ThreadPool` struct that we can have for now:

Filename: src/lib.rs

```
pub struct ThreadPool;
```

Then create a new directory, *src/bin*, and move the binary crate rooted in *src/main.rs* into *src/bin/main.rs*. This will make the library crate be the primary crate in the *hello* directory; we can still run the binary in *src/bin/main.rs* using `cargo run` though. After moving the *main.rs* file, edit it to bring the library crate in and bring `ThreadPool` into scope by adding this at the top of *src/bin/main.rs*:

Filename: src/bin/main.rs

```
extern crate hello;
use hello::ThreadPool;
```

And try again in order to get the next error that we need to address:

```
$ cargo check
   Compiling hello v0.1.0 (file:///projects/hello)
error: no associated item named `new` found for type `hello::ThreadPool` in the
current scope
  --> src\main.rs:13:16
   |
13 |     let pool = ThreadPool::new(4);
   |                ^^^^^^^^^^^^^^^
   |
```

Cool, the next thing is to create an associated function named `new` for `ThreadPool`. We also know that `new` needs to have one parameter that can accept `4` as an argument, and `new` should return a `ThreadPool` instance. Let's implement the simplest `new` function that will have those characteristics:

Filename: src/lib.rs

```
pub struct ThreadPool;

impl ThreadPool {
    pub fn new(size: u32) -> ThreadPool {
        ThreadPool
    }
}
```

We picked `u32` as the type of the `size` parameter, since we know that a negative number of threads makes no sense. `u32` is a solid default. Once we actually implement `new` for real, we'll reconsider whether this is the right choice for what the implementation needs, but for now, we're just working through compiler errors.

Let's check the code again:

```
$ cargo check
   Compiling hello v0.1.0 (file:///projects/hello)
warning: unused variable: `size`, #[warn(unused_variables)] on by default
 --> src/lib.rs:4:16
  |
4 |     pub fn new(size: u32) -> ThreadPool {
  |                ^^^^

error: no method named `execute` found for type `hello::ThreadPool` in the
current scope
  --> src/main.rs:18:14
   |
18 |         pool.execute(|| {
   |              ^^^^^^^
```

Okay, a warning and an error. Ignoring the warning for a moment, the error is because we don't have an `execute` method on `ThreadPool`. Let's define one, and we need it to take a closure. If you remember from Chapter 13, we can take closures as arguments with three different traits: `Fn`, `FnMut`, and `FnOnce`. What kind of closure should we use? Well, we know we're going to end up doing something similar to `thread::spawn`; what bounds does the signature of `thread::spawn` have on its argument? Let's look at the documentation, which says:

```
pub fn spawn<F, T>(f: F) -> JoinHandle<T>
    where
        F: FnOnce() -> T + Send + 'static,
        T: Send + 'static
```

`F` is the parameter we care about here; `T` is related to the return value and we're not concerned with that. Given that `spawn` uses `FnOnce` as the trait bound on `F`, it's probably what we want as well, since we'll eventually be passing the argument we get in `execute` to `spawn`. We can be further confident that `FnOnce` is the trait that we want to use since the thread for running a request is only going to execute that request's closure one time.

`F` also has the trait bound `Send` and the lifetime bound `'static`, which also make sense for our situation: we need `Send` to transfer the closure from one thread to another, and `'static` because we don't know how long the thread will execute. Let's create an `execute` method on `ThreadPool` that will take a generic parameter `F` with these bounds:

Filename: src/lib.rs

```
impl ThreadPool {
    // ...snip...

    pub fn execute<F>(&self, f: F)
        where
            F: FnOnce() + Send + 'static
    {

    }
}
```

The `FnOnce` trait still needs the `()` after it since this `FnOnce` is representing a closure that takes no parameters and doesn't return a value. Just like function definitions, the return type can be omitted from the signature, but even if we have no parameters, we still need the parentheses.

Again, since we're working on getting the interface compiling, we're adding the simplest implementation of the `execute` method, which does nothing. Let's check again:

```
$ cargo check
   Compiling hello v0.1.0 (file:///projects/hello)
warning: unused variable: `size`, #[warn(unused_variables)] on by default
 --> src/lib.rs:4:16
  |
4 |     pub fn new(size: u32) -> ThreadPool {
  |                ^^^^

warning: unused variable: `f`, #[warn(unused_variables)] on by default
 --> src/lib.rs:8:30
  |
8 |     pub fn execute<F>(&self, f: F)
  |                              ^
```

Only warnings now! It compiles! Note that if you try `cargo run` and making a request in the browser, though, you'll see the errors in the browser again that we saw in the beginning of the chapter. Our library isn't actually calling the closure passed to `execute` yet!

> A saying you might hear about languages with strict compilers like Haskell and Rust is "if the code compiles, it works." This is a good time to remember that this is just a phrase and a feeling people sometimes have, it's not actually universally true. Our project compiles, but it does absolutely nothing! If we were building a real, complete project, this would be a great time to start writing unit tests to check that the code compiles *and* has the behavior we want.

Creating the Thread Pool and Storing Threads

The warnings are because we aren't doing anything with the parameters to `new` and `execute`. Let's implement the bodies of both of these with the actual behavior we want.

Validating the Number of Threads in the Pool

To start, let's think about `new`. We mentioned before that we picked an unsigned type for the `size` parameter since a pool with a negative number of threads makes no sense. However, a pool with zero threads also makes no sense, yet zero is a perfectly valid `u32`. Let's check that `size` is greater than zero before we return a `ThreadPool` instance and panic if we get zero by using the `assert!` macro as shown in Listing 20-13:

Filename: src/lib.rs

```
impl ThreadPool {
    /// Create a new ThreadPool.
    ///
    /// The size is the number of threads in the pool.
    ///
    /// # Panics
    ///
    /// The `new` function will panic if the size is zero.
    pub fn new(size: u32) -> ThreadPool {
        assert!(size > 0);

        ThreadPool
    }

    // ...snip...
}
```

Listing 20-13: Implementing `ThreadPool::new` to panic if `size` is zero

We've taken this opportunity to add some documentation for our `ThreadPool` with doc comments. Note that we followed good documentation practices and added a section that calls out the situations in which our function can panic as we discussed in Chapter 14. Try running `cargo doc --open` and clicking on the `ThreadPool` struct to see what the generate docs for `new` look like!

Instead of adding the use of the `assert!` macro as we've done here, we could make `new` return a `Result` instead like we did with `Config::new` in the I/O project in Listing 12-9, but we've decided in this case that trying to create a thread pool without any threads should be an unrecoverable error. If you're feeling ambitious, try to write a version of `new` with this signature to see how you feel about both versions:

```
fn new(size: u32) -> Result<ThreadPool, PoolCreationError> {
```

Storing Threads in the Pool

Now that we know we have a valid number of threads to store in the pool, we can actually create that many threads and store them in the `ThreadPool` struct before returning it.

This raises a question: how do we "store" a thread? Let's take another look at the signature of `thread::spawn`:

```
pub fn spawn<F, T>(f: F) -> JoinHandle<T>
    where
        F: FnOnce() -> T + Send + 'static,
        T: Send + 'static
```

`spawn` returns a `JoinHandle<T>`, where `T` is the type that's returned from the closure. Let's try using `JoinHandle` too and see what happens. In our case, the closures we're passing to the thread pool will handle the connection and not return anything, so `T` will be the unit type `()`.

This won't compile yet, but let's consider the code shown in Listing 20-14. We've changed the definition of `ThreadPool` to hold a vector of `thread::JoinHandle<()>` instances, initialized the vector with a capacity of `size`, set up a `for` loop that will run some code to create the threads, and returned a `ThreadPool` instance containing them:

Filename: src/lib.rs

```
use std::thread;

pub struct ThreadPool {
    threads: Vec<thread::JoinHandle<()>>,
}

impl ThreadPool {
    // ...snip...
    pub fn new(size: u32) -> ThreadPool {
        assert!(size > 0);

        let mut threads = Vec::with_capacity(size);

        for _ in 0..size {
            // create some threads and store them in the vector
        }

        ThreadPool {
            threads
        }
    }

    // ...snip...
}
```

Listing 20-14: Creating a vector for `ThreadPool` to hold the threads

We've brought `std::thread` into scope in the library crate, since we're using `thread::JoinHandle` as the type of the items in the vector in `ThreadPool`.

After we have a valid size, we're creating a new vector that can hold `size` items. We haven't used `with_capacity` in this book yet; it does the same thing as `Vec::new`, but with an important difference: it pre-allocates space in the vector. Since we know that we need to store `size` elements in the vector, doing this allocation up-front is slightly more efficient than only writing `Vec::new`, since `Vec::new` resizes itself as elements get inserted. Since we've created a vector the exact size that we need up front, no resizing of the underlying vector will happen while we populate the items.

That is, if this code works, which it doesn't quite yet! If we check this code, we get an error:

```
$ cargo check
   Compiling hello v0.1.0 (file:///projects/hello)
error[E0308]: mismatched types
  --> src\main.rs:70:46
   |
70 |         let mut threads = Vec::with_capacity(size);
   |                                              ^^^^ expected usize, found u32

error: aborting due to previous error
```

`size` is a `u32`, but `Vec::with_capacity` needs a `usize`. We have two options here: we can change our function's signature, or we can cast the `u32` as a `usize`. If you remember when we defined `new`, we didn't think too hard about what number type made sense, we just chose one. Let's give it some more thought now. Given that `size` is the length of a vector, `usize` makes a lot of sense. They even almost share a name! Let's change the signature of `new`, which will get the code in Listing 20-14 to compile:

```
fn new(size: usize) -> ThreadPool {
```

If run `cargo check` again, you'll get a few more warnings, but it should succeed.

We left a comment in the `for` loop in Listing 20-14 regarding the creation of threads. How do we actually create threads? This is a tough question. What should go in these threads? We don't know what work they need to do at this point, since the `execute` method takes the closure and gives it to the pool.

Let's refactor slightly: instead of storing a vector of `JoinHandle<()>` instances, let's create a new struct to represent the concept of a *worker*. A worker will be what receives a closure in the `execute` method, and it will take care of actually calling the closure. In addition to letting us store a fixed `size` number of `Worker` instances that don't yet know about the closures they're going to be executing, we can also give each worker an `id` so we can tell the different workers in the pool apart when logging or debugging.

Let's make these changes:

1. Define a `Worker` struct that holds an `id` and a `JoinHandle<()>`
2. Change `ThreadPool` to hold a vector of `Worker` instances
3. Define a `Worker::new` function that takes an `id` number and returns a `Worker` instance with that `id` and a thread spawned with an empty closure, which we'll fix soon
4. In `ThreadPool::new`, use the `for` loop counter to generate an `id`, create a new `Worker` with that `id`, and store the worker in the vector

If you're up for a challenge, try implementing these changes on your own before taking a look at the code in Listing 20-15.

Ready? Here's Listing 20-15 with one way to make these modifications:

Filename: src/lib.rs

```
use std::thread;

pub struct ThreadPool {
    workers: Vec<Worker>,
}

impl ThreadPool {
    // ...snip...
    pub fn new(size: usize) -> ThreadPool {
        assert!(size > 0);

        let mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id));
        }

        ThreadPool {
            workers
        }
    }
    // ...snip...
}

struct Worker {
    id: usize,
    thread: thread::JoinHandle<()>,
}

impl Worker {
    fn new(id: usize) -> Worker {
        let thread = thread::spawn(|| {});

        Worker {
            id,
            thread,
        }
    }
}
```

Listing 20-15: Modifying `ThreadPool` to hold `Worker` instances instead of threads directly

We've chosen to change the name of the field on `ThreadPool` from `threads` to `workers` since we've changed what we're holding, which is now `Worker` instances instead of `JoinHandle<()>` instances. We use the counter in the `for` loop as an argument to `Worker::new`, and we store each new `Worker` in the vector named `workers`.

The `Worker` struct and its `new` function are private since external code (like our server in *src/bin/main.rs*) doesn't need to know the implementation detail that we're using a `Worker` struct within `ThreadPool`. The `Worker::new` function uses the given `id` and stores a `JoinHandle<()>` created by spawning a new thread using an empty closure.

This code compiles and is storing the number of `Worker` instances that we specified as an argument to `ThreadPool::new`, but we're *still* not processing the closure that we get in `execute`. Let's talk about how to do that next.

Sending Requests to Threads Via Channels

The next problem to tackle is that our closures do absolutely nothing. We've been working around the problem that we get the actual closure we want to execute in the `execute` method, but it feels like we need to know the actual closures when we create the `ThreadPool`.

Let's think about what we really want to do though: we want the `Worker` structs that we just created to fetch jobs from a queue that the `ThreadPool` holds, and run those jobs in a thread.

In Chapter 16, we learned about channels. Channels are a great way to communicate between two threads, and they're perfect for this use-case. The channel will function as the queue of jobs, and `execute` will send a job from the `ThreadPool` to the `Worker` instances that are checking for jobs in the thread they've spawned. Here's the plan:

1. `ThreadPool` will create a channel and hold on to the sending side.
2. Each `Worker` will hold on to the receiving side of the channel.
3. A new `Job` struct will hold the closures we want to send down the channel.
4. The `execute` method of `ThreadPool` will send the job it wants to execute down the sending side of the channel.
5. In a thread, the `Worker` will loop over its receiving side of the channel and execute the closures of any jobs it receives.

Let's start by creating a channel in `ThreadPool::new` and holding the sending side in the `ThreadPool` instance, as shown in Listing 20-16. `Job` is the type of item we're going to be sending down the channel; it's a struct that doesn't hold anything for now:

Filename: src/lib.rs

```
// ...snip...
use std::sync::mpsc;

pub struct ThreadPool {
    workers: Vec<Worker>,
    sender: mpsc::Sender<Job>,
}

struct Job;

impl ThreadPool {
    // ...snip...
    pub fn new(size: usize) -> ThreadPool {
        assert!(size > 0);

        let (sender, receiver) = mpsc::channel();

        let mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id));
        }

        ThreadPool {
            workers,
            sender,
        }
    }
    // ...snip...
}
```

Listing 20-16: Modifying `ThreadPool` to store the sending end of a channel that sends `Job` instances

In `ThreadPool::new`, we create our new channel, and then have the pool hang on to the sending end. This will successfully compile, still with warnings.

Let's try passing a receiving end of the channel into each worker when the thread pool creates them. We know we want to use the receiving end of the channel in the thread that the workers spawn, so we're going to reference the `receiver` parameter in the closure. The code shown here in Listing 20-17 won't quite compile yet:

Filename: src/lib.rs

```rust
impl ThreadPool {
    // ...snip...
    pub fn new(size: usize) -> ThreadPool {
        assert!(size > 0);

        let (sender, receiver) = mpsc::channel();

        let mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id, receiver));
        }

        ThreadPool {
            workers,
            sender,
        }
    }
    // ...snip...
}

// ...snip...

impl Worker {
    fn new(id: usize, receiver: mpsc::Receiver<Job>) -> Worker {
        let thread = thread::spawn(|| {
            receiver;
        });

        Worker {
            id,
            thread,
        }
    }
}
```

Listing 20-17: Passing the receiving end of the channel to the workers

These are small and straightforward changes: we pass in the receiving end of the channel into `Worker::new`, and then we use it inside of the closure.

If we try to check this, we get this error:

```
$ cargo check
   Compiling hello v0.1.0 (file:///projects/hello)
error[E0382]: use of moved value: `receiver`
  --> src/lib.rs:27:42
   |
27 |             workers.push(Worker::new(id, receiver));
   |                                          ^^^^^^^^ value moved here in
   previous iteration of loop
   |
   = note: move occurs because `receiver` has type
   `std::sync::mpsc::Receiver<Job>`, which does not implement the `Copy` trait
```

The code as written won't quite work since it's trying to pass `receiver` to multiple `Worker` instances. Recall from Chapter 16 that the channel implementation provided by Rust is multiple *producer*, single *consumer*, so we can't just clone the consuming end of the channel to fix this. We also don't want to clone the consuming end even if we wanted to; sharing the single `receiver` between all of the workers is the mechanism by which we'd like to distribute the jobs across the threads.

Additionally, taking a job off the channel queue involves mutating `receiver`, so the threads need a safe way to share `receiver` and be allowed to modify it. If the modifications weren't threadsafe, we might get race conditions such as two threads executing the same job if they both take the same job off the queue at the same time.

So remembering the threadsafe smart pointers that we discussed in Chapter 16, in order to share ownership across multiple threads and allow the threads to mutate the value, we need to use `Arc<Mutex<T>>`. `Arc` will let multiple workers own the receiver, and `Mutex` will make sure that only one worker is getting a job from the receiver at a time. Listing 20-18 shows the changes we need to make:

Filename: src/lib.rs

```
use std::sync::Arc;
use std::sync::Mutex;

// ...snip...

impl ThreadPool {
    // ...snip...
    pub fn new(size: usize) -> ThreadPool {
        assert!(size > 0);

        let (sender, receiver) = mpsc::channel();

        let receiver = Arc::new(Mutex::new(receiver));

        let mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id, Arc::clone(&receiver)));
        }

        ThreadPool {
            workers,
            sender,
        }
    }

    // ...snip...
}
impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
        // ...snip...
    }
}
```

Listing 20-18: Sharing the receiving end of the channel between the workers by using `Arc` and `Mutex`

In `ThreadPool::new`, we put the receiving end of the channel in an `Arc` and a `Mutex`. For each new worker, we clone the `Arc` to bump the reference count so the workers can share ownership of the receiving end.

With these changes, the code compiles! We're getting there!

Let's finally implement the `execute` method on `ThreadPool`. We're also going to change the `Job` struct: instead of being a struct, `Job` is going to be a type alias for a trait object that holds the type of closure that `execute` receives. We discussed how type aliases can help make long types shorter, and this is such a case! Take a look at Listing 20-19:

Filename: src/lib.rs

```
// ...snip...

type Job = Box<FnOnce() + Send + 'static>;

impl ThreadPool {
    // ...snip...

    pub fn execute<F>(&self, f: F)
        where
            F: FnOnce() + Send + 'static
    {
        let job = Box::new(f);

        self.sender.send(job).unwrap();
    }
}

// ...snip...
```

Listing 20-19: Creating a `Job` type alias for a `Box` that holds each closure, then sending the job down the channel

After creating a new `Job` instance using the closure we get in `execute`, we send that job down the sending end of the channel. We're calling `unwrap` on `send` since sending may fail if the receiving end has stopped receiving new messages, which would happen if we stop all of our threads from executing. This isn't possible right now, though, since our threads continue executing as long as the pool exists. We use `unwrap` since we know the failure case won't happen even though the compiler can't tell that, which is an appropriate use of `unwrap` as we discussed in Chapter 9.

Are we done yet? Not quite! In the worker, we've still got a closure being passed to `thread::spawn` that only *references* the receiving end of the channel. Instead, we need the closure to loop forever, asking the receiving end of the channel for a job, and running the job when it gets one. Let's make the change shown in Listing 20-20 to `Worker::new`:

Filename: src/lib.rs

```
// ...snip...

impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
        let thread = thread::spawn(move || {
            loop {
                let job = receiver.lock().unwrap().recv().unwrap();

                println!("Worker {} got a job; executing.", id);

                (*job)();
            }
        });

        Worker {
            id,
            thread,
        }
    }
}
```

Listing 20-20: Receiving and executing the jobs in the worker's thread

Here, we first call `lock` on the `receiver` to acquire the mutex, then `unwrap` to panic on any errors. Acquiring a lock might fail if the mutex is in a state called *poisoned*, which can happen if some other thread panicked while holding the lock rather than releasing it. If this thread can't get the lock for that reason, calling `unwrap` to have this thread panic is the correct action to take as well. Feel free to change this `unwrap` to an `expect` with an error message that is meaningful to you if you'd like.

If we get the lock on the mutex, then we call `recv` to receive a `Job` from the channel. A final `unwrap` moves past those errors as well. `recv` will return `Err` if the thread holding the sending side of the channel has shut down, similar to how the `send` method returns `Err` if the receiving side shuts down.

The call to `recv` blocks; that is, if there's no job yet, this thread will sit here until a job becomes available. The `Mutex<T>` makes sure that only one `Worker` thread at a time is trying to request a job.

Theoretically, this code should compile. Unfortunately, the Rust compiler isn't perfect yet, and we get this error:

```
error[E0161]: cannot move a value of type std::ops::FnOnce() +
std::marker::Send: the size of std::ops::FnOnce() + std::marker::Send cannot be
statically determined
  --> src/lib.rs:63:17
   |
63 |                 (*job)();
   |                 ^^^^^^
```

This error is fairly cryptic, and that's because the problem is fairly cryptic. In order to call a `FnOnce` closure that is stored in a `Box<T>` (which is what our `Job` type alias is), the closure needs to be able to move itself out of the `Box<T>` since when we call the closure, it takes ownership of `self`. In general, moving a value out of a `Box<T>` isn't allowed since Rust doesn't know how big the value inside the `Box<T>` is going to be; recall in Chapter 15 that we used `Box<T>` precisely because we had something of an unknown size that we wanted to store in a `Box<T>` to get a value of a known size.

We saw in Chapter 17, Listing 17-15 that we can write methods that use the syntax `self: Box<Self>` so that the method takes ownership of a `Self` value that is stored in a `Box<T>`. That's what we want to do here, but unfortunately the part of Rust that implements what happens when we call a closure isn't implemented using `self: Box<Self>`. So Rust doesn't yet understand that it could use `self: Box<Self>` in this situation in order to take ownership of the closure and move the closure out of the `Box<T>`.

In the future, the code in Listing 20-20 should work just fine. Rust is still a work in progress with places that the compiler could be improved. There are people just like you working to fix this and other issues! Once you've finished the book, we would love for you to join in.

But for now, let's work around this problem. Luckily, there's a trick that involves telling Rust explicitly that we're in a case where we can take ownership of the value inside the `Box<T>` using `self: Box<Self>`, and once we have ownership of the closure, we can call it. This involves defining a new trait that has a method `call_box` that uses `self: Box<Self>` in its signature, defining that trait for any type that implements `FnOnce()`, changing our type alias to use the new trait, and changing `Worker` to use the `call_box` method. These changes are shown in Listing 20-21:

Filename: src/lib.rs

```
trait FnBox {
    fn call_box(self: Box<Self>);
}

impl<F: FnOnce()> FnBox for F {
    fn call_box(self: Box<F>) {
        (*self)()
    }
}

type Job = Box<FnBox + Send + 'static>;

// ...snip...

impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
        let thread = thread::spawn(move || {
            loop {
                let job = receiver.lock().unwrap().recv().unwrap();

                println!("Worker {} got a job; executing.", id);

                job.call_box();
            }
        });

        Worker {
            id,
            thread,
        }
    }
}
```

Listing 20-21: Adding a new trait `FnBox` to work around the current limitations of `Box<FnOnce()>`

First, we create a new trait named `FnBox`. This trait has one method, `call_box`, similar to the `call` methods on the other `Fn*` traits, except this method takes `self: Box<Self>` in order to take ownership of `self` and move the value out of the `Box<T>`.

Next, we implement the `FnBox` trait for any type `F` that implements the `FnOnce()` trait. Effectively, this means that any `FnOnce()` closures can use our `call_box` method. The implementation of `call_box` uses `(*self)()` to move the closure out of the `Box<T>` and call the closure.

Instead of `FnOnce()`, we now want our `Job` type alias to be a `Box` of anything that implements our new trait `FnBox`. This will allow us to use `call_box` in `Worker` when we get a `Job` value. Because we implemented the `FnBox` trait for any `FnOnce()` closure, we don't have to change anything about the actual values we're sending down the channel.

Finally, in the closure run in the thread in `Worker::new`, we use `call_box` instead of invoking the closure directly. Now Rust is able to understand that what we want to do is fine.

This is a very sneaky, complicated trick. Don't worry too much if it doesn't make perfect sense; someday, it will be completely unnecessary.

With this trick, our thread pool is in a working state! Give it a `cargo run`, and make some requests:

```
$ cargo run
   Compiling hello v0.1.0 (file:///projects/hello)
warning: field is never used: `workers`
 --> src/lib.rs:7:5
  |
7 |     workers: Vec<Worker>,
  |     ^^^^^^^^^^^^^^^^^^^^
  |
  = note: #[warn(dead_code)] on by default

warning: field is never used: `id`
  --> src/lib.rs:61:5
   |
61 |     id: usize,
   |     ^^^^^^^^^
   |
   = note: #[warn(dead_code)] on by default

warning: field is never used: `thread`
  --> src/lib.rs:62:5
   |
62 |     thread: thread::JoinHandle<()>,
   |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
   |
   = note: #[warn(dead_code)] on by default

    Finished dev [unoptimized + debuginfo] target(s) in 0.99 secs
     Running `target/debug/hello`
     Worker 0 got a job; executing.
Worker 2 got a job; executing.
Worker 1 got a job; executing.
Worker 3 got a job; executing.
Worker 0 got a job; executing.
Worker 2 got a job; executing.
Worker 1 got a job; executing.
Worker 3 got a job; executing.
Worker 0 got a job; executing.
Worker 2 got a job; executing.
```

Success! We now have a thread pool executing connections asynchronously. We never create more than four threads, so our system won't get overloaded if the server gets a lot of requests.

If we make a request to `/sleep`, the server will be able to serve other requests by having another thread run them.

What about those warnings, though? Don't we use the `workers`, `id`, and `thread` fields? Well, right now, we're using all three of these fields to hold onto some data, but we don't actually *do* anything with the data once we've set up the thread pool and started running the code that sends jobs down the channel to the threads. If we didn't hold onto these values, though, they'd go out of scope: for example, if we didn't return the `Vec<Worker>` value as part of the `ThreadPool`, the vector would get cleaned up at the end of `ThreadPool::new`.

So are these warnings wrong? In one sense yes, the warnings are wrong, since we are using the fields to store data we need to keep around. In another sense, no, the warnings aren't wrong, and they're telling us that we've forgotten to do something: we never do anything to clean up our thread pool once it's done being used, we just use CTRL-C to stop the program and let the operating system clean up after us. Let's implement a graceful shutdown that cleans up everything we've created instead.

Graceful Shutdown and Cleanup

The code in Listing 20-21 is responding to requests asynchronously through the use of a thread pool, as we intended. We get some warnings about fields that we're not using in a direct way, which are a reminder that we're not cleaning anything up. When we use CTRL-C to halt the main thread, all the other threads are stopped immediately as well, even if they're in the middle of serving a request.

We're now going to implement the `Drop` trait for `ThreadPool` to call `join` on each of the threads in the pool so that the threads will finish the requests they're working on. Then we'll implement a way for the `ThreadPool` to tell the threads they should stop accepting new requests and shut down. To see this code in action, we'll modify our server to only accept two requests before gracefully shutting down its thread pool.

Let's start with implementing `Drop` for our thread pool. When the pool is dropped, we should join on all of our threads to make sure they finish their work. Listing 20-22 shows a first attempt at a `Drop` implementation; this code won't quite work yet:

Filename: src/lib.rs

```
impl Drop for ThreadPool {
    fn drop(&mut self) {
        for worker in &mut self.workers {
            println!("Shutting down worker {}", worker.id);

            worker.thread.join().unwrap();
        }
    }
}
```

Listing 20-22: Joining each thread when the thread pool goes out of scope

We loop through each of the thread pool `workers`, using `&mut` because `self` is itself a mutable reference and we also need to be able to mutate `worker`. We print out a message saying that this particular worker is shutting down, and then we call `join` on that worker's thread. If the call to `join` fails, we `unwrap` the error to panic and go into an ungraceful shutdown.

Here's the error we get if we compile this code:

```
error[E0507]: cannot move out of borrowed content
  --> src/lib.rs:65:13
   |
65 |             worker.thread.join().unwrap();
   |             ^^^^^^ cannot move out of borrowed content
```

Because we only have a mutable borrow of each `worker`, we can't call `join`: `join` takes ownership of its argument. In order to solve this, we need a way to move the `thread` out of the `Worker` instance that owns `thread` so that `join` can consume the thread. We saw a way to do this in Listing 17-15: if the `Worker` holds an `Option<thread::JoinHandle<()>` instead, we can call the `take` method on the `Option` to move the value out of the `Some` variant and leave a `None` variant in its place. In other words, a `Worker` that is running will have a `Some` variant in `thread`, and when we want to clean up a worker, we'll replace `Some` with `None` so the worker doesn't have a thread to run.

So we know we want to update the definition of `Worker` like this:

Filename: src/lib.rs

```
struct Worker {
    id: usize,
    thread: Option<thread::JoinHandle<()>>,
}
```

Now let's lean on the compiler to find the other places that need to change. We get two errors:

```
error: no method named `join` found for type
`std::option::Option<std::thread::JoinHandle<()>>` in the current scope
  --> src/lib.rs:65:27
   |
65 |             worker.thread.join().unwrap();
   |                           ^^^^

error[E0308]: mismatched types
  --> src/lib.rs:89:21
   |
89 |             thread,
   |             ^^^^^^ expected enum `std::option::Option`, found
   struct `std::thread::JoinHandle`
   |
   = note: expected type `std::option::Option<std::thread::JoinHandle<()>>`
              found type `std::thread::JoinHandle<_>`
```

The second error is pointing to the code at the end of `Worker::new`; we need to wrap the `thread` value in `Some` when we create a new `Worker`:

Filename: src/lib.rs

```
impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
        // ...snip...

        Worker {
            id,
            thread: Some(thread),
        }
    }
}
```

The first error is in our `Drop` implementation, and we mentioned that we'll be calling `take` on the `Option` value to move `thread` out of `worker`. Here's what that looks like:

Filename: src/lib.rs

```
impl Drop for ThreadPool {
    fn drop(&mut self) {
        for worker in &mut self.workers {
            println!("Shutting down worker {}", worker.id);

            if let Some(thread) = worker.thread.take() {
                thread.join().unwrap();
            }
        }
    }
}
```

As we saw in Chapter 17, the `take` method on `Option` takes the `Some` variant out and leaves `None` in its place. We're using `if let` to destructure the `Some` and get the thread, then call `join` on the thread. If a worker's thread is already `None`, then we know this worker has already had its thread cleaned up so we don't do anything in that case.

With this, our code compiles without any warnings. Bad news though, this code doesn't function the way we want it to yet. The key is the logic in the closures that the spawned threads of the `Worker` instances run: calling `join` won't shut down the threads since they `loop` forever looking for jobs. If we try to drop our `ThreadPool` with this implementation, the main thread will block forever waiting for the first thread to finish.

To fix this, we're going to modify the threads to listen for either a `Job` to run or a signal that they should stop listening and exit the infinite loop. So instead of `Job` instances, our channel will send one of these two enum variants:

Filename: src/lib.rs

```
enum Message {
    NewJob(Job),
    Terminate,
}
```

This `Message` enum will either be a `NewJob` variant that holds the `Job` the thread should run, or it will be a `Terminate` variant that will cause the thread to exit its loop and stop.

We need to adjust the channel to use values of type `Message` rather than type `Job`, as shown in Listing 20-23:

Filename: src/lib.rs

```
pub struct ThreadPool {
    workers: Vec<Worker>,
    sender: mpsc::Sender<Message>,
}

// ...snip...

impl ThreadPool {
    // ...snip...
    pub fn new(size: usize) -> ThreadPool {
        assert!(size > 0);

        let (sender, receiver) = mpsc::channel();

        // ...snip...
    }

    pub fn execute<F>(&self, f: F)
        where
            F: FnOnce() + Send + 'static
    {
        let job = Box::new(f);

        self.sender.send(Message::NewJob(job)).unwrap();
    }
}

// ...snip...

impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Message>>>) ->
        Worker {

        let thread = thread::spawn(move ||{
            loop {
                let message = receiver.lock().unwrap().recv().unwrap();

                match message {
                    Message::NewJob(job) => {
                        println!("Worker {} got a job; executing.", id);

                        job.call_box();
                    },
                    Message::Terminate => {
                        println!("Worker {} was told to terminate.", id);

                        break;
                    },
                }
            }
        });

        Worker {
            id,
```

```
            thread: Some(thread),
        }
    }
}
```

Listing 20-23: Sending and receiving `Message` values and exiting the loop if a `Worker` receives `Message::Terminate`

We need to change `Job` to `Message` in the definition of `ThreadPool`, in `ThreadPool::new` where we create the channel, and in the signature of `Worker::new`. The `execute` method of `ThreadPool` needs to send jobs wrapped in the `Message::NewJob` variant. Then, in `Worker::new` where we receive a `Message` from the channel, we'll process the job if we get the `NewJob` variant and break out of the loop if we get the `Terminate` variant.

With these changes, the code will compile again and continue to function in the same way as it has been. We'll get a warning, though, because we aren't using the `Terminate` variant in any messages. Let's change our `Drop` implementation to look like Listing 20-24:

Filename: src/lib.rs

```
impl Drop for ThreadPool {
    fn drop(&mut self) {
        println!("Sending terminate message to all workers.");

        for _ in &mut self.workers {
            self.sender.send(Message::Terminate).unwrap();
        }

        println!("Shutting down all workers.");

        for worker in &mut self.workers {
            println!("Shutting down worker {}", worker.id);

            if let Some(thread) = worker.thread.take() {
                thread.join().unwrap();
            }
        }
    }
}
```

Listing 20-24: Sending `Message::Terminate` to the workers before calling `join` on each worker thread

We're now iterating over the workers twice, once to send one `Terminate` message for each worker, and once to call `join` on each worker's thread. If we tried to send a message and join immediately in the same loop, it's not guaranteed that the worker in the current iteration will be the one that gets the message from the channel.

To understand better why we need two separate loops, imagine a scenario with two workers. If we iterated through each worker in one loop, on the first iteration where `worker` is the first worker, we'd send a terminate message down the channel and call `join` on the first worker's thread. If the first worker was busy processing a request at that moment, the second worker would pick up the terminate message from the channel and shut down. We're waiting on the first worker to shut down, but it never will since the second thread picked up the terminate message. We're now blocking forever waiting for the first worker to shut down, and we'll never send the second message to terminate. Deadlock!

To prevent this, we first put all of our `Terminate` messages on the channel, and then we join on all the threads. Because each worker will stop receiving requests on the channel once it gets a terminate message, we can be sure that if we send the same number of terminate messages as there are workers, each worker will receive a terminate message before we call `join` on its thread.

In order to see this code in action, let's modify `main` to only accept two requests before gracefully shutting the server down as shown in Listing 20-25:

Filename: src/bin/main.rs

```
fn main() {
    let listener = TcpListener::bind("127.0.0.1:8080").unwrap();
    let pool = ThreadPool::new(4);

    for stream in listener.incoming().take(2) {
        let stream = stream.unwrap();

        pool.execute(|| {
            handle_connection(stream);
        });
    }

    println!("Shutting down.");
}
```

Listing 20-25: Shut down the server after serving two requests by exiting the loop

Only serving two requests isn't behavior you'd like a production web server to have, but this will let us see the graceful shutdown and cleanup working since we won't be stopping the server with CTRL-C.

The `.take(2)` we added to `listener.incoming()` artificially limits the iteration to the first 2 items at most. This combinator works for any implementation of the `Iterator` trait. The `ThreadPool` will go out of scope at the end of `main`, and we'll see the `drop` implementation run.

Start the server with `cargo run`, and make three requests. The third request should error, and in your terminal you should see output that looks like:

```
$ cargo run
   Compiling hello v0.1.0 (file:///projects/hello)
    Finished dev [unoptimized + debuginfo] target(s) in 1.0 secs
     Running `target/debug/hello`
Worker 0 got a job; executing.
Worker 3 got a job; executing.
Shutting down.
Sending terminate message to all workers.
Shutting down all workers.
Shutting down worker 0
Worker 1 was told to terminate.
Worker 2 was told to terminate.
Worker 0 was told to terminate.
Worker 3 was told to terminate.
Shutting down worker 1
Shutting down worker 2
Shutting down worker 3
```

You may get a different ordering, of course. We can see how this works from the messages: workers zero and three got the first two requests, and then on the third request, we stop accepting connections. When the `ThreadPool` goes out of scope at the end of `main`, its `Drop` implementation kicks in, and the pool tells all workers to terminate. The workers each print a message when they see the terminate message, and then the thread pool calls `join` to shut down each worker thread.

One interesting aspect of this particular execution: notice that we sent the terminate messages down the channel, and before any worker received the messages, we tried to join worker zero. Worker zero had not yet gotten the terminate message, so the main thread blocked waiting for worker zero to finish. In the meantime, each of the workers received the termination messages. Once worker zero finished, the main thread waited for the rest of the workers to finish, and they had all received the termination message and were able to shut down at that point.

Congrats! We now have completed our project, and we have a basic web server that uses a thread pool to respond asynchronously. We're able to perform a graceful shutdown of the server, which cleans up all the threads in the pool. Here's the full code for reference:

Filename: src/bin/main.rs

```
extern crate hello;
use hello::ThreadPool;

use std::io::prelude::*;
use std::net::TcpListener;
use std::net::TcpStream;
use std::fs::File;
use std::thread;
use std::time::Duration;

fn main() {
    let listener = TcpListener::bind("127.0.0.1:8080").unwrap();
    let pool = ThreadPool::new(4);

    for stream in listener.incoming().take(2) {
        let stream = stream.unwrap();

        pool.execute(|| {
            handle_connection(stream);
        });
    }

    println!("Shutting down.");
}

fn handle_connection(mut stream: TcpStream) {
    let mut buffer = [0; 512];
    stream.read(&mut buffer).unwrap();

    let get = b"GET / HTTP/1.1\r\n";
    let sleep = b"GET /sleep HTTP/1.1\r\n";

    let (status_line, filename) = if buffer.starts_with(get) {
        ("HTTP/1.1 200 OK\r\n\r\n", "hello.html")
    } else if buffer.starts_with(sleep) {
        thread::sleep(Duration::from_secs(5));
        ("HTTP/1.1 200 OK\r\n\r\n", "hello.html")
    } else {
        ("HTTP/1.1 404 NOT FOUND\r\n\r\n", "404.html")
    };

     let mut file = File::open(filename).unwrap();
     let mut contents = String::new();

     file.read_to_string(&mut contents).unwrap();

     let response = format!("{}{}", status_line, contents);

     stream.write(response.as_bytes()).unwrap();
     stream.flush().unwrap();
}
```

Filename: src/lib.rs

```
use std::thread;
use std::sync::mpsc;
use std::sync::Arc;
use std::sync::Mutex;

enum Message {
    NewJob(Job),
    Terminate,
}

pub struct ThreadPool {
    workers: Vec<Worker>,
    sender: mpsc::Sender<Message>,
}

trait FnBox {
    fn call_box(self: Box<Self>);
}

impl<F: FnOnce()> FnBox for F {
    fn call_box(self: Box<F>) {
        (*self)()
    }
}

type Job = Box<FnBox + Send + 'static>;

impl ThreadPool {
    /// Create a new ThreadPool.
    ///
    /// The size is the number of threads in the pool.
    ///
    /// # Panics
    ///
    /// The `new` function will panic if the size is zero.
    pub fn new(size: usize) -> ThreadPool {
        assert!(size > 0);

        let (sender, receiver) = mpsc::channel();

        let receiver = Arc::new(Mutex::new(receiver));

        let mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id, Arc::clone(&receiver)));
        }

        ThreadPool {
            workers,
            sender,
        }
    }
```

```
    pub fn execute<F>(&self, f: F)
        where
            F: FnOnce() + Send + 'static
    {
        let job = Box::new(f);

        self.sender.send(Message::NewJob(job)).unwrap();
    }
}

impl Drop for ThreadPool {
    fn drop(&mut self) {
        println!("Sending terminate message to all workers.");

        for _ in &mut self.workers {
            self.sender.send(Message::Terminate).unwrap();
        }

        println!("Shutting down all workers.");

        for worker in &mut self.workers {
            println!("Shutting down worker {}", worker.id);

            if let Some(thread) = worker.thread.take() {
                thread.join().unwrap();
            }
        }
    }
}

struct Worker {
    id: usize,
    thread: Option<thread::JoinHandle<()>>,
}

impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Message>>>) ->
        Worker {

        let thread = thread::spawn(move ||{
            loop {
                let message = receiver.lock().unwrap().recv().unwrap();

                match message {
                    Message::NewJob(job) => {
                        println!("Worker {} got a job; executing.", id);

                        job.call_box();
                    },
                    Message::Terminate => {
                        println!("Worker {} was told to terminate.", id);

                        break;
```

```
                },
            }
        }
    });

    Worker {
        id,
        thread: Some(thread),
    }
  }
}
```

There's more we could do here! If you'd like to continue enhancing this project, here are some ideas:

- Add more documentation to `ThreadPool` and its public methods
- Add tests of the library's functionality
- Change calls to `unwrap` to more robust error handling
- Use `ThreadPool` to perform some other task rather than serving web requests
- Find a thread pool crate on crates.io and implement a similar web server using the crate instead and compare its API and robustness to the thread pool we implemented

Summary

Well done! You've made it to the end of the book! We'd like to thank you for joining us on this tour of Rust. You're now ready to go out and implement your own Rust projects or help with other people's. Remember there's a community of other Rustaceans who would love to help you with any challenges you encounter on your Rust journey.

Appendix

The following sections contain reference material you may find useful in your Rust journey.

Appendix A: Keywords

The following keywords are reserved by the Rust language and may not be used as identifiers such as names of functions, variables, parameters, struct fields, modules, crates, constants, macros, static values, attributes, types, traits, or lifetimes.

Keywords Currently in Use

- `as` - primitive casting, disambiguating the specific trait containing an item, or renaming items in `use` and `extern crate` statements
- `break` - exit a loop immediately
- `const` - constant items and constant raw pointers
- `continue` - continue to the next loop iteration
- `crate` - external crate linkage or a macro variable representing the crate in which the macro is defined
- `else` - fallback for `if` and `if let` control flow constructs
- `enum` - defining an enumeration
- `extern` - external crate, function, and variable linkage
- `false` - boolean false literal
- `fn` - function definition and function pointer type
- `for` - iterator loop, part of trait impl syntax, and higher-ranked lifetime syntax
- `if` - conditional branching
- `impl` - inherent and trait implementation block
- `in` - part of `for` loop syntax
- `let` - variable binding
- `loop` - unconditional, infinite loop
- `match` - pattern matching
- `mod` - module declaration
- `move` - makes a closure take ownership of all its captures
- `mut` - denotes mutability in references, raw pointers, and pattern bindings
- `pub` - denotes public visibility in struct fields, `impl` blocks, and modules
- `ref` - by-reference binding
- `return` - return from function
- `Self` - type alias for the type implementing a trait
- `self` - method subject or current module
- `static` - global variable or lifetime lasting the entire program execution
- `struct` - structure definition
- `super` - parent module of the current module
- `trait` - trait definition
- `true` - boolean true literal
- `type` - type alias and associated type definition
- `unsafe` - denotes unsafe code, functions, traits, and implementations
- `use` - import symbols into scope
- `where` - type constraint clauses
- `while` - conditional loop

Keywords Reserved for Future Use

These keywords do not have any functionality, but are reserved by Rust for potential future use.

- `abstract`
- `alignof`
- `become`
- `box`
- `do`
- `final`
- `macro`
- `offsetof`
- `override`
- `priv`
- `proc`
- `pure`
- `sizeof`
- `typeof`
- `unsized`
- `virtual`
- `yield`

Appendix B: Operators

Unary operator expressions

Rust defines the following unary operators. They are all written as prefix operators, before the expression they apply to.

- `-` : Negation. Signed integer types and floating-point types support negation. It is an error to apply negation to unsigned types; for example, the compiler rejects `-1u32`.
- `*` : Dereference. When applied to a pointer, it denotes the pointed-to location. For pointers to mutable locations, the resulting value can be assigned to. On non-pointer types, it calls the `deref` method of the `std::ops::Deref` trait, or the `deref_mut` method of the `std::ops::DerefMut` trait (if implemented by the type and required for an outer expression that will or could mutate the dereference), and produces the result of dereferencing the `&` or `&mut` borrowed pointer returned from the overload method.
- `!` : Logical negation. On the boolean type, this flips between `true` and `false`. On integer types, this inverts the individual bits in the two's complement representation of the value.
- `&` and `&mut` : Borrowing. When applied to a value, these operators produce a reference (pointer) to that value. The value is also placed into a borrowed state for the duration of

the reference. For a shared borrow (`&`), this implies that the value may not be mutated, but it may be read or shared again. For a mutable borrow (`&mut`), the value may not be accessed in any way until the borrow expires.

Binary operator expressions

Binary operators expressions are given in order of operator precedence.

Arithmetic operators

Binary arithmetic expressions are syntactic sugar for calls to built-in traits, defined in the `std::ops` module of the `std` library. This means arithmetic operators can be overridden for user-defined types. The default meaning of the operators on standard types is given here.

- `+` : Addition and array/string concatenation. Calls the `add` method on the `std::ops::Add` trait.
- `-` : Subtraction. Calls the `sub` method on the `std::ops::Sub` trait.
- `*` : Multiplication. Calls the `mul` method on the `std::ops::Mul` trait.
- `/` : Quotient. Calls the `div` method on the `std::ops::Div` trait.
- `%` : Remainder. Calls the `rem` method on the `std::ops::Rem` trait.

Note that Rust does not have a built-in operator for exponential (power) calculation; see the `pow` method on the numeric types.

Bitwise operators

Like the arithmetic operators, bitwise operators are syntactic sugar for calls to methods of built-in traits. This means bitwise operators can be overridden for user-defined types. The default meaning of the operators on standard types is given here. Bitwise `&`, `|` and `^` applied to boolean arguments are equivalent to logical `&&`, `||` and `!=` evaluated in non-lazy fashion.

- `&` : Bitwise AND. Calls the `bitand` method of the `std::ops::BitAnd` trait.
- `|` : Bitwise inclusive OR. Calls the `bitor` method of the `std::ops::BitOr` trait.
- `^` : Bitwise exclusive OR. Calls the `bitxor` method of the `std::ops::BitXor` trait.
- `<<` : Left shift. Calls the `shl` method of the `std::ops::Shl` trait.
- `>>` : Right shift (arithmetic). Calls the `shr` method of the `std::ops::Shr` trait.

Lazy boolean operators

The operators `||` and `&&` may be applied to operands of boolean type. The `||` operator denotes logical 'or', and the `&&` operator denotes logical 'and'. They differ from `|` and `&` in that the right-hand operand is only evaluated when the left-hand operand does not already determine the result of the expression. That is, `||` only evaluates its right-hand operand when the left-hand operand evaluates to `false`, and `&&` only when it evaluates to `true`.

Comparison operators

Comparison operators are, like the arithmetic operators and bitwise operators, syntactic sugar for calls to built-in traits. This means that comparison operators can be overridden for user-defined types. The default meaning of the operators on standard types is given here.

- `==` : Equal to. Calls the `eq` method on the `std::cmp::PartialEq` trait.
- `!=` : Unequal to. Calls the `ne` method on the `std::cmp::PartialEq` trait.
- `<` : Less than. Calls the `lt` method on the `std::cmp::PartialOrd` trait.
- `>` : Greater than. Calls the `gt` method on the `std::cmp::PartialOrd` trait.
- `<=` : Less than or equal. Calls the `le` method on the `std::cmp::PartialOrd` trait.
- `>=` : Greater than or equal. Calls the `ge` method on the `std::cmp::PartialOrd` trait.

Type cast expressions

A type cast expression is denoted with the binary operator `as`.

Executing an `as` expression casts the value on the left-hand side to the type on the right-hand side.

An example of an `as` expression:

```
fn average(values: &[f64]) -> f64 {
    let sum: f64 = sum(values);
    let size: f64 = len(values) as f64;
    sum / size
}
```

Some of the conversions which can be done through the `as` operator can also be done implicitly at various points in the program, such as argument passing and assignment to a `let` binding with an explicit type. Implicit conversions are limited to “harmless” conversions that do not lose information and which have minimal or no risk of surprising side-effects on the dynamic execution semantics.

Assignment expressions

An *assignment expression* consists of a pattern followed by an equals sign (`=`) and an expression.

Evaluating an assignment expression either copies or moves its right-hand operand to its left-hand operand.

```
# let mut x = 0;
# let y = 0;
x = y;
```

Compound assignment expressions

The `+`, `-`, `*`, `/`, `%`, `&`, `|`, `^`, `<<`, and `>>` operators may be composed with the `=` operator. The expression `lval OP= val` is equivalent to `lval = lval OP val`. For example, `x = x + 1` may be written as `x += 1`.

Any such expression always has the `unit` type.

Operator precedence

The precedence of Rust operators is ordered as follows, going from strong to weak. Binary Operators at the same precedence level are evaluated in the order given by their associativity.

Operator	Associativity
`?`	
Unary `-` `*` `!` `&` `&mut`	
`as` `:`	left to right
`*` `/` `%`	left to right
`+` `-`	left to right
`<<` `>>`	left to right
`&`	left to right
`^`	left to right
`|`	left to right
`==` `!=` `<` `>` `<=` `>=`	Require parentheses
`&&`	left to right
`||`	left to right
`..` `...`	Require parentheses
`<-`	right to left
`=` `+=` `-=` `*=` `/=` `%=` `&=` `|=` `^=` `<<=` `>>=`	right to left

Appendix G - Newest Features

This appendix documents features that have been added to stable Rust since the main part of the book was completed.

Field init shorthand

We can initialize a data structure (struct, enum, union) with named fields, by writing `fieldname` as a shorthand for `fieldname: fieldname`. This allows a compact syntax for initialization, with less duplication:

```
#[derive(Debug)]
struct Person {
    name: String,
    age: u8,
}

fn main() {
    let name = String::from("Peter");
    let age = 27;

    // Using full syntax:
    let peter = Person { name: name, age: age };

    let name = String::from("Portia");
    let age = 27;

    // Using field init shorthand:
    let portia = Person { name, age };

    println!("{:?}", portia);
}
```

Returning from loops

One of the uses of a `loop` is to retry an operation you know can fail, such as checking if a thread completed its job. However, you might need to pass the result of that operation to the rest of your code. If you add it to the `break` expression you use to stop the loop, it will be returned by the broken loop:

```rust
fn main() {
    let mut counter = 0;

    let result = loop {
        counter += 1;

        if counter == 10 {
            break counter * 2;
        }
    };

    assert_eq!(result, 20);
}
```