The Rust Programming Language

by Steve Klabnik, Carol Nichols, and Chris Krycho, with contributions from the Rust Community

This version of the text assumes you're using Rust 1.85.0 (released 2025-02-17) or later with `edition = "2024"` in the Cargo.toml file of all projects to configure them to use Rust 2024 edition idioms. See the "Installation" section of Chapter 1 to install or update Rust.

The HTML format is available online at https://doc.rust-lang.org/stable/book/ and offline with installations of Rust made with `rustup`; run `rustup doc --book` to open.

Several community translations are also available.

This text is available in paperback and ebook format from No Starch Press.

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Foreword

It wasn't always so clear, but the Rust programming language is fundamentally about *empowerment*: no matter what kind of code you are writing now, Rust empowers you to reach farther, to program with confidence in a wider variety of domains than you did before.

Take, for example, "systems-level" work that deals with low-level details of memory management, data representation, and concurrency. Traditionally, this realm of programming is seen as arcane, accessible only to a select few who have devoted the necessary years learning to avoid its infamous pitfalls. And even those who practice it do so with caution, lest their code be open to exploits, crashes, or corruption.

Rust breaks down these barriers by eliminating the old pitfalls and providing a friendly, polished set of tools to help you along the way. Programmers who need to "dip down" into lower-level control can do so with Rust, without taking on the customary risk of crashes or security holes, and without having to learn the fine points of a fickle toolchain. Better yet, the language is designed to guide you naturally towards reliable code that is efficient in terms of speed and memory usage.

Programmers who are already working with low-level code can use Rust to raise their ambitions. For example, introducing parallelism in Rust is a relatively low-risk operation: the compiler will catch the classical mistakes for you. And you can tackle more aggressive optimizations in your code with the confidence that you won't accidentally introduce crashes or vulnerabilities.

But Rust isn't limited to low-level systems programming. It's expressive and ergonomic enough to make CLI apps, web servers, and many other kinds of code quite pleasant to write — you'll find simple examples of both later in the book. Working with Rust allows you to build skills that transfer from one domain to another; you can learn Rust by writing a web app, then apply those same skills to target your Raspberry Pi.

This book fully embraces the potential of Rust to empower its users. It's a friendly and approachable text intended to help you level up not just your knowledge of Rust, but also your reach and confidence as a programmer in general. So dive in, get ready to learn—and welcome to the Rust community!

— Nicholas Matsakis and Aaron Turon

Introduction

> Note: This edition of the book is the same as The Rust Programming Language available in print and ebook format from No Starch Press.

Welcome to *The Rust Programming Language*, an introductory book about Rust. The Rust programming language helps you write faster, more reliable software. High-level ergonomics and low-level control are often at odds in programming language design; Rust challenges that conflict. Through balancing powerful technical capacity and a great developer experience, Rust gives you the option to control low-level details (such as memory usage) without all the hassle traditionally associated with such control.

Who Rust Is For

Rust is ideal for many people for a variety of reasons. Let’s look at a few of the most important groups.

Teams of Developers

Rust is proving to be a productive tool for collaborating among large teams of developers with varying levels of systems programming knowledge. Low-level code is prone to various subtle bugs, which in most other languages can be caught only through extensive testing and careful code review by experienced developers. In Rust, the compiler plays a gatekeeper role by refusing to compile code with these elusive bugs, including concurrency bugs. By working alongside the compiler, the team can spend their time focusing on the program’s logic rather than chasing down bugs.

Rust also brings contemporary developer tools to the systems programming world:

- Cargo, the included dependency manager and build tool, makes adding, compiling, and managing dependencies painless and consistent across the Rust ecosystem.
- The Rustfmt formatting tool ensures a consistent coding style across developers.
- The rust-analyzer powers Integrated Development Environment (IDE) integration for code completion and inline error messages.

By using these and other tools in the Rust ecosystem, developers can be productive while writing systems-level code.

Students

Rust is for students and those who are interested in learning about systems concepts. Using Rust, many people have learned about topics like operating systems development. The community is very welcoming and happy to answer student questions. Through efforts such as this book, the Rust teams want to make systems concepts more accessible to more people, especially those new to programming.

Companies

Hundreds of companies, large and small, use Rust in production for a variety of tasks, including command line tools, web services, DevOps tooling, embedded devices, audio and video analysis and transcoding, cryptocurrencies, bioinformatics, search engines, Internet of Things applications, machine learning, and even major parts of the Firefox web browser.

Open Source Developers

Rust is for people who want to build the Rust programming language, community, developer tools, and libraries. We'd love to have you contribute to the Rust language.

People Who Value Speed and Stability

Rust is for people who crave speed and stability in a language. By speed, we mean both how quickly Rust code can run and the speed at which Rust lets you write programs. The Rust compiler's checks ensure stability through feature additions and refactoring. This is in contrast to the brittle legacy code in languages without these checks, which developers are often afraid to modify. By striving for zero-cost abstractions—higher-level features that compile to lower-level code as fast as code written manually—Rust endeavors to make safe code be fast code as well.

The Rust language hopes to support many other users as well; those mentioned here are merely some of the biggest stakeholders. Overall, Rust's greatest ambition is to eliminate the trade-offs that programmers have accepted for decades by providing safety *and* productivity, speed *and* ergonomics. Give Rust a try and see if its choices work for you.

Who This Book Is For

This book assumes that you’ve written code in another programming language but doesn’t make any assumptions about which one. We’ve tried to make the material broadly accessible to those from a wide variety of programming backgrounds. We don’t spend a lot of time talking about what programming *is* or how to think about it. If you’re entirely new to programming, you would be better served by reading a book that specifically provides an introduction to programming.

How to Use This Book

In general, this book assumes that you're reading it in sequence from front to back. Later chapters build on concepts in earlier chapters, and earlier chapters might not delve into details on a particular topic but will revisit the topic in a later chapter.

You'll find two kinds of chapters in this book: concept chapters and project chapters. In concept chapters, you'll learn about an aspect of Rust. In project chapters, we'll build small programs together, applying what you've learned so far. Chapters 2, 12, and 21 are project chapters; the rest are concept chapters.

Chapter 1 explains how to install Rust, how to write a "Hello, world!" program, and how to use Cargo, Rust's package manager and build tool. Chapter 2 is a hands-on introduction to writing a program in Rust, having you build up a number guessing game. Here we cover concepts at a high level, and later chapters will provide additional detail. If you want to get your hands dirty right away, Chapter 2 is the place for that. Chapter 3 covers Rust features that are similar to those of other programming languages, and in Chapter 4 you'll learn about Rust's ownership system. If you're a particularly meticulous learner who prefers to learn every detail before moving on to the next, you might want to skip Chapter 2 and go straight to Chapter 3, returning to Chapter 2 when you'd like to work on a project applying the details you've learned.

Chapter 5 discusses structs and methods, and Chapter 6 covers enums, `match` expressions, and the `if let` control flow construct. You'll use structs and enums to make custom types in Rust.

In Chapter 7, you'll learn about Rust's module system and about privacy rules for organizing your code and its public Application Programming Interface (API). Chapter 8 discusses some common collection data structures that the standard library provides, such as vectors, strings, and hash maps. Chapter 9 explores Rust's error-handling philosophy and techniques.

Chapter 10 digs into generics, traits, and lifetimes, which give you the power to define code that applies to multiple types. Chapter 11 is all about testing, which even with Rust's safety guarantees is necessary to ensure your program's logic is correct. In Chapter 12, we'll build our own implementation of a subset of functionality from the `grep` command line tool that searches for text within files. For this, we'll use many of the concepts we discussed in the previous chapters.

Chapter 13 explores closures and iterators: features of Rust that come from functional programming languages. In Chapter 14, we'll examine Cargo in more depth and talk about best practices for sharing your libraries with others. Chapter 15 discusses smart pointers that the standard library provides and the traits that enable their functionality.

In Chapter 16, we'll walk through different models of concurrent programming and talk about how Rust helps you to program in multiple threads fearlessly. In Chapter 17, we build on that by exploring Rust's async and await syntax, along with tasks, futures, and streams, and the lightweight concurrency model they enable.

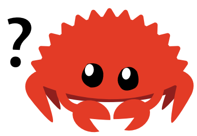
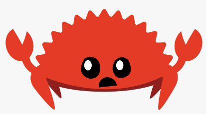
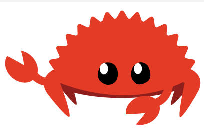
Chapter 18 looks at how Rust idioms compare to object-oriented programming principles you might be familiar with. Chapter 19 is a reference on patterns and pattern matching, which are powerful ways of expressing ideas throughout Rust programs. Chapter 20 contains a smorgasbord of advanced topics of interest, including unsafe Rust, macros, and more about lifetimes, traits, types, functions, and closures.

In Chapter 21, we'll complete a project in which we'll implement a low-level multithreaded web server!

Finally, some appendixes contain useful information about the language in a more reference-like format. **Appendix A** covers Rust's keywords, **Appendix B** covers Rust's operators and symbols, **Appendix C** covers derivable traits provided by the standard library, **Appendix D** covers some useful development tools, and **Appendix E** explains Rust editions. In **Appendix F**, you can find translations of the book, and in **Appendix G** we'll cover how Rust is made and what nightly Rust is.

There is no wrong way to read this book: if you want to skip ahead, go for it! You might have to jump back to earlier chapters if you experience any confusion. But do whatever works for you.

An important part of the process of learning Rust is learning how to read the error messages the compiler displays: these will guide you toward working code. As such, we'll provide many examples that don't compile along with the error message the compiler will show you in each situation. Know that if you enter and run a random example, it may not compile! Make sure you read the surrounding text to see whether the example you're trying to run is meant to error. Ferris will also help you distinguish code that isn't meant to work:

Ferris	Meaning
	This code does not compile!
	This code panics!
	This code does not produce the desired behavior.

In most situations, we'll lead you to the correct version of any code that doesn't compile.

Source Code

The source files from which this book is generated can be found on GitHub.

Getting Started

Let’s start your Rust journey! There’s a lot to learn, but every journey starts somewhere. In this chapter, we’ll discuss:

- Installing Rust on Linux, macOS, and Windows
- Writing a program that prints `Hello, world!`
- Using `cargo`, Rust’s package manager and build system

Installation

The first step is to install Rust. We'll download Rust through `rustup`, a command line tool for managing Rust versions and associated tools. You'll need an internet connection for the download.

> Note: If you prefer not to use `rustup` for some reason, please see the Other Rust Installation Methods page for more options.

The following steps install the latest stable version of the Rust compiler. Rust's stability guarantees ensure that all the examples in the book that compile will continue to compile with newer Rust versions. The output might differ slightly between versions because Rust often improves error messages and warnings. In other words, any newer, stable version of Rust you install using these steps should work as expected with the content of this book.

Command Line Notation

In this chapter and throughout the book, we'll show some commands used in the terminal. Lines that you should enter in a terminal all start with `$`. You don't need to type the `$` character; it's the command line prompt shown to indicate the start of each command. Lines that don't start with `$` typically show the output of the previous command. Additionally, PowerShell-specific examples will use `>` rather than `$`.

Installing `rustup` on Linux or macOS

If you're using Linux or macOS, open a terminal and enter the following command:

```
$ curl --proto '=https' --tlsv1.2 https://sh.rustup.rs -sSf | sh
```

The command downloads a script and starts the installation of the `rustup` tool, which installs the latest stable version of Rust. You might be prompted for your password. If the install is successful, the following line will appear:

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

You will also need a *linker*, which is a program that Rust uses to join its compiled outputs into one file. It is likely you already have one. If you get linker errors, you should install a C compiler, which will typically include a linker. A C compiler is also useful because some common Rust packages depend on C code and will need a C compiler.

On macOS, you can get a C compiler by running:

```
$ xcode-select --install
```

Linux users should generally install GCC or Clang, according to their distribution's documentation. For example, if you use Ubuntu, you can install the `build-essential` package.

Installing `rustup` on Windows

On Windows, go to https://www.rust-lang.org/tools/install and follow the instructions for installing Rust. At some point in the installation, you'll be prompted to install Visual Studio. This provides a linker and the native libraries needed to compile programs. If you need more help with this step, see https://rust-lang.github.io/rustup/installation/windows-msvc.html

The rest of this book uses commands that work in both *cmd.exe* and PowerShell. If there are specific differences, we'll explain which to use.

Troubleshooting

To check whether you have Rust installed correctly, open a shell and enter this line:

```
$ rustc --version
```

You should see the version number, commit hash, and commit date for the latest stable version that has been released, in the following format:

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

If you see this information, you have installed Rust successfully! If you don't see this information, check that Rust is in your `%PATH%` system variable as follows.

In Windows CMD, use:

```
> echo %PATH%
```

In PowerShell, use:

```
> echo $env:Path
```

In Linux and macOS, use:

```
$ echo $PATH
```

If that's all correct and Rust still isn't working, there are a number of places you can get help. Find out how to get in touch with other Rustaceans (a silly nickname we call ourselves) on the community page.

Updating and Uninstalling

Once Rust is installed via `rustup`, updating to a newly released version is easy. From your shell, run the following update script:

```
$ rustup update
```

To uninstall Rust and `rustup`, run the following uninstall script from your shell:

```
$ rustup self uninstall
```

Local Documentation

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

Any time a type or function is provided by the standard library and you're not sure what it does or how to use it, use the application programming interface (API) documentation to find out!

Text Editors and Integrated Development Environments

This book makes no assumptions about what tools you use to author Rust code. Just about any text editor will get the job done! However, many text editors and integrated development environments (IDEs) have built-in support for Rust. You can always find a fairly current list of many editors and IDEs on the tools page on the Rust website.

Working Offline with This Book

In several examples, we will use Rust packages beyond the standard library. To work through those examples, you will either need to have an internet connection or to have downloaded those dependencies ahead of time. To download the dependencies ahead of time, you can run the following commands. (We'll explain what `cargo` is and what each of these commands does in detail later.)

```
$ cargo new get-dependencies
$ cd get-dependencies
$ cargo add rand@0.8.5 trpl@0.2.0
```

This will cache the downloads for these packages so you will not need to download them later. Once you have run this command, you do not need to keep the `get-dependencies` folder. If you have run this command, you can use the `--offline` flag with all `cargo` commands in the rest of the book to use these cached versions instead of attempting to use the network.

Hello, World!

Now that you've installed Rust, it's time to write your first Rust program. It's traditional when learning a new language to write a little program that prints the text `Hello, world!` to the screen, so we'll do the same here!

> Note: This book assumes basic familiarity with the command line. Rust makes no specific demands about your editing or tooling or where your code lives, so if you prefer to use an integrated development environment (IDE) instead of the command line, feel free to use your favorite IDE. Many IDEs now have some degree of Rust support; check the IDE's documentation for details. The Rust team has been focusing on enabling great IDE support via `rust-analyzer`. See [Appendix D]() for more details.

Creating a Project Directory

You'll start by making a directory to store your Rust code. It doesn't matter to Rust where your code lives, but for the exercises and projects in this book, we 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 *projects* directory and a directory for the "Hello, world!" project within the *projects* directory.

For Linux, macOS, and PowerShell on Windows, enter this:

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

For Windows CMD, enter this:

```
> mkdir "%USERPROFILE%\projects"
> cd /d "%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, the convention is to use an underscore to separate them. For example, use *hello_world.rs* rather than *helloworld.rs*.

Now open the *main.rs* file you just created and enter the code in Listing 1-1.

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

Save the file and go back to your terminal window in the *~/projects/hello_world* directory. On Linux or macOS, enter the following commands to compile and run the file:

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

On Windows, enter the command `.\main` instead of `./main`:

```
> rustc main.rs
> .\main
Hello, world!
```

Regardless of your operating system, the string `Hello, world!` should print to the terminal. If you don't see this output, refer back to the "Troubleshooting" part of the Installation section for ways to get help.

If `Hello, world!` did print, congratulations! You've officially written a Rust program. That makes you a Rust programmer—welcome!

Anatomy of a Rust Program

Let's review this "Hello, world!" program in detail. Here's the first piece of the puzzle:

```
fn main() {

}
```

These lines define a function named `main`. The `main` function is special: it is always the first code that runs in every executable Rust program. Here, the first line declares a function named `main` that has no parameters and returns nothing. If there were parameters, they would go inside the parentheses `()`.

The function body is wrapped in `{}`. Rust requires curly brackets around all function bodies. It's good style to place the opening curly bracket on the same line as the function declaration, adding one space in between.

> Note: If you want to stick to a standard style across Rust projects, you can use an automatic formatter tool called `rustfmt` to format your code in a particular style (more on `rustfmt` in Appendix D). The Rust team has included this tool with the standard Rust distribution, as `rustc` is, so it should already be installed on your computer!

The body of the `main` function holds the following code:

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

This line does all the work in this little program: it prints text to the screen. There are three important details to notice here.

First, `println!` calls a Rust macro. If it had called a function instead, it would be entered as `println` (without the `!`). Rust macros are a way to write code that generates code to extend Rust syntax, and we'll discuss them in more detail in Chapter 20. For now, you just need to know that using a `!` means that you're calling a macro instead of a normal function and that macros don't always follow the same rules as functions.

Second, you see the `"Hello, world!"` string. We pass this string as an argument to `println!`, and the string is printed to the screen.

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

Compiling and Running Are Separate Steps

You've just run a newly created program, so let's examine each step in the process.

Before running a Rust program, you must compile it using the Rust compiler by entering the `rustc` command and passing it the name of your source file, like this:

```
$ rustc main.rs
```

If you have a C or C++ background, you'll notice that this is similar to `gcc` or `clang`. After compiling successfully, Rust outputs a binary executable.

On Linux, macOS, and PowerShell on Windows, you can see the executable by entering the `ls` command in your shell:

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

On Linux and macOS, you'll see two files. With PowerShell on Windows, you'll see the same three files that you would see using CMD. With CMD on Windows, you would enter the following:

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

This shows the source code file with the *.rs* extension, the executable file (*main.exe* on Windows, but *main* on all other platforms), and, when using Windows, a file containing debugging information with the *.pdb* extension. From here, you run the *main* or *main.exe* file, like this:

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

If your *main.rs* is your "Hello, world!" program, this line prints `Hello, world!` to your terminal.

If you're more familiar with a dynamic language, such as Ruby, Python, or JavaScript, you might not be used to compiling and running a program as separate steps. Rust is an *ahead-of-time compiled* language, meaning you can compile a program and give the executable to someone else, and they can run it even without having Rust installed. If you give someone a *.rb*, *.py*, or *.js* file, they need to have a Ruby, Python, or JavaScript implementation installed (respectively). But in those languages, you only need one command to compile and run your program. Everything is a trade-off in language design.

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

Hello, Cargo!

Cargo is Rust's build system and package manager. Most Rustaceans use this tool to manage their Rust projects because Cargo handles a lot of tasks for you, such as building your code, downloading the libraries your code depends on, and building those libraries. (We call the libraries that your code needs *dependencies*.)

The simplest Rust programs, like the one we've written so far, don't have any dependencies. If we had built the "Hello, world!" project with Cargo, it would only use the part of Cargo that handles building your code. As you write more complex Rust programs, you'll add dependencies, and if you start a project using Cargo, adding dependencies will be much easier to do.

Because the vast majority of Rust projects use Cargo, the rest of this book assumes that you're using Cargo too. Cargo comes installed with Rust if you used the official installers discussed in the "Installation" section. If you installed Rust through some other means, check whether Cargo is installed by entering the following in your terminal:

```
$ cargo --version
```

If you see a version number, you have it! If you see an error, such as `command not found`, 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 original "Hello, world!" project. Navigate back to your *projects* directory (or wherever you decided to store your code). Then, on any operating system, run the following:

```
$ cargo new hello_cargo
$ cd hello_cargo
```

The first command creates a new directory and project called *hello_cargo*. We've named our project *hello_cargo*, and Cargo creates its files in a directory of the same name.

Go into the *hello_cargo* directory and list the files. You'll see that Cargo has generated two files and one directory for us: a *Cargo.toml* file and a *src* directory with a *main.rs* file inside.

It has also initialized a new Git repository along with a *.gitignore* file. Git files won't be generated if you run `cargo new` within an existing Git repository; you can override this behavior by using `cargo new --vcs=git`.

> Note: Git is a common version control system. You can change `cargo new` to use a different version control system or no version control system by using the `--vcs` flag. Run `cargo new --help` to see the available options.

Open *Cargo.toml* in your text editor of choice. It should look similar to the code in Listing 1-2.

```
[package]
name = "hello_cargo"
version = "0.1.0"
edition = "2024"

[dependencies]
```

This file is in the *TOML* (*Tom's Obvious, Minimal Language*) format, which is 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 configuration information Cargo needs to compile your program: the name, the version, and the edition of Rust to use. We'll talk about the `edition` key in Appendix E.

The last line, `[dependencies]`, is the start of a section for you to list any of your project's dependencies. In Rust, packages of code are referred to as *crates*. We won't need any other crates for this project, but we will in the first project in Chapter 2, so we'll use this dependencies section then.

Now open *src/main.rs* and take a look:

Filename: src/main.rs

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

Cargo has generated a "Hello, world!" program for you, just like the one we wrote in Listing 1-1! So far, the differences between our project and the project Cargo generated are that Cargo placed the code in the *src* directory and we have a *Cargo.toml* configuration file in the top directory.

Cargo expects your source files to live inside the *src* directory. The top-level project directory is just for README files, license information, configuration files, and anything else not related to your code. Using Cargo helps you organize your projects. 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 the "Hello, world!" project, you can convert it to a project that does use Cargo. Move the project code into the *src* directory and create an appropriate *Cargo.toml* file. One easy way to get that *Cargo.toml* file is to run `cargo init`, which will create it for you automatically.

Building and Running a Cargo Project

Now let's look at what's different when we build and run the "Hello, world!" program with Cargo! From your *hello_cargo* directory, build your project by entering the following command:

```
$ cargo build
   Compiling hello_cargo v0.1.0 (file:///projects/hello_cargo)
    Finished dev [unoptimized + debuginfo] target(s) in 2.85
secs
```

This command creates an executable file in *target/debug/hello_cargo* (or *target\debug\hello_cargo.exe* on Windows) rather than in your current directory. Because the default build is a debug build, Cargo puts the binary in a directory named *debug*. You can run the executable with this command:

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

If all goes well, `Hello, world!` should print to the terminal. Running `cargo build` for the first time also causes Cargo to create a new file at the top level: *Cargo.lock*. This file keeps track of the exact versions of dependencies in your project. This project doesn't have dependencies, so the file is a bit sparse. You won't ever need to change this file manually; Cargo manages its contents for you.

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 the code and then run the resultant executable all in one command:

```
$ cargo run
     Finished dev [unoptimized + debuginfo] target(s) in 0.0
secs
     Running `target/debug/hello_cargo`
Hello, world!
```

Using `cargo run` is more convenient than having to remember to run `cargo build` and then use the whole path to the binary, so most developers use `cargo run`.

Notice that this time we didn't see output indicating that Cargo was compiling `hello_cargo`. Cargo figured out that the files hadn't changed, so it didn't rebuild but 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 this output:

```
$ cargo run
   Compiling hello_cargo v0.1.0 (file:///projects/hello_cargo)
     Finished dev [unoptimized + debuginfo] target(s) in 0.33
secs
     Running `target/debug/hello_cargo`
Hello, world!
```

Cargo also provides a command called `cargo check`. This command quickly checks your code to make sure it compiles but doesn't produce an executable:

```
$ cargo check
   Checking hello_cargo v0.1.0 (file:///projects/hello_cargo)
```

```
    Finished dev [unoptimized + debuginfo] target(s) in 0.32
secs
```

Why would you not want an executable? Often, `cargo check` is much faster than `cargo build` because it skips the step of producing an executable. If you're continually checking your work while writing the code, using `cargo check` will speed up the process of letting you know if your project is still compiling! As such, many Rustaceans run `cargo check` periodically as they write their program to make sure it compiles. Then they run `cargo build` when they're ready to use the executable.

Let's recap what we've learned so far about Cargo:

- We can create a project using `cargo new`.
- We can build a project using `cargo build`.
- We can build and run a project in one step using `cargo run`.
- We can build a project without producing a binary to check for errors using `cargo check`.
- Instead of saving the result of the build in the same directory as our code, Cargo stores it in the *target/debug* directory.

An additional advantage of using Cargo is that the commands are the same no matter which operating system you're working on. So, at this point, we'll no longer provide specific instructions for Linux and macOS versus Windows.

Building for Release

When your project is finally ready for release, you can use `cargo build --release` to compile it with optimizations. This command will create an executable in *target/release* instead of *target/debug*. The optimizations make your Rust code run faster, but turning them on lengthens the time it takes for your program to compile. This is why there are two different profiles: one for development, when you want to rebuild quickly and often, and another for building the final program you'll give to a user that won't be rebuilt repeatedly and that will run as fast as possible. If you're benchmarking your code's running time, 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 lot of value over just using `rustc`, but it will prove its worth as your programs become more intricate. Once programs grow to multiple files or need a dependency, it's much easier to let Cargo coordinate the build.

Even though the `hello_cargo` project is simple, it now uses much of the real tooling you'll use in the rest of your Rust career. In fact, to work on any existing projects, you can use the following commands to check out the code using Git, change to that project's directory, and build:

```
$ git clone example.org/someproject
$ cd someproject
$ cargo build
```

For more information about Cargo, check out its documentation.

Summary

You're already off to a great start on your Rust journey! In this chapter, you've learned how to:

- Install the latest stable version of Rust using `rustup`
- Update to a newer Rust version
- Open locally installed documentation
- Write and run a "Hello, world!" program using `rustc` directly
- Create and run a new project using the conventions of Cargo

This is a great time to build a more substantial program to get used to reading and writing Rust code. So, in Chapter 2, we'll build a guessing game program. If you would rather start by learning how common programming concepts work in Rust, see Chapter 3 and then return to Chapter 2.

Programming a 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, external crates, and more! In the following chapters, we’ll explore these ideas in more detail. In this chapter, you’ll just 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 a guess is entered, the program will indicate whether the guess is too low or too high. If the guess is correct, the game will print a congratulatory message 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
$ cd guessing_game
```

The first command, `cargo new`, takes the name of the project (`guessing_game`) as the first argument. 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"
edition = "2024"

[dependencies]
```

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` profile [unoptimized + debuginfo] target(s) in 0.08s
     Running `target/debug/guessing_game`
Hello, world!
```

The `run` command comes in handy when you need to rapidly iterate on a project, as we'll do in this game, quickly testing 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 guessing game 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*.

```
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}");
}
```

This code contains a lot of information, so let's go over it line by line. 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, known as `std`:

```
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}");
# }
```

By default, Rust has a set of items defined in the standard library that it brings into the scope of every program. This set is called the *prelude*, and you can see everything in it in the standard library documentation.

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 features, including the ability to accept user input.

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

```
# 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}");
# }
```

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

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

```
# 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}");
# }
```

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 *variable* to store the user input, like this:

```
# 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}");
# }
```

Now the program is getting interesting! There's a lot going on in this little line. We use the `let` statement to create the variable. Here's another example:

```
let apples = 5;
```

This line creates a new variable named `apples` and binds it to the value 5. In Rust, variables are immutable by default, meaning once we give the variable a value, the value won't change. We'll be discussing this concept in detail in the "Variables and Mutability" section in Chapter 3. To make a variable mutable, we add `mut` before the variable name:

```
let apples = 5; // immutable
let mut bananas = 5; // mutable
```

> Note: The `//` syntax starts a comment that continues until the end of the line. Rust ignores everything in comments. We'll discuss comments in more detail in Chapter 3.

Returning to the guessing game program, you now know that `let mut guess` will introduce a mutable variable named `guess`. The equal sign (`=`) tells Rust we want to bind something to the variable now. On the right 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 a function that's implemented on a type, in this case `String`. 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.

In full, 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!

Receiving User Input

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 the `stdin` function from the `io` module, which will allow us to handle user input:

```
# 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}");
# }
```

If we hadn't imported the `io` module with `use std::io;` at the beginning of the program, we could still use the function by writing 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.

Next, the line `.read_line(&mut guess)` calls the `read_line` method on the standard input handle to get input from the user. We're also passing `&mut guess` as the argument to `read_line` to tell it what string to store the user input in. The full job of `read_line` is to take whatever the user types into standard input and append that into a string (without overwriting its contents), so we therefore pass that string as an argument. The string argument needs to be mutable so the method can change the string's content.

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. For now, all you need to know is that, like variables, references are immutable by default. Hence, you need to write `&mut guess` rather than `&guess` to make it mutable. (Chapter 4 will explain references more thoroughly.)

Handling Potential Failure with `Result`

We're still working on this line of code. We're now discussing a third line of text, but note that it's still part of a single logical line of code. The next part is this method:

```
# 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}");
# }
```

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. It's often wise to introduce a newline and other whitespace to help break up long lines when you call a method with the `.method_name()` syntax. Now let's discuss what this line does.

As mentioned earlier, `read_line` puts whatever the user enters into the string we pass to it, but it also returns a `Result` value. `Result` is an *enumeration*, often called an *enum*, which is a type that can be in one of multiple possible states. We call each possible state a *variant*.

Chapter 6 will cover enums in more detail. The purpose of these `Result` types is to encode error-handling information.

`Result`'s variants are `Ok` and `Err`. The `Ok` variant indicates the operation was successful, and it contains the successfully generated value. The `Err` variant means the operation failed, and it contains information about how or why the operation failed.

Values of the `Result` type, like values of any type, have methods defined on them. An instance of `Result` has an `expect` method that you can call. If this instance of `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 `Result` is an `Ok` value, `expect` will take the return value that `Ok` is holding and return just that value to you so you can use it. In this case, that value is the number of bytes in the user's input.

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

```
$ cargo build
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
warning: unused `Result` that must be used
  --> src/main.rs:10:5
```

```
   |
10 |     io::stdin().read_line(&mut guess);
   |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
   |
   = note: this `Result` may be an `Err` variant, which should
be handled
   = note: `#[warn(unused_must_use)]` on by default
help: use `let _ = ...` to ignore the resulting value
   |
10 |     let _ = io::stdin().read_line(&mut guess);
   |     +++++++

warning: `guessing_game` (bin "guessing_game") generated 1
warning
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.59s
```

Rust warns that you 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 code, but in our case we just want to crash this program when a problem occurs, so we can use `expect`. You'll learn about recovering from errors in Chapter 9.

Printing Values with `println!` Placeholders

Aside from the closing curly bracket, there's only one more line to discuss in the code so far:

```
# 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}");
# }
```

This line prints the string that now contains the user's input. The `{}` set of curly brackets is a placeholder: think of `{}` as little crab pincers that hold a value in place. When printing the value of a variable, the variable name can go inside the curly brackets. When printing the result of evaluating an expression, place empty curly brackets in the format string, then follow the format string with a comma-separated list of expressions to print in each empty curly bracket placeholder in the same order. Printing a variable and the result of an expression in one call to `println!` would look like this:

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

println!("x = {x} and y + 2 = {}", y + 2);
```

This code would print `x = 5 and y + 2 = 12`.

Testing the First Part

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

```
$ cargo run
                    Compiling       guessing_game       v0.1.0
(file:///projects/guessing_game)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 6.44s
     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. We'll 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 with said functionality.

Using a Crate to Get More Functionality

Remember that a crate is a collection of Rust source code files. The project we've been building is a *binary crate*, which is an executable. The `rand` crate is a *library crate*, which contains code that is intended to be used in other programs and can't be executed on its own.

Cargo's coordination of external crates is where Cargo 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. Be sure to specify `rand` exactly as we have here, with this version number, or the code examples in this tutorial may not work:

Filename: Cargo.toml

```
[dependencies]
rand = "0.8.5"
```

In the *Cargo.toml* file, everything that follows a header is part of that section that continues until another section starts. In `[dependencies]` you tell Cargo which external crates your project depends on and which versions of those crates you require. In this case, we specify the `rand` crate with the semantic version specifier `0.8.5`. Cargo understands Semantic Versioning (sometimes called *SemVer*), which is a standard for writing version numbers. The specifier `0.8.5` is actually shorthand for `^0.8.5`, which means any version that is at least 0.8.5 but below 0.9.0.

Cargo considers these versions to have public APIs compatible with version 0.8.5, and this specification ensures you'll get the latest patch release that will still compile with the code in this chapter. Any version 0.9.0 or greater is not guaranteed to have the same API as what the following examples use.

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

```
$ cargo build
  Updating crates.io index
     Locking 15 packages to latest Rust 1.85.0 compatible versions
    Adding rand v0.8.5 (available: v0.9.0)
 Compiling proc-macro2 v1.0.93
 Compiling unicode-ident v1.0.17
 Compiling libc v0.2.170
 Compiling cfg-if v1.0.0
 Compiling byteorder v1.5.0
 Compiling getrandom v0.2.15
 Compiling rand_core v0.6.4
 Compiling quote v1.0.38
 Compiling syn v2.0.98
 Compiling zerocopy-derive v0.7.35
 Compiling zerocopy v0.7.35
 Compiling ppv-lite86 v0.2.20
 Compiling rand_chacha v0.3.1
 Compiling rand v0.8.5
 Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
  Finished `dev` profile [unoptimized + debuginfo] target(s) in 2.48s
```

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

When we include an external dependency, Cargo fetches the latest versions of everything that dependency needs from the *registry*, which is a copy of data from [Crates.io](https://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 crates listed that aren't already downloaded. In this case, although we only listed `rand` as a dependency, Cargo also grabbed other crates that `rand` depends on to work. After downloading the crates, 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 aside from the `Finished` line. 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 the *src/main.rs* file, make a trivial change, and then save it and build again, you'll only see two lines of output:

```
$ cargo build
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.13s
```

These lines show that 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.

Ensuring Reproducible Builds with the *Cargo.lock* File

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, say that next week version 0.8.6 of the `rand` crate comes out, and that version contains an important bug fix, but it also contains a regression that will break your code. To handle this, Rust creates the *Cargo.lock* file the first time you run `cargo build`, so we now have this in the *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 will 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 0.8.5 until you explicitly upgrade, thanks to the *Cargo.lock* file. Because the *Cargo.lock* file is important for reproducible builds, it's often checked into source control with the rest of the code in your project.

Updating a Crate to Get a New Version

When you *do* want to update a crate, Cargo provides the command `update`, which will ignore the *Cargo.lock* file and figure out all the latest versions that fit your specifications in *Cargo.toml*. Cargo will then write those versions to the *Cargo.lock* file. In this case, Cargo will only look for versions greater than 0.8.5 and less than 0.9.0. If the `rand` crate has released the two new versions 0.8.6 and 0.9.0, you would see the following if you ran `cargo update`:

```
$ cargo update
    Updating crates.io index
        Locking 1 package to latest Rust 1.85.0 compatible version
    Updating rand v0.8.5 -> v0.8.6 (available: v0.9.0)
```

Cargo ignores the 0.9.0 release. 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 0.8.6. To use `rand` version 0.9.0 or any version in the 0.9.*x* series, you'd have to update the *Cargo.toml* file to look like this instead:

```
[dependencies]
rand = "0.9.0"
```

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 have specified.

There's a lot more to say about Cargo and its ecosystem, which we'll discuss in Chapter 14, 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` to generate a number to guess. The next step is to update *src/main.rs*, as shown in Listing 2-3.

```
use std::io;

use rand::Rng;

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

    let secret_number = rand::thread_rng().gen_range(1..=100);

    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}");
}
```

First we add the line `use rand::Rng;`. The `Rng` trait 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.

Next, we're adding two lines in the middle. In the first line, we call the `rand::thread_rng` function that gives us the particular random number generator we're going to use: one that is local to the current thread of execution and is seeded by the operating system. Then 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 a range expression as an argument and generates a random number in the range. The kind of range expression we're using here takes the form `start..=end` and is inclusive on the lower and upper bounds, so we need to specify `1..=100` to request a number between 1 and 100.

> Note: You won't just know which traits to use and which methods and functions to call from a crate, so each crate has documentation with instructions for using it. Another neat feature of Cargo is that running the `cargo doc --open` command will build documentation provided by all 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 new line 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` profile [unoptimized + debuginfo] target(s) in 0.02s
     Running `target/debug/guessing_game`
```

```
Guess the number!
The secret number is: 7
Please input your guess.
4
You guessed: 4

$ cargo run
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.02s
     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. Note that this code won't compile just yet, as we will explain.

```
use std::cmp::Ordering;
use std::io;

use rand::Rng;

fn main() {
    // --snip--
#     println!("Guess the number!");
#
#     let secret_number = rand::thread_rng().gen_range(1..=100);
#
#     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!"),
    }
}
```

First we add another `use` statement, bringing a type called `std::cmp::Ordering` into scope from the standard library. The `Ordering` type is another enum and has the variants `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. 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 `guess` to `secret_number`. Then it 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* to match against, and the code that should be run if the value given to `match` fits that arm's pattern. Rust takes the value given to `match` and looks through each arm's pattern in turn. Patterns and the `match` construct are powerful Rust features: they let you express a variety of situations your code might encounter and they make sure you handle them all. These features will be covered in detail in Chapter 6 and Chapter 19, respectively.

Let's walk through an example with the `match` expression we use 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. The `match` expression gets the `Ordering::Greater` value and starts checking each arm's pattern. It looks at the first arm's pattern, `Ordering::Less`, and sees that 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 is `Ordering::Greater`, which *does* match `Ordering::Greater`! The associated code in that arm will execute and print `Too big!` to the screen. The `match` expression ends after the first successful match, so it won't look at the last arm in this scenario.

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

```
$ cargo build
   Compiling libc v0.2.86
   Compiling getrandom v0.2.2
   Compiling cfg-if v1.0.0
   Compiling ppv-lite86 v0.2.10
   Compiling rand_core v0.6.2
   Compiling rand_chacha v0.3.0
   Compiling rand v0.8.5
                     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 `&String`,
found `&{integer}`
   |                 |
   |                 arguments to this method are incorrect
   |
   = note: expected reference `&String`
              found reference `&{integer}`
note: method defined here
                                                              -->
/rustc/4eb161250e340c8f48f66e2b929ef4a5bed7c181/library/core/s
rc/cmp.rs:964:8

For more information about this error, try `rustc --explain
E0308`.
error: could not compile `guessing_game` (bin "guessing_game")
due to 1 previous error
```

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 mut 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 of Rust's 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. Unless otherwise specified, Rust defaults to an `i32`, which is the type of `secret_number` unless you add type information elsewhere that would cause Rust to infer a different numerical type. The reason for the error is that Rust cannot compare a string and a number type.

Ultimately, we want to convert the `String` the program reads as input into a number type so we can compare it numerically to the secret number. We do so by adding this line to the `main` function body:

Filename: src/main.rs

```
# use std::cmp::Ordering;
# use std::io;
#
# use rand::Rng;
#
# fn main() {
#     println!("Guess the number!");
#
#                                 let      secret_number      =
rand::thread_rng().gen_range(1..=100);
#
#     println!("The secret number is: {secret_number}");
#
#     println!("Please input your guess.");
#
    // --snip--

    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 line is:

```
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 helpfully Rust allows us to shadow the previous value of `guess` with a new one. *Shadowing* lets us reuse the `guess` variable name rather than forcing us to create two unique variables, such as `guess_str` and `guess`, for example. We'll cover this in more detail in [Chapter 3](), but for now, know that this feature is often used when you want to convert a value from one type to another type.

We bind this new variable to the expression `guess.trim().parse()`. The `guess` in the expression refers to the original `guess` variable that contained the input as a string. The `trim` method on a `String` instance will eliminate any whitespace at the beginning and end, which we must do before we can convert the string to a `u32`, which can only contain numerical data. The user must press `enter` to satisfy `read_line` and input their guess, which adds a newline character to the string. For example, if the user types `5` and presses `enter`, `guess` looks like this: `5\n`. The `\n` represents "newline." (On Windows, pressing `enter` results in a carriage return and a newline, `\r\n`.) The `trim` method eliminates `\n` or `\r\n`, resulting in just `5`.

The `parse` method on strings converts a string to another type. Here, we use it to convert from a string to a number. 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 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 `parse` method will only work on characters that can logically be converted into numbers and so can easily cause errors. 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 as the `read_line` method does (discussed earlier in "Handling Potential Failure with `Result`"). 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` profile [unoptimized + debuginfo] target(s)
in 0.26s
     Running `target/debug/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 creates an infinite loop. We'll add a loop to give users more chances at guessing the number:

Filename: src/main.rs

```
# use std::cmp::Ordering;
# use std::io;
#
# use rand::Rng;
#
# fn main() {
#     println!("Guess the number!");
#
#                                let       secret_number       =
rand::thread_rng().gen_range(1..=100);
#
    // --snip--

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

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

        // --snip--


#
#         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 from the guess input prompt onward into a loop. Be sure to indent the lines inside the loop another four spaces each and run the program again. The program will now ask for another guess forever, which actually introduces a new problem. It doesn't seem like the user can quit!

The user could always interrupt the program by using the keyboard shortcut `ctrl-c`. But there's another way to escape this insatiable monster, as 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. We can take advantage of that to allow the user to quit, as shown here:

```
$ cargo run
                    Compiling      guessing_game      v0.1.0
(file:///projects/guessing_game)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.23s
     Running `target/debug/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 src/main.rs:28:47:
Please type a number!: ParseIntError { kind: InvalidDigit }
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace
```

Typing `quit` will quit the game, but as you'll notice, so will entering any other non-number input. This is suboptimal, to say the least; we want the game to also 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` statement:

Filename: src/main.rs

```
# use std::cmp::Ordering;
# use std::io;
#
# use rand::Rng;
#
# fn main() {
#     println!("Guess the number!");
#
#     let secret_number =
rand::thread_rng().gen_range(1..=100);
#
#     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}");
#
        // --snip--

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

Adding the `break` line after `You win!` makes the program 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`, as shown in Listing 2-5.

```
# use std::cmp::Ordering;
# use std::io;
#
# use rand::Rng;
#
# fn main() {
#     println!("Guess the number!");
#
#                                   let      secret_number      =
rand::thread_rng().gen_range(1..=100);
#
#     println!("The secret number is: {secret_number}");
#
#     loop {
#         println!("Please input your guess.");
#
#         let mut guess = String::new();
#
        // --snip--

        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}");

        // --snip--
#
```

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

We switch from an `expect` call to a `match` expression to move from crashing on an error to handling the error. Remember that `parse` returns a `Result` type and `Result` is an enum that has the variants `Ok` and `Err`. We're using a `match` expression here, as 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 resultant 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 underscore, `_`, is a catch-all 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 tells the program 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:

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.13s
     Running `target/debug/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 the secret number. That worked well for testing, but it ruins the game. Let's delete the `println!` that outputs the secret number. Listing 2-6 shows the final code.

```
use std::cmp::Ordering;
use std::io;

use rand::Rng;

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

```
    let secret_number = rand::thread_rng().gen_range(1..=100);

    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;
            }
        }
    }
}
```

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

Summary

This project was a hands-on way to introduce you to many new Rust concepts: `let`, `match`, functions, the use of 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, a feature that makes Rust different from other languages. Chapter 5 discusses structs and method syntax, and Chapter 6 explains how enums work.

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 the conventions around using these concepts.

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 are reserved for use by the language only, much as in other languages. 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 the “Storing Values with Variables” section, by default, variables are immutable. This is one of many nudges Rust gives 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 sometimes you might want to opt out.

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

Then, in your new *variables* directory, open *src/main.rs* and replace its code with the following code, which won’t compile just yet:

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 regarding an immutability error, as shown in this output:

```
$ cargo run
   Compiling variables v0.1.0 (file:///projects/variables)
error[E0384]: cannot assign twice to 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;
  |     ^^^^^ cannot assign twice to immutable variable
  |
help: consider making this binding mutable
```

```
  |
2 |     let mut x = 5;
  |         +++

For more information about this error, try `rustc --explain
E0384`.
error: could not compile `variables` (bin "variables") due to
1 previous error
```

This example shows how the compiler helps you find errors in your programs. Compiler errors can be frustrating, but really 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.

You received the error message `cannot assign twice to immutable variable `x`` because you 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's 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. The cause of this kind of bug can be difficult to track down after the fact, especially when the second piece of code changes the value only *sometimes*. The Rust compiler guarantees that when you state that a value won't change, it really won't change, so you don't have to keep track of it yourself. Your code is thus easier to reason through.

But mutability can be very useful, and can make code more convenient to write. Although variables are immutable by default, you can make them mutable by adding `mut` in front of the variable name as you did in [Chapter 2](). Adding `mut` also conveys intent to future readers of the code by indicating that other parts of the code will be changing this variable's value.

For example, let's 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 the program now, we get this:

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

We're allowed to change the value bound to `x` from `5` to `6` when `mut` is used. Ultimately, deciding whether to use mutability or not is up to you and depends on what you think is clearest in that particular situation.

Constants

Like immutable variables, *constants* are values that are bound to a name and are not allowed to change, but there are a few differences between constants and variables.

First, you aren't allowed to use `mut` with constants. Constants aren't just immutable by default—they're always immutable. You declare constants using the `const` keyword instead of the `let` keyword, and the type of the value *must* be annotated. We'll cover types and type annotations in the next section, "Data Types", so don't worry about the details right now. Just know that you 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 be set only to a constant expression, not the result of a value that could only be computed at runtime.

Here's an example of a constant declaration:

```
const THREE_HOURS_IN_SECONDS: u32 = 60 * 60 * 3;
```

The constant's name is `THREE_HOURS_IN_SECONDS` and its value is set to the result of multiplying 60 (the number of seconds in a minute) by 60 (the number of minutes in an hour) by 3 (the number of hours we want to count in this program). Rust's naming convention for constants is to use all uppercase with underscores between words. The compiler is able to evaluate a limited set of operations at compile time, which lets us choose to write out this value in a way that's easier to understand and verify, rather than setting this constant to the value 10,800. See the Rust Reference's section on constant evaluation for more information on what operations can be used when declaring constants.

Constants are valid for the entire time a program runs, within the scope in which they were declared. This property makes constants useful 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 you saw in the guessing game tutorial in Chapter 2, you can declare a new variable with the same name as a previous variable. Rustaceans say that the first variable is *shadowed* by the second, which means that the second variable is what the compiler will see when you use the name of the variable. In effect, the second variable overshadows the first, taking any uses of the variable name to itself until either it itself is shadowed or the scope ends. 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 in the inner scope is: {x}");
    }

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

This program first binds `x` to a value of `5`. Then it creates a new variable `x` by repeating `let x =`, taking the original value and adding `1` so the value of `x` is then `6`. Then, within an inner scope created with the curly brackets, the third `let` statement also shadows `x` and creates a new variable, multiplying the previous value by `2` to give `x` a value of `12`. When that scope is over, the inner shadowing ends and `x` returns to being `6`. When we run this program, it will output the following:

```
$ cargo run
   Compiling variables v0.1.0 (file:///projects/variables)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.31s
     Running `target/debug/variables`
The value of x in the inner scope is: 12
The value of x is: 6
```

Shadowing is different from marking a variable as `mut` because we'll get a compile-time error if we accidentally try to reassign to this variable without using the `let` keyword. By using `let`, 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, and then we want to store that input as a number:

```
# fn main() {
    let spaces = "   ";
    let spaces = spaces.len();
# }
```

The first `spaces` variable is a string type and the second `spaces` variable is a number type. Shadowing thus spares us from having to come up with different names, such as `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, we'll get a compile-time error:

```
# fn main() {
    let mut spaces = "   ";
    spaces = spaces.len();
# }
```

The error says we're not allowed to mutate a variable's type:

```
$ cargo run
   Compiling variables v0.1.0 (file:///projects/variables)
error[E0308]: mismatched types
 --> src/main.rs:3:14
  |
2 |     let mut spaces = "   ";
  |                      ----- expected due to this value
3 |     spaces = spaces.len();
  |              ^^^^^^^^^^^^ expected `&str`, found `usize`

For more information about this error, try `rustc --explain E0308`.
error: could not compile `variables` (bin "variables") due to 1 previous error
```

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 *data type*, which tells Rust what kind of data is being specified so it knows how to work with that data. We'll look at two data type subsets: scalar and compound.

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 the "Comparing the Guess to the Secret Number" section 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 `: u32` type annotation shown in the preceding code, Rust will display the following error, which means the compiler needs more information from us to know which type we want to use:

```
$ cargo build
                 Compiling      no_type_annotations      v0.1.0
(file:///projects/no_type_annotations)
error[E0284]: type annotations needed
 --> src/main.rs:2:9
  |
2 |     let guess = "42".parse().expect("Not a number!");
  |          ^^^^^          ----- type must be known at this
point
  |
  = note: cannot satisfy `<_ as FromStr>::Err == _`
help: consider giving `guess` an explicit type
  |
2 |     let guess: /* Type */ = "42".parse().expect("Not a
number!");
  |              ++++++++++++

For more information about this error, try `rustc --explain
```

```
E0284`.
error: could not compile `no_type_annotations` (bin
"no_type_annotations") due to 1 previous error
```

You'll see different type annotations for other 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 may recognize these from other programming languages. 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 in Chapter 2, 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. We can use any of these variants to declare the type of an integer value.

Table 3-1: Integer Types in Rust

Length	Signed	Unsigned
8-bit	`i8`	`u8`
16-bit	`i16`	`u16`
32-bit	`i32`	`u32`
64-bit	`i64`	`u64`
128-bit	`i128`	`u128`
architecture dependent	`isize`	`usize`

Each variant can be either signed or unsigned and has an explicit size. *Signed* and *unsigned* refer to whether it's possible for the number to be negative—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.

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 architecture of the 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 number literals that can be multiple numeric types allow a type suffix, such as `57u8`, to designate the type. Number literals can also use `_` as a visual separator to make the number easier to read, such as `1_000`, which will have the same value as if you had specified `1000`.

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 places to start: integer types default to `i32`. The primary situation in which you'd use `isize` or `usize` is when indexing some sort of collection.

Integer Overflow

Let’s say you have a variable of type `u8` that can hold values between 0 and 255. If you try to change the variable to a value outside that range, such as 256, *integer overflow* will occur, which can result in one of two behaviors. When you’re compiling in debug mode, Rust includes checks for integer overflow that cause your program to *panic* at runtime if this behavior occurs. Rust uses the term *panicking* when a program exits with an error; we’ll discuss panics in more depth in the “Unrecoverable Errors with `panic!`” section in Chapter 9.

When you’re compiling in release mode with the `--release` flag, Rust does *not* include checks for integer overflow that cause panics. Instead, if overflow occurs, Rust performs *two’s complement wrapping*. In short, values greater than the maximum value the type can hold “wrap around” to the minimum of the values the type can hold. In the case of a `u8`, the value 256 becomes 0, the value 257 becomes 1, and so on. The program won’t panic, but the variable will have a value that probably isn’t what you were expecting it to have. Relying on integer overflow’s wrapping behavior is considered an error.

To explicitly handle the possibility of overflow, you can use these families of methods provided by the standard library for primitive numeric types:

- Wrap in all modes with the `wrapping_*` methods, such as `wrapping_add`.
- Return the `None` value if there is overflow with the `checked_*` methods.
- Return the value and a Boolean indicating whether there was overflow with the `overflowing_*` methods.
- Saturate at the value’s minimum or maximum values with the `saturating_*` methods.

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. All floating-point types are signed.

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.

Numeric Operations

Rust supports the basic mathematical operations you'd expect for all the number types: addition, subtraction, multiplication, division, and remainder. Integer division truncates toward zero to the nearest integer. The following code shows how you'd use each numeric operation 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;
    let truncated = -5 / 3; // Results in -1

    // 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`. Booleans are one byte in size. 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 use 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

Rust’s `char` type is the language’s most primitive alphabetic type. Here are some examples of declaring `char` values:

Filename: src/main.rs

```
fn main() {
    let c = 'z';
    let z: char = 'ℤ'; // with explicit type annotation
    let heart_eyed_cat = '😻';
}
```

Note that we specify `char` literals with single quotes, as opposed to string literals, which use double quotes. Rust’s `char` type is four bytes in size and represents a Unicode scalar value, which means it can represent a lot more than just ASCII. Accented letters; Chinese, Japanese, and Korean characters; emoji; and zero-width spaces are all valid `char` values 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 "Storing UTF-8 Encoded Text with Strings" in Chapter 8.

Compound Types

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

The Tuple Type

A *tuple* is a general way of grouping together a number of values with a variety of types into one compound type. Tuples have a fixed length: once declared, they cannot grow or shrink in size.

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 because 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`.

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 the tuple `x` and then accesses each element of the tuple using their respective indices. As with most programming languages, the first index in a tuple is 0.

The tuple without any values has a special name, *unit*. This value and its corresponding type are both written `()` and represent an empty value or an empty return type. Expressions implicitly return the unit value if they don't return any other value.

The Array Type

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. Unlike arrays in some other languages, arrays in Rust have a fixed length.

We write the values in an array 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, the same as the other types we have seen so far, 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. An array isn't as flexible as the vector type, though. A *vector* is a similar collection type provided by the standard library that *is* allowed to grow or shrink in size because its contents live on the heap. If you're unsure whether to use an array or a vector, chances are you should use a vector. Chapter 8 discusses vectors in more detail.

However, arrays are more useful when you know the number of elements will not need to change. For example, if you were using the names of the month in a program, you would probably use an array rather than a vector because you know it will always contain 12 elements:

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

You write an array's type using square brackets with the type of each element, a semicolon, and then the number of elements in the array, like so:

```
let a: [i32; 5] = [1, 2, 3, 4, 5];
```

Here, `i32` is the type of each element. After the semicolon, the number `5` indicates the array contains five elements.

You can also initialize an array to contain the same value for each element by specifying the initial value, followed by a semicolon, and then the length of the array in square brackets, as shown here:

```
let a = [3; 5];
```

The array named `a` will contain `5` elements that will all be set to the value `3` initially. This is the same as writing `let a = [3, 3, 3, 3, 3];` but in a more concise way.

Accessing Array Elements

An array is a single chunk of memory of a known, fixed size that can be allocated on the stack. You 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

Let's see what happens if you try to access an element of an array that is past the end of the array. Say you run this code, similar to the guessing game in Chapter 2, to get an array index from the user:

Filename: src/main.rs

```
use std::io;

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

    println!("Please enter an array index.");

    let mut index = String::new();

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

    let index: usize = index
        .trim()
```

```
        .parse()
        .expect("Index entered was not a number");

    let element = a[index];

    println!("The value of the element at index {index} is:
{element}");
}
```

This code compiles successfully. If you run this code using `cargo run` and enter `0`, `1`, `2`, `3`, or `4`, the program will print out the corresponding value at that index in the array. If you instead enter a number past the end of the array, such as `10`, you'll see output like this:

```
thread 'main' panicked at src/main.rs:19:19:
index out of bounds: the len is 5 but the index is 10
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace
```

The program resulted in a *runtime* error at the point of using an invalid value in the indexing operation. The program exited with an error message and didn't execute the final `println!` statement. 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 or equal to the length, Rust will panic. This check has to happen at runtime, especially in this case, because the compiler can't possibly know what value a user will enter when they run the code later.

This is an example of Rust's memory 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 and how you can write readable, safe code that neither panics nor allows invalid memory access.

Functions

Functions are prevalent 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 which 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.");
}
```

We define a function in Rust by entering `fn` followed by a function name and a set of parentheses. 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 in a scope that can be seen by the caller.

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` profile [unoptimized + debuginfo] target(s)
in 0.28s
     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.

Parameters

We can define functions to have *parameters*, which are special variables that are part of a function’s signature. When a function has parameters, you 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.

In this version of `another_function` we add a parameter:

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` profile [unoptimized + debuginfo] target(s)
in 1.21s
```

```
     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 we pass `5` in to `another_function`, the `println!` macro puts `5` where the pair of curly brackets containing `x` was 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 type you mean. The compiler is also able to give more helpful error messages if it knows what types the function expects.

When defining multiple parameters, separate the parameter declarations with commas, like this:

Filename: src/main.rs

```
fn main() {
    print_labeled_measurement(5, 'h');
}

fn print_labeled_measurement(value: i32, unit_label: char) {
    println!("The measurement is: {value}{unit_label}");
}
```

This example creates a function named `print_labeled_measurement` with two parameters. The first parameter is named `value` and is an `i32`. The second is named `unit_label` and is type `char`. The function then prints text containing both the `value` and the `unit_label`.

Let's try running this code. Replace the program currently in your *functions* 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` profile [unoptimized + debuginfo] target(s)
in 0.31s
```

```
     Running `target/debug/functions`
The measurement is: 5h
```

Because we called the function with `5` as the value for `value` and `'h'` as the value for `unit_label`, the program output contains those values.

Statements and Expressions

Function bodies are made up of a series of statements optionally ending in an expression. So far, the functions we've covered haven't included an ending expression, but you have seen an expression as part of a statement. 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 are instructions that perform some action and do not return a value.
- Expressions evaluate to a resultant value.

Let's look at some examples.

We've actually already used statements and expressions. Creating a variable and assigning a value to it with the `let` keyword is a statement. In Listing 3-1, `let y = 6;` is a statement.

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

Function definitions are also statements; the entire preceding example is a statement in itself. (As we'll see below, *calling* a function is not a statement, though.)

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

Filename: src/main.rs

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

```
}
```

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

```
$ cargo run
   Compiling functions v0.1.0 (file:///projects/functions)
error: expected expression, found `let` statement
 --> src/main.rs:2:14
  |
2 |     let x = (let y = 6);
  |              ^^^
  |
  = note: only supported directly in conditions of `if` and
`while` expressions

warning: unnecessary parentheses around assigned value
 --> src/main.rs:2:13
  |
2 |     let x = (let y = 6);
  |             ^         ^
  |
  = note: `#[warn(unused_parens)]` on by default
help: remove these parentheses
  |
2 -     let x = (let y = 6);
2 +     let x = let y = 6;
  |

warning: `functions` (bin "functions") generated 1 warning
error: could not compile `functions` (bin "functions") due to
1 previous error; 1 warning emitted
```

The `let y = 6` statement does not return a value, so there isn't anything for `x` to bind to. This is different from what happens 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 a value and make up most of the rest of the code that you'll write in Rust. Consider a math operation, such as `5 + 6`, which is an expression that evaluates to the value `11`. Expressions can be part of statements: in Listing 3-1, the `6` in the statement `let y = 6;` is an expression that evaluates to the value `6`. Calling a function is an expression. Calling a macro is an expression. A new scope block created with curly brackets is an expression, for example:

Filename: src/main.rs

```
fn main() {
    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 that the `x + 1` line doesn't have a semicolon at the end, which is 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, and it 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 must 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` profile [unoptimized + debuginfo] target(s)
in 0.30s
     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`. But if we place a semicolon at the end of the line containing `x + 1`, changing it from an expression to a statement, we'll get an error:

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;
}
```

Compiling this code produces an error, as follows:

```
$ cargo run
   Compiling functions v0.1.0 (file:///projects/functions)
error[E0308]: mismatched types
 --> src/main.rs:7:24
  |
7 | fn plus_one(x: i32) -> i32 {
  |    --------            ^^^ expected `i32`, found `()`
```

```
  |    |
   |     implicitly returns `()` as its body has no tail or
`return` expression
8 |     x + 1;
   |            - help: remove this semicolon to return this
value

For more information about this error, try `rustc --explain
E0308`.
error: could not compile `functions` (bin "functions") due to
1 previous error
```

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 unit type. 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 *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, the idiomatic comment style starts a comment with two slashes, and the comment continues 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 the "Publishing a Crate to Crates.io" section of Chapter 14.

Control Flow

The ability to run some code depending on whether a condition is `true` and 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 you to branch your code depending on conditions. You 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`, followed by a condition. In this case, the condition checks whether or not the variable `number` has a value less than 5. We place the block of code to execute if the condition is `true` 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` profile [unoptimized + debuginfo] target(s)
in 0.31s
     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:

```
# fn main() {
    let number = 7;
#
#     if number < 5 {
#         println!("condition was true");
#     } else {
#         println!("condition was false");
#     }
# }
```

Run the program again, and look at the output:

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

It's also worth noting that the condition in this code *must* be a `bool`. If the condition isn't a `bool`, we'll get an error. For example, 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:

```
$ cargo run
   Compiling branches v0.1.0 (file:///projects/branches)
error[E0308]: mismatched types
 --> src/main.rs:4:8
  |
4 |     if number {
  |        ^^^^^^ expected `bool`, found integer

For more information about this error, try `rustc --explain E0308`.
error: could not compile `branches` (bin "branches") due to 1 previous error
```

The error indicates that Rust expected a `bool` but got an integer. Unlike languages such as Ruby and JavaScript, Rust will not automatically try to convert non-Boolean types to a Boolean. 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`.

Handling Multiple Conditions with `else if`

You can use 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` profile [unoptimized + debuginfo] target(s)
in 0.31s
     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 evaluates to `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. That's because Rust only executes the block for the first `true` condition, and once it finds one, it doesn'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 to assign the outcome to a variable, as in Listing 3-2.

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

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

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` profile [unoptimized + debuginfo] target(s)
in 0.30s
     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 3-2, the results of both the `if` arm and the `else` arm were `i32` integers. If the types are mismatched, as in the following example, we'll get an error:

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 compile 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:

```
$ cargo run
   Compiling branches v0.1.0 (file:///projects/branches)
error[E0308]: `if` and `else` have incompatible types
 --> src/main.rs:4:44
  |
4 |     let number = if condition { 5 } else { "six" };
  |                                 -          ^^^^^ expected
integer, found `&str`
  |                                 |
  |                                 expected because of this

For more information about this error, try `rustc --explain
E0308`.
error: could not compile `branches` (bin "branches") due to 1
previous error
```

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, and Rust needs to know at compile time what type the `number` variable is, definitively. Knowing the type of `number` lets the compiler verify the 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*, which will run through the code inside the loop body to the end and then start 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 the keyboard shortcut `ctrl-c` to interrupt 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` profile [unoptimized + debuginfo] target(s)
in 0.08s
     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 interrupt signal.

Fortunately, Rust also provides a way to break out of a loop using code. 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.

We also used `continue` in the guessing game, which in a loop tells the program to skip over any remaining code in this iteration of the loop and go to the next iteration.

Returning Values from Loops

One of the uses of a `loop` is to retry an operation you know might fail, such as checking whether a thread has completed its job. You might also need to pass the result of that operation out of the loop to the rest of your code. To do this, you can add the value you want returned after the `break` expression you use to stop the loop; that value will be returned out of the loop so you can use it, as shown here:

```
fn main() {
    let mut counter = 0;

    let result = loop {
        counter += 1;

        if counter == 10 {
            break counter * 2;
        }
    };
```

```
    println!("The result is {result}");
}
```

Before the loop, we declare a variable named `counter` and initialize it to `0`. Then we declare a variable named `result` to hold the value returned from the loop. On every iteration of the loop, we add `1` to the `counter` variable, and then check whether the `counter` is equal to `10`. When it is, we use the `break` keyword with the value `counter * 2`. After the loop, we use a semicolon to end the statement that assigns the value to `result`. Finally, we print the value in `result`, which in this case is `20`.

You can also `return` from inside a loop. While `break` only exits the current loop, `return` always exits the current function.

Loop Labels to Disambiguate Between Multiple Loops

If you have loops within loops, `break` and `continue` apply to the innermost loop at that point. You can optionally specify a *loop label* on a loop that you can then use with `break` or `continue` to specify that those keywords apply to the labeled loop instead of the innermost loop. Loop labels must begin with a single quote. Here's an example with two nested loops:

```
fn main() {
    let mut count = 0;
    'counting_up: loop {
        println!("count = {count}");
        let mut remaining = 10;

        loop {
            println!("remaining = {remaining}");
            if remaining == 9 {
                break;
            }
            if count == 2 {
                break 'counting_up;
            }
            remaining -= 1;
```

```
        }

        count += 1;
    }
    println!("End count = {count}");
}
```

The outer loop has the label `'counting_up`, and it will count up from 0 to 2. The inner loop without a label counts down from 10 to 9. The first `break` that doesn't specify a label will exit the inner loop only. The `break 'counting_up;` statement will exit the outer loop. This code prints:

```
$ cargo run
   Compiling loops v0.1.0 (file:///projects/loops)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.58s
     Running `target/debug/loops`
count = 0
remaining = 10
remaining = 9
count = 1
remaining = 10
remaining = 9
count = 2
remaining = 10
End count = 2
```

Conditional Loops with `while`

A program will often need to evaluate a condition within a loop. While the condition is `true`, the loop runs. When the condition ceases to be `true`, the program calls `break`, stopping the loop. It's possible to implement behavior like this 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, called a `while` loop. In Listing 3-3, we use `while` to loop the program three times, counting down each time, and then, after the loop, print a message and exit.

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

    while number != 0 {
        println!("{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 evaluates to `true`, the code runs; otherwise, it exits the loop.

Looping Through a Collection with `for`

You can choose to use the `while` construct to loop over the elements of a collection, such as an array. For example, the loop in Listing 3-4 prints each element in the array `a`.

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

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

        index += 1;
    }
}
```

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 every element in the array:

```
$ cargo run
   Compiling loops v0.1.0 (file:///projects/loops)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.32s
     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.

However, this approach is error prone; we could cause the program to panic if the index value or test condition is incorrect. For example, if you changed the definition of the `a` array to have four elements but forgot to update the condition to `while index < 4`, the code would panic. It's also slow, because the compiler adds runtime code to perform the conditional check of whether the index is within the bounds of the array on every iteration through the loop.

As a more concise alternative, you can use a `for` loop and execute some code for each item in a collection. A `for` loop looks like the code in Listing 3-5.

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

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

When we run this code, we'll see the same output as in Listing 3-4. 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. Machine code generated from `for` loops can be more efficient as well, because the index doesn't need to be compared to the length of the array at every iteration.

Using the `for` loop, you wouldn't need to remember to change any other code if you changed the number of values in the array, as you would with the method used in Listing 3-4.

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 3-3, most Rustaceans would use a `for` loop. The way to do that would be to use a `Range`, provided by the standard library, which 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! This was a sizable chapter: you learned about variables, scalar and compound data types, functions, comments, `if` expressions, and loops! To practice with the concepts discussed in this chapter, try building programs to do the following:

- Convert temperatures between Fahrenheit and Celsius.
- Generate the *n*th 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 has deep implications for the rest of the language. It enables Rust to make memory safety guarantees without needing a garbage collector, so it’s important to understand how ownership works. 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?

Ownership is a set of rules that govern how a Rust program manages memory. All programs have to manage the way they use a computer's memory while running. Some languages have garbage collection that regularly 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. If any of the rules are violated, the program won't compile. None of the features of ownership will slow down your program while it's running.

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 easier you'll find it 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

Many programming languages don't require you 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 affects how the language behaves and why you have to make certain decisions. Parts of ownership will be described 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 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*. All data stored on the stack must have a known, fixed size. Data with an unknown size at compile time or a size that might change must be stored on the heap instead.

The heap is less organized: when you put data on the heap, you request a certain amount of space. The memory allocator finds an empty spot in the heap that is big enough, marks it as being in use, and returns a *pointer*, which is the address of that location. This process is called *allocating on the heap* and is sometimes abbreviated as just *allocating* (pushing values onto the stack is not considered allocating). Because the pointer to the heap is a known, fixed size, you can store the pointer on the stack, but when you want the actual data, you must follow the pointer. Think of being seated at a restaurant. When you enter, you state the number of people in your group, and the host 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.

Pushing to the stack is faster than allocating on the heap because the allocator never has to search for a place to store new data; that location is always at the top of the stack. Comparatively, allocating space on the heap requires more work because the allocator must first find a big enough space to hold the data and then perform bookkeeping to prepare for the next allocation.

Accessing data in the heap is generally slower than accessing data on the stack because you 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 usually 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).

When your 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 you 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 the main purpose of ownership is to manage heap data 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 them:

- Each value in Rust has an *owner*.
- There can only be one owner at a time.
- When the owner goes out of scope, the value will be dropped.

Variable Scope

Now that we're past basic Rust syntax, we won't include all the `fn main() {` code in examples, so if you're following along, make sure 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. Take the following variable:

```
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 shows a program with comments annotating where the variable `s` would be valid.

```
# fn main() {
    {                      // s is not valid here, since 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
# }
```

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

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

At this point, the relationship between scopes and when variables are valid is similar to that in 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 those we covered in the "Data Types" section of Chapter 3. The types covered previously are of a known size, can be stored on the stack and popped off the stack when their scope is over, and can be quickly and trivially copied to make a new, independent instance if another part of code needs to use the same value in a different scope. But we want to look at data that is stored on the heap and explore how Rust knows when to clean up that data, and the `String` type is a great example.

We'll concentrate on the parts of `String` that relate to ownership. These aspects also apply to other complex data types, whether they are provided by the standard library or created by you. 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 suitable for every situation in which we may 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 manages data 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 `::` operator 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 "Paths for Referring to an Item in the Module Tree" in Chapter 7.

This kind of string *can* be mutated:

```
# fn main() {
    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 in 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. This is why string literals are fast and efficient. But these properties only come from the string literal's 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:

- The memory must be requested from the memory allocator at runtime.
- We need a way of returning this memory to the allocator 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 of and cleans up memory that isn’t being used anymore, and we don’t need to think about it. In most languages without a GC, it’s our responsibility to identify when memory is no longer being used and to call code to explicitly free 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:

```
# fn main() {
    {
        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 allocator: 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 curly bracket.

> 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.

Variables and Data Interacting with 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.

```
# fn main() {
    let x = 5;
    let y = x;
# }
```

We can probably guess what this is doing: "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:

```
# fn main() {
    let s1 = String::from("hello");
    let s2 = s1;
# }
```

This looks very similar, 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.

Take a look at Figure 4-1 to see what is happening to `String` under the covers. 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.

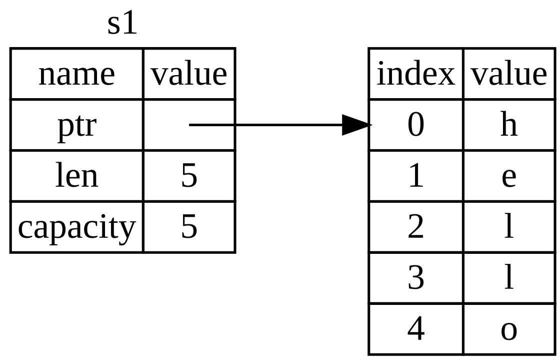


Figure 4-1: Representation in memory of a `String` holding the value `"hello"` bound to `s1`

The length is how much memory, in bytes, the contents of the `String` are currently using. The capacity is the total amount of memory, in bytes, that the `String` has received from the allocator. 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 4-2.

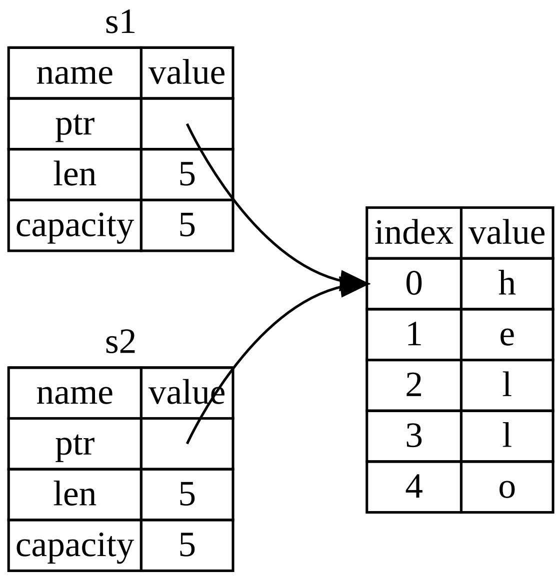


Figure 4-2: Representation in memory of the variable `s2` that has a copy of the pointer, length, and capacity of `s1`

The representation does *not* look like Figure 4-3, 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 be very expensive in terms of runtime performance if the data on the heap were large.

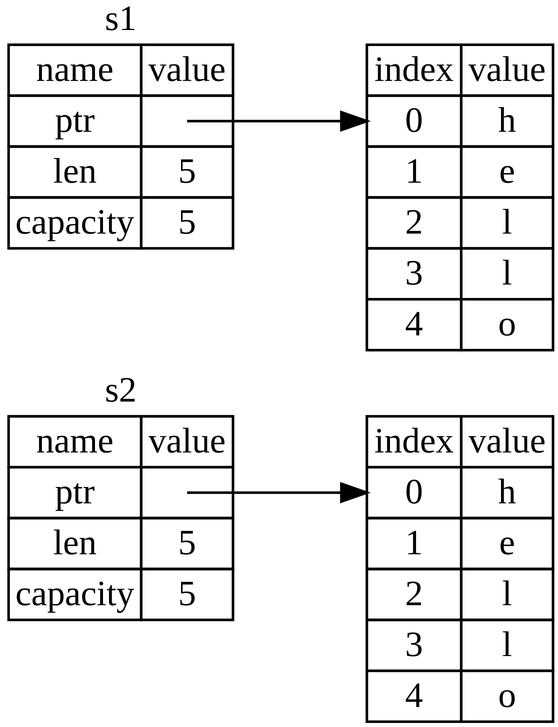


Figure 4-3: Another possibility for what `s2 = s1` might do if Rust copied the heap data as well

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 4-2 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, after the line `let s2 = s1;`, Rust considers `s1` as no longer valid. 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; it won't work:

```
# fn main() {
    let s1 = String::from("hello");
    let s2 = s1;
```

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

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

```
$ cargo run
   Compiling ownership v0.1.0 (file:///projects/ownership)
error[E0382]: borrow of moved value: `s1`
 --> src/main.rs:5:15
  |
2 |     let s1 = String::from("hello");
  |         -- move occurs because `s1` has type `String`, which does not implement the `Copy` trait
3 |     let s2 = s1;
  |              -- value moved here
4 |
5 |     println!("{s1}, world!");
  |               ^^^^ value borrowed here after move
  |
  = note: this error originates in the macro `$crate::format_args_nl` which comes from the expansion of the macro `println` (in Nightly builds, run with -Z macro-backtrace for more info)
help: consider cloning the value if the performance cost is acceptable
  |
3 |     let s2 = s1.clone();
  |                ++++++++

For more information about this error, try `rustc --explain E0382`.
error: could not compile `ownership` (bin "ownership") due to 1 previous error
```

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 making a shallow copy. But because Rust also invalidates the first variable, instead of being called a shallow copy, it's known as a *move*. In this example, we would say that `s1` was *moved* into `s2`. So, what actually happens is shown in Figure 4-4.

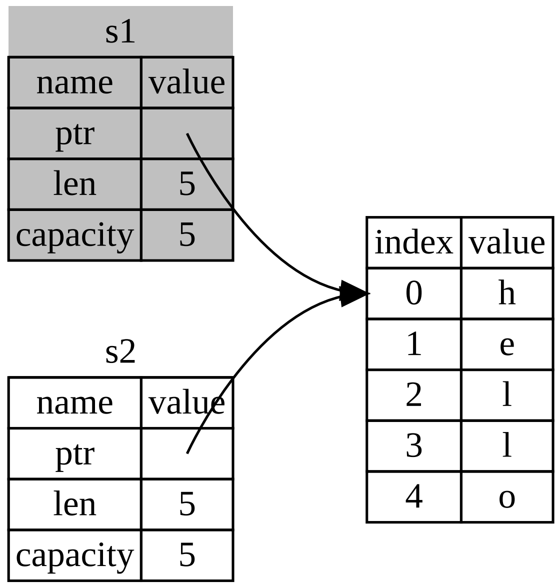


Figure 4-4: Representation in memory after `s1` has been invalidated

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.

Scope and Assignment

The inverse of this is true for the relationship between scoping, ownership, and memory being freed via the `drop` function as well. When you assign a completely new value to an existing variable, Rust will call `drop` and free the original value's memory immediately. Consider this code, for example:

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

```
    println!("{s}, world!");
# }
```

We initially declare a variable `s` and bind it to a `String` with the value `"hello"`. Then we immediately create a new `String` with the value `"ahoy"` and assign it to `s`. At this point, nothing is referring to the original value on the heap at all.

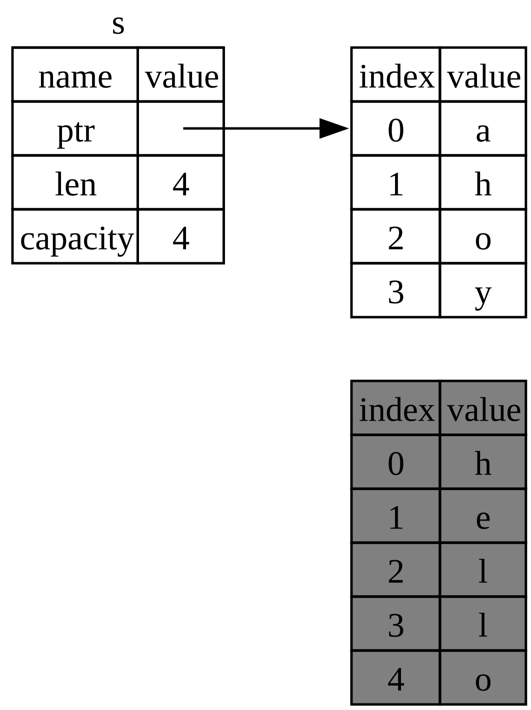


Figure 4-5: Representation in memory after the initial value has been replaced in its entirety.

The original string thus immediately goes out of scope. Rust will run the `drop` function on it and its memory will be freed right away. When we print the value at the end, it will be `"ahoy, world!"`.

Variables and Data Interacting with 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:

```
# fn main() {
    let s1 = String::from("hello");
    let s2 = s1.clone();

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

This works just fine and explicitly produces the behavior shown in Figure 4-3, 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 in Listing 4-2—works and is valid:

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

    println!("x = {x}, y = {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 such as 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 different 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 that are stored on the stack, as integers are (we'll talk more about traits in Chapter 10). If a type implements the `Copy` trait, variables that use it do not move, but rather are trivially copied, making them still valid after assignment to another variable.

Rust won't let us annotate a type with `Copy` 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 to implement the trait, see "Derivable Traits" in Appendix C.

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

- All the integer types, such as `u32`.
- The Boolean type, `bool`, with values `true` and `false`.
- All the floating-point types, such as `f64`.
- The character type, `char`.
- Tuples, if they only contain types that also implement `Copy`. For example, `(i32, i32)` implements `Copy`, but `(i32, String)` does not.

Ownership and Functions

The mechanics of passing a value to a function are similar to those when assigning a value to a variable. Passing a variable to a function will move or copy, just as assignment does. Listing 4-3 has an example with some annotations showing where variables go into and out of scope.

```
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);                  // Because i32 implements the Copy trait,
                                    // x does NOT move into the function,
                                    // so it's okay to use x afterward.

} // Here, x goes out of scope, then s. However, because 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.
```

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. Listing 4-4 shows an example of a function that returns some value, with similar annotations as those in Listing 4-3.

```
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 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("yours"); // some_string
comes into scope

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

```
// This function takes a String and returns a String.
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 ownership of the data has been moved to another variable.

While this works, 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.

Rust does let us return multiple values using a tuple, as shown in Listing 4-5.

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

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

    println!("The length of '{s2}' is {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 using a value without transferring ownership, called *references*.

References and Borrowing

The issue with the tuple code in Listing 4-5 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`. Instead, we can provide a reference to the `String` value. A *reference* is like a pointer in that it’s an address we can follow to access the data stored at that address; that data is owned by some other variable. Unlike a pointer, a reference is guaranteed to point to a valid value of a particular type for the life of that reference.

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:

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

    let len = calculate_length(&s1);

    println!("The length of '{s1}' is {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 represent *references*, and they allow you to refer to some value without taking ownership of it. Figure 4-6 depicts this concept.

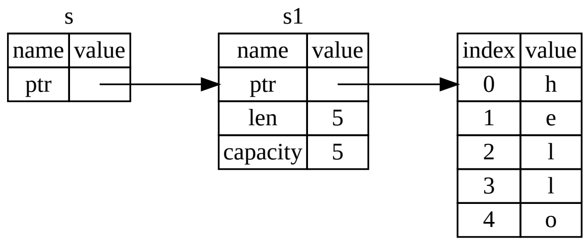


Figure 4-6: A diagram of `&String s` pointing at `String s1`

> Note: The opposite of referencing by using `&` is *dereferencing*, which is accomplished with the dereference operator, `*`. We'll see some uses of the dereference operator in Chapter 8 and discuss details of dereferencing in Chapter 15.

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

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

    let len = calculate_length(&s1);
#
#     println!("The length of '{s1}' is {len}.");
# }
#
# fn calculate_length(s: &String) -> usize {
#     s.len()
# }
```

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

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 main() {
#     let s1 = String::from("hello");
#
#     let len = calculate_length(&s1);
#
```

```
#     println!("The length of '{s1}' is {len}.");
# }
#
fn calculate_length(s: &String) -> usize { // s is a reference to a String
    s.len()
} // Here, s goes out of scope. But because s does not have ownership of what
  // it refers to, the String is not dropped.
```

The scope in which the variable `s` is valid is the same as any function parameter's scope, but the value pointed to by the reference is not dropped when `s` stops being used, because `s` doesn't have ownership. When functions have references as parameters instead of the actual values, we won't need to return the values in order to give back ownership, because we never had ownership.

We call the action of creating a reference *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. You don't own it.

So, what happens if we try to modify something we're borrowing? Try the code in Listing 4-6. Spoiler alert: it doesn't work!

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

    change(&s);
}

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

Here's the error:

```
$ cargo run
   Compiling ownership v0.1.0 (file:///projects/ownership)
error[E0596]: cannot borrow `*some_string` as mutable, as it is behind a `&` reference
```

```
 --> src/main.rs:8:5
  |
8 |     some_string.push_str(", world");
  |      ^^^^^^^^^^^ `some_string` is a `&` reference, so the
data it refers to cannot be borrowed as mutable
  |
help: consider changing this to be a mutable reference
  |
7 | fn change(some_string: &mut String) {
  |                         +++

For more information about this error, try `rustc --explain
E0596`.
error: could not compile `ownership` (bin "ownership") due to
1 previous error
```

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 code from Listing 4-6 to allow us to modify a borrowed value with just a few small tweaks that use, instead, a *mutable reference*:

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

    change(&mut s);
}

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

First we change `s` to be `mut`. Then we create a mutable reference with `&mut s` where we call the `change` function, and update the function signature to accept a mutable reference with `some_string: &mut String`.

This makes it very clear that the `change` function will mutate the value it borrows.

Mutable references have one big restriction: if you have a mutable reference to a value, you can have no other references to that value. This code that attempts to create two mutable references to `s` will fail:

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

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

    println!("{r1}, {r2}");
# }
```

Here's the error:

```
$ cargo run
   Compiling ownership v0.1.0 (file:///projects/ownership)
error[E0499]: cannot borrow `s` as mutable more than once at a
time
 --> src/main.rs:5:14
  |
4 |     let r1 = &mut s;
  |              ------ first mutable borrow occurs here
5 |     let r2 = &mut s;
  |              ^^^^^^ second mutable borrow occurs here
6 |
7 |     println!("{r1}, {r2}");
  |               ---- first borrow later used here

For more information about this error, try `rustc --explain
E0499`.
error: could not compile `ownership` (bin "ownership") due to
1 previous error
```

This error says that this code is invalid because we cannot borrow `s` as mutable more than once at a time. The first mutable borrow is in `r1` and must last until it's used in the `println!`, but between the creation of that mutable reference and its usage, we tried to create another mutable reference in `r2` that borrows the same data as `r1`.

The restriction preventing multiple mutable references to the same data at the same time 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 similar to a race condition and happens when these three behaviors occur:

- Two or more pointers access the same data at the same time.
- At least one of the pointers is being used to write to the data.
- 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 by refusing to 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:

```
# fn main() {
    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;
# }
```

Rust enforces a similar rule for combining mutable and immutable references. This code results in an error:

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

    let r1 = &s; // no problem
```

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

    println!("{r1}, {r2}, and {r3}");
# }
```

Here’s the error:

```
$ cargo run
   Compiling ownership v0.1.0 (file:///projects/ownership)
error[E0502]: cannot borrow `s` as mutable because it is also
borrowed as immutable
 --> src/main.rs:6:14
  |
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 |
8 |     println!("{r1}, {r2}, and {r3}");
  |               ---- immutable borrow later used here

For more information about this error, try `rustc --explain
E0502`.
error: could not compile `ownership` (bin "ownership") due to
1 previous error
```

Whew! We *also* cannot have a mutable reference while we have an immutable one to the same value.

Users of an immutable reference don’t expect the value to suddenly change out from under them! However, multiple immutable references are allowed because no one who is just reading the data has the ability to affect anyone else’s reading of the data.

Note that a reference’s scope starts from where it is introduced and continues through the last time that reference is used. For instance, this code will compile because the last usage of the immutable references is in the `println!`, before the mutable reference is introduced:

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

    let r1 = &s; // no problem
    let r2 = &s; // no problem
    println!("{r1} and {r2}");
    // Variables r1 and r2 will not be used after this point.

    let r3 = &mut s; // no problem
    println!("{r3}");
# }
```

The scopes of the immutable references `r1` and `r2` end after the `println!` where they are last used, which is before the mutable reference `r3` is created. These scopes don't overlap, so this code is allowed: the compiler can tell that the reference is no longer being used at a point before the end of the scope.

Even though borrowing 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. Then you don't have to track down why your data isn't what you thought it was.

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 you 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 to see how Rust prevents them with a compile-time error:

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

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

    &s
}
```

Here's the error:

```
$ cargo run
   Compiling ownership v0.1.0 (file:///projects/ownership)
error[E0106]: missing lifetime specifier
 --> src/main.rs:5:16
  |
5 | fn dangle() -> &String {
  |                ^ expected named lifetime parameter
  |
   = help: this function's return type contains a borrowed value, but there is no value for it to be borrowed from
help: consider using the `'static` lifetime, but this is uncommon unless you're returning a borrowed value from a `const` or a `static`
  |
5 | fn dangle() -> &'static String {
  |                 +++++++
help: instead, you are more likely to want to return an owned value
  |
5 - fn dangle() -> &String {
5 + fn dangle() -> String {
  |

error[E0515]: cannot return reference to local variable `s`
 --> src/main.rs:8:5
```

```
  |
8 |     &s
  |      ^^ returns a reference to data owned by the current
function

Some errors have detailed explanations: E0106, E0515.
For more information about an error, try `rustc --explain
E0106`.
error: could not compile `ownership` (bin "ownership") due to
2 previous errors
```

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 main() {
#     let reference_to_nothing = dangle();
# }
#
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, so 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 main() {
#     let string = no_dangle();
# }
#
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:

- At any given time, you can have *either* one mutable reference *or* any number of immutable references.
- References must always be valid.

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

The Slice Type

Slices let you reference a contiguous sequence of elements in a collection. A slice is a kind of reference, so it does not have ownership.

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

> Note: For the purposes of introducing string slices, we are assuming ASCII only in this section; a more thorough discussion of UTF-8 handling is in the "Storing UTF-8 Encoded Text with Strings" section of Chapter 8.

Let's work through how we'd write the signature of this function without using slices, to understand the problem that slices will solve:

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

The `first_word` function has a parameter of type `&String`. We don't need ownership, so this is fine. (In idiomatic Rust, functions do not take ownership of their arguments unless they need to, and the reasons for that will become clear as we keep going.) 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, indicated by a space. Let's try that, as shown in Listing 4-7.

```
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()
}
```

```
#
# fn main() {}
```

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.

```
# 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()
# }
#
# fn main() {}
```

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

```
# 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()
# }
#
# fn main() {}
```

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 that `enumerate` wraps the result of `iter` and returns each element as part of a tuple instead. The first element of the tuple returned from `enumerate` 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. We'll be discussing patterns more in Chapter 6. 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.

Inside the `for` loop, 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()`.

```
# 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()
# }
#
# fn main() {}
```

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 4-8 that uses the `first_word` function from Listing 4-7.

```
# 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()
# }
#
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 s no longer has
any content that we
    // could meaningfully use with the value 5, so word is now
totally invalid!
}
```

This program compiles without any errors and would also do so if we used `word` after calling `s.clear()`. Because `word` isn't connected to the state of `s` at all, `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 starting *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 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 a contiguous sequence of the elements of a `String`, and it looks like this:

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

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

Rather than a reference to the entire `String`, `hello` is a reference to a portion of the `String`, specified in the extra `[0..5]` bit. We create slices using a range within brackets by specifying `[starting_index..ending_index]`, where *`starting_index`* is the first position in the slice and *`ending_index`* is one more than the last position 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 byte at index 6 of `s` with a length value of `5`.

Figure 4-7 shows this in a diagram.

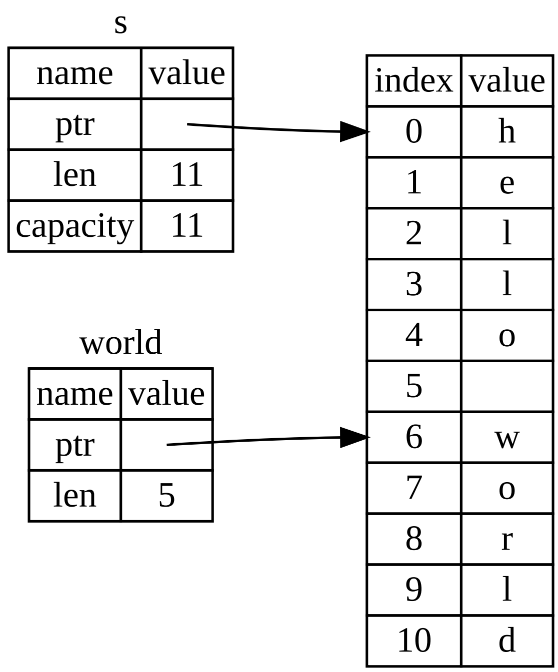


Figure 4-7: String slice referring to part of a `String`

With Rust's `..` range syntax, if you want to start at index 0, 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[..];
```

> Note: String slice range indices must occur at valid UTF-8 character boundaries. If you attempt to create a string slice in the middle of a multibyte character, your program will exit with an error.

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`:

```
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[..]
}
#
# fn main() {}
```

We get the index for the end of the word the same way we did in Listing 4-7, 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 because the compiler will ensure the references into the `String` remain valid. Remember the bug in the program in Listing 4-8, 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:

```
# 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[..]
# }
#
fn main() {
    let mut s = String::from("hello world");

    let word = first_word(&s);

    s.clear(); // error!

    println!("the first word is: {word}");
}
```

Here's the compiler error:

```
$ cargo run
   Compiling ownership v0.1.0 (file:///projects/ownership)
error[E0502]: cannot borrow `s` as mutable because it is also
```

```
borrowed as immutable
  --> src/main.rs:18:5
   |
16 |     let word = first_word(&s);
   |                           -- immutable borrow occurs here
17 |
18 |     s.clear(); // error!
   |     ^^^^^^^^^ mutable borrow occurs here
19 |
20 |     println!("the first word is: {word}");
   |                                  ------ immutable borrow
later used here

For more information about this error, try `rustc --explain
E0502`.
error: could not compile `ownership` (bin "ownership") due to
1 previous error
```

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 needs to get a mutable reference. The `println!` after the call to `clear` uses the reference in `word`, so the immutable reference must still be active at that point. Rust disallows the mutable reference in `clear` and the immutable reference in `word` from existing at the same time, and compilation 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 as 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` values 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 signature shown in Listing 4-9 instead because it allows us to use the same function on both `&String` values and `&str` values.

```
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[..]
# }
#
# fn main() {
#     let my_string = String::from("hello world");
#
#     // `first_word` works on slices of `String`s, whether
partial or whole.
#     let word = first_word(&my_string[0..6]);
#     let word = first_word(&my_string[..]);
#     // `first_word` also works on references to `String`s,
which are equivalent
#     // to whole slices of `String`s.
#     let word = first_word(&my_string);
#
#     let my_string_literal = "hello world";
#
#     // `first_word` works on slices of string literals,
```

```
whether partial or
#     // whole.
#     let word = first_word(&my_string_literal[0..6]);
#     let word = first_word(&my_string_literal[..]);
#
#     // Because string literals *are* string slices already,
#     // this works too, without the slice syntax!
#     let word = first_word(my_string_literal);
# }
```

If we have a string slice, we can pass that directly. If we have a `String`, we can pass a slice of the `String` or a reference to the `String`. This flexibility takes advantage of *deref coercions*, a feature we will cover in the "Implicit Deref Coercions with Functions and Methods" section of Chapter 15.

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:

```
# 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[..]
# }
#
fn main() {
    let my_string = String::from("hello world");

    // `first_word` works on slices of `String`s, whether
partial or whole.
```

```
    let word = first_word(&my_string[0..6]);
    let word = first_word(&my_string[..]);
    // `first_word` also works on references to `String`s, which are equivalent
    // to whole slices of `String`s.
    let word = first_word(&my_string);

    let my_string_literal = "hello world";

    // `first_word` works on slices of string literals, whether partial or
    // whole.
    let word = first_word(&my_string_literal[0..6]);
    let word = first_word(&my_string_literal[..]);

    // Because 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 as we might want to refer to part of a string, we might want to refer to part of an array. We'd do so like this:

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

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

assert_eq!(slice, &[2, 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 ensure memory safety in Rust programs at compile time. The Rust language gives you control over your memory usage in the same way as 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 Chapter 5 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 you package together and name 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 to build on what you already know and demonstrate when structs are a better way to group data.

We'll demonstrate how to define and instantiate structs. We'll discuss how to define associated functions, especially the kind of associated functions called *methods*, to specify behavior associated with a struct type. Structs and enums (discussed in Chapter 6) 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, discussed in [“The Tuple Type”](#) section, in that both hold multiple related values. Like tuples, the pieces of a struct can be different types. Unlike with tuples, in a struct you’ll name each piece of data so it’s clear what the values mean. Adding these names means that structs are more flexible than tuples: you 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 that stores information about a user account.

```
struct User {
    active: bool,
    username: String,
    email: String,
    sign_in_count: u64,
}
#
# fn main() {}
```

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.

```
# struct User {
#     active: bool,
#     username: String,
#     email: String,
```

```
#     sign_in_count: u64,
# }
#
fn main() {
    let user1 = User {
        active: true,
        username: String::from("someusername123"),
        email: String::from("someone@example.com"),
        sign_in_count: 1,
    };
}
```

To get a specific value from a struct, we use dot notation. For example, to access this user's email address, we use `user1.email`. 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.

```
# struct User {
#     active: bool,
#     username: String,
#     email: String,
#     sign_in_count: u64,
# }
#
fn main() {
    let mut user1 = User {
        active: true,
        username: String::from("someusername123"),
        email: String::from("someone@example.com"),
        sign_in_count: 1,
    };

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

Note that the entire instance must be mutable; Rust doesn't allow us to mark only certain fields as mutable. 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`.

```
# struct User {
#     active: bool,
#     username: String,
#     email: String,
#     sign_in_count: u64,
# }
#
fn build_user(email: String, username: String) -> User {
    User {
        active: true,
        username: username,
        email: email,
        sign_in_count: 1,
    }
}
#
# fn main() {
#     let user1 = build_user(
#         String::from("someone@example.com"),
#         String::from("someusername123"),
#     );
# }
```

It makes sense to name the function parameters 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

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 it behaves exactly the same but doesn't have the repetition of `username` and `email`, as shown in Listing 5-5.

```
# struct User {
#     active: bool,
#     username: String,
#     email: String,
#     sign_in_count: u64,
# }
#
fn build_user(email: String, username: String) -> User {
    User {
        active: true,
        username,
        email,
        sign_in_count: 1,
    }
}
#
# fn main() {
#     let user1 = build_user(
#         String::from("someone@example.com"),
#         String::from("someusername123"),
#     );
# }
```

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 includes most of the values from another instance of the same type, but changes some. You can do this using *struct update syntax*.

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

```
# struct User {
#     active: bool,
#     username: String,
#     email: String,
#     sign_in_count: u64,
# }
#
fn main() {
    // --snip--
#
#     let user1 = User {
#         email: String::from("someone@example.com"),
#         username: String::from("someusername123"),
#         active: true,
#         sign_in_count: 1,
#     };

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

Using struct update syntax, we can achieve the same effect with less code, as 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.

```
# struct User {
#     active: bool,
#     username: String,
#     email: String,
#     sign_in_count: u64,
# }
#
fn main() {
    // --snip--
#
#     let user1 = User {
#         email: String::from("someone@example.com"),
#         username: String::from("someusername123"),
#         active: true,
#         sign_in_count: 1,
#     };

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

The code in Listing 5-7 also creates an instance in `user2` that has a different value for `email` but has the same values for the `username`, `active`, and `sign_in_count` fields from `user1`. The `..user1` must come last to specify that any remaining fields should get their values from the corresponding fields in `user1`, but we can choose to specify values for as many fields as we want in any order, regardless of the order of the fields in the struct's definition.

Note that the struct update syntax uses `=` like an assignment; this is because it moves the data, just as we saw in the "Variables and Data Interacting with Move" section. In this example, we can no longer use `user1` after creating `user2` because the `String` in the `username` field of `user1` was moved into `user2`. If we had given `user2` new `String` values for both `email` and `username`, and thus only used the `active` and `sign_in_count` values from `user1`, then `user1` would still be valid after creating `user2`. Both `active` and `sign_in_count` are types that implement the `Copy` trait, so the behavior we discussed in the "Stack-Only Data: Copy" section would apply. We can also still use `user1.email` in this example, because its value was not moved out of `user1`.

Using Tuple Structs Without Named Fields to Create Different Types

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

To define a tuple struct, start with the `struct` keyword and the struct name followed by the types in the tuple. For example, here we define and use two tuple structs named `Color` and `Point`:

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

fn main() {
    let black = Color(0, 0, 0);
    let origin = Point(0, 0, 0);
}
```

Note that the `black` and `origin` values are different types because they're instances of different tuple structs. Each struct you define is its own type, even though the fields within the struct might 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 are similar to tuples in that you can destructure them into their individual pieces, and you can use a `.` followed by the index to access an individual value. Unlike tuples, tuple structs require you to name the type of the struct when you destructure them. For example, we would write `let Point(x, y, z) = origin;` to destructure the values in the `origin` point into variables named `x`, `y`, and `z`.

Unit-Like Structs Without Any Fields

You can also define structs that don't have any fields! These are called *unit-like structs* because they behave similarly to `()`, the unit type that we mentioned in "The Tuple Type" section. Unit-like structs can be useful when you need to implement a trait on some type but don't have any data that you want to store in the type itself. We'll discuss traits in Chapter 10. Here's an example of declaring and instantiating a unit struct named `AlwaysEqual`:

```
struct AlwaysEqual;

fn main() {
    let subject = AlwaysEqual;
}
```

To define `AlwaysEqual`, we use the `struct` keyword, the name we want, and then a semicolon. No need for curly brackets or parentheses! Then we can get an instance of `AlwaysEqual` in the `subject` variable in a similar way: using the name we defined, without any curly brackets or parentheses. Imagine that later we'll implement behavior for this type such that every instance of `AlwaysEqual` is always equal to every instance of any other type, perhaps to have a known result for testing purposes. We wouldn't need any data to implement that behavior! You'll see in Chapter 10 how to define traits and implement them on any type, including unit-like structs.

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 each instance 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 also 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 we’ll discuss 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 the following; this won’t work:

```
struct User {
    active: bool,
    username: &str,
    email: &str,
    sign_in_count: u64,
}

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

The compiler will complain that it needs lifetime specifiers:

```
$ cargo run
   Compiling structs v0.1.0 (file:///projects/structs)
error[E0106]: missing lifetime specifier
 --> src/main.rs:3:15
  |
3 |     username: &str,
  |               ^ expected named lifetime parameter
  |
```

```
help: consider introducing a named lifetime parameter
  |
1 ~ struct User<'a> {
2 |     active: bool,
3 ~     username: &'a str,
  |

error[E0106]: missing lifetime specifier
 --> src/main.rs:4:12
  |
4 |     email: &str,
  |            ^ expected named lifetime parameter
  |
help: consider introducing a named lifetime parameter
  |
1 ~ struct User<'a> {
2 |     active: bool,
3 |     username: &str,
4 ~     email: &'a str,
  |

For more information about this error, try `rustc --explain E0106`.
error: could not compile `structs` (bin "structs") due to 2 previous errors
```

In Chapter 10, we'll discuss how to fix these errors so you can store references in structs, 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 by using 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 calculate the area of the rectangle. Listing 5-8 shows a short program with one way of doing exactly that in our project's *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
}
```

Now, run this program using `cargo run`:

```
$ cargo run
   Compiling rectangles v0.1.0 (file:///projects/rectangles)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.42s
     Running `target/debug/rectangles`
The area of the rectangle is 1500 square pixels.
```

This code succeeds in figuring out the area of the rectangle by calling the `area` function with each dimension, but we can do more to make this code clear and readable.

The issue with this code is evident in the signature of `area`:

```
# 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
# }
```

The `area` function is supposed to calculate the area of one rectangle, but the function we wrote has two parameters, and it's not clear anywhere in our program that the parameters are related. 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 Tuple Type" section of Chapter 3: by using tuples.

Refactoring with Tuples

Listing 5-9 shows another version of our program that uses tuples.

```
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
}
```

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 we have to index into the parts of the tuple, making our calculation less obvious.

Mixing up the width and height wouldn't matter 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`. This would be even harder for someone else to figure out and keep in mind if they were to use our code. Because we haven't conveyed the meaning of our data in our code, it's now easier to introduce errors.

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 struct with a name for the whole as well as names for the parts, as shown in Listing 5-10.

```
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
}
```

Here, we've defined a struct and named it `Rectangle`. Inside the curly brackets, we defined the fields as `width` and `height`, both of which have type `u32`. Then, in `main`, we created a particular instance of `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 (note that accessing fields of a borrowed struct instance does not move the field values, which is why you often see borrows of structs). Our function signature for `area` now says exactly what we mean: calculate the area of `Rectangle`, using its `width` and `height` fields. This conveys that the width and height are related to each other, and it gives descriptive names to the values rather than using the tuple index values of `0` and `1`. This is a win for clarity.

Adding Useful Functionality with Derived Traits

It'd be useful to be able to print an instance of `Rectangle` while we're debugging our program and see the values for all its fields. Listing 5-11 tries using the [`println!` macro](#) as we have used in previous chapters. This won't work, however.

```
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
    let rect1 = Rectangle {
```

```
        width: 30,
        height: 50,
    };

    println!("rect1 is {rect1}");
}
```

When we compile this code, we get an error with this core message:

```
error[E0277]: `Rectangle` doesn't implement
`std::fmt::Display`
```

The `println!` macro can do many kinds of formatting, and by default, the curly brackets tell `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` to use with `println!` and the `{}` placeholder.

If we continue reading the errors, we'll find this helpful note:

```
   = help: the trait `std::fmt::Display` is not implemented
for `Rectangle`
   = note: in format strings you may be able to use `{:?}` (or
{:#?} for pretty-print) instead
```

Let's try it! The `println!` macro call will now look like `println!("rect1 is {rect1:?}");`. Putting the specifier `:?` inside the curly brackets tells `println!` we want to use an output format called `Debug`. The `Debug` trait enables us to print our struct in a way that is useful for developers so we can see its value while we're debugging our code.

Compile the code with this change. Drat! We still get an error:

```
error[E0277]: `Rectangle` doesn't implement `Debug`
```

But again, the compiler gives us a helpful note:

```
      = help: the trait `Debug` is not implemented for
`Rectangle`
    = note: add `#[derive(Debug)]` to `Rectangle` or manually
`impl Debug for Rectangle`
```

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 outer attribute `#[derive(Debug)]` just before the struct definition, as shown in Listing 5-12.

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
    let rect1 = Rectangle {
        width: 30,
        height: 50,
    };

    println!("rect1 is {rect1:?}");
}
```

Now when we run the program, we won't get any errors, and we'll see the following output:

```
$ cargo run
   Compiling rectangles v0.1.0 (file:///projects/rectangles)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.48s
     Running `target/debug/rectangles`
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. In this example, using the `{:#?}` style will output the following:

```
$ cargo run
   Compiling rectangles v0.1.0 (file:///projects/rectangles)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.48s
     Running `target/debug/rectangles`
rect1 is Rectangle {
    width: 30,
    height: 50,
}
```

Another way to print out a value using the `Debug` format is to use the [`dbg!` macro](), which takes ownership of an expression (as opposed to `println!`, which takes a reference), prints the file and line number of where that `dbg!` macro call occurs in your code along with the resultant value of that expression, and returns ownership of the value.

> Note: Calling the `dbg!` macro prints to the standard error console stream (`stderr`), as opposed to `println!`, which prints to the standard output console stream (`stdout`). We'll talk more about `stderr` and `stdout` in the [“Writing Error Messages to Standard Error Instead of Standard Output” section in Chapter 12]().

Here's an example where we're interested in the value that gets assigned to the `width` field, as well as the value of the whole struct in `rect1`:

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
    let scale = 2;
    let rect1 = Rectangle {
```

```
        width: dbg!(30 * scale),
        height: 50,
    };

    dbg!(&rect1);
}
```

We can put `dbg!` around the expression `30 * scale` and, because `dbg!` returns ownership of the expression's value, the `width` field will get the same value as if we didn't have the `dbg!` call there. We don't want `dbg!` to take ownership of `rect1`, so we use a reference to `rect1` in the next call. Here's what the output of this example looks like:

```
$ cargo run
   Compiling rectangles v0.1.0 (file:///projects/rectangles)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.61s
     Running `target/debug/rectangles`
[src/main.rs:10:16] 30 * scale = 60
[src/main.rs:14:5] &rect1 = Rectangle {
    width: 60,
    height: 50,
}
```

We can see the first bit of output came from *src/main.rs* line 10 where we're debugging the expression `30 * scale`, and its resultant value is `60` (the `Debug` formatting implemented for integers is to print only their value). The `dbg!` call on line 14 of *src/main.rs* outputs the value of `&rect1`, which is the `Rectangle` struct. This output uses the pretty `Debug` formatting of the `Rectangle` type. The `dbg!` macro can be really helpful when you're trying to figure out what your code is doing!

In addition to the `Debug` trait, Rust has provided a number of traits for us to use with the `derive` attribute 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. There are also many attributes other than `derive`; for more information, see [the “Attributes” section of the Rust Reference].

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: we declare them with the `fn` keyword and a name, they can have parameters and a return value, and they contain some code that's run when the method is called from somewhere else. Unlike functions, methods are defined within the context of a struct (or an enum or a trait object, which we cover in Chapter 6 and Chapter 18, 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.

```
#[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()
```

```
    );
}
```

To define the function within the context of `Rectangle`, we start an `impl` (implementation) block for `Rectangle`. Everything within this `impl` block will be associated with the `Rectangle` type. 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`. The `&self` is actually short for `self: &Self`. Within an `impl` block, the type `Self` is an alias for the type that the `impl` block is for. Methods must have a parameter named `self` of type `Self` for their first parameter, so Rust lets you abbreviate this with only the name `self` in the first parameter spot. Note that we still need to use the `&` in front of the `self` shorthand to indicate that this method borrows the `Self` instance, just as we did in `rectangle: &Rectangle`. Methods can take ownership of `self`, borrow `self` immutably, as we've done here, or borrow `self` mutably, just as they can any other parameter.

We chose `&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 you want to prevent the caller from using the original instance after the transformation.

The main reason for using methods instead of functions, in addition to providing 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.

Note that we can choose to give a method the same name as one of the struct's fields. For example, we can define a method on `Rectangle` that is also named `width`:

```
# #[derive(Debug)]
# struct Rectangle {
#     width: u32,
#     height: u32,
# }
#
impl Rectangle {
    fn width(&self) -> bool {
        self.width > 0
    }
}

fn main() {
    let rect1 = Rectangle {
        width: 30,
        height: 50,
    };

    if rect1.width() {
        println!("The rectangle has a nonzero width; it is
{}", rect1.width);
    }
}
```

Here, we're choosing to make the `width` method return `true` if the value in the instance's `width` field is greater than `0` and `false` if the value is `0`: we can use a field within a method of the same name for any purpose. In `main`, when we follow `rect1.width` with parentheses, Rust knows we mean the method `width`. When we don't use parentheses, Rust knows we mean the field `width`.

Often, but not always, when we give a method the same name as a field we want it to only return the value in the field and do nothing else. Methods like this are called *getters*, and Rust does not implement them automatically for struct fields as some other languages do. Getters are useful because you can make the field private but the method public, and thus enable read-only access to that field as part of the type's public API. We will discuss what public and private are and how to designate a field or method as public or private in Chapter 7.

Where's the -> Operator?

In C and 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 with 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:

```
# #[derive(Debug,Copy,Clone)]
# struct Point {
#     x: f64,
#     y: f64,
# }
#
# impl Point {
#    fn distance(&self, other: &Point) -> f64 {
#        let x_squared = f64::powi(other.x - self.x, 2);
#        let y_squared = f64::powi(other.y - self.y, 2);
```

```
#
#         f64::sqrt(x_squared + y_squared)
#     }
# }
# let p1 = Point { x: 0.0, y: 0.0 };
# let p2 = Point { x: 5.0, y: 6.5 };
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` (the first `Rectangle`); otherwise, it should return `false`. That is, once we've defined the `can_hold` method, we want to be able to write the program shown in Listing 5-14.

```
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));
}
```

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 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.

```
# #[derive(Debug)]
# struct Rectangle {
#     width: u32,
#     height: u32,
# }
#
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
    }
}
#
# 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));
# }
```

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

All functions defined within an `impl` block are called *associated functions* because they're associated with the type named after the `impl`. We can define associated functions that don't have `self` as their first parameter (and thus are not methods) because they don't need an instance of the type to work with. We've already used one function like this: the `String::from` function that's defined on the `String` type.

Associated functions that aren't methods are often used for constructors that will return a new instance of the struct. These are often called `new`, but `new` isn't a special name and isn't built into the language. For example, we could choose to provide an associated function named `square` 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

```
# #[derive(Debug)]
# struct Rectangle {
#     width: u32,
#     height: u32,
# }
#
impl Rectangle {
    fn square(size: u32) -> Self {
        Self {
            width: size,
            height: size,
        }
    }
}
#
# fn main() {
#     let sq = Rectangle::square(3);
# }
```

The `Self` keywords in the return type and in the body of the function are aliases for the type that appears after the `impl` keyword, which in this case is `Rectangle`.

To call this associated function, we use the `::` syntax with the struct name; `let sq = Rectangle::square(3);` is an example. This function is namespaced by the struct: the `::` syntax is used for both associated functions and namespaces created by modules. We'll discuss modules 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.

```
# #[derive(Debug)]
# struct Rectangle {
#     width: u32,
#     height: u32,
# }
#
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
    }
}
#
# 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));
# }
```

There’s no reason to separate these methods into multiple `impl` blocks here, but this is valid syntax. We’ll see a case in which multiple `impl` blocks are useful in Chapter 10, where we discuss generic types and traits.

Summary

Structs let you create custom types that are meaningful for your domain. By using structs, you can keep associated pieces of data connected to each other and name each piece to make your code clear. In `impl` blocks, you can define functions that are associated with your type, and methods are a kind of associated function that let you specify the behavior that instances of your structs have.

But structs aren't the only way you can create custom types: let's turn to Rust's enum feature to add another tool to your 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 *variants*. 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 handle enums in your code.

Defining an Enum

Where structs give you a way of grouping together related fields and data, like a `Rectangle` with its `width` and `height`, enums give you a way of saying a value is one of a possible set of values. For example, we may want to say that `Rectangle` is one of a set of possible shapes that also includes `Circle` and `Triangle`. To do this, Rust allows us to encode these possibilities as 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. Because these are the only possibilities for an IP address that our program will come across, we can *enumerate* all possible variants, 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 because an enum value can only be one of its 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 the variants of the enum:

```
enum IpAddrKind {
    V4,
    V6,
}
#
# fn main() {
#     let four = IpAddrKind::V4;
#     let six = IpAddrKind::V6;
#
#     route(IpAddrKind::V4);
#     route(IpAddrKind::V6);
```

```
# }
#
# fn route(ip_kind: IpAddrKind) {}
```

`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:

```
# enum IpAddrKind {
#     V4,
#     V6,
# }
#
# fn main() {
    let four = IpAddrKind::V4;
    let six = IpAddrKind::V6;
#
#     route(IpAddrKind::V4);
#     route(IpAddrKind::V6);
# }
#
# fn route(ip_kind: IpAddrKind) {}
```

Note that the variants of the enum are namespaced under its identifier, and we use a double colon to separate the two. This is useful because 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`:

```
# enum IpAddrKind {
#     V4,
#     V6,
# }
#
# fn main() {
```

```
#     let four = IpAddrKind::V4;
#     let six = IpAddrKind::V6;
#
#     route(IpAddrKind::V4);
#     route(IpAddrKind::V6);
# }
#
fn route(ip_kind: IpAddrKind) {}
```

And we can call this function with either variant:

```
# enum IpAddrKind {
#     V4,
#     V6,
# }
#
# fn main() {
#     let four = IpAddrKind::V4;
#     let six = IpAddrKind::V6;
#
    route(IpAddrKind::V4);
    route(IpAddrKind::V6);
# }
#
# fn route(ip_kind: IpAddrKind) {}
```

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 be tempted to tackle this problem with structs as shown in Listing 6-1.

```
# fn main() {
    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"),
    };
# }
```

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 is `home`, and it has the value `IpAddrKind::V4` as its `kind` with associated address data of `127.0.0.1`. The second instance is `loopback`. It 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.

However, representing the same concept using just an enum is more concise: rather than an enum inside a struct, we can put 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:

```
# fn main() {
    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. Here, it's also easier to see another detail of how enums work: the name of each enum variant that we define also becomes a function that constructs an instance of the enum. That is, `IpAddr::V4()` is a function call that takes a `String` argument and returns an instance of the `IpAddr` type. We automatically get this constructor function defined as a result of defining the enum.

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 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:

```
# fn main() {
    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 ways to define data structures to store version four and version six IP addresses. 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:

```
struct Ipv4Addr {
    // --snip--
}

struct Ipv6Addr {
    // --snip--
}

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 bringing types into scope 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.

```
enum Message {
    Quit,
    Move { x: i32, y: i32 },
    Write(String),
    ChangeColor(i32, i32, i32),
}
#
# fn main() {}
```

This enum has four variants with different types:

- `Quit`: Has no data associated with it at all
- `Move`: Has named fields, like a struct does

- `Write`: Includes a single `String`
- `ChangeColor`: Includes three `i32` values

Defining an enum with variants such as 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
#
# fn main() {}
```

But if we used the different structs, each of which has its own type, we couldn't as easily define a function to 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:

```
# fn main() {
#     enum Message {
#         Quit,
#         Move { x: i32, y: i32 },
#         Write(String),
#         ChangeColor(i32, i32, i32),
#     }
#
    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

This section explores a case study of `Option`, which is another enum defined by the standard library. The `Option` type encodes the very common scenario in which a value could be something or it could be nothing.

For example, if you request the first item in a non-empty list, you would get a value. If you request the first item in an empty list, you would get nothing. Expressing this concept in terms of the type system means the compiler can check whether you've handled all the cases you should be handling; this functionality 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 his 2009 presentation "Null References: The Billion Dollar Mistake," Tony Hoare, the inventor of null, had 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 use a null value as 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 really with the 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> {
    None,
    Some(T),
}
```

The `Option<T>` enum is so useful that it's even included in the prelude; you don't need to bring it into scope explicitly. Its variants are also included in the prelude: you can use `Some` and `None` directly without the `Option::` prefix. The `Option<T>` enum 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 that the `Some` variant of the `Option` enum can hold one piece of data of any type, and that each concrete type that gets used in place of `T` makes the overall `Option<T>`

type a different type. Here are some examples of using `Option` values to hold number types and char types:

```
# fn main() {
    let some_number = Some(5);
    let some_char = Some('e');

    let absent_number: Option<i32> = None;
# }
```

The type of `some_number` is `Option<i32>`. The type of `some_char` is `Option<char>`, which is a different type. Rust can infer these types because we've specified a value inside the `Some` variant. For `absent_number`, Rust requires us to annotate the overall `Option` type: the compiler can't infer the type that the corresponding `Some` variant will hold by looking only at a `None` value. Here, we tell Rust that we mean for `absent_number` to be of type `Option<i32>`.

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 were definitely a valid value. For example, this code won't compile, because it's trying to add an `i8` to an `Option<i8>`:

```
# fn main() {
    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 one:

```
$ cargo run
   Compiling enums v0.1.0 (file:///projects/enums)
```

```
error[E0277]: cannot add `Option<i8>` to `i8`
 --> src/main.rs:5:17
  |
5 |     let sum = x + y;
  |                 ^ no implementation for `i8 + Option<i8>`
  |
  = help: the trait `Add<Option<i8>>` is not implemented for
`i8`
  = help: the following other types implement trait
`Add<Rhs>`:
            `&i8` implements `Add<i8>`
            `&i8` implements `Add`
            `i8` implements `Add<&i8>`
            `i8` implements `Add`

For more information about this error, try `rustc --explain
E0277`.
error: could not compile `enums` (bin "enums") due to 1
previous error
```

Intense! In effect, this error message means that Rust doesn't understand how to add an `i8` and an `Option<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.

Eliminating the risk of incorrectly assuming 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 that 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, you want to have code that will handle each variant. You want some code that will run only when you have a `Some(T)` value, and this code is allowed to use the inner `T`. You want some other code to run only if you 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 Construct

Rust has an extremely powerful control flow construct called `match` that allows you 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 19](#) covers all the different kinds of patterns and what they do. The power of `match` comes from the expressiveness of the patterns and the fact that the compiler confirms that all possible cases are handled.

Think of a `match` expression as being 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 falls into the associated code block to be used during execution.

Speaking of coins, let's use them as an example using `match`! We can write a function that takes an unknown US coin and, in a similar way as the counting machine, determines which coin it is and returns its value in cents, as shown in Listing 6-3.

```
enum Coin {
    Penny,
    Nickel,
    Dime,
    Quarter,
}

fn value_in_cents(coin: Coin) -> u8 {
    match coin {
        Coin::Penny => 1,
        Coin::Nickel => 5,
        Coin::Dime => 10,
        Coin::Quarter => 25,
    }
}
```

```
#
# fn main() {}
```

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 a conditional expression used with `if`, but there's a big difference: with `if`, the condition needs to evaluate to a Boolean value, but here it can be any type. The type of `coin` in this example is the `Coin` enum that we defined on the first line.

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 resultant 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 as in 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 resultant value of the expression in the matching arm is the value that gets returned for the entire `match` expression.

We don't typically use curly brackets 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 must use curly brackets, and the comma following the arm is then optional. For example, the following code prints "Lucky penny!" every time the method is called with a `Coin::Penny`, but still returns the last value of the block, `1`:

```
# enum Coin {
#     Penny,
#     Nickel,
```

```
#     Dime,
#     Quarter,
# }
#
fn value_in_cents(coin: Coin) -> u8 {
    match coin {
        Coin::Penny => {
            println!("Lucky penny!");
            1
        }
        Coin::Nickel => 5,
        Coin::Dime => 10,
        Coin::Quarter => 25,
    }
}
#
# fn main() {}
```

Patterns That Bind to Values

Another useful feature of match arms is that they can bind to the 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 in Listing 6-4.

```
#[derive(Debug)] // so we can inspect the state in a minute
enum UsState {
    Alabama,
    Alaska,
    // --snip--
}
```

```
enum Coin {
    Penny,
    Nickel,
    Dime,
    Quarter(UsState),
}
#
# fn main() {}
```

Let’s imagine that a friend 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 that 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:

```
# #[derive(Debug)]
# enum UsState {
#     Alabama,
#     Alaska,
#     // --snip--
# }
#
# enum Coin {
#     Penny,
#     Nickel,
#     Dime,
#     Quarter(UsState),
# }
#
fn value_in_cents(coin: Coin) -> u8 {
    match coin {
```

```
        Coin::Penny => 1,
        Coin::Nickel => 5,
        Coin::Dime => 10,
        Coin::Quarter(state) => {
            println!("State quarter from {state:?}!");
            25
        }
    }
}
#
# fn main() {
#     value_in_cents(Coin::Quarter(UsState::Alaska));
# }
```

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 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 1 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 main() {
    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);
# }
```

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:

```
# fn main() {
#     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);
# }
```

The `Some(5)` value doesn't match the pattern `None`, so we continue to the next arm:

```
# fn main() {
#     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);
# }
```

Does `Some(5)` match `Some(i)`? 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 1 to the value of `i` and create a new `Some` value with our total `6` inside.

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:

```
# fn main() {
#     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);
# }
```

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: the arms' patterns must cover all possibilities. Consider this version of our `plus_one` function, which has a bug and won't compile:

```
# fn main() {
    fn plus_one(x: Option<i32>) -> Option<i32> {
        match x {
            Some(i) => Some(i + 1),
        }
    }
#
#     let five = Some(5);
#     let six = plus_one(five);
#     let none = plus_one(None);
# }
```

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:

```
$ cargo run
   Compiling enums v0.1.0 (file:///projects/enums)
error[E0004]: non-exhaustive patterns: `None` not covered
 --> src/main.rs:3:15
  |
3 |         match x {
  |               ^ pattern `None` not covered
  |
note: `Option<i32>` defined here
                                                            -->
```

```
/rustc/4eb161250e340c8f48f66e2b929ef4a5bed7c181/library/core/s
rc/option.rs:572:1
                                                            :::
/rustc/4eb161250e340c8f48f66e2b929ef4a5bed7c181/library/core/s
rc/option.rs:576:5
  |
  = note: not covered
  = note: the matched value is of type `Option<i32>`
help: ensure that all possible cases are being handled by
adding a match arm with a wildcard pattern or an explicit
pattern as shown
  |
4 ~             Some(i) => Some(i + 1),
5 ~             None => todo!(),
  |

For more information about this error, try `rustc --explain
E0004`.
error: could not compile `enums` (bin "enums") due to 1
previous error
```

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 impossible.

Catch-All Patterns and the _ Placeholder

Using enums, we can also take special actions for a few particular values, but for all other values take one default action. Imagine we're implementing a game where, if you roll a 3 on a dice roll, your player doesn't move, but instead gets a new fancy hat. If you roll a 7, your player loses a fancy hat. For all other values, your player moves that number of spaces on the game board. Here's a `match` that implements that logic, with the result of the dice roll hardcoded rather than a random value, and all other logic represented by functions without bodies because actually implementing them is out of scope for this example:

```
# fn main() {
    let dice_roll = 9;
    match dice_roll {
        3 => add_fancy_hat(),
        7 => remove_fancy_hat(),
        other => move_player(other),
    }

    fn add_fancy_hat() {}
    fn remove_fancy_hat() {}
    fn move_player(num_spaces: u8) {}
# }
```

For the first two arms, the patterns are the literal values `3` and `7`. For the last arm that covers every other possible value, the pattern is the variable we've chosen to name `other`. The code that runs for the `other` arm uses the variable by passing it to the `move_player` function.

This code compiles, even though we haven't listed all the possible values a `u8` can have, because the last pattern will match all values not specifically listed. This catch-all pattern meets the requirement that `match` must be exhaustive. Note that we have to put the catch-all arm last because the patterns are evaluated in order. If we put the catch-all arm earlier, the other arms would never run, so Rust will warn us if we add arms after a catch-all!

Rust also has a pattern we can use when we want a catch-all but don't want to *use* the value in the catch-all pattern: `_` is a special pattern that matches any value and does not bind to that value. This tells Rust we aren't going to use the value, so Rust won't warn us about an unused variable.

Let's change the rules of the game: now, if you roll anything other than a 3 or a 7, you must roll again. We no longer need to use the catch-all value, so we can change our code to use `_` instead of the variable named `other`:

```
# fn main() {
    let dice_roll = 9;
    match dice_roll {
        3 => add_fancy_hat(),
        7 => remove_fancy_hat(),
        _ => reroll(),
    }

    fn add_fancy_hat() {}
    fn remove_fancy_hat() {}
    fn reroll() {}
# }
```

This example also meets the exhaustiveness requirement because we're explicitly ignoring all other values in the last arm; we haven't forgotten anything.

Finally, we'll change the rules of the game one more time so that nothing else happens on your turn if you roll anything other than a 3 or a 7. We can express that by using the unit value (the empty tuple type we mentioned in "The Tuple Type" section) as the code that goes with the `_` arm:

```
# fn main() {
    let dice_roll = 9;
    match dice_roll {
        3 => add_fancy_hat(),
        7 => remove_fancy_hat(),
        _ => (),
    }

    fn add_fancy_hat() {}
    fn remove_fancy_hat() {}
# }
```

Here, we're telling Rust explicitly that we aren't going to use any other value that doesn't match a pattern in an earlier arm, and we don't want to run any code in this case.

There’s more about patterns and matching that we’ll cover in Chapter 19. For now, we’re going to move on to the `if let` syntax, which can be useful in situations where the `match` expression is a bit wordy.

Concise Control Flow with `if let` and `let else`

The `if let` syntax lets you combine `if` and `let` into a less verbose way to handle values that match one pattern while ignoring the rest. Consider the program in Listing 6-6 that matches on an `Option<u8>` value in the `config_max` variable but only wants to execute code if the value is the `Some` variant.

```
# fn main() {
    let config_max = Some(3u8);
    match config_max {
        Some(max) => println!("The maximum is configured to be
{max}"),
        _ => (),
    }
# }
```

If the value is `Some`, we print out the value in the `Some` variant by binding the value to the variable `max` in the pattern. We don't want to do anything with the `None` value. To satisfy the `match` expression, we have to add `_ => ()` after processing just one variant, which is annoying 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:

```
# fn main() {
    let config_max = Some(3u8);
    if let Some(max) = config_max {
        println!("The maximum is configured to be {max}");
    }
# }
```

The syntax `if let` takes a pattern and an expression separated by an equal sign. It works the same way as a `match`, where the expression is given to the `match` and the pattern is its first arm. In this case, the pattern is `Some(max)`, and the `max` binds to the value inside the `Some`. We can then use `max` in the body of the `if let` block in the same way we used `max` in the corresponding `match` arm. The code in the `if let` block only runs if the value matches the pattern.

Using `if let` means less typing, less indentation, and less boilerplate code. However, you lose the exhaustive checking `match` enforces that ensures you aren't forgetting to handle any cases. Choosing between `match` and `if let` depends on what you're doing in your particular situation and whether 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:

```
# #[derive(Debug)]
# enum UsState {
#     Alabama,
#     Alaska,
#     // --snip--
# }
#
# enum Coin {
#     Penny,
#     Nickel,
#     Dime,
#     Quarter(UsState),
# }
#
```

```
# fn main() {
#     let coin = Coin::Penny;
    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:

```
# #[derive(Debug)]
# enum UsState {
#     Alabama,
#     Alaska,
#     // --snip--
# }
#
# enum Coin {
#     Penny,
#     Nickel,
#     Dime,
#     Quarter(UsState),
# }
#
# fn main() {
#     let coin = Coin::Penny;
    let mut count = 0;
    if let Coin::Quarter(state) = coin {
        println!("State quarter from {state:?}!");
    } else {
        count += 1;
    }
# }
```

Staying on the “Happy Path” with `let...else`

The common pattern is to perform some computation when a value is present and return a default value otherwise. Continuing on with our example of coins with a `UsState` value, if we wanted to say something funny depending on how old the state on the quarter was, we might introduce a method on `UsState` to check the age of a state, like so:

```
# #[derive(Debug)] // so we can inspect the state in a minute
# enum UsState {
#     Alabama,
#     Alaska,
#     // --snip--
# }
#
impl UsState {
    fn existed_in(&self, year: u16) -> bool {
        match self {
            UsState::Alabama => year >= 1819,
            UsState::Alaska => year >= 1959,
            // -- snip --
        }
    }
}
#
# enum Coin {
#     Penny,
#     Nickel,
#     Dime,
#     Quarter(UsState),
# }
#
# fn describe_state_quarter(coin: Coin) -> Option<String> {
#     if let Coin::Quarter(state) = coin {
#         if state.existed_in(1900) {
#                  Some(format!("{state:?} is pretty old, for
```

```
America!"))
#         } else {
#             Some(format!("{state:?} is relatively new."))
#         }
#     } else {
#         None
#     }
# }
#
# fn main() {
#                             if      let      Some(desc)      =
describe_state_quarter(Coin::Quarter(UsState::Alaska)) {
#         println!("{desc}");
#     }
# }
```

Then we might use `if let` to match on the type of coin, introducing a `state` variable within the body of the condition, as in Listing 6-7.

```
# #[derive(Debug)] // so we can inspect the state in a minute
# enum UsState {
#     Alabama,
#     Alaska,
#     // --snip--
# }
#
# impl UsState {
#     fn existed_in(&self, year: u16) -> bool {
#         match self {
#             UsState::Alabama => year >= 1819,
#             UsState::Alaska => year >= 1959,
#             // -- snip --
#         }
#     }
# }
#
# enum Coin {
```

```
#     Penny,
#     Nickel,
#     Dime,
#     Quarter(UsState),
# }
#
fn describe_state_quarter(coin: Coin) -> Option<String> {
    if let Coin::Quarter(state) = coin {
        if state.existed_in(1900) {
                  Some(format!("{state:?} is pretty old, for
America!"))
        } else {
            Some(format!("{state:?} is relatively new."))
        }
    } else {
        None
    }
}
#
# fn main() {
#     if let Some(desc) =
describe_state_quarter(Coin::Quarter(UsState::Alaska)) {
#         println!("{desc}");
#     }
# }
```

That gets the job done, but it has pushed the work into the body of the `if let` statement, and if the work to be done is more complicated, it might be hard to follow exactly how the top-level branches relate. We could also take advantage of the fact that expressions produce a value either to produce the `state` from the `if let` or to return early, as in Listing 6-8. (You could do similar with a `match`, too.)

```
# #[derive(Debug)] // so we can inspect the state in a minute
# enum UsState {
#     Alabama,
#     Alaska,
```

```
#     // --snip--
# }
#
# impl UsState {
#     fn existed_in(&self, year: u16) -> bool {
#         match self {
#             UsState::Alabama => year >= 1819,
#             UsState::Alaska => year >= 1959,
#             // -- snip --
#         }
#     }
# }
#
# enum Coin {
#     Penny,
#     Nickel,
#     Dime,
#     Quarter(UsState),
# }
#
fn describe_state_quarter(coin: Coin) -> Option<String> {
    let state = if let Coin::Quarter(state) = coin {
        state
    } else {
        return None;
    };

    if state.existed_in(1900) {
        Some(format!("{state:?} is pretty old, for America!"))
    } else {
        Some(format!("{state:?} is relatively new."))
    }
}
#
# fn main() {
#                              if      let      Some(desc)      =
```

```
describe_state_quarter(Coin::Quarter(UsState::Alaska)) {
#         println!("{desc}");
#     }
# }
```

This is a bit annoying to follow in its own way, though! One branch of the `if let` produces a value, and the other one returns from the function entirely.

To make this common pattern nicer to express, Rust has `let...else`. The `let...else` syntax takes a pattern on the left side and an expression on the right, very similar to `if let`, but it does not have an `if` branch, only an `else` branch. If the pattern matches, it will bind the value from the pattern in the outer scope. If the pattern does *not* match, the program will flow into the `else` arm, which must return from the function.

In Listing 6-9, you can see how Listing 6-8 looks when using `let...else` in place of `if let`.

```
# #[derive(Debug)] // so we can inspect the state in a minute
# enum UsState {
#     Alabama,
#     Alaska,
#     // --snip--
# }
#
# impl UsState {
#     fn existed_in(&self, year: u16) -> bool {
#         match self {
#             UsState::Alabama => year >= 1819,
#             UsState::Alaska => year >= 1959,
#             // -- snip --
#         }
#     }
# }
#
# enum Coin {
#     Penny,
```

```
#     Nickel,
#     Dime,
#     Quarter(UsState),
# }
#
fn describe_state_quarter(coin: Coin) -> Option<String> {
    let Coin::Quarter(state) = coin else {
        return None;
    };

    if state.existed_in(1900) {
        Some(format!("{state:?} is pretty old, for America!"))
    } else {
        Some(format!("{state:?} is relatively new."))
    }
}
#
# fn main() {
#                             if      let      Some(desc)      =
describe_state_quarter(Coin::Quarter(UsState::Alaska)) {
#         println!("{desc}");
#     }
# }
```

Notice that it stays "on the happy path" in the main body of the function this way, without having significantly different control flow for two branches the way the `if let` did.

If you have a situation in which your program has logic that is too verbose to express using a `match`, remember that `if let` and `let...else` are 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.

Managing Growing Projects with Packages, Crates, and Modules

As you write large programs, organizing your code will become increasingly important. By grouping related functionality and separating code with distinct features, you'll clarify where to find code that implements a particular feature and where to go to change how a feature works.

The programs we've written so far have been in one module in one file. As a project grows, you should organize code by splitting it into multiple modules and then multiple files. A package can contain multiple binary crates and optionally one library crate. As a package grows, you can extract parts into separate crates that become external dependencies. This chapter covers all these techniques. For very large projects comprising a set of interrelated packages that evolve together, Cargo provides *workspaces*, which we'll cover in “Cargo Workspaces” in Chapter 14.

We'll also discuss encapsulating implementation details, which lets you reuse code at a higher level: once you've implemented an operation, other code can call your code via its public interface without having to know how the implementation works. The way you write code defines which parts are public for other code to use and which parts are private implementation details that you reserve the right to change. This is another way to limit the amount of detail you have to keep in your head.

A related concept is scope: the nested context in which code is written has a set of names that are defined as “in scope.” When reading, writing, and compiling code, programmers and compilers need to know whether a particular name at a particular spot refers to a variable, function, struct, enum, module, constant, or other item and what that item means. You can create scopes and change which names are in or out of scope. You can't have two items with the same name in the same scope; tools are available to resolve name conflicts.

Rust has a number of features that allow you to manage your code's organization, including which details are exposed, which details are private, and what names are in each scope in your programs. These features, sometimes collectively referred to as the *module system*, include:

- **Packages**: A Cargo feature that lets you build, test, and share crates
- **Crates**: A tree of modules that produces a library or executable
- **Modules and use**: Let you control the organization, scope, and privacy of paths
- **Paths**: A way of naming an item, such as a struct, function, or module

In this chapter, we'll cover all these features, discuss how they interact, and explain how to use them to manage scope. By the end, you should have a solid understanding of the module system and be able to work with scopes like a pro!

Packages and Crates

The first parts of the module system we'll cover are packages and crates.

A *crate* is the smallest amount of code that the Rust compiler considers at a time. Even if you run `rustc` rather than `cargo` and pass a single source code file (as we did all the way back in "Writing and Running a Rust Program" in Chapter 1), the compiler considers that file to be a crate. Crates can contain modules, and the modules may be defined in other files that get compiled with the crate, as we'll see in the coming sections.

A crate can come in one of two forms: a binary crate or a library crate. *Binary crates* are programs you can compile to an executable that you can run, such as a command line program or a server. Each must have a function called `main` that defines what happens when the executable runs. All the crates we've created so far have been binary crates.

Library crates don't have a `main` function, and they don't compile to an executable. Instead, they define functionality intended to be shared with multiple projects. For example, the `rand` crate we used in Chapter 2 provides functionality that generates random numbers. Most of the time when Rustaceans say "crate," they mean library crate, and they use "crate" interchangeably with the general programming concept of a "library."

The *crate root* is a source file that the Rust compiler starts from and makes up the root module of your crate (we'll explain modules in depth in "Defining Modules to Control Scope and Privacy").

A *package* is a bundle of one or more crates that provides a set of functionality. A package contains a *Cargo.toml* file that describes how to build those crates. Cargo is actually a package that contains the binary crate for the command line tool you've been using to build your code. The Cargo package also contains a library crate that the binary crate depends on. Other projects can depend on the Cargo library crate to use the same logic the Cargo command line tool uses.

A package can contain as many binary crates as you like, but at most only one library crate. A package must contain at least one crate, whether that's a library or binary crate.

Let's walk through what happens when we create a package. First we enter the command `cargo new my-project`:

```
$ cargo new my-project
     Created binary (application) `my-project` package
$ ls my-project
Cargo.toml
src
$ ls my-project/src
main.rs
```

After we run `cargo new my-project`, we use `ls` to see what Cargo creates. In the project directory, there's a *Cargo.toml* file, giving us a package. There's also a *src* directory that contains *main.rs*. Open *Cargo.toml* in your text editor, and note there's no mention of *src/main.rs*. Cargo follows a convention that *src/main.rs* is the crate root of a binary crate with the same name as the package. Likewise, Cargo knows that if the package directory contains *src/lib.rs*, the package contains a library crate with the same name as the package, and *src/lib.rs* is its crate root. Cargo passes the crate root files to `rustc` to build the library or binary.

Here, we have a package that only contains *src/main.rs*, meaning it only contains a binary crate named `my-project`. If a package contains *src/main.rs* and *src/lib.rs*, it has two crates: a binary and a library, both with the same name as the package. A package can have multiple binary crates by placing files in the *src/bin* directory: each file will be a separate binary crate.

Defining Modules to Control Scope and Privacy

In this section, we’ll talk about modules and other parts of the module system, namely *paths*, which allow you to name items; the `use` keyword that brings a path into scope; and the `pub` keyword to make items public. We’ll also discuss the `as` keyword, external packages, and the glob operator.

Modules Cheat Sheet

Before we get to the details of modules and paths, here we provide a quick reference on how modules, paths, the `use` keyword, and the `pub` keyword work in the compiler, and how most developers organize their code. We’ll be going through examples of each of these rules throughout this chapter, but this is a great place to refer to as a reminder of how modules work.

- **Start from the crate root**: When compiling a crate, the compiler first looks in the crate root file (usually *src/lib.rs* for a library crate or *src/main.rs* for a binary crate) for code to compile.
- **Declaring modules**: In the crate root file, you can declare new modules; say you declare a “garden” module with `mod garden;`. The compiler will look for the module’s code in these places:
    - Inline, within curly brackets that replace the semicolon following `mod garden`
    - In the file *src/garden.rs*
    - In the file *src/garden/mod.rs*
- **Declaring submodules**: In any file other than the crate root, you can declare submodules. For example, you might declare `mod vegetables;` in *src/garden.rs*. The compiler will look for the submodule’s code within the directory named for the parent module in these places:
    - Inline, directly following `mod vegetables`, within curly brackets instead of the semicolon

    - In the file *src/garden/vegetables.rs*
    - In the file *src/garden/vegetables/mod.rs*
- **Paths to code in modules**: Once a module is part of your crate, you can refer to code in that module from anywhere else in that same crate, as long as the privacy rules allow, using the path to the code. For example, an `Asparagus` type in the garden vegetables module would be found at `crate::garden::vegetables::Asparagus`.
- **Private vs. public**: Code within a module is private from its parent modules by default. To make a module public, declare it with `pub mod` instead of `mod`. To make items within a public module public as well, use `pub` before their declarations.
- **The `use` keyword**: Within a scope, the `use` keyword creates shortcuts to items to reduce repetition of long paths. In any scope that can refer to `crate::garden::vegetables::Asparagus`, you can create a shortcut with `use crate::garden::vegetables::Asparagus;` and from then on you only need to write `Asparagus` to make use of that type in the scope.

Here, we create a binary crate named `backyard` that illustrates these rules. The crate's directory, also named `backyard`, contains these files and directories:

```
backyard
├── Cargo.lock
├── Cargo.toml
└── src
    ├── garden
    │   └── vegetables.rs
    ├── garden.rs
    └── main.rs
```

The crate root file in this case is *src/main.rs*, and it contains:

```
use crate::garden::vegetables::Asparagus;

pub mod garden;
```

```
fn main() {
    let plant = Asparagus {};
    println!("I'm growing {plant:?}!");
}
```

The `pub mod garden;` line tells the compiler to include the code it finds in *src/garden.rs*, which is:

```
pub mod vegetables;
```

Here, `pub mod vegetables;` means the code in *src/garden/vegetables.rs* is included too. That code is:

```
#[derive(Debug)]
pub struct Asparagus {}
```

Now let's get into the details of these rules and demonstrate them in action!

Grouping Related Code in Modules

Modules let us organize code within a crate for readability and easy reuse. Modules also allow us to control the *privacy* of items because code within a module is private by default. Private items are internal implementation details not available for outside use. We can choose to make modules and the items within them public, which exposes them to allow external code to use and depend on them.

As an example, let's write a library crate that provides the functionality of a restaurant. We'll define the signatures of functions but leave their bodies empty to concentrate on the organization of the code rather than the implementation of a restaurant.

In the restaurant industry, some parts of a restaurant are referred to as *front of house* and others as *back of house*. Front of house is where customers are; this encompasses where the hosts seat customers, servers take orders and payment, and bartenders make drinks. Back of house is where the chefs and cooks work in the kitchen, dishwashers clean up, and managers do administrative work.

To structure our crate in this way, we can organize its functions into nested modules. Create a new library named `restaurant` by running `cargo` `new restaurant --lib`. Then enter the code in Listing 7-1 into *src/lib.rs* to define some modules and function signatures; this code is the front of house section.

```
mod front_of_house {
    mod hosting {
        fn add_to_waitlist() {}

        fn seat_at_table() {}
    }

    mod serving {
        fn take_order() {}

        fn serve_order() {}

        fn take_payment() {}
    }
}
```

We define a module with the `mod` keyword followed by the name of the module (in this case, `front_of_house`). The body of the module then goes inside curly brackets. Inside modules, we can place other modules, as in this case with the modules `hosting` and `serving`. Modules can also hold definitions for other items, such as structs, enums, constants, traits, and as in Listing 7-1, functions.

By using modules, we can group related definitions together and name why they're related. Programmers using this code can navigate the code based on the groups rather than having to read through all the definitions, making it easier to find the definitions relevant to them. Programmers adding new functionality to this code would know where to place the code to keep the program organized.

Earlier, we mentioned that *src/main.rs* and *src/lib.rs* are called crate roots. The reason for their name is that the contents of either of these two files form a module named `crate` at the root of the crate's module structure, known as the *module tree*.

Listing 7-2 shows the module tree for the structure in Listing 7-1.

```
crate
 └── front_of_house
     ├── hosting
     │   ├── add_to_waitlist
     │   └── seat_at_table
     └── serving
         ├── take_order
         ├── serve_order
         └── take_payment
```

This tree shows how some of the modules nest inside other modules; for example, `hosting` nests inside `front_of_house`. The tree also shows that some modules are *siblings*, meaning they're defined in the same module; `hosting` and `serving` are siblings defined within `front_of_house`. If module A is contained inside module B, we say that module A is the *child* of module B and that module B is the *parent* of module A. Notice that the entire module tree is rooted under the implicit module named `crate`.

The module tree might remind you of the filesystem's directory tree on your computer; this is a very apt comparison! Just like directories in a filesystem, you use modules to organize your code. And just like files in a directory, we need a way to find our modules.

Paths for Referring to an Item in the Module Tree

To show Rust where to find an item in a module tree, we use a path in the same way we use a path when navigating a filesystem. To call a function, we need to know its path.

A path can take two forms:

- An *absolute path* is the full path starting from a crate root; for code from an external crate, the absolute path begins with the crate name, and for code from the current crate, it starts with the literal `crate`.
- A *relative path* starts from the current module and uses `self`, `super`, or an identifier in the current module.

Both absolute and relative paths are followed by one or more identifiers separated by double colons (`::`).

Returning to Listing 7-1, say we want to call the `add_to_waitlist` function. This is the same as asking: what's the path of the `add_to_waitlist` function? Listing 7-3 contains Listing 7-1 with some of the modules and functions removed.

We'll show two ways to call the `add_to_waitlist` function from a new function, `eat_at_restaurant`, defined in the crate root. These paths are correct, but there's another problem remaining that will prevent this example from compiling as is. We'll explain why in a bit.

The `eat_at_restaurant` function is part of our library crate's public API, so we mark it with the `pub` keyword. In the "Exposing Paths with the `pub` Keyword" section, we'll go into more detail about `pub`.

```
mod front_of_house {
    mod hosting {
        fn add_to_waitlist() {}
    }
}

pub fn eat_at_restaurant() {
    // Absolute path
```

```
    crate::front_of_house::hosting::add_to_waitlist();

    // Relative path
    front_of_house::hosting::add_to_waitlist();
}
```

The first time we call the `add_to_waitlist` function in `eat_at_restaurant`, we use an absolute path. The `add_to_waitlist` function is defined in the same crate as `eat_at_restaurant`, which means we can use the `crate` keyword to start an absolute path. We then include each of the successive modules until we make our way to `add_to_waitlist`. You can imagine a filesystem with the same structure: we'd specify the path `/front_of_house/hosting/add_to_waitlist` to run the `add_to_waitlist` program; using the `crate` name to start from the crate root is like using `/` to start from the filesystem root in your shell.

The second time we call `add_to_waitlist` in `eat_at_restaurant`, we use a relative path. The path starts with `front_of_house`, the name of the module defined at the same level of the module tree as `eat_at_restaurant`. Here the filesystem equivalent would be using the path `front_of_house/hosting/add_to_waitlist`. Starting with a module name means that the path is relative.

Choosing whether to use a relative or absolute path is a decision you'll make based on your project, and it depends on whether you're more likely to move item definition code separately from or together with the code that uses the item. For example, if we moved the `front_of_house` module and the `eat_at_restaurant` function into a module named `customer_experience`, we'd need to update the absolute path to `add_to_waitlist`, but the relative path would still be valid. However, if we moved the `eat_at_restaurant` function separately into a module named `dining`, the absolute path to the `add_to_waitlist` call would stay the same, but the relative path would need to be updated. Our preference in general is to specify absolute paths because it's more likely we'll want to move code definitions and item calls independently of each other.

Let’s try to compile Listing 7-3 and find out why it won’t compile yet! The errors we get are shown in Listing 7-4.

```
$ cargo build
   Compiling restaurant v0.1.0 (file:///projects/restaurant)
error[E0603]: module `hosting` is private
 --> src/lib.rs:9:28
  |
9 |     crate::front_of_house::hosting::add_to_waitlist();
   |                                ^^^^^^^  ---------------
function `add_to_waitlist` is not publicly re-exported
  |                            |
  |                            private module
  |
note: the module `hosting` is defined here
 --> src/lib.rs:2:5
  |
2 |     mod hosting {
  |     ^^^^^^^^^^^

error[E0603]: module `hosting` is private
  --> src/lib.rs:12:21
   |
12 |     front_of_house::hosting::add_to_waitlist();
    |                        ^^^^^^^  --------------- function
`add_to_waitlist` is not publicly re-exported
   |                      |
   |                      private module
   |
note: the module `hosting` is defined here
  --> src/lib.rs:2:5
   |
2  |     mod hosting {
   |     ^^^^^^^^^^^

For more information about this error, try `rustc --explain
```

```
E0603`.
error: could not compile `restaurant` (lib) due to 2 previous
errors
```

The error messages say that module `hosting` is private. In other words, we have the correct paths for the `hosting` module and the `add_to_waitlist` function, but Rust won't let us use them because it doesn't have access to the private sections. In Rust, all items (functions, methods, structs, enums, modules, and constants) are private to parent modules by default. If you want to make an item like a function or struct private, you put it in a module.

Items in a parent module can't use the private items inside child modules, but items in child modules can use the items in their ancestor modules. This is because child modules wrap and hide their implementation details, but the child modules can see the context in which they're defined. To continue with our metaphor, think of the privacy rules as being like the back office of a restaurant: what goes on in there is private to restaurant customers, but office managers can see and do everything in the restaurant they operate.

Rust chose to have the module system function this way so that hiding inner implementation details is the default. That way, you know which parts of the inner code you can change without breaking outer code. However, Rust does give you the option to expose inner parts of child modules' code to outer ancestor modules by using the `pub` keyword to make an item public.

Exposing Paths with the `pub` Keyword

Let's return to the error in Listing 7-4 that told us the `hosting` module is private. We want the `eat_at_restaurant` function in the parent module to have access to the `add_to_waitlist` function in the child module, so we mark the `hosting` module with the `pub` keyword, as shown in Listing 7-5.

```
mod front_of_house {
    pub mod hosting {
        fn add_to_waitlist() {}
    }
```

```
}

// -- snip --
# pub fn eat_at_restaurant() {
#     // Absolute path
#     crate::front_of_house::hosting::add_to_waitlist();
#
#     // Relative path
#     front_of_house::hosting::add_to_waitlist();
# }
```

Unfortunately, the code in Listing 7-5 still results in compiler errors, as shown in Listing 7-6.

```
$ cargo build
   Compiling restaurant v0.1.0 (file:///projects/restaurant)
error[E0603]: function `add_to_waitlist` is private
  --> src/lib.rs:10:37
   |
10 |     crate::front_of_house::hosting::add_to_waitlist();
   |                                     ^^^^^^^^^^^^^^^
private function
   |
note: the function `add_to_waitlist` is defined here
  --> src/lib.rs:3:9
   |
3  |         fn add_to_waitlist() {}
   |         ^^^^^^^^^^^^^^^^^^^^

error[E0603]: function `add_to_waitlist` is private
  --> src/lib.rs:13:30
   |
13 |     front_of_house::hosting::add_to_waitlist();
   |                              ^^^^^^^^^^^^^^^ private
function
   |
note: the function `add_to_waitlist` is defined here
```

```
  --> src/lib.rs:3:9
   |
3  |         fn add_to_waitlist() {}
   |         ^^^^^^^^^^^^^^^^^^^^

For more information about this error, try `rustc --explain
E0603`.
error: could not compile `restaurant` (lib) due to 2 previous
errors
```

What happened? Adding the `pub` keyword in front of `mod hosting` makes the module public. With this change, if we can access `front_of_house`, we can access `hosting`. But the *contents* of `hosting` are still private; making the module public doesn't make its contents public. The `pub` keyword on a module only lets code in its ancestor modules refer to it, not access its inner code. Because modules are containers, there's not much we can do by only making the module public; we need to go further and choose to make one or more of the items within the module public as well.

The errors in Listing 7-6 say that the `add_to_waitlist` function is private. The privacy rules apply to structs, enums, functions, and methods as well as modules.

Let's also make the `add_to_waitlist` function public by adding the `pub` keyword before its definition, as in Listing 7-7.

```
mod front_of_house {
    pub mod hosting {
        pub fn add_to_waitlist() {}
    }
}

// -- snip --
# pub fn eat_at_restaurant() {
#     // Absolute path
#     crate::front_of_house::hosting::add_to_waitlist();
#
```

```
#     // Relative path
#     front_of_house::hosting::add_to_waitlist();
# }
```

Now the code will compile! To see why adding the `pub` keyword lets us use these paths in `eat_at_restaurant` with respect to the privacy rules, let's look at the absolute and the relative paths.

In the absolute path, we start with `crate`, the root of our crate's module tree. The `front_of_house` module is defined in the crate root. While `front_of_house` isn't public, because the `eat_at_restaurant` function is defined in the same module as `front_of_house` (that is, `eat_at_restaurant` and `front_of_house` are siblings), we can refer to `front_of_house` from `eat_at_restaurant`. Next is the `hosting` module marked with `pub`. We can access the parent module of `hosting`, so we can access `hosting`. Finally, the `add_to_waitlist` function is marked with `pub` and we can access its parent module, so this function call works!

In the relative path, the logic is the same as the absolute path except for the first step: rather than starting from the crate root, the path starts from `front_of_house`. The `front_of_house` module is defined within the same module as `eat_at_restaurant`, so the relative path starting from the module in which `eat_at_restaurant` is defined works. Then, because `hosting` and `add_to_waitlist` are marked with `pub`, the rest of the path works, and this function call is valid!

If you plan on sharing your library crate so other projects can use your code, your public API is your contract with users of your crate that determines how they can interact with your code. There are many considerations around managing changes to your public API to make it easier for people to depend on your crate. These considerations are beyond the scope of this book; if you're interested in this topic, see [The Rust API Guidelines]().

Best Practices for Packages with a Binary and a Library

We mentioned that a package can contain both a *src/main.rs* binary crate root as well as a *src/lib.rs* library crate root, and both crates will have the package name by default. Typically, packages with this pattern of containing both a library and a binary crate will have just enough code in the binary crate to start an executable that calls code defined in the library crate. This lets other projects benefit from the most functionality that the package provides because the library crate's code can be shared.

The module tree should be defined in *src/lib.rs*. Then, any public items can be used in the binary crate by starting paths with the name of the package. The binary crate becomes a user of the library crate just like a completely external crate would use the library crate: it can only use the public API. This helps you design a good API; not only are you the author, you're also a client!

In Chapter 12, we'll demonstrate this organizational practice with a command line program that will contain both a binary crate and a library crate.

Starting Relative Paths with `super`

We can construct relative paths that begin in the parent module, rather than the current module or the crate root, by using `super` at the start of the path. This is like starting a filesystem path with the `..` syntax that means to go to the parent directory. Using `super` allows us to reference an item that we know is in the parent module, which can make rearranging the module tree easier when the module is closely related to the parent but the parent might be moved elsewhere in the module tree someday.

Consider the code in Listing 7-8 that models the situation in which a chef fixes an incorrect order and personally brings it out to the customer. The function `fix_incorrect_order` defined in the `back_of_house` module calls the function `deliver_order` defined in the parent module by specifying the path to `deliver_order`, starting with `super`.

```
fn deliver_order() {}

mod back_of_house {
    fn fix_incorrect_order() {
        cook_order();
```

```
        super::deliver_order();
    }

    fn cook_order() {}
}
```

The `fix_incorrect_order` function is in the `back_of_house` module, so we can use `super` to go to the parent module of `back_of_house`, which in this case is `crate`, the root. From there, we look for `deliver_order` and find it. Success! We think the `back_of_house` module and the `deliver_order` function are likely to stay in the same relationship to each other and get moved together should we decide to reorganize the crate's module tree. Therefore, we used `super` so we'll have fewer places to update code in the future if this code gets moved to a different module.

Making Structs and Enums Public

We can also use `pub` to designate structs and enums as public, but there are a few extra details to the usage of `pub` with structs and enums. If we use `pub` before a struct definition, we make the struct public, but the struct's fields will still be private. We can make each field public or not on a case-by-case basis. In Listing 7-9, we've defined a public `back_of_house::Breakfast` struct with a public `toast` field but a private `seasonal_fruit` field. This models the case in a restaurant where the customer can pick the type of bread that comes with a meal, but the chef decides which fruit accompanies the meal based on what's in season and in stock. The available fruit changes quickly, so customers can't choose the fruit or even see which fruit they'll get.

```
mod back_of_house {
    pub struct Breakfast {
        pub toast: String,
        seasonal_fruit: String,
    }

    impl Breakfast {
        pub fn summer(toast: &str) -> Breakfast {
```

```
            Breakfast {
                toast: String::from(toast),
                seasonal_fruit: String::from("peaches"),
            }
        }
    }
}

pub fn eat_at_restaurant() {
    // Order a breakfast in the summer with Rye toast.
    let mut meal = back_of_house::Breakfast::summer("Rye");
    // Change our mind about what bread we'd like.
    meal.toast = String::from("Wheat");
    println!("I'd like {} toast please", meal.toast);

    // The next line won't compile if we uncomment it; we're
not allowed
    // to see or modify the seasonal fruit that comes with the
meal.
    // meal.seasonal_fruit = String::from("blueberries");
}
```

Because the `toast` field in the `back_of_house::Breakfast` struct is public, in `eat_at_restaurant` we can write and read to the `toast` field using dot notation. Notice that we can't use the `seasonal_fruit` field in `eat_at_restaurant`, because `seasonal_fruit` is private. Try uncommenting the line modifying the `seasonal_fruit` field value to see what error you get!

Also, note that because `back_of_house::Breakfast` has a private field, the struct needs to provide a public associated function that constructs an instance of `Breakfast` (we've named it `summer` here). If `Breakfast` didn't have such a function, we couldn't create an instance of `Breakfast` in `eat_at_restaurant` because we couldn't set the value of the private `seasonal_fruit` field in `eat_at_restaurant`.

In contrast, if we make an enum public, all of its variants are then public. We only need the `pub` before the `enum` keyword, as shown in Listing 7-10.

```
mod back_of_house {
    pub enum Appetizer {
        Soup,
        Salad,
    }
}

pub fn eat_at_restaurant() {
    let order1 = back_of_house::Appetizer::Soup;
    let order2 = back_of_house::Appetizer::Salad;
}
```

Because we made the `Appetizer` enum public, we can use the `Soup` and `Salad` variants in `eat_at_restaurant`.

Enums aren't very useful unless their variants are public; it would be annoying to have to annotate all enum variants with `pub` in every case, so the default for enum variants is to be public. Structs are often useful without their fields being public, so struct fields follow the general rule of everything being private by default unless annotated with `pub`.

There's one more situation involving `pub` that we haven't covered, and that is our last module system feature: the `use` keyword. We'll cover `use` by itself first, and then we'll show how to combine `pub` and `use`.

Bringing Paths into Scope with the `use` Keyword

Having to write out the paths to call functions can feel inconvenient and repetitive. In Listing 7-7, whether we chose the absolute or relative path to the `add_to_waitlist` function, every time we wanted to call `add_to_waitlist` we had to specify `front_of_house` and `hosting` too. Fortunately, there's a way to simplify this process: we can create a shortcut to a path with the `use` keyword once, and then use the shorter name everywhere else in the scope.

In Listing 7-11, we bring the `crate::front_of_house::hosting` module into the scope of the `eat_at_restaurant` function so we only have to specify `hosting::add_to_waitlist` to call the `add_to_waitlist` function in `eat_at_restaurant`.

```
mod front_of_house {
    pub mod hosting {
        pub fn add_to_waitlist() {}
    }
}

use crate::front_of_house::hosting;

pub fn eat_at_restaurant() {
    hosting::add_to_waitlist();
}
```

Adding `use` and a path in a scope is similar to creating a symbolic link in the filesystem. By adding `use crate::front_of_house::hosting` in the crate root, `hosting` is now a valid name in that scope, just as though the `hosting` module had been defined in the crate root. Paths brought into scope with `use` also check privacy, like any other paths.

Note that `use` only creates the shortcut for the particular scope in which the `use` occurs. Listing 7-12 moves the `eat_at_restaurant` function into a new child module named `customer`, which is then a different scope than the `use` statement, so the function body won't compile.

```
mod front_of_house {
    pub mod hosting {
        pub fn add_to_waitlist() {}
    }
}

use crate::front_of_house::hosting;

mod customer {
    pub fn eat_at_restaurant() {
        hosting::add_to_waitlist();
    }
}
```

The compiler error shows that the shortcut no longer applies within the `customer` module:

```
$ cargo build
   Compiling restaurant v0.1.0 (file:///projects/restaurant)
error[E0433]: failed to resolve: use of undeclared crate or module `hosting`
  --> src/lib.rs:11:9
   |
11 |         hosting::add_to_waitlist();
   |         ^^^^^^^ use of undeclared crate or module `hosting`
   |
help: consider importing this module through its public re-export
   |
10 +     use crate::hosting;
   |

warning: unused import: `crate::front_of_house::hosting`
```

```
 --> src/lib.rs:7:5
  |
7 | use crate::front_of_house::hosting;
  |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
  |
  = note: `#[warn(unused_imports)]` on by default

For more information about this error, try `rustc --explain
E0433`.
warning: `restaurant` (lib) generated 1 warning
error: could not compile `restaurant` (lib) due to 1 previous
error; 1 warning emitted
```

Notice there's also a warning that the `use` is no longer used in its scope! To fix this problem, move the `use` within the `customer` module too, or reference the shortcut in the parent module with `super::hosting` within the child `customer` module.

Creating Idiomatic `use` Paths

In Listing 7-11, you might have wondered why we specified `use crate::front_of_house::hosting` and then called `hosting::add_to_waitlist` in `eat_at_restaurant`, rather than specifying the `use` path all the way out to the `add_to_waitlist` function to achieve the same result, as in Listing 7-13.

```
mod front_of_house {
    pub mod hosting {
        pub fn add_to_waitlist() {}
    }
}

use crate::front_of_house::hosting::add_to_waitlist;

pub fn eat_at_restaurant() {
    add_to_waitlist();
}
```

Although both Listing 7-11 and Listing 7-13 accomplish the same task, Listing 7-11 is the idiomatic way to bring a function into scope with `use`. Bringing the function's parent module into scope with `use` means we have to specify the parent module when calling the function. Specifying the parent module when calling the function makes it clear that the function isn't locally defined while still minimizing repetition of the full path. The code in Listing 7-13 is unclear as to where `add_to_waitlist` is defined.

On the other hand, when bringing in structs, enums, and other items with `use`, it's idiomatic to specify the full path. Listing 7-14 shows the idiomatic way to bring the standard library's `HashMap` struct into the scope of a binary crate.

```
use std::collections::HashMap;

fn main() {
    let mut map = HashMap::new();
    map.insert(1, 2);
}
```

There's no strong reason behind this idiom: it's just the convention that has emerged, and folks have gotten used to reading and writing Rust code this way.

The exception to this idiom is if we're bringing two items with the same name into scope with `use` statements, because Rust doesn't allow that. Listing 7-15 shows how to bring two `Result` types into scope that have the same name but different parent modules, and how to refer to them.

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

fn function1() -> fmt::Result {
    // --snip--
#     Ok(())
}

fn function2() -> io::Result<()> {
```

```
    // --snip--
#     Ok(())
}
```

As you can see, using the parent modules distinguishes the two `Result` types. If instead we specified `use std::fmt::Result` and `use std::io::Result`, we'd have two `Result` types in the same scope, and Rust wouldn't know which one we meant when we used `Result`.

Providing New Names with the `as` Keyword

There's another solution to the problem of bringing two types of the same name into the same scope with `use`: after the path, we can specify `as` and a new local name, or *alias*, for the type. Listing 7-16 shows another way to write the code in Listing 7-15 by renaming one of the two `Result` types using `as`.

```
use std::fmt::Result;
use std::io::Result as IoResult;

fn function1() -> Result {
    // --snip--
#     Ok(())
}

fn function2() -> IoResult<()> {
    // --snip--
#     Ok(())
}
```

In the second `use` statement, we chose the new name `IoResult` for the `std::io::Result` type, which won't conflict with the `Result` from `std::fmt` that we've also brought into scope. Listing 7-15 and Listing 7-16 are considered idiomatic, so the choice is up to you!

Re-exporting Names with `pub use`

When we bring a name into scope with the `use` keyword, the name is private to the scope into which we imported it. To enable code outside that scope to refer to that name as if it had been defined in that scope, we can combine `pub` and `use`. This technique is called *re-exporting* because we're bringing an item into scope but also making that item available for others to bring into their scope.

Listing 7-17 shows the code in Listing 7-11 with `use` in the root module changed to `pub use`.

```
mod front_of_house {
    pub mod hosting {
        pub fn add_to_waitlist() {}
    }
}

pub use crate::front_of_house::hosting;

pub fn eat_at_restaurant() {
    hosting::add_to_waitlist();
}
```

Before this change, external code would have to call the `add_to_waitlist` function by using the path `restaurant::front_of_house::hosting::add_to_waitlist()`, which also would have required the `front_of_house` module to be marked as `pub`. Now that this `pub use` has re-exported the `hosting` module from the root module, external code can use the path `restaurant::hosting::add_to_waitlist()` instead.

Re-exporting is useful when the internal structure of your code is different from how programmers calling your code would think about the domain. For example, in this restaurant metaphor, the people running the restaurant think about "front of house" and "back of house." But customers visiting a restaurant probably won't think about the parts of the restaurant in those terms. With `pub use`, we can write our code with one structure but expose a different structure. Doing so makes our library well organized for programmers working on the library and programmers calling the library. We'll look at another example of `pub use` and how it affects your crate's documentation in "Exporting a Convenient Public API with `pub use`" in Chapter 14.

Using External Packages

In Chapter 2, we programmed a guessing game project that used an external package called `rand` to get random numbers. To use `rand` in our project, we added this line to *Cargo.toml*:

```
rand = "0.8.5"
```

Adding `rand` as a dependency in *Cargo.toml* tells Cargo to download the `rand` package and any dependencies from crates.io and make `rand` available to our project.

Then, to bring `rand` definitions into the scope of our package, we added a `use` line starting with the name of the crate, `rand`, and listed the items we wanted to bring into scope. Recall that in "Generating a Random Number" in Chapter 2, we brought the `Rng` trait into scope and called the `rand::thread_rng` function:

```
# use std::io;
#
use rand::Rng;

fn main() {
#     println!("Guess the number!");
#
    let secret_number = rand::thread_rng().gen_range(1..=100);
#
#     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}");
}
```

Members of the Rust community have made many packages available at crates.io, and pulling any of them into your package involves these same steps: listing them in your package's *Cargo.toml* file and using `use` to bring items from their crates into scope.

Note that the standard `std` library is also a crate that's external to our package. Because the standard library is shipped with the Rust language, we don't need to change *Cargo.toml* to include `std`. But we do need to refer to it with `use` to bring items from there into our package's scope. For example, with `HashMap` we would use this line:

```
use std::collections::HashMap;
```

This is an absolute path starting with `std`, the name of the standard library crate.

Using Nested Paths to Clean Up Large `use` Lists

If we're using multiple items defined in the same crate or same module, listing each item on its own line can take up a lot of vertical space in our files. For example, these two `use` statements we had in the guessing game in Listing 2-4 bring items from `std` into scope:

```
# use rand::Rng;
// --snip--
use std::cmp::Ordering;
use std::io;
// --snip--
#
# fn main() {
#     println!("Guess the number!");
#
```

```
#                                let      secret_number      =
rand::thread_rng().gen_range(1..=100);
#
#     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!"),
#     }
# }
```

Instead, we can use nested paths to bring the same items into scope in one line. We do this by specifying the common part of the path, followed by two colons, and then curly brackets around a list of the parts of the paths that differ, as shown in Listing 7-18.

```
# use rand::Rng;
// --snip--
use std::{cmp::Ordering, io};
// --snip--
#
# fn main() {
#     println!("Guess the number!");
#
#                                let      secret_number      =
rand::thread_rng().gen_range(1..=100);
```

```
#
#     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!"),
#     }
# }
```

In bigger programs, bringing many items into scope from the same crate or module using nested paths can reduce the number of separate `use` statements needed by a lot!

We can use a nested path at any level in a path, which is useful when combining two `use` statements that share a subpath. For example, Listing 7-19 shows two `use` statements: one that brings `std::io` into scope and one that brings `std::io::Write` into scope.

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

The common part of these two paths is `std::io`, and that's the complete first path. To merge these two paths into one `use` statement, we can use `self` in the nested path, as shown in Listing 7-20.

```
use std::io::{self, Write};
```

This line brings `std::io` and `std::io::Write` into scope.

The Glob Operator

If we want to bring *all* public items defined in a path into scope, we can specify that path followed by the `*` glob operator:

```
use std::collections::*;
```

This `use` statement brings all public items defined in `std::collections` into the current scope. Be careful when using the glob operator! Glob can make it harder to tell what names are in scope and where a name used in your program was defined. Additionally, if the dependency changes its definitions, what you've imported changes as well, which may lead to compiler errors when you upgrade the dependency if the dependency adds a definition with the same name as a definition of yours in the same scope, for example.

The glob operator is often used when testing to bring everything under test into the `tests` module; we'll talk about that in "How to Write Tests" in Chapter 11. The glob operator is also sometimes used as part of the prelude pattern: see the standard library documentation for more information on that pattern.

Separating Modules into Different Files

So far, all the examples in this chapter defined multiple modules in one file. When modules get large, you might want to move their definitions to a separate file to make the code easier to navigate.

For example, let's start from the code in Listing 7-17 that had multiple restaurant modules. We'll extract modules into files instead of having all the modules defined in the crate root file. In this case, the crate root file is *src/lib.rs*, but this procedure also works with binary crates whose crate root file is *src/main.rs*.

First we'll extract the `front_of_house` module to its own file. Remove the code inside the curly brackets for the `front_of_house` module, leaving only the `mod front_of_house;` declaration, so that *src/lib.rs* contains the code shown in Listing 7-21. Note that this won't compile until we create the *src/front_of_house.rs* file in Listing 7-22.

```
mod front_of_house;

pub use crate::front_of_house::hosting;

pub fn eat_at_restaurant() {
    hosting::add_to_waitlist();
}
```

Next, place the code that was in the curly brackets into a new file named *src/front_of_house.rs*, as shown in Listing 7-22. The compiler knows to look in this file because it came across the module declaration in the crate root with the name `front_of_house`.

```
pub mod hosting {
    pub fn add_to_waitlist() {}
}
```

Note that you only need to load a file using a `mod` declaration *once* in your module tree. Once the compiler knows the file is part of the project (and knows where in the module tree the code resides because of where you've put the `mod` statement), other files in your project should refer to the loaded file's code using a path to where it was declared, as covered in the "Paths for Referring to an Item in the Module Tree" section. In other words, `mod` is *not* an "include" operation that you may have seen in other programming languages.

Next, we'll extract the `hosting` module to its own file. The process is a bit different because `hosting` is a child module of `front_of_house`, not of the root module. We'll place the file for `hosting` in a new directory that will be named for its ancestors in the module tree, in this case *src/front_of_house*.

To start moving `hosting`, we change *src/front_of_house.rs* to contain only the declaration of the `hosting` module:

```
pub mod hosting;
```

Then we create a *src/front_of_house* directory and a *hosting.rs* file to contain the definitions made in the `hosting` module:

```
pub fn add_to_waitlist() {}
```

If we instead put *hosting.rs* in the *src* directory, the compiler would expect the *hosting.rs* code to be in a `hosting` module declared in the crate root, and not declared as a child of the `front_of_house` module. The compiler's rules for which files to check for which modules' code mean the directories and files more closely match the module tree.

Alternate File Paths

So far we've covered the most idiomatic file paths the Rust compiler uses, but Rust also supports an older style of file path. For a module named `front_of_house` declared in the crate root, the compiler will look for the module's code in:

- *src/front_of_house.rs* (what we covered)
- *src/front_of_house/mod.rs* (older style, still supported path)

For a module named `hosting` that is a submodule of `front_of_house`, the compiler will look for the module's code in:

- *src/front_of_house/hosting.rs* (what we covered)

- *src/front_of_house/hosting/mod.rs* (older style, still supported path)

If you use both styles for the same module, you'll get a compiler error. Using a mix of both styles for different modules in the same project is allowed, but might be confusing for people navigating your project.

The main downside to the style that uses files named *mod.rs* is that your project can end up with many files named *mod.rs*, which can get confusing when you have them open in your editor at the same time.

We've moved each module's code to a separate file, and the module tree remains the same. The function calls in `eat_at_restaurant` will work without any modification, even though the definitions live in different files. This technique lets you move modules to new files as they grow in size.

Note that the `pub use crate::front_of_house::hosting` statement in *src/lib.rs* also hasn't changed, nor does `use` have any impact on what files are compiled as part of the crate. The `mod` keyword declares modules, and Rust looks in a file with the same name as the module for the code that goes into that module.

Summary

Rust lets you split a package into multiple crates and a crate into modules so you can refer to items defined in one module from another module. You can do this by specifying absolute or relative paths. These paths can be brought into scope with a `use` statement so you can use a shorter path for multiple uses of the item in that scope. Module code is private by default, but you can make definitions public by adding the `pub` keyword.

In the next chapter, we’ll look at some collection data structures in the standard library that you can use in your neatly organized 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 that 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 you to store a variable number of values next to each other.
- A *string* is a collection of characters. We've mentioned the `String` type previously, but in this chapter we'll talk about it in depth.
- A *hash map* allows you to associate a value with a specific 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.

Storing Lists of Values with Vectors

The first collection type we'll look at is `Vec<T>`, also known as a *vector*. Vectors allow you 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 when 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 call the `Vec::new` function, as shown in Listing 8-1.

```
# fn main() {
    let v: Vec<i32> = Vec::new();
# }
```

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. When we create a vector to hold a specific type, we can specify the type within angle brackets. In Listing 8-1, we've told Rust that the `Vec<T>` in `v` will hold elements of the `i32` type.

More often, you'll create a `Vec<T>` with initial values and Rust will infer the type of value you want to store, so you rarely need to do this type annotation. Rust conveniently provides the `vec!` macro, which will create a new vector that holds the values you give it. Listing 8-2 creates a new `Vec<i32>` that holds the values `1`, `2`, and `3`. The integer type is `i32` because that's the default integer type, as we discussed in the "Data Types" section of Chapter 3.

```
# fn main() {
    let v = vec![1, 2, 3];
# }
```

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.

```
# fn main() {
    let mut v = Vec::new();

    v.push(5);
    v.push(6);
    v.push(7);
    v.push(8);
# }
```

As with any variable, if we want to be able to change its value, we need to make it mutable using the `mut` keyword, as discussed in Chapter 3. 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.

Reading Elements of Vectors

There are two ways to reference a value stored in a vector: via indexing or by using the `get` method. In the following examples, we've annotated the types of the values that are returned from these functions for extra clarity.

Listing 8-4 shows both methods of accessing a value in a vector, with indexing syntax and the `get` method.

```
# fn main() {
    let v = vec![1, 2, 3, 4, 5];

    let third: &i32 = &v[2];
    println!("The third element is {third}");
```

```
    let third: Option<&i32> = v.get(2);
    match third {
            Some(third) => println!("The third element is {third}"),
        None => println!("There is no third element."),
    }
# }
```

Note a few details here. We use the index value of `2` to get the third element because vectors are indexed by number, starting at zero. Using `&` and `[]` gives us a reference to the element at the index value. When we use the `get` method with the index passed as an argument, we get an `Option<&T>` that we can use with `match`.

Rust provides these two ways to reference an element so you can choose how the program behaves when you try to use an index value outside the range of existing elements. As an example, let's see what happens when we have a vector of five elements and then we try to access an element at index 100 with each technique, as shown in Listing 8-5.

```
# fn main() {
    let v = vec![1, 2, 3, 4, 5];

    let does_not_exist = &v[100];
    let does_not_exist = v.get(100);
# }
```

When we run this code, the first `[]` method will cause the program to panic because it references a nonexistent element. This method is best used when you want your program to crash if there's an attempt to access an element past the end of the vector.

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 may happen 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 vector and give them another chance to enter a valid value. That would be more user-friendly than crashing the program due to a typo!

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 you can't have mutable and immutable references in the same scope. That rule applies in Listing 8-6, where we hold an immutable reference to the first element in a vector and try to add an element to the end. This program won't work if we also try to refer to that element later in the function.

```
# fn main() {
    let mut v = vec![1, 2, 3, 4, 5];

    let first = &v[0];

    v.push(6);

    println!("The first element is: {first}");
# }
```

Compiling this code will result in this error:

```
$ cargo run
   Compiling collections v0.1.0 (file:///projects/collections)
error[E0502]: cannot borrow `v` as mutable because it is also
borrowed as immutable
 --> src/main.rs:6:5
  |
4 |     let first = &v[0];
  |                  - immutable borrow occurs here
5 |
6 |     v.push(6);
  |     ^^^^^^^^^ mutable borrow occurs here
7 |
```

```
8 |     println!("The first element is: {first}");
  |                                      ------- immutable
borrow later used here

For more information about this error, try `rustc --explain
E0502`.
error: could not compile `collections` (bin "collections") due
to 1 previous error
```

The code in Listing 8-6 might look like it should work: why should a reference to the first element care about changes at the end of the vector? This error is due to the way vectors work: because vectors put the values next to each other in memory, 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 is currently stored. 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 Rustonomicon".

Iterating Over the Values in a Vector

To access each element in a vector in turn, we would iterate through all of the elements rather than use indices to access one at a time. Listing 8-7 shows how to use a `for` loop to get immutable references to each element in a vector of `i32` values and print them.

```
# fn main() {
    let v = vec![100, 32, 57];
    for i in &v {
        println!("{i}");
    }
# }
```

We can also iterate over mutable references to each element in a mutable vector in order to make changes to all the elements. The `for` loop in

Listing 8-8 will add `50` to each element.

```
# fn main() {
    let mut v = vec![100, 32, 57];
    for i in &mut v {
        *i += 50;
    }
# }
```

To change the value that the mutable reference refers to, we have to use the `*` dereference operator to get to the value in `i` before we can use the `+=` operator. We'll talk more about the dereference operator in the "Following the Reference to the Value" section of Chapter 15.

Iterating over a vector, whether immutably or mutably, is safe because of the borrow checker's rules. If we attempted to insert or remove items in the `for` loop bodies in Listing 8-7 and Listing 8-8, we would get a compiler error similar to the one we got with the code in Listing 8-6. The reference to the vector that the `for` loop holds prevents simultaneous modification of the whole vector.

Using an Enum to Store Multiple Types

Vectors can only store values that are of 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 one type to represent elements of different types, we can define and use an enum!

For example, say we want to get values from a row in a spreadsheet in which 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 all the enum variants will be considered the same type: that of the enum. Then we can create a vector to hold that enum and so, ultimately, hold different types. We've demonstrated this in Listing 8-9.

```
# fn main() {
    enum SpreadsheetCell {
        Int(i32),
```

```
        Float(f64),
        Text(String),
    }

    let row = vec![
        SpreadsheetCell::Int(3),
        SpreadsheetCell::Text(String::from("blue")),
        SpreadsheetCell::Float(10.12),
    ];
# }
```

Rust needs to know what types will be in the vector at compile time so it knows exactly how much memory on the heap will be needed to store each element. We must also 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 every possible case is handled, as discussed in Chapter 6.

If you don't know the exhaustive set of types a 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 18.

Now that we've discussed some of the most common ways to use vectors, be sure to review the API documentation for all of the many useful methods defined on `Vec<T>` by the standard library. For example, in addition to `push`, a `pop` method removes and returns the last element.

Dropping a Vector Drops Its Elements

Like any other `struct`, a vector is freed when it goes out of scope, as annotated in Listing 8-10.

```
# fn main() {
    {
        let v = vec![1, 2, 3, 4];

        // do stuff with v
```

```
    } // <- v goes out of scope and is freed here
# }
```

When the vector gets dropped, all of its contents are also dropped, meaning the integers it holds will be cleaned up. The borrow checker ensures that any references to contents of a vector are only used while the vector itself is valid.

Let’s move on to the next collection type: `String`!

Storing UTF-8 Encoded Text with 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 for a combination of three reasons: 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 factors combine in a way that can seem difficult when you're coming from other programming languages.

We discuss strings in the context of collections 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 from 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 program's binary and are therefore string slices.

The `String` type, which is provided by Rust's standard library rather than coded into the core language, is a growable, mutable, owned, UTF-8 encoded string type. When Rustaceans refer to "strings" in Rust, they might be referring to either the `String` or 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.

Creating a New String

Many of the same operations available with `Vec<T>` are available with `String` as well because `String` is actually implemented as a wrapper around a vector of bytes with some extra guarantees, restrictions, and capabilities. An example of a function that works the same way with `Vec<T>` and `String` is the `new` function to create an instance, shown in Listing 8-11.

```
# fn main() {
    let mut s = String::new();
# }
```

This line creates a new, empty string called `s`, into which we can then load data. Often, we'll have some initial data with which we want to start the string. For that, we use the `to_string` method, which is available on any type that implements the `Display` trait, as string literals do. Listing 8-12 shows two examples.

```
# fn main() {
    let data = "initial contents";

    let s = data.to_string();

    // The method also works on a literal directly:
    let s = "initial contents".to_string();
# }
```

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 8-13 is equivalent to the code in Listing 8-12 that uses `to_string`.

```
# fn main() {
    let s = String::from("initial contents");
# }
```

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 one you choose is a matter of style and readability.

Remember that strings are UTF-8 encoded, so we can include any properly encoded data in them, as shown in Listing 8-14.

```
# fn main() {
    let hello = String::from("السلام عليكم");
    let hello = String::from("Dobrý den");
    let hello = String::from("Hello");
    let hello = String::from("שלום");
    let hello = String::from("      ");
    let hello = String::from("     ");
    let hello = String::from("     ");
    let hello = String::from("  ");
    let hello = String::from("Olá");
    let hello = String::from("Здравствуйте");
    let hello = String::from("Hola");
# }
```

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<T>`, if you push more data into it. In addition, you can conveniently use the `+` operator or the `format!` macro to concatenate `String` values.

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 8-15.

```
# fn main() {
    let mut s = String::from("foo");
    s.push_str("bar");
# }
```

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, in the code in Listing 8-16, we want to be able to use `s2` after appending its contents to `s1`.

```
# fn main() {
    let mut s1 = String::from("foo");
    let s2 = "bar";
    s1.push_str(s2);
    println!("s2 is {s2}");
# }
```

If the `push_str` method took ownership of `s2`, we wouldn't be able to print 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 8-17 adds the letter *l* to a `String` using the `push` method.

```
# fn main() {
    let mut s = String::from("lo");
    s.push('l');
# }
```

As a result, `s` will contain `lol`.

Concatenation with the + Operator or the `format!` Macro

Often, you'll want to combine two existing strings. One way to do so is to use the `+` operator, as shown in Listing 8-18.

```
# fn main() {
    let s1 = String::from("Hello, ");
    let s2 = String::from("world!");
    let s3 = s1 + &s2; // note s1 has been moved here and can
no longer be used
# }
```

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's called when we use the `+` operator.

The `+` operator uses the `add` method, whose signature looks something like this:

```
fn add(self, s: &str) -> String {
```

In the standard library, you'll see `add` defined using generics and associated types. Here, we've substituted in concrete types, 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 in order 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. This is 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`. So why does Listing 8-18 compile?

The reason we're able to use `&s2` in the call to `add` is that the compiler can *coerce* the `&String` argument into a `&str`. When we call the `add` method, Rust uses a *deref coercion*, which here turns `&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 8-18 will be moved into the `add` call and will 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 it isn't; the implementation is more efficient than copying.

If we need to concatenate multiple strings, the behavior of the `+` operator gets unwieldy:

```
# fn main() {
    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 combining strings in more complicated ways, we can instead use the `format!` macro:

```
# fn main() {
    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 like `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 the code generated by the `format!` macro uses references so that this call 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 you try to access parts of a `String` using indexing syntax in Rust, you'll get an error. Consider the invalid code in Listing 8-19.

```
# fn main() {
    let s1 = String::from("hi");
    let h = s1[0];
# }
```

This code will result in the following error:

```
$ cargo run
   Compiling collections v0.1.0 (file:///projects/collections)
error[E0277]: the type `str` cannot be indexed by `{integer}`
 --> src/main.rs:3:16
  |
3 |     let h = s1[0];
  |                ^ string indices are ranges of `usize`
  |
  = note: you can use `.chars().nth()` or `.bytes().nth()`
          for more information, see chapter 8 in The Book:
<https://doc.rust-lang.org/book/ch08-02-strings.html#indexing-
into-strings>
  = help: the trait `SliceIndex<str>` is not implemented for
`{integer}`
          but trait `SliceIndex<[_]>` is implemented for
`usize`
  = help: for that trait implementation, expected `[_]`, found
`str`
  = note: required for `String` to implement
`Index<{integer}>`

For more information about this error, try `rustc --explain
E0277`.
error: could not compile `collections` (bin "collections") due
to 1 previous error
```

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 8-14. First, this one:

```
# fn main() {
#     let hello = String::from("السلام عليكم");
#     let hello = String::from("Dobrý den");
```

```
#     let hello = String::from("Hello");
#     let hello = String::from("שלום");
#     let hello = String::from("      ");
#     let hello = String::from("     ");
#     let hello = String::from("     ");
#     let hello = String::from("  ");
#     let hello = String::from("Olá");
#     let hello = String::from("Здравствуйте");
    let hello = String::from("Hola");
# }
```

In this case, `len` will be `4`, which means the vector storing the string `"Hola"` is 4 bytes long. Each of these letters takes one byte when encoded in UTF-8. The following line, however, may surprise you (note that this string begins with the capital Cyrillic letter *Ze*, not the number 3):

```
# fn main() {
#     let hello = String::from("السلام عليكم");
#     let hello = String::from("Dobrý den");
#     let hello = String::from("Hello");
#     let hello = String::from("שלום");
#     let hello = String::from("      ");
#     let hello = String::from("     ");
#     let hello = String::from("     ");
#     let hello = String::from("  ");
#     let hello = String::from("Olá");
    let hello = String::from("Здравствуйте");
#     let hello = String::from("Hola");
# }
```

If you were asked how long the string is, you might say 12. In fact, Rust's answer is 24: that's the number of bytes it takes to encode “Здравствуйте” in UTF-8, because each Unicode scalar value in that string takes 2 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];
```

You already know that `answer` will not be `З`, the first letter. When encoded in UTF-8, the first byte of `З` is `208` and the second is `151`, so it would seem that `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. Users generally don't want the byte value returned, even if the string contains only Latin letters: if `&"hi"[0]` were valid code that returned the byte value, it would return `104`, not `h`.

The answer, then, is that 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 early 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 “ ” written in the Devanagari script, it is stored as a vector 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:

```
[' ', ' ', ' ', ' ', ' ', ' ']
```

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:

```
[" ", " ", "  ", "  "]
```

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. If you really need to use indices to create string slices, therefore, Rust asks you to be more specific.

Rather than indexing using `[]` with a single number, you can use `[]` with a range to create a string slice containing particular bytes:

```
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`.

If we were to try to slice only part of a character's bytes with something like `&hello[0..1]`, Rust would panic at runtime in the same way as if an invalid index were accessed in a vector:

```
$ cargo run
   Compiling collections v0.1.0 (file:///projects/collections)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.43s
     Running `target/debug/collections`

thread 'main' panicked at src/main.rs:4:19:
```

```
byte index 1 is not a char boundary; it is inside 'З' (bytes
0..2) of `Здравствуйте`
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace
```

You should use caution when creating string slices with ranges, because doing so can crash your program.

Methods for Iterating Over Strings

The best way to operate on pieces of strings is to be explicit about whether you want characters or bytes. For individual Unicode scalar values, use the `chars` method. Calling `chars` on "Зд" separates out and returns two values of type `char`, and you can iterate over the result to access each element:

```
for c in "Зд".chars() {
    println!("{c}");
}
```

This code will print the following:

```
З
д
```

Alternatively, the `bytes` method returns each raw byte, which might be appropriate for your domain:

```
for b in "Зд".bytes() {
    println!("{b}");
}
```

This code will print the four bytes that make up this string:

```
208
151
208
180
```

But be sure to remember that valid Unicode scalar values may be made up of more than one byte.

Getting grapheme clusters from strings, as with the Devanagari script, 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 up front. This trade-off exposes more of the complexity of strings than is apparent in other programming languages, but it prevents you from having to handle errors involving non-ASCII characters later in your development life cycle.

The good news is that the standard library offers a lot of functionality built off the `String` and `&str` types to help handle these complex situations correctly. Be sure to check out the documentation for useful methods like `contains` for searching in a string and `replace` for substituting parts of a string with another string.

Let's switch to something a bit less complex: hash maps!

Storing Keys with Associated Values in 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` using a *hashing function*, which determines how it places these keys and values into memory. Many programming languages support this kind of data structure, but they often use a different name, such as *hash*, *map*, *object*, *hash table*, *dictionary*, or *associative array*, just to name a few.

Hash maps are useful when you want to look up data not by using 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 in which 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

One way to create an empty hash map is to use `new` and to add elements with `insert`. In Listing 8-20, we're keeping track of the scores of two teams whose names are *Blue* and *Yellow*. The Blue team starts with 10 points, and the Yellow team starts with 50.

```
# fn main() {
    use std::collections::HashMap;

    let mut scores = HashMap::new();

    scores.insert(String::from("Blue"), 10);
    scores.insert(String::from("Yellow"), 50);
# }
```

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 brought into scope 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.

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.

```
# fn main() {
    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).copied().unwrap_or(0);
# }
```

Here, `score` will have the value that's associated with the Blue team, and the result will be `10`. The `get` method returns an `Option<&V>`; if there's no value for that key in the hash map, `get` will return `None`. This program handles the `Option` by calling `copied` to get an `Option<i32>` rather than an `Option<&i32>`, then `unwrap_or` to set `score` to zero if `scores` doesn't have an entry for the key.

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:

```
# fn main() {
    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
```

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 8-22.

```
# fn main() {
    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!
# }
```

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 "Validating References with Lifetimes" in Chapter 10.

Updating a Hash Map

Although the number of key and value pairs is growable, each unique key can only have one value associated with it at a time (but not vice versa: for example, both the Blue team and the Yellow team could have the value `10` stored in the `scores` hash map).

When you want to change the data in a hash map, you have to decide how to handle the case when a key already has a value assigned. You could replace the old value with the new value, completely disregarding the old value. You could keep the old value and ignore the new value, only adding the new value if the key *doesn't* already have a value. Or you 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 8-23 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.

```
# fn main() {
    use std::collections::HashMap;

    let mut scores = HashMap::new();

    scores.insert(String::from("Blue"), 10);
    scores.insert(String::from("Blue"), 25);
```

```
    println!("{scores:?}");
# }
```

This code will print `{"Blue": 25}`. The original value of `10` has been overwritten.

Adding a Key and Value Only If a Key Isn't Present

It's common to check whether a particular key already exists in the hash map with a value and then to take the following actions: if the key does exist in the hash map, the existing value should remain the way it is; if the key doesn't exist, insert it and a value for it.

Hash maps have a special API for this called `entry` that takes the key you want to check as a parameter. The return value of the `entry` method 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 8-24.

```
# fn main() {
    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:?}");
# }
```

The `or_insert` method on `Entry` is defined to return a mutable reference to the value for the corresponding `Entry` key if that key exists, and if not, it inserts the parameter as the new value for this key and returns a mutable reference to the new value. 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 8-24 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 8-25 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`.

```
# fn main() {
    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:?}");
# }
```

This code will print `{"world": 2, "hello": 1, "wonderful": 1}`. You might see the same key-value pairs printed in a different order: recall from “Accessing Values in a Hash Map” that iterating over a hash map happens in an arbitrary order.

The `split_whitespace` method returns an iterator over subslices, separated by whitespace, of the value in `text`. The `or_insert` method returns a mutable reference (`&mut V`) to the value for the specified 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 Functions

By default, `HashMap` uses a hashing function called *SipHash* that can provide resistance to denial-of-service (DoS) attacks involving hash tables[1]. 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.

1

https://en.wikipedia.org/wiki/SipHash

Summary

Vectors, strings, and hash maps will provide a large amount of functionality necessary in programs when you need to store, access, and modify data. Here are some exercises you should now be equipped to solve:

1. Given a list of integers, use a vector and return the 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.
2. 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!
3. 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. We’ll do that next!

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 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 deploying your code to production!

Rust groups errors into two major categories: *recoverable* and *unrecoverable* errors. For a recoverable error, such as a *file not found* error, we most likely just want to report the problem to the user and retry the operation. Unrecoverable errors are always symptoms of bugs, such as trying to access a location beyond the end of an array, and so we want to immediately stop the program.

Most languages don't distinguish between these two kinds of errors and handle both in the same way, using mechanisms such as exceptions. Rust doesn't have exceptions. Instead, it has the type `Result<T, E>` for recoverable errors and the `panic!` macro that stops execution when the program encounters an unrecoverable error. This chapter covers calling `panic!` first and then talks about returning `Result<T, E>` values. Additionally, we'll explore considerations 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. There are two ways to cause a panic in practice: by taking an action that causes our code to panic (such as accessing an array past the end) or by explicitly calling the `panic!` macro. In both cases, we cause a panic in our program. By default, these panics will print a failure message, unwind, clean up the stack, and quit. Via an environment variable, you can also have Rust display the call stack when a panic occurs to make it easier to track down the source of the panic.

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. However, walking back and cleaning up is a lot of work. Rust, therefore, allows you to choose the alternative of immediately *aborting*, 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 resultant binary as small as possible, you can switch from unwinding to aborting upon a 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:

```
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` profile [unoptimized + debuginfo] target(s)
in 0.25s
     Running `target/debug/panic`

thread 'main' panicked at src/main.rs:2:5:
crash and burn
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace
```

The call to `panic!` causes the error message contained in the last two lines. The first line shows our panic message and the place in our source code where the panic occurred: *src/main.rs:2:5* indicates that it's the second line, fifth character 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, and 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. To understand how to use a `panic!` backtrace, let's look at another example and 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 index in a vector beyond the range of valid indexes.

```
fn main() {
    let v = vec![1, 2, 3];

    v[99];
}
```

Here, we're attempting to access the 100th element of our vector (which is at index 99 because indexing starts at zero), but the vector 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.

In C, attempting to read beyond the end of a data structure is undefined behavior. You might get whatever is at the location in memory that would correspond to that element in the data structure, even though the memory doesn't belong to that structure. 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 data structure.

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` profile [unoptimized + debuginfo] target(s)
in 0.27s
     Running `target/debug/panic`

thread 'main' panicked at src/main.rs:4:6:
index out of bounds: the len is 3 but the index is 99
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace
```

This error points at line 4 of our *main.rs* where we attempt to access index `99` of the vector in `v`.

The `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 as 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 that spot are code that your code has called; the lines below are code that called your code. These before-and-after lines might include core Rust code, standard library code, or crates that you're using. Let's try getting a backtrace by setting the `RUST_BACKTRACE` environment variable to any value except `0`. Listing 9-2 shows output similar to what you’ll see.

```
$ RUST_BACKTRACE=1 cargo run
thread 'main' panicked at src/main.rs:4:6:
index out of bounds: the len is 3 but the index is 99
stack backtrace:
   0: rust_begin_unwind
                                                                 at
/rustc/4d91de4e48198da2e33413efdcd9cd2cc0c46688/library/std/sr
c/panicking.rs:692:5
   1: core::panicking::panic_fmt
                                                                 at
/rustc/4d91de4e48198da2e33413efdcd9cd2cc0c46688/library/core/s
rc/panicking.rs:75:14
   2: core::panicking::panic_bounds_check
                                                                 at
/rustc/4d91de4e48198da2e33413efdcd9cd2cc0c46688/library/core/s
rc/panicking.rs:273:5
   3: <usize as core::slice::index::SliceIndex<[T]>>::index
                                                                 at
file:///home/.rustup/toolchains/1.85/lib/rustlib/src/rust/libr
ary/core/src/slice/index.rs:274:10
   4: core::slice::index::<impl core::ops::index::Index<I> for
[T]>::index
                                                                 at
file:///home/.rustup/toolchains/1.85/lib/rustlib/src/rust/libr
ary/core/src/slice/index.rs:16:9
   5: <alloc::vec::Vec<T,A> as
core::ops::index::Index<I>>::index
                                                                 at
file:///home/.rustup/toolchains/1.85/lib/rustlib/src/rust/libr
ary/alloc/src/vec/mod.rs:3361:9
   6: panic::main
             at ./src/main.rs:4:6
   7: core::ops::function::FnOnce::call_once
```

```
                                                              at
file:///home/.rustup/toolchains/1.85/lib/rustlib/src/rust/libr
ary/core/src/ops/function.rs:250:5
note: Some details are omitted, run with `RUST_BACKTRACE=full`
for a verbose backtrace.
```

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 6 of the backtrace points to the line in our project that's causing the problem: line 4 of *src/main.rs*. If we don't want our program to panic, we should start our investigation at the location pointed to by the first line mentioning a file we wrote. In Listing 9-1, where we deliberately wrote code that would panic, the way to fix the panic is to not request an element beyond the range of the vector indexes. When your code panics in the future, you'll need to figure out what action the code is taking with what values to cause 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 in the "To `panic!` or Not to `panic!`" section later in this 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 you can easily interpret and respond to. For example, if you try to open a file and that operation fails because the file doesn't exist, you might want to create the file instead of terminating the process.

Recall from "Handling Potential Failure with `Result`" in Chapter 2 that the `Result` enum is defined as having two variants, `Ok` and `Err`, as follows:

```
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 defined on it in many different situations where the success 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.

```
use std::fs::File;

fn main() {
    let greeting_file_result = File::open("hello.txt");
}
```

The return type of `File::open` is a `Result<T, E>`. The generic parameter `T` has been filled in by the implementation of `File::open` 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 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 in the variable `greeting_file_result` will be an instance of `Ok` that contains a file handle. In the case where it fails, the value in `greeting_file_result` will be an instance of `Err` that contains more information about the kind of error that occurred.

We need to add to the code in Listing 9-3 to take different actions depending on the value `File::open` returns. Listing 9-4 shows one way to handle the `Result` using a basic tool, the `match` expression that we discussed in Chapter 6.

```
use std::fs::File;

fn main() {
    let greeting_file_result = File::open("hello.txt");

    let greeting_file = match greeting_file_result {
        Ok(file) => file,
            Err(error) => panic!("Problem opening the file:
{error:?}"),
    };
}
```

Note that, like the `Option` enum, the `Result` enum and its variants have been brought into scope by the prelude, so we don't need to specify `Result::` before the `Ok` and `Err` variants in the `match` arms.

When the result is `Ok`, this code will return the inner `file` value out of the `Ok` variant, and we then assign that file handle value to the variable `greeting_file`. After the `match`, we can 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:

```
$ cargo run
   Compiling error-handling v0.1.0 (file:///projects/error-handling)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.73s
     Running `target/debug/error-handling`

thread 'main' panicked at src/main.rs:8:23:
Problem opening the file: Os { code: 2, kind: NotFound, message: "No such file or directory" }
note: run with `RUST_BACKTRACE=1` environment variable to display a backtrace
```

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 why `File::open` failed. However, we want to 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 it did in Listing 9-4. For this, we add an inner `match` expression, shown in Listing 9-5.

```
use std::fs::File;
use std::io::ErrorKind;

fn main() {
    let greeting_file_result = File::open("hello.txt");

    let greeting_file = match greeting_file_result {
        Ok(file) => file,
        Err(error) => match error.kind() {
            ErrorKind::NotFound => match File::create("hello.txt") {
                Ok(fc) => fc,
                Err(e) => panic!("Problem creating the file: {e:?}"),
            },
            _ => {
                panic!("Problem opening the file: {error:?}");
            }
        },
    };
}
```

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. The enum `io::ErrorKind` is provided by the standard library and 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. So we match on `greeting_file_result`, but we also have an inner match on `error.kind()`.

The condition we want to check in the inner match 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 a second arm in the inner `match` expression. When the file can't be created, a different error message is printed. The second arm of the outer `match` stays the same, so the program panics on any error besides the missing file error.

Alternatives to Using `match` with `Result<T, E>`

That's a lot of `match`! The `match` expression is very useful but also very much a primitive. In Chapter 13, you'll learn about closures, which are used with many of the methods defined on `Result<T, E>`. These methods can be more concise than using `match` when handling `Result<T, E>` values in your code.

For example, here's another way to write the same logic as shown in Listing 9-5, this time using closures and the `unwrap_or_else` method:

```
use std::fs::File;
use std::io::ErrorKind;

fn main() {
                            let       greeting_file       =
File::open("hello.txt").unwrap_or_else(|error| {
        if error.kind() == ErrorKind::NotFound {

File::create("hello.txt").unwrap_or_else(|error| {
                      panic!("Problem creating the file:
{error:?}");
            })
        } else {
                      panic!("Problem opening the file:
{error:?}");
        }
```

```
    });
}
```

Although this code has the same behavior as Listing 9-5, it doesn't contain any `match` expressions and is cleaner to read. Come back to this example after you've read Chapter 13, and look up the `unwrap_or_else` method in the standard library documentation. Many more of these methods can clean up huge nested `match` expressions when you're dealing with errors.

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, more specific tasks. The `unwrap` method is a shortcut method implemented just like the `match` expression 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:

```
use std::fs::File;

fn main() {
    let greeting_file = 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 src/main.rs:4:49:
called `Result::unwrap()` on an `Err` value: Os { code: 2,
kind: NotFound, message: "No such file or directory" }
```

Similarly, the `expect` method 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:

```
use std::fs::File;

fn main() {
    let greeting_file = File::open("hello.txt")
              .expect("hello.txt  should  be  included  in  this
project");
}
```

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 src/main.rs:5:10:
hello.txt  should  be  included  in  this  project:  Os  {  code:  2,
kind: NotFound, message: "No such file or directory" }
```

In production-quality code, most Rustaceans choose `expect` rather than `unwrap` and give more context about why the operation is expected to always succeed. That way, if your assumptions are ever proven wrong, you have more information to use in debugging.

Propagating Errors

When a function's implementation calls something that might fail, instead of handling the error within the function itself, 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 the function.

```
use std::fs::File;
use std::io::{self, Read};

fn read_username_from_file() -> Result<String, io::Error> {
    let username_file_result = File::open("hello.txt");

    let mut username_file = match username_file_result {
        Ok(file) => file,
        Err(e) => return Err(e),
    };

    let mut username = String::new();

    match username_file.read_to_string(&mut username) {
        Ok(_) => Ok(username),
        Err(e) => Err(e),
    }
}
```

This function can be written in a much shorter way, but we're going to start by doing a lot of it manually in order to explore error handling; at the end, we'll show the shorter way. 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 calling code 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 with a `match` similar to the `match` in Listing 9-4. If `File::open` succeeds, the file handle in the pattern variable `file` becomes the value in the mutable variable `username_file` and the function continues. In the `Err` case, instead of calling `panic!`, we use the `return` keyword to return early out of the function entirely and pass the error value from `File::open`, now in the pattern variable `e`, back to the calling code as this function's error value.

So, if we have a file handle in `username_file`, the function then creates a new `String` in variable `username` and calls the `read_to_string` method on the file handle in `username_file` to read the contents of the file into `username`. 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 `username` 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`. It's up to the calling code to decide what to 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 upward 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: The `?` Operator

Listing 9-7 shows an implementation of `read_username_from_file` that has the same functionality as in Listing 9-6, but this implementation uses the `?` operator.

```
use std::fs::File;
use std::io::{self, Read};

fn read_username_from_file() -> Result<String, io::Error> {
    let mut username_file = File::open("hello.txt")?;
    let mut username = String::new();
    username_file.read_to_string(&mut username)?;
    Ok(username)
}
```

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 `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.

There is a difference between what the `match` expression from Listing 9-6 does and what the `?` operator does: error values that have the `?` operator called on them go through the `from` function, defined in the `From` trait in the standard library, which is used to convert values from one type into another. When the `?` operator calls the `from` function, the error type received is converted into the error type defined in the return type of the current function. This is useful when a function returns one error type to represent all the ways a function might fail, even if parts might fail for many different reasons.

For example, we could change the `read_username_from_file` function in Listing 9-7 to return a custom error type named `OurError` that we define. If we also define `impl From<io::Error> for OurError` to construct an instance of `OurError` from an `io::Error`, then the `?` operator calls in the body of `read_username_from_file` will call `from` and convert the error types without needing to add any more code to the function.

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 `username_file`. If an error occurs, the `?` operator 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 `?` operator 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.

```
use std::fs::File;
use std::io::{self, Read};

fn read_username_from_file() -> Result<String, io::Error> {
    let mut username = String::new();

    File::open("hello.txt")?.read_to_string(&mut username)?;

    Ok(username)
}
```

We've moved the creation of the new `String` in `username` to the beginning of the function; that part hasn't changed. Instead of creating a variable `username_file`, 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 `username` 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.

Listing 9-9 shows a way to make this even shorter using `fs::read_to_string`.

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

fn read_username_from_file() -> Result<String, io::Error> {
    fs::read_to_string("hello.txt")
}
```

Reading a file into a string is a fairly common operation, so the standard library provides the convenient `fs::read_to_string` function that opens the file, creates a new `String`, reads the contents of the file, puts the contents into that `String`, and returns it. Of course, using `fs::read_to_string` doesn't give us the opportunity to explain all the error handling, so we did it the longer way first.

Where the `?` Operator Can Be Used

The `?` operator can only be used in functions whose return type is compatible with the value the `?` is used on. This is because the `?` operator is defined to perform an early return of a value out of the function, in the same manner as the `match` expression we defined in Listing 9-6. In Listing 9-6, the `match` was using a `Result` value, and the early return arm returned an `Err(e)` value. The return type of the function has to be a `Result` so that it's compatible with this `return`.

In Listing 9-10, let's look at the error we'll get if we use the `?` operator in a `main` function with a return type that is incompatible with the type of the value we use `?` on.

```
use std::fs::File;

fn main() {
    let greeting_file = File::open("hello.txt")?;
}
```

This code opens a file, which might fail. The `?` operator follows the `Result` value returned by `File::open`, but this `main` function has the return type of `()`, not `Result`. When we compile this code, we get the following error message:

```
$ cargo run
   Compiling error-handling v0.1.0 (file:///projects/error-handling)
error[E0277]: the `?` operator can only be used in a function that returns `Result` or `Option` (or another type that implements `FromResidual`)
 --> src/main.rs:4:48
  |
3 | fn main() {
  | --------- this function should return `Result` or `Option` to accept `?`
4 |     let greeting_file = File::open("hello.txt")?;
  |                                                ^ cannot use the `?` operator in a function that returns `()`
  |
  = help: the trait `FromResidual<Result<Infallible, std::io::Error>>` is not implemented for `()`
help: consider adding return type
  |
3 ~ fn main() -> Result<(), Box<dyn std::error::Error>> {
4 |     let greeting_file = File::open("hello.txt")?;
5 +     Ok(())
  |
```

```
For more information about this error, try `rustc --explain E0277`.
error: could not compile `error-handling` (bin "error-handling") due to 1 previous error
```

This error points out that we're only allowed to use the `?` operator in a function that returns `Result`, `Option`, or another type that implements `FromResidual`.

To fix the error, you have two choices. One choice is to change the return type of your function to be compatible with the value you're using the `?` operator on as long as you have no restrictions preventing that. The other choice is to use a `match` or one of the `Result<T, E>` methods to handle the `Result<T, E>` in whatever way is appropriate.

The error message also mentioned that `?` can be used with `Option<T>` values as well. As with using `?` on `Result`, you can only use `?` on `Option` in a function that returns an `Option`. The behavior of the `?` operator when called on an `Option<T>` is similar to its behavior when called on a `Result<T, E>`: if the value is `None`, the `None` will be returned early from the function at that point. If the value is `Some`, the value inside the `Some` is the resultant value of the expression, and the function continues. Listing 9-11 has an example of a function that finds the last character of the first line in the given text.

```
fn last_char_of_first_line(text: &str) -> Option<char> {
    text.lines().next()?.chars().last()
}
#
# fn main() {
#     assert_eq!(
#         last_char_of_first_line("Hello, world\nHow are you today?"),
#         Some('d')
#     );
#
#     assert_eq!(last_char_of_first_line(""), None);
```

```
#     assert_eq!(last_char_of_first_line("\nhi"), None);
# }
```

This function returns `Option<char>` because it's possible that there is a character there, but it's also possible that there isn't. This code takes the `text` string slice argument and calls the `lines` method on it, which returns an iterator over the lines in the string. Because this function wants to examine the first line, it calls `next` on the iterator to get the first value from the iterator. If `text` is the empty string, this call to `next` will return `None`, in which case we use `?` to stop and return `None` from `last_char_of_first_line`. If `text` is not the empty string, `next` will return a `Some` value containing a string slice of the first line in `text`.

The `?` extracts the string slice, and we can call `chars` on that string slice to get an iterator of its characters. We're interested in the last character in this first line, so we call `last` to return the last item in the iterator. This is an `Option` because it's possible that the first line is the empty string; for example, if `text` starts with a blank line but has characters on other lines, as in `"\nhi"`. However, if there is a last character on the first line, it will be returned in the `Some` variant. The `?` operator in the middle gives us a concise way to express this logic, allowing us to implement the function in one line. If we couldn't use the `?` operator on `Option`, we'd have to implement this logic using more method calls or a `match` expression.

Note that you can use the `?` operator on a `Result` in a function that returns `Result`, and you can use the `?` operator on an `Option` in a function that returns `Option`, but you can't mix and match. The `?` operator won't automatically convert a `Result` to an `Option` or vice versa; in those cases, you can use methods like the `ok` method on `Result` or the `ok_or` method on `Option` to do the conversion explicitly.

So far, all the `main` functions we've used return `()`. The `main` function is special because it's the entry point and exit point of an executable program, and there are restrictions on what its return type can be for the program to behave as expected.

Luckily, `main` can also return a `Result<(), E>`. Listing 9-12 has the code from Listing 9-10, but we've changed the return type of `main` to be `Result<(), Box<dyn Error>>` and added a return value `Ok(())` to the end. This code will now compile.

```
use std::error::Error;
use std::fs::File;

fn main() -> Result<(), Box<dyn Error>> {
    let greeting_file = File::open("hello.txt")?;

    Ok(())
}
```

The `Box<dyn Error>` type is a *trait object*, which we'll talk about in "Using Trait Objects That Allow for Values of Different Types" in Chapter 18. For now, you can read `Box<dyn Error>` to mean "any kind of error." Using `?` on a `Result` value in a `main` function with the error type `Box<dyn Error>` is allowed because it allows any `Err` value to be returned early. Even though the body of this `main` function will only ever return errors of type `std::io::Error`, by specifying `Box<dyn Error>`, this signature will continue to be correct even if more code that returns other errors is added to the body of `main`.

When a `main` function returns a `Result<(), E>`, the executable will exit with a value of `0` if `main` returns `Ok(())` and will exit with a nonzero value if `main` returns an `Err` value. Executables written in C return integers when they exit: programs that exit successfully return the integer `0`, and programs that error return some integer other than `0`. Rust also returns integers from executables to be compatible with this convention.

The `main` function may return any types that implement [the `std::process::Termination` trait], which contains a function `report` that returns an `ExitCode`. Consult the standard library documentation for more information on implementing the `Termination` trait for your own types.

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 call `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 that a situation is unrecoverable on behalf of the calling code. When you choose to return a `Result` value, you give the calling code options. 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 situations such as examples, prototype code, and tests, it's more appropriate to write code that panics instead of returning a `Result`. Let's explore why, then discuss situations in which the compiler can't tell that failure is impossible, but you as a human can. The chapter will conclude with some general guidelines on how to decide whether to panic in library code.

Examples, Prototype Code, and Tests

When you're writing an example to illustrate some concept, also including robust error-handling code 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 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, you'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 in Which You Have More Information Than the Compiler

It would also be appropriate to call `expect` 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 `expect` and document the reason you think you'll never have an `Err` variant in the argument text. Here's an example:

```
# fn main() {
    use std::net::IpAddr;

    let home: IpAddr = "127.0.0.1"
        .parse()
        .expect("Hardcoded IP address should be valid");
# }
```

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 `expect` 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 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. Mentioning the assumption that this IP address is hardcoded will prompt us to change `expect` to better error-handling code if, in the future, we need to get the IP address from some other source 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, a *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 something that is unexpected, as opposed to something that will likely happen occasionally, like a user entering data in the wrong format.
- Your code after this point needs to rely on not being in this bad state, rather than checking for the problem at every step.
- There's not a good way to encode this information in the types you use. We'll work through an example of what we mean in "Encoding States and Behavior as Types" in Chapter 18.

If someone calls your code and passes in values that don't make sense, it's best to return an error if you can so the user of the library can decide what they want to do in that case. However, in cases where continuing could be insecure or harmful, the best choice might be to call `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.

However, when failure is expected, it's more appropriate to return a `Result` than to make a `panic!` call. Examples 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, returning a `Result` indicates that failure is an expected possibility that the calling code must decide how to handle.

When your code performs an operation that could put a user at risk if it's called using invalid 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 call `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 done by the compiler) 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 such as `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 in which 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. But it would be a useful enhancement to guide the user toward valid guesses and have different behavior when the user guesses a number that's out of range versus when the 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:

```
# use rand::Rng;
# use std::cmp::Ordering;
# use std::io;
#
# fn main() {
#     println!("Guess the number!");
#
#                                 let       secret_number       =
rand::thread_rng().gen_range(1..=100);
#
    loop {
        // --snip--

#         println!("Please input your guess.");
#
#         let mut guess = String::new();
#
#         io::stdin()
#             .read_line(&mut guess)
#             .expect("Failed to read line");
#
        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--
```

```
#             Ordering::Less => println!("Too small!"),
#             Ordering::Greater => println!("Too big!"),
#             Ordering::Equal => {
#                 println!("You win!");
#                 break;
#             }
#         }
    }
# }
```

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 were absolutely critical that the program only operated on values between 1 and 100, and it had many functions with this requirement, having a check like this in every function would be tedious (and might impact performance).

Instead, we can make a new type in a dedicated module 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 9-13 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: i32,
}

impl Guess {
    pub fn new(value: i32) -> Guess {
        if value < 1 || value > 100 {
            panic!("Guess value must be between 1 and 100, got
{value}.");
        }
```

```
        Guess { value }
    }

    pub fn value(&self) -> i32 {
        self.value
    }
}
```

Note that this code in *src/guessing_game.rs* depends on adding a module declaration `mod guessing_game;` in *src/lib.rs* that we haven't shown here. Within this new module's file, we define a struct in that module named `Guess` that has a field named `value` that holds an `i32`. 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 `i32` 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 an `i32`. This kind of method is 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 be private so code using the `Guess` struct is not allowed to set `value` directly:

code outside the `guessing_game` module *must* use the `Guess::new` function to create an instance of `Guess`, thereby ensuring 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 an `i32` 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.

Generic Types, Traits, and Lifetimes

Every programming language has tools for effectively handling the duplication of concepts. In Rust, one such tool is *generics*: abstract stand-ins for concrete types or other properties. We can express the behavior of generics or how they relate to other generics without knowing what will be in their place when compiling and running the code.

Functions can take parameters of some generic type, instead of a concrete type like `i32` or `String`, in the same way they take parameters with unknown values to run the same code on multiple concrete values. In fact, we've already used generics in Chapter 6 with `Option<T>`, in Chapter 8 with `Vec<T>` and `HashMap<K, V>`, and in Chapter 9 with `Result<T, E>`. In this chapter, you'll explore how to define your own types, functions, and methods with generics!

First we'll review how to extract a function to reduce code duplication. We'll then use the same technique to make a generic function from two functions that differ only in the types of their parameters. We'll also explain how to use generic types in struct and enum definitions.

Then you'll learn how to use *traits* to define behavior in a generic way. You can combine traits with generic types to constrain a generic type to accept only those types that have a particular behavior, as opposed to just any type.

Finally, we'll discuss *lifetimes*: a variety of generics that give the compiler information about how references relate to each other. Lifetimes allow us to give the compiler enough information about borrowed values so that it can ensure references will be valid in more situations than it could without our help.

Removing Duplication by Extracting a Function

Generics allow us to replace specific types with a placeholder that represents multiple types to remove code duplication. Before diving into generics syntax, let's first look at how to remove duplication in a way that doesn't involve generic types by extracting a function that replaces specific values with a placeholder that represents multiple values. Then we'll apply the same technique to extract a generic function! By looking at how to recognize duplicated code you can extract into a function, you'll start to recognize duplicated code that can use generics.

We'll begin with the short program in Listing 10-1 that finds the largest number in a list.

```
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}");
#     assert_eq!(*largest, 100);
}
```

We store a list of integers in the variable `number_list` and place a reference to the first number in the list in a variable named `largest`. We then iterate through all the numbers in the list, and if the current number is greater than the number stored in `largest`, we replace the reference in that variable. However, if the current number is less than or equal to the largest number seen so far, the variable doesn't change, and the code moves on to the next number in the list. After considering all the numbers in the list, `largest` should refer to the largest number, which in this case is 100.

We’ve now been tasked with finding the largest number in two different lists of numbers. To do so, we can choose to duplicate the code in Listing 10-1 and use the same logic at two different places in the program, as shown in Listing 10-2.

```
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}");
}
```

Although this code works, duplicating code is tedious and error prone. We also have to remember to update the code in multiple places when we want to change it.

To eliminate this duplication, we’ll create an abstraction by defining a function that operates on any list of integers passed in as a parameter. This solution makes our code clearer and lets us express the concept of finding the largest number in a list abstractly.

In Listing 10-3, we extract the code that finds the largest number into a function named `largest`. Then we call the function to find the largest number in the two lists from Listing 10-2. We could also use the function on any other list of `i32` values we might have in the future.

```
fn largest(list: &[i32]) -> &i32 {
    let mut largest = &list[0];

    for item in list {
        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}");
#     assert_eq!(*result, 100);

    let number_list = vec![102, 34, 6000, 89, 54, 2, 43, 8];

    let result = largest(&number_list);
    println!("The largest number is {result}");
#     assert_eq!(*result, 6000);
}
```

The `largest` function has a parameter called `list`, which represents any concrete slice of `i32` values we might pass into the function. As a result, when we call the function, the code runs on the specific values that we pass in.

In summary, here are the steps we took to change the code from Listing 10-2 to Listing 10-3:

1. Identify duplicate code.
2. Extract the duplicate code into the body of the function, and specify the inputs and return values of that code in the function signature.
3. Update the two instances of duplicated code to call the function instead.

Next, we'll use these same steps with generics to reduce code duplication. In the same way that the function body can operate on an abstract `list` instead of specific values, generics allow code to operate on abstract types.

For example, say we had two functions: one that finds the largest item in a slice of `i32` values and one that finds the largest item in a slice of `char` values. How would we eliminate that duplication? Let's find out!

Generic Data Types

We use generics to create definitions for items like function signatures or structs, which we can then use with many different concrete data types. Let’s first look at how to define functions, structs, enums, and methods using generics. Then we’ll discuss how generics affect code performance.

In Function Definitions

When defining a function that uses generics, we place the generics in the signature of the function where we would usually specify the data types of the parameters and return value. Doing so makes our code more flexible and provides more functionality to callers of our function while preventing code duplication.

Continuing with our `largest` function, Listing 10-4 shows two functions that both find the largest value in a slice. We’ll then combine these into a single function that uses generics.

```
fn largest_i32(list: &[i32]) -> &i32 {
    let mut largest = &list[0];

    for item in list {
        if item > largest {
            largest = item;
        }
    }

    largest
}

fn largest_char(list: &[char]) -> &char {
    let mut largest = &list[0];

    for item in list {
        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}");
#     assert_eq!(*result, 100);

    let char_list = vec!['y', 'm', 'a', 'q'];

    let result = largest_char(&char_list);
    println!("The largest char is {result}");
#     assert_eq!(*result, 'y');
}
```

The `largest_i32` function is the one we extracted in Listing 10-3 that finds the largest `i32` in a slice. The `largest_char` function finds the largest `char` in a slice. The function bodies have the same code, so let's eliminate the duplication by introducing a generic type parameter in a single function.

To parameterize the types in a new single function, we need to name the type parameter, just as we do for the value parameters to a function. You can use any identifier as a type parameter name. But we'll use `T` because, by convention, type parameter names in Rust are short, often just one letter, and Rust's type-naming convention is CamelCase. 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 name in the signature so the compiler knows what that name 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. To define the generic `largest` function, we place type name declarations inside angle brackets, `<>`, between the name of the function and the parameter list, like this:

```
fn largest<T>(list: &[T]) -> &T {
```

We read this definition as: the function `largest` is generic over some type `T`. This function has one parameter named `list`, which is a slice of values of type `T`. The `largest` function will return a reference to a value of the same type `T`.

Listing 10-5 shows the combined `largest` function definition using the generic data type in its signature. The listing also shows how we can call the function with either a slice of `i32` values or `char` values. Note that this code won't compile yet.

```
fn largest<T>(list: &[T]) -> &T {
    let mut largest = &list[0];

    for item in list {
        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}");
}
```

If we compile this code right now, we'll get this error:

```
$ cargo run
   Compiling chapter10 v0.1.0 (file:///projects/chapter10)
error[E0369]: binary operation `>` cannot be applied to type
`&T`
 --> src/main.rs:5:17
  |
5 |         if item > largest {
  |            ---- ^ ------- &T
  |            |
  |            &T
  |
help: consider restricting type parameter `T` with trait
`PartialOrd`
  |
1 | fn largest<T: std::cmp::PartialOrd>(list: &[T]) -> &T {
  |             ++++++++++++++++++++++

For more information about this error, try `rustc --explain
E0369`.
error: could not compile `chapter10` (bin "chapter10") due to
1 previous error
```

The help text mentions `std::cmp::PartialOrd`, which is a *trait*, and we're going to talk about traits in the next section. For now, know that this error states that the body of `largest` won't work for all possible types that `T` could be. Because we want to compare values of type `T` in the body, we can only use types whose values can be ordered. To enable comparisons, the standard library has the `std::cmp::PartialOrd` trait that you can implement on types (see Appendix C for more on this trait). To fix Listing 10-5, we can follow the help text's suggestion and restrict the types valid for `T` to only those that implement `PartialOrd`. The listing will then compile, because the standard library implements `PartialOrd` on both `i32` and `char`.

In Struct Definitions

We can also define structs to use a generic type parameter in one or more fields using the `<>` syntax. Listing 10-6 defines a `Point<T>` struct to hold `x` and `y` coordinate values of any type.

```
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 };
}
```

The syntax for using generics in struct definitions is similar to that used in function definitions. First we declare the name of the type parameter inside angle brackets just after the name of the struct. Then we use the generic type in the struct definition where we would otherwise specify concrete data types.

Note that because we've used only one generic type to define `Point<T>`, this definition says that the `Point<T>` struct is generic over some type `T`, and the fields `x` and `y` are *both* that same type, whatever that type may be. If we create an instance of a `Point<T>` that has values of different types, as in Listing 10-7, our code won't compile.

```
struct Point<T> {
    x: T,
    y: T,
}
```

```
fn main() {
    let wont_work = Point { x: 5, y: 4.0 };
}
```

In this example, when we assign the integer value `5` to `x`, we let the compiler know that the generic type `T` will be an integer for this instance of `Point<T>`. Then when we specify `4.0` for `y`, which we've defined to have the same type as `x`, we'll get a type mismatch error like this:

```
$ cargo run
   Compiling chapter10 v0.1.0 (file:///projects/chapter10)
error[E0308]: mismatched types
 --> src/main.rs:7:38
  |
7 |     let wont_work = Point { x: 5, y: 4.0 };
  |                                      ^^^ expected integer,
found floating-point number

For more information about this error, try `rustc --explain
E0308`.
error: could not compile `chapter10` (bin "chapter10") due to
1 previous error
```

To define a `Point` struct where `x` and `y` are both generics but could have different types, we can use multiple generic type parameters. For example, in Listing 10-8, we change the definition of `Point` to be generic over types `T` and `U` where `x` is of type `T` and `y` is of type `U`.

```
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 };
}
```

Now all the instances of `Point` shown are allowed! You can use as many generic type parameters in a definition as you want, but using more than a few makes your code hard to read. If you're finding you need lots of generic types in your code, it could indicate that your code needs restructuring into smaller pieces.

In Enum Definitions

As we did with structs, we can define enums to hold generic data types in their variants. Let's take another look at the `Option<T>` enum that the standard library provides, which we used in Chapter 6:

```
enum Option<T> {
    Some(T),
    None,
}
```

This definition should now make more sense to you. As you can see, the `Option<T>` enum is generic over type `T` and has two variants: `Some`, which holds one value of type `T`, and a `None` variant that doesn't hold any value. By using the `Option<T>` enum, we can express the abstract concept of an optional value, and because `Option<T>` is generic, we can use this abstraction no matter what the type of the optional value is.

Enums can use multiple generic types as well. The definition of the `Result` enum that we used in Chapter 9 is one example:

```
enum Result<T, E> {
    Ok(T),
    Err(E),
}
```

The `Result` enum is generic over two types, `T` and `E`, and 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 (return a value of some type `T`) or fail (return an error of some type `E`). In fact, this is what we used to open a file in Listing 9-3, where `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 avoid duplication by using generic types instead.

In Method Definitions

We can implement methods on structs and enums (as we did in Chapter 5) and use generic types in their definitions too. Listing 10-9 shows the `Point<T>` struct we defined in Listing 10-6 with a method named `x` implemented on it.

```
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());
}
```

Here, we've defined a method named `x` on `Point<T>` that returns a reference to the data in the field `x`.

Note that we have to declare `T` just after `impl` so we can use `T` to specify that we're implementing methods on the type `Point<T>`. By declaring `T` as a generic type after `impl`, Rust can identify that the type in the angle brackets in `Point` is a generic type rather than a concrete type. We could have chosen a different name for this generic parameter than the generic parameter declared in the struct definition, but using the same name is conventional. If you write a method within an `impl` that declares a generic type, that method will be defined on any instance of the type, no matter what concrete type ends up substituting for the generic type.

We can also specify constraints on generic types when defining methods on the type. We could, for example, implement methods only on `Point<f32>` instances rather than on `Point<T>` instances with any generic type. In Listing 10-10 we use the concrete type `f32`, meaning we don't declare any types after `impl`.

```
# struct Point<T> {
#     x: T,
#     y: T,
# }
#
# impl<T> Point<T> {
#     fn x(&self) -> &T {
#         &self.x
#     }
# }
#
impl Point<f32> {
    fn distance_from_origin(&self) -> f32 {
        (self.x.powi(2) + self.y.powi(2)).sqrt()
    }
```

```
}
#
# fn main() {
#     let p = Point { x: 5, y: 10 };
#
#     println!("p.x = {}", p.x());
# }
```

This code means the type `Point<f32>` will have a `distance_from_origin` method; other instances of `Point<T>` where `T` is not of type `f32` will not have this method defined. The method measures how far our point is from the point at coordinates (0.0, 0.0) and uses mathematical operations that are available only for floating-point types.

Generic type parameters in a struct definition aren't always the same as those you use in that same struct's method signatures. Listing 10-11 uses the generic types `X1` and `Y1` for the `Point` struct and `X2` `Y2` for the `mixup` method signature to make the example clearer. The method creates a new `Point` instance with the `x` value from the `self` `Point` (of type `X1`) and the `y` value from the passed-in `Point` (of type `Y2`).

```
struct Point<X1, Y1> {
    x: X1,
    y: Y1,
}

impl<X1, Y1> Point<X1, Y1> {
    fn mixup<X2, Y2>(self, other: Point<X2, Y2>) -> Point<X1,
Y2> {
        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);
}
```

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`). The `p2` variable is a `Point` struct 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` because `x` came from `p1`. The `p3` variable will have a `char` for `y` because `y` came from `p2`. The `println!` macro call will print `p3.x = 5, p3.y = c`.

The purpose of this example is to demonstrate a situation in which some generic parameters are declared with `impl` and some are declared with the method definition. Here, the generic parameters `X1` and `Y1` are declared after `impl` because they go with the struct definition. The generic parameters `X2` and `Y2` are declared after `fn mixup` because they're only relevant to the method.

Performance of Code Using Generics

You might be wondering whether there is a runtime cost when using generic type parameters. The good news is that using generic types won't make your program run any slower than it would with concrete types.

Rust accomplishes this by performing monomorphization of the code using generics at compile time. *Monomorphization* is the process of turning generic code into specific code by filling in the concrete types that are used when compiled. In this process, the compiler does the opposite of the steps we used to create the generic function in Listing 10-5: the compiler looks at all the places where generic code is called and generates code for the concrete types the generic code is called with.

Let’s look at how this works by using the standard library’s generic `Option<T>` enum:

```
let integer = Some(5);
let float = Some(5.0);
```

When Rust compiles this code, it performs monomorphization. During that process, the compiler reads the values that have been used in `Option<T>` instances and identifies two kinds of `Option<T>`: one is `i32` and the other is `f64`. As such, it expands the generic definition of `Option<T>` into two definitions specialized to `i32` and `f64`, thereby replacing the generic definition with the specific ones.

The monomorphized version of the code looks similar to the following (the compiler uses different names than what we’re using here for illustration):

```
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);
}
```

The generic `Option<T>` is replaced with the specific definitions created by the compiler. Because Rust compiles generic code into code that specifies the type in each instance, we pay no runtime cost for using generics. When the code runs, it performs just as it would if we had duplicated each definition by hand. The process of monomorphization makes Rust's generics extremely efficient at runtime.

Traits: Defining Shared Behavior

A *trait* defines the functionality a particular type has and can share with other types. We can use traits to define shared behavior in an abstract way. We can use *trait bounds* to specify that a generic type can be any type that has certain behavior.

> Note: Traits are similar to a feature often called *interfaces* in other languages, although with some differences.

Defining a Trait

A type's behavior 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 to define a set of behaviors necessary to accomplish some purpose.

For example, let's 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 location and a `SocialPost` that can have, at most, 280 characters along with metadata that indicates whether it was a new post, a repost, or a reply to another post.

We want to make a media aggregator library crate named `aggregator` that can display summaries of data that might be stored in a `NewsArticle` or `SocialPost` instance. To do this, we need a summary from each type, and we'll request that summary by calling a `summarize` method on an instance. Listing 10-12 shows the definition of a public `Summary` trait that expresses this behavior.

```
pub trait Summary {
    fn summarize(&self) -> String;
}
```

Here, we declare a trait using the `trait` keyword and then the trait's name, which is `Summary` in this case. We also declare the trait as `pub` so that crates depending on this crate can make use of this trait too, as we'll see in a few examples. Inside the curly brackets, we declare the method signatures that describe the behaviors of the types that implement this trait, which in this case is `fn summarize(&self) -> String`.

After the method signature, instead of providing an implementation within curly brackets, we use a semicolon. Each type implementing this trait must provide its own custom behavior for the body of the method. The compiler will enforce that any type that has the `Summary` trait will have the method `summarize` defined with this signature exactly.

A trait can have multiple methods in its body: the method signatures are listed one per line, and each line ends in a semicolon.

Implementing a Trait on a Type

Now that we've defined the desired signatures of the `Summary` trait's methods, we can implement it on the types in our media aggregator. Listing 10-13 shows an implementation of the `Summary` trait on the `NewsArticle` struct that uses the headline, the author, and the location to create the return value of `summarize`. For the `SocialPost` struct, we define `summarize` as the username followed by the entire text of the post, assuming that the post content is already limited to 280 characters.

```
# pub trait Summary {
#     fn summarize(&self) -> String;
# }
#
pub struct NewsArticle {
    pub headline: String,
    pub location: String,
    pub author: String,
    pub content: String,
}

impl Summary for NewsArticle {
    fn summarize(&self) -> String {
        format!("{}, by {} ({})", self.headline, self.author,
self.location)
    }
```

```
}

pub struct SocialPost {
    pub username: String,
    pub content: String,
    pub reply: bool,
    pub repost: bool,
}

impl Summary for SocialPost {
    fn summarize(&self) -> String {
        format!("{}: {}", self.username, self.content)
    }
}
```

Implementing a trait on a type is similar to implementing regular methods. The difference is that after `impl`, we put the trait name we want to implement, then use the `for` keyword, and then specify the name of the type we want to implement the trait for. Within the `impl` block, we put the method signatures that the trait definition has defined. Instead of adding a semicolon after each signature, we use 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.

Now that the library has implemented the `Summary` trait on `NewsArticle` and `SocialPost`, users of the crate can call the trait methods on instances of `NewsArticle` and `SocialPost` in the same way we call regular methods. The only difference is that the user must bring the trait into scope as well as the types. Here's an example of how a binary crate could use our `aggregator` library crate:

```
use aggregator::{SocialPost, Summary};

fn main() {
    let post = SocialPost {
        username: String::from("horse_ebooks"),
        content: String::from(
```

```
            "of course, as you probably already know, people",
        ),
        reply: false,
        repost: false,
    };

    println!("1 new post: {}", post.summarize());
}
```

This code prints `1 new post: horse_ebooks: of course, as you probably already know, people`.

Other crates that depend on the `aggregator` crate can also bring the `Summary` trait into scope to implement `Summary` on their own types. One restriction to note is that we can implement a trait on a type only if either the trait or the type, or both, are local to our crate. For example, we can implement standard library traits like `Display` on a custom type like `SocialPost` as part of our `aggregator` crate functionality because the type `SocialPost` is local to our `aggregator` crate. We can also implement `Summary` on `Vec<T>` in our `aggregator` crate because the trait `Summary` is local to our `aggregator` crate.

But we can't implement external traits on external types. For example, we can't implement the `Display` trait on `Vec<T>` within our `aggregator` crate because `Display` and `Vec<T>` are both defined in the standard library and aren't local to our `aggregator` crate. This restriction is part of a property called *coherence*, and more specifically the *orphan rule*, so named because the parent type is not present. This rule ensures that other people's code can't break your code and vice versa. Without the rule, two crates could implement the same trait for the same type, and Rust wouldn't know which implementation to use.

Default Implementations

Sometimes it's useful to have default behavior for some or all of the methods in a trait instead of requiring implementations for all methods on every type. Then, as we implement the trait on a particular type, we can keep or override each method's default behavior.

In Listing 10-14, we specify a default string for the `summarize` method of the `Summary` trait instead of only defining the method signature, as we did in Listing 10-12.

```
pub trait Summary {
    fn summarize(&self) -> String {
        String::from("(Read more...)")
    }
}
#
# pub struct NewsArticle {
#     pub headline: String,
#     pub location: String,
#     pub author: String,
#     pub content: String,
# }
#
# impl Summary for NewsArticle {}
#
# pub struct SocialPost {
#     pub username: String,
#     pub content: String,
#     pub reply: bool,
#     pub repost: bool,
# }
#
# impl Summary for SocialPost {
#     fn summarize(&self) -> String {
#         format!("{}: {}", self.username, self.content)
#     }
# }
```

To use a default implementation to summarize instances of `NewsArticle`, we specify an empty `impl` block with `impl Summary for`

`NewsArticle {}`.

Even though we're no longer defining the `summarize` method on `NewsArticle` directly, we've provided a default implementation and specified that `NewsArticle` implements the `Summary` trait. As a result, we can still call the `summarize` method on an instance of `NewsArticle`, like this:

```
# use aggregator::{self, NewsArticle, Summary};
#
# fn main() {
    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.summarize());
# }
```

This code prints `New article available! (Read more...)`.

Creating a default implementation doesn't require us to change anything about the implementation of `Summary` on `SocialPost` in Listing 10-13. The reason is that the syntax for overriding a default implementation is the same as the syntax for implementing a trait method that doesn't have a default implementation.

Default implementations can call 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. For example, we could define the `Summary` trait to have a `summarize_author` method whose implementation is required, and then define a `summarize` method that has a default implementation that calls the `summarize_author` method:

```
pub trait Summary {
    fn summarize_author(&self) -> String;

    fn summarize(&self) -> String {
                        format!("(Read   more   from   {}...)",
self.summarize_author())
    }
}
#
# pub struct SocialPost {
#     pub username: String,
#     pub content: String,
#     pub reply: bool,
#     pub repost: bool,
# }
#
# impl Summary for SocialPost {
#     fn summarize_author(&self) -> String {
#         format!("@{}", self.username)
#     }
# }
```

To use this version of `Summary`, we only need to define `summarize_author` when we implement the trait on a type:

```
# pub trait Summary {
#     fn summarize_author(&self) -> String;
#
#     fn summarize(&self) -> String {
#                         format!("(Read   more   from   {}...)",
self.summarize_author())
#     }
# }
```

```
#
# pub struct SocialPost {
#     pub username: String,
#     pub content: String,
#     pub reply: bool,
#     pub repost: bool,
# }
#
impl Summary for SocialPost {
    fn summarize_author(&self) -> String {
        format!("@{}", self.username)
    }
}
```

After we define `summarize_author`, we can call `summarize` on instances of the `SocialPost` struct, and the default implementation of `summarize` will call the definition of `summarize_author` that we've provided. Because we've implemented `summarize_author`, the `Summary` trait has given us the behavior of the `summarize` method without requiring us to write any more code. Here's what that looks like:

```
# use aggregator::{self, SocialPost, Summary};
#
# fn main() {
    let post = SocialPost {
        username: String::from("horse_ebooks"),
        content: String::from(
            "of course, as you probably already know, people",
        ),
        reply: false,
        repost: false,
    };

    println!("1 new post: {}", post.summarize());
# }
```

This code prints `1 new post: (Read more from @horse_ebooks...)`.

Note that it isn't possible to call the default implementation from an overriding implementation of that same method.

Traits as Parameters

Now that you know how to define and implement traits, we can explore how to use traits to define functions that accept many different types. We'll use the `Summary` trait we implemented on the `NewsArticle` and `SocialPost` types in Listing 10-13 to define a `notify` function that calls the `summarize` method on its `item` parameter, which is of some type that implements the `Summary` trait. To do this, we use the `impl Trait` syntax, like this:

```
# pub trait Summary {
#     fn summarize(&self) -> String;
# }
#
# pub struct NewsArticle {
#     pub headline: String,
#     pub location: String,
#     pub author: String,
#     pub content: String,
# }
#
# impl Summary for NewsArticle {
#     fn summarize(&self) -> String {
#             format!("{}, by {} ({})", self.headline,
self.author, self.location)
#     }
# }
#
# pub struct SocialPost {
#     pub username: String,
#     pub content: String,
#     pub reply: bool,
#     pub repost: bool,
# }
```

```
#
# impl Summary for SocialPost {
#     fn summarize(&self) -> String {
#         format!("{}: {}", self.username, self.content)
#     }
# }
#
pub fn notify(item: &impl Summary) {
    println!("Breaking news! {}", item.summarize());
}
```

Instead of a concrete type for the `item` parameter, we specify the `impl` keyword and the trait name. This parameter accepts any type that implements the specified trait. In the body of `notify`, we can call any methods on `item` that come from the `Summary` trait, such as `summarize`. We can call `notify` and pass in any instance of `NewsArticle` or `SocialPost`. Code that calls the function with any other type, such as a `String` or an `i32`, won't compile because those types don't implement `Summary`.

Trait Bound Syntax

The `impl Trait` syntax works for straightforward cases but is actually syntax sugar for a longer form known as a *trait bound*; it looks like this:

```
pub fn notify<T: Summary>(item: &T) {
    println!("Breaking news! {}", item.summarize());
}
```

This longer form is equivalent to the example in the previous section but is more verbose. We place trait bounds with the declaration of the generic type parameter after a colon and inside angle brackets.

The `impl Trait` syntax is convenient and makes for more concise code in simple cases, while the fuller trait bound syntax can express more complexity in other cases. For example, we can have two parameters that implement `Summary`. Doing so with the `impl Trait` syntax looks like this:

```
pub fn notify(item1: &impl Summary, item2: &impl Summary) {
```

Using `impl Trait` is appropriate if we want this function to allow `item1` and `item2` to have different types (as long as both types implement `Summary`). If we want to force both parameters to have the same type, however, we must use a trait bound, like this:

```
pub fn notify<T: Summary>(item1: &T, item2: &T) {
```

The generic type `T` specified as the type of the `item1` and `item2` parameters constrains the function such that the concrete type of the value passed as an argument for `item1` and `item2` must be the same.

Specifying Multiple Trait Bounds with the + Syntax

We can also specify more than one trait bound. Say we wanted `notify` to use display formatting as well as `summarize` on `item`: we specify in the `notify` definition that `item` must implement both `Display` and `Summary`. We can do so using the `+` syntax:

```
pub fn notify(item: &(impl Summary + Display)) {
```

The `+` syntax is also valid with trait bounds on generic types:

```
pub fn notify<T: Summary + Display>(item: &T) {
```

With the two trait bounds specified, the body of `notify` can call `summarize` and use `{}` to format `item`.

Clearer Trait Bounds with `where` Clauses

Using too many trait bounds has its downsides. Each generic has its own trait bounds, so functions with multiple generic type parameters can contain lots of trait bound information between the function's name and its parameter list, making the function signature hard to read. For this reason, Rust has alternate syntax for specifying trait bounds inside a `where` clause after the function signature. So, instead of writing this:

```
fn some_function<T: Display + Clone, U: Clone + Debug>(t: &T,
u: &U) -> i32 {
```

we can use a `where` clause, like this:

```
fn some_function<T, U>(t: &T, u: &U) -> i32
where
```

```
    T: Display + Clone,
    U: Clone + Debug,
{
#     unimplemented!()
# }
```

This function's signature is less cluttered: the function name, parameter list, and return type are close together, similar to a function without lots of trait bounds.

Returning Types That Implement Traits

We can also use the `impl Trait` syntax in the return position to return a value of some type that implements a trait, as shown here:

```
# pub trait Summary {
#     fn summarize(&self) -> String;
# }
#
# pub struct NewsArticle {
#     pub headline: String,
#     pub location: String,
#     pub author: String,
#     pub content: String,
# }
#
# impl Summary for NewsArticle {
#     fn summarize(&self) -> String {
#             format!("{}, by {} ({})", self.headline,
self.author, self.location)
#     }
# }
#
# pub struct SocialPost {
#     pub username: String,
#     pub content: String,
#     pub reply: bool,
#     pub repost: bool,
```

```
# }
#
# impl Summary for SocialPost {
#     fn summarize(&self) -> String {
#         format!("{}: {}", self.username, self.content)
#     }
# }
#
fn returns_summarizable() -> impl Summary {
    SocialPost {
        username: String::from("horse_ebooks"),
        content: String::from(
            "of course, as you probably already know, people",
        ),
        reply: false,
        repost: false,
    }
}
```

By using `impl Summary` for the return type, we specify that the `returns_summarizable` function returns some type that implements the `Summary` trait without naming the concrete type. In this case, `returns_summarizable` returns a `SocialPost`, but the code calling this function doesn't need to know that.

The ability to specify a return type only by the trait it implements is especially useful in the context of closures and iterators, which we cover in Chapter 13. Closures and iterators create types that only the compiler knows or types that are very long to specify. The `impl Trait` syntax lets you concisely specify that a function returns some type that implements the `Iterator` trait without needing to write out a very long type.

However, you can only use `impl Trait` if you're returning a single type. For example, this code that returns either a `NewsArticle` or a `SocialPost` with the return type specified as `impl Summary` wouldn't work:

```
# pub trait Summary {
#     fn summarize(&self) -> String;
# }
#
# pub struct NewsArticle {
#     pub headline: String,
#     pub location: String,
#     pub author: String,
#     pub content: String,
# }
#
# impl Summary for NewsArticle {
#     fn summarize(&self) -> String {
#             format!("{}, by {} ({})", self.headline,
self.author, self.location)
#     }
# }
#
# pub struct SocialPost {
#     pub username: String,
#     pub content: String,
#     pub reply: bool,
#     pub repost: bool,
# }
#
# impl Summary for SocialPost {
#     fn summarize(&self) -> String {
#         format!("{}: {}", self.username, self.content)
#     }
# }
#
fn returns_summarizable(switch: bool) -> impl Summary {
    if switch {
        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.",
            ),
        }
    } else {
        SocialPost {
            username: String::from("horse_ebooks"),
            content: String::from(
                   "of course, as you probably already know,
people",
            ),
            reply: false,
            repost: false,
        }
    }
}
```

Returning either a `NewsArticle` or a `SocialPost` isn't allowed due to restrictions around how the `impl Trait` syntax is implemented in the compiler. We'll cover how to write a function with this behavior in the "Using Trait Objects That Allow for Values of Different Types" section of Chapter 18.

Using Trait Bounds to Conditionally Implement Methods

By using a trait bound with an `impl` block that uses generic type parameters, we can implement methods conditionally for types that implement the specified traits. For example, the type `Pair<T>` in Listing 10-15 always implements the `new` function to return a new instance of

`Pair<T>` (recall from the "Defining Methods" section of Chapter 5 that `Self` is a type alias for the type of the `impl` block, which in this case is `Pair<T>`). But in the next `impl` block, `Pair<T>` only implements the `cmp_display` method if its inner type `T` implements the `PartialOrd` trait that enables comparison *and* the `Display` trait that enables printing.

```
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);
        }
    }
}
```

We can also conditionally implement a trait for any type that implements another trait. Implementations of a trait on any type that satisfies the trait bounds are called *blanket implementations* and are used extensively in the Rust standard library. For example, the standard library implements the `ToString` trait on any type that implements the `Display` trait. The `impl` block in the standard library 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` trait on any type that implements the `Display` trait. For example, we can turn integers into their corresponding `String` values like this because 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 to reduce duplication but also specify to the compiler that we want the generic type to have particular behavior. The compiler can then use the trait bound information to check that all the concrete types used with our code provide the correct behavior. In dynamically typed languages, we would get an error at runtime if we called a method on a type which didn't define the method. But Rust moves these errors to compile time so 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 because we've already checked at compile time. Doing so improves performance without having to give up the flexibility of generics.

Validating References with Lifetimes

Lifetimes are another kind of generic that we've already been using. Rather than ensuring that a type has the behavior we want, lifetimes ensure that references are valid as long as we need them to be.

One detail we didn't discuss in the "References and Borrowing" section in Chapter 4 is that 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. We are only required to annotate types when multiple types are possible. In a similar way, we have to annotate lifetimes when the lifetimes of references could be related in a few different ways. Rust requires us to annotate the relationships using generic lifetime parameters to ensure the actual references used at runtime will definitely be valid.

Annotating lifetimes is not even a concept most other programming languages have, so this is going to feel unfamiliar. Although we won't cover lifetimes in their entirety in this chapter, we'll discuss common ways you might encounter lifetime syntax so you can get comfortable with the concept.

Preventing Dangling References with Lifetimes

The main aim of lifetimes is to prevent *dangling references*, which cause a program to reference data other than the data it's intended to reference. Consider the program in Listing 10-16, which has an outer scope and an inner scope.

```
fn main() {
    let r;

    {
        let x = 5;
        r = &x;
    }

    println!("r: {r}");
}
```

> Note: The examples in Listings 10-16, 10-17, and 10-23 declare variables without giving them an initial value, so the variable name exists in the outer scope. At first glance, this might appear to be in conflict with Rust's having no null values. However, if we try to use a variable before giving it a value, we'll get a compile-time error, which shows that Rust indeed does not allow null values.

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 the value in `r`. This code won't compile because the value that `r` is referring to has gone out of scope before we try to use it. Here is the error message:

```
$ cargo run
   Compiling chapter10 v0.1.0 (file:///projects/chapter10)
error[E0597]: `x` does not live long enough
 --> src/main.rs:6:13
  |
5 |         let x = 5;
  |             - binding `x` declared here
6 |         r = &x;
  |             ^^ borrowed value does not live long enough
7 |     }
  |     - `x` dropped here while still borrowed
8 |
9 |     println!("r: {r}");
  |                  --- borrow later used here

For more information about this error, try `rustc --explain E0597`.
error: could not compile `chapter10` (bin "chapter10") due to 1 previous error
```

The error message says that the variable `x` "does not live long enough." The reason is that `x` will be out of scope when the inner scope ends on line

7. But `r` is still valid for the outer scope; because its scope is larger, 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 is invalid? It uses a borrow checker.

The Borrow Checker

The Rust compiler has a *borrow checker* that compares scopes to determine whether all borrows are valid. Listing 10-17 shows the same code as Listing 10-16 but with annotations showing the lifetimes of the variables.

```
fn main() {
    let r;                // ---------+-- 'a
                          //          |
    {                     //          |
        let x = 5;        // -+-- 'b  |
        r = &x;           //  |       |
    }                     // -+       |
                          //          |
    println!("r: {r}");   //          |
}                         // ---------+
```

Here, 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 memory with a lifetime of `'b`. The program is rejected because `'b` is shorter than `'a`: the subject of the reference doesn’t live as long as the reference.

Listing 10-18 fixes the code so it doesn’t have a dangling reference and it compiles without any errors.

```
fn main() {
    let x = 5;            // ----------+-- 'b
                          //           |
    let r = &x;           // --+-- 'a  |
```

```
                          //   |       |
    println!("r: {r}");   //   |       |
                          // --+       |
}                         // ----------+
```

Here, `x` has the lifetime `'b`, which in this case is larger than `'a`. This means `r` can reference `x` because Rust knows that the reference in `r` will always be valid while `x` is valid.

Now that you know where the lifetimes of references are and how Rust analyzes lifetimes to ensure references will always be valid, let's explore generic lifetimes of parameters and return values in the context of functions.

Generic Lifetimes in Functions

We'll write a function that returns the longer of two string slices. This function will take two string slices and return a single string slice. After we've implemented the `longest` function, the code in Listing 10-19 should print `The longest string is abcd`.

```
fn main() {
    let string1 = String::from("abcd");
    let string2 = "xyz";

    let result = longest(string1.as_str(), string2);
    println!("The longest string is {result}");
}
```

Note that we want the function to take string slices, which are references, rather than strings, because we don't want the `longest` function to take ownership of its parameters. Refer to [“String Slices as Parameters”] in Chapter 4 for more discussion about why the parameters we use in Listing 10-19 are the ones we want.

If we try to implement the `longest` function as shown in Listing 10-20, it won't compile.

```
# fn main() {
#     let string1 = String::from("abcd");
```

```
#     let string2 = "xyz";
#
#     let result = longest(string1.as_str(), string2);
#     println!("The longest string is {result}");
# }
#
fn longest(x: &str, y: &str) -> &str {
    if x.len() > y.len() { x } else { y }
}
```

Instead, we get the following error that talks about lifetimes:

```
$ cargo run
   Compiling chapter10 v0.1.0 (file:///projects/chapter10)
error[E0106]: missing lifetime specifier
 --> src/main.rs:9:33
  |
9 | fn longest(x: &str, y: &str) -> &str {
  |               ----     ----     ^ expected named 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`
help: consider introducing a named lifetime parameter
  |
9 | fn longest<'a>(x: &'a str, y: &'a str) -> &'a str {
  |           ++++     ++          ++          ++

For more information about this error, try `rustc --explain
E0106`.
error: could not compile `chapter10` (bin "chapter10") due to
1 previous error
```

The help text reveals that the return type needs a generic lifetime parameter on it because Rust can't tell whether the reference being returned refers to `x` or `y`. Actually, we don't know either, because the `if` block in the body of this function returns a reference to `x` and the `else` block returns a reference to `y`!

When 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 as we did in Listings 10-17 and 10-18 to determine whether 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. To fix this error, we'll add generic lifetime parameters that define the relationship between the references so the borrow checker can perform its analysis.

Lifetime Annotation Syntax

Lifetime annotations don't change how long any of the references live. Rather, they describe the relationships of the lifetimes of multiple references to each other without affecting the lifetimes. Just as functions can accept any type when the signature specifies a generic type parameter, functions can accept references with any lifetime by specifying a generic lifetime parameter.

Lifetime annotations have a slightly unusual syntax: the names of lifetime parameters must start with an apostrophe (`'`) and are usually all lowercase and very short, like generic types. Most people use the name `'a` for the first lifetime annotation. We place lifetime parameter annotations after the `&` of a reference, using a space to separate the annotation from the reference's type.

Here are some examples: 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 because the annotations are meant to tell Rust how generic lifetime parameters of multiple references relate to each other. Let's examine how the lifetime annotations relate to each other in the context of the `longest` function.

Lifetime Annotations in Function Signatures

To use lifetime annotations in function signatures, we need to declare the generic *lifetime* parameters inside angle brackets between the function name and the parameter list, just as we did with generic *type* parameters.

We want the signature to express the following constraint: the returned reference will be valid as long as both the parameters are valid. This is the relationship between lifetimes of the parameters and the return value. We'll name the lifetime `'a` and then add it to each reference, as shown in Listing 10-21.

```
# fn main() {
#     let string1 = String::from("abcd");
#     let string2 = "xyz";
#
#     let result = longest(string1.as_str(), string2);
#     println!("The longest string is {result}");
# }
#
fn longest<'a>(x: &'a str, y: &'a str) -> &'a str {
    if x.len() > y.len() { x } else { y }
}
```

This code should compile and produce the result we want when we use it with the `main` function in Listing 10-19.

The function signature now tells Rust that for some lifetime `'a`, the function takes two parameters, both of which are string slices that live at least as long as lifetime `'a`. The function signature also tells Rust that the string slice returned from the function will live at least as long as lifetime `'a`. In practice, it means that the lifetime of the reference returned by the `longest` function is the same as the smaller of the lifetimes of the values referred to by the function arguments. These relationships are what we want Rust to use when analyzing this code.

Remember, when we specify the lifetime parameters in this function signature, we're not changing the lifetimes of any values passed in or returned. Rather, we're specifying that the borrow checker should reject any values that don't adhere to these constraints. Note that the `longest` function doesn't need to know exactly how long `x` and `y` will live, only that some scope can be substituted for `'a` that will satisfy this signature.

When annotating lifetimes in functions, the annotations go in the function signature, not in the function body. The lifetime annotations become part of the contract of the function, much like the types in the signature. Having function signatures contain the lifetime contract means the analysis the Rust compiler does can be simpler. If there's a problem with the way a function is annotated or the way it is called, the compiler errors can point to the part of our code and the constraints more precisely. If, instead, the Rust compiler made more inferences about what we intended the relationships of the lifetimes to be, the compiler might only be able to point to a use of our code many steps away from the cause of the problem.

When we pass concrete references to `longest`, the concrete lifetime that is substituted for `'a` is the part of the scope of `x` that overlaps with the scope of `y`. In other words, the generic lifetime `'a` will get the concrete lifetime that is 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 also be valid for the length of the smaller of the lifetimes of `x` and `y`.

Let's look at how the lifetime annotations restrict the `longest` function by passing in references that have different concrete lifetimes. Listing 10-22 is a straightforward example.

```
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}");
    }
}
#
# fn longest<'a>(x: &'a str, y: &'a str) -> &'a str {
#     if x.len() > y.len() { x } else { y }
# }
```

In this example, `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. Run this code and you'll see that the borrow checker approves; it will compile and print `The longest string is long string is long`.

Next, let's try an example that shows 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`. Then we'll move the `println!` that uses `result` to outside the inner scope, after the inner scope has ended. The code in Listing 10-23 will not compile.

```
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}");
}
#
# fn longest<'a>(x: &'a str, y: &'a str) -> &'a str {
#     if x.len() > y.len() { x } else { y }
# }
```

When we try to compile this code, we get this error:

```
$ cargo run
   Compiling chapter10 v0.1.0 (file:///projects/chapter10)
error[E0597]: `string2` does not live long enough
 --> src/main.rs:6:44
  |
5 |         let string2 = String::from("xyz");
  |             ------- binding `string2` declared here
6 |         result = longest(string1.as_str(),
string2.as_str());
  |                                            ^^^^^^^
borrowed value does not live long enough
7 |     }
  |     - `string2` dropped here while still borrowed
8 |     println!("The longest string is {result}");
  |                                     -------- borrow later
used here

For more information about this error, try `rustc --explain
E0597`.
error: could not compile `chapter10` (bin "chapter10") due to
1 previous error
```

The error shows that for `result` to be valid for the `println!` statement, `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 using the same lifetime parameter `'a`.

As humans, we can look at this code and see that `string1` is longer than `string2`, 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!` statement. However, the compiler can't see that the reference is valid in this case. We've told Rust 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 10-23 as possibly having an invalid reference.

Try designing 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 or not your experiments will pass the borrow checker before you compile; then check to see if you're right!

Thinking in Terms of Lifetimes

The way in which you need 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 parameter rather than the longest string slice, we wouldn't need to specify a lifetime on the `y` parameter. The following code will compile:

```
# fn main() {
#     let string1 = String::from("abcd");
#     let string2 = "efghijklmnopqrstuvwxyz";
#
#     let result = longest(string1.as_str(), string2);
#     println!("The longest string is {result}");
# }
#
fn longest<'a>(x: &'a str, y: &str) -> &'a str {
    x
}
```

We've specified a lifetime parameter `'a` for the parameter `x` and the return type, but not for the parameter `y`, because 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 for one of the parameters. If the reference returned does *not* refer to one of the parameters, it must refer to a value created within this function. However, this would be a dangling reference because 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:

```
# fn main() {
#     let string1 = String::from("abcd");
#     let string2 = "xyz";
#
#     let result = longest(string1.as_str(), string2);
#     println!("The longest string is {result}");
# }
#
fn longest<'a>(x: &str, y: &str) -> &'a str {
    let result = String::from("really long string");
    result.as_str()
}
```

Here, even though we've specified a lifetime parameter `'a` for the return type, this implementation will fail to compile because the return value lifetime is not related to the lifetime of the parameters at all. Here is the error message we get:

```
$ cargo run
   Compiling chapter10 v0.1.0 (file:///projects/chapter10)
error[E0515]: cannot return value referencing local variable
`result`
  --> src/main.rs:11:5
   |
11 |     result.as_str()
   |     ------^^^^^^^^^
   |     |
   |     returns a value referencing data owned by the current
function
   |     `result` is borrowed here

For more information about this error, try `rustc --explain
E0515`.
error: could not compile `chapter10` (bin "chapter10") due to
1 previous error
```

The problem is that `result` goes out of scope and gets cleaned up at the end of the `longest` function. We're also trying to return a reference to `result` from the function. There is 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 the calling function is then responsible for cleaning up the value.

Ultimately, lifetime syntax is about connecting the lifetimes of various parameters 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

So far, the structs we've defined all hold owned types. We can define structs to hold references, but in that case we would need to add a lifetime annotation on every reference in the struct's definition. Listing 10-24 has a struct named `ImportantExcerpt` that holds a string slice.

```
struct ImportantExcerpt<'a> {
    part: &'a str,
}

fn main() {
    let novel = String::from("Call me Ishmael. Some years ago...");
    let first_sentence = novel.split('.').next().unwrap();
    let i = ImportantExcerpt {
        part: first_sentence,
    };
}
```

This struct has the single field `part` that holds a string slice, which is a reference. As with generic data types, we declare the name of the generic lifetime parameter inside angle brackets after the name of the struct so we can use the lifetime parameter in the body of the struct definition. This annotation means an instance of `ImportantExcerpt` can't outlive the reference it holds in its `part` field.

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`. The data in `novel` exists before the `ImportantExcerpt` instance is created. In addition, `novel` doesn't go out of scope until after the `ImportantExcerpt` goes out of scope, so the reference in the `ImportantExcerpt` instance is valid.

Lifetime Elision

You've learned that every reference has a lifetime and that you need to specify lifetime parameters for functions or structs that use references. However, we had a function in Listing 4-9, shown again in Listing 10-25, that compiled without lifetime annotations.

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

The reason this function compiles without lifetime annotations is historical: in early versions (pre-1.0) of Rust, this code wouldn't have compiled because 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 entering the same lifetime annotations over and over in particular situations. These situations were predictable and followed a few deterministic patterns. The developers programmed these patterns into the compiler's code so the borrow checker could infer the lifetimes in these situations and wouldn't need explicit annotations.

This piece of Rust history is relevant because it's 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; they're 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 there is still ambiguity about what lifetimes the references have after Rust applies the rules, the compiler won't guess what the lifetime of the remaining references should be. Instead of guessing, the compiler will give you an error that you can resolve by adding the lifetime annotations.

Lifetimes on function or method parameters are called *input lifetimes*, and lifetimes on return values are called *output lifetimes*.

The compiler uses three rules to figure out the lifetimes of the references when there aren't explicit annotations. The first rule applies to input lifetimes, and the second and third rules apply to output lifetimes. If the compiler gets to the end of the three rules and there are still references for which it can't figure out lifetimes, the compiler will stop with an error. These rules apply to `fn` definitions as well as `impl` blocks.

The first rule is that the compiler assigns a lifetime parameter to each parameter that's a reference. In other words, a function with one parameter gets one lifetime parameter: `fn foo<'a>(x: &'a i32)`; a function with two parameters gets two separate lifetime parameters: `fn foo<'a, 'b>(x: &'a i32, y: &'b i32)`; and so on.

The second rule is that, 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`.

The third rule is that, if there are multiple input lifetime parameters, but one of them is `&self` or `&mut self` because this is a method, the lifetime of `self` is assigned to all output lifetime parameters. This third rule makes methods much nicer to read and write because fewer symbols are necessary.

Let's pretend we're the compiler. We'll apply these rules to figure out the lifetimes of the references in the signature of the `first_word` function in Listing 10-25. The signature starts without any lifetimes associated with the references:

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

Then the compiler applies the first rule, which specifies that each parameter gets its own lifetime. We'll call it `'a` as usual, so now the signature is this:

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

The second rule applies because there is exactly one input lifetime. The second rule specifies that the lifetime of the one input parameter gets assigned to the output lifetime, so the signature is now this:

```
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 look at another example, this time using the `longest` function that had no lifetime parameters when we started working with it in Listing 10-20:

```
fn longest(x: &str, y: &str) -> &str {
```

Let's apply the first rule: each parameter gets its own lifetime. This time we have two parameters instead of one, so we have two lifetimes:

```
fn longest<'a, 'b>(x: &'a str, y: &'b str) -> &str {
```

You can see that the second rule doesn't apply because there is more than one input lifetime. The third rule doesn't apply either, because `longest` is a function rather than a method, so none of the parameters are `self`. After working through all three rules, we still haven't figured out what the return type's lifetime is. This is why we got an error trying to compile the code in Listing 10-20: the compiler worked through the lifetime elision rules but still couldn't figure out all the lifetimes of the references in the signature.

Because the third rule really only applies in method signatures, we'll look at lifetimes in that context next to 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, we use the same syntax as that of generic type parameters, as shown in Listing 10-11. Where we declare and use the lifetime parameters depends on whether they're related to the struct fields or the method parameters 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 because 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 10-24.

First we’ll use a method named `level` whose only parameter is a reference to `self` and whose return value is an `i32`, which is not a reference to anything:

```
# struct ImportantExcerpt<'a> {
#     part: &'a str,
# }
#
impl<'a> ImportantExcerpt<'a> {
    fn level(&self) -> i32 {
        3
    }
}
#
# impl<'a> ImportantExcerpt<'a> {
#     fn announce_and_return_part(&self, announcement: &str) -
> &str {
#         println!("Attention please: {announcement}");
#         self.part
#     }
# }
#
# fn main() {
#     let novel = String::from("Call me Ishmael. Some years
ago...");
#     let first_sentence = novel.split('.').next().unwrap();
#     let i = ImportantExcerpt {
#         part: first_sentence,
#     };
# }
```

The lifetime parameter declaration after `impl` and its use after the type name are required, but we’re not required to annotate the lifetime of the reference to `self` because of the first elision rule.

Here is an example where the third lifetime elision rule applies:

```
# struct ImportantExcerpt<'a> {
#     part: &'a str,
# }
#
# impl<'a> ImportantExcerpt<'a> {
#     fn level(&self) -> i32 {
#         3
#     }
# }
#
impl<'a> ImportantExcerpt<'a> {
    fn announce_and_return_part(&self, announcement: &str) ->
&str {
        println!("Attention please: {announcement}");
        self.part
    }
}
#
# fn main() {
#     let novel = String::from("Call me Ishmael. Some years
ago...");
#     let first_sentence = novel.split('.').next().unwrap();
#     let i = ImportantExcerpt {
#         part: first_sentence,
#     };
# }
```

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

One special lifetime we need to discuss is `'static`, which denotes that the affected reference *can* live for the entire duration of the program. All string literals have the `'static` lifetime, which we can annotate as follows:

```
let s: &'static str = "I have a static lifetime.";
```

The text of this string is stored directly in the program's binary, which is always available. Therefore, the lifetime of all string literals is `'static`.

You might see suggestions in error messages to use the `'static` lifetime. But before specifying `'static` as the lifetime for a reference, think about whether the reference you have actually lives the entire lifetime of your program or not, and whether you want it to. Most of the time, an error message suggesting the `'static` lifetime results from attempting to create a dangling reference or a mismatch of the available lifetimes. In such cases, the solution is to fix those problems, not to specify 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!

```
# fn main() {
#     let string1 = String::from("abcd");
#     let string2 = "xyz";
#
#     let result = longest_with_an_announcement(
#         string1.as_str(),
#         string2,
#         "Today is someone's birthday!",
#     );
#     println!("The longest string is {result}");
# }
#
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 10-21 that returns the longer of two string slices. But now it has an extra parameter named `ann` of the generic type `T`, which can be filled in by any type that implements the `Display` trait as specified by the `where` clause. This extra parameter will be printed using `{}`, which is why the `Display` trait bound is necessary. Because lifetimes are a type of generic, the declarations of the lifetime parameter `'a` and the generic type parameter `T` go in the same list inside 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 without repetition that works in many different situations. Generic type parameters let you apply the code to different types. Traits and trait bounds ensure that even though the types are generic, they'll have the behavior the code needs. You learned how to use lifetime annotations to ensure that this flexible code won't have any dangling references. And all of this analysis happens at compile time, which doesn't affect runtime performance!

Believe it or not, there is much more to learn on the topics we discussed in this chapter: Chapter 18 discusses trait objects, which are another way to use traits. There are also more complex scenarios involving lifetime annotations that you will only need in very advanced scenarios; for those, you should read the Rust Reference. But next, you'll learn how to write tests in Rust so you can make sure your code is working the way it should.

Writing Automated Tests

In his 1972 essay “The Humble Programmer,” Edsger W. Dijkstra said that “program testing can be a very effective way to show the presence of bugs, but it is hopelessly inadequate for showing their absence.” That doesn’t mean we shouldn’t try to test as much as we can!

Correctness in our programs is the extent to which our code does what we intend it to do. Rust is designed with a high degree of concern about the correctness of programs, but correctness is complex and not easy to prove. Rust’s type system shoulders a huge part of this burden, but the type system cannot catch everything. As such, Rust includes support for writing automated software tests.

Say we write a function `add_two` that adds 2 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 does all the type checking and borrow checking that you’ve learned so far to ensure that, for instance, we aren’t passing a `String` value or an invalid reference to this function. But Rust *can’t* check that this function will do precisely what we intend, which is return the parameter plus 2 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, the returned value is `5`. 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: although we can’t cover in one chapter every detail about how to write good tests, in this chapter we will 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 these three actions:

- Set up any needed data or state.
- Run the code you want to test.
- Assert that the results are what you expect.

Let's look at the features Rust provides specifically for writing tests that take these actions, which include 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; one example is the `derive` attribute we used with structs in Chapter 5. To change a function into a test function, add `#[test]` on the line before `fn`. When you run your tests with the `cargo test` command, Rust builds a test runner binary that runs the annotated functions and reports on whether each test function passes or fails.

Whenever we make a new library project with Cargo, a test module with a test function in it is automatically generated for us. This module gives you a template for writing your tests so you don't have to look up the exact structure and syntax every time you start a new project. You can add as many additional test functions and as many test modules as you want!

We'll explore some aspects of how tests work by experimenting with the template test before we actually test 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` that will add two numbers:

```
$ cargo new adder --lib
     Created library `adder` project
```

```
$ cd adder
```

The contents of the *src/lib.rs* file in your `adder` library should look like Listing 11-1.

```
pub fn add(left: u64, right: u64) -> u64 {
    left + right
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_works() {
        let result = add(2, 2);
        assert_eq!(result, 4);
    }
}
```

The file starts with an example `add` function, so that we have something to test.

For now, let's focus solely on the `it_works` function. Note the `#[test]` annotation: this attribute indicates this is a test function, so the test runner knows to treat this function as a test. We might also have non-test functions in the `tests` module to help set up common scenarios or perform common operations, so we always need to indicate which functions are tests.

The example function body uses the `assert_eq!` macro to assert that `result`, which contains the result of calling `add` with 2 and 2, equals 4. This assertion serves as an example of the format for a typical test. Let's run it to see that this test passes.

The `cargo test` command runs all tests in our project, as shown in Listing 11-2.

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
     Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.57s
     Running unittests src/lib.rs (target/debug/deps/adder-
01ad14159ff659ab)

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

Cargo compiled and ran the test. We see the line `running 1 test`. The next line shows the name of the generated test function, called `tests::it_works`, and that the result of running that test is `ok`. The overall summary `test result: ok.` means that all the tests passed, and the portion that reads `1 passed; 0 failed` totals the number of tests that passed or failed.

It's possible to mark a test as ignored so it doesn't run in a particular instance; we'll cover that in the "Ignoring Some Tests Unless Specifically Requested" section later in this chapter. Because we haven't done that here, the summary shows `0 ignored`. We can also pass an argument to the `cargo test` command to run only tests whose name matches a string; this is called *filtering* and we'll cover it in the "Running a Subset of Tests by

Name” section. Here we haven’t filtered the tests being run, so the end of the summary shows `0 filtered out`.

The `0 measured` statistic is for benchmark tests that measure performance. Benchmark tests are, as of this writing, only available in nightly Rust. See the documentation about benchmark tests to learn more.

The next part of the test output starting at `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 keep your docs and your code in sync! We’ll discuss how to write documentation tests in the “Documentation Comments as Tests” section of Chapter 14. For now, we’ll ignore the `Doc-tests` output.

Let’s start to customize the test to our own needs. First, change the name of the `it_works` function to a different name, such as `exploration`, like so:

Filename: src/lib.rs

```
pub fn add(left: u64, right: u64) -> u64 {
    left + right
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn exploration() {
        let result = add(2, 2);
        assert_eq!(result, 4);
    }
}
```

Then run `cargo test` again. The output now shows `exploration` instead of `it_works`:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.59s
     Running unittests src/lib.rs (target/debug/deps/adder-
92948b65e88960b4)

running 1 test
test tests::exploration ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

Now we’ll 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. In Chapter 9, we talked about how the simplest way to panic is to call the `panic!` macro. Enter the new test as a function named `another`, so your *src/lib.rs* file looks like Listing 11-3.

```
pub fn add(left: u64, right: u64) -> u64 {
    left + right
}

#[cfg(test)]
mod tests {
    use super::*;
```

```
    #[test]
    fn exploration() {
        let result = add(2, 2);
        assert_eq!(result, 4);
    }

    #[test]
    fn another() {
        panic!("Make this test fail");
    }
}
```

Run the tests again using `cargo test`. The output should look like Listing 11-4, which shows that our `exploration` test passed and `another` failed.

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.72s
       Running unittests src/lib.rs (target/debug/deps/adder-
92948b65e88960b4)

running 2 tests
test tests::another ... FAILED
test tests::exploration ... ok

failures:

---- tests::another stdout ----

thread 'tests::another' panicked at src/lib.rs:17:9:
Make this test fail
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace
```

```
failures:
    tests::another

test result: FAILED. 1 passed; 1 failed; 0 ignored; 0
measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

Instead of `ok`, the line `test tests::another` shows `FAILED`. Two new sections appear between the individual results and the summary: the first displays the detailed reason for each test failure. In this case, we get the details that `tests::another` failed because it panicked with the message `Make this test fail` on line 17 in the *src/lib.rs* file. 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 to more easily debug it; we'll talk more about ways to run tests in the "Controlling How Tests Are Run" section.

The summary line displays at the end: overall, our test result is `FAILED`. We had one test pass and one test fail.

Now that you'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`, nothing happens and the test passes. If the value is `false`, the `assert!` macro calls `panic!` to cause the test to fail. Using the `assert!` macro helps us check that our code is functioning in the way we intend.

In Chapter 5, Listing 5-15, we used a `Rectangle` struct and a `can_hold` method, which are repeated here in Listing 11-5. Let's put this code in the *src/lib.rs* file, then write some tests for it using the `assert!` macro.

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}

impl Rectangle {
    fn can_hold(&self, other: &Rectangle) -> bool {
        self.width > other.width && self.height > other.height
    }
}
```

The `can_hold` method returns a Boolean, which means it's a perfect use case for the `assert!` macro. In Listing 11-6, we write a test that exercises the `can_hold` method by creating a `Rectangle` instance that has a width of 8 and a height of 7 and asserting that it can hold another `Rectangle` instance that has a width of 5 and a height of 1.

```
# #[derive(Debug)]
# struct Rectangle {
#     width: u32,
#     height: u32,
# }
#
# impl Rectangle {
#     fn can_hold(&self, other: &Rectangle) -> bool {
#         self.width > other.width && self.height > other.height
#     }
# }
```

```
#
#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn larger_can_hold_smaller() {
        let larger = Rectangle {
            width: 8,
            height: 7,
        };
        let smaller = Rectangle {
            width: 5,
            height: 1,
        };

        assert!(larger.can_hold(&smaller));
    }
}
```

Note the `use super::*;` line inside the `tests` module. The `tests` module is a regular module that follows the usual visibility rules we covered in Chapter 7 in the "Paths for Referring to an Item in the Module Tree" section. Because the `tests` module is an inner module, we need to bring the code under test in the outer module into the scope of the inner module. We use a glob here, so 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!

```
$ cargo test
   Compiling rectangle v0.1.0 (file:///projects/rectangle)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.66s
                         Running unittests src/lib.rs
(target/debug/deps/rectangle-6584c4561e48942e)

running 1 test
test tests::larger_can_hold_smaller ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests rectangle

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

It does pass! Let’s add another test, this time asserting that a smaller rectangle cannot hold a larger rectangle:

Filename: src/lib.rs

```
# #[derive(Debug)]
# struct Rectangle {
#     width: u32,
#     height: u32,
# }
#
# impl Rectangle {
#     fn can_hold(&self, other: &Rectangle) -> bool {
#                 self.width > other.width && self.height >
other.height
#     }
# }
```

```
#
#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn larger_can_hold_smaller() {
        // --snip--
#         let larger = Rectangle {
#             width: 8,
#             height: 7,
#         };
#         let smaller = Rectangle {
#             width: 5,
#             height: 1,
#         };
#
#         assert!(larger.can_hold(&smaller));
    }

    #[test]
    fn smaller_cannot_hold_larger() {
        let larger = Rectangle {
            width: 8,
            height: 7,
        };
        let smaller = Rectangle {
            width: 5,
            height: 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. As a result, our test will pass if `can_hold` returns `false`:

```
$ cargo test
   Compiling rectangle v0.1.0 (file:///projects/rectangle)
        Finished  `test`  profile  [unoptimized  +  debuginfo]
target(s) in 0.66s
                          Running     unittests     src/lib.rs
(target/debug/deps/rectangle-6584c4561e48942e)

running 2 tests
test tests::larger_can_hold_smaller ... ok
test tests::smaller_cannot_hold_larger ... ok

test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests rectangle

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

Two tests that pass! Now let’s see what happens to our test results when we introduce a bug in our code. We’ll change the implementation of the `can_hold` method by replacing the greater-than sign with a less-than sign when it compares the widths:

```
# #[derive(Debug)]
# struct Rectangle {
#     width: u32,
#     height: u32,
# }
#
```

```
// --snip--
impl Rectangle {
    fn can_hold(&self, other: &Rectangle) -> bool {
        self.width < other.width && self.height > other.height
    }
}
#
# #[cfg(test)]
# mod tests {
#     use super::*;
#
#     #[test]
#     fn larger_can_hold_smaller() {
#         let larger = Rectangle {
#             width: 8,
#             height: 7,
#         };
#         let smaller = Rectangle {
#             width: 5,
#             height: 1,
#         };
#
#         assert!(larger.can_hold(&smaller));
#     }
#
#     #[test]
#     fn smaller_cannot_hold_larger() {
#         let larger = Rectangle {
#             width: 8,
#             height: 7,
#         };
#         let smaller = Rectangle {
#             width: 5,
#             height: 1,
#         };
#
```

```
#         assert!(!smaller.can_hold(&larger));
#     }
# }
```

Running the tests now produces the following:

```
$ cargo test
   Compiling rectangle v0.1.0 (file:///projects/rectangle)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.66s
                          Running unittests src/lib.rs
(target/debug/deps/rectangle-6584c4561e48942e)

running 2 tests
test tests::larger_can_hold_smaller ... FAILED
test tests::smaller_cannot_hold_larger ... ok

failures:

---- tests::larger_can_hold_smaller stdout ----

thread 'tests::larger_can_hold_smaller' panicked at
src/lib.rs:28:9:
assertion failed: larger.can_hold(&smaller)
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace


failures:
    tests::larger_can_hold_smaller

test result: FAILED. 1 passed; 1 failed; 0 ignored; 0
measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

Our tests caught the bug! Because `larger.width` is `8` and `smaller.width` is `5`, the comparison of the widths in `can_hold` now returns `false`: 8 is not less than 5.

Testing Equality with the `assert_eq!` and `assert_ne!` Macros

A common way to verify functionality is to test for equality between the result of the code under test and the value you expect the code to return. You could do this by 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—`assert_eq!` and `assert_ne!`—to perform this test more conveniently. These macros compare two arguments for equality or inequality, respectively. They'll also print the two values if the assertion fails, which makes it easier to see *why* the test failed; conversely, the `assert!` macro only indicates that it got a `false` value for the `==` expression, without printing the values that led to the `false` value.

In Listing 11-7, we write a function named `add_two` that adds `2` to its parameter, then we test this function using the `assert_eq!` macro.

```
pub fn add_two(a: u64) -> u64 {
    a + 2
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_adds_two() {
        let result = add_two(2);
        assert_eq!(result, 4);
    }
}
```

Let's check that it passes!

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.58s
       Running unittests src/lib.rs (target/debug/deps/adder-
92948b65e88960b4)

running 1 test
test tests::it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

We create a variable named `result` that holds the result of calling `add_two(2)`. Then we pass `result` and `4` as the arguments to the `assert_eq!` macro. The output line for this test is `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 `assert_eq!` looks like when it fails. Change the implementation of the `add_two` function to instead add `3`:

```
pub fn add_two(a: u64) -> u64 {
    a + 3
}
#
# #[cfg(test)]
```

```
# mod tests {
#     use super::*;
#
#     #[test]
#     fn it_adds_two() {
#         let result = add_two(2);
#         assert_eq!(result, 4);
#     }
# }
```

Run the tests again:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished `test` profile [unoptimized + debuginfo] target(s) in 0.61s
     Running unittests src/lib.rs (target/debug/deps/adder-92948b65e88960b4)

running 1 test
test tests::it_adds_two ... FAILED

failures:

---- tests::it_adds_two stdout ----

thread 'tests::it_adds_two' panicked at src/lib.rs:12:9:
assertion `left == right` failed
  left: 5
 right: 4
note: run with `RUST_BACKTRACE=1` environment variable to display a backtrace


failures:
    tests::it_adds_two
```

```
test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

Our test caught the bug! The `tests::it_adds_two` test failed, and the message tells us that the assertion that failed was `left == right` and what the `left` and `right` values are. This message helps us start debugging: the `left` argument, where we had the result of calling `add_two(2)`, was `5` but the `right` argument was `4`. You can imagine that this would be especially helpful when we have a lot of tests going on.

Note that in some languages and test frameworks, the parameters to equality assertion functions are called `expected` and `actual`, and the order in which we specify the arguments matters. However, in Rust, they're called `left` and `right`, and the order in which we specify the value we expect and the value the code produces doesn't matter. We could write the assertion in this test as `assert_eq!(4, result)`, which would result in the same failure message that displays `` assertion `left == right` failed ``.

The `assert_ne!` macro will pass if the two values we give it are not equal and fail if they're equal. This macro is most useful for cases when we're not sure what a value *will* be, but we know what the value definitely *shouldn't* be. For example, if we're testing 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 primitive types and most of the standard library types implement these traits. For structs and enums that you define yourself, you'll need to implement `PartialEq` to assert equality of those types. You'll also need to implement `Debug` to print the values when the assertion fails. Because both traits are derivable traits, as mentioned in Listing 5-12 in Chapter 5, this is usually as straightforward as adding the `#[derive(PartialEq, Debug)]` annotation to your struct or enum definition. See Appendix C, "Derivable Traits," for more details about these and other derivable traits.

Adding Custom Failure Messages

You can also add a custom message to be printed with the failure message as optional arguments to the `assert!`, `assert_eq!`, and `assert_ne!` macros. Any arguments specified after the required arguments are passed along to the `format!` macro (discussed in "Concatenation with the `+` Operator or the `format!` Macro" in Chapter 8), so you can pass a format string that contains `{}` placeholders and values to go in those placeholders. Custom messages are useful for documenting what an assertion means; when a test fails, you'll 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 when the requirements change, so instead of checking for exact equality to the value returned from the `greeting` function, we'll just assert that the output contains the text of the input parameter.

Now let's introduce a bug into this code by changing `greeting` to exclude `name` to see what the default test failure looks like:

```
pub fn greeting(name: &str) -> String {
    String::from("Hello!")
}
#
# #[cfg(test)]
# mod tests {
#     use super::*;
#
#     #[test]
#     fn greeting_contains_name() {
#         let result = greeting("Carol");
#         assert!(result.contains("Carol"));
#     }
# }
```

Running this test produces the following:

```
$ cargo test
   Compiling greeter v0.1.0 (file:///projects/greeter)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.91s
      Running unittests src/lib.rs (target/debug/deps/greeter-
170b942eb5bf5e3a)

running 1 test
test tests::greeting_contains_name ... FAILED

failures:

---- tests::greeting_contains_name stdout ----
```

```
thread 'tests::greeting_contains_name' panicked at src/lib.rs:12:9:
assertion failed: result.contains("Carol")
note: run with `RUST_BACKTRACE=1` environment variable to display a backtrace


failures:
    tests::greeting_contains_name

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

This result just indicates that the assertion failed and which line the assertion is on. A more useful failure message would print the value from the `greeting` function. Let's add a custom failure message composed of a format string with a placeholder filled in with the actual value we got from the `greeting` function:

```
# pub fn greeting(name: &str) -> String {
#     String::from("Hello!")
# }
#
# #[cfg(test)]
# mod tests {
#     use super::*;
#
    #[test]
    fn greeting_contains_name() {
        let result = greeting("Carol");
        assert!(
            result.contains("Carol"),
                  "Greeting did not contain name, value was `{result}`"
```

```
        );
    }
# }
```

Now when we run the test, we’ll get a more informative error message:

```
$ cargo test
   Compiling greeter v0.1.0 (file:///projects/greeter)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.93s
      Running unittests src/lib.rs (target/debug/deps/greeter-
170b942eb5bf5e3a)

running 1 test
test tests::greeting_contains_name ... FAILED

failures:

---- tests::greeting_contains_name stdout ----

thread 'tests::greeting_contains_name' panicked at
src/lib.rs:12:9:
Greeting did not contain name, value was `Hello!`
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace


failures:
    tests::greeting_contains_name

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0
measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

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 return values, it's important to check that our code handles error conditions as we expect. For example, consider the `Guess` type that we created in Chapter 9, Listing 9-13. Other code that uses `Guess` depends on the guarantee that `Guess` instances will contain only 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 do this by adding the attribute `should_panic` to our test function. The test passes if the code inside the function panics; the test fails if the code inside the function doesn't panic.

Listing 11-8 shows a test that checks that the error conditions of `Guess::new` happen when we expect them to.

```
pub struct Guess {
    value: i32,
}

impl Guess {
    pub fn new(value: i32) -> 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);
    }
}
```

We place the `#[should_panic]` attribute after the `#[test]` attribute and before the test function it applies to. Let's look at the result when this test passes:

```
$ cargo test
   Compiling guessing_game v0.1.0 (file:///projects/guessing_game)
    Finished `test` profile [unoptimized + debuginfo] target(s) in 0.58s
     Running unittests src/lib.rs (target/debug/deps/guessing_game-57d70c3acb738f4d)

running 1 test
test tests::greater_than_100 - should panic ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s

   Doc-tests guessing_game

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s
```

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:

```
# pub struct Guess {
#     value: i32,
# }
```

```
#
// --snip--
impl Guess {
    pub fn new(value: i32) -> Guess {
        if value < 1 {
            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);
#     }
# }
```

When we run the test in Listing 11-8, it will fail:

```
$ cargo test
                    Compiling       guessing_game       v0.1.0
(file:///projects/guessing_game)
        Finished  `test`  profile  [unoptimized  +  debuginfo]
target(s) in 0.62s
                         Running     unittests     src/lib.rs
(target/debug/deps/guessing_game-57d70c3acb738f4d)

running 1 test
test tests::greater_than_100 - should panic ... FAILED
```

```
failures:

---- tests::greater_than_100 stdout ----
note: test did not panic as expected

failures:
    tests::greater_than_100

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0
measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

We don't get a very helpful message in this case, but when we look at the test function, we see that it's annotated with `#[should_panic]`. The failure we got means that the code in the test function did not cause a panic.

Tests that use `should_panic` can be imprecise. A `should_panic` test would pass even if the test panics for a different reason from the one we were expecting. 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 is too small or too large.

```
# pub struct Guess {
#     value: i32,
# }
#
// --snip--

impl Guess {
    pub fn new(value: i32) -> 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 = "less than or equal to 100")]
    fn greater_than_100() {
        Guess::new(200);
    }
}
```

This test will pass because the value we put in the `should_panic` attribute's `expected` parameter is a substring of the message that the `Guess::new` function panics with. We could have specified the entire panic message that we expect, which in this case would be `Guess value must be less than or equal to 100, got 200`. What you choose to specify 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 test function executes 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:

```
# pub struct Guess {
#     value: i32,
# }
#
# impl Guess {
#     pub fn new(value: i32) -> Guess {
        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}."
            );
        }
#
#         Guess { value }
#     }
# }
#
# #[cfg(test)]
# mod tests {
#     use super::*;
#
#     #[test]
#     #[should_panic(expected = "less than or equal to 100")]
#     fn greater_than_100() {
#         Guess::new(200);
#     }
# }
```

This time when we run the `should_panic` test, it will fail:

```
$ cargo test
                    Compiling      guessing_game      v0.1.0
(file:///projects/guessing_game)
        Finished  `test`  profile  [unoptimized  +  debuginfo]
target(s) in 0.66s
                         Running     unittests     src/lib.rs
(target/debug/deps/guessing_game-57d70c3acb738f4d)

running 1 test
test tests::greater_than_100 - should panic ... FAILED

failures:

---- tests::greater_than_100 stdout ----

thread 'tests::greater_than_100' panicked at src/lib.rs:12:13:
Guess value must be greater than or equal to 1, got 200.
note:  run  with  `RUST_BACKTRACE=1`  environment  variable  to
display a backtrace
note: panic did not contain expected string
        panic  message:  `"Guess  value  must  be  greater  than  or
equal to 1, got 200."`,
 expected substring: `"less than or equal to 100"`

failures:
    tests::greater_than_100

test  result:  FAILED.  0  passed;  1  failed;  0  ignored;  0
measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

The failure message indicates that this test did indeed panic as we expected, but the panic message did not include the expected string `less than or equal to 100`. The panic message that we did get in this case was

`Guess value must be greater than or equal to 1, got 200.` Now we can start figuring out where our bug is!

Using `Result<T, E>` in Tests

Our tests so far all panic when they fail. We can also write tests that use `Result<T, E>`! Here's the test from Listing 11-1, rewritten to use `Result<T, E>` and return an `Err` instead of panicking:

```
# pub fn add(left: u64, right: u64) -> u64 {
#     left + right
# }
#
# #[cfg(test)]
# mod tests {
#     use super::*;
#
    #[test]
    fn it_works() -> Result<(), String> {
        let result = add(2, 2);

        if result == 4 {
            Ok(())
        } else {
            Err(String::from("two plus two does not equal four"))
        }
    }
# }
```

The `it_works` function now has the `Result<(), String>` return type. In the body of the function, rather than calling the `assert_eq!` macro, we return `Ok(())` when the test passes and an `Err` with a `String` inside when the test fails.

Writing tests so they return a `Result<T, E>` enables you to use the question mark operator in the body of tests, which can be a convenient way to write tests that should fail if any operation within them returns an `Err` variant.

You can't use the `#[should_panic]` annotation on tests that use `Result<T, E>`. To assert that an operation returns an `Err` variant, *don't* use the question mark operator on the `Result<T, E>` value. Instead, use `assert!(value.is_err())`.

Now that you know several ways to write tests, let's look at what is happening when we run our tests and explore 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 resultant binary, `cargo test` compiles your code in test mode and runs the resultant test binary. 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 the output from being displayed and making it easier to read the output related to the test results. You can, however, specify command line options to change this default behavior.

Some command line options go to `cargo test`, and some go to the resultant test binary. To separate these two types of arguments, you list the arguments that go to `cargo test` followed by the separator `--` and then the ones that go to the test binary. Running `cargo test --help` displays the options you can use with `cargo test`, and running `cargo test -- --help` displays the options you can use after the separator. Those options are also documented in the "Tests" section of the the rustc book.

Running Tests in Parallel or Consecutively

When you run multiple tests, by default they run in parallel using threads, meaning they finish running faster and you get feedback quicker. Because the tests are running at the same time, you must make sure your tests don't 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 run at the same time, one test might overwrite the file in the time between another test writing and reading 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 is 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. Take a look at the following example:

```
$ cargo test -- --test-threads=1
```

We set the number of test threads to `1`, telling the program not to use any parallelism. Running the tests using one thread will take longer than running them in parallel, but the tests won’t interfere 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 see only the line that indicates the test passed. If a test fails, we’ll see whatever was printed to standard output with the rest of the failure message.

As an example, Listing 11-10 has a silly function that prints the value of its parameter and returns 10, as well as a test that passes and a test that fails.

```
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!(value, 10);
    }

    #[test]
```

```
    fn this_test_will_fail() {
        let value = prints_and_returns_10(8);
        assert_eq!(value, 5);
    }
}
```

When we run these tests with `cargo test`, we’ll see the following output:

```
$ cargo test
    Compiling silly-function v0.1.0 (file:///projects/silly-function)
        Finished `test` profile [unoptimized + debuginfo] target(s) in 0.58s
                         Running unittests src/lib.rs (target/debug/deps/silly_function-160869f38cff9166)

running 2 tests
test tests::this_test_will_fail ... FAILED
test tests::this_test_will_pass ... ok

failures:

---- tests::this_test_will_fail stdout ----
I got the value 8

thread 'tests::this_test_will_fail' panicked at src/lib.rs:19:9:
assertion `left == right` failed
  left: 10
 right: 5
note: run with `RUST_BACKTRACE=1` environment variable to display a backtrace


failures:
    tests::this_test_will_fail
```

```
test result: FAILED. 1 passed; 1 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

Note that nowhere in this output do we see `I got the value 4`, which is 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, which also shows the cause of the test failure.

If we want to see printed values for passing tests as well, we can tell Rust to also show the output of successful tests with `--show-output`:

```
$ cargo test -- --show-output
```

When we run the tests in Listing 11-10 again with the `--show-output` flag, we see the following output:

```
$ cargo test -- --show-output
    Compiling silly-function v0.1.0 (file:///projects/silly-function)
        Finished `test` profile [unoptimized + debuginfo] target(s) in 0.60s
         Running unittests src/lib.rs (target/debug/deps/silly_function-160869f38cff9166)

running 2 tests
test tests::this_test_will_fail ... FAILED
test tests::this_test_will_pass ... ok

successes:

---- tests::this_test_will_pass stdout ----
I got the value 4



successes:
    tests::this_test_will_pass
```

```
failures:

---- tests::this_test_will_fail stdout ----
I got the value 8

thread 'tests::this_test_will_fail' panicked at
src/lib.rs:19:9:
assertion `left == right` failed
  left: 10
 right: 5
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace


failures:
    tests::this_test_will_fail

test result: FAILED. 1 passed; 1 failed; 0 ignored; 0
measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

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 first create three tests for our `add_two` function, as shown in Listing 11-11, and choose which ones to run.

```
pub fn add_two(a: u64) -> u64 {
    a + 2
}
```

```
#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn add_two_and_two() {
        let result = add_two(2);
        assert_eq!(result, 4);
    }

    #[test]
    fn add_three_and_two() {
        let result = add_two(3);
        assert_eq!(result, 5);
    }

    #[test]
    fn one_hundred() {
        let result = add_two(100);
        assert_eq!(result, 102);
    }
}
```

If we run the tests without passing any arguments, as we saw earlier, all the tests will run in parallel:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.62s
       Running unittests src/lib.rs (target/debug/deps/adder-
92948b65e88960b4)

running 3 tests
test tests::add_three_and_two ... ok
test tests::add_two_and_two ... ok
test tests::one_hundred ... ok
```

```
test result: ok. 3 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

Running Single Tests

We can pass the name of any test function to `cargo test` to run only that test:

```
$ cargo test one_hundred
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.69s
     Running unittests src/lib.rs (target/debug/deps/adder-
92948b65e88960b4)

running 1 test
test tests::one_hundred ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 2
filtered out; finished in 0.00s
```

Only the test with the name `one_hundred` ran; the other two tests didn't match that name. The test output lets us know we had more tests that didn't run by displaying `2 filtered out` at the end.

We can't specify the names of multiple tests in this way; only the first value given to `cargo test` will be used. But there is a way to run multiple tests.

Filtering to Run Multiple Tests

We can specify part of a test name, and any test whose name matches that value will be run. For example, because two of our tests' names contain `add`, we can run those two by running `cargo test add`:

```
$ cargo test add
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished `test` profile [unoptimized + debuginfo] target(s) in 0.61s
     Running unittests src/lib.rs (target/debug/deps/adder-92948b65e88960b4)

running 2 tests
test tests::add_three_and_two ... ok
test tests::add_two_and_two ... ok

test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured; 1 filtered out; finished in 0.00s
```

This command ran all tests with `add` in the name and filtered out the test named `one_hundred`. Also note that the module in which a test appears becomes part of the test's name, so we can run all the tests in a module by filtering on the module's name.

Ignoring 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, you can instead annotate the time-consuming tests using the `ignore` attribute to exclude them, as shown here:

Filename: src/lib.rs

```
# pub fn add(left: u64, right: u64) -> u64 {
#     left + right
# }
```

```
#
#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_works() {
        let result = add(2, 2);
        assert_eq!(result, 4);
    }

    #[test]
    #[ignore]
    fn expensive_test() {
        // code that takes an hour to run
    }
}
```

After `#[test]`, we add the `#[ignore]` line to the test we want to exclude. Now when we run our tests, `it_works` runs, but `expensive_test` doesn't:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.60s
      Running unittests src/lib.rs (target/debug/deps/adder-
92948b65e88960b4)

running 2 tests
test tests::expensive_test ... ignored
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 1 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests adder
```

```
running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s
```

The `expensive_test` function is listed as `ignored`. If we want to run only the ignored tests, we can use `cargo test -- --ignored`:

```
$ cargo test -- --ignored
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished `test` profile [unoptimized + debuginfo] target(s) in 0.61s
     Running unittests src/lib.rs (target/debug/deps/adder-92948b65e88960b4)

running 1 test
test tests::expensive_test ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 1 filtered out; finished in 0.00s

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s
```

By controlling which tests run, you can make sure your `cargo test` results will be returned quickly. When you're at a point where it makes sense to check the results of the `ignored` tests and you have time to wait for the results, you can run `cargo test -- --ignored` instead. If you want to run all tests whether they're ignored or not, you can run `cargo test -- --include-ignored`.

Test Organization

As mentioned at the start of the chapter, testing is a complex discipline, and different people use different terminology and organization. The Rust community thinks about tests in terms of two main categories: unit tests and integration tests. *Unit tests* are small 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 potentially 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 to quickly pinpoint where code is and isn't working as expected. You'll put unit tests in the *src* directory in each file with the code that they're testing. The convention is to create a module named `tests` in each file to contain the test functions and to 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 you run `cargo test`, not when you run `cargo build`. This saves compile time when you only want to build the library and saves space in the resultant compiled artifact because the tests are not included. You'll see that because integration tests go in a different directory, they don't need the `#[cfg(test)]` annotation. However, because unit tests go in the same files as the code, you'll use `#[cfg(test)]` to specify that they shouldn't be included in the compiled result.

Recall 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

```
pub fn add(left: u64, right: u64) -> u64 {
    left + right
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_works() {
        let result = add(2, 2);
        assert_eq!(result, 4);
    }
}
```

On the automatically generated `tests` 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`, which is provided by Rust for compiling and running tests. By using the `cfg` attribute, Cargo compiles our test code only 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 or not private functions should be tested directly, 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`.

```
pub fn add_two(a: u64) -> u64 {
    internal_adder(a, 2)
}
```

```
fn internal_adder(left: u64, right: u64) -> u64 {
    left + right
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn internal() {
        let result = internal_adder(2, 2);
        assert_eq!(result, 4);
    }
}
```

Note that the `internal_adder` function is not marked as `pub`. Tests are just Rust code, and the `tests` module is just another module. As we discussed in “Paths for Referring to an Item in the Module Tree”, items in child modules can use the items in their ancestor modules. In this test, we bring all of the `tests` module’s parent’s items into scope with `use super::*`, and then the test can call `internal_adder`. 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 whether many parts of your library work together correctly. Units of code that work correctly on their own 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

We create 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 want, and Cargo will compile each of the files as an individual crate.

Let’s create an integration test. With the code in Listing 11-12 still in the *src/lib.rs* file, make a *tests* directory, and create a new file named *tests/integration_test.rs*. Your directory structure should look like this:

```
adder
├── Cargo.lock
├── Cargo.toml
├── src
│   └── lib.rs
└── tests
    └── integration_test.rs
```

Enter the code in Listing 11-13 into the *tests/integration_test.rs* file.

```
use adder::add_two;

#[test]
fn it_adds_two() {
    let result = add_two(2);
    assert_eq!(result, 4);
}
```

Each file in the *tests* directory is a separate crate, so we need to bring our library into each test crate’s scope. For that reason we add `use adder::add_two;` at the top of the code, which we didn’t need in the unit tests.

We don’t need to annotate any code in *tests/integration_test.rs* with `#[cfg(test)]`. Cargo treats the *tests* directory specially and compiles files in this directory only when we run `cargo test`. Run `cargo test` now:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished `test` profile [unoptimized + debuginfo] target(s) in 1.31s
     Running unittests src/lib.rs (target/debug/deps/adder-1082c4b063a8fbe6)
```

```
running 1 test
test tests::internal ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

                         Running     tests/integration_test.rs
(target/debug/deps/integration_test-1082c4b063a8fbe6)

running 1 test
test it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

The three sections of output include the unit tests, the integration test, and the doc tests. Note that if any test in a section fails, the following sections will not be run. For example, if a unit test fails, there won't be any output for integration and doc tests because those tests will only be run if all unit tests are passing.

The first section for the unit tests is the same as we've been seeing: one line for each unit test (one named `internal` that we added in Listing 11-12) and then a summary line for the unit tests.

The integration tests section starts with the line `Running tests/integration_test.rs`. Next, there is 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.

Each integration test file has 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 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
   Compiling adder v0.1.0 (file:///projects/adder)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.64s
                         Running tests/integration_test.rs
(target/debug/deps/integration_test-82e7799c1bc62298)

running 1 test
test it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

This command runs only the tests in the *tests/integration_test.rs* file.

Submodules in Integration Tests

As you add more integration tests, you might want to make more files in the *tests* directory to help organize them; for example, you can group the test functions by the functionality they're testing. As mentioned earlier, each file in the *tests* directory is compiled as its own separate crate, which is useful for creating separate scopes to more closely imitate 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, as you learned in Chapter 7 regarding how to separate code into modules and files.

The different behavior of *tests* directory files is most noticeable when you have a set of helper functions to use in multiple integration test files and you try to follow the steps in the “Separating Modules into Different Files” section of Chapter 7 to extract them into a common module. For example, if we create *tests/common.rs* and place a function named `setup` in it, we can add some code to `setup` that we want 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
}
```

When 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 did we call the `setup` function from anywhere:

```
$ cargo test
   Compiling adder v0.1.0 (file:///projects/adder)
    Finished `test` profile [unoptimized + debuginfo] target(s) in 0.89s
     Running unittests src/lib.rs (target/debug/deps/adder-92948b65e88960b4)

running 1 test
test tests::internal ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s

     Running tests/common.rs (target/debug/deps/common-92948b65e88960b4)

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s

```

```
     Running tests/integration_test.rs (target/debug/deps/integration_test-92948b65e88960b4)

running 1 test
test it_adds_two ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in 0.00s
```

Having `common` appear in the test results with `running 0 tests` displayed for it is not what we wanted. We just wanted to share some code with the other integration test files. To avoid having `common` appear in the test output, instead of creating *tests/common.rs*, we'll create *tests/common/mod.rs*. The project directory now looks like this:

```
├── Cargo.lock
├── Cargo.toml
├── src
│   └── lib.rs
└── tests
    ├── common
    │   └── mod.rs
    └── integration_test.rs
```

This is the older naming convention that Rust also understands that we mentioned in [“Alternate File Paths”] in Chapter 7. Naming the file this way tells Rust not to treat the `common` module as an integration test file. When we move the `setup` function code into *tests/common/mod.rs* and delete the *tests/common.rs* file, the section in the test output will no longer appear.

Files in subdirectories of the *tests* directory don't get compiled as separate crates or have sections in the test output.

After we've created *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

```
use adder::add_two;

mod common;

#[test]
fn it_adds_two() {
    common::setup();

    let result = add_two(2);
    assert_eq!(result, 4);
}
```

Note that the `mod common;` declaration is the same as the module declaration we demonstrated in Listing 7-21. 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* file and doesn't have a *src/lib.rs* file, we can't create integration tests in the *tests* directory and bring functions defined in the *src/main.rs* file into scope with a `use` statement. Only library crates expose functions that other crates can 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* file that calls logic that lives in the *src/lib.rs* file. Using that structure, integration tests *can* test the library crate with `use` to make the important functionality available. If the important functionality works, the small amount of code in the *src/main.rs* file will work as well, and that small amount of code doesn't 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 you expect, even as you make changes. Unit tests exercise different parts of a library separately and can test private implementation details. Integration tests check that many parts of the library work together correctly, 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 reduce logic bugs having to do with how your code is expected to behave.

Let’s combine the knowledge you learned in this chapter and in previous chapters to work on a project!

An I/O Project: Building a Command Line Program

This chapter is a recap of the many skills you've learned so far and an exploration of a few more standard library features. We'll build a command line tool that interacts with file and command line input/output to practice some of the Rust concepts you now have under your belt.

Rust's speed, safety, single binary output, and cross-platform support make it an ideal language for creating command line tools, so for our project, we'll make our own version of the classic command line search tool `grep` (**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 as its arguments a file path and a string. Then it reads the file, finds lines in that file that contain the string argument, and prints those lines.

Along the way, we'll show how to make our command line tool use the terminal features that many other command line tools use. We'll read the value of an environment variable to allow the user to configure the behavior of our tool. We'll also print error messages to the standard error console stream (`stderr`) instead of standard output (`stdout`) so that, for example, the user can redirect successful output to a file while still seeing error messages onscreen.

One Rust community member, Andrew Gallant, has already created a fully featured, very fast version of `grep`, called `ripgrep`. By comparison, our version will be fairly simple, but this chapter will give you some of the background knowledge you need to understand a real-world project such as `ripgrep`.

Our `grep` project will combine a number of concepts you've learned so far:

- Organizing code (Chapter 7)
- Using vectors and strings (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 Chapter 13 and Chapter 18 will cover in detail.

Accepting Command Line Arguments

Let's create a new project with, as always, `cargo new`. We'll call our project `minigrep` to distinguish it from the `grep` tool that you might already have on your system.

```
$ cargo new minigrep
     Created binary (application) `minigrep` project
$ cd minigrep
```

The first task is to make `minigrep` accept its two command line arguments: the file path and a string to search for. That is, we want to be able to run our program with `cargo run`, two hyphens to indicate the following arguments are for our program rather than for `cargo`, 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. Some existing libraries on crates.io can help with writing a program that accepts command line arguments, but because you're just learning this concept, let's implement this capability ourselves.

Reading the Argument Values

To enable `minigrep` to read the values of command line arguments we pass to it, we'll need the `std::env::args` function provided in Rust's standard library. This function returns an iterator of the command line arguments passed to `minigrep`. We'll cover iterators fully in Chapter 13. For now, you only need to know two details about iterators: iterators produce a series of values, and we can call the `collect` method on an iterator to turn it into a collection, such as a vector, that contains all the elements the iterator produces.

The code in Listing 12-1 allows your `minigrep` program to read any command line arguments passed to it, and then collect the values into a vector.

```
use std::env;

fn main() {
    let args: Vec<String> = env::args().collect();
    dbg!(args);
}
```

First we bring the `std::env` module into scope with a `use` statement so we can use its `args` function. Notice that the `std::env::args` function is nested in two levels of modules. As we discussed in Chapter 7, in cases where the desired function is nested in more than one module, we've chosen to bring the parent module into scope rather than the function. By doing so, we can easily use other functions from `std::env`. It's also less ambiguous than adding `use std::env::args` and then calling the function with just `args`, because `args` 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 your program needs to accept arguments containing invalid Unicode, use `std::env::args_os` instead. That function returns an iterator that produces `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 we immediately use `collect` to turn the iterator into a vector containing all the values produced by the iterator. We can use the `collect` function to create many kinds of collections, so we explicitly annotate the type of `args` to specify that we want a vector of strings. Although you 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 the kind of collection you want.

Finally, we print the vector using the debug macro. Let’s try running the code first with no arguments and then with two arguments:

```
$ cargo run
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.61s
     Running `target/debug/minigrep`
[src/main.rs:5:5] args = [
    "target/debug/minigrep",
]
```

```
$ cargo run -- needle haystack
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 1.57s
     Running `target/debug/minigrep needle haystack`
[src/main.rs:5:5] args = [
    "target/debug/minigrep",
    "needle",
    "haystack",
]
```

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, letting programs use the name by which they were invoked in their execution. It’s often convenient to have access to the program name in case you want to print it in messages or change the behavior of the program based on what command line alias was used to invoke the program. But for the purposes of this chapter, we’ll ignore it and save only the two arguments we need.

Saving the Argument Values in Variables

The program is currently able to access the values specified as command line arguments. Now we need to save the values of the two arguments in variables so we can use the values throughout the rest of the program. We do that in Listing 12-2.

```
use std::env;

fn main() {
    let args: Vec<String> = env::args().collect();

    let query = &args[1];
    let file_path = &args[2];

    println!("Searching for {query}");
    println!("In file {file_path}");
}
```

As we saw when we printed the vector, the program's name takes up the first value in the vector at `args[0]`, so we're starting arguments 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 file path, so we put a reference to the second argument in the variable `file_path`.

We temporarily print the values of these variables to prove that the code is working as we intend. Let's run this program again with the arguments `test` and `sample.txt`:

```
$ cargo run -- test sample.txt
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.0s
     Running `target/debug/minigrep test sample.txt`
Searching for test
In file sample.txt
```

Great, the program is 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; for now, we'll ignore that situation and work on adding file-reading capabilities instead.

Reading a File

Now we'll add functionality to read the file specified in the `file_path` argument. First we need a sample file to test it with: we'll use a file 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?"

```
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!
```

With the text in place, edit *src/main.rs* and add code to read the file, as shown in Listing 12-4.

```
use std::env;
use std::fs;

fn main() {
    // --snip--
#     let args: Vec<String> = env::args().collect();
#
#     let query = &args[1];
#     let file_path = &args[2];
#
#     println!("Searching for {query}");
    println!("In file {file_path}");

    let contents = fs::read_to_string(file_path)
        .expect("Should have been able to read the file");
```

```
    println!("With text:\n{contents}");
}
```

First we bring in a relevant part of the standard library with a `use` statement: we need `std::fs` to handle files.

In `main`, the new statement `fs::read_to_string` takes the `file_path`, opens that file, and returns a value of type `std::io::Result<String>` that contains the file's contents.

After that, we again add a temporary `println!` statement that prints the value of `contents` after the file is read, so we can check that the program is working so far.

Let's run this code with any string as the first command line argument (because we haven't implemented the searching part yet) and the *poem.txt* file as the second argument:

```
$ cargo run -- the poem.txt
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.0s
     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! The code read and then printed the contents of the file. But the code has a few flaws. At the moment, 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. The program is still small, so these flaws aren't a big problem, but as the program grows, it will be harder to fix them cleanly. It's a good practice to begin refactoring early on when developing a program because it's much easier to refactor smaller amounts of code. We'll do that next.

Refactoring to Improve Modularity and Error Handling

To improve our program, we'll fix four problems that have to do with the program's structure and how it's handling potential errors. First, our `main` function now performs two tasks: it parses arguments and reads files. As our program grows, the number of separate tasks the `main` function handles will increase. As a function gains responsibilities, it becomes more difficult to reason about, harder to test, and harder to change without breaking one of its parts. It's best to separate functionality so each function is responsible for one task.

This issue also ties into the second problem: although `query` and `file_path` are configuration variables to our program, variables like `contents` are used to perform the program's logic. The longer `main` becomes, the more variables we'll need to bring into scope; the more variables we have in scope, the harder it will be to keep track of the purpose of each. It's best to group the configuration variables into one structure to make their purpose clear.

The third problem is that we've used `expect` to print an error message when reading the file fails, but the error message just prints `Should have been able to read the file`. Reading a file can fail in a number of ways: for example, the file could be missing, or we might not have permission to open it. Right now, regardless of the situation, we'd print the same error message for everything, which wouldn't give the user any information!

Fourth, we use `expect` to handle an error, and if the user runs our program 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 best if all the error-handling code were in one place so future maintainers had only one place to consult the code if the error-handling logic needed to change. Having all the error-handling code in one place will also ensure that we're printing messages that will be meaningful to our end users.

Let’s address these four problems by refactoring our project.

Separation of Concerns for Binary Projects

The organizational problem of allocating responsibility for multiple tasks to the `main` function is common to many binary projects. As a result, many Rust programmers find it useful to split up the separate concerns of a binary program when the `main` function starts getting large. This process has the following steps:

- Split your program into a *main.rs* file and a *lib.rs* file and move your program’s logic to *lib.rs*.
- As long as your command line parsing logic is small, it can remain in the `main` function.
- When the command line parsing logic starts getting complicated, extract it from the `main` function into other functions or types.

The responsibilities that remain in the `main` function after this process should be limited to the following:

- Calling the command line parsing logic with the argument values
- Setting up any other configuration
- Calling a `run` function in *lib.rs*
- Handling the error if `run` returns an error

This pattern is about separating concerns: *main.rs* handles running the program and *lib.rs* handles all the logic of the task at hand. Because you can’t test the `main` function directly, this structure lets you test all of your program’s logic by moving it out of the `main` function. The code that remains in the `main` function will be small enough to verify its correctness by reading it. Let’s rework our program by following this process.

Extracting the Argument Parser

We’ll extract the functionality for parsing arguments into a function that `main` will call. Listing 12-5 shows the new start of the `main` function that calls a new function `parse_config`, which we’ll define in *src/main.rs*.

```
# use std::env;
# use std::fs;
#
fn main() {
    let args: Vec<String> = env::args().collect();

    let (query, file_path) = parse_config(&args);

    // --snip--
#
#     println!("Searching for {query}");
#     println!("In file {file_path}");
#
#     let contents = fs::read_to_string(file_path)
#         .expect("Should have been able to read the file");
#
#     println!("With text:\n{contents}");
}

fn parse_config(args: &[String]) -> (&str, &str) {
    let query = &args[1];
    let file_path = &args[2];

    (query, file_path)
}
```

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 `file_path` 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 `file_path` variables in `main`, but `main` no longer has the responsibility of determining how the command line arguments and variables correspond.

This rework 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, to help identify the cause of problems when they occur.

Grouping Configuration Values

We can take another small step to improve the `parse_config` function further. At the moment, we're returning a tuple, but then we immediately break that tuple into individual parts again. This is a sign that perhaps we don't have the right abstraction yet.

Another indicator that shows 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 by grouping the two values into a tuple; we'll instead put the two values into one struct and give each of the struct fields a meaningful name. Doing so 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.

Listing 12-6 shows the improvements to the `parse_config` function.

```
# use std::env;
# use std::fs;
#
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = parse_config(&args);

    println!("Searching for {}", config.query);
    println!("In file {}", config.file_path);

    let contents = fs::read_to_string(config.file_path)
        .expect("Should have been able to read the file");

    // --snip--
```

```
#
#     println!("With text:\n{contents}");
}

struct Config {
    query: String,
    file_path: String,
}

fn parse_config(args: &[String]) -> Config {
    let query = args[1].clone();
    let file_path = args[2].clone();

    Config { query, file_path }
}
```

We’ve added a struct named `Config` defined to have fields named `query` and `file_path`. 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 now 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, 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 ways we could manage the `String` data; 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 takes more time and memory than storing a reference to the string data. However, cloning the data also makes our code very straightforward because we don’t have to manage the lifetimes of the references; in this circumstance, giving up a little performance to gain simplicity is a worthwhile trade-off.

The Trade-Offs 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, you’ll learn how to use more efficient methods in this type of situation. But for now, it’s okay to copy a few strings to continue making progress because you’ll make these copies only once and your file path and query string are very small. It’s better to have a working program that’s a bit inefficient than to try to hyperoptimize code on your first pass. As you become more experienced with Rust, it’ll be easier to start with the most efficient solution, but for now, it’s perfectly acceptable to call `clone`.

We’ve updated `main` so it places the instance of `Config` returned by `parse_config` into a variable named `config`, and we updated the code that previously used the separate `query` and `file_path` variables so it now uses the fields on the `Config` struct instead.

Now our code more clearly conveys that `query` and `file_path` are related and that 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` and placed it in the `parse_config` function. Doing so helped us see that the `query` and `file_path` 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 `file_path` 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 a plain function to a function named `new` that is associated with the `Config` struct. Making this change will make the code more idiomatic. We can create instances of types in the standard library, such as `String`, by calling `String::new`. Similarly, 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 need to make.

```
# use std::env;
# use std::fs;
#
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::new(&args);
#
#     println!("Searching for {}", config.query);
#     println!("In file {}", config.file_path);
#
#     let contents = fs::read_to_string(config.file_path)
#         .expect("Should have been able to read the file");
#
#     println!("With text:\n{contents}");

    // --snip--
}

// --snip--

# struct Config {
#     query: String,
#     file_path: String,
# }
#
impl Config {
    fn new(args: &[String]) -> Config {
        let query = args[1].clone();
        let file_path = args[2].clone();

        Config { query, file_path }
```

```
    }
}
```

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 associates the `new` function with `Config`. Try compiling this code again to make sure it works.

Fixing the Error Handling

Now we’ll work on fixing our error handling. Recall 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 three items. Try running the program without any arguments; it will look like this:

```
$ cargo run
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.0s
     Running `target/debug/minigrep`

thread 'main' panicked at src/main.rs:27:21:
index out of bounds: the len is 1 but the index is 1
note:  run  with  `RUST_BACKTRACE=1`  environment  variable  to
display a backtrace
```

The line `index out of bounds: the len is 1 but the index is 1` is an error message intended for programmers. It won’t help our end users understand what they should do instead. Let’s fix that now.

Improving the Error Message

In Listing 12-8, we add a check in the `new` function that will verify that the slice is long enough before accessing index 1 and index 2. If the slice isn’t long enough, the program panics and displays a better error message.

```
# use std::env;
# use std::fs;
#
# fn main() {
```

```
#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::new(&args);
#
#     println!("Searching for {}", config.query);
#     println!("In file {}", config.file_path);
#
#     let contents = fs::read_to_string(config.file_path)
#         .expect("Should have been able to read the file");
#
#     println!("With text:\n{contents}");
# }
#
# struct Config {
#     query: String,
#     file_path: String,
# }
#
# impl Config {
    // --snip--
    fn new(args: &[String]) -> Config {
        if args.len() < 3 {
            panic!("not enough arguments");
        }
        // --snip--
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         Config { query, file_path }
#     }
# }
```

This code is similar to the `Guess::new` function we wrote in Listing 9-13, where we called `panic!` 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 three 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 run the program without any arguments again to see what the error looks like now:

```
$ cargo run
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.0s
     Running `target/debug/minigrep`

thread 'main' panicked at src/main.rs:26:13:
not enough arguments
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace
```

This output is better: we now have a reasonable error message. However, we also have extraneous information we don't want to give to our users. Perhaps the technique we used in Listing 9-13 isn't the best one to use here: a call to `panic!` is more appropriate for a programming problem than a usage problem, as discussed in Chapter 9. Instead, we'll use the other technique you learned about in Chapter 9—returning a `Result` that indicates either success or an error.

Returning a `Result` Instead of Calling `panic!`

We can instead return a `Result` value that will contain a `Config` instance in the successful case and will describe the problem in the error case. We're also going to change the function name from `new` to `build` because many programmers expect `new` functions to never fail. When `Config::build` is communicating to `main`, we can use the `Result` type to signal 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 we need to make to the return value of the function we’re now calling `Config::build` and the body of the function needed to return a `Result`. Note that this won’t compile until we update `main` as well, which we’ll do in the next listing.

```
# use std::env;
# use std::fs;
#
# fn main() {
#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::new(&args);
#
#     println!("Searching for {}", config.query);
#     println!("In file {}", config.file_path);
#
#     let contents = fs::read_to_string(config.file_path)
#         .expect("Should have been able to read the file");
#
#     println!("With text:\n{contents}");
# }
#
# struct Config {
#     query: String,
#     file_path: String,
# }
#
impl Config {
    fn build(args: &[String]) -> Result<Config, &'static str>
{
        if args.len() < 3 {
            return Err("not enough arguments");
        }

        let query = args[1].clone();
        let file_path = args[2].clone();
```

```
        Ok(Config { query, file_path })
    }
}
```

Our `build` function returns a `Result` with a `Config` instance in the success case and a string literal in the error case. Our error values will always be string literals that have the `'static` lifetime.

We've made two changes in the body of the 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::build` allows the `main` function to handle the `Result` value returned from the `build` function and exit the process more cleanly in the error case.

Calling `Config::build` and Handling Errors

To handle the error case and print a user-friendly message, we need to update `main` to handle the `Result` being returned by `Config::build`, as shown in Listing 12-10. We'll also take the responsibility of exiting the command line tool with a nonzero error code away from `panic!` and instead implement it by hand. A nonzero exit status is a convention to signal to the process that called our program that the program exited with an error state.

```
# use std::env;
# use std::fs;
use std::process;

fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::build(&args).unwrap_or_else(|err| {
        println!("Problem parsing arguments: {err}");
        process::exit(1);
    });
```

```
    // --snip--
#
#     println!("Searching for {}", config.query);
#     println!("In file {}", config.file_path);
#
#     let contents = fs::read_to_string(config.file_path)
#         .expect("Should have been able to read the file");
#
#     println!("With text:\n{contents}");
# }
#
# struct Config {
#     query: String,
#     file_path: String,
# }
#
# impl Config {
#     fn build(args: &[String]) -> Result<Config, &'static str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         Ok(Config { query, file_path })
#     }
# }
```

In this listing, we've used a method we haven't covered in detail yet: `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 that `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 cover closures in more detail in Chapter 13. For now, you just need to know 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 bring `process` from the standard library into scope. The code in the closure that will be run in the error case is only two lines: we print the `err` value and 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` profile [unoptimized + debuginfo] target(s)
in 0.48s
     Running `target/debug/minigrep`
Problem parsing arguments: not enough arguments
```

Great! This output is much friendlier for our users.

Extracting Logic from the `main` Function

Now that we've finished refactoring the configuration parsing, let's turn to the program's logic. As we stated in "Separation of Concerns for Binary Projects", we'll extract a function named `run` that will hold all the logic currently in the `main` function that isn't involved with setting up configuration or handling errors. When we're done, the `main` function will be concise and easy to verify by inspection, and we'll be able to write tests for all the other logic.

Listing 12-11 shows the small, incremental improvement of extracting a `run` function.

```
# use std::env;
# use std::fs;
# use std::process;
#
fn main() {
    // --snip--

#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
    println!("Searching for {}", config.query);
    println!("In file {}", config.file_path);

    run(config);
}

fn run(config: Config) {
    let contents = fs::read_to_string(config.file_path)
        .expect("Should have been able to read the file");

    println!("With text:\n{contents}");
}

// --snip--
#
# struct Config {
#     query: String,
#     file_path: String,
# }
#
# impl Config {
```

```
#       fn build(args: &[String]) -> Result<Config, &'static str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         Ok(Config { query, file_path })
#     }
# }
```

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, as we did with `Config::build` 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 the logic around handling errors into `main` in a user-friendly way. Listing 12-12 shows the changes we need to make to the signature and body of `run`.

```
# use std::env;
# use std::fs;
# use std::process;
use std::error::Error;

// --snip--

#
# fn main() {
#     let args: Vec<String> = env::args().collect();
```

```
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
#     println!("Searching for {}", config.query);
#     println!("In file {}", config.file_path);
#
#     run(config);
# }
#
fn run(config: Config) -> Result<(), Box<dyn Error>> {
    let contents = fs::read_to_string(config.file_path)?;

    println!("With text:\n{contents}");

    Ok(())
}
#
# struct Config {
#     query: String,
#     file_path: String,
# }
#
# impl Config {
#     fn build(args: &[String]) -> Result<Config, &'static
str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         Ok(Config { query, file_path })
```

```
#     }
# }
```

We've made three significant changes here. First, we changed the return type of the `run` function to `Result<(), Box<dyn Error>>`. This function previously returned the unit type, `()`, and we keep that as the value returned in the `Ok` case.

For the error type, we used the *trait object* `Box<dyn Error>` (and we've brought `std::error::Error` into scope with a `use` statement at the top). We'll cover trait objects in Chapter 18. For now, just know that `Box<dyn 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 `dyn` keyword is short for *dynamic*.

Second, we've removed the call to `expect` in favor of the `?` operator, as we talked about in Chapter 9. Rather than `panic!` on an error, `?` will return the error value from the current function for the caller to handle.

Third, the `run` 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 might 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 code, it will compile but will display a warning:

```
$ cargo run -- the poem.txt
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
warning: unused `Result` that must be used
  --> src/main.rs:19:5
   |
19 |     run(config);
   |     ^^^^^^^^^^^
   |
   = note: this `Result` may be an `Err` variant, which should
```

```
be handled
   = note: `#[warn(unused_must_use)]` on by default
help: use `let _ = ...` to ignore the resulting value
   |
19 |     let _ = run(config);
   |     +++++++

warning: `minigrep` (bin "minigrep") generated 1 warning
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.71s
     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!
```

Rust tells us that our code ignored the `Result` value and the `Result` value might indicate that an error occurred. But we're not checking to see whether or not there was an error, and the compiler reminds us that we probably meant to have some error-handling code here! Let's rectify that problem now.

Handling Errors Returned from `run` in `main`

We'll check for errors and handle them using a technique similar to one we used with `Config::build` in Listing 12-10, but with a slight difference:

Filename: src/main.rs

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
fn main() {
    // --snip--

#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
    println!("Searching for {}", config.query);
    println!("In file {}", config.file_path);

    if let Err(e) = run(config) {
        println!("Application error: {e}");
        process::exit(1);
    }
}
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     println!("With text:\n{contents}");
#
#     Ok(())
# }
#
# struct Config {
#     query: String,
#     file_path: String,
```

```
# }
#
# impl Config {
#     fn build(args: &[String]) -> Result<Config, &'static
str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         Ok(Config { query, file_path })
#     }
# }
```

We use `if let` rather than `unwrap_or_else` to check whether `run` returns an `Err` value and to call `process::exit(1)` if it does. The `run` function doesn't return a value that we want to `unwrap` in the same way that `Config::build` returns the `Config` instance. Because `run` returns `()` in the success case, we only care about detecting an error, so we don't need `unwrap_or_else` to return the unwrapped value, which would only be `()`.

The bodies of the `if let` and the `unwrap_or_else` functions are the same in both cases: we print the error and exit.

Splitting Code into a Library Crate

Our `minigrep` project is looking good so far! Now we'll split the *src/main.rs* file and put some code into the *src/lib.rs* file. That way, we can test the code and have a *src/main.rs* file with fewer responsibilities.

Let's define the code responsible for searching text in *src/lib.rs* rather than in *src/main.rs*, which will let us (or anyone else using our `minigrep` library) call the searching function from more contexts than our `minigrep` binary.

First, let’s define the `search` function signature in *src/lib.rs* as shown in Listing 12-13, with a body that calls the `unimplemented!` macro. We’ll explain the signature in more detail when we fill in the implementation.

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a
str> {
    unimplemented!();
}
```

We’ve used the `pub` keyword on the function definition to designate `search` as part of our library crate’s public API. We now have a library crate that we can use from our binary crate and that we can test!

Now we need to bring the code defined in *src/lib.rs* into the scope of the binary crate in *src/main.rs* and call it, as shown in Listing 12-14.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
// --snip--
use minigrep::search;

fn main() {
    // --snip--
#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
#     if let Err(e) = run(config) {
#         println!("Application error: {e}");
#         process::exit(1);
#     }
}
```

```
// --snip--

#
# struct Config {
#     query: String,
#     file_path: String,
# }
#
# impl Config {
#       fn build(args: &[String]) -> Result<Config, &'static
str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         Ok(Config { query, file_path })
#     }
# }
#
fn run(config: Config) -> Result<(), Box<dyn Error>> {
    let contents = fs::read_to_string(config.file_path)?;

    for line in search(&config.query, &contents) {
        println!("{line}");
    }

    Ok(())
}
```

We add a `use minigrep::search` line to bring the `search` function from the library crate into the binary crate's scope. Then, in the `run` function, rather than printing out the contents of the file, we call the `search` function and pass the `config.query` value and `contents` as arguments. Then `run` will use a `for` loop to print each line returned from `search` that matched the query. This is also a good time to remove the `println!` calls in the `main` function that displayed the query and the file path so that our program only prints the search results (if no errors occur).

Note that the search function will be collecting all the results into a vector it returns before any printing happens. This implementation could be slow to display results when searching large files because results aren't printed as they're found; we'll discuss a possible way to fix this using iterators in Chapter 13.

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 the 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 difficult with the old code but is easy with the new code: we'll write some tests!

Developing the Library’s Functionality with Test-Driven Development

Now that we have the search logic in *src/lib.rs* separate from the `main` function, it’s much easier to write tests for the core functionality of our code. We can call functions directly with various arguments and check return values without having to call our binary from the command line.

In this section, we’ll add the searching logic to the `minigrep` program using the test-driven development (TDD) process with the following steps:

1. Write a test that fails and run it to make sure it fails for the reason you expect.
2. Write or modify just enough code to make the new test pass.
3. Refactor the code you just added or changed and make sure the tests continue to pass.
4. Repeat from step 1!

Though it’s just one of many ways to write software, TDD can help drive code design. Writing the test before you write the code that makes the test pass helps to maintain high test coverage throughout the process.

We’ll 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’ll add this functionality in a function called `search`.

Writing a Failing Test

In *src/lib.rs*, we’ll add a `tests` module with a test function, as we did in Chapter 11. The test function specifies the behavior we want the `search` function to have: it will take a query and the text to search, and it will return only the lines from the text that contain the query. Listing 12-15 shows this test.

```
# pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a
str> {
#     unimplemented!();
```

```
# }
#
// --snip--

#[cfg(test)]
mod tests {
    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));
    }
}
```

This test searches for the string `"duct"`. The text we're searching is three lines, only one of which contains `"duct"` (note that the backslash after the opening double quote tells Rust not to put a newline character at the beginning of the contents of this string literal). We assert that the value returned from the `search` function contains only the line we expect.

If we run this test, it will currently fail because the `unimplemented!` macro panics with the message "not implemented". In accordance with TDD principles, we'll take a small step of adding just enough code to get the test to not panic when calling the function by defining the `search` function to always return an empty vector, as shown in Listing 12-16. Then the test should compile and fail because an empty vector doesn't match a vector containing the line `"safe, fast, productive."`

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a
str> {
```

```
    vec![]
}
#
# #[cfg(test)]
# mod tests {
#     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));
#     }
# }
```

Now let's discuss why we need to define an explicit lifetime `'a` in the signature of `search` and use that lifetime with the `contents` argument and the return value. Recall in Chapter 10 that the lifetime parameters specify which argument lifetime is connected to the lifetime of the return value. In this case, we indicate that the returned vector should contain string slices that reference slices of the argument `contents` (rather than the argument `query`).

In other words, we tell 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 for the reference to be valid; if the compiler assumes we're making string slices of `query` rather than `contents`, it will do its safety checking incorrectly.

If we forget the lifetime annotations and try to compile this function, we'll get this error:

```
$ cargo build
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
error[E0106]: missing lifetime specifier
 --> src/lib.rs:1:51
  |
1 | pub fn search(query: &str, contents: &str) -> Vec<&str> {
  |                      ----            ----         ^
expected named 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`
help: consider introducing a named lifetime parameter
  |
1 | pub fn search<'a>(query: &'a str, contents: &'a str) ->
Vec<&'a str> {
  |              ++++         ++                 ++
++

For more information about this error, try `rustc --explain
E0106`.
error: could not compile `minigrep` (lib) due to 1 previous
error
```

Rust can’t know which of the two parameters we need for the output, so we need to tell it explicitly. Note that the help text suggests specifying the same lifetime parameter for all the parameters and the output type, which is incorrect! Because `contents` is the parameter that contains all of our text and we want to return the parts of that text that match, we know `contents` is the only parameter 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, but this practice will get easier over time. You might want to compare this example with the examples in the “Validating References with Lifetimes” section in Chapter 10.

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:

1. Iterate through each line of the contents.
2. Check whether the line contains our query string.
3. If it does, add it to the list of values we're returning.
4. If it doesn't, do nothing.
5. Return the list of results that match.

Let's work through each step, 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. Note that this won't compile yet.

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a
str> {
    for line in contents.lines() {
        // do something with line
    }
}
#
# #[cfg(test)]
# mod tests {
#     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));
#     }
# }
```

The `lines` method returns an iterator. We'll talk about iterators in depth in Chapter 13, but recall that you saw this way of using an iterator in Listing 3-5, 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 check whether the current line contains our query string. Fortunately, strings have a 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. Note that this still won't compile yet.

```
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
        }
    }
}
#
# #[cfg(test)]
# mod tests {
#     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));
#     }
# }
```

At the moment, we're building up functionality. To get the code to compile, we need to return a value from the body as we indicated we would in the function signature.

Storing Matching Lines

To finish this function, we need a way to store the matching lines that we want to return. 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.

```
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
}
#
# #[cfg(test)]
# mod tests {
#     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));
#     }
# }
```

Now the `search` function should return only the lines that contain `query`, and our test should pass. Let's run the test:

```
$ cargo test
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
        Finished  `test`  profile  [unoptimized  +  debuginfo]
target(s) in 1.22s
     Running unittests src/lib.rs (target/debug/deps/minigrep-
9cd200e5fac0fc94)

running 1 test
test tests::one_result ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

                         Running     unittests     src/main.rs
(target/debug/deps/minigrep-9cd200e5fac0fc94)

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests minigrep

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
```

```
filtered out; finished in 0.00s
```

Our test passed, so we know it works!

At this point, we could consider opportunities for refactoring the implementation of the search function while keeping the tests passing to maintain the same functionality. The code in the search function isn't too bad, but it doesn't take advantage of some useful features of iterators. We'll return to this example in Chapter 13, where we'll explore iterators in detail, and look at how to improve it.

Now the entire program should work! 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` profile [unoptimized + debuginfo] target(s)
in 0.38s
     Running `target/debug/minigrep frog poem.txt`
How public, like a frog
```

Cool! Now let's try a word that will match multiple lines, like *body*:

```
$ cargo run -- body poem.txt
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.0s
     Running `target/debug/minigrep body poem.txt`
I'm nobody! Who are you?
Are you nobody, too?
How dreary to be somebody!
```

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, such as *monomorphization*:

```
$ cargo run -- monomorphization poem.txt
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.0s
     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, we’ll briefly demonstrate how to work with environment variables and how to print to standard error, both of which are useful when you’re writing command line programs.

Working with Environment Variables

We'll improve the `minigrep` binary by adding an extra feature: an option for case-insensitive searching that the user can turn on via an environment variable. We could make this feature a command line option and require that users enter it each time they want it to apply, but by instead making it an environment variable, we allow 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 first add a new `search_case_insensitive` function to the `minigrep` library that will be called when the environment variable has a value. We'll continue to follow the TDD process, so the first step is again to write a failing test. We'll add a new test for the new `search_case_insensitive` function and rename our old test from `one_result` to `case_sensitive` to clarify the differences between the two tests, as shown in Listing 12-20.

```
# 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
# }
#
#[cfg(test)]
```

```
mod tests {
    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)
        );
    }
}
```

Note that we've edited the old test's `contents` too. We've added a new line with the text `"Duct tape."` using 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 about to add, the query `"rUsT"` should match the line containing `"Rust:"` with a capital *R* and match the line `"Trust me."` even though both have different casing from 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, similar to the way we did for the `search` function in Listing 12-16 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'll be the same case when we check whether the line contains the query.

```
# 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
```

```
# }
#
pub 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
}
#
# #[cfg(test)]
# mod tests {
#     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)
#         );
#     }
# }
```

First we lowercase the `query` string and store it in a new variable with the same name, shadowing the original `query`. Calling `to_lowercase` on the query is necessary so that no matter whether the user's query is `"rust"`, `"RUST"`, `"Rust"`, or `"``rUsT``"`, we'll treat the query as if it were `"rust"` and be insensitive to the case. While `to_lowercase` will handle basic Unicode, it won't be 100 percent accurate. If we were writing a real application, we'd want to do a bit more work here, but this section is about environment variables, not Unicode, so we'll leave it at that here.

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 doesn't 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` to lowercase all characters. Now that we've converted `line` and `query` to lowercase, we'll find matches no matter what the case of the query is.

Let's see if this implementation passes the tests:

```
$ cargo test
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 1.33s
     Running unittests src/lib.rs (target/debug/deps/minigrep-
9cd200e5fac0fc94)

running 2 tests
test tests::case_insensitive ... ok
test tests::case_sensitive ... ok

test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

                         Running     unittests     src/main.rs
(target/debug/deps/minigrep-9cd200e5fac0fc94)

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests minigrep

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

Great! They passed. Now, let's call the new `search_case_insensitive` function from the `run` function. First we'll add a configuration option to the `Config` struct to switch between case-sensitive and case-insensitive search. Adding this field will cause compiler errors because we aren't initializing this field anywhere yet:

Filename: src/main.rs

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
# // --snip--
#
#
# fn main() {
#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
#     if let Err(e) = run(config) {
#         println!("Application error: {e}");
#         process::exit(1);
#     }
# }
#
pub struct Config {
    pub query: String,
    pub file_path: String,
    pub ignore_case: bool,
}
#
# impl Config {
#     fn build(args: &[String]) -> Result<Config, &'static
str> {
#         if args.len() < 3 {
```

```
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         Ok(Config { query, file_path })
#     }
# }
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
#         println!("{line}");
#     }
#
#     Ok(())
# }
```

We added the `ignore_case` field that holds a Boolean. Next, we need the `run` function to check the `ignore_case` 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. This still won't compile yet.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
```

```
#
use minigrep::{search, search_case_insensitive};

// --snip--

#
# fn main() {
#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
#     if let Err(e) = run(config) {
#         println!("Application error: {e}");
#         process::exit(1);
#     }
# }
#
# pub struct Config {
#     pub query: String,
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
# impl Config {
#     fn build(args: &[String]) -> Result<Config, &'static
str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
```

```
#         Ok(Config { query, file_path })
#     }
# }
#
fn run(config: Config) -> Result<(), Box<dyn Error>> {
    let contents = fs::read_to_string(config.file_path)?;

    let results = if config.ignore_case {
        search_case_insensitive(&config.query, &contents)
    } else {
        search(&config.query, &contents)
    };

    for line in results {
        println!("{line}");
    }

    Ok(())
}
```

Finally, we need to check for the environment variable. The functions for working with environment variables are in the `env` module in the standard library, which is already in scope at the top of *src/main.rs*. We'll use the `var` function from the `env` module to check to see if any value has been set for an environment variable named `IGNORE_CASE`, as shown in Listing 12-23.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
# fn main() {
```

```
#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
#     if let Err(e) = run(config) {
#         println!("Application error: {e}");
#         process::exit(1);
#     }
# }
#
# pub struct Config {
#     pub query: String,
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
impl Config {
    fn build(args: &[String]) -> Result<Config, &'static str>
{
        if args.len() < 3 {
            return Err("not enough arguments");
        }

        let query = args[1].clone();
        let file_path = args[2].clone();

        let ignore_case = env::var("IGNORE_CASE").is_ok();

        Ok(Config {
            query,
            file_path,
            ignore_case,
        })
```

```
    }
}
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
#         println!("{line}");
#     }
#
#     Ok(())
# }
```

Here, we create a new variable, `ignore_case`. To set its value, we call the `env::var` function and pass it the name of the `IGNORE_CASE` environment variable. The `env::var` function returns a `Result` that will be the successful `Ok` variant that contains the value of the environment variable if the environment variable is set to any value. It will return the `Err` variant if the environment variable is not set.

We're using the `is_ok` method on the `Result` to check whether the environment variable is set, which means the program should do a case-insensitive search. If the `IGNORE_CASE` environment variable isn't set to anything, `is_ok` will return `false` and the program will perform a case-sensitive search. We don't care about the *value* of the environment variable, just whether it's set or unset, so we're checking `is_ok` rather than using `unwrap`, `expect`, or any of the other methods we've seen on `Result`.

We pass the value in the `ignore_case` variable to the `Config` instance so the `run` function can read that value and decide whether to call `search_case_insensitive` or `search`, 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
   Compiling minigrep v0.1.0 (file:///projects/minigrep)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.0s
     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 `IGNORE_CASE` set to `1` but with the same query *to*:

```
$ IGNORE_CASE=1 cargo run -- to poem.txt
```

If you're using PowerShell, you will need to set the environment variable and run the program as separate commands:

```
PS> $Env:IGNORE_CASE=1; cargo run -- to poem.txt
```

This will make `IGNORE_CASE` persist for the remainder of your shell session. It can be unset with the `Remove-Item` cmdlet:

```
PS> Remove-Item Env:IGNORE_CASE
```

We should get lines that contain *to* that might have uppercase letters:

```
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 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 sensitivity 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 ignore case.

The `std::env` module contains many more useful features for dealing with environment variables: check out its documentation to see what is available.

Writing Error Messages to Standard Error Instead of Standard Output

At the moment, we're writing all of our output to the terminal using the `println!` macro. In most terminals, there are two kinds of output: *standard output* (`stdout`) for general information and *standard error* (`stderr`) for error messages. 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!` macro is only capable of printing to standard output, so we have to use something else to print to standard error.

Checking Where Errors Are Written

First let's observe how the content printed by `minigrep` is currently being written to standard output, including any error messages we want to write to standard error instead. We'll do that by redirecting the standard output stream to a file while intentionally causing 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 we can still see error messages on the screen even if we 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 a file instead!

To demonstrate this behavior, we'll run the program with `>` and the file path, *output.txt*, that we want to redirect the standard output stream to. We won't 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 to the screen, so that means it must have ended up in the file. This is 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 so only data from a successful run ends up in the file. We'll change that.

Printing Errors to Standard Error

We'll use the code in Listing 12-24 to change how error messages are printed. Because of the refactoring we did earlier in this chapter, all the code that prints error messages is in one function, `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 to use `eprintln!` instead.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::build(&args).unwrap_or_else(|err| {
        eprintln!("Problem parsing arguments: {err}");
        process::exit(1);
    });

    if let Err(e) = run(config) {
        eprintln!("Application error: {e}");
        process::exit(1);
    }
}
#
# pub struct Config {
#     pub query: String,
```

```
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
# impl Config {
#       fn build(args: &[String]) -> Result<Config, &'static
str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         let ignore_case = env::var("IGNORE_CASE").is_ok();
#
#         Ok(Config {
#             query,
#             file_path,
#             ignore_case,
#         })
#     }
# }
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
#         println!("{line}");
#     }
```

```
#
#     Ok(())
# }
```

Let’s now run 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 the error onscreen and *output.txt* contains nothing, which is the behavior we expect of command line programs.

Let’s run the program again with arguments that don’t cause an error but still redirect standard output to a file, like so:

```
$ cargo run -- to poem.txt > output.txt
```

We won’t see any output to the 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

This chapter recapped some of the major concepts you've learned so far and covered how to perform common I/O operations in Rust. By using command line arguments, files, environment variables, and the `eprintln!` macro for printing errors, you're now prepared to write command line applications. Combined with the concepts in previous chapters, your code will be well organized, store data effectively in the appropriate data structures, handle errors nicely, and be well tested.

Next, we'll explore some Rust features that were influenced by functional languages: closures and iterators.

Functional Language Features: Iterators and Closures

Rust’s design has taken inspiration from many 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.

In this chapter, we won’t debate the issue of what functional programming is or isn’t but will instead discuss some features of Rust that are similar to features in many languages often referred to as functional.

More specifically, we’ll cover:

- *Closures*, a function-like construct you can store in a variable
- *Iterators*, a way of processing a series of elements
- How to use closures and iterators to improve the I/O project in Chapter 12
- The performance of closures and iterators (spoiler alert: they’re faster than you might think!)

We’ve already covered some other Rust features, such as pattern matching and enums, that are also influenced by the functional style. Because mastering closures and iterators is an important part of writing idiomatic, fast Rust code, we’ll devote this entire chapter to them.

Closures: Anonymous Functions That 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 elsewhere to evaluate it in a different context. Unlike functions, closures can capture values from the scope in which they're defined. We'll demonstrate how these closure features allow for code reuse and behavior customization.

Capturing the Environment with Closures

We'll first examine how we can use closures to capture values from the environment they're defined in for later use. Here's the scenario: every so often, our T-shirt company gives away an exclusive, limited-edition shirt to someone on our mailing list as a promotion. People on the mailing list can optionally add their favorite color to their profile. If the person chosen for a free shirt has their favorite color set, they get that color shirt. If the person hasn't specified a favorite color, they get whatever color the company currently has the most of.

There are many ways to implement this. For this example, we're going to use an enum called `ShirtColor` that has the variants `Red` and `Blue` (limiting the number of colors available for simplicity). We represent the company's inventory with an `Inventory` struct that has a field named `shirts` that contains a `Vec<ShirtColor>` representing the shirt colors currently in stock. The method `giveaway` defined on `Inventory` gets the optional shirt color preference of the free-shirt winner, and returns the shirt color the person will get. This setup is shown in Listing 13-1.

```
#[derive(Debug, PartialEq, Copy, Clone)]
enum ShirtColor {
    Red,
    Blue,
}

struct Inventory {
```

```
    shirts: Vec<ShirtColor>,
}

impl Inventory {
    fn giveaway(&self, user_preference: Option<ShirtColor>) ->
ShirtColor {
        user_preference.unwrap_or_else(|| self.most_stocked())
    }

    fn most_stocked(&self) -> ShirtColor {
        let mut num_red = 0;
        let mut num_blue = 0;

        for color in &self.shirts {
            match color {
                ShirtColor::Red => num_red += 1,
                ShirtColor::Blue => num_blue += 1,
            }
        }
        if num_red > num_blue {
            ShirtColor::Red
        } else {
            ShirtColor::Blue
        }
    }
}

fn main() {
    let store = Inventory {
              shirts:  vec![ShirtColor::Blue,  ShirtColor::Red,
ShirtColor::Blue],
    };

    let user_pref1 = Some(ShirtColor::Red);
    let giveaway1 = store.giveaway(user_pref1);
    println!(
```

```
        "The user with preference {:?} gets {:?}",
        user_pref1, giveaway1
    );

    let user_pref2 = None;
    let giveaway2 = store.giveaway(user_pref2);
    println!(
        "The user with preference {:?} gets {:?}",
        user_pref2, giveaway2
    );
}
```

The `store` defined in `main` has two blue shirts and one red shirt remaining to distribute for this limited-edition promotion. We call the `giveaway` method for a user with a preference for a red shirt and a user without any preference.

Again, this code could be implemented in many ways, and here, to focus on closures, we've stuck to concepts you've already learned, except for the body of the `giveaway` method that uses a closure. In the `giveaway` method, we get the user preference as a parameter of type `Option<ShirtColor>` and call the `unwrap_or_else` method on `user_preference`. The [`unwrap_or_else` method on `Option<T>`] is defined by the standard library. It takes one argument: a closure without any arguments that returns a value `T` (the same type stored in the `Some` variant of the `Option<T>`, in this case `ShirtColor`). If the `Option<T>` is the `Some` variant, `unwrap_or_else` returns the value from within the `Some`. If the `Option<T>` is the `None` variant, `unwrap_or_else` calls the closure and returns the value returned by the closure.

We specify the closure expression `|| self.most_stocked()` as the argument to `unwrap_or_else`. This is a closure that takes no parameters itself (if the closure had parameters, they would appear between the two vertical pipes). The body of the closure calls `self.most_stocked()`. We're defining the closure here, and the implementation of `unwrap_or_else` will evaluate the closure later if the result is needed.

Running this code prints the following:

```
$ cargo run
     Compiling shirt-company v0.1.0 (file:///projects/shirt-company)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.27s
     Running `target/debug/shirt-company`
The user with preference Some(Red) gets Red
The user with preference None gets Blue
```

One interesting aspect here is that we've passed a closure that calls `self.most_stocked()` on the current `Inventory` instance. The standard library didn't need to know anything about the `Inventory` or `ShirtColor` types we defined, or the logic we want to use in this scenario. The closure captures an immutable reference to the `self` `Inventory` instance and passes it with the code we specify to the `unwrap_or_else` method. Functions, on the other hand, are not able to capture their environment in this way.

Closure Type Inference and Annotation

There are more differences between functions and closures. Closures don't usually require you to annotate the types of the parameters or the return value like `fn` functions do. Type annotations are required on functions because the types 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, on the other hand, aren't used in an exposed interface like this: they're stored in variables and used without naming them and exposing them to users of our library.

Closures are typically short and relevant only within a narrow context rather than in any arbitrary scenario. Within these limited contexts, the compiler can infer the types of the parameters and the return type, similar to how it's able to infer the types of most variables (there are rare cases where the compiler needs closure type annotations too).

As with variables, we can 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 a closure would look like the definition shown in Listing 13-2. In this example, we're defining a closure and storing it in a variable rather than defining the closure in the spot we pass it as an argument, as we did in Listing 13-1.

```
# use std::thread;
# use std::time::Duration;
#
# fn generate_workout(intensity: u32, random_number: u32) {
    let expensive_closure = |num: u32| -> u32 {
        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)
#             );
#         }
#     }
# }
#
# fn main() {
```

```
#     let simulated_user_specified_value = 10;
#     let simulated_random_number = 7;
#
#             generate_workout(simulated_user_specified_value,
simulated_random_number);
# }
```

With type annotations added, the syntax of closures looks more similar to the syntax of functions. Here, we define a function that adds 1 to its parameter and a closure that has the same behavior, for comparison. We've added some spaces 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. In the third line, we remove the type annotations from the closure definition. In the fourth line, we remove the brackets, which are optional because the closure body has only one expression. These are all valid definitions that will produce the same behavior when they're called. The `add_one_v3` and `add_one_v4` lines require the closures to be evaluated to be able to compile because the types will be inferred from their usage. This is similar to `let v = Vec::new();` needing either type annotations or values of some type to be inserted into the `Vec` for Rust to be able to infer the type.

For closure definitions, the compiler will infer one concrete type for each of their parameters and for their return value. For instance, Listing 13-3 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. Because there are no type annotations, we can call the closure with any type, which we've done here with `String` the first time. If we then try to call `example_closure` with an integer, we'll get an error.

```
# fn main() {
    let example_closure = |x| x;

    let s = example_closure(String::from("hello"));
    let n = example_closure(5);
# }
```

The compiler gives us this error:

```
$ cargo run
   Compiling closure-example v0.1.0 (file:///projects/closure-example)
error[E0308]: mismatched types
 --> src/main.rs:5:29
  |
5 |     let n = example_closure(5);
   |                    --------------- ^- help: try using a conversion method: `.to_string()`
  |             |               |
   |                |                  expected `String`, found integer
  |             arguments to this function are incorrect
  |
note: expected because the closure was earlier called with an argument of type `String`
 --> src/main.rs:4:29
  |
4 |     let s = example_closure(String::from("hello"));
  |             --------------- ^^^^^^^^^^^^^^^^^^^^^ expected because this argument is of type `String`
  |             |
  |             in this closure call
note: closure parameter defined here
 --> src/main.rs:2:28
  |
2 |     let example_closure = |x| x;
  |                            ^
```

```
For more information about this error, try `rustc --explain
E0308`.
error: could not compile `closure-example` (bin "closure-
example") due to 1 previous error
```

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 into the closure in `example_closure`, and we get a type error when we next try to use a different type with the same closure.

Capturing References or Moving Ownership

Closures can capture values from their environment in three ways, which directly map to the three ways a function can take a parameter: borrowing immutably, borrowing mutably, and taking ownership. The closure will decide which of these to use based on what the body of the function does with the captured values.

In Listing 13-4, we define a closure that captures an immutable reference to the vector named `list` because it only needs an immutable reference to print the value.

```
fn main() {
    let list = vec![1, 2, 3];
    println!("Before defining closure: {list:?}");

    let only_borrows = || println!("From closure: {list:?}");

    println!("Before calling closure: {list:?}");
    only_borrows();
    println!("After calling closure: {list:?}");
}
```

This example also illustrates that a variable can bind to a closure definition, and we can later call the closure by using the variable name and parentheses as if the variable name were a function name.

Because we can have multiple immutable references to `list` at the same time, `list` is still accessible from the code before the closure definition, after the closure definition but before the closure is called, and after the closure is called. This code compiles, runs, and prints:

```
$ cargo run
   Compiling closure-example v0.1.0 (file:///projects/closure-example)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.43s
     Running `target/debug/closure-example`
Before defining closure: [1, 2, 3]
Before calling closure: [1, 2, 3]
From closure: [1, 2, 3]
After calling closure: [1, 2, 3]
```

Next, in Listing 13-5, we change the closure body so that it adds an element to the `list` vector. The closure now captures a mutable reference.

```
fn main() {
    let mut list = vec![1, 2, 3];
    println!("Before defining closure: {list:?}");

    let mut borrows_mutably = || list.push(7);

    borrows_mutably();
    println!("After calling closure: {list:?}");
}
```

This code compiles, runs, and prints:

```
$ cargo run
   Compiling closure-example v0.1.0 (file:///projects/closure-example)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.43s
     Running `target/debug/closure-example`
Before defining closure: [1, 2, 3]
After calling closure: [1, 2, 3, 7]
```

Note that there's no longer a `println!` between the definition and the call of the `borrows_mutably` closure: when `borrows_mutably` is defined, it captures a mutable reference to `list`. We don't use the closure again after the closure is called, so the mutable borrow ends. Between the closure definition and the closure call, an immutable borrow to print isn't allowed because no other borrows are allowed when there's a mutable borrow. Try adding a `println!` there to see what error message you get!

If you want to force the closure to take ownership of the values it uses in the environment even though the body of the closure doesn't strictly need ownership, you can use the `move` keyword before the parameter list.

This technique is mostly useful when passing a closure to a new thread to move the data so that it's owned by the new thread. We'll discuss threads and why you would want to use them in detail in Chapter 16 when we talk about concurrency, but for now, let's briefly explore spawning a new thread using a closure that needs the `move` keyword. Listing 13-6 shows Listing 13-4 modified to print the vector in a new thread rather than in the main thread.

```
use std::thread;

fn main() {
    let list = vec![1, 2, 3];
    println!("Before defining closure: {list:?}");

    thread::spawn(move || println!("From thread: {list:?}"))
        .join()
        .unwrap();
}
```

We spawn a new thread, giving the thread a closure to run as an argument. The closure body prints out the list. In Listing 13-4, the closure only captured `list` using an immutable reference because that's the least amount of access to `list` needed to print it. In this example, even though the closure body still only needs an immutable reference, we need to specify that `list` should be moved into the closure by putting the `move` keyword at the beginning of the closure definition. If the main thread performed more operations before calling `join` on the new thread, the new thread might finish before the rest of the main thread finishes, or the main thread might finish first. If the main thread maintained ownership of `list` but ended before the new thread and drops `list`, the immutable reference in the thread would be invalid. Therefore, the compiler requires that `list` be moved into the closure given to the new thread so the reference will be valid. Try removing the `move` keyword or using `list` in the main thread after the closure is defined to see what compiler errors you get!

Moving Captured Values Out of Closures and the `Fn` Traits

Once a closure has captured a reference or captured ownership of a value from the environment where the closure is defined (thus affecting what, if anything, is moved *into* the closure), the code in the body of the closure defines what happens to the references or values when the closure is evaluated later (thus affecting what, if anything, is moved *out of* the closure).

A closure body can do any of the following: move a captured value out of the closure, mutate the captured value, neither move nor mutate the value, or capture nothing from the environment to begin with.

The way a closure captures and handles values from the environment affects which traits the closure implements, and traits are how functions and structs can specify what kinds of closures they can use. Closures will automatically implement one, two, or all three of these `Fn` traits, in an additive fashion, depending on how the closure's body handles the values:

- `FnOnce` applies to closures that can be called once. All closures implement at least this trait because all closures can be called. A closure that moves captured values out of its body will only implement `FnOnce` and none of the other `Fn` traits because it can only be called once.
- `FnMut` applies to closures that don't move captured values out of their body, but that might mutate the captured values. These closures can be

called more than once.

- `Fn` applies to closures that don't move captured values out of their body and that don't mutate captured values, as well as closures that capture nothing from their environment. These closures can be called more than once without mutating their environment, which is important in cases such as calling a closure multiple times concurrently.

Let's look at the definition of the `unwrap_or_else` method on `Option<T>` that we used in Listing 13-1:

```
impl<T> Option<T> {
    pub fn unwrap_or_else<F>(self, f: F) -> T
    where
        F: FnOnce() -> T
    {
        match self {
            Some(x) => x,
            None => f(),
        }
    }
}
```

Recall that `T` is the generic type representing the type of the value in the `Some` variant of an `Option`. That type `T` is also the return type of the `unwrap_or_else` function: code that calls `unwrap_or_else` on an `Option<String>`, for example, will get a `String`.

Next, notice that the `unwrap_or_else` function has the additional generic type parameter `F`. The `F` type is the type of the parameter named `f`, which is the closure we provide when calling `unwrap_or_else`.

The trait bound specified on the generic type `F` is `FnOnce() -> T`, which means `F` must be able to be called once, take no arguments, and return a `T`. Using `FnOnce` in the trait bound expresses the constraint that `unwrap_or_else` is only going to call `f` at most one time. In the body of `unwrap_or_else`, we can see that if the `Option` is `Some`, `f` won't be called. If the `Option` is `None`, `f` will be called once. Because all closures implement `FnOnce`, `unwrap_or_else` accepts all three kinds of closures and is as flexible as it can be.

> Note: If what we want to do doesn't require capturing a value from the environment, we can use the name of a function rather than a closure where we need something that implements one of the `Fn` traits. For example, on an `Option<Vec<T>>` value, we could call `unwrap_or_else(Vec::new)` to get a new, empty vector if the value is `None`. The compiler automatically implements whichever of the `Fn` traits is applicable for a function definition.

Now let's look at the standard library method `sort_by_key`, defined on slices, to see how that differs from `unwrap_or_else` and why `sort_by_key` uses `FnMut` instead of `FnOnce` for the trait bound. The closure gets one argument in the form of a reference to the current item in the slice being considered, and returns a value of type `K` that can be ordered. This function is useful when you want to sort a slice by a particular attribute of each item. In Listing 13-7, we have a list of `Rectangle` instances and we use `sort_by_key` to order them by their `width` attribute from low to high.

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
    let mut list = [
        Rectangle { width: 10, height: 1 },
        Rectangle { width: 3, height: 5 },
        Rectangle { width: 7, height: 12 },
    ];

    list.sort_by_key(|r| r.width);
```

```
    println!("{list:#?}");
}
```

This code prints:

```
$ cargo run
   Compiling rectangles v0.1.0 (file:///projects/rectangles)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.41s
     Running `target/debug/rectangles`
[
    Rectangle {
        width: 3,
        height: 5,
    },
    Rectangle {
        width: 7,
        height: 12,
    },
    Rectangle {
        width: 10,
        height: 1,
    },
]
```

The reason `sort_by_key` is defined to take an `FnMut` closure is that it calls the closure multiple times: once for each item in the slice. The closure `|r| r.width` doesn't capture, mutate, or move anything out from its environment, so it meets the trait bound requirements.

In contrast, Listing 13-8 shows an example of a closure that implements just the `FnOnce` trait, because it moves a value out of the environment. The compiler won't let us use this closure with `sort_by_key`.

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}
```

```
fn main() {
    let mut list = [
        Rectangle { width: 10, height: 1 },
        Rectangle { width: 3, height: 5 },
        Rectangle { width: 7, height: 12 },
    ];

    let mut sort_operations = vec![];
    let value = String::from("closure called");

    list.sort_by_key(|r| {
        sort_operations.push(value);
        r.width
    });
    println!("{list:#?}");
}
```

This is a contrived, convoluted way (that doesn't work) to try and count the number of times `sort_by_key` calls the closure when sorting `list`. This code attempts to do this counting by pushing `value`—a `String` from the closure's environment—into the `sort_operations` vector. The closure captures `value` and then moves `value` out of the closure by transferring ownership of `value` to the `sort_operations` vector. This closure can be called once; trying to call it a second time wouldn't work because `value` would no longer be in the environment to be pushed into `sort_operations` again! Therefore, this closure only implements `FnOnce`. When we try to compile this code, we get this error that `value` can't be moved out of the closure because the closure must implement `FnMut`:

```
$ cargo run
   Compiling rectangles v0.1.0 (file:///projects/rectangles)
error[E0507]: cannot move out of `value`, a captured variable
in an `FnMut` closure
  --> src/main.rs:18:30
   |
```

```
15 |     let value = String::from("closure called");
   |         ----- captured outer variable
16 |
17 |     list.sort_by_key(|r| {
   |                      --- captured by this `FnMut` closure
18 |         sort_operations.push(value);
   |                              ^^^^^ move occurs because
`value` has type `String`, which does not implement the `Copy`
trait
   |
help: consider cloning the value if the performance cost is
acceptable
   |
18 |         sort_operations.push(value.clone());
   |                                   ++++++++

For more information about this error, try `rustc --explain
E0507`.
error: could not compile `rectangles` (bin "rectangles") due
to 1 previous error
```

The error points to the line in the closure body that moves `value` out of the environment. To fix this, we need to change the closure body so that it doesn't move values out of the environment. Keeping a counter in the environment and incrementing its value in the closure body is a more straightforward way to count the number of times the closure is called. The closure in Listing 13-9 works with `sort_by_key` because it is only capturing a mutable reference to the `num_sort_operations` counter and can therefore be called more than once:

```
#[derive(Debug)]
struct Rectangle {
    width: u32,
    height: u32,
}

fn main() {
```

```
    let mut list = [
        Rectangle { width: 10, height: 1 },
        Rectangle { width: 3, height: 5 },
        Rectangle { width: 7, height: 12 },
    ];

    let mut num_sort_operations = 0;
    list.sort_by_key(|r| {
        num_sort_operations += 1;
        r.width
    });
        println!("{list:#?}, sorted in {num_sort_operations}
operations");
}
```

The `Fn` traits are important when defining or using functions or types that make use of closures. In the next section, we'll discuss iterators. Many iterator methods take closure arguments, so keep these closure details in mind as we continue!

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 you use iterators, you don't have to reimplement that logic yourself.

In Rust, iterators are *lazy*, meaning they have no effect until you call methods that consume the iterator to use it up. For example, the code in Listing 13-10 creates an iterator over the items in the vector `v1` by calling the `iter` method defined on `Vec<T>`. This code by itself doesn't do anything useful.

```
# fn main() {
    let v1 = vec![1, 2, 3];

    let v1_iter = v1.iter();
# }
```

The iterator is stored in the `v1_iter` variable. Once we've created an iterator, we can use it in a variety of ways. In Listing 3-5, we iterated over an array using a `for` loop to execute some code on each of its items. Under the hood, this implicitly created and then consumed an iterator, but we glossed over how exactly that works until now.

In the example in Listing 13-11, we separate the creation of the iterator from the use of the iterator in the `for` loop. When the `for` loop is called using the iterator in `v1_iter`, each element in the iterator is used in one iteration of the loop, which prints out each value.

```
# fn main() {
    let v1 = vec![1, 2, 3];

    let v1_iter = v1.iter();

    for val in v1_iter {
        println!("Got: {val}");
```

```
    }
# }
```

In languages that don't have iterators provided by their standard libraries, you 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 reached the total number of items in the vector.

Iterators handle all of that logic for you, cutting down on repetitive code you could potentially mess up. Iterators give you more flexibility to use the same logic with many different kinds of sequences, not just data structures you can index into, like vectors. Let's examine how iterators do that.

The `Iterator` Trait and the `next` Method

All iterators implement a trait named `Iterator` that is defined in the standard library. The definition of the trait looks like this:

```
pub trait Iterator {
    type Item;

    fn next(&mut self) -> Option<Self::Item>;

    // methods with default implementations elided
}
```

Notice that this definition uses some new syntax: `type Item` and `Self::Item`, which are defining an *associated type* with this trait. We'll talk about associated types in depth in Chapter 20. 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, returns `None`.

We can call the `next` method on iterators directly; Listing 13-12 demonstrates what values are returned from repeated calls to `next` on the iterator created from the vector.

```
# #[cfg(test)]
# mod tests {
    #[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);
    }
# }
```

Note that we needed to make `v1_iter` mutable: calling the `next` method on an iterator changes internal state that the iterator uses to keep track of where it is in the sequence. In other words, 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 That Consume the Iterator

The `Iterator` trait has a number of different methods with default implementations provided by the standard library; you can find out 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 you're required to implement the `next` method when implementing the `Iterator` trait.

Methods that call `next` are called *consuming adapters*, 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 13-13 has a test illustrating a use of the `sum` method.

```
# #[cfg(test)]
# mod tests {
    #[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);
    }
# }
```

We aren't allowed to use `v1_iter` after the call to `sum` because `sum` takes ownership of the iterator we call it on.

Methods That Produce Other Iterators

Iterator adapters are methods defined on the `Iterator` trait that don't consume the iterator. Instead, they produce different iterators by changing some aspect of the original iterator.

Listing 13-14 shows an example of calling the iterator adapter method `map`, which takes a closure to call on each item as the items are iterated through. The `map` method returns a new iterator that produces the modified items. The closure here creates a new iterator in which each item from the vector will be incremented by 1.

```
# fn main() {
    let v1: Vec<i32> = vec![1, 2, 3];

    v1.iter().map(|x| x + 1);
# }
```

However, this code produces a warning:

```
$ cargo run
   Compiling iterators v0.1.0 (file:///projects/iterators)
warning: unused `Map` that must be used
 --> src/main.rs:4:5
  |
4 |     v1.iter().map(|x| x + 1);
  |     ^^^^^^^^^^^^^^^^^^^^^^^^
  |
  = note: iterators are lazy and do nothing unless consumed
  = note: `#[warn(unused_must_use)]` on by default
help: use `let _ = ...` to ignore the resulting value
  |
4 |     let _ = v1.iter().map(|x| x + 1);
  |     +++++++

warning: `iterators` (bin "iterators") generated 1 warning
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.47s
     Running `target/debug/iterators`
```

The code in Listing 13-14 doesn’t do anything; the closure we’ve specified never gets called. The warning reminds us why: iterator adapters are lazy, and we need to consume the iterator here.

To fix this warning and consume the iterator, we'll use the `collect` method, which we used with `env::args` in Listing 12-1. This method consumes the iterator and collects the resultant values into a collection data type.

In Listing 13-15, 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.

```
# fn main() {
    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]);
# }
```

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 you customize some behavior while reusing the iteration behavior that the `Iterator` trait provides.

You can chain multiple calls to iterator adapters to perform complex actions in a readable way. But because all iterators are lazy, you have to call one of the consuming adapter methods to get results from calls to iterator adapters.

Using Closures That Capture Their Environment

Many iterator adapters take closures as arguments, and commonly the closures we'll specify as arguments to iterator adapters will be closures that capture their environment.

For this example, we'll use the `filter` method that takes a closure. The closure gets an item from the iterator and returns a `bool`. If the closure returns `true`, the value will be included in the iteration produced by `filter`. If the closure returns `false`, the value won't be included.

In Listing 13-16, we use `filter` with a closure that captures the `shoe_size` variable from its environment to iterate over a collection of

`Shoe` struct instances. It will return only shoes that are the specified size.

```
#[derive(PartialEq, Debug)]
struct Shoe {
    size: u32,
    style: String,
}

fn shoes_in_size(shoes: Vec<Shoe>, shoe_size: u32) -> Vec<Shoe> {
    shoes.into_iter().filter(|s| s.size == shoe_size).collect()
}

#[cfg(test)]
mod tests {
    use super::*;

    #[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_size(shoes, 10);
```

```
        assert_eq!(
            in_my_size,
            vec![
                Shoe {
                    size: 10,
                    style: String::from("sneaker")
                },
                Shoe {
                    size: 10,
                    style: String::from("boot")
                },
            ]
        );
    }
}
```

The `shoes_in_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_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_size`, we get back only shoes that have the same size as the value we specified.

Improving Our I/O Project

With this new knowledge about iterators, 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 look at how iterators can improve our implementation of the `Config::build` 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. In Listing 13-17, we've reproduced the implementation of the `Config::build` function as it was in Listing 12-23.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
# fn main() {
#     let args: Vec<String> = env::args().collect();
#
#     let config = Config::build(&args).unwrap_or_else(|err| {
#         println!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
#     if let Err(e) = run(config) {
#         println!("Application error: {e}");
#         process::exit(1);
#     }
# }
#
```

```
# pub struct Config {
#     pub query: String,
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
impl Config {
    fn build(args: &[String]) -> Result<Config, &'static str>
{
        if args.len() < 3 {
            return Err("not enough arguments");
        }

        let query = args[1].clone();
        let file_path = args[2].clone();

        let ignore_case = env::var("IGNORE_CASE").is_ok();

        Ok(Config {
            query,
            file_path,
            ignore_case,
        })
    }
}
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
```

```
#         println!("{line}");
#     }
#
#     Ok(())
# }
```

At the time, we said not to worry about the inefficient `clone` calls 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 `build` function doesn't own `args`. To return ownership of a `Config` instance, we had to clone the values from the `query` and `file_path` fields of `Config` so the `Config` instance can own its values.

With our new knowledge about iterators, we can change the `build` 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 clarify what the `Config::build` function is doing because the iterator will access the values.

Once `Config::build` 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 Returned Iterator Directly

Open your I/O project's *src/main.rs* file, which should look like this:

Filename: src/main.rs

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
```

```
fn main() {
    let args: Vec<String> = env::args().collect();

    let config = Config::build(&args).unwrap_or_else(|err| {
        eprintln!("Problem parsing arguments: {err}");
        process::exit(1);
    });

    // --snip--
#
#     if let Err(e) = run(config) {
#         eprintln!("Application error: {e}");
#         process::exit(1);
#     }
}
#
# pub struct Config {
#     pub query: String,
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
# impl Config {
#     fn build(args: &[String]) -> Result<Config, &'static str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         let ignore_case = env::var("IGNORE_CASE").is_ok();
#
#         Ok(Config {
#             query,
```

```
#             file_path,
#             ignore_case,
#         })
#     }
# }
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
#         println!("{line}");
#     }
#
#     Ok(())
# }
```

We'll first change the start of the `main` function that we had in Listing 12-24 to the code in Listing 13-18, which this time uses an iterator. This won't compile until we update `Config::build` as well.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
fn main() {
    let config = Config::build(env::args()).unwrap_or_else(|err| {
        eprintln!("Problem parsing arguments: {err}");
```

```
        process::exit(1);
    });

    // --snip--
#
#     if let Err(e) = run(config) {
#         eprintln!("Application error: {e}");
#         process::exit(1);
#     }
}
#
# pub struct Config {
#     pub query: String,
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
# impl Config {
#     fn build(args: &[String]) -> Result<Config, &'static
str> {
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         let ignore_case = env::var("IGNORE_CASE").is_ok();
#
#         Ok(Config {
#             query,
#             file_path,
#             ignore_case,
#         })
#     }
# }
```

```
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
#         println!("{line}");
#     }
#
#     Ok(())
# }
```

The `env::args` function returns an iterator! Rather than collecting the iterator values into a vector and then passing a slice to `Config::build`, now we're passing ownership of the iterator returned from `env::args` to `Config::build` directly.

Next, we need to update the definition of `Config::build`. Let's change the signature of `Config::build` to look like Listing 13-19. This still won't compile, because we need to update the function body.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
# fn main() {
#                                      let       config       =
Config::build(env::args()).unwrap_or_else(|err| {
#         eprintln!("Problem parsing arguments: {err}");
```

```
#         process::exit(1);
#     });
#
#
#     if let Err(e) = run(config) {
#         eprintln!("Application error: {e}");
#         process::exit(1);
#     }
# }
#
# pub struct Config {
#     pub query: String,
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
impl Config {
    fn build(
        mut args: impl Iterator<Item = String>,
    ) -> Result<Config, &'static str> {
        // --snip--
#         if args.len() < 3 {
#             return Err("not enough arguments");
#         }
#
#         let query = args[1].clone();
#         let file_path = args[2].clone();
#
#         let ignore_case = env::var("IGNORE_CASE").is_ok();
#
#         Ok(Config {
#             query,
#             file_path,
#             ignore_case,
#         })
#     }
```

```
# }
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
#         println!("{line}");
#     }
#
#     Ok(())
# }
```

The standard library documentation for the `env::args` function shows that the type of the iterator it returns is `std::env::Args`, and that type implements the `Iterator` trait and returns `String` values.

We've updated the signature of the `Config::build` function so the parameter `args` has a generic type with the trait bounds `impl Iterator<Item = String>` instead of `&[String]`. This usage of the `impl Trait` syntax we discussed in the "Traits as Parameters" section of Chapter 10 means that `args` can be any type that implements the `Iterator` trait and returns `String` items.

Because we're taking ownership of `args` and we'll 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::build`. Because `args` implements the `Iterator` trait, we know we can call the `next` method on it! Listing

13-20 updates the code from Listing 12-23 to use the `next` method.

```
# use std::env;
# use std::error::Error;
# use std::fs;
# use std::process;
#
# use minigrep::{search, search_case_insensitive};
#
# fn main() {
#                                      let        config        =
Config::build(env::args()).unwrap_or_else(|err| {
#         eprintln!("Problem parsing arguments: {err}");
#         process::exit(1);
#     });
#
#     if let Err(e) = run(config) {
#         eprintln!("Application error: {e}");
#         process::exit(1);
#     }
# }
#
# pub struct Config {
#     pub query: String,
#     pub file_path: String,
#     pub ignore_case: bool,
# }
#
impl Config {
    fn build(
        mut args: impl Iterator<Item = String>,
    ) -> Result<Config, &'static str> {
        args.next();

        let query = match args.next() {
            Some(arg) => arg,
```

```
            None => return Err("Didn't get a query string"),
        };

        let file_path = match args.next() {
            Some(arg) => arg,
            None => return Err("Didn't get a file path"),
        };

        let ignore_case = env::var("IGNORE_CASE").is_ok();

        Ok(Config {
            query,
            file_path,
            ignore_case,
        })
    }
}
#
# fn run(config: Config) -> Result<(), Box<dyn Error>> {
#     let contents = fs::read_to_string(config.file_path)?;
#
#     let results = if config.ignore_case {
#         search_case_insensitive(&config.query, &contents)
#     } else {
#         search(&config.query, &contents)
#     };
#
#     for line in results {
#         println!("{line}");
#     }
#
#     Ok(())
# }
```

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. Then we call `next` to get the value we want to put in the `query` field of `Config`. If `next` returns `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 `file_path` value.

Making Code Clearer with Iterator Adapters

We can also take advantage of iterators in the `search` function in our I/O project, which is reproduced here in Listing 13-21 as it was in Listing 12-19.

```
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
}
#
# #[cfg(test)]
# mod tests {
#     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));
#     }
# }
```

We can write this code in a more concise way using iterator adapter methods. Doing so 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 enable a future enhancement to make searching happen in parallel because we wouldn't have to manage concurrent access to the `results` vector. Listing 13-22 shows this change.

```
pub fn search<'a>(query: &str, contents: &'a str) -> Vec<&'a
str> {
    contents
        .lines()
        .filter(|line| line.contains(query))
        .collect()
}
#
# pub 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
# }
```

```
#
# #[cfg(test)]
# mod tests {
#     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)
#         );
#     }
# }
```

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 13-16, this code uses the `filter` adapter to keep only the lines for which `line.contains(query)` returns `true`. We then collect the matching lines 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.

For a further improvement, return an iterator from the `search` function by removing the call to `collect` and changing the return type to `impl Iterator<Item = &'a str>` so that the function becomes an iterator adapter. Note that you'll also need to update the tests! Search through a large file using your `minigrep` tool before and after making this change to observe the difference in behavior. Before this change, the program won't print any results until it has collected all of the results, but after the change, the results will be printed as each matching line is found because the `for` loop in the `run` function is able to take advantage of the laziness of the iterator.

Choosing Between Loops and Iterators

The next logical question is which style you should choose in your own code and why: the original implementation in Listing 13-21 or the version using iterators in Listing 13-22 (assuming we're collecting all the results before returning them rather than returning the iterator). 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 adapters 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 it's easier to see the concepts that are unique to this code, such as the filtering condition each element in the iterator must pass.

But are the two implementations truly equivalent? The intuitive assumption might be that the lower-level loop will be faster. Let's talk about performance.

Comparing Performance: Loops vs. Iterators

To determine whether to use loops or iterators, you need to know which implementation is faster: the version of the `search` function 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 are 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 two implementations have similar performance! We won't explain the benchmark code here because the point is not to prove that the two versions are equivalent but to get a general sense of how these two implementations compare performance-wise.

For a more comprehensive benchmark, you should check using various texts of various sizes as the `contents`, different words and words of different lengths as the `query`, and all kinds of other variations. The point is this: iterators, although 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 that using the abstraction imposes no additional runtime overhead. This is analogous to how Bjarne Stroustrup, the original designer and implementor of C++, defines *zero-overhead* in "Foundations of C++" (2012):

> 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.

In many cases, Rust code using iterators compiles to the same assembly you'd write by hand. Optimizations such as loop unrolling and eliminating bounds checking on array access apply and make the resultant code extremely efficient. Now that you know this, you can use iterators and closures without fear! They make code seem like it’s 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 capability 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 will help us 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. In this chapter, we'll discuss some of its other, more advanced features to show you how to do the following:

- Customize your build through release profiles
- Publish libraries on crates.io
- Organize large projects with workspaces
- Install binaries from crates.io
- Extend Cargo using custom commands

Cargo can do even more than the functionality we cover in this chapter, so for a full explanation of all its features, see its documentation.

Customizing Builds with Release Profiles

In Rust, *release profiles* are predefined and customizable profiles with different configurations that allow a programmer to have more control over various options for compiling code. Each profile is configured independently of the others.

Cargo has two main profiles: 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 development, and the `release` profile has good defaults for release builds.

These profile names might be familiar from the output of your builds:

```
$ cargo build
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.00s
$ cargo build --release
    Finished `release` profile [optimized] target(s) in 0.32s
```

The `dev` and `release` are these different profiles used by the compiler.

Cargo has default settings for each of the profiles that apply when you haven't explicitly added any `[profile.*]` sections in the project's *Cargo.toml* file. By adding `[profile.*]` sections for any profile you want to customize, you 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 the number of optimizations Rust will apply to your code, with a range of 0 to 3. Applying more optimizations extends compiling time, so if you're in development and compiling your code often, you'll want fewer optimizations to compile faster even if the resultant code runs slower. The default `opt-level` for `dev` is therefore `0`. When you're ready to release your code, it's best to spend more time compiling. You'll only compile in release mode once, but you'll run the compiled program many times, so release mode trades longer compile time for code that runs faster. That is why the default `opt-level` for the `release` profile is `3`.

You can override a default setting by adding a different value for it in *Cargo.toml*. For example, if we want to use optimization level 1 in the development profile, we can add these two lines to our project's *Cargo.toml* file:

Filename: Cargo.toml

```
[profile.dev]
opt-level = 1
```

This code 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 in 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 with other people by publishing your own packages. The crate registry at crates.io distributes the source code of your packages, so it primarily hosts code that is open source.

Rust and Cargo have features that make your published package easier for people to find and use. We’ll talk about some of these features next and then explain 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 investing the time to write documentation. In Chapter 3, we discussed how to comment Rust code using two slashes, `//`. Rust also has a particular kind of comment for documentation, known conveniently as a *documentation comment*, 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 three slashes, `///`, instead of two and support Markdown notation for formatting the text. Place documentation comments just before the item they’re documenting. Listing 14-1 shows documentation comments for an `add_one` function in a crate named `my_crate`.

````
/// Adds one to the number given.
///
/// # Examples
///
/// ```
/// let arg = 5;
/// let answer = my_crate::add_one(arg);
///
/// assert_eq!(6, answer);
````

```
/// ```
pub fn add_one(x: i32) -> i32 {
    x + 1
}
```

Here, we give a description of what the `add_one` function does, start a section with the heading `Examples`, and then provide 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 is rendered, as shown in Figure 14-1.

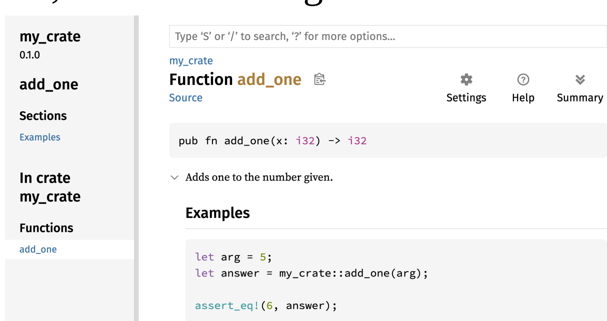


Figure 14-1: HTML documentation for the `add_one` function

Commonly Used Sections

We used the `# Examples` Markdown heading in Listing 14-1 to create a section in the HTML with the title "Examples." Here are some other sections that crate authors commonly use in their documentation:

- **Panics**: The scenarios in which the function being documented could panic. Callers of the function who don't want their programs to panic should make sure they don't call the function in these situations.

- **Errors**: If the 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 they can write code to handle the different kinds of errors in different ways.
- **Safety**: If the function is `unsafe` to call (we discuss unsafety in Chapter 20), there should be a section explaining why the function is unsafe and covering the invariants that the function expects callers to uphold.

Most documentation comments don't need all of these sections, but this is a good checklist to remind you of the aspects of your code users will be interested in knowing about.

Documentation Comments as Tests

Adding example code blocks in your documentation comments can help demonstrate how to use your library, and doing so has an additional bonus: running `cargo test` will run the code examples in your documentation as tests! Nothing is better than documentation with examples. But nothing is worse than examples that don't work because the code has changed since the documentation was written. If we run `cargo test` with the documentation for the `add_one` function from Listing 14-1, we will see a section in the test results that looks 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; 0
filtered out; finished in 0.27s
```

Now, if we change either the function or the example so the `assert_eq!` in the example panics, and run `cargo test` again, we'll see that the doc tests catch that the example and the code are out of sync with each other!

Commenting Contained Items

The style of doc comment `//!` adds documentation to the item that *contains* the comments rather than to the items *following* the comments. We typically use these doc comments 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, to add documentation that describes the purpose of the `my_crate` crate that contains the `add_one` function, we add documentation comments that start with `//!` to the beginning of the *src/lib.rs* file, as shown in Listing 14-2.

```
//! # My Crate
//!
//! `my_crate` is a collection of utilities to make performing
certain
//! calculations more convenient.

/// Adds one to the number given.
// --snip--
# ///
# /// # Examples
# ///
# /// ```
# /// let arg = 5;
# /// let answer = my_crate::add_one(arg);
# ///
# /// assert_eq!(6, answer);
# /// ```
# pub fn add_one(x: i32) -> i32 {
#     x + 1
# }
```

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, that item is the *src/lib.rs* file, which is the crate root. These comments describe the entire crate.

When we run `cargo doc --open`, these comments will display on the front page of the documentation for `my_crate` above the list of public items in the crate, as shown in Figure 14-2.

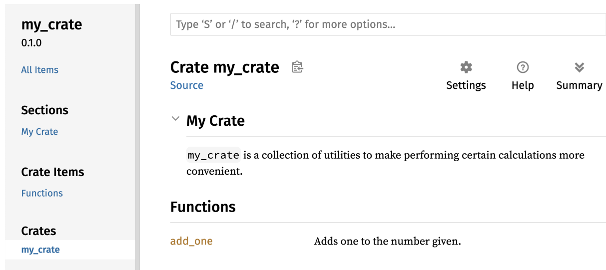


Figure 14-2: Rendered documentation for `my_crate`, including the comment describing the crate as a whole

Documentation comments within items are useful for describing crates and modules especially. Use them to explain the overall purpose of the container to help your users understand the crate's organization.

Exporting a Convenient Public API with `pub use`

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 difficulty finding the pieces they want to use if your crate has a large module hierarchy.

In Chapter 7, we covered how to make items public using the `pub` keyword, and how to bring items into a scope with the `use` keyword. However, the structure that makes sense to you while you're developing a crate might not be very convenient for your users. You might want to organize your structs in a hierarchy containing multiple levels, but then people who want to use a type you've defined deep in the hierarchy might have trouble finding out that type exists. They might also be annoyed at having to enter `use my_crate::some_module::another_module::UsefulType;` rather than `use my_crate::UsefulType;`.

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: instead, you can re-export items to make a public structure that's different from your private structure by using `pub use`. *Re-exporting* takes a public item in one location and makes it public in another location, as if it were defined in the other location instead.

For example, say we made a library named `art` for modeling artistic concepts. Within this library are two modules: a `kinds` module containing two enums named `PrimaryColor` and `SecondaryColor` and a `utils` module containing a function named `mix`, as shown in Listing 14-3.

```
//! # 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 crate::kinds::*;

    /// Combines two primary colors in equal amounts to create
```

```
    /// a secondary color.
        pub fn mix(c1: PrimaryColor, c2: PrimaryColor) ->
SecondaryColor {
        // --snip--
#          unimplemented!();
    }
}
```

Figure 14-3 shows what the front page of the documentation for this crate generated by `cargo doc` would look like.

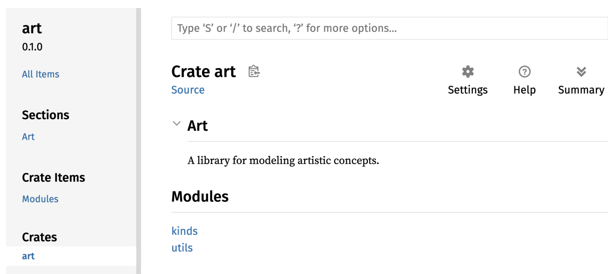


Figure 14-3: Front page of the documentation for `art` that lists the `kinds` and `utils` modules

Note that the `PrimaryColor` and `SecondaryColor` types aren't listed on the front page, nor is the `mix` function. We have to click `kinds` and `utils` to see them.

Another crate that depends on this library would need `use` statements that bring the items from `art` into scope, specifying the module structure that's currently defined. Listing 14-4 shows an example of a crate that uses the `PrimaryColor` and `mix` items from the `art` crate.

```
use art::kinds::PrimaryColor;
use art::utils::mix;

fn main() {
    let red = PrimaryColor::Red;
    let yellow = PrimaryColor::Yellow;
```

```
    mix(red, yellow);
}
```

The author of the code in Listing 14-4, which 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 to those using it. The internal structure doesn't contain any useful information for someone trying to understand how to use the `art` crate, but rather causes confusion because developers who use it have to figure out where to look, and must specify the module names in the `use` statements.

To remove the internal organization from the public API, we can modify the `art` crate code in Listing 14-3 to add `pub use` statements to re-export the items at the top level, as shown in Listing 14-5.

```
//! # Art
//!
//! A library for modeling artistic concepts.

pub use self::kinds::PrimaryColor;
pub use self::kinds::SecondaryColor;
pub use self::utils::mix;

pub mod kinds {
    // --snip--
#     /// 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 {
    // --snip--
#     use crate::kinds::*;
#
#     /// Combines two primary colors in equal amounts to
create
#     /// a secondary color.
#     pub fn mix(c1: PrimaryColor, c2: PrimaryColor) ->
SecondaryColor {
#         SecondaryColor::Orange
#     }
}
```

The API documentation that `cargo doc` generates for this crate will now list and link re-exports on the front page, as shown in Figure 14-4, making the `PrimaryColor` and `SecondaryColor` types and the `mix` function easier to find.

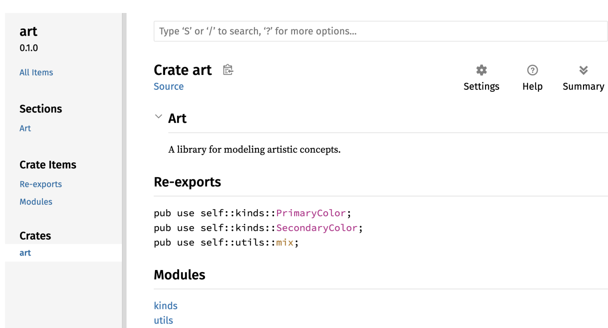


Figure 14-4: The front page of the documentation for `art` that lists the re-exports

The `art` crate users can still see and use the internal structure from Listing 14-3 as demonstrated in Listing 14-4, or they can use the more convenient structure in Listing 14-5, as shown in Listing 14-6.

```
use art::PrimaryColor;
use art::mix;

fn main() {
    // --snip--
#     let red = PrimaryColor::Red;
#     let yellow = PrimaryColor::Yellow;
#     mix(red, yellow);
}
```

In cases where there are many nested modules, re-exporting the types at the top level with `pub use` can make a significant difference in the experience of people who use the crate. Another common use of `pub use` is to re-export definitions of a dependency in the current crate to make that crate's definitions part of your crate’s public API.

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 from what you present to your users. 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 crates.io and log in via a GitHub account. (The GitHub account is currently a requirement, but the site might 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 and paste your API key when prompted, like this:

```
$ cargo login
abcdefghijklmnopqrstuvwxyz012345
```

This command will inform Cargo of your API token and store it locally in *~/.cargo/credentials.toml*. Note that this token is a *secret*: do not share it with anyone else. If you do share it with anyone for any reason, you should revoke it and generate a new token on crates.io.

Adding Metadata to a New Crate

Let's say you have a crate you want to publish. Before publishing, you'll need to add some metadata in the `[package]` section of the crate's *Cargo.toml* file.

Your crate will need a unique name. While you're working on a crate locally, you can name a crate whatever you'd like. However, crate names on crates.io are allocated on a first-come, first-served basis. Once a crate name is taken, no one else can publish a crate with that name. Before attempting to publish a crate, search for the name you want to use. If the name has been used, you will need to find another name and edit the `name` field in the *Cargo.toml* file under the `[package]` section to use the new name for publishing, like so:

Filename: Cargo.toml

```
[package]
name = "guessing_game"
```

Even if you've chosen a unique name, when you run `cargo publish` to publish the crate at this point, you'll get a warning and then an error:

```
$ cargo publish
    Updating crates.io index
warning: manifest has no description, license, license-file,
documentation, homepage or repository.
See                                          https://doc.rust-
lang.org/cargo/reference/manifest.html#package-metadata    for
more info.
--snip--
error: failed to publish to registry at https://crates.io
```

```
Caused by:
  the remote server responded with an error (status 400 Bad Request): missing or empty metadata fields: description, license. Please see https://doc.rust-lang.org/cargo/reference/manifest.html for more information on configuring these fields
```

This results in an error because you’re missing some crucial information: a description and license are required so people will know what your crate does and under what terms they can use it. In *Cargo.toml*, add a description that's just a sentence or two, because it will appear with your crate in search results. For the `license` field, you need to give a *license identifier value*. The [Linux Foundation’s Software Package Data Exchange (SPDX)]() 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, and then use `license-file` to specify the name of that file instead of using the `license` key.

Guidance on which license is appropriate for your project is beyond the scope of this book. Many people in the Rust community license their projects in the same way as Rust by using a dual license of `MIT OR Apache-2.0`. This practice demonstrates that you can also specify multiple license identifiers separated by `OR` to have multiple licenses for your project.

With a unique name, the version, your description, and a license added, the *Cargo.toml* file for a project that is ready to publish might look like this:

Filename: Cargo.toml

```
[package]
name = "guessing_game"
version = "0.1.0"
edition = "2024"
description = "A fun game where you guess what number the computer has chosen."
license = "MIT OR Apache-2.0"

[dependencies]
```

Cargo's documentation describes other metadata you can specify to ensure that others can discover and use your crate 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.

Be careful, because a publish is *permanent*. The version can never be overwritten, and the code cannot be deleted except in certain circumstances. 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 version deletions would make fulfilling that goal impossible. However, there is no limit to the number of crate versions you can publish.

Run the `cargo publish` command again. It should succeed now:

```
$ cargo publish
    Updating crates.io index
   Packaging guessing_game v0.1.0 (file:///projects/guessing_game)
    Packaged 6 files, 1.2KiB (895.0B compressed)
   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` profile [unoptimized + debuginfo] target(s)
in 0.19s
                    Uploading      guessing_game      v0.1.0
(file:///projects/guessing_game)
    Uploaded guessing_game v0.1.0 to registry `crates-io`
note: waiting for `guessing_game v0.1.0` to be available at
registry
`crates-io`.
You may press ctrl-c to skip waiting; the crate should be
available shortly.
   Published guessing_game v0.1.0 at registry `crates-io`
```

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* file 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.

Deprecating Versions from Crates.io with `cargo yank`

Although 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 crate version is broken for one reason or another. In such situations, Cargo supports yanking a crate version.

Yanking a version prevents new projects from depending on that version while allowing all existing projects that depend on it to continue. Essentially, a yank means that all projects with a *Cargo.lock* will not break, and any future *Cargo.lock* files generated will not use the yanked version.

To yank a version of a crate, in the directory of the crate that you've previously published, run `cargo yank` and specify which version you want to yank. For example, if we've published a crate named `guessing_game` version 1.0.1 and we want to yank it, in the project directory for `guessing_game` we'd run:

```
$ cargo yank --vers 1.0.1
    Updating crates.io index
        Yank guessing_game@1.0.1
```

By adding `--undo` to the command, you can also undo a yank and allow projects to start depending on a version again:

```
$ cargo yank --vers 1.0.1 --undo
    Updating crates.io index
      Unyank guessing_game@1.0.1
```

A yank *does not* delete any code. It cannot, for example, delete accidentally uploaded secrets. If that happens, you must reset those secrets immediately.

Cargo Workspaces

In Chapter 12, we built a package that included a binary crate and a library crate. As your project develops, you might find that the library crate continues to get bigger and you want to split your package further into multiple library crates. Cargo offers a feature called *workspaces* that can help manage multiple related packages that are developed in tandem.

Creating a Workspace

A *workspace* is a set of packages that share the same *Cargo.lock* and output directory. Let’s make a project using a workspace—we’ll use trivial code so we can concentrate on the structure of the workspace. There are multiple ways to structure a workspace, so we'll just show one common way. We’ll have a workspace containing a binary and two libraries. The binary, which will provide the main functionality, will depend on the two libraries. One library will provide an `add_one` function and the other library an `add_two` function. These three crates will be part of the same workspace. We’ll start by creating a new directory for the workspace:

```
$ mkdir add
$ cd add
```

Next, in the *add* directory, we create the *Cargo.toml* file that will configure the entire workspace. This file won’t have a `[package]` section. Instead, it will start with a `[workspace]` section that will allow us to add members to the workspace. We also make a point to use the latest and greatest version of Cargo’s resolver algorithm in our workspace by setting the `resolver` value to `"3"`.

Filename: Cargo.toml

```
[workspace]
resolver = "3"
```

Next, we’ll create the `adder` binary crate by running `cargo new` within the *add* directory:

```
$ cargo new
    Created binary (application) `adder` package
```

```
      Adding `adder` as member of workspace at `file:///projects/add`
```

Running `cargo new` inside a workspace also automatically adds the newly created package to the `members` key in the `[workspace]` definition in the workspace *Cargo.toml*, like this:

```
[workspace]
resolver = "3"
members = ["adder"]
```

At this point, we can build the workspace by running `cargo build`. The files in your *add* directory should look like this:

```
├── Cargo.lock
├── Cargo.toml
├── adder
│   ├── Cargo.toml
│   └── src
│       └── main.rs
└── target
```

The workspace has one *target* directory at the top level that the compiled artifacts will be placed into; the `adder` package doesn't have its own *target* directory. Even if we were to run `cargo build` from inside the *adder* directory, the compiled artifacts would still end up in *add/target* rather than *add/adder/target*. Cargo structures the *target* directory in a workspace like this because the crates in a workspace are meant to depend on each other. If each crate had its own *target* directory, each crate would have to recompile each of the other crates in the workspace to place the artifacts in its own *target* directory. By sharing one *target* directory, the crates can avoid unnecessary rebuilding.

Creating the Second Package in the Workspace

Next, let's create another member package in the workspace and call it `add_one`. Generate a new library crate named `add_one`:

```
$ cargo new add_one --lib
     Created library `add_one` package
```

```
             Adding `add_one` as member of workspace at
`file:///projects/add`
```

The top-level *Cargo.toml* will now include the *add_one* path in the `members` list:

Filename: Cargo.toml

```
[workspace]
resolver = "3"
members = ["adder", "add_one"]
```

Your *add* directory should now have these directories and files:

```
├── Cargo.lock
├── Cargo.toml
├── add_one
│   ├── Cargo.toml
│   └── src
│       └── lib.rs
├── adder
│   ├── Cargo.toml
│   └── src
│       └── main.rs
└── target
```

In the *add_one/src/lib.rs* file, let's add an `add_one` function:

Filename: add_one/src/lib.rs

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

Now we can have the `adder` package with our binary depend on the `add_one` package that has our library. First, we'll need to add a path dependency on `add_one` to *adder/Cargo.toml*.

Filename: adder/Cargo.toml

```
[dependencies]
add_one = { path = "../add_one" }
```

Cargo doesn't assume that crates in a workspace will depend on each other, so we need to be explicit about the dependency relationships.

Next, let's use the `add_one` function (from the `add_one` crate) in the `adder` crate. Open the *adder/src/main.rs* file and change the `main` function to call the `add_one` function, as in Listing 14-7.

```
fn main() {
    let num = 10;
    println!("Hello, world! {num} plus one is {}!", add_one::add_one(num));
}
```

Let's build the workspace by running `cargo build` in the top-level *add* directory!

```
$ cargo build
   Compiling add_one v0.1.0 (file:///projects/add/add_one)
   Compiling adder v0.1.0 (file:///projects/add/adder)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.22s
```

To run the binary crate from the *add* directory, we can specify which package in the workspace we want to run by using the `-p` argument and the package name with `cargo run`:

```
$ cargo run -p adder
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.00s
     Running `target/debug/adder`
Hello, world! 10 plus one is 11!
```

This runs the code in *adder/src/main.rs*, which depends on the `add_one` crate.

Depending on an External Package in a Workspace

Notice that the workspace has only one *Cargo.lock* file at the top level, rather than having a *Cargo.lock* in each crate's directory. This ensures that all crates are using the same version of all dependencies. If we add the `rand` package to the *adder/Cargo.toml* and *add_one/Cargo.toml* files, 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 will always be compatible with each other. Let's add the `rand` crate to the `[dependencies]` section in the *add_one/Cargo.toml* file so we can use the `rand` crate in the `add_one` crate:

Filename: add_one/Cargo.toml

```
[dependencies]
rand = "0.8.5"
```

We can now add `use rand;` to the *add_one/src/lib.rs* file, and building the whole workspace by running `cargo build` in the *add* directory will bring in and compile the `rand` crate. We will get one warning because we aren't referring to the `rand` we brought into scope:

```
$ cargo build
    Updating crates.io index
  Downloaded rand v0.8.5
   --snip--
   Compiling rand v0.8.5
   Compiling add_one v0.1.0 (file:///projects/add/add_one)
warning: unused import: `rand`
 --> add_one/src/lib.rs:1:5
  |
1 | use rand;
  |     ^^^^
  |
  = note: `#[warn(unused_imports)]` on by default

warning: `add_one` (lib) generated 1 warning (run `cargo fix -
-lib -p add_one` to apply 1 suggestion)
   Compiling adder v0.1.0 (file:///projects/add/adder)
```

```
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.95s
```

The top-level *Cargo.lock* now contains information about the dependency of `add_one` 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* files as well. For example, if we add `use rand;` to the *adder/src/main.rs* file for the `adder` package, we'll get an error:

```
$ cargo build
  --snip--
   Compiling adder v0.1.0 (file:///projects/add/adder)
error[E0432]: unresolved import `rand`
 --> adder/src/main.rs:2:5
  |
2 | use rand;
  |     ^^^^ no external crate `rand`
```

To fix this, edit the *Cargo.toml* file for the `adder` package and indicate that `rand` is a dependency for it as well. Building the `adder` package will add `rand` to the list of dependencies for `adder` in *Cargo.lock*, but no additional copies of `rand` will be downloaded. Cargo will ensure that every crate in every package in the workspace using the `rand` package will use the same version as long as they specify compatible versions of `rand`, saving us space and ensuring that the crates in the workspace will be compatible with each other.

If crates in the workspace specify incompatible versions of the same dependency, Cargo will resolve each of them, but will still try to resolve as few versions as possible.

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 *add* directory. Running `cargo test` in a workspace structured like this one will run the tests for all the crates in the workspace:

```
$ cargo test
   Compiling add_one v0.1.0 (file:///projects/add/add_one)
   Compiling adder v0.1.0 (file:///projects/add/adder)
        Finished `test` profile [unoptimized + debuginfo]
target(s) in 0.20s
     Running unittests src/lib.rs (target/debug/deps/add_one-
93c49ee75dc46543)

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

      Running unittests src/main.rs (target/debug/deps/adder-
3a47283c568d2b6a)

running 0 tests
```

```
test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests add_one

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

The first section of the output shows that the `it_works` test in the `add_one` crate passed. The next section shows that zero tests were found in the `adder` crate, and then the last section shows zero documentation tests were found in the `add_one` crate.

We can also 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 `test` profile [unoptimized + debuginfo]
target(s) in 0.00s
      Running unittests src/lib.rs (target/debug/deps/add_one-
93c49ee75dc46543)

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s

   Doc-tests add_one

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out; finished in 0.00s
```

This output shows `cargo test` only ran the tests for the `add_one` crate and didn't run the `adder` crate tests.

If you publish the crates in the workspace to crates.io, each crate in the workspace will need to be published separately. Like `cargo test`, we can publish a particular crate in our workspace by using the `-p` flag and specifying the name of the crate we want to publish.

For additional practice, add an `add_two` crate to this workspace in a similar way as the `add_one` crate!

As your project grows, consider using a workspace: it enables you to work with smaller, easier-to-understand components than one big blob of code. Furthermore, keeping the crates in a workspace can make coordination between crates easier if they are often changed at the same time.

Installing Binaries 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. Note that you can only install packages that have binary targets. A *binary target* is the runnable program that is created if the crate has a *src/main.rs* file 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 installed with `cargo install` are stored in the installation root's *bin* folder. If you installed Rust using *rustup.rs* and don't have any custom configurations, this directory will be *$HOME/.cargo/bin*. Ensure that directory is in your `$PATH` to be able to run programs you've installed with `cargo install`.

For example, in Chapter 12 we mentioned that there's a Rust implementation of the `grep` tool called `ripgrep` for searching files. To install `ripgrep`, we can run the following:

```
$ cargo install ripgrep
    Updating crates.io index
  Downloaded ripgrep v14.1.1
  Downloaded 1 crate (213.6 KB) in 0.40s
  Installing ripgrep v14.1.1
--snip--
   Compiling grep v0.3.2
    Finished `release` profile [optimized + debuginfo] target(s) in 6.73s
  Installing ~/.cargo/bin/rg
   Installed package `ripgrep v14.1.1` (executable `rg`)
```

The second-to-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 previously, 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 it. 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 use `cargo install` to 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 that of the language. 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 you learned about in Chapter 4. References are indicated by the `&` symbol and borrow the value they point to. They don't have any special capabilities other than referring to data, and they have no overhead.

Smart pointers, on the other hand, are data structures that act like a pointer but also have additional metadata and capabilities. The concept of smart pointers isn't unique to Rust: smart pointers originated in C++ and exist in other languages as well. Rust has a variety of smart pointers defined in the standard library that provide functionality beyond that provided by references. To explore the general concept, we'll look at a couple of different examples of smart pointers, including a *reference counting* smart pointer type. This pointer enables you to allow data to have multiple owners by keeping track of the number of owners and, when no owners remain, cleaning up the data.

Rust, with its concept of ownership and borrowing, has an additional difference between references and smart pointers: while references only borrow data, in many cases smart pointers *own* the data they point to.

Smart pointers are usually implemented using structs. Unlike an ordinary struct, 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 you can write your code to work with either references or smart pointers. The `Drop` trait allows you to customize the code that's run when an instance of the smart pointer goes out of scope. In this chapter, we'll discuss both of these traits and demonstrate 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 existing smart pointer. Many libraries have their own smart pointers, and you can even write your own. We'll cover the most common smart pointers in the standard library:

- `Box<T>`, for allocating values on the heap
- `Rc<T>`, a reference counting 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

In addition, 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!

Using `Box<T>` to Point to Data on the Heap

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 to Chapter 4 to review the difference between the stack and the heap.

Boxes don't have performance overhead, other than storing their data on the heap instead of on the stack. But they don't have many extra capabilities either. You'll use them most often 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 requires 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 you care only that it's a type that implements a particular trait rather than being of a specific type

We'll demonstrate the first situation in "Enabling Recursive Types with Boxes". In the second case, transferring ownership of a large amount of data can take a long time because the data is 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, while the data it references stays in one place on the heap. The third case is known as a *trait object*, and "Using Trait Objects That Allow for Values of Different Types," in Chapter 18 is devoted to that topic. So what you learn here you'll apply again in that section!

Using `Box<T>` to Store Data on the Heap

Before we discuss the heap storage use case for `Box<T>`, we'll cover 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` value on the heap.

```
fn main() {
    let b = Box::new(5);
```

```
    println!("b = {b}");
}
```

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 similarly to how we would if this data were on the stack. Just like any owned value, when a box goes out of scope, as `b` does at the end of `main`, it will be deallocated. The deallocation happens both for 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 this way very often. Having values like a single `i32` on the stack, where they're stored by default, is more appropriate in the majority of situations. Let's look at a case where boxes allow us to define types that we wouldn't be allowed to define if we didn't have boxes.

Enabling Recursive Types with Boxes

A value of a *recursive type* can have another value of the same type as part of itself. Recursive types pose an issue because Rust needs to know at compile time how much space a type takes up. However, the nesting of values of recursive types could theoretically continue infinitely, so Rust can't know how much space the value needs. Because boxes have a known size, we can enable recursive types by inserting a box in the recursive type definition.

As an example of a recursive type, let's explore the *cons list*. This is a data type commonly found in functional programming languages. The cons list type we'll define is straightforward except for the recursion; therefore, the concepts in the example we'll work with will be useful any time you get into more complex situations involving recursive types.

More Information About the Cons List

A *cons list* is a data structure that comes from the Lisp programming language and its dialects, is made up of nested pairs, and is the Lisp version of a linked list. Its name comes from the `cons` function (short for *construct* *function*) in Lisp that constructs a new pair from its two arguments. By calling `cons` on a pair consisting of a value and another pair, we can construct cons lists made up of recursive pairs.

For example, here's a pseudocode representation of a cons list containing the list `1, 2, 3` with each pair in parentheses:

```
(1, (2, (3, Nil)))
```

Each item in a cons list contains two elements: 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. A cons list is produced by recursively calling the `cons` function. The canonical name to denote the base case of the recursion is `Nil`. Note that this is not the same as the "null" or "nil" concept discussed in Chapter 6, which is an invalid or absent value.

The cons list 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 to use. Other, more complex recursive data types *are* useful in various situations, but by starting with the cons list in this chapter, 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 code won't compile yet because the `List` type doesn't have a known size, which we'll demonstrate.

```
enum List {
    Cons(i32, List),
    Nil,
}
#
# fn main() {}
```

> Note: We're implementing a cons list that holds only `i32` values for the purposes of this example. We could have implemented it using generics, as we discussed in Chapter 10, to define a cons list type that could store values of any type.

Using the `List` type to store the list `1, 2, 3` would look like the code in Listing 15-3.

```
# enum List {
#     Cons(i32, List),
#     Nil,
# }
#
// --snip--

use crate::List::{Cons, Nil};

fn main() {
    let list = Cons(1, Cons(2, Cons(3, Nil)));
}
```

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 `List` value 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 code in Listing 15-3, we get the error shown in Listing 15-4.

```
$ cargo run
   Compiling cons-list v0.1.0 (file:///projects/cons-list)
error[E0072]: recursive type `List` has infinite size
 --> src/main.rs:1:1
  |
1 | enum List {
  | ^^^^^^^^^
2 |     Cons(i32, List),
  |               ---- recursive without indirection
  |
help: insert some indirection (e.g., a `Box`, `Rc`, or `&`) to
```

```
break the cycle
  |
2 |     Cons(i32, Box<List>),
  |               ++++    +

error[E0391]: cycle detected when computing when `List` needs
drop
 --> src/main.rs:1:1
  |
1 | enum List {
  | ^^^^^^^^^
  |
  = note: ...which immediately requires computing when `List`
needs drop again
  = note: cycle used when computing whether `List` needs drop
  = note: see https://rustc-dev-guide.rust-
lang.org/overview.html#queries and https://rustc-dev-
guide.rust-lang.org/query.html for more information

Some errors have detailed explanations: E0072, E0391.
For more information about an error, try `rustc --explain
E0072`.
error: could not compile `cons-list` (bin "cons-list") due to
2 previous errors
```

The error shows this type "has infinite size." The reason is that we've defined `List` with a variant that is recursive: it holds another value of itself directly. As a result, Rust can't figure out how much space it needs to store a `List` value. Let's break down why we get this error. First we'll 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),
}
#
# fn main() {}
```

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. Because only one variant will be used, the most space a `Message` value will need is the space it would take to store the largest of its variants.

Contrast this with 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 process continues infinitely, as shown in Figure 15-1.

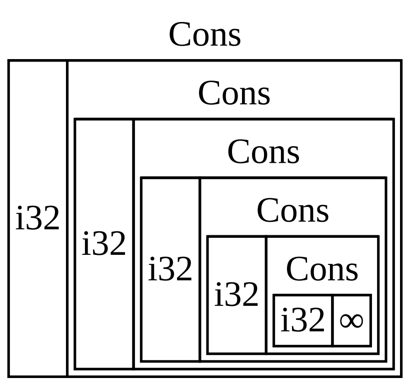


Figure 15-1: An infinite `List` consisting of infinite `Cons` variants

Using Box<T> to Get a Recursive Type with a Known Size

Because Rust can't figure out how much space to allocate for recursively defined types, the compiler gives an error with this helpful suggestion:

```
help: insert some indirection (e.g., a `Box`, `Rc`, or `&`) to
break the cycle
  |
2 |     Cons(i32, Box<List>),
  |               ++++    +
```

In this suggestion, *indirection* means that instead of storing a value directly, we should change the data structure 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. This means we can put a `Box<T>` inside the `Cons` variant instead of another `List` value directly. The `Box<T>` 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 with lists holding other lists, but this implementation is now more like placing the items next to one another rather than inside one another.

We can change the definition of the `List` enum in Listing 15-2 and the usage of the `List` in Listing 15-3 to the code in Listing 15-5, which will compile.

```
enum List {
    Cons(i32, Box<List>),
    Nil,
}

use crate::List::{Cons, Nil};

fn main() {
    let list = Cons(1, Box::new(Cons(2, Box::new(Cons(3,
```

```
Box::new(Nil))))));
}
```

The `Cons` variant needs 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 on the stack 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 can figure out the size it needs to store a `List` value. Figure 15-2 shows what the `Cons` variant looks like now.

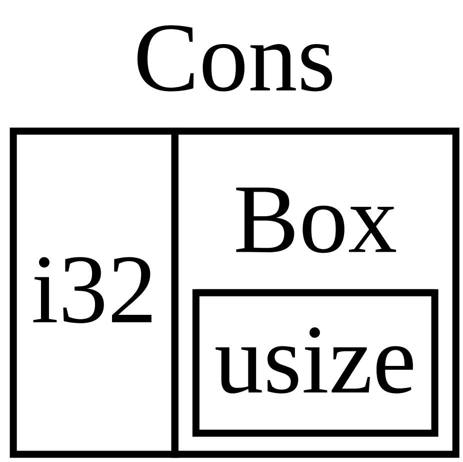


Figure 15-2: A `List` that is not infinitely sized because `Cons` holds a `Box`

Boxes provide only the indirection and heap allocation; they don't have any other special capabilities, like those we'll see with the other smart pointer types. They also don't have the performance overhead that these special capabilities 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 18.

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 `Drop` trait implementation. These two traits will be even more important to the functionality provided by the other smart pointer types we'll discuss in the rest of this chapter. Let's explore these two traits in more detail.

Treating Smart Pointers Like Regular References with `Deref`

Implementing the `Deref` trait allows you to customize the behavior of the *dereference operator* `*` (not to be confused with the multiplication or glob operator). By implementing `Deref` in such a way that a smart pointer can be treated like a regular reference, you can write code that operates on references and use that code with smart pointers too.

Let's first look at how the dereference operator works with regular references. Then we'll try to define a custom type that behaves like `Box<T>`, and see why the dereference operator doesn't work like a reference on our newly defined type. We'll explore how implementing the `Deref` trait makes it possible for smart pointers to work in ways similar to references. Then we'll look at Rust's *deref coercion* feature and how it lets us work with either references or smart pointers.

Following the Reference to the Value

A regular reference is a type of pointer, and one way to think of a pointer is as an arrow to a value stored somewhere else. In Listing 15-6, we create a reference to an `i32` value and then use the dereference operator to follow the reference to the value.

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

    assert_eq!(5, x);
    assert_eq!(5, *y);
}
```

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 it's pointing to (hence *dereference*) so the compiler can compare the actual value. Once we dereference `y`, we have access to the integer value `y` is pointing to that we can compare with `5`.

If we tried to write `assert_eq!(5, y);` instead, we would get this compilation error:

```
$ cargo run
     Compiling deref-example v0.1.0 (file:///projects/deref-example)
error[E0277]: can't compare `{integer}` with `&{integer}`
 --> src/main.rs:6:5
  |
6 |     assert_eq!(5, y);
  |     ^^^^^^^^^^^^^^^^ no implementation for `{integer} == &{integer}`
  |
  = help: the trait `PartialEq<&{integer}>` is not implemented for `{integer}`
  = note: this error originates in the macro `assert_eq` (in Nightly builds, run with -Z macro-backtrace for more info)

For more information about this error, try `rustc --explain E0277`.
error: could not compile `deref-example` (bin "deref-example") due to 1 previous error
```

Comparing a number and a reference to a number isn't allowed because they're different types. We must use the dereference operator to follow the reference to the value it's pointing to.

Using `Box<T>` Like a Reference

We can rewrite the code in Listing 15-6 to use a `Box<T>` instead of a reference; the dereference operator used on the `Box<T>` in Listing 15-7 functions in the same way as the dereference operator used on the reference in Listing 15-6.

```
fn main() {
    let x = 5;
    let y = Box::new(x);

    assert_eq!(5, x);
    assert_eq!(5, *y);
}
```

The main difference between Listing 15-7 and Listing 15-6 is that here we set `y` to be an instance of a box pointing to a copied value of `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. Next, we'll explore what is special about `Box<T>` that enables us to use the dereference operator by defining our own box type.

Defining Our Own Smart Pointer

Let's build a wrapper type similar to the `Box<T>` type provided by the standard library to experience how smart pointer types behave differently from references by default. Then we'll look at how to add the ability to use the dereference operator.

> Note: There's one big difference between the `MyBox<T>` type we're about to build and the real `Box<T>`: our version will not store its data on the heap. We are focusing this example on `Deref`, so where the data is actually stored is less important than the pointer-like behavior.

The `Box<T>` type is ultimately defined as a tuple struct with one element, so Listing 15-8 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>`.

```
struct MyBox<T>(T);

impl<T> MyBox<T> {
    fn new(x: T) -> MyBox<T> {
```

```
        MyBox(x)
    }
}
#
# fn main() {}
```

We define a struct named `MyBox` and declare a generic parameter `T` because we want our type to hold values of any type. The `MyBox` type 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 `main` function in Listing 15-7 to Listing 15-8 and changing it to use the `MyBox<T>` type we've defined instead of `Box<T>`. The code in Listing 15-9 won't compile because Rust doesn't know how to dereference `MyBox`.

```
# struct MyBox<T>(T);
#
# impl<T> MyBox<T> {
#     fn new(x: T) -> MyBox<T> {
#         MyBox(x)
#     }
# }
#
fn main() {
    let x = 5;
    let y = MyBox::new(x);

    assert_eq!(5, x);
    assert_eq!(5, *y);
}
```

Here's the resultant compilation error:

```
$ cargo run
     Compiling deref-example v0.1.0 (file:///projects/deref-example)
error[E0614]: type `MyBox<{integer}>` cannot be dereferenced
  --> src/main.rs:14:19
   |
14 |     assert_eq!(5, *y);
   |                   ^^

For more information about this error, try `rustc --explain E0614`.
error: could not compile `deref-example` (bin "deref-example") due to 1 previous error
```

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 implement the `Deref` trait.

Implementing the `Deref` Trait

As discussed in "Implementing a Trait on a Type" in Chapter 10, to implement a trait we need to provide implementations for the trait's required methods. The `Deref` trait, provided by the standard library, requires us to implement one method named `deref` that borrows `self` and returns a reference to the inner data. Listing 15-10 contains an implementation of `Deref` to add to the definition of `MyBox<T>`.

```
use std::ops::Deref;

impl<T> Deref for MyBox<T> {
    type Target = T;

    fn deref(&self) -> &Self::Target {
        &self.0
    }
}
#
```

```
# struct MyBox<T>(T);
#
# impl<T> MyBox<T> {
#     fn new(x: T) -> MyBox<T> {
#         MyBox(x)
#     }
# }
#
# fn main() {
#     let x = 5;
#     let y = MyBox::new(x);
#
#     assert_eq!(5, x);
#     assert_eq!(5, *y);
# }
```

The `type Target = T;` syntax defines an associated type for the `Deref` trait to use. Associated types are a slightly different way of declaring a generic parameter, but you don't need to worry about them for now; we'll cover them in more detail in Chapter 20.

We fill in the body of the `deref` method with `&self.0` so `deref` returns a reference to the value we want to access with the `*` operator; recall from [“Using Tuple Structs Without Named Fields to Create Different Types”]() in Chapter 5 that `.0` accesses the first value in a tuple struct. The `main` function in Listing 15-9 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` method gives the compiler the ability to take a value of any type that implements `Deref` and call the `deref` method to get an `&` reference that it knows how to dereference.

When we entered `*y` in Listing 15-9, behind the scenes Rust actually ran this code:

```
*(y.deref())
```

Rust substitutes the `*` operator with a call to the `deref` method and then a plain dereference so we don't have to think about whether or not we need to call the `deref` method. This Rust feature 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 that the plain dereference outside the parentheses in `*(y.deref())` is still necessary, has to do with the ownership system. 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 or in most cases where we use the dereference operator.

Note that the `*` operator is replaced with a call to the `deref` method and then a call to the `*` operator just once, each time we use a `*` in our code. Because the substitution of the `*` operator does not recurse infinitely, we end up with data of type `i32`, which matches the `5` in `assert_eq!` in Listing 15-9.

Implicit Deref Coercions with Functions and Methods

Deref coercion converts a reference to a type that implements the `Deref` trait into a reference to another type. For example, deref coercion can convert `&String` to `&str` because `String` implements the `Deref` trait such that it returns `&str`. Deref coercion is a convenience Rust performs on arguments to functions and methods, and works only on types that implement the `Deref` trait. It happens automatically when we pass a reference to a particular type's value as an argument to a function or method that doesn't match the parameter type in the function or method definition. A sequence of calls to the `deref` method converts the type we provided into the type 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 `*`. The deref coercion feature also lets us write more code that can work for either references or smart pointers.

To see deref coercion in action, let's use the `MyBox<T>` type we defined in Listing 15-8 as well as the implementation of `Deref` that we added in Listing 15-10. Listing 15-11 shows the definition of a function that has a string slice parameter.

```
fn hello(name: &str) {
    println!("Hello, {name}!");
}
#
# fn main() {}
```

We can call the `hello` function with a string slice as an argument, such as `hello("Rust");`, for example. Deref coercion makes it possible to call `hello` with a reference to a value of type `MyBox<String>`, as shown in Listing 15-12.

```
# use std::ops::Deref;
#
# impl<T> Deref for MyBox<T> {
#     type Target = T;
#
#     fn deref(&self) -> &T {
#         &self.0
#     }
# }
#
# struct MyBox<T>(T);
#
# impl<T> MyBox<T> {
#     fn new(x: T) -> MyBox<T> {
#         MyBox(x)
#     }
```

```
# }
#
# fn hello(name: &str) {
#     println!("Hello, {name}!");
# }
#
fn main() {
    let m = MyBox::new(String::from("Rust"));
    hello(&m);
}
```

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 15-10, 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, and this is 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, we would have to write the code in Listing 15-13 instead of the code in Listing 15-12 to call `hello` with a value of type `&MyBox<String>`.

```
# use std::ops::Deref;
#
# impl<T> Deref for MyBox<T> {
#     type Target = T;
#
#     fn deref(&self) -> &T {
#         &self.0
#     }
# }
#
# struct MyBox<T>(T);
#
```

```
# impl<T> MyBox<T> {
#     fn new(x: T) -> MyBox<T> {
#         MyBox(x)
#     }
# }
#
# fn hello(name: &str) {
#     println!("Hello, {name}!");
# }
#
fn main() {
    let m = MyBox::new(String::from("Rust"));
    hello(&(*m)[..]);
}
```

The `(*m)` dereferences the `MyBox<String>` into a `String`. Then the `&` and `[..]` take a string slice of the `String` that is equal to the whole string to match the signature of `hello`. This code without deref coercions is harder to read, write, and understand with all of these symbols involved. Deref coercion allows Rust to handle 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 necessary to get a reference to match the parameter's type. The number of times that `Deref::deref` needs to be inserted is resolved at compile time, so there is no runtime penalty for taking advantage of deref coercion!

How Deref Coercion Interacts with Mutability

Similar to how you use the `Deref` trait to override the `*` operator on immutable references, you can use the `DerefMut` trait to override the `*` operator on mutable references.

Rust does deref coercion when it finds types and trait implementations in three cases:

1. From `&T` to `&U` when `T: Deref<Target=U>`
2. From `&mut T` to `&mut U` when `T: DerefMut<Target=U>`
3. From `&mut T` to `&U` when `T: Deref<Target=U>`

The first two cases are the same except that the second implements mutability. The first case states 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 third case is trickier: Rust will also coerce a mutable reference to an immutable one. But the reverse is *not* possible: immutable references will never coerce to mutable references. 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 the initial immutable reference is the only immutable reference to that data, but 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.

Running Code on Cleanup with the `Drop` Trait

The second trait important to the smart pointer pattern is `Drop`, which lets you customize what happens when a value is about to go out of scope. You can provide an implementation for the `Drop` trait on any type, and that code 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, when a `Box<T>` is dropped it will deallocate the space on the heap that the box points to.

In some languages, for some types, the programmer must call code to free memory or resources every time they finish using an instance of those types. Examples include file handles, sockets, and locks. If they forget, the system might become overloaded and crash. In Rust, you can specify that a particular bit of code be run whenever a value goes out of scope, and the compiler will insert this code automatically. As a result, you don't need to be careful about placing cleanup code everywhere in a program that an instance of a particular type is finished with—you still won't leak resources!

You specify the code to run when a value goes out of scope by implementing the `Drop` trait. The `Drop` trait requires you to implement one method named `drop` that takes a mutable reference to `self`. To see when Rust calls `drop`, let's implement `drop` with `println!` statements for now.

Listing 15-14 shows a `CustomSmartPointer` struct whose only custom functionality is that it will print `Dropping CustomSmartPointer!` when the instance goes out of scope, to show when Rust runs the `drop` method.

```
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.");
}
```

The `Drop` trait is included in the prelude, so we don't need to bring it into scope. We implement the `Drop` trait on `CustomSmartPointer` and provide an implementation for the `drop` method that calls `println!`. The body of the `drop` method is where you would place any logic that you wanted to run when an instance of your type goes out of scope. We're printing some text here to demonstrate visually when Rust will call `drop`.

In `main`, we create two instances of `CustomSmartPointer` and then print `CustomSmartPointers created`. At the end of `main`, our instances 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:

```
$ cargo run
      Compiling  drop-example  v0.1.0  (file:///projects/drop-example)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.60s
     Running `target/debug/drop-example`
CustomSmartPointers created.
```

```
Dropping CustomSmartPointer with data `other stuff`!
Dropping CustomSmartPointer with data `my stuff`!
```

Rust automatically called `drop` for us when our instances went out of scope, calling the code we specified. Variables are dropped in the reverse order of their creation, so `d` was dropped before `c`. This example's purpose is to give you a visual guide to how the `drop` method works; usually you would specify the cleanup code that your type needs to run rather than a print message.

Unfortunately, it's not straightforward to disable the automatic `drop` functionality. Disabling `drop` isn't usually necessary; the whole point of the `Drop` trait is that it's taken care of automatically. Occasionally, however, you might want to clean up a value early. One example is when using smart pointers that manage locks: you might want to force the `drop` method that releases the lock so that other code in the same scope can acquire the lock. Rust doesn't let you call the `Drop` trait's `drop` method manually; instead, you have to call the `std::mem::drop` function provided by the standard library if you want to force a value to be dropped before the end of its scope.

If we try to call the `Drop` trait's `drop` method manually by modifying the `main` function from Listing 15-14, as shown in Listing 15-15, we'll get a compiler error.

```
# 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("some data"),
    };
    println!("CustomSmartPointer created.");
    c.drop();
    println!("CustomSmartPointer dropped before the end of main.");
}
```

When we try to compile this code, we'll get this error:

```
$ cargo run
   Compiling drop-example v0.1.0 (file:///projects/drop-example)
error[E0040]: explicit use of destructor method
  --> src/main.rs:16:7
   |
16 |     c.drop();
   |       ^^^^ explicit destructor calls not allowed
   |
help: consider using `drop` function
   |
16 |     drop(c);
   |     +++++ ~

For more information about this error, try `rustc --explain E0040`.
error: could not compile `drop-example` (bin "drop-example") due to 1 previous error
```

This error message states that 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*, which 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`. This would cause a *double free* error because Rust would be trying to clean up the same value twice.

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. So, if we need to force a value to be cleaned up early, we use the `std::mem::drop` function.

The `std::mem::drop` function is different from the `drop` method in the `Drop` trait. We call it by passing as an argument the value we want to force-drop. The function is in the prelude, so we can modify `main` in Listing 15-15 to call the `drop` function, as shown in Listing 15-16.

```
# 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("some data"),
    };
    println!("CustomSmartPointer created.");
    drop(c);
    println!("CustomSmartPointer dropped before the end of main.");
}
```

Running this code will print the following:

```
$ cargo run
   Compiling drop-example v0.1.0 (file:///projects/drop-example)
```

```
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.73s
     Running `target/debug/drop-example`
CustomSmartPointer created.
Dropping CustomSmartPointer with data `some data`!
CustomSmartPointer dropped before the end of main.
```

The text `Dropping CustomSmartPointer with data `some data`!` is printed between the `CustomSmartPointer created.` and `CustomSmartPointer dropped before the end of main.` text, showing that the `drop` method code is called to drop `c` at that point.

You can use code specified in a `Drop` trait implementation in many ways to make cleanup convenient and safe: for instance, you could use it to create your own memory allocator! With the `Drop` trait and Rust’s ownership system, you don’t have to remember to clean up because Rust does it automatically.

You also don’t have to worry about problems resulting from accidentally cleaning up values still in use: the ownership system that makes sure references are always valid also ensures that `drop` gets called only once when the value is no longer being used.

Now that we’ve examined `Box<T>` and some of the characteristics of smart pointers, let’s look at 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 might have multiple owners. For example, in graph data structures, multiple edges might 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 and so has no owners.

You have to enable multiple ownership explicitly by using the Rust type `Rc<T>`, which is an abbreviation for *reference counting*. The `Rc<T>` type keeps track of the number of references to a value to determine whether or not the value is still in use. If there are zero references to a value, the value can be cleaned up without any references becoming invalid.

Imagine `Rc<T>` as 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 off the TV because it's no longer being used. If someone turns off the TV while others are still watching it, there would be an uproar from the remaining TV watchers!

We use the `Rc<T>` type 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 knew which part would finish last, we could just make that part the data's owner, and the normal ownership rules enforced at compile time would take effect.

Note that `Rc<T>` is only for use in single-threaded scenarios. When we discuss concurrency in Chapter 16, we'll cover how to do reference counting in multithreaded programs.

Using `Rc<T>` to Share Data

Let's return to our cons list example in Listing 15-5. Recall that we defined it using `Box<T>`. This time, we'll create two lists that both share ownership of a third list. Conceptually, this looks similar to Figure 15-3.

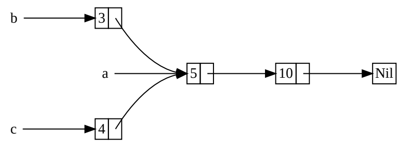


Figure 15-3: Two lists, `b` and `c`, sharing ownership of a third list, `a`

We'll create list `a` that contains `5` and then `10`. Then we'll 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 share the first list containing `5` and `10`.

Trying to implement this scenario using our definition of `List` with `Box<T>` won't work, as shown in Listing 15-17.

```
enum List {
    Cons(i32, Box<List>),
    Nil,
}

use crate::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));
}
```

When we compile this code, we get this error:

```
$ cargo run
   Compiling cons-list v0.1.0 (file:///projects/cons-list)
error[E0382]: use of moved value: `a`
  --> src/main.rs:11:30
   |
9  |     let a = Cons(5, Box::new(Cons(10, Box::new(Nil))));
   |         - move occurs because `a` has type `List`, which
```

```
does not implement the `Copy` trait
10 |     let b = Cons(3, Box::new(a));
   |                              - value moved here
11 |     let c = Cons(4, Box::new(a));
   |                              ^ value used here after move

For more information about this error, try `rustc --explain
E0382`.
error: could not compile `cons-list` (bin "cons-list") due to
1 previous error
```

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 would have to specify lifetime parameters. By specifying lifetime parameters, we would be specifying that every element in the list will live at least as long as the entire list. This is the case for the elements and lists in Listing 15-17, but not in every scenario.

Instead, we'll change our definition of `List` to use `Rc<T>` in place of `Box<T>`, as shown in Listing 15-18. Each `Cons` variant will now hold a value and an `Rc<T>` pointing to a `List`. When we create `b`, instead of taking ownership of `a`, we'll clone the `Rc<List>` that `a` is holding, thereby increasing the number of references from one to two and letting `a` and `b` share ownership of the data in that `Rc<List>`. We'll also clone `a` when creating `c`, increasing the number of references from two to three. Every time we call `Rc::clone`, the reference count to the data within the `Rc<List>` will increase, and the data won't be cleaned up unless there are zero references to it.

```
enum List {
    Cons(i32, Rc<List>),
    Nil,
}
```

```
use crate::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));
}
```

We need to add a `use` statement to bring `Rc<T>` 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<List>` in `a`. Then, when we create `b` and `c`, we call the `Rc::clone` function and pass a reference to the `Rc<List>` in `a` as an argument.

We could have called `a.clone()` rather than `Rc::clone(&a)`, but Rust's 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. The call to `Rc::clone` only increments the reference count, which doesn't take much time. Deep copies of data can take a lot of time. By using `Rc::clone` for reference counting, we can visually distinguish between the deep-copy kinds of clones and the kinds of clones that increase the reference count. When looking for performance problems in the code, we only need to consider the deep-copy clones and can disregard calls to `Rc::clone`.

Cloning an `Rc<T>` Increases the Reference Count

Let's change our working example in Listing 15-18 so we can see the reference counts changing as we create and drop references to the `Rc<List>` in `a`.

In Listing 15-19, we'll change `main` so it has an inner scope around list `c`; then we can see how the reference count changes when `c` goes out of scope.

```
# enum List {
#     Cons(i32, Rc<List>),
#     Nil,
# }
#
# use crate::List::{Cons, Nil};
# use std::rc::Rc;
#
// --snip--

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));
}
```

At each point in the program where the reference count changes, we print the reference count, which we get by calling the `Rc::strong_count` function. This function is named `strong_count` rather than `count` because the `Rc<T>` type also has a `weak_count`; we'll see what `weak_count` is used for in "Preventing Reference Cycles Using `Weak<T>`".

This code prints the following:

```
$ cargo run
   Compiling cons-list v0.1.0 (file:///projects/cons-list)
```

```
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.45s
     Running `target/debug/cons-list`
count after creating a = 1
count after creating b = 2
count after creating c = 3
count after c goes out of scope = 2
```

We can see that the `Rc<List>` in `a` has an initial reference count of 1; then each time we call `clone`, the count goes up by 1. When `c` goes out of scope, the count goes down by 1. 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<T>` value goes out of scope.

What we can't see in 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<List>` is cleaned up completely. Using `Rc<T>` allows a single value to have multiple owners, and the count ensures that the value remains valid as long as any of the owners still exist.

Via immutable references, `Rc<T>` allows you to share data between multiple parts of your program for reading only. If `Rc<T>` allowed you to have multiple mutable references too, you might violate one of the borrowing rules 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 you can use in conjunction with an `Rc<T>` to work with this immutability restriction.

`RefCell<T>` and the Interior Mutability Pattern

Interior mutability is a design pattern in Rust that allows you to mutate data even when there are immutable references to that data; normally, this action is disallowed by the borrowing rules. To mutate data, the pattern uses `unsafe` code inside a data structure to bend Rust's usual rules that govern mutation and borrowing. Unsafe code indicates to the compiler that we're checking the rules manually instead of relying on the compiler to check them for us; we will discuss unsafe code more in Chapter 20.

We can use types that use the interior mutability pattern only when we can ensure that the borrowing rules will be followed at runtime, even though the compiler can't guarantee that. The `unsafe` code involved is then wrapped in a safe API, and the outer type is still immutable.

Let's explore this concept 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 from a type like `Box<T>`? Recall the borrowing rules you learned in Chapter 4:

- At any given time, you can have *either* one mutable reference or any number of immutable references (but not both).
- 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, your program will panic and exit.

The advantages of 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 because all the analysis is completed beforehand. For those reasons, checking the borrowing rules at compile time is the best choice in the majority of cases, which is why this is Rust's default.

The advantage of checking the borrowing rules at runtime instead is that certain memory-safe scenarios are then allowed, where they would've been 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 beyond the scope of this book but is an interesting topic to research.

Because some analysis is impossible, if the Rust compiler can't be sure the code complies with the ownership rules, it might reject a correct program; in this way, it's conservative. If Rust accepted an incorrect program, users wouldn't be able to trust the guarantees Rust makes. However, if Rust rejects a correct program, the programmer will be inconvenienced, but nothing catastrophic can occur. The `RefCell<T>` type is useful when you're sure your code follows the borrowing rules but the compiler is unable to understand and guarantee that.

Similar to `Rc<T>`, `RefCell<T>` is only for use in single-threaded scenarios and will give you a compile-time error if you try using it in a multithreaded context. We'll talk about how to get the functionality of `RefCell<T>` in a multithreaded program in Chapter 16.

Here is a recap of 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>` allows only 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, you can mutate the value inside the `RefCell<T>` even when the

`RefCell<T>` is immutable.

Mutating the value inside an immutable value is the *interior mutability* pattern. Let’s look at a situation in which interior mutability is useful and examine how it’s possible.

Interior Mutability: A Mutable Borrow to an Immutable Value

A consequence of the borrowing rules is that when you have an immutable value, you can’t borrow it mutably. For example, this code won’t compile:

```
fn main() {
    let x = 5;
    let y = &mut x;
}
```

If you tried to compile this code, you’d get the following error:

```
$ cargo run
   Compiling borrowing v0.1.0 (file:///projects/borrowing)
error[E0596]: cannot borrow `x` as mutable, as it is not
declared as mutable
 --> src/main.rs:3:13
  |
3 |     let y = &mut x;
  |             ^^^^^^ cannot borrow as mutable
  |
help: consider changing this to be mutable
  |
2 |     let mut x = 5;
  |         +++

For more information about this error, try `rustc --explain
E0596`.
error: could not compile `borrowing` (bin "borrowing") due to
1 previous error
```

However, there are situations in which it would be useful for a value to mutate itself in its methods but appear immutable to other code. Code outside the value's methods would not be able to mutate the value. Using `RefCell<T>` is one way to get the ability to have interior mutability, but `RefCell<T>` doesn't get around the borrowing rules completely: the borrow checker in the compiler allows this interior mutability, and the borrowing rules are checked at runtime instead. If you violate the rules, you'll get a `panic!` instead of a compiler error.

Let's work through a practical example where we can use `RefCell<T>` to mutate an immutable value and see why that is useful.

A Use Case for Interior Mutability: Mock Objects

Sometimes during testing a programmer will use a type in place of another type, in order to observe particular behavior and assert that it's implemented correctly. This placeholder type is called a *test double*. Think of it in the sense of a stunt double in filmmaking, where a person steps in and substitutes for an actor to do a particularly tricky scene. Test doubles stand in for other types when we're running tests. *Mock objects* are specific types of test doubles that record what happens during a test so you can assert that the correct actions took place.

Rust doesn't have objects in the same sense as other languages have objects, and Rust doesn't have mock object functionality built into the standard library as some other languages do. However, you can definitely create a struct that will serve the same purposes as a mock object.

Here's the scenario we'll test: we'll create 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 library could be used to keep track of a user's quota for the number of API calls they're allowed to make, for example.

Our library will only 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 mechanism for sending the messages: the application could put a message in the application, send an email, send a text message, or do something else. The library doesn't need to know that detail. All it needs is something that implements a trait we'll provide called `Messenger`. Listing 15-20 shows the library code.

```
pub trait Messenger {
    fn send(&self, msg: &str);
}

pub struct LimitTracker<'a, T: Messenger> {
    messenger: &'a T,
    value: usize,
    max: usize,
}

impl<'a, T> LimitTracker<'a, T>
where
    T: Messenger,
{
    pub fn new(messenger: &'a T, max: usize) -> LimitTracker<'a, 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 >= 1.0 {
            self.messenger.send("Error: You are over your quota!");
        } else if percentage_of_max >= 0.9 {
```

```
            self.messenger
                .send("Urgent warning: You've used up over 90%
of your quota!");
        } else if percentage_of_max >= 0.75 {
            self.messenger
                   .send("Warning: You've used up over 75% of
your quota!");
        }
    }
}
```

One important part of this code is that the `Messenger` trait has one method called `send` that takes an immutable reference to `self` and the text of the message. This trait is the interface our mock object needs to implement so that the mock can be used in the same way a real object is. 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. We want to be able to say 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 is told to send the appropriate messages.

We need a mock object that, instead of 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`, and then check that the mock object has the messages we expect. Listing 15-21 shows an attempt to implement a mock object to do just that, but the borrow checker won't allow it.

```
# pub trait Messenger {
#     fn send(&self, msg: &str);
# }
#
```

```
# pub struct LimitTracker<'a, T: Messenger> {
#     messenger: &'a T,
#     value: usize,
#     max: usize,
# }
#
# impl<'a, T> LimitTracker<'a, T>
# where
#     T: Messenger,
# {
#           pub  fn  new(messenger:  &'a  T,  max:  usize)  ->
LimitTracker<'a, 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 >= 1.0 {
#                 self.messenger.send("Error: You are over your
quota!");
#         } else if percentage_of_max >= 0.9 {
#             self.messenger
#                    .send("Urgent warning: You've used up over
90% of your quota!");
#         } else if percentage_of_max >= 0.75 {
#             self.messenger
#                    .send("Warning: You've used up over 75% of
your quota!");
```

```
#         }
#     }
# }
#
#[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);
```

```
    }
}
```

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 define 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 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 is more than 75 percent 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 percent of 100. Then we assert that the list of messages that the `MockMessenger` is keeping track of should now have one message in it.

However, there's one problem with this test, as shown here:

```
$ cargo test
     Compiling limit-tracker v0.1.0 (file:///projects/limit-tracker)
error[E0596]: cannot borrow `self.sent_messages` as mutable, as it is behind a `&` reference
  --> src/lib.rs:58:13
   |
58 |             self.sent_messages.push(String::from(message));
   |             ^^^^^^^^^^^^^^^^^^ `self` is a `&` reference, so the data it refers to cannot be borrowed as mutable
   |
```

```
help: consider changing this to be a mutable reference in the
`impl` method and the `trait` definition
   |
2  ~     fn send(&mut self, msg: &str);
3  | }
...
56 |     impl Messenger for MockMessenger {
57 ~         fn send(&mut self, message: &str) {
   |

For more information about this error, try `rustc --explain
E0596`.
error: could not compile `limit-tracker` (lib test) due to 1
previous error
```

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` in both the `impl` method and the trait definition. We do not want to change the `Messenger` trait solely for the sake of testing. Instead, we need to find a way to make our test code work correctly with our existing design.

This is a situation in which interior mutability can help! We’ll store the `sent_messages` within a `RefCell<T>`, and then the `send` method will be able to modify `sent_messages` to store the messages we’ve seen. Listing 15-22 shows what that looks like.

```
# pub trait Messenger {
#     fn send(&self, msg: &str);
# }
#
# pub struct LimitTracker<'a, T: Messenger> {
#     messenger: &'a T,
#     value: usize,
#     max: usize,
# }
```

```
#
# impl<'a, T> LimitTracker<'a, T>
# where
#     T: Messenger,
# {
#           pub  fn  new(messenger:  &'a  T,  max:  usize)  ->
LimitTracker<'a, 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 >= 1.0 {
#                 self.messenger.send("Error: You are over your
quota!");
#         } else if percentage_of_max >= 0.9 {
#             self.messenger
#                  .send("Urgent warning: You've used up over
90% of your quota!");
#         } else if percentage_of_max >= 0.75 {
#             self.messenger
#                  .send("Warning: You've used up over 75% of
your quota!");
#         }
#     }
# }
#
#[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--
#         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.borrow().len(), 1);
    }
}
```

The `sent_messages` field is now of type `RefCell<Vec<String>>` instead of `Vec<String>`. In the `new` function, we create a new `RefCell<Vec<String>>` 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<Vec<String>>` in `self.sent_messages` to get a mutable reference to the value inside the `RefCell<Vec<String>>`, which is the vector. Then we can call `push` on the mutable reference to the vector to keep track of the messages sent during the test.

The last change we have to make is in the assertion: to see how many items are in the inner vector, we call `borrow` on the `RefCell<Vec<String>>` to get an immutable reference to the vector.

Now that you've seen how to use `RefCell<T>`, let's dig into how it works!

Keeping Track of Borrows at Runtime with `RefCell<T>`

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<T>`, and `borrow_mut` returns the smart pointer type `RefMut<T>`. Both types implement `Deref`, so we can treat them like regular references.

The `RefCell<T>` keeps track of how many `Ref<T>` and `RefMut<T>` 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<T>` value goes out of scope, the count of immutable borrows goes down by 1. 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 as we would with references, the implementation of `RefCell<T>` will panic at runtime. Listing 15-23 shows a modification of the implementation of `send` in Listing 15-22. We're deliberately trying to create two mutable borrows active for the same scope to illustrate that `RefCell<T>` prevents us from doing this at runtime.

```
# pub trait Messenger {
#     fn send(&self, msg: &str);
# }
#
# pub struct LimitTracker<'a, T: Messenger> {
#     messenger: &'a T,
#     value: usize,
#     max: usize,
# }
#
# impl<'a, T> LimitTracker<'a, T>
# where
#     T: Messenger,
# {
#          pub  fn  new(messenger:  &'a  T,  max:  usize)  ->
LimitTracker<'a, 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 >= 1.0 {
#                 self.messenger.send("Error: You are over your
quota!");
#         } else if percentage_of_max >= 0.9 {
#             self.messenger
#                  .send("Urgent warning: You've used up over
90% of your quota!");
#         } else if percentage_of_max >= 0.75 {
#             self.messenger
#                  .send("Warning: You've used up over 75% of
your quota!");
#         }
#     }
# }
#
# #[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) {
                                    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));
        }
    }
#
#     #[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.borrow().len(), 1);
#     }
# }
```

We create a variable `one_borrow` for the `RefMut<T>` 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. When we run the tests for our library, the code in Listing 15-23 will compile without any errors, but the test will fail:

```
$ cargo test
     Compiling  limit-tracker  v0.1.0  (file:///projects/limit-
tracker)
        Finished  `test`  profile  [unoptimized  +  debuginfo]
target(s) in 0.91s
                          Running     unittests     src/lib.rs
```

```
(target/debug/deps/limit_tracker-e599811fa246dbde)

running 1 test
test tests::it_sends_an_over_75_percent_warning_message ...
FAILED

failures:

---- tests::it_sends_an_over_75_percent_warning_message stdout
----

thread 'tests::it_sends_an_over_75_percent_warning_message'
panicked at src/lib.rs:60:53:
already borrowed: BorrowMutError
note: run with `RUST_BACKTRACE=1` environment variable to
display a backtrace


failures:
    tests::it_sends_an_over_75_percent_warning_message

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0
measured; 0 filtered out; finished in 0.00s

error: test failed, to rerun pass `--lib`
```

Notice that the code panicked with the message `already borrowed: BorrowMutError`. This is how `RefCell<T>` handles violations of the borrowing rules at runtime.

Choosing to catch borrowing errors at runtime rather than compile time, as we've done here, means you'd potentially be finding mistakes in your code later in the development process: possibly not until your code was deployed to production. Also, your code would incur a small runtime performance penalty as a result of keeping track of the borrows at runtime rather than compile time. However, using `RefCell<T>` makes it possible to write a mock object that can modify itself to keep track of the messages it has seen while you’re using it in a context where only immutable values are allowed. You can use `RefCell<T>` despite its trade-offs to get more functionality than regular references provide.

Allowing Multiple Owners of Mutable Data with `Rc<T>` and `RefCell<T>`

A common way to use `RefCell<T>` is in combination with `Rc<T>`. Recall that `Rc<T>` lets you have multiple owners of some data, but it only gives immutable access to that data. If you have an `Rc<T>` that holds a `RefCell<T>`, you can get a value that can have multiple owners *and* that you can mutate!

For example, recall the cons list example in Listing 15-18 where we used `Rc<T>` to allow multiple lists to share ownership of another list. Because `Rc<T>` holds only immutable values, we can’t change any of the values in the list once we’ve created them. Let’s add in `RefCell<T>` for its ability to change the values in the lists. Listing 15-24 shows that by using a `RefCell<T>` in the `Cons` definition, we can modify the value stored in all the lists.

```
#[derive(Debug)]
enum List {
    Cons(Rc<RefCell<i32>>, Rc<List>),
    Nil,
}

use crate::List::{Cons, Nil};
use std::cell::RefCell;
use std::rc::Rc;

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(3)), Rc::clone(&a));
    let c = Cons(Rc::new(RefCell::new(4)), Rc::clone(&a));

    *value.borrow_mut() += 10;

    println!("a after = {a:?}");
    println!("b after = {b:?}");
    println!("c after = {c:?}");
}
```

We create a value that is 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 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`, which is what we did in Listing 15-18.

After we've created the lists in `a`, `b`, and `c`, we want to 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 "Where's the `->` Operator?") in Chapter 5 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 `a`, `b`, and `c`, we can see that they all have the modified value of `15` rather than `5`:

```
$ cargo run
   Compiling cons-list v0.1.0 (file:///projects/cons-list)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.63s
     Running `target/debug/cons-list`
a after = Cons(RefCell { value: 15 }, Nil)
```

```
b after = Cons(RefCell { value: 3 }, Cons(RefCell { value: 15
}, Nil))
c after = Cons(RefCell { value: 4 }, Cons(RefCell { value: 15
}, Nil))
```

This technique is pretty neat! By using `RefCell<T>`, we have an outwardly immutable `List` value. 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. Note that `RefCell<T>` does not work for multithreaded code! `Mutex<T>` is the thread-safe version of `RefCell<T>`, and we’ll discuss `Mutex<T>` in Chapter 16.

Reference Cycles Can Leak Memory

Rust's memory safety guarantees make it difficult, but not impossible, to accidentally create memory that is never cleaned up (known as a *memory leak*). Preventing memory leaks entirely is not one of Rust's guarantees, meaning memory leaks are memory safe in Rust. We can see that Rust allows memory leaks by using `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 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 15-25.

```
use crate::List::{Cons, Nil};
use std::cell::RefCell;
use std::rc::Rc;

#[derive(Debug)]
enum List {
    Cons(i32, RefCell<Rc<List>>),
    Nil,
}

impl List {
    fn tail(&self) -> Option<&RefCell<Rc<List>>> {
        match self {
            Cons(_, item) => Some(item),
            Nil => None,
        }
    }
}
```

```
fn main() {}
```

We're using another variation of the `List` definition from Listing 15-5. The second element in the `Cons` variant is now `RefCell<Rc<List>>`, meaning that instead of having the ability to modify the `i32` value as we did in Listing 15-24, we want to modify the `List` value a `Cons` variant is pointing to. We're also adding a `tail` method to make it convenient for us to access the second item if we have a `Cons` variant.

In Listing 15-26, we're adding a `main` function that uses the definitions in Listing 15-25. This code creates a list in `a` and a list in `b` that points to the list in `a`. Then it modifies the list in `a` to point to `b`, creating a reference cycle. There are `println!` statements along the way to show what the reference counts are at various points in this process.

```
# use crate::List::{Cons, Nil};
# use std::cell::RefCell;
# use std::rc::Rc;
#
# #[derive(Debug)]
# enum List {
#     Cons(i32, RefCell<Rc<List>>),
#     Nil,
# }
#
# impl List {
#     fn tail(&self) -> Option<&RefCell<Rc<List>>> {
#         match self {
#             Cons(_, item) => Some(item),
#             Nil => None,
#         }
#     }
# }
```

```
#
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(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());
}
```

We create an `Rc<List>` instance holding a `List` value in the variable `a` with an initial list of `5, Nil`. We then create an `Rc<List>` instance holding another `List` value in the variable `b` that contains the value `10` and points to the list in `a`.

We modify `a` so it points to `b` instead of `Nil`, creating a cycle. We do that by using the `tail` method to get a reference to the

`RefCell<Rc<List>>` in `a`, which we put in the variable `link`. Then we use the `borrow_mut` method on the `RefCell<Rc<List>>` to change the value inside from an `Rc<List>` that holds a `Nil` value to the `Rc<List>` in `b`.

When we run this code, keeping the last `println!` commented out for the moment, we'll get this output:

```
$ cargo run
   Compiling cons-list v0.1.0 (file:///projects/cons-list)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.53s
     Running `target/debug/cons-list`
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
```

The reference count of the `Rc<List>` instances in both `a` and `b` is 2 after we change the list in `a` to point to `b`. At the end of `main`, Rust drops the variable `b`, which decreases the reference count of the `b` `Rc<List>` instance from 2 to 1. The memory that `Rc<List>` has on the heap won't be dropped at this point because its reference count is 1, not 0. Then Rust drops `a`, which decreases the reference count of the `a` `Rc<List>` instance from 2 to 1 as well. This instance's memory can't be dropped either, because the other `Rc<List>` instance still refers to it. The memory allocated to the list will remain uncollected forever. To visualize this reference cycle, we've created the diagram in Figure 15-4.

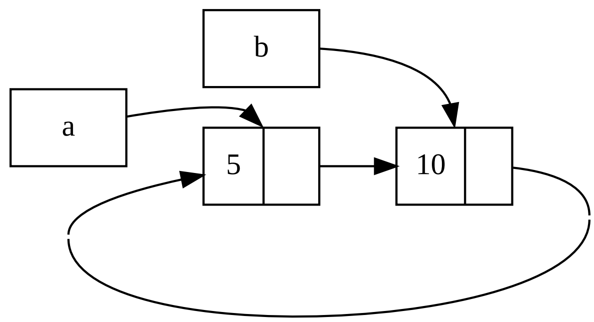


Figure 15-4: A reference cycle of lists `a` and `b` pointing to each other

If you uncomment the last `println!` and run the program, Rust will try to print this cycle with `a` pointing to `b` pointing to `a` and so forth until it overflows the stack.

Compared to a real-world program, the consequences of creating a reference cycle in this example aren't very dire: right after we create the reference cycle, the program ends. However, if a more complex program allocated lots of memory in a cycle and held onto it for a long time, the program would use more memory than it needed and might overwhelm the system, causing 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, you must ensure that you don't create cycles; 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 for avoiding reference cycles is reorganizing your data structures so that some references express ownership and some references don't. As a result, you can have cycles made up of some ownership relationships and some non-ownership relationships, and only the ownership relationships affect whether or not a value can be dropped. In Listing 15-25, 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 Using `Weak<T>`

So far, we've demonstrated that calling `Rc::clone` increases the `strong_count` of an `Rc<T>` instance, and an `Rc<T>` instance is only cleaned up if its `strong_count` is 0. You can also create a weak reference to the value within an `Rc<T>` instance by calling `Rc::downgrade` and passing a reference to the `Rc<T>`. *Strong references* are how you can share ownership of an `Rc<T>` instance. *Weak references* don't express an ownership relationship, and their count doesn't affect when an `Rc<T>` instance is cleaned up. They won't cause a reference cycle because any cycle involving some weak references will be broken once the strong reference count of values involved is 0.

When you call `Rc::downgrade`, you get a smart pointer of type `Weak<T>`. Instead of increasing the `strong_count` in the `Rc<T>` instance by 1, calling `Rc::downgrade` increases the `weak_count` by 1. The `Rc<T>` type uses `weak_count` to keep track of how many `Weak<T>` references exist, similar to `strong_count`. The difference is the `weak_count` doesn't need to be 0 for the `Rc<T>` instance to be cleaned up.

Because the value that `Weak<T>` references might have been dropped, to do anything with the value that a `Weak<T>` is pointing to you must make sure the value still exists. Do this by calling the `upgrade` method on a `Weak<T>` instance, which will return an `Option<Rc<T>>`. You'll get a result of `Some` if the `Rc<T>` value has not been dropped yet and a result of `None` if the `Rc<T>` value has been dropped. Because `upgrade` returns an `Option<Rc<T>>`, Rust will ensure that the `Some` case and the `None` case are handled, 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, we'll build a tree with nodes that know about their child nodes. 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::cell::RefCell;
use std::rc::Rc;

#[derive(Debug)]
struct Node {
    value: i32,
    children: RefCell<Vec<Rc<Node>>>,
}
#
# 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)]),
#     });
# }
```

We want a `Node` to own its children, and we want to share that ownership with variables so we can access each `Node` in the tree directly. To do this, we define the `Vec<T>` items to be values of type `Rc<Node>`. We also want to modify which nodes are children of another node, so we have a `RefCell<T>` in `children` around the `Vec<Rc<Node>>`.

Next, we'll 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 15-27.

```
# use std::cell::RefCell;
# use std::rc::Rc;
```

```
#
# #[derive(Debug)]
# struct Node {
#     value: i32,
#     children: RefCell<Vec<Rc<Node>>>,
# }
#
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)]),
    });
}
```

We clone the `Rc<Node>` 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`. The reason is that `leaf` has no reference to `branch` and doesn't know they're related. We want `leaf` to know that `branch` is its parent. We'll do that next.

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 0.

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<T>`, 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::cell::RefCell;
use std::rc::{Rc, Weak};

#[derive(Debug)]
struct Node {
    value: i32,
    parent: RefCell<Weak<Node>>,
    children: RefCell<Vec<Rc<Node>>>,
}
#
# 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());
# }
```

A node will be able to refer to its parent node but doesn’t own its parent. In Listing 15-28, we update `main` to use this new definition so the `leaf` node will have a way to refer to its parent, `branch`.

```
# use std::cell::RefCell;
# use std::rc::{Rc, Weak};
#
# #[derive(Debug)]
# struct Node {
#     value: i32,
#     parent: RefCell<Weak<Node>>,
#     children: RefCell<Vec<Rc<Node>>>,
# }
#
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());
}
```

Creating the `leaf` node looks similar to Listing 15-27 with the exception of the `parent` field: `leaf` starts out without a parent, so we create a new, empty `Weak<Node>` 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!` statement:

```
leaf parent = None
```

When we create the `branch` node, it will also have a new `Weak<Node>` reference in the `parent` field because `branch` doesn't 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<Node>` reference to its parent. We use the `borrow_mut` method on the `RefCell<Weak<Node>>` in the `parent` field of `leaf`, and then we use the `Rc::downgrade` function to create a `Weak<Node>` reference to `branch` from the `Rc<Node>` in `branch`.

When we print the parent of `leaf` again, this time we'll get a `Some` variant holding `branch`: now `leaf` can access its parent! When we print `leaf`, we also avoid the cycle that eventually ended in a stack overflow like we had in Listing 15-26; the `Weak<Node>` 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<Node>` instances change by creating a new inner scope and moving the creation of `branch` into that scope. By doing so, we can see what happens when `branch` is created and then dropped when it goes out of scope. The modifications are shown in Listing 15-29.

```
# use std::cell::RefCell;
# use std::rc::{Rc, Weak};
#
# #[derive(Debug)]
# struct Node {
#     value: i32,
#     parent: RefCell<Weak<Node>>,
#     children: RefCell<Vec<Rc<Node>>>,
# }
#
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),
    );
}
```

After `leaf` is created, its `Rc<Node>` 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 when we print the counts, the `Rc<Node>` in `branch` will have a strong count of 1 and a weak count of 1 (for `leaf.parent` pointing to `branch` with a `Weak<Node>`). When we print the counts in `leaf`, we'll see it will have a strong count of 2 because `branch` now has a clone of the `Rc<Node>` 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<Node>` decreases to 0, so its `Node` is dropped. The weak count of 1 from `leaf.parent` has no bearing on whether or not `Node` is dropped, 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<Node>` 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<Node>` again.

All of the logic that manages the counts and value dropping is built into `Rc<T>` and `Weak<T>` 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`, you'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 to use smart pointers to make different guarantees and trade-offs from those Rust makes by default with regular references. The `Box<T>` type has a known size and points to data allocated on the heap. The `Rc<T>` type keeps track of the number of references to data on the heap so that data can have multiple owners. The `RefCell<T>` type with its interior mutability gives us a type that we can use when we need an immutable type but need to change an inner value of that type; it also enforces the borrowing rules at runtime instead of at compile time.

Also discussed were the `Deref` and `Drop` traits, which 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 Rustonomicon” for more useful information.

Next, we’ll talk about concurrency in Rust. You’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*, in which different parts of a program execute independently, and *parallel programming*, in which different parts of a program execute at the same time, are becoming increasingly important as more computers take advantage of their multiple processors. 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, the team discovered that the ownership and type systems are a powerful set of tools to help manage memory safety *and* concurrency problems! By leveraging ownership and type checking, many concurrency errors are compile-time errors in Rust rather than runtime errors. Therefore, rather than making you spend lots of time trying to reproduce the exact circumstances under which a runtime concurrency bug occurs, incorrect code will refuse to compile and present an error explaining the problem. As a result, you can fix your code while you're working on it rather than potentially after it has been shipped to production. We've nicknamed this aspect of Rust *fearless concurrency*. Fearless concurrency allows you to write code that is free of subtle bugs and is easy to refactor without introducing new bugs.

> Note: For simplicity's sake, we'll refer to many of the problems as *concurrent* rather than being more precise by saying *concurrent and/or parallel*. For this chapter, please mentally substitute *concurrent and/or parallel* whenever we use *concurrent*. In the next chapter, where the distinction matters more, we'll be more specific.

Many languages are dogmatic about the solutions they offer for handling concurrent problems. For example, Erlang has elegant functionality for message-passing concurrency but has only obscure ways to share state between threads. Supporting only a subset of possible solutions is a reasonable strategy for higher-level languages, because a higher-level language promises benefits from giving up some control 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. Therefore, Rust offers a variety of tools for modeling problems in whatever way is appropriate for your situation and requirements.

Here are the topics 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 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 current operating systems, an executed program's code is run in a *process*, and the operating system will manage multiple processes at once. Within a program, you can also have independent parts that run simultaneously. The features that run these independent parts are called *threads*. For example, a web server could have multiple threads so that it can respond to more than one request at the same time.

Splitting the computation in your program into multiple threads to run multiple tasks at the same time can improve performance, but it also adds complexity. Because threads can 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, in which threads are accessing data or resources in an inconsistent order
- Deadlocks, in which two threads are waiting for each other, preventing both threads from continuing
- Bugs that happen only in certain situations and are hard to reproduce and fix reliably

Rust attempts to mitigate the negative effects of using threads, but programming in a multithreaded context still takes careful thought and requires a code structure that is different from that in programs running in a single thread.

Programming languages implement threads in a few different ways, and many operating systems provide an API the language can call for creating new threads. The Rust standard library uses a *1:1* model of thread implementation, whereby a program uses one operating system thread per one language thread. There are crates that implement other models of threading that make different tradeoffs to the 1:1 model. (Rust's async system, which we will see in the next chapter, provides another approach to concurrency as well.)

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:

```
use std::thread;
use std::time::Duration;

fn main() {
    thread::spawn(|| {
        for i in 1..10 {
            println!("hi number {i} from the spawned thread!");
            thread::sleep(Duration::from_millis(1));
        }
    });

    for i in 1..5 {
        println!("hi number {i} from the main thread!");
        thread::sleep(Duration::from_millis(1));
    }
}
```

Note that when the main thread of a Rust program completes, all spawned threads are shut down, whether or not they have finished running. The output from this program might be a little different every time, but it will look similar to the following:

```
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 calls to `thread::sleep` force a thread to stop its execution for a short duration, allowing a different thread to run. The threads will probably take turns, but that isn't 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 output from the main thread, or don't see any overlap, try increasing the numbers in the ranges to create more opportunities for the operating system to switch between the threads.

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 due to the main thread ending, but because there is no guarantee on the order in which threads run, we also can't guarantee that the spawned thread will get to run at all!

We can fix the problem of the spawned thread not running or ending prematurely by saving the return value of `thread::spawn` in a variable. The return type of `thread::spawn` is `JoinHandle<T>`. A `JoinHandle<T>` 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<T>` of the thread we created in Listing 16-1 and how to call `join` to make sure the spawned thread finishes before `main` exits.

```
use std::thread;
use std::time::Duration;

fn main() {
    let handle = thread::spawn(|| {
        for i in 1..10 {
                   println!("hi number {i} from the spawned
```

```
thread!");
            thread::sleep(Duration::from_millis(1));
        }
    });

    for i in 1..5 {
        println!("hi number {i} from the main thread!");
        thread::sleep(Duration::from_millis(1));
    }

    handle.join().unwrap();
}
```

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 Listing 16-2 should produce output similar to 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 continue alternating, but the main thread waits because of the call to `handle.join()` and does not end until the spawned thread is finished.

But let's see what happens when we instead move `handle.join()` before the `for` loop in `main`, like this:

```
use std::thread;
use std::time::Duration;

fn main() {
    let handle = thread::spawn(|| {
        for i in 1..10 {
            println!("hi number {i} from the spawned thread!");
            thread::sleep(Duration::from_millis(1));
        }
    });

    handle.join().unwrap();

    for i in 1..5 {
        println!("hi number {i} from the main thread!");
        thread::sleep(Duration::from_millis(1));
    }
}
```

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, as shown here:

```
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!
```

Small details, such as where `join` is called, can affect whether or not your threads run at the same time.

Using `move` Closures with Threads

We'll often use the `move` keyword with closures passed to `thread::spawn` because the closure will then take ownership of the values it uses from the environment, thus transferring ownership of those values from one thread to another. In “Capturing the Environment With Closures” in Chapter 13, we discussed `move` in the context of closures. Now, we’ll concentrate more on the interaction between `move` and `thread::spawn`.

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. To use data from the main thread in the spawned thread, 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 work yet, as you’ll see in a moment.

```
use std::thread;

fn main() {
    let v = vec![1, 2, 3];

    let handle = thread::spawn(|| {
        println!("Here's a vector: {v:?}");
    });

    handle.join().unwrap();
}
```

The closure uses `v`, so it 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. But when we compile this example, we get the following error:

```
$ cargo run
   Compiling threads v0.1.0 (file:///projects/threads)
error[E0373]: closure may outlive the current function, but it
borrows `v`, which is owned by the current function
 --> src/main.rs:6:32
  |
6 |     let handle = thread::spawn(|| {
  |                                ^^ may outlive borrowed
value `v`
7 |         println!("Here's a vector: {v:?}");
  |                                     - `v` is borrowed here
  |
note: function requires argument type to outlive `'static`
 --> src/main.rs:6:18
  |
6 |       let handle = thread::spawn(|| {
  |  __________________^
7 | |         println!("Here's a vector: {v:?}");
8 | |     });
  | |______^
help: to force the closure to take ownership of `v` (and any
other referenced variables), use the `move` keyword
  |
6 |     let handle = thread::spawn(move || {
  |                                ++++

For more information about this error, try `rustc --explain
E0373`.
error: could not compile `threads` (bin "threads") due to 1
previous error
```

Rust *infers* how to capture `v`, and because `println!` only needs a reference to `v`, the closure tries to borrow `v`. However, there's a problem: Rust can't tell how long the spawned thread will run, so it doesn't know whether the reference to `v` will always be valid.

Listing 16-4 provides a scenario that's more likely to have a reference to `v` that won't be valid:

```
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().unwrap();
}
```

If Rust allowed us to run this code, there's a possibility that the spawned thread would be immediately put in the background without running 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 compiler error in Listing 16-3, we can use the error message's advice:

```
help: to force the closure to take ownership of `v` (and any
other referenced variables), use the `move` keyword
  |
```

```
6 |     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 values. The modification to Listing 16-3 shown in Listing 16-5 will compile and run as we intend.

```
use std::thread;

fn main() {
    let v = vec![1, 2, 3];

    let handle = thread::spawn(move || {
        println!("Here's a vector: {v:?}");
    });

    handle.join().unwrap();
}
```

We might be tempted to try the same thing to fix the code in Listing 16-4 where the main thread called `drop` by using a `move` closure. However, this fix will not work because what Listing 16-4 is trying to do is disallowed for a different reason. If we added `move` to the closure, we would 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:

```
$ cargo run
   Compiling threads v0.1.0 (file:///projects/threads)
error[E0382]: use of moved value: `v`
  --> src/main.rs:10:10
   |
4  |     let v = vec![1, 2, 3];
   |         - move occurs because `v` has type `Vec<i32>`,
which does not implement the `Copy` trait
5  |
```

```
6  |     let handle = thread::spawn(move || {
   |                                  ------- value moved into
closure here
7  |         println!("Here's a vector: {v:?}");
   |                                      - variable moved due
to use in closure
...
10 |     drop(v); // oh no!
   |          ^ value used here after move

For more information about this error, try `rustc --explain
E0382`.
error: could not compile `threads` (bin "threads") due to 1
previous error
```

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've covered what threads are and the methods supplied by the thread API, let's look at some situations in which we can use threads.

Using 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 a slogan from [the Go language documentation](): "Do not communicate by sharing memory; instead, share memory by communicating."

To accomplish message-sending concurrency, Rust's standard library provides an implementation of channels. A *channel* is a general programming concept by which data is sent from one thread to another.

You can imagine a channel in programming as being like a directional channel of water, such as a stream or a river. If you put something like a rubber duck into a river, it will travel downstream to the end of the waterway.

A channel has two halves: a transmitter and a receiver. The transmitter half is the upstream location where you put the rubber duck into the river, and the receiver half is where the rubber duck ends up downstream. One part of your code calls methods on the transmitter with the data you want to send, and another part checks the receiving end for arriving messages. A channel is said to be *closed* if either the transmitter or receiver half is dropped.

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'll be sending simple values between threads using a channel to illustrate the feature. Once you're familiar with the technique, you could use channels for any threads that need to communicate with each other, such as 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, in Listing 16-6, we'll create a channel but not do anything with it. Note that this won't compile yet because Rust can't tell what type of values we want to send over the channel.

```
use std::sync::mpsc;

fn main() {
    let (tx, rx) = mpsc::channel();
}
```

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 implements channels means a channel can have multiple *sending* ends that produce values but only one *receiving* end that consumes those values. Imagine multiple streams flowing together into one big river: everything sent down any of the streams will end up in one river at the end. We'll start with a single producer for now, but we'll add multiple producers when we get this example working.

The `mpsc::channel` function returns a tuple, the first element of which is the sending end—the transmitter—and the second element of which is the receiving end—the receiver. The abbreviations `tx` and `rx` are traditionally used in many fields for *transmitter* and *receiver*, respectively, so we name our variables as such to indicate each end. We're using a `let` statement with a pattern that destructures the tuples; we'll discuss the use of patterns in `let` statements and destructuring in Chapter 19. For now, know that using a `let` statement this way is a convenient approach 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 the spawned thread is communicating with the main thread, as 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.

```
use std::sync::mpsc;
use std::thread;

fn main() {
    let (tx, rx) = mpsc::channel();

    thread::spawn(move || {
        let val = String::from("hi");
```

```
        tx.send(val).unwrap();
    });
}
```

Again, we're using `thread::spawn` to create a new thread and then using `move` to move `tx` into the closure so the spawned thread owns `tx`. The spawned thread needs to own the transmitter to be able to send messages through the channel.

The transmitter has a `send` method that takes the value we want to send. The `send` method returns a `Result<T, E>` type, so if the receiver has already been dropped and there's nowhere to send a value, the send operation will return an error. In this example, we're calling `unwrap` to panic in case of an error. But in a real application, we would 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 receiver in the main thread. This is like retrieving the rubber duck from the water at the end of the river or receiving a chat message.

```
use std::sync::mpsc;
use std::thread;

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}");
}
```

The receiver 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 transmitter 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 used `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.

When we run the code in Listing 16-8, we'll see the value printed from the main thread:

```
Got: hi
```

Perfect!

Channels and Ownership Transference

The ownership rules play a vital role in message sending because they help you write safe, concurrent code. Preventing errors in concurrent programming is the advantage of thinking about ownership throughout your 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 to see why this code isn't allowed.

```
use std::sync::mpsc;
use std::thread;

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}");
}
```

Here, we try to print `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. Potentially, the other thread's modifications could cause errors or unexpected results due to inconsistent or nonexistent data. However, Rust gives us an error if we try to compile the code in Listing 16-9:

```
$ cargo run
   Compiling message-passing v0.1.0 (file:///projects/message-passing)
error[E0382]: borrow of moved value: `val`
  --> src/main.rs:10:26
   |
8  |         let val = String::from("hi");
   |             --- move occurs because `val` has type `String`, which does not implement the `Copy` trait
9  |         tx.send(val).unwrap();
   |                 --- value moved here
10 |         println!("val is {val}");
   |                          ^^^^^ value borrowed here after move
   |
   = note: this error originates in the macro `$crate::format_args_nl` which comes from the expansion of the macro `println` (in Nightly builds, run with -Z macro-backtrace for more info)

For more information about this error, try `rustc --explain
```

```
E0382`.
error: could not compile `message-passing` (bin "message-passing") due to 1 previous error
```

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 using 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 it didn't clearly show us that two separate threads were talking to each other over the channel. In Listing 16-10 we've made some modifications that will prove the code in Listing 16-8 is running concurrently: the spawned thread will now send multiple messages and pause for a second between each message.

```
use std::sync::mpsc;
use std::thread;
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}");
    }
}
```

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. 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

Earlier we mentioned that `mpsc` was an acronym for *multiple producer, single consumer*. Let's put `mpsc` to use and expand the code in Listing 16-10 to create multiple threads that all send values to the same receiver. We can do so by cloning the transmitter, as shown in Listing 16-11.

```
# use std::sync::mpsc;
# use std::thread;
# use std::time::Duration;
```

```
#
# fn main() {
    // --snip--

    let (tx, rx) = mpsc::channel();

    let tx1 = tx.clone();
    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));
        }
    });

    for received in rx {
```

```
        println!("Got: {received}");
    }

    // --snip--
# }
```

This time, before we create the first spawned thread, we call `clone` on the transmitter. This will give us a new transmitter we can pass to the first spawned thread. We pass the original transmitter to a second spawned thread. This gives us two threads, each sending different messages to the one receiver.

When you run the code, your output should look something like this:

```
Got: hi
Got: more
Got: from
Got: messages
Got: for
Got: the
Got: thread
Got: you
```

You might see the values in another order, depending on your system. This is what makes concurrency interesting as well as difficult. If you experiment with `thread::sleep`, giving it various values in the different threads, each run will be more nondeterministic and create different output each time.

Now that we've looked at how channels work, let's look at a different method of concurrency.

Shared-State Concurrency

Message passing is a fine way to handle concurrency, but it's not the only way. Another method would be for multiple threads to access the same shared data. Consider this part of the slogan from the Go language documentation again: "Do not communicate by sharing memory."

What would communicating by sharing memory look like? In addition, why would message-passing enthusiasts caution not to use memory sharing?

In a way, channels in any programming language are similar to single ownership, because once you transfer a value down a channel, you should no longer use that value. Shared-memory concurrency is like multiple ownership: multiple threads can access the same memory location at the same time. As you saw in Chapter 15, where smart pointers made multiple ownership possible, multiple ownership can add complexity because these different owners need managing. Rust's type system and ownership rules greatly assist in getting this management correct. For an example, let's look at mutexes, one of the more common concurrency primitives for shared memory.

Using Mutexes to Allow Access to Data from One Thread at a Time

Mutex is an abbreviation for *mutual exclusion*, as in a mutex allows only one thread to access some data at any given time. 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. Therefore, the mutex is described as *guarding* the data it holds via the locking system.

Mutexes have a reputation for being difficult to use because you have to remember two rules:

1. You must attempt to acquire the lock before using the data.
2. When you're done with the data that the mutex guards, you must unlock the data so other threads can acquire the lock.

For a real-world metaphor for a mutex, imagine a panel discussion at a conference with only one microphone. Before a panelist can speak, they have to ask or signal that they want to use the microphone. When they get the microphone, they can talk for as long as they want to and 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 won't work as planned!

Management of mutexes can be incredibly tricky to get right, which is why so many people are enthusiastic about channels. However, thanks to Rust's type system and ownership rules, you can't get locking and unlocking wrong.

The API of `Mutex<T>`

As an example of how to use a mutex, let's start by using a mutex in a single-threaded context, as shown in Listing 16-12.

```
use std::sync::Mutex;

fn main() {
    let m = Mutex::new(5);

    {
        let mut num = m.lock().unwrap();
        *num = 6;
    }

    println!("m = {m:?}");
}
```

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 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.

After 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 the value in `m`. The type of `m` is `Mutex<i32>`, not `i32`, so we *must* call `lock` to be able to use the `i32` value. We can't forget; the type system won't let us access the inner `i32` otherwise.

As you might suspect, `Mutex<T>` is a smart pointer. More accurately, the call to `lock` *returns* a smart pointer called `MutexGuard`, wrapped in a `LockResult` that we handled with the call to `unwrap`. The `MutexGuard` smart pointer implements `Deref` to point at our inner data; the smart pointer also has a `Drop` implementation that releases the lock automatically when a `MutexGuard` goes out of scope, which happens at the end of the inner scope. As a result, we don't risk forgetting to release the lock and blocking the mutex from being used by other threads, because the lock release happens automatically.

After dropping the lock, we can print the mutex value and see that we were able to change the inner `i32` to 6.

Sharing a `Mutex<T>` Between Multiple Threads

Now let's try to share a value between multiple threads using `Mutex<T>`. We'll spin up 10 threads and have them each increment a counter value by 1, so the counter goes from 0 to 10. The example in Listing 16-13 will have a compiler error, and we'll use that error to learn more about using `Mutex<T>` and how Rust helps us use it correctly.

```
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());
}
```

We create a `counter` variable to hold an `i32` inside a `Mutex<T>`, as we did in Listing 16-12. Next, we create 10 threads by iterating 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. Then, as we did in Listing 16-2, we call `join` on each handle to make sure all the threads finish. At that point, the main thread will acquire the lock and print the result of this program.

We hinted that this example wouldn't compile. Now let's find out why!

```
$ cargo run
     Compiling shared-state v0.1.0 (file:///projects/shared-
state)
error[E0382]: borrow of moved value: `counter`
```

```
  --> src/main.rs:21:29
   |
5  |     let counter = Mutex::new(0);
   |         ------- move occurs because `counter` has type
`Mutex<i32>`, which does not implement the `Copy` trait
...
8  |     for _ in 0..10 {
   |     -------------- inside of this loop
9  |         let handle = thread::spawn(move || {
   |                                    ------- value moved
into closure here, in previous iteration of loop
...
21 |     println!("Result: {}", *counter.lock().unwrap());
   |                             ^^^^^^^ value borrowed here
after move
   |
help: consider moving the expression out of the loop so it is
only moved once
   |
8  ~     let mut value = counter.lock();
9  ~     for _ in 0..10 {
10 |         let handle = thread::spawn(move || {
11 ~             let mut num = value.unwrap();
   |

For more information about this error, try `rustc --explain
E0382`.
error: could not compile `shared-state` (bin "shared-state")
due to 1 previous error
```

The error message states that the `counter` value was moved in the previous iteration of the loop. Rust is telling us that we can’t move the ownership of lock `counter` into multiple threads. Let’s fix the compiler error with the multiple-ownership method we discussed in Chapter 15.

Multiple Ownership with Multiple Threads

In Chapter 15, we gave a value to multiple owners by using the smart pointer `Rc<T>` to create a reference counted value. Let's 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.

```
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());
}
```

Once again, we compile and get… different errors! The compiler is teaching us a lot.

```
$ cargo run
     Compiling  shared-state  v0.1.0  (file:///projects/shared-
```

```
state)
error[E0277]: `Rc<Mutex<i32>>` cannot be sent between threads
safely
  --> src/main.rs:11:36
   |
11 |           let handle = thread::spawn(move || {
   |                        ------------- ^------
   |                        |             |
       |     ______________________|_____________within  this
`{closure@src/main.rs:11:36: 11:43}`
   | |                     |
   | |                      required by a bound introduced by
this call
12 | |             let mut num = counter.lock().unwrap();
13 | |
14 | |             *num += 1;
15 | |         });
     |  |_________^  `Rc<Mutex<i32>>`  cannot  be  sent  between
threads safely
   |
    = help: within `{closure@src/main.rs:11:36: 11:43}`, the
trait `Send` is not implemented for `Rc<Mutex<i32>>`
note: required because it's used within this closure
  --> src/main.rs:11:36
   |
11 |         let handle = thread::spawn(move || {
   |                                    ^^^^^^^
note: required by a bound in `spawn`
                                                              -->
/rustc/4eb161250e340c8f48f66e2b929ef4a5bed7c181/library/std/sr
c/thread/mod.rs:728:1

For more information about this error, try `rustc --explain
E0277`.
error: could not compile `shared-state` (bin "shared-state")
due to 1 previous error
```

Wow, that error message is very wordy! Here's the important part to focus on: `` `Rc<Mutex<i32>>` cannot be sent between threads safely ``. The compiler is also telling us the reason why: `` the trait `Send` is not implemented for `Rc<Mutex<i32>>` ``. We'll 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 that is exactly like `Rc<T>` but one that makes changes to the reference count in a thread-safe way.

Atomic Reference Counting with `Arc<T>`

Fortunately, `Arc<T>` *is* a type like `Rc<T>` that is safe to use in concurrent situations. 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. At this point, you just need to know 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 just performing operations on values within a single thread, your code can run faster if it doesn't have to enforce the guarantees atomics provide.

Let's return to our example: `Arc<T>` and `Rc<T>` have the same API, so we fix our program by changing the `use` line, the call to `new`, and the call to `clone`. The code in Listing 16-15 will finally compile and run.

```
use std::sync::{Arc, Mutex};
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());
}
```

This code will print the following:

```
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. You could also use this program's structure to do more complicated operations than just incrementing a counter. Using this strategy, you can divide a calculation into independent parts, split those parts across threads, and then use a `Mutex<T>` to have each thread update the final result with its part.

Note that if you are doing simple numerical operations, there are types simpler than `Mutex<T>` types provided by the [`std::sync::atomic` module of the standard library](). These types provide safe, concurrent, atomic access to primitive types. We chose to use `Mutex<T>` with a primitive type for this example so we could concentrate on how `Mutex<T>` works.

Similarities Between `RefCell<T>`/`Rc<T>` and `Mutex<T>`/`Arc<T>`

You might 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, as 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 an `Arc<T>`.

Another detail to note is that Rust can't protect you from all kinds of logic errors when you use `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 with the risk of creating *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 deadlocks, 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` offers useful information.

We'll round out this chapter by talking about the `Send` and `Sync` traits and how we can use them with custom types.

Extensible Concurrency with the `Send` and `Sync` Traits

Interestingly, almost every concurrency feature we've talked about so far in this chapter has been part of the standard library, not the language. Your options for handling concurrency are not limited to the language or the standard library; you can write your own concurrency features or use those written by others.

However, among the key concurrency concepts that are embedded in the language rather than the standard library are the `std::marker` traits `Send` and `Sync`.

Allowing Transference of Ownership Between Threads with `Send`

The `Send` marker trait indicates that ownership of values of the type implementing `Send` can be transferred between threads. Almost every Rust type is `Send`, but there are some exceptions, including `Rc<T>`: this cannot implement `Send` because if you 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 thread-safe performance penalty.

Therefore, Rust's type system and trait bounds ensure that you can never accidentally send an `Rc<T>` value across threads unsafely. When we tried to do this in Listing 16-14, we got the error `the trait Send is not implemented for Rc<Mutex<i32>>`. When we switched to `Arc<T>`, which does implement `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 20.

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. In other words, any type `T` implements `Sync` if `&T` (an immutable reference to `T`) implements `Send`, meaning the reference can be sent safely to another thread. Similar to `Send`, primitive types all implement `Sync`, and types composed entirely of types that implement `Sync` also implement `Sync`.

The smart pointer `Rc<T>` also doesn't implement `Sync` for the same reasons that it doesn't implement `Send`. The `RefCell<T>` type (which we talked about in Chapter 15) and the family of related `Cell<T>` types don't implement `Sync`. The implementation of borrow checking that `RefCell<T>` does at runtime is not thread-safe. The smart pointer `Mutex<T>` implements `Sync` and can be used to share access with multiple threads as you saw in "Sharing a `Mutex<T>` Between Multiple Threads".

Implementing `Send` and `Sync` Manually Is Unsafe

Because types composed entirely of other types that implement the `Send` and `Sync` traits also automatically implement `Send` and `Sync`, we don't have to implement those traits manually. As marker traits, they don't even have any methods to implement. They're just useful for enforcing invariants related to concurrency.

Manually implementing these traits involves implementing unsafe Rust code. We'll talk about using unsafe Rust code in Chapter 20; for now, the important information is that building new concurrent types not made up of `Send` and `Sync` parts requires careful thought to uphold the safety guarantees. "The Rustonomicon" has more information about these guarantees and how to uphold them.

Summary

This isn’t the last you’ll see of concurrency in this book: the next chapter focuses on async programming, and the project in Chapter 21 will use the concepts in this chapter in a more realistic situation than the smaller examples discussed here.

As mentioned earlier, because very little of how Rust handles concurrency is part of the language, many concurrency solutions are implemented as crates. These evolve more quickly than the standard library, so be sure to search online for the current, state-of-the-art crates to use in multithreaded situations.

The Rust standard library provides channels for message passing and smart pointer types, such as `Mutex<T>` and `Arc<T>`, that are safe to use in concurrent contexts. The type system and the borrow checker ensure that the code using these solutions won’t end up with data races or invalid references. Once you get your code to compile, you 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 a concept to be afraid of: go forth and make your programs concurrent, fearlessly!

Fundamentals of Asynchronous Programming: Async, Await, Futures, and Streams

Many operations we ask the computer to do can take a while to finish. It would be nice if we could do something else while we are waiting for those long-running processes to complete. Modern computers offer two techniques for working on more than one operation at a time: parallelism and concurrency. Once we start writing programs that involve parallel or concurrent operations, though, we quickly encounter new challenges inherent to *asynchronous programming*, where operations may not finish sequentially in the order they were started. This chapter builds on Chapter 16's use of threads for parallelism and concurrency by introducing an alternative approach to asynchronous programming: Rust's Futures, Streams, the `async` and `await` syntax that supports them, and the tools for managing and coordinating between asynchronous operations.

Let's consider an example. Say you're exporting a video you've created of a family celebration, an operation that could take anywhere from minutes to hours. The video export will use as much CPU and GPU power as it can. If you had only one CPU core and your operating system didn't pause that export until it completed—that is, if it executed the export *synchronously*—you couldn't do anything else on your computer while that task was running. That would be a pretty frustrating experience. Fortunately, your computer's operating system can, and does, invisibly interrupt the export often enough to let you get other work done simultaneously.

Now say you're downloading a video shared by someone else, which can also take a while but does not take up as much CPU time. In this case, the CPU has to wait for data to arrive from the network. While you can start reading the data once it starts to arrive, it might take some time for all of it to show up. Even once the data is all present, if the video is quite large, it could take at least a second or two to load it all. That might not sound like much, but it’s a very long time for a modern processor, which can perform billions of operations every second. Again, your operating system will invisibly interrupt your program to allow the CPU to perform other work while waiting for the network call to finish.

The video export is an example of a *CPU-bound* or *compute-bound* operation. It’s limited by the computer’s potential data processing speed within the CPU or GPU, and how much of that speed it can dedicate to the operation. The video download is an example of an *IO-bound* operation, because it’s limited by the speed of the computer’s *input and output*; it can only go as fast as the data can be sent across the network.

In both of these examples, the operating system’s invisible interrupts provide a form of concurrency. That concurrency happens only at the level of the entire program, though: the operating system interrupts one program to let other programs get work done. In many cases, because we understand our programs at a much more granular level than the operating system does, we can spot opportunities for concurrency that the operating system can’t see.

For example, if we’re building a tool to manage file downloads, we should be able to write our program so that starting one download won’t lock up the UI, and users should be able to start multiple downloads at the same time. Many operating system APIs for interacting with the network are *blocking*, though; that is, they block the program’s progress until the data they’re processing is completely ready.

> Note: This is how *most* function calls work, if you think about it. However, the term *blocking* is usually reserved for function calls that interact with files, the network, or other resources on the computer, because those are the cases where an individual program would benefit from the operation being *non*-blocking.

We could avoid blocking our main thread by spawning a dedicated thread to download each file. However, the overhead of those threads would eventually become a problem. It would be preferable if the call didn’t block in the first place. It would also be better if we could write in the same direct style we use in blocking code, similar to this:

```
let data = fetch_data_from(url).await;
println!("{data}");
```

That is exactly what Rust's *async* (short for *asynchronous*) abstraction gives us. In this chapter, you'll learn all about async as we cover the following topics:

- How to use Rust's `async` and `await` syntax
- How to use the async model to solve some of the same challenges we looked at in Chapter 16
- How multithreading and async provide complementary solutions, that you can combine in many cases

Before we see how async works in practice, though, we need to take a short detour to discuss the differences between parallelism and concurrency.

Parallelism and Concurrency

We've treated parallelism and concurrency as mostly interchangeable so far. Now we need to distinguish between them more precisely, because the differences will show up as we start working.

Consider the different ways a team could split up work on a software project. You could assign a single member multiple tasks, assign each member one task, or use a mix of the two approaches.

When an individual works on several different tasks before any of them is complete, this is *concurrency*. Maybe you have two different projects checked out on your computer, and when you get bored or stuck on one project, you switch to the other. You're just one person, so you can't make progress on both tasks at the exact same time, but you can multi-task, making progress on one at a time by switching between them (see Figure 17-1).

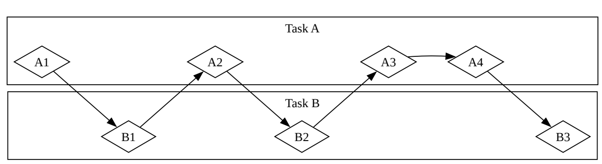


Figure 17-1: A concurrent workflow, switching between Task A and Task B

When the team splits up a group of tasks by having each member take one task and work on it alone, this is *parallelism*. Each person on the team can make progress at the exact same time (see Figure 17-2).

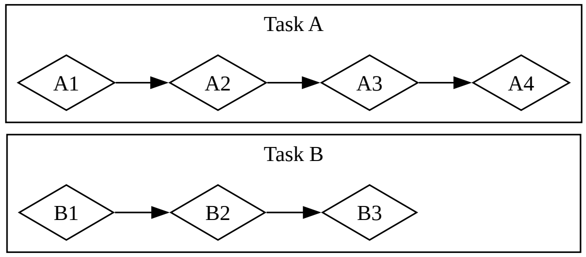


Figure 17-2: A parallel workflow, where work happens on Task A and Task B independently

In both of these workflows, you might have to coordinate between different tasks. Maybe you *thought* the task assigned to one person was totally independent from everyone else's work, but it actually requires another person on the team to finish their task first. Some of the work could be done in parallel, but some of it was actually *serial*: it could only happen in a series, one task after the other, as in Figure 17-3.

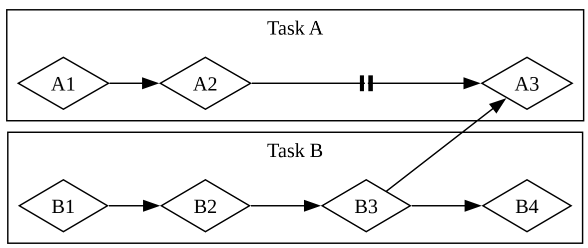


Figure 17-3: A partially parallel workflow, where work happens on Task A and Task B independently until Task A3 is blocked on the results of Task B3.

Likewise, you might realize that one of your own tasks depends on another of your tasks. Now your concurrent work has also become serial.

Parallelism and concurrency can intersect with each other, too. If you learn that a colleague is stuck until you finish one of your tasks, you'll probably focus all your efforts on that task to "unblock" your colleague. You and your coworker are no longer able to work in parallel, and you're also no longer able to work concurrently on your own tasks.

The same basic dynamics come into play with software and hardware. On a machine with a single CPU core, the CPU can perform only one operation at a time, but it can still work concurrently. Using tools such as threads, processes, and async, the computer can pause one activity and switch to others before eventually cycling back to that first activity again. On a machine with multiple CPU cores, it can also do work in parallel. One core can be performing one task while another core performs a completely unrelated one, and those operations actually happen at the same time.

When working with async in Rust, we're always dealing with concurrency. Depending on the hardware, the operating system, and the async runtime we are using (more on async runtimes shortly), that concurrency may also use parallelism under the hood.

Now, let's dive into how async programming in Rust actually works.

Futures and the Async Syntax

The key elements of asynchronous programming in Rust are *futures* and Rust’s `async` and `await` keywords.

A *future* is a value that may not be ready now but will become ready at some point in the future. (This same concept shows up in many languages, sometimes under other names such as *task* or *promise*.) Rust provides a `Future` trait as a building block so that different async operations can be implemented with different data structures but with a common interface. In Rust, futures are types that implement the `Future` trait. Each future holds its own information about the progress that has been made and what "ready" means.

You can apply the `async` keyword to blocks and functions to specify that they can be interrupted and resumed. Within an async block or async function, you can use the `await` keyword to *await a future* (that is, wait for it to become ready). Any point where you await a future within an async block or function is a potential spot for that async block or function to pause and resume. The process of checking with a future to see if its value is available yet is called *polling*.

Some other languages, such as C# and JavaScript, also use `async` and `await` keywords for async programming. If you’re familiar with those languages, you may notice some significant differences in how Rust does things, including how it handles the syntax. That’s for good reason, as we’ll see!

When writing async Rust, we use the `async` and `await` keywords most of the time. Rust compiles them into equivalent code using the `Future` trait, much as it compiles `for` loops into equivalent code using the `Iterator` trait. Because Rust provides the `Future` trait, though, you can also implement it for your own data types when you need to. Many of the functions we’ll see throughout this chapter return types with their own implementations of `Future`. We’ll return to the definition of the trait at the end of the chapter and dig into more of how it works, but this is enough detail to keep us moving forward.

This may all feel a bit abstract, so let's write our first async program: a little web scraper. We'll pass in two URLs from the command line, fetch both of them concurrently, and return the result of whichever one finishes first. This example will have a fair bit of new syntax, but don't worry—we'll explain everything you need to know as we go.

Our First Async Program

To keep the focus of this chapter on learning async rather than juggling parts of the ecosystem, we've created the `trpl` crate (`trpl` is short for "The Rust Programming Language"). It re-exports all the types, traits, and functions you'll need, primarily from the [`futures`]() and [`tokio`]() crates. The `futures` crate is an official home for Rust experimentation for async code, and it's actually where the `Future` trait was originally designed. Tokio is the most widely used async runtime in Rust today, especially for web applications. There are other great runtimes out there, and they may be more suitable for your purposes. We use the `tokio` crate under the hood for `trpl` because it's well tested and widely used.

In some cases, `trpl` also renames or wraps the original APIs to keep you focused on the details relevant to this chapter. If you want to understand what the crate does, we encourage you to check out [its source code](). You'll be able to see what crate each re-export comes from, and we've left extensive comments explaining what the crate does.

Create a new binary project named `hello-async` and add the `trpl` crate as a dependency:

```
$ cargo new hello-async
$ cd hello-async
$ cargo add trpl
```

Now we can use the various pieces provided by `trpl` to write our first async program. We'll build a little command line tool that fetches two web pages, pulls the `<title>` element from each, and prints out the title of whichever page finishes that whole process first.

Defining the page_title Function

Let's start by writing a function that takes one page URL as a parameter, makes a request to it, and returns the text of the title element (see Listing 17-1).

```
# extern crate trpl; // required for mdbook test
#
```

```
# fn main() {
#     // TODO: we'll add this next!
# }
#
use trpl::Html;

async fn page_title(url: &str) -> Option<String> {
    let response = trpl::get(url).await;
    let response_text = response.text().await;
    Html::parse(&response_text)
        .select_first("title")
        .map(|title_element| title_element.inner_html())
}
```

First, we define a function named `page_title` and mark it with the `async` keyword. Then we use the `trpl::get` function to fetch whatever URL is passed in and add the `await` keyword to await the response. To get the text of the response, we call its `text` method, and once again await it with the `await` keyword. Both of these steps are asynchronous. For the `get` function, we have to wait for the server to send back the first part of its response, which will include HTTP headers, cookies, and so on, and can be delivered separately from the response body. Especially if the body is very large, it can take some time for it all to arrive. Because we have to wait for the *entirety* of the response to arrive, the `text` method is also async.

We have to explicitly await both of these futures, because futures in Rust are *lazy*: they don't do anything until you ask them to with the `await` keyword. (In fact, Rust will show a compiler warning if you don't use a future.) This might remind you of Chapter 13's discussion of iterators in the section Processing a Series of Items With Iterators. Iterators do nothing unless you call their `next` method—whether directly or by using `for` loops or methods such as `map` that use `next` under the hood. Likewise, futures do nothing unless you explicitly ask them to. This laziness allows Rust to avoid running async code until it's actually needed.

> Note: This is different from the behavior we saw in the previous chapter when using `thread::spawn` in [Creating a New Thread with spawn](), where the closure we passed to another thread started running immediately. It's also different from how many other languages approach async. But it's important for Rust to be able to provide its performance guarantees, just as it is with iterators.

Once we have `response_text`, we can parse it into an instance of the `Html` type using `Html::parse`. Instead of a raw string, we now have a data type we can use to work with the HTML as a richer data structure. In particular, we can use the `select_first` method to find the first instance of a given CSS selector. By passing the string `"title"`, we'll get the first `<title>` element in the document, if there is one. Because there may not be any matching element, `select_first` returns an `Option<ElementRef>`. Finally, we use the `Option::map` method, which lets us work with the item in the `Option` if it's present, and do nothing if it isn't. (We could also use a `match` expression here, but `map` is more idiomatic.) In the body of the function we supply to `map`, we call `inner_html` on the `title_element` to get its content, which is a `String`. When all is said and done, we have an `Option<String>`.

Notice that Rust's `await` keyword goes *after* the expression you're awaiting, not before it. That is, it's a *postfix* keyword. This may differ from what you're used to if you've used `async` in other languages, but in Rust it makes chains of methods much nicer to work with. As a result, we can change the body of `page_title` to chain the `trpl::get` and `text` function calls together with `await` between them, as shown in Listing 17-2.

```
# extern crate trpl; // required for mdbook test
#
# use trpl::Html;
#
# fn main() {
#     // TODO: we'll add this next!
# }
```

```
#
# async fn page_title(url: &str) -> Option<String> {
    let response_text = trpl::get(url).await.text().await;
#     Html::parse(&response_text)
#         .select_first("title")
#         .map(|title_element| title_element.inner_html())
# }
```

With that, we have successfully written our first async function! Before we add some code in `main` to call it, let's talk a little more about what we've written and what it means.

When Rust sees a block marked with the `async` keyword, it compiles it into a unique, anonymous data type that implements the `Future` trait. When Rust sees a function marked with `async`, it compiles it into a non-async function whose body is an async block. An async function's return type is the type of the anonymous data type the compiler creates for that async block.

Thus, writing `async fn` is equivalent to writing a function that returns a *future* of the return type. To the compiler, a function definition such as the `async fn page_title` in Listing 17-1 is equivalent to a non-async function defined like this:

```
# extern crate trpl; // required for mdbook test
use std::future::Future;
use trpl::Html;

fn page_title(url: &str) -> impl Future<Output =
Option<String>> {
    async move {
        let text = trpl::get(url).await.text().await;
        Html::parse(&text)
            .select_first("title")
            .map(|title| title.inner_html())
    }
}
```

Let's walk through each part of the transformed version:

- It uses the `impl Trait` syntax we discussed back in Chapter 10 in the "Traits as Parameters" section.
- The returned trait is a `Future` with an associated type of `Output`. Notice that the `Output` type is `Option<String>`, which is the same as the original return type from the `async fn` version of `page_title`.
- All of the code called in the body of the original function is wrapped in an `async move` block. Remember that blocks are expressions. This whole block is the expression returned from the function.
- This async block produces a value with the type `Option<String>`, as just described. That value matches the `Output` type in the return type. This is just like other blocks you have seen.
- The new function body is an `async move` block because of how it uses the `url` parameter. (We'll talk much more about `async` versus `async move` later in the chapter.)

Now we can call `page_title` in `main`.

Determining a Single Page's Title

To start, we'll just get the title for a single page. In Listing 17-3, we follow the same pattern we used in Chapter 12 to get command line arguments in the Accepting Command Line Arguments section. Then we pass the first URL `page_title` and await the result. Because the value produced by the future is an `Option<String>`, we use a `match` expression to print different messages to account for whether the page had a `<title>`.

```
# extern crate trpl; // required for mdbook test
#
# use trpl::Html;
#
async fn main() {
    let args: Vec<String> = std::env::args().collect();
    let url = &args[1];
    match page_title(url).await {
        Some(title) => println!("The title for {url} was {title}"),
        None => println!("{url} had no title"),
    }
}
#
# async fn page_title(url: &str) -> Option<String> {
#     let response_text = trpl::get(url).await.text().await;
#     Html::parse(&response_text)
#         .select_first("title")
#         .map(|title_element| title_element.inner_html())
# }
```

Unfortunately, this code doesn't compile. The only place we can use the `await` keyword is in async functions or blocks, and Rust won't let us mark the special `main` function as `async`.

```
error[E0752]: `main` function is not allowed to be `async`
 --> src/main.rs:6:1
  |
```

```
6 | async fn main() {
   |  ^^^^^^^^^^^^^^^ `main` function is not allowed to be
`async`
```

The reason `main` can't be marked `async` is that async code needs a *runtime*: a Rust crate that manages the details of executing asynchronous code. A program's `main` function can *initialize* a runtime, but it's not a runtime *itself*. (We'll see more about why this is the case in a bit.) Every Rust program that executes async code has at least one place where it sets up a runtime and executes the futures.

Most languages that support async bundle a runtime, but Rust does not. Instead, there are many different async runtimes available, each of which makes different tradeoffs suitable to the use case it targets. For example, a high-throughput web server with many CPU cores and a large amount of RAM has very different needs than a microcontroller with a single core, a small amount of RAM, and no heap allocation ability. The crates that provide those runtimes also often supply async versions of common functionality such as file or network I/O.

Here, and throughout the rest of this chapter, we'll use the `run` function from the `trpl` crate, which takes a future as an argument and runs it to completion. Behind the scenes, calling `run` sets up a runtime that's used to run the future passed in. Once the future completes, `run` returns whatever value the future produced.

We could pass the future returned by `page_title` directly to `run`, and once it completed, we could match on the resulting `Option<String>`, as we tried to do in Listing 17-3. However, for most of the examples in the chapter (and most async code in the real world), we'll be doing more than just one async function call, so instead we'll pass an `async` block and explicitly await the result of the `page_title` call, as in Listing 17-4.

```
# extern crate trpl; // required for mdbook test
#
# use trpl::Html;
#
fn main() {
```

```
    let args: Vec<String> = std::env::args().collect();

    trpl::run(async {
        let url = &args[1];
        match page_title(url).await {
            Some(title) => println!("The title for {url} was
{title}"),
            None => println!("{url} had no title"),
        }
    })
}
#
# async fn page_title(url: &str) -> Option<String> {
#     let response_text = trpl::get(url).await.text().await;
#     Html::parse(&response_text)
#         .select_first("title")
#         .map(|title_element| title_element.inner_html())
# }
```

When we run this code, we get the behavior we expected initially:

```
$ cargo run -- https://www.rust-lang.org
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.05s
     Running `target/debug/async_await 'https://www.rust-
lang.org'`
The title for https://www.rust-lang.org was
            Rust Programming Language
```

Phew—we finally have some working async code! But before we add the code to race the two sites against each other, let's briefly turn our attention back to how futures work.

Each *await point*—that is, every place where the code uses the `await` keyword—represents a place where control is handed back to the runtime. To make that work, Rust needs to keep track of the state involved in the async block so that the runtime can kick off some other work and then come back when it's ready to try advancing the first one again. This is an invisible state machine, as if you'd written an enum like this to save the current state at each await point:

```
# extern crate trpl; // required for mdbook test
#
enum PageTitleFuture<'a> {
    Initial { url: &'a str },
    GetAwaitPoint { url: &'a str },
    TextAwaitPoint { response: trpl::Response },
}
```

Writing the code to transition between each state by hand would be tedious and error-prone, however, especially when you need to add more functionality and more states to the code later. Fortunately, the Rust compiler creates and manages the state machine data structures for async code automatically. The normal borrowing and ownership rules around data structures all still apply, and happily, the compiler also handles checking those for us and provides useful error messages. We'll work through a few of those later in the chapter.

Ultimately, something has to execute this state machine, and that something is a runtime. (This is why you may come across references to *executors* when looking into runtimes: an executor is the part of a runtime responsible for executing the async code.)

Now you can see why the compiler stopped us from making `main` itself an async function back in Listing 17-3. If `main` were an async function, something else would need to manage the state machine for whatever future `main` returned, but `main` is the starting point for the program! Instead, we called the `trpl::run` function in `main` to set up a runtime and run the future returned by the `async` block until it is done.

> Note: Some runtimes provide macros so you *can* write an async `main` function. Those macros rewrite `async fn main() { ... }` to be a normal `fn main`, which does the same thing we did by hand in Listing 17-4: call a function that runs a future to completion the way `trpl::run` does.

Now let's put these pieces together and see how we can write concurrent code.

Racing Our Two URLs Against Each Other

In Listing 17-5, we call `page_title` with two different URLs passed in from the command line and race them.

```
# extern crate trpl; // required for mdbook test
#
use trpl::{Either, Html};

fn main() {
    let args: Vec<String> = std::env::args().collect();

    trpl::run(async {
        let title_fut_1 = page_title(&args[1]);
        let title_fut_2 = page_title(&args[2]);

        let (url, maybe_title) =
            match trpl::race(title_fut_1, title_fut_2).await {
                Either::Left(left) => left,
                Either::Right(right) => right,
            };

        println!("{url} returned first");
        match maybe_title {
                Some(title) => println!("Its page title is:
'{title}'"),
                  None => println!("Its title could not be
parsed."),
        }
    })
}

async fn page_title(url: &str) -> (&str, Option<String>) {
    let text = trpl::get(url).await.text().await;
```

```
    let title = Html::parse(&text)
        .select_first("title")
        .map(|title| title.inner_html());
    (url, title)
}
```

We begin by calling `page_title` for each of the user-supplied URLs. We save the resulting futures as `title_fut_1` and `title_fut_2`. Remember, these don't do anything yet, because futures are lazy and we haven't yet awaited them. Then we pass the futures to `trpl::race`, which returns a value to indicate which of the futures passed to it finishes first.

> Note: Under the hood, `race` is built on a more general function, `select`, which you will encounter more often in real-world Rust code. A `select` function can do a lot of things that the `trpl::race` function can't, but it also has some additional complexity that we can skip over for now.

Either future can legitimately "win," so it doesn't make sense to return a `Result`. Instead, `race` returns a type we haven't seen before, `trpl::Either`. The `Either` type is somewhat similar to a `Result` in that it has two cases. Unlike `Result`, though, there is no notion of success or failure baked into `Either`. Instead, it uses `Left` and `Right` to indicate "one or the other":

```
enum Either<A, B> {
    Left(A),
    Right(B),
}
```

The `race` function returns `Left` with the output from the first future argument it finishes first, or `Right` with the output of the second future argument if that one finishes first. This matches the order the arguments appear in when calling the function: the first argument is to the left of the second argument.

We also update `page_title` to return the same URL passed in. That way, if the page that returns first does not have a `<title>` we can resolve, we can still print a meaningful message. With that information available, we wrap up by updating our `println!` output to indicate both which URL finished first and what, if any, the `<title>` is for the web page at that URL.

You have built a small working web scraper now! Pick a couple URLs and run the command line tool. You may discover that some sites are consistently faster than others, while in other cases the faster site varies from run to run. More importantly, you've learned the basics of working with futures, so now we can dig deeper into what we can do with async.

Applying Concurrency with Async

In this section, we'll apply async to some of the same concurrency challenges we tackled with threads in chapter 16. Because we already talked about a lot of the key ideas there, in this section we'll focus on what's different between threads and futures.

In many cases, the APIs for working with concurrency using async are very similar to those for using threads. In other cases, they end up being quite different. Even when the APIs *look* similar between threads and async, they often have different behavior—and they nearly always have different performance characteristics.

Creating a New Task with `spawn_task`

The first operation we tackled in [Creating a New Thread with Spawn]() was counting up on two separate threads. Let's do the same using async. The `trpl` crate supplies a `spawn_task` function that looks very similar to the `thread::spawn` API, and a `sleep` function that is an async version of the `thread::sleep` API. We can use these together to implement the counting example, as shown in Listing 17-6.

```
# extern crate trpl; // required for mdbook test
#
use std::time::Duration;

fn main() {
    trpl::run(async {
        trpl::spawn_task(async {
            for i in 1..10 {
                println!("hi number {i} from the first
task!");
                trpl::sleep(Duration::from_millis(500)).await;
            }
        });

        for i in 1..5 {
```

```
            println!("hi number {i} from the second task!");
            trpl::sleep(Duration::from_millis(500)).await;
        }
    });
}
```

As our starting point, we set up our `main` function with `trpl::run` so that our top-level function can be async.

> Note: From this point forward in the chapter, every example will include this exact same wrapping code with `trpl::run` in `main`, so we'll often skip it just as we do with `main`. Don't forget to include it in your code!

Then we write two loops within that block, each containing a `trpl::sleep` call, which waits for half a second (500 milliseconds) before sending the next message. We put one loop in the body of a `trpl::spawn_task` and the other in a top-level `for` loop. We also add an `await` after the `sleep` calls.

This code behaves similarly to the thread-based implementation—including the fact that you may see the messages appear in a different order in your own terminal when you run it:

```
hi number 1 from the second task!
hi number 1 from the first task!
hi number 2 from the first task!
hi number 2 from the second task!
hi number 3 from the first task!
hi number 3 from the second task!
hi number 4 from the first task!
hi number 4 from the second task!
hi number 5 from the first task!
```

This version stops as soon as the `for` loop in the body of the main async block finishes, because the task spawned by `spawn_task` is shut down when the `main` function ends. If you want it to run all the way to the task's completion, you will need to use a join handle to wait for the first task to complete. With threads, we used the `join` method to “block” until the thread was done running. In Listing 17-7, we can use `await` to do the same thing, because the task handle itself is a future. Its `Output` type is a `Result`, so we also unwrap it after awaiting it.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
        let handle = trpl::spawn_task(async {
            for i in 1..10 {
                println!("hi number {i} from the first
task!");
                trpl::sleep(Duration::from_millis(500)).await;
            }
        });

        for i in 1..5 {
            println!("hi number {i} from the second task!");
            trpl::sleep(Duration::from_millis(500)).await;
        }

        handle.await.unwrap();
#     });
# }
```

This updated version runs until *both* loops finish.

```
hi number 1 from the second task!
hi number 1 from the first task!
hi number 2 from the first task!
hi number 2 from the second task!
hi number 3 from the first task!
hi number 3 from the second task!
hi number 4 from the first task!
```

```
hi number 4 from the second task!
hi number 5 from the first task!
hi number 6 from the first task!
hi number 7 from the first task!
hi number 8 from the first task!
hi number 9 from the first task!
```

So far, it looks like async and threads give us the same basic outcomes, just with different syntax: using `await` instead of calling `join` on the join handle, and awaiting the `sleep` calls.

The bigger difference is that we didn't need to spawn another operating system thread to do this. In fact, we don't even need to spawn a task here. Because async blocks compile to anonymous futures, we can put each loop in an async block and have the runtime run them both to completion using the `trpl::join` function.

In the section Waiting for All Threads to Finishing Using `join` Handles, we showed how to use the `join` method on the `JoinHandle` type returned when you call `std::thread::spawn`. The `trpl::join` function is similar, but for futures. When you give it two futures, it produces a single new future whose output is a tuple containing the output of each future you passed in once they *both* complete. Thus, in Listing 17-8, we use `trpl::join` to wait for both `fut1` and `fut2` to finish. We do *not* await `fut1` and `fut2` but instead the new future produced by `trpl::join`. We ignore the output, because it's just a tuple containing two unit values.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
        let fut1 = async {
            for i in 1..10 {
                println!("hi number {i} from the first task!");
                trpl::sleep(Duration::from_millis(500)).await;
```

```
            }
        };

        let fut2 = async {
            for i in 1..5 {
                         println!("hi number {i} from the second
task!");
                trpl::sleep(Duration::from_millis(500)).await;
            }
        };

        trpl::join(fut1, fut2).await;
#     });
# }
```

When we run this, we see both futures run to completion:

```
hi number 1 from the first task!
hi number 1 from the second task!
hi number 2 from the first task!
hi number 2 from the second task!
hi number 3 from the first task!
hi number 3 from the second task!
hi number 4 from the first task!
hi number 4 from the second task!
hi number 5 from the first task!
hi number 6 from the first task!
hi number 7 from the first task!
hi number 8 from the first task!
hi number 9 from the first task!
```

Now, you'll see the exact same order every time, which is very different from what we saw with threads. That is because the `trpl::join` function is *fair*, meaning it checks each future equally often, alternating between them, and never lets one race ahead if the other is ready. With threads, the operating system decides which thread to check and how long to let it run. With async Rust, the runtime decides which task to check. (In practice, the details get complicated because an async runtime might use operating system threads under the hood as part of how it manages concurrency, so guaranteeing fairness can be more work for a runtime—but it's still possible!) Runtimes don't have to guarantee fairness for any given operation, and they often offer different APIs to let you choose whether or not you want fairness.

Try some of these variations on awaiting the futures and see what they do:

- Remove the async block from around either or both of the loops.
- Await each async block immediately after defining it.
- Wrap only the first loop in an async block, and await the resulting future after the body of second loop.

For an extra challenge, see if you can figure out what the output will be in each case *before* running the code!

Counting Up on Two Tasks Using Message Passing

Sharing data between futures will also be familiar: we'll use message passing again, but this time with async versions of the types and functions. We'll take a slightly different path than we did in Using Message Passing to Transfer Data Between Threads to illustrate some of the key differences between thread-based and futures-based concurrency. In Listing 17-9, we'll begin with just a single async block—*not* spawning a separate task as we spawned a separate thread.

```
# extern crate trpl; // required for mdbook test
#
# fn main() {
#     trpl::run(async {
        let (tx, mut rx) = trpl::channel();

        let val = String::from("hi");
        tx.send(val).unwrap();

        let received = rx.recv().await.unwrap();
```

```
        println!("Got: {received}");
#     });
# }
```

Here, we use `trpl::channel`, an async version of the multiple-producer, single-consumer channel API we used with threads back in Chapter 16. The async version of the API is only a little different from the thread-based version: it uses a mutable rather than an immutable receiver `rx`, and its `recv` method produces a future we need to await rather than producing the value directly. Now we can send messages from the sender to the receiver. Notice that we don't have to spawn a separate thread or even a task; we merely need to await the `rx.recv` call.

The synchronous `Receiver::recv` method in `std::mpsc::channel` blocks until it receives a message. The `trpl::Receiver::recv` method does not, because it is async. Instead of blocking, it hands control back to the runtime until either a message is received or the send side of the channel closes. By contrast, we don't await the `send` call, because it doesn't block. It doesn't need to, because the channel we're sending it into is unbounded.

> Note: Because all of this async code runs in an async block in a `trpl::run` call, everything within it can avoid blocking. However, the code *outside* it will block on the `run` function returning. That's the whole point of the `trpl::run` function: it lets you *choose* where to block on some set of async code, and thus where to transition between sync and async code. In most async runtimes, `run` is actually named `block_on` for exactly this reason.

Notice two things about this example. First, the message will arrive right away. Second, although we use a future here, there's no concurrency yet. Everything in the listing happens in sequence, just as it would if there were no futures involved.

Let's address the first part by sending a series of messages and sleeping in between them, as shown in Listing 17-10.

```
# extern crate trpl; // required for mdbook test
#
```

```rust
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
        let (tx, mut rx) = trpl::channel();

        let vals = vec![
            String::from("hi"),
            String::from("from"),
            String::from("the"),
            String::from("future"),
        ];

        for val in vals {
            tx.send(val).unwrap();
            trpl::sleep(Duration::from_millis(500)).await;
        }

        while let Some(value) = rx.recv().await {
            println!("received '{value}'");
        }
#     });
# }
```

In addition to sending the messages, we need to receive them. In this case, because we know how many messages are coming in, we could do that manually by calling `rx.recv().await` four times. In the real world, though, we'll generally be waiting on some *unknown* number of messages, so we need to keep waiting until we determine that there are no more messages.

In Listing 16-10, we used a `for` loop to process all the items received from a synchronous channel. Rust doesn't yet have a way to write a `for` loop over an *asynchronous* series of items, however, so we need to use a loop we haven't seen before: the `while let` conditional loop. This is the loop version of the `if let` construct we saw back in the section Concise

[Control Flow with `if let` and `let else`](). The loop will continue executing as long as the pattern it specifies continues to match the value.

The `rx.recv` call produces a future, which we await. The runtime will pause the future until it is ready. Once a message arrives, the future will resolve to `Some(message)` as many times as a message arrives. When the channel closes, regardless of whether *any* messages have arrived, the future will instead resolve to `None` to indicate that there are no more values and thus we should stop polling—that is, stop awaiting.

The `while let` loop pulls all of this together. If the result of calling `rx.recv().await` is `Some(message)`, we get access to the message and we can use it in the loop body, just as we could with `if let`. If the result is `None`, the loop ends. Every time the loop completes, it hits the await point again, so the runtime pauses it again until another message arrives.

The code now successfully sends and receives all of the messages. Unfortunately, there are still a couple of problems. For one thing, the messages do not arrive at half-second intervals. They arrive all at once, 2 seconds (2,000 milliseconds) after we start the program. For another, this program never exits! Instead, it waits forever for new messages. You will need to shut it down using ctrl-c.

Let's start by examining why the messages come in all at once after the full delay, rather than coming in with delays between each one. Within a given async block, the order in which `await` keywords appear in the code is also the order in which they're executed when the program runs.

There's only one async block in Listing 17-10, so everything in it runs linearly. There's still no concurrency. All the `tx.send` calls happen, interspersed with all of the `trpl::sleep` calls and their associated await points. Only then does the `while let` loop get to go through any of the `await` points on the `recv` calls.

To get the behavior we want, where the sleep delay happens between each message, we need to put the `tx` and `rx` operations in their own async blocks, as shown in Listing 17-11. Then the runtime can execute each of them separately using `trpl::join`, just as in the counting example. Once again, we await the result of calling `trpl::join`, not the individual futures.

If we awaited the individual futures in sequence, we would just end up back in a sequential flow—exactly what we're trying *not* to do.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
#         let (tx, mut rx) = trpl::channel();
#
        let tx_fut = async {
            let vals = vec![
                String::from("hi"),
                String::from("from"),
                String::from("the"),
                String::from("future"),
            ];

            for val in vals {
                tx.send(val).unwrap();
                trpl::sleep(Duration::from_millis(500)).await;
            }
        };

        let rx_fut = async {
            while let Some(value) = rx.recv().await {
                println!("received '{value}'");
            }
        };

        trpl::join(tx_fut, rx_fut).await;
#     });
# }
```

With the updated code in Listing 17-11, the messages get printed at 500-millisecond intervals, rather than all in a rush after 2 seconds.

The program still never exits, though, because of the way the `while let` loop interacts with `trpl::join`:

- The future returned from `trpl::join` completes only once *both* futures passed to it have completed.
- The `tx` future completes once it finishes sleeping after sending the last message in `vals`.
- The `rx` future won't complete until the `while let` loop ends.
- The `while let` loop won't end until awaiting `rx.recv` produces `None`.
- Awaiting `rx.recv` will return `None` only once the other end of the channel is closed.
- The channel will close only if we call `rx.close` or when the sender side, `tx`, is dropped.
- We don't call `rx.close` anywhere, and `tx` won't be dropped until the outermost async block passed to `trpl::run` ends.
- The block can't end because it is blocked on `trpl::join` completing, which takes us back to the top of this list.

We could manually close `rx` by calling `rx.close` somewhere, but that doesn't make much sense. Stopping after handling some arbitrary number of messages would make the program shut down, but we could miss messages. We need some other way to make sure that `tx` gets dropped *before* the end of the function.

Right now, the async block where we send the messages only borrows `tx` because sending a message doesn't require ownership, but if we could move `tx` into that async block, it would be dropped once that block ends. In the Chapter 13 section [Capturing References or Moving Ownership](), you learned how to use the `move` keyword with closures, and, as discussed in the Chapter 16 section [Using `move` Closures with Threads](), we often need to move data into closures when working with threads. The same basic dynamics apply to async blocks, so the `move` keyword works with async blocks just as it does with closures.

In Listing 17-12, we change the block used to send messages from `async` to `async move`. When we run *this* version of the code, it shuts down gracefully after the last message is sent and received.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
        let (tx, mut rx) = trpl::channel();

        let tx_fut = async move {
            let vals = vec![
                String::from("hi"),
                String::from("from"),
                String::from("the"),
                String::from("future"),
            ];

            for val in vals {
                tx.send(val).unwrap();
                trpl::sleep(Duration::from_millis(500)).await;
            }
        };

        let rx_fut = async {
            while let Some(value) = rx.recv().await {
                println!("received '{value}'");
            }
        };

        trpl::join(tx_fut, rx_fut).await;
#     });
# }
```

This async channel is also a multiple-producer channel, so we can call `clone` on `tx` if we want to send messages from multiple futures, as shown in Listing 17-13.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
        let (tx, mut rx) = trpl::channel();

        let tx1 = tx.clone();
        let tx1_fut = async move {
            let vals = vec![
                String::from("hi"),
                String::from("from"),
                String::from("the"),
                String::from("future"),
            ];

            for val in vals {
                tx1.send(val).unwrap();
                trpl::sleep(Duration::from_millis(500)).await;
            }
        };

        let rx_fut = async {
            while let Some(value) = rx.recv().await {
                println!("received '{value}'");
            }
        };

        let tx_fut = async move {
            let vals = vec![
                String::from("more"),
```

```
                String::from("messages"),
                String::from("for"),
                String::from("you"),
            ];

            for val in vals {
                tx.send(val).unwrap();

trpl::sleep(Duration::from_millis(1500)).await;
            }
        };

        trpl::join3(tx1_fut, tx_fut, rx_fut).await;
#     });
# }
```

First, we clone `tx`, creating `tx1` outside the first async block. We move `tx1` into that block just as we did before with `tx`. Then, later, we move the original `tx` into a *new* async block, where we send more messages on a slightly slower delay. We happen to put this new async block after the async block for receiving messages, but it could go before it just as well. The key is the order in which the futures are awaited, not in which they're created.

Both of the async blocks for sending messages need to be `async move` blocks so that both `tx` and `tx1` get dropped when those blocks finish. Otherwise, we'll end up back in the same infinite loop we started out in. Finally, we switch from `trpl::join` to `trpl::join3` to handle the additional future.

Now we see all the messages from both sending futures, and because the sending futures use slightly different delays after sending, the messages are also received at those different intervals.

```
received 'hi'
received 'more'
received 'from'
received 'the'
received 'messages'
```

```
received 'future'
received 'for'
received 'you'
```

This is a good start, but it limits us to just a handful of futures: two with `join`, or three with `join3`. Let's see how we might work with more futures.

Working with Any Number of Futures

When we switched from using two futures to three in the previous section, we also had to switch from using `join` to using `join3`. It would be annoying to have to call a different function every time we changed the number of futures we wanted to join. Happily, we have a macro form of `join` to which we can pass an arbitrary number of arguments. It also handles awaiting the futures itself. Thus, we could rewrite the code from Listing 17-13 to use `join!` instead of `join3`, as in Listing 17-14.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
#         let (tx, mut rx) = trpl::channel();
#
#         let tx1 = tx.clone();
#         let tx1_fut = async move {
#             let vals = vec![
#                 String::from("hi"),
#                 String::from("from"),
#                 String::from("the"),
#                 String::from("future"),
#             ];
#
#             for val in vals {
#                 tx1.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
#         let rx_fut = async {
#             while let Some(value) = rx.recv().await {
#                 println!("received '{value}'");
```

```
#             }
#         };
#
#         let tx_fut = async move {
#             let vals = vec![
#                 String::from("more"),
#                 String::from("messages"),
#                 String::from("for"),
#                 String::from("you"),
#             ];
#
#             for val in vals {
#                 tx.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
        trpl::join!(tx1_fut, tx_fut, rx_fut);
#     });
# }
```

This is definitely an improvement over swapping between `join` and `join3` and `join4` and so on! However, even this macro form only works when we know the number of futures ahead of time. In real-world Rust, though, pushing futures into a collection and then waiting on some or all the futures of them to complete is a common pattern.

To check all the futures in some collection, we'll need to iterate over and join on *all* of them. The `trpl::join_all` function accepts any type that implements the `Iterator` trait, which you learned about back in [The Iterator Trait and the `next` Method]() Chapter 13, so it seems like just the ticket. Let's try putting our futures in a vector and replacing `join!` with `join_all` as shown in Listing 17-15.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
```

```
#
# fn main() {
#     trpl::run(async {
#         let (tx, mut rx) = trpl::channel();
#
#         let tx1 = tx.clone();
#         let tx1_fut = async move {
#             let vals = vec![
#                 String::from("hi"),
#                 String::from("from"),
#                 String::from("the"),
#                 String::from("future"),
#             ];
#
#             for val in vals {
#                 tx1.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
#         let rx_fut = async {
#             while let Some(value) = rx.recv().await {
#                 println!("received '{value}'");
#             }
#         };
#
#         let tx_fut = async move {
#             let vals = vec![
#                 String::from("more"),
#                 String::from("messages"),
#                 String::from("for"),
#                 String::from("you"),
#             ];
#
#             for val in vals {
#                 tx.send(val).unwrap();
```

```
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
        let futures = vec![tx1_fut, rx_fut, tx_fut];

        trpl::join_all(futures).await;
#     });
# }
```

Unfortunately, this code doesn't compile. Instead, we get this error:

```
error[E0308]: mismatched types
  --> src/main.rs:45:37
   |
10 |         let tx1_fut = async move {
   |                       ---------- the expected `async`
block
...
24 |         let rx_fut = async {
   |                      ----- the found `async` block
...
45 |         let futures = vec![tx1_fut, rx_fut, tx_fut];
   |                                     ^^^^^^ expected
`async` block, found a different `async` block
   |
   = note: expected `async` block `{async
block@src/main.rs:10:23: 10:33}`
              found `async` block `{async
block@src/main.rs:24:22: 24:27}`
   = note: no two async blocks, even if identical, have the
same type
   = help: consider pinning your async block and casting it to
a trait object
```

This might be surprising. After all, none of the async blocks returns anything, so each one produces a `Future<Output = ()>`. Remember that

`Future` is a trait, though, and that the compiler creates a unique enum for each async block. You can't put two different hand-written structs in a `Vec`, and the same rule applies to the different enums generated by the compiler.

To make this work, we need to use *trait objects*, just as we did in "Returning Errors from the run function" in Chapter 12. (We'll cover trait objects in detail in Chapter 18.) Using trait objects lets us treat each of the anonymous futures produced by these types as the same type, because all of them implement the `Future` trait.

> Note: In Using an Enum to Store Multiple Values in Chapter 8, we discussed another way to include multiple types in a `Vec`: using an enum to represent each type that can appear in the vector. We can't do that here, though. For one thing, we have no way to name the different types, because they are anonymous. For another, the reason we reached for a vector and `join_all` in the first place was to be able to work with a dynamic collection of futures where we only care that they have the same output type.

We start by wrapping each future in the `vec!` in a `Box::new`, as shown in Listing 17-16.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
#         let (tx, mut rx) = trpl::channel();
#
#         let tx1 = tx.clone();
#         let tx1_fut = async move {
#             let vals = vec![
#                 String::from("hi"),
#                 String::from("from"),
#                 String::from("the"),
#                 String::from("future"),
```

```
#             ];
#
#             for val in vals {
#                 tx1.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
#         let rx_fut = async {
#             while let Some(value) = rx.recv().await {
#                 println!("received '{value}'");
#             }
#         };
#
#         let tx_fut = async move {
#             let vals = vec![
#                 String::from("more"),
#                 String::from("messages"),
#                 String::from("for"),
#                 String::from("you"),
#             ];
#
#             for val in vals {
#                 tx.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
        let futures =
                    vec![Box::new(tx1_fut), Box::new(rx_fut),
Box::new(tx_fut)];

        trpl::join_all(futures).await;
#     });
# }
```

Unfortunately, this code still doesn't compile. In fact, we get the same basic error we got before for both the second and third `Box::new` calls, as well as new errors referring to the `Unpin` trait. We'll come back to the `Unpin` errors in a moment. First, let's fix the type errors on the `Box::new` calls by explicitly annotating the type of the `futures` variable (see Listing 17-17).

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
#         let (tx, mut rx) = trpl::channel();
#
#         let tx1 = tx.clone();
#         let tx1_fut = async move {
#             let vals = vec![
#                 String::from("hi"),
#                 String::from("from"),
#                 String::from("the"),
#                 String::from("future"),
#             ];
#
#             for val in vals {
#                 tx1.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
#         let rx_fut = async {
#             while let Some(value) = rx.recv().await {
#                 println!("received '{value}'");
#             }
#         };
#
```

```
#         let tx_fut = async move {
#             let vals = vec![
#                 String::from("more"),
#                 String::from("messages"),
#                 String::from("for"),
#                 String::from("you"),
#             ];
#
#             for val in vals {
#                 tx.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
        let futures: Vec<Box<dyn Future<Output = ()>>> =
                     vec![Box::new(tx1_fut),  Box::new(rx_fut),
Box::new(tx_fut)];
#
#         trpl::join_all(futures).await;
#     });
# }
```

This type declaration is a little involved, so let's walk through it:

1. The innermost type is the future itself. We note explicitly that the output of the future is the unit type `()` by writing `Future<Output = ()>`.
2. Then we annotate the trait with `dyn` to mark it as dynamic.
3. The entire trait reference is wrapped in a `Box`.
4. Finally, we state explicitly that `futures` is a `Vec` containing these items.

That already made a big difference. Now when we run the compiler, we get only the errors mentioning `Unpin`. Although there are three of them, their contents are very similar.

```
error[E0277]: `dyn Future<Output = ()>` cannot be unpinned
   --> src/main.rs:49:24
    |
49  |         trpl::join_all(futures).await;
    |          -------------- ^^^^^^^ the trait `Unpin` is not
implemented for `dyn Future<Output = ()>`
    |         |
    |         required by a bound introduced by this call
    |
    = note: consider using the `pin!` macro
            consider using `Box::pin` if you need to access
the pinned value outside of the current scope
    = note: required for `Box<dyn Future<Output = ()>>` to
implement `Future`
note: required by a bound in `join_all`
   -->  file:///home/.cargo/registry/src/index.crates.io-
1949cf8c6b5b557f/futures-util-
0.3.30/src/future/join_all.rs:105:14
    |
102 | pub fn join_all<I>(iter: I) -> JoinAll<I::Item>
    |        -------- required by a bound in this function
...
105 |     I::Item: Future,
    |              ^^^^^^ required by this bound in `join_all`

error[E0277]: `dyn Future<Output = ()>` cannot be unpinned
  --> src/main.rs:49:9
   |
49 |         trpl::join_all(futures).await;
   |         ^^^^^^^^^^^^^^^^^^^^^^^ the trait `Unpin` is not
implemented for `dyn Future<Output = ()>`
   |
   = note: consider using the `pin!` macro
           consider using `Box::pin` if you need to access the
pinned value outside of the current scope
```

```
    = note: required for `Box<dyn Future<Output = ()>>` to
implement `Future`
note: required by a bound in
`futures_util::future::join_all::JoinAll`
      --> file:///home/.cargo/registry/src/index.crates.io-
1949cf8c6b5b557f/futures-util-
0.3.30/src/future/join_all.rs:29:8
   |
27 | pub struct JoinAll<F>
   |            ------- required by a bound in this struct
28 | where
29 |     F: Future,
   |        ^^^^^^ required by this bound in `JoinAll`

error[E0277]: `dyn Future<Output = ()>` cannot be unpinned
  --> src/main.rs:49:33
   |
49 |         trpl::join_all(futures).await;
   |                                 ^^^^^ the trait `Unpin`
is not implemented for `dyn Future<Output = ()>`
   |
   = note: consider using the `pin!` macro
           consider using `Box::pin` if you need to access the
pinned value outside of the current scope
    = note: required for `Box<dyn Future<Output = ()>>` to
implement `Future`
note: required by a bound in
`futures_util::future::join_all::JoinAll`
      --> file:///home/.cargo/registry/src/index.crates.io-
1949cf8c6b5b557f/futures-util-
0.3.30/src/future/join_all.rs:29:8
   |
27 | pub struct JoinAll<F>
   |            ------- required by a bound in this struct
28 | where
29 |     F: Future,
```

```
   |        ^^^^^^ required by this bound in `JoinAll`

For more information about this error, try `rustc --explain
E0277`.
error: could not compile `async_await` (bin "async_await") due
to 3 previous errors
```

That is a *lot* to digest, so let's pull it apart. The first part of the message tell us that the first async block (`src/main.rs:8:23: 20:10`) does not implement the `Unpin` trait and suggests using `pin!` or `Box::pin` to resolve it. Later in the chapter, we'll dig into a few more details about `Pin` and `Unpin`. For the moment, though, we can just follow the compiler's advice to get unstuck. In Listing 17-18, we start by importing `Pin` from `std::pin`. Next we update the type annotation for `futures`, with a `Pin` wrapping each `Box`. Finally, we use `Box::pin` to pin the futures themselves.

```
# extern crate trpl; // required for mdbook test
#
use std::pin::Pin;

// -- snip --

# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
#         let (tx, mut rx) = trpl::channel();
#
#         let tx1 = tx.clone();
#         let tx1_fut = async move {
#             let vals = vec![
#                 String::from("hi"),
#                 String::from("from"),
#                 String::from("the"),
#                 String::from("future"),
```

```
#             ];
#
#             for val in vals {
#                 tx1.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
#         let rx_fut = async {
#             while let Some(value) = rx.recv().await {
#                 println!("received '{value}'");
#             }
#         };
#
#         let tx_fut = async move {
#             let vals = vec![
#                 String::from("more"),
#                 String::from("messages"),
#                 String::from("for"),
#                 String::from("you"),
#             ];
#
#             for val in vals {
#                 tx.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
#         };
#
        let futures: Vec<Pin<Box<dyn Future<Output = ()>>>> =
                    vec![Box::pin(tx1_fut), Box::pin(rx_fut),
Box::pin(tx_fut)];
#
#         trpl::join_all(futures).await;
#     });
# }
```

If we compile and run this, we finally get the output we hoped for:

```
received 'hi'
received 'more'
received 'from'
received 'messages'
received 'the'
received 'for'
received 'future'
received 'you'
```

Phew!

There's a bit more to explore here. For one thing, using `Pin<Box<T>>` adds a small amount of overhead from putting these futures on the heap with `Box`—and we're only doing that to get the types to line up. We don't actually *need* the heap allocation, after all: these futures are local to this particular function. As noted before, `Pin` is itself a wrapper type, so we can get the benefit of having a single type in the `Vec`—the original reason we reached for `Box`—without doing a heap allocation. We can use `Pin` directly with each future, using the `std::pin::pin` macro.

However, we must still be explicit about the type of the pinned reference; otherwise, Rust will still not know to interpret these as dynamic trait objects, which is what we need them to be in the `Vec`. We therefore add `pin` to our list of imports from `std::pin`. Then we can `pin!` each future when we define it and define `futures` as a `Vec` containing pinned mutable references to the dynamic future type, as in Listing 17-19.

```
# extern crate trpl; // required for mdbook test
#
use std::pin::{Pin, pin};

// -- snip --

# use std::time::Duration;
#
# fn main() {
```

```
#     trpl::run(async {
#         let (tx, mut rx) = trpl::channel();
#
#         let tx1 = tx.clone();
        let tx1_fut = pin!(async move {
            // --snip--
#             let vals = vec![
#                 String::from("hi"),
#                 String::from("from"),
#                 String::from("the"),
#                 String::from("future"),
#             ];
#
#             for val in vals {
#                 tx1.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
        });

        let rx_fut = pin!(async {
            // --snip--
#             while let Some(value) = rx.recv().await {
#                 println!("received '{value}'");
#             }
        });

        let tx_fut = pin!(async move {
            // --snip--
#             let vals = vec![
#                 String::from("more"),
#                 String::from("messages"),
#                 String::from("for"),
#                 String::from("you"),
#             ];
#
#             for val in vals {
```

```
#                 tx.send(val).unwrap();
#                 trpl::sleep(Duration::from_secs(1)).await;
#             }
        });

        let futures: Vec<Pin<&mut dyn Future<Output = ()>>> =
            vec![tx1_fut, rx_fut, tx_fut];
#
#         trpl::join_all(futures).await;
#     });
# }
```

We got this far by ignoring the fact that we might have different `Output` types. For example, in Listing 17-20, the anonymous future for `a` implements `Future<Output = u32>`, the anonymous future for `b` implements `Future<Output = &str>`, and the anonymous future for `c` implements `Future<Output = bool>`.

```
# extern crate trpl; // required for mdbook test
#
# fn main() {
#     trpl::run(async {
        let a = async { 1u32 };
        let b = async { "Hello!" };
        let c = async { true };

        let (a_result, b_result, c_result) = trpl::join!(a, b,
c);
        println!("{a_result}, {b_result}, {c_result}");
#     });
# }
```

We can use `trpl::join!` to await them, because it allows us to pass in multiple future types and produces a tuple of those types. We *cannot* use `trpl::join_all`, because it requires all of the futures passed in to have the same type. Remember, that error is what got us started on this adventure with `Pin`!

This is a fundamental tradeoff: we can either deal with a dynamic number of futures with `join_all`, as long as they all have the same type, or we can deal with a set number of futures with the `join` functions or the `join!` macro, even if they have different types. This is the same scenario we'd face when working with any other types in Rust. Futures are not special, even though we have some nice syntax for working with them, and that's a good thing.

Racing Futures

When we "join" futures with the `join` family of functions and macros, we require *all* of them to finish before we move on. Sometimes, though, we only need *some* future from a set to finish before we move on—kind of similar to racing one future against another.

In Listing 17-21, we once again use `trpl::race` to run two futures, `slow` and `fast`, against each other.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
        let slow = async {
            println!("'slow' started.");
            trpl::sleep(Duration::from_millis(100)).await;
            println!("'slow' finished.");
        };

        let fast = async {
            println!("'fast' started.");
            trpl::sleep(Duration::from_millis(50)).await;
            println!("'fast' finished.");
        };

        trpl::race(slow, fast).await;
```

```
#     });
# }
```

Each future prints a message when it starts running, pauses for some amount of time by calling and awaiting `sleep`, and then prints another message when it finishes. Then we pass both `slow` and `fast` to `trpl::race` and wait for one of them to finish. (The outcome here isn't too surprising: `fast` wins.) Unlike when we used `race` back in "Our First Async Program", we just ignore the `Either` instance it returns here, because all of the interesting behavior happens in the body of the async blocks.

Notice that if you flip the order of the arguments to `race`, the order of the "started" messages changes, even though the `fast` future always completes first. That's because the implementation of this particular `race` function is not fair. It always runs the futures passed in as arguments in the order in which they're passed. Other implementations *are* fair and will randomly choose which future to poll first. Regardless of whether the implementation of race we're using is fair, though, *one* of the futures will run up to the first `await` in its body before another task can start.

Recall from Our First Async Program that at each await point, Rust gives a runtime a chance to pause the task and switch to another one if the future being awaited isn't ready. The inverse is also true: Rust *only* pauses async blocks and hands control back to a runtime at an await point. Everything between await points is synchronous.

That means if you do a bunch of work in an async block without an await point, that future will block any other futures from making progress. You may sometimes hear this referred to as one future *starving* other futures. In some cases, that may not be a big deal. However, if you are doing some kind of expensive setup or long-running work, or if you have a future that will keep doing some particular task indefinitely, you'll need to think about when and where to hand control back to the runtime.

By the same token, if you have long-running blocking operations, async can be a useful tool for providing ways for different parts of the program to relate to each other.

But *how* would you hand control back to the runtime in those cases?

Yielding Control to the Runtime

Let's simulate a long-running operation. Listing 17-22 introduces a `slow` function.

```
# extern crate trpl; // required for mdbook test
#
# use std::{thread, time::Duration};
#
# fn main() {
#     trpl::run(async {
#         // We will call `slow` here later
#     });
# }
#
fn slow(name: &str, ms: u64) {
    thread::sleep(Duration::from_millis(ms));
    println!("'{name}' ran for {ms}ms");
}
```

This code uses `std::thread::sleep` instead of `trpl::sleep` so that calling `slow` will block the current thread for some number of milliseconds. We can use `slow` to stand in for real-world operations that are both long-running and blocking.

In Listing 17-23, we use `slow` to emulate doing this kind of CPU-bound work in a pair of futures.

```
# extern crate trpl; // required for mdbook test
#
# use std::{thread, time::Duration};
#
# fn main() {
#     trpl::run(async {
        let a = async {
            println!("'a' started.");
            slow("a", 30);
```

```
            slow("a", 10);
            slow("a", 20);
            trpl::sleep(Duration::from_millis(50)).await;
            println!("'a' finished.");
        };

        let b = async {
            println!("'b' started.");
            slow("b", 75);
            slow("b", 10);
            slow("b", 15);
            slow("b", 350);
            trpl::sleep(Duration::from_millis(50)).await;
            println!("'b' finished.");
        };

        trpl::race(a, b).await;
#     });
# }
#
# fn slow(name: &str, ms: u64) {
#     thread::sleep(Duration::from_millis(ms));
#     println!("'{name}' ran for {ms}ms");
# }
```

To begin, each future only hands control back to the runtime *after* carrying out a bunch of slow operations. If you run this code, you will see this output:

```
'a' started.
'a' ran for 30ms
'a' ran for 10ms
'a' ran for 20ms
'b' started.
'b' ran for 75ms
'b' ran for 10ms
'b' ran for 15ms
```

```
'b' ran for 350ms
'a' finished.
```

As with our earlier example, `race` still finishes as soon as `a` is done. There's no interleaving between the two futures, though. The `a` future does all of its work until the `trpl::sleep` call is awaited, then the `b` future does all of its work until its own `trpl::sleep` call is awaited, and finally the `a` future completes. To allow both futures to make progress between their slow tasks, we need await points so we can hand control back to the runtime. That means we need something we can await!

We can already see this kind of handoff happening in Listing 17-23: if we removed the `trpl::sleep` at the end of the `a` future, it would complete without the `b` future running *at all*. Let's try using the `sleep` function as a starting point for letting operations switch off making progress, as shown in Listing 17-24.

```
# extern crate trpl; // required for mdbook test
#
# use std::{thread, time::Duration};
#
# fn main() {
#     trpl::run(async {
        let one_ms = Duration::from_millis(1);

        let a = async {
            println!("'a' started.");
            slow("a", 30);
            trpl::sleep(one_ms).await;
            slow("a", 10);
            trpl::sleep(one_ms).await;
            slow("a", 20);
            trpl::sleep(one_ms).await;
            println!("'a' finished.");
        };

        let b = async {
```

```
            println!("'b' started.");
            slow("b", 75);
            trpl::sleep(one_ms).await;
            slow("b", 10);
            trpl::sleep(one_ms).await;
            slow("b", 15);
            trpl::sleep(one_ms).await;
            slow("b", 350);
            trpl::sleep(one_ms).await;
            println!("'b' finished.");
        };
#
#         trpl::race(a, b).await;
#     });
# }
#
# fn slow(name: &str, ms: u64) {
#     thread::sleep(Duration::from_millis(ms));
#     println!("'{name}' ran for {ms}ms");
# }
```

In Listing 17-24, we add `trpl::sleep` calls with await points between each call to `slow`. Now the two futures' work is interleaved:

```
'a' started.
'a' ran for 30ms
'b' started.
'b' ran for 75ms
'a' ran for 10ms
'b' ran for 10ms
'a' ran for 20ms
'b' ran for 15ms
'a' finished.
```

The `a` future still runs for a bit before handing off control to `b`, because it calls `slow` before ever calling `trpl::sleep`, but after that the futures swap back and forth each time one of them hits an await point. In this case, we have done that after every call to `slow`, but we could break up the work in whatever way makes the most sense to us.

We don't really want to *sleep* here, though: we want to make progress as fast as we can. We just need to hand back control to the runtime. We can do that directly, using the `yield_now` function. In Listing 17-25, we replace all those `sleep` calls with `yield_now`.

```
# extern crate trpl; // required for mdbook test
#
# use std::{thread, time::Duration};
#
# fn main() {
#     trpl::run(async {
        let a = async {
            println!("'a' started.");
            slow("a", 30);
            trpl::yield_now().await;
            slow("a", 10);
            trpl::yield_now().await;
            slow("a", 20);
            trpl::yield_now().await;
            println!("'a' finished.");
        };

        let b = async {
            println!("'b' started.");
            slow("b", 75);
            trpl::yield_now().await;
            slow("b", 10);
            trpl::yield_now().await;
            slow("b", 15);
            trpl::yield_now().await;
            slow("b", 350);
            trpl::yield_now().await;
            println!("'b' finished.");
        };
```

```
#
#         trpl::race(a, b).await;
#     });
# }
#
# fn slow(name: &str, ms: u64) {
#     thread::sleep(Duration::from_millis(ms));
#     println!("'{name}' ran for {ms}ms");
# }
```

This code is both clearer about the actual intent and can be significantly faster than using `sleep`, because timers such as the one used by `sleep` often have limits on how granular they can be. The version of `sleep` we are using, for example, will always sleep for at least a millisecond, even if we pass it a `Duration` of one nanosecond. Again, modern computers are *fast*: they can do a lot in one millisecond!

You can see this for yourself by setting up a little benchmark, such as the one in Listing 17-26. (This isn't an especially rigorous way to do performance testing, but it suffices to show the difference here.)

```
# extern crate trpl; // required for mdbook test
#
# use std::time::{Duration, Instant};
#
# fn main() {
#     trpl::run(async {
        let one_ns = Duration::from_nanos(1);
        let start = Instant::now();
        async {
            for _ in 1..1000 {
                trpl::sleep(one_ns).await;
            }
        }
        .await;
        let time = Instant::now() - start;
        println!(
```

```
            "'sleep' version finished after {} seconds.",
            time.as_secs_f32()
        );

        let start = Instant::now();
        async {
            for _ in 1..1000 {
                trpl::yield_now().await;
            }
        }
        .await;
        let time = Instant::now() - start;
        println!(
            "'yield' version finished after {} seconds.",
            time.as_secs_f32()
        );
#     });
# }
```

Here, we skip all the status printing, pass a one-nanosecond `Duration` to `trpl::sleep`, and let each future run by itself, with no switching between the futures. Then we run for 1,000 iterations and see how long the future using `trpl::sleep` takes compared to the future using `trpl::yield_now`.

The version with `yield_now` is *way* faster!

This means that async can be useful even for compute-bound tasks, depending on what else your program is doing, because it provides a useful tool for structuring the relationships between different parts of the program. This is a form of *cooperative multitasking*, where each future has the power to determine when it hands over control via await points. Each future therefore also has the responsibility to avoid blocking for too long. In some Rust-based embedded operating systems, this is the *only* kind of multitasking!

In real-world code, you won't usually be alternating function calls with await points on every single line, of course. While yielding control in this way is relatively inexpensive, it's not free. In many cases, trying to break up a compute-bound task might make it significantly slower, so sometimes it's better for *overall* performance to let an operation block briefly. Always measure to see what your code's actual performance bottlenecks are. The underlying dynamic is important to keep in mind, though, if you *are* seeing a lot of work happening in serial that you expected to happen concurrently!

Building Our Own Async Abstractions

We can also compose futures together to create new patterns. For example, we can build a `timeout` function with async building blocks we already have. When we're done, the result will be another building block we could use to create still more async abstractions.

Listing 17-27 shows how we would expect this `timeout` to work with a slow future.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
        let slow = async {
            trpl::sleep(Duration::from_millis(100)).await;
            "I finished!"
        };

        match timeout(slow, Duration::from_millis(10)).await {
                         Ok(message)  =>  println!("Succeeded  with
'{message}'"),
            Err(duration) => {
                          println!("Failed  after  {}  seconds",
duration.as_secs())
            }
        }
#     });
# }
```

Let’s implement this! To begin, let’s think about the API for `timeout`:

- It needs to be an async function itself so we can await it.
- Its first parameter should be a future to run. We can make it generic to allow it to work with any future.
- Its second parameter will be the maximum time to wait. If we use a `Duration`, that will make it easy to pass along to `trpl::sleep`.
- It should return a `Result`. If the future completes successfully, the `Result` will be `Ok` with the value produced by the future. If the timeout elapses first, the `Result` will be `Err` with the duration that the timeout waited for.

Listing 17-28 shows this declaration.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
# fn main() {
#     trpl::run(async {
#         let slow = async {
#             trpl::sleep(Duration::from_secs(5)).await;
#             "Finally finished"
#         };
#
#         match timeout(slow, Duration::from_millis(10)).await
{
#                     Ok(message) => println!("Succeeded with
'{message}'"),
#             Err(duration) => {
#                         println!("Failed after {} seconds",
duration.as_secs())
#             }
#         }
#     });
# }
#
```

```
async fn timeout<F: Future>(
    future_to_try: F,
    max_time: Duration,
) -> Result<F::Output, Duration> {
    // Here is where our implementation will go!
}
```

That satisfies our goals for the types. Now let's think about the *behavior* we need: we want to race the future passed in against the duration. We can use `trpl::sleep` to make a timer future from the duration, and use `trpl::race` to run that timer with the future the caller passes in.

We also know that `race` is not fair, polling arguments in the order in which they are passed. Thus, we pass `future_to_try` to `race` first so it gets a chance to complete even if `max_time` is a very short duration. If `future_to_try` finishes first, `race` will return `Left` with the output from `future_to_try`. If `timer` finishes first, `race` will return `Right` with the timer's output of `()`.

In Listing 17-29, we match on the result of awaiting `trpl::race`.

```
# extern crate trpl; // required for mdbook test
#
# use std::time::Duration;
#
use trpl::Either;

// --snip--

fn main() {
    trpl::run(async {
        let slow = async {
            trpl::sleep(Duration::from_secs(5)).await;
            "Finally finished"
        };

        match timeout(slow, Duration::from_secs(2)).await {
```

```
                     Ok(message) => println!("Succeeded with
'{message}'"),
            Err(duration) => {
                             println!("Failed after {} seconds",
duration.as_secs())
            }
        }
    });
}

async fn timeout<F: Future>(
    future_to_try: F,
    max_time: Duration,
) -> Result<F::Output, Duration> {
                          match      trpl::race(future_to_try,
trpl::sleep(max_time)).await {
        Either::Left(output) => Ok(output),
        Either::Right(_) => Err(max_time),
    }
# }
```

If the `future_to_try` succeeds and we get a `Left(output)`, we return `Ok(output)`. If the sleep timer elapses instead and we get a `Right(())`, we ignore the `()` with `_` and return `Err(max_time)` instead.

With that, we have a working `timeout` built out of two other async helpers. If we run our code, it will print the failure mode after the timeout:

```
Failed after 2 seconds
```

Because futures compose with other futures, you can build really powerful tools using smaller async building blocks. For example, you can use this same approach to combine timeouts with retries, and in turn use those with operations such as network calls (one of the examples from the beginning of the chapter).

In practice, you'll usually work directly with `async` and `await`, and secondarily with functions and macros such as `join`, `join_all`, `race`, and so on. You’ll only need to reach for `pin` now and again to use futures with those APIs.

We’ve now seen a number of ways to work with multiple futures at the same time. Up next, we’ll look at how we can work with multiple futures in a sequence over time with *streams*. Here are a couple more things you might want to consider first, though:

- We used a `Vec` with `join_all` to wait for all of the futures in some group to finish. How could you use a `Vec` to process a group of futures in sequence instead? What are the tradeoffs of doing that?
- Take a look at the `futures::stream::FuturesUnordered` type from the `futures` crate. How would using it be different from using a `Vec`? (Don’t worry about the fact that it’s from the `stream` part of the crate; it works just fine with any collection of futures.)

Streams: Futures in Sequence

So far in this chapter, we've mostly stuck to individual futures. The one big exception was the async channel we used. Recall how we used the receiver for our async channel earlier in this chapter in the "Message Passing" section. The async `recv` method produces a sequence of items over time. This is an instance of a much more general pattern known as a *stream*.

We saw a sequence of items back in Chapter 13, when we looked at the `Iterator` trait in The Iterator Trait and the `next` Method section, but there are two differences between iterators and the async channel receiver. The first difference is time: iterators are synchronous, while the channel receiver is asynchronous. The second is the API. When working directly with `Iterator`, we call its synchronous `next` method. With the `trpl::Receiver` stream in particular, we called an asynchronous `recv` method instead. Otherwise, these APIs feel very similar, and that similarity isn't a coincidence. A stream is like an asynchronous form of iteration. Whereas the `trpl::Receiver` specifically waits to receive messages, though, the general-purpose stream API is much broader: it provides the next item the way `Iterator` does, but asynchronously.

The similarity between iterators and streams in Rust means we can actually create a stream from any iterator. As with an iterator, we can work with a stream by calling its `next` method and then awaiting the output, as in Listing 17-30.

```
# extern crate trpl; // required for mdbook test
#
# fn main() {
#     trpl::run(async {
        let values = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10];
        let iter = values.iter().map(|n| n * 2);
        let mut stream = trpl::stream_from_iter(iter);

        while let Some(value) = stream.next().await {
            println!("The value was: {value}");
```

```
        }
#     });
# }
```

We start with an array of numbers, which we convert to an iterator and then call `map` on to double all the values. Then we convert the iterator into a stream using the `trpl::stream_from_iter` function. Next, we loop over the items in the stream as they arrive with the `while let` loop.

Unfortunately, when we try to run the code, it doesn't compile, but instead it reports that there's no `next` method available:

```
error[E0599]: no method named `next` found for struct `Iter`
in the current scope
  --> src/main.rs:10:40
   |
10 |         while let Some(value) = stream.next().await {
   |                                        ^^^^
   |
      = note: the full type name has been written to
'file:///projects/async-await/target/debug/deps/async_await-
575db3dd3197d257.long-type-14490787947592691573.txt'
   = note: consider using `--verbose` to print the full type
name to the console
   = help: items from traits can only be used if the trait is
in scope
help: the following traits which provide `next` are
implemented but not in scope; perhaps you want to import one
of them
   |
1  + use crate::trpl::StreamExt;
   |
1  + use futures_util::stream::stream::StreamExt;
   |
1  + use std::iter::Iterator;
   |
1  + use std::str::pattern::Searcher;
```

```
   |
help: there is a method `try_next` with a similar name
   |
10 |         while let Some(value) = stream.try_next().await {
   |                                        ~~~~~~~~
```

As this output explains, the reason for the compiler error is that we need the right trait in scope to be able to use the `next` method. Given our discussion so far, you might reasonably expect that trait to be `Stream`, but it's actually `StreamExt`. Short for *extension*, `Ext` is a common pattern in the Rust community for extending one trait with another.

We'll explain the `Stream` and `StreamExt` traits in a bit more detail at the end of the chapter, but for now all you need to know is that the `Stream` trait defines a low-level interface that effectively combines the `Iterator` and `Future` traits. `StreamExt` supplies a higher-level set of APIs on top of `Stream`, including the `next` method as well as other utility methods similar to those provided by the `Iterator` trait. `Stream` and `StreamExt` are not yet part of Rust's standard library, but most ecosystem crates use the same definition.

The fix to the compiler error is to add a `use` statement for `trpl::StreamExt`, as in Listing 17-31.

```
# extern crate trpl; // required for mdbook test
#
use trpl::StreamExt;

fn main() {
    trpl::run(async {
        let values = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10];
        let iter = values.iter().map(|n| n * 2);
        let mut stream = trpl::stream_from_iter(iter);

        while let Some(value) = stream.next().await {
            println!("The value was: {value}");
        }
```

```
    });
}
```

With all those pieces put together, this code works the way we want! What's more, now that we have `StreamExt` in scope, we can use all of its utility methods, just as with iterators. For example, in Listing 17-32, we use the `filter` method to filter out everything but multiples of three and five.

```
# extern crate trpl; // required for mdbook test
#
use trpl::StreamExt;

fn main() {
    trpl::run(async {
        let values = 1..101;
        let iter = values.map(|n| n * 2);
        let stream = trpl::stream_from_iter(iter);

        let mut filtered =
            stream.filter(|value| value % 3 == 0 || value % 5
== 0);

        while let Some(value) = filtered.next().await {
            println!("The value was: {value}");
        }
    });
}
```

Of course, this isn't very interesting, since we could do the same with normal iterators and without any async at all. Let's look at what we can do that *is* unique to streams.

Composing Streams

Many concepts are naturally represented as streams: items becoming available in a queue, chunks of data being pulled incrementally from the filesystem when the full data set is too large for the computer's memory, or data arriving over the network over time. Because streams are futures, we can use them with any other kind of future and combine them in interesting ways. For example, we can batch up events to avoid triggering too many network calls, set timeouts on sequences of long-running operations, or throttle user interface events to avoid doing needless work.

Let's start by building a little stream of messages as a stand-in for a stream of data we might see from a WebSocket or another real-time communication protocol, as shown in Listing 17-33.

```
# extern crate trpl; // required for mdbook test
#
use trpl::{ReceiverStream, Stream, StreamExt};

fn main() {
    trpl::run(async {
        let mut messages = get_messages();

        while let Some(message) = messages.next().await {
            println!("{message}");
        }
    });
}

fn get_messages() -> impl Stream<Item = String> {
    let (tx, rx) = trpl::channel();

    let messages = ["a", "b", "c", "d", "e", "f", "g", "h",
"i", "j"];
    for message in messages {
        tx.send(format!("Message: '{message}'")).unwrap();
    }

    ReceiverStream::new(rx)
}
```

First, we create a function called `get_messages` that returns `impl Stream<Item = String>`. For its implementation, we create an async channel, loop over the first 10 letters of the English alphabet, and send them across the channel.

We also use a new type: `ReceiverStream`, which converts the `rx` receiver from the `trpl::channel` into a `Stream` with a `next` method. Back in `main`, we use a `while let` loop to print all the messages from the stream.

When we run this code, we get exactly the results we would expect:

```
Message: 'a'
Message: 'b'
Message: 'c'
Message: 'd'
Message: 'e'
Message: 'f'
Message: 'g'
Message: 'h'
Message: 'i'
Message: 'j'
```

Again, we could do this with the regular `Receiver` API or even the regular `Iterator` API, though, so let's add a feature that requires streams: adding a timeout that applies to every item in the stream, and a delay on the items we emit, as shown in Listing 17-34.

```
# extern crate trpl; // required for mdbook test
#
use std::{pin::pin, time::Duration};
use trpl::{ReceiverStream, Stream, StreamExt};

fn main() {
    trpl::run(async {
        let mut messages =
                                                           pin!
(get_messages().timeout(Duration::from_millis(200)));

        while let Some(result) = messages.next().await {
            match result {
```

```
                Ok(message) => println!("{message}"),
                           Err(reason)  =>  eprintln!("Problem:
{reason:?}"),
            }
        }
    })
}
#
# fn get_messages() -> impl Stream<Item = String> {
#     let (tx, rx) = trpl::channel();
#
#     let messages = ["a", "b", "c", "d", "e", "f", "g", "h",
"i", "j"];
#     for message in messages {
#         tx.send(format!("Message: '{message}'")).unwrap();
#     }
#
#     ReceiverStream::new(rx)
# }
```

We start by adding a timeout to the stream with the `timeout` method, which comes from the `StreamExt` trait. Then we update the body of the `while let` loop, because the stream now returns a `Result`. The `Ok` variant indicates a message arrived in time; the `Err` variant indicates that the timeout elapsed before any message arrived. We `match` on that result and either print the message when we receive it successfully or print a notice about the timeout. Finally, notice that we pin the messages after applying the timeout to them, because the timeout helper produces a stream that needs to be pinned to be polled.

However, because there are no delays between messages, this timeout does not change the behavior of the program. Let’s add a variable delay to the messages we send, as shown in Listing 17-35.

```
# extern crate trpl; // required for mdbook test
#
# use std::{pin::pin, time::Duration};
```

```
#
# use trpl::{ReceiverStream, Stream, StreamExt};
#
# fn main() {
#     trpl::run(async {
#         let mut messages =
#                                                                    pin!
(get_messages().timeout(Duration::from_millis(200)));
#
#         while let Some(result) = messages.next().await {
#             match result {
#                 Ok(message) => println!("{message}"),
#                          Err(reason)  =>  eprintln!("Problem:
{reason:?}"),
#             }
#         }
#     })
# }
#
fn get_messages() -> impl Stream<Item = String> {
    let (tx, rx) = trpl::channel();

    trpl::spawn_task(async move {
          let messages = ["a", "b", "c", "d", "e", "f", "g",
"h", "i", "j"];
                               for    (index,    message)    in
messages.into_iter().enumerate() {
            let time_to_sleep = if index % 2 == 0 { 100 } else
{ 300 };

trpl::sleep(Duration::from_millis(time_to_sleep)).await;

            tx.send(format!("Message: '{message}'")).unwrap();
        }
    });
```

```
    ReceiverStream::new(rx)
}
```

In `get_messages`, we use the `enumerate` iterator method with the `messages` array so that we can get the index of each item we're sending along with the item itself. Then we apply a 100-millisecond delay to even-index items and a 300-millisecond delay to odd-index items to simulate the different delays we might see from a stream of messages in the real world. Because our timeout is for 200 milliseconds, this should affect half of the messages.

To sleep between messages in the `get_messages` function without blocking, we need to use async. However, we can't make `get_messages` itself into an async function, because then we'd return a `Future<Output = Stream<Item = String>>` instead of a `Stream<Item = String>>`. The caller would have to await `get_messages` itself to get access to the stream. But remember: everything in a given future happens linearly; concurrency happens *between* futures. Awaiting `get_messages` would require it to send all the messages, including the sleep delay between each message, before returning the receiver stream. As a result, the timeout would be useless. There would be no delays in the stream itself; they would all happen before the stream was even available.

Instead, we leave `get_messages` as a regular function that returns a stream, and we spawn a task to handle the async `sleep` calls.

> Note: Calling `spawn_task` in this way works because we already set up our runtime; had we not, it would cause a panic. Other implementations choose different tradeoffs: they might spawn a new runtime and avoid the panic but end up with a bit of extra overhead, or they may simply not provide a standalone way to spawn tasks without reference to a runtime. Make sure you know what tradeoff your runtime has chosen and write your code accordingly!

Now our code has a much more interesting result. Between every other pair of messages, a `Problem: Elapsed(())` error.

```
Message: 'a'
Problem: Elapsed(())
Message: 'b'
Message: 'c'
Problem: Elapsed(())
Message: 'd'
Message: 'e'
Problem: Elapsed(())
Message: 'f'
Message: 'g'
Problem: Elapsed(())
Message: 'h'
Message: 'i'
Problem: Elapsed(())
Message: 'j'
```

The timeout doesn't prevent the messages from arriving in the end. We still get all of the original messages, because our channel is *unbounded*: it can hold as many messages as we can fit in memory. If the message doesn't arrive before the timeout, our stream handler will account for that, but when it polls the stream again, the message may now have arrived.

You can get different behavior if needed by using other kinds of channels or other kinds of streams more generally. Let's see one of those in practice by combining a stream of time intervals with this stream of messages.

Merging Streams

First, let's create another stream, which will emit an item every millisecond if we let it run directly. For simplicity, we can use the `sleep` function to send a message on a delay and combine it with the same approach we used in `get_messages` of creating a stream from a channel. The difference is that this time, we're going to send back the count of intervals that have elapsed, so the return type will be `impl Stream<Item = u32>`, and we can call the function `get_intervals` (see Listing 17-36).

```
# extern crate trpl; // required for mdbook test
#
# use std::{pin::pin, time::Duration};
#
# use trpl::{ReceiverStream, Stream, StreamExt};
#
# fn main() {
#     trpl::run(async {
#         let mut messages =
#                                                                  pin!
(get_messages().timeout(Duration::from_millis(200)));
#
#         while let Some(result) = messages.next().await {
#             match result {
#                 Ok(message) => println!("{message}"),
#                          Err(reason)  =>  eprintln!("Problem:
{reason:?}"),
#             }
#         }
#     })
# }
#
# fn get_messages() -> impl Stream<Item = String> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
#          let messages = ["a", "b", "c", "d", "e", "f", "g",
"h", "i", "j"];
#                               for   (index,   message)   in
messages.into_iter().enumerate() {
#              let time_to_sleep = if index % 2 == 0 { 100 }
else { 300 };
#
trpl::sleep(Duration::from_millis(time_to_sleep)).await;
#
```

```
#                                    tx.send(format!("Message:
'{message}'")).unwrap();
#          }
#      });
#
#      ReceiverStream::new(rx)
# }
#
fn get_intervals() -> impl Stream<Item = u32> {
    let (tx, rx) = trpl::channel();

    trpl::spawn_task(async move {
        let mut count = 0;
        loop {
            trpl::sleep(Duration::from_millis(1)).await;
            count += 1;
            tx.send(count).unwrap();
        }
    });

    ReceiverStream::new(rx)
}
```

We start by defining a `count` in the task. (We could define it outside the task, too, but it's clearer to limit the scope of any given variable.) Then we create an infinite loop. Each iteration of the loop asynchronously sleeps for one millisecond, increments the count, and then sends it over the channel. Because this is all wrapped in the task created by `spawn_task`, all of it—including the infinite loop—will get cleaned up along with the runtime.

This kind of infinite loop, which ends only when the whole runtime gets torn down, is fairly common in async Rust: many programs need to keep running indefinitely. With async, this doesn't block anything else, as long as there is at least one await point in each iteration through the loop.

Now, back in our main function's async block, we can attempt to merge the `messages` and `intervals` streams, as shown in Listing 17-37.

```
# extern crate trpl; // required for mdbook test
#
# use std::{pin::pin, time::Duration};
#
# use trpl::{ReceiverStream, Stream, StreamExt};
#
# fn main() {
#     trpl::run(async {
                                        let     messages     =
get_messages().timeout(Duration::from_millis(200));
        let intervals = get_intervals();
        let merged = messages.merge(intervals);
#
#         while let Some(result) = merged.next().await {
#             match result {
#                 Ok(message) => println!("{message}"),
#                          Err(reason)  =>  eprintln!("Problem:
{reason:?}"),
#             }
#         }
#     })
# }
#
# fn get_messages() -> impl Stream<Item = String> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
#          let messages = ["a", "b", "c", "d", "e", "f", "g",
"h", "i", "j"];
#                               for   (index,   message)   in
messages.into_iter().enumerate() {
#              let time_to_sleep = if index % 2 == 0 { 100 }
else { 300 };
#
trpl::sleep(Duration::from_millis(time_to_sleep)).await;
```

```
#
#                                     tx.send(format!("Message:
'{message}'")).unwrap();
#         }
#     });
#
#     ReceiverStream::new(rx)
# }
#
# fn get_intervals() -> impl Stream<Item = u32> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
#         let mut count = 0;
#         loop {
#             trpl::sleep(Duration::from_millis(1)).await;
#             count += 1;
#             tx.send(count).unwrap();
#         }
#     });
#
#     ReceiverStream::new(rx)
# }
```

We start by calling `get_intervals`. Then we merge the `messages` and `intervals` streams with the `merge` method, which combines multiple streams into one stream that produces items from any of the source streams as soon as the items are available, without imposing any particular ordering. Finally, we loop over that combined stream instead of over `messages`.

At this point, neither `messages` nor `intervals` needs to be pinned or mutable, because both will be combined into the single `merged` stream. However, this call to `merge` doesn't compile! (Neither does the `next` call in the `while let` loop, but we'll come back to that.) This is because the two streams have different types. The `messages` stream has the type `Timeout<impl Stream<Item = String>>`, where `Timeout` is the type that implements `Stream` for a `timeout` call. The `intervals` stream has the type `impl Stream<Item = u32>`. To merge these two streams, we need to transform one of them to match the other. We'll rework the intervals stream, because messages is already in the basic format we want and has to handle timeout errors (see Listing 17-38).

```
# extern crate trpl; // required for mdbook test
#
# use std::{pin::pin, time::Duration};
#
# use trpl::{ReceiverStream, Stream, StreamExt};
#
# fn main() {
#     trpl::run(async {
        let messages = get_messages().timeout(Duration::from_millis(200));
        let intervals = get_intervals()
            .map(|count| format!("Interval: {count}"))
            .timeout(Duration::from_secs(10));
        let merged = messages.merge(intervals);
        let mut stream = pin!(merged);
#
#         while let Some(result) = stream.next().await {
#             match result {
#                 Ok(message) => println!("{message}"),
#                 Err(reason) => eprintln!("Problem: {reason:?}"),
#             }
#         }
#     })
# }
#
# fn get_messages() -> impl Stream<Item = String> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
```

```
#         let messages = ["a", "b", "c", "d", "e", "f", "g",
"h", "i", "j"];
#                               for   (index,   message)   in
messages.into_iter().enumerate() {
#               let time_to_sleep = if index % 2 == 0 { 100 }
else { 300 };
#
trpl::sleep(Duration::from_millis(time_to_sleep)).await;
#
#                                    tx.send(format!("Message:
'{message}'")).unwrap();
#         }
#     });
#
#     ReceiverStream::new(rx)
# }
#
# fn get_intervals() -> impl Stream<Item = u32> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
#         let mut count = 0;
#         loop {
#             trpl::sleep(Duration::from_millis(1)).await;
#             count += 1;
#             tx.send(count).unwrap();
#         }
#     });
#
#     ReceiverStream::new(rx)
# }
```

First, we can use the `map` helper method to transform the `intervals` into a string. Second, we need to match the `Timeout` from `messages`. Because we don't actually *want* a timeout for `intervals`, though, we can just create a timeout which is longer than the other durations we are using.

Here, we create a 10-second timeout with `Duration::from_secs(10)`. Finally, we need to make `stream` mutable, so that the `while let` loop's `next` calls can iterate through the stream, and pin it so that it's safe to do so. That gets us *almost* to where we need to be. Everything type checks. If you run this, though, there will be two problems. First, it will never stop! You'll need to stop it with ctrl-c. Second, the messages from the English alphabet will be buried in the midst of all the interval counter messages:

```
--snip--
Interval: 38
Interval: 39
Interval: 40
Message: 'a'
Interval: 41
Interval: 42
Interval: 43
--snip--
```

Listing 17-39 shows one way to solve these last two problems.

```
# extern crate trpl; // required for mdbook test
#
# use std::{pin::pin, time::Duration};
#
# use trpl::{ReceiverStream, Stream, StreamExt};
#
# fn main() {
#     trpl::run(async {
        let messages = get_messages().timeout(Duration::from_millis(200));
        let intervals = get_intervals()
            .map(|count| format!("Interval: {count}"))
            .throttle(Duration::from_millis(100))
            .timeout(Duration::from_secs(10));
        let merged = messages.merge(intervals).take(20);
        let mut stream = pin!(merged);
#
```

```
#         while let Some(result) = stream.next().await {
#             match result {
#                 Ok(message) => println!("{message}"),
#                          Err(reason)  =>  eprintln!("Problem:
{reason:?}"),
#             }
#         }
#     })
# }
#
# fn get_messages() -> impl Stream<Item = String> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
#          let messages = ["a", "b", "c", "d", "e", "f", "g",
"h", "i", "j"];
#                               for   (index,   message)   in
messages.into_iter().enumerate() {
#               let time_to_sleep = if index % 2 == 0 { 100 }
else { 300 };
#
trpl::sleep(Duration::from_millis(time_to_sleep)).await;
#
#                                   tx.send(format!("Message:
'{message}'")).unwrap();
#         }
#     });
#
#     ReceiverStream::new(rx)
# }
#
# fn get_intervals() -> impl Stream<Item = u32> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
#         let mut count = 0;
```

```
#         loop {
#             trpl::sleep(Duration::from_millis(1)).await;
#             count += 1;
#             tx.send(count).unwrap();
#         }
#     });
#
#     ReceiverStream::new(rx)
# }
```

First, we use the `throttle` method on the `intervals` stream so that it doesn't overwhelm the `messages` stream. *Throttling* is a way of limiting the rate at which a function will be called—or, in this case, how often the stream will be polled. Once every 100 milliseconds should do, because that's roughly how often our messages arrive.

To limit the number of items we will accept from a stream, we apply the `take` method to the `merged` stream, because we want to limit the final output, not just one stream or the other.

Now when we run the program, it stops after pulling 20 items from the stream, and the intervals don't overwhelm the messages. We also don't get `Interval: 100` or `Interval: 200` or so on, but instead get `Interval: 1`, `Interval: 2`, and so on—even though we have a source stream that *can* produce an event every millisecond. That's because the `throttle` call produces a new stream that wraps the original stream so that the original stream gets polled only at the throttle rate, not its own "native" rate. We don't have a bunch of unhandled interval messages we're choosing to ignore. Instead, we never produce those interval messages in the first place! This is the inherent "laziness" of Rust's futures at work again, allowing us to choose our performance characteristics.

```
Interval: 1
Message: 'a'
Interval: 2
Interval: 3
Problem: Elapsed(())
Interval: 4
```

```
Message: 'b'
Interval: 5
Message: 'c'
Interval: 6
Interval: 7
Problem: Elapsed(())
Interval: 8
Message: 'd'
Interval: 9
Message: 'e'
Interval: 10
Interval: 11
Problem: Elapsed(())
Interval: 12
```

There's one last thing we need to handle: errors! With both of these channel-based streams, the `send` calls could fail when the other side of the channel closes—and that's just a matter of how the runtime executes the futures that make up the stream. Up until now, we've ignored this possibility by calling `unwrap`, but in a well-behaved app, we should explicitly handle the error, at minimum by ending the loop so we don't try to send any more messages. Listing 17-40 shows a simple error strategy: print the issue and then `break` from the loops.

```
# extern crate trpl; // required for mdbook test
#
# use std::{pin::pin, time::Duration};
#
# use trpl::{ReceiverStream, Stream, StreamExt};
#
# fn main() {
#     trpl::run(async {
#                                          let     messages     =
get_messages().timeout(Duration::from_millis(200));
#         let intervals = get_intervals()
#             .map(|count| format!("Interval #{count}"))
#             .throttle(Duration::from_millis(500))
```

```
#             .timeout(Duration::from_secs(10));
#         let merged = messages.merge(intervals).take(20);
#         let mut stream = pin!(merged);
#
#         while let Some(result) = stream.next().await {
#             match result {
#                 Ok(item) => println!("{item}"),
#                         Err(reason) => eprintln!("Problem:
{reason:?}"),
#             }
#         }
#     });
# }
#
fn get_messages() -> impl Stream<Item = String> {
    let (tx, rx) = trpl::channel();

    trpl::spawn_task(async move {
          let messages = ["a", "b", "c", "d", "e", "f", "g",
"h", "i", "j"];

                              for (index, message) in
messages.into_iter().enumerate() {
            let time_to_sleep = if index % 2 == 0 { 100 } else
{ 300 };

trpl::sleep(Duration::from_millis(time_to_sleep)).await;

            if let Err(send_error) = tx.send(format!("Message:
'{message}'")) {
                  eprintln!("Cannot send message '{message}':
{send_error}");
                break;
            }
        }
    });
```

```
    ReceiverStream::new(rx)
}

fn get_intervals() -> impl Stream<Item = u32> {
    let (tx, rx) = trpl::channel();

    trpl::spawn_task(async move {
        let mut count = 0;
        loop {
            trpl::sleep(Duration::from_millis(1)).await;
            count += 1;

            if let Err(send_error) = tx.send(count) {
                eprintln!("Could not send interval {count}:
{send_error}");
                break;
            };
        }
    });

    ReceiverStream::new(rx)
}
```

As usual, the correct way to handle a message send error will vary; just make sure you have a strategy.

Now that we've seen a bunch of async in practice, let's take a step back and dig into a few of the details of how `Future`, `Stream`, and the other key traits Rust uses to make async work.

A Closer Look at the Traits for Async

Throughout the chapter, we've used the `Future`, `Pin`, `Unpin`, `Stream`, and `StreamExt` traits in various ways. So far, though, we've avoided getting too far into the details of how they work or how they fit together, which is fine most of the time for your day-to-day Rust work. Sometimes, though, you'll encounter situations where you'll need to understand a few more of these details. In this section, we'll dig in just enough to help in those scenarios, still leaving the *really* deep dive for other documentation.

The `Future` Trait

Let's start by taking a closer look at how the `Future` trait works. Here's how Rust defines it:

```
use std::pin::Pin;
use std::task::{Context, Poll};

pub trait Future {
    type Output;

     fn poll(self: Pin<&mut Self>, cx: &mut Context<'_>) ->
Poll<Self::Output>;
}
```

That trait definition includes a bunch of new types and also some syntax we haven't seen before, so let's walk through the definition piece by piece.

First, `Future`'s associated type `Output` says what the future resolves to. This is analogous to the `Item` associated type for the `Iterator` trait. Second, `Future` also has the `poll` method, which takes a special `Pin` reference for its `self` parameter and a mutable reference to a `Context` type, and returns a `Poll<Self::Output>`. We'll talk more about `Pin` and `Context` in a moment. For now, let's focus on what the method returns, the `Poll` type:

```
enum Poll<T> {
    Ready(T),
```

```
    Pending,
}
```

This `Poll` type is similar to an `Option`. It has one variant that has a value, `Ready(T)`, and one which does not, `Pending`. `Poll` means something quite different from `Option`, though! The `Pending` variant indicates that the future still has work to do, so the caller will need to check again later. The `Ready` variant indicates that the future has finished its work and the `T` value is available.

> Note: With most futures, the caller should not call `poll` again after the future has returned `Ready`. Many futures will panic if polled again after becoming ready. Futures that are safe to poll again will say so explicitly in their documentation. This is similar to how `Iterator::next` behaves.

When you see code that uses `await`, Rust compiles it under the hood to code that calls `poll`. If you look back at Listing 17-4, where we printed out the page title for a single URL once it resolved, Rust compiles it into something kind of (although not exactly) like this:

```
match page_title(url).poll() {
    Ready(page_title) => match page_title {
            Some(title) => println!("The title for {url} was
{title}"),
        None => println!("{url} had no title"),
    }
    Pending => {
        // But what goes here?
    }
}
```

What should we do when the future is still `Pending`? We need some way to try again, and again, and again, until the future is finally ready. In other words, we need a loop:

```
let mut page_title_fut = page_title(url);
loop {
```

```
    match page_title_fut.poll() {
        Ready(value) => match page_title {
             Some(title) => println!("The title for {url} was
{title}"),
            None => println!("{url} had no title"),
        }
        Pending => {
            // continue
        }
    }
}
```

If Rust compiled it to exactly that code, though, every `await` would be blocking—exactly the opposite of what we were going for! Instead, Rust makes sure that the loop can hand off control to something that can pause work on this future to work on other futures and then check this one again later. As we've seen, that something is an async runtime, and this scheduling and coordination work is one of its main jobs.

Earlier in the chapter, we described waiting on `rx.recv`. The `recv` call returns a future, and awaiting the future polls it. We noted that a runtime will pause the future until it's ready with either `Some(message)` or `None` when the channel closes. With our deeper understanding of the `Future` trait, and specifically `Future::poll`, we can see how that works. The runtime knows the future isn't ready when it returns `Poll::Pending`. Conversely, the runtime knows the future *is* ready and advances it when `poll` returns `Poll::Ready(Some(message))` or `Poll::Ready(None)`.

The exact details of how a runtime does that are beyond the scope of this book, but the key is to see the basic mechanics of futures: a runtime *polls* each future it is responsible for, putting the future back to sleep when it is not yet ready.

The `Pin` and `Unpin` Traits

When we introduced the idea of pinning in Listing 17-16, we ran into a very gnarly error message. Here is the relevant part of it again:

```
error[E0277]: `{async block@src/main.rs:10:23: 10:33}` cannot
be unpinned
  --> src/main.rs:48:33
   |
48 |         trpl::join_all(futures).await;
   |                                 ^^^^^ the trait `Unpin`
is not implemented for `{async block@src/main.rs:10:23:
10:33}`
   |
   = note: consider using the `pin!` macro
           consider using `Box::pin` if you need to access the
pinned value outside of the current scope
   = note: required for `Box<{async block@src/main.rs:10:23:
10:33}>` to implement `Future`
note: required by a bound in
`futures_util::future::join_all::JoinAll`
  --> file:///home/.cargo/registry/src/index.crates.io-
1949cf8c6b5b557f/futures-util-
0.3.30/src/future/join_all.rs:29:8
   |
27 | pub struct JoinAll<F>
   |            ------- required by a bound in this struct
28 | where
29 |     F: Future,
   |        ^^^^^^ required by this bound in `JoinAll`
```

This error message tells us not only that we need to pin the values but also why pinning is required. The `trpl::join_all` function returns a struct called `JoinAll`. That struct is generic over a type `F`, which is constrained to implement the `Future` trait. Directly awaiting a future with `await` pins the future implicitly. That's why we don't need to use `pin!` everywhere we want to await futures.

However, we're not directly awaiting a future here. Instead, we construct a new future, `JoinAll`, by passing a collection of futures to the `join_all` function. The signature for `join_all` requires that the types of the items in the collection all implement the `Future` trait, and `Box<T>` implements `Future` only if the `T` it wraps is a future that implements the `Unpin` trait.

That's a lot to absorb! To really understand it, let's dive a little further into how the `Future` trait actually works, in particular around *pinning*.

Look again at the definition of the `Future` trait:

```
use std::pin::Pin;
use std::task::{Context, Poll};

pub trait Future {
    type Output;

    // Required method
      fn poll(self: Pin<&mut Self>, cx: &mut Context<'_>) ->
Poll<Self::Output>;
}
```

The `cx` parameter and its `Context` type are the key to how a runtime actually knows when to check any given future while still being lazy. Again, the details of how that works are beyond the scope of this chapter, and you generally only need to think about this when writing a custom `Future` implementation. We'll focus instead on the type for `self`, as this is the first time we've seen a method where `self` has a type annotation. A type annotation for `self` works like type annotations for other function parameters, but with two key differences:

- It tells Rust what type `self` must be for the method to be called.
- It can't be just any type. It's restricted to the type on which the method is implemented, a reference or smart pointer to that type, or a `Pin` wrapping a reference to that type.

We'll see more on this syntax in Chapter 18. For now, it's enough to know that if we want to poll a future to check whether it is `Pending` or `Ready(Output)`, we need a `Pin`-wrapped mutable reference to the type.

`Pin` is a wrapper for pointer-like types such as `&`, `&mut`, `Box`, and `Rc`. (Technically, `Pin` works with types that implement the `Deref` or `DerefMut` traits, but this is effectively equivalent to working only with pointers.) `Pin` is not a pointer itself and doesn't have any behavior of its own like `Rc` and `Arc` do with reference counting; it's purely a tool the compiler can use to enforce constraints on pointer usage.

Recalling that `await` is implemented in terms of calls to `poll` starts to explain the error message we saw earlier, but that was in terms of `Unpin`, not `Pin`. So how exactly does `Pin` relate to `Unpin`, and why does `Future` need `self` to be in a `Pin` type to call `poll`?

Remember from earlier in this chapter a series of await points in a future get compiled into a state machine, and the compiler makes sure that state machine follows all of Rust's normal rules around safety, including borrowing and ownership. To make that work, Rust looks at what data is needed between one await point and either the next await point or the end of the async block. It then creates a corresponding variant in the compiled state machine. Each variant gets the access it needs to the data that will be used in that section of the source code, whether by taking ownership of that data or by getting a mutable or immutable reference to it.

So far, so good: if we get anything wrong about the ownership or references in a given async block, the borrow checker will tell us. When we want to move around the future that corresponds to that block—like moving it into a `Vec` to pass to `join_all`—things get trickier.

When we move a future—whether by pushing it into a data structure to use as an iterator with `join_all` or by returning it from a function—that actually means moving the state machine Rust creates for us. And unlike most other types in Rust, the futures Rust creates for async blocks can end up with references to themselves in the fields of any given variant, as shown in the simplified illustration in Figure 17-4.

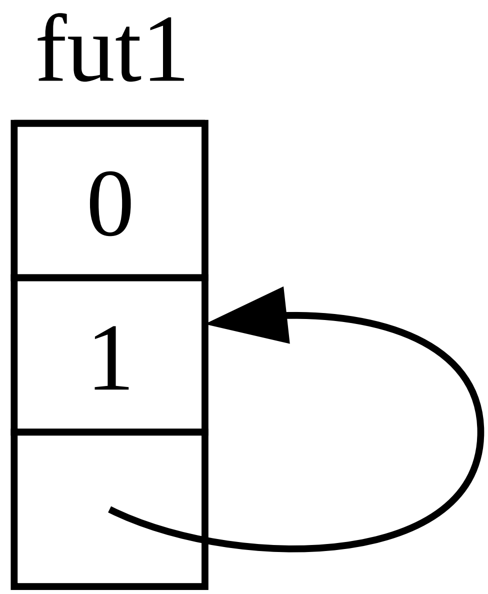


Figure 17-4: A self-referential data type.

By default, though, any object that has a reference to itself is unsafe to move, because references always point to the actual memory address of whatever they refer to (see Figure 17-5). If you move the data structure itself, those internal references will be left pointing to the old location. However, that memory location is now invalid. For one thing, its value will not be updated when you make changes to the data structure. For another—more important—thing, the computer is now free to reuse that memory for other purposes! You could end up reading completely unrelated data later.

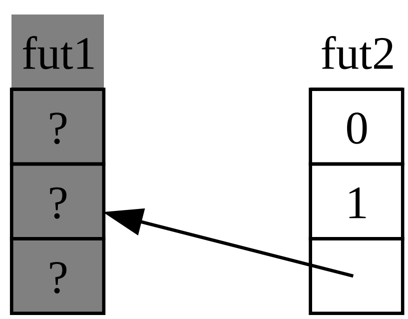


Figure 17-5: The unsafe result of moving a self-referential data type

Theoretically, the Rust compiler could try to update every reference to an object whenever it gets moved, but that could add a lot of performance overhead, especially if a whole web of references needs updating. If we could instead make sure the data structure in question *doesn't move in memory*, we wouldn't have to update any references. This is exactly what Rust's borrow checker requires: in safe code, it prevents you from moving any item with an active reference to it.

`Pin` builds on that to give us the exact guarantee we need. When we *pin* a value by wrapping a pointer to that value in `Pin`, it can no longer move. Thus, if you have `Pin<Box<SomeType>>`, you actually pin the `SomeType` value, *not* the `Box` pointer. Figure 17-6 illustrates this process.

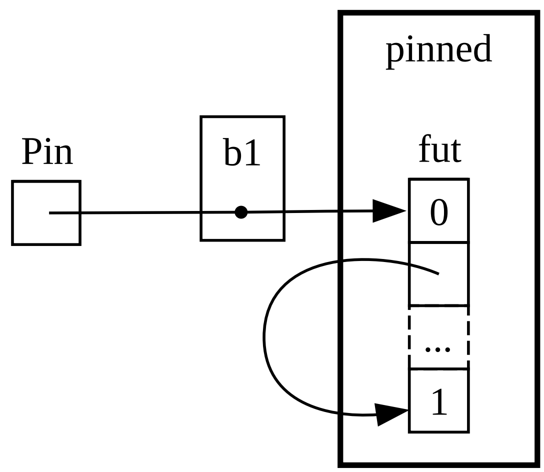


Figure 17-6: Pinning a `Box` that points to a self-referential future type.

In fact, the `Box` pointer can still move around freely. Remember: we care about making sure the data ultimately being referenced stays in place. If a pointer moves around, *but the data it points to is in the same place*, as in Figure 17-7, there's no potential problem. As an independent exercise, look at the docs for the types as well as the `std::pin` module and try to work out how you'd do this with a `Pin` wrapping a `Box`.) The key is that the self-referential type itself cannot move, because it is still pinned.

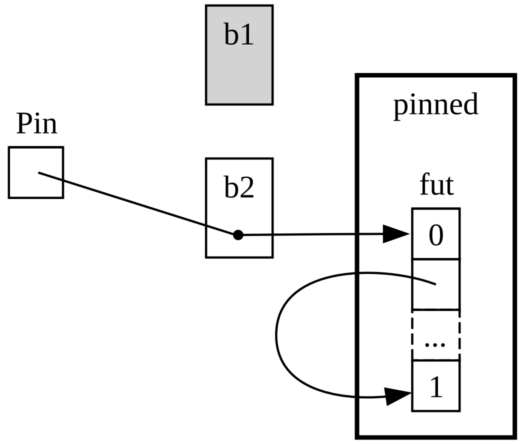


Figure 17-7: Moving a `Box` which points to a self-referential future type.

However, most types are perfectly safe to move around, even if they happen to be behind a `Pin` wrapper. We only need to think about pinning when items have internal references. Primitive values such as numbers and Booleans are safe because they obviously don't have any internal references. Neither do most types you normally work with in Rust. You can move around a `Vec`, for example, without worrying. Given only what we have seen so far, if you have a `Pin<Vec<String>>`, you'd have to do everything via the safe but restrictive APIs provided by `Pin`, even though a `Vec<String>` is always safe to move if there are no other references to it. We need a way to tell the compiler that it's fine to move items around in cases like this—and that's where `Unpin` comes into play.

`Unpin` is a marker trait, similar to the `Send` and `Sync` traits we saw in Chapter 16, and thus has no functionality of its own. Marker traits exist only to tell the compiler it's safe to use the type implementing a given trait in a particular context. `Unpin` informs the compiler that a given type does *not* need to uphold any guarantees about whether the value in question can be safely moved.

Just as with `Send` and `Sync`, the compiler implements `Unpin` automatically for all types where it can prove it is safe. A special case, again similar to `Send` and `Sync`, is where `Unpin` is *not* implemented for a type. The notation for this is `impl !Unpin for *SomeType*`, where

SomeType is the name of a type that *does* need to uphold those guarantees to be safe whenever a pointer to that type is used in a `Pin`.

In other words, there are two things to keep in mind about the relationship between `Pin` and `Unpin`. First, `Unpin` is the "normal" case, and `!Unpin` is the special case. Second, whether a type implements `Unpin` or `!Unpin` *only* matters when you're using a pinned pointer to that type like `Pin<&mut SomeType>`.

To make that concrete, think about a `String`: it has a length and the Unicode characters that make it up. We can wrap a `String` in `Pin`, as seen in Figure 17-8. However, `String` automatically implements `Unpin`, as do most other types in Rust.

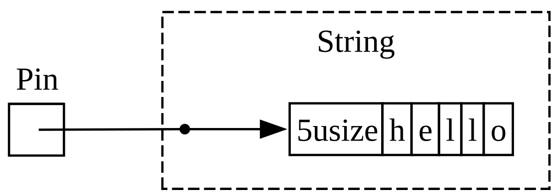


Figure 17-8: Pinning a `String`; the dotted line indicates that the `String` implements the `Unpin` trait, and thus is not pinned.

As a result, we can do things that would be illegal if `String` implemented `!Unpin` instead, such as replacing one string with another at the exact same location in memory as in Figure 17-9. This doesn't violate the `Pin` contract, because `String` has no internal references that make it unsafe to move around! That is precisely why it implements `Unpin` rather than `!Unpin`.

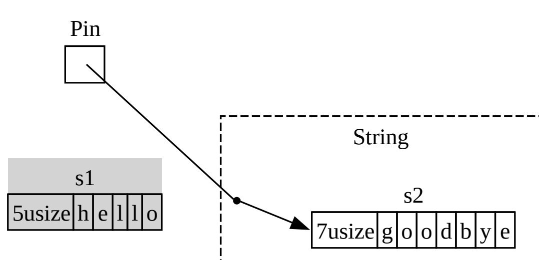


Figure 17-9: Replacing the `String` with an entirely different `String` in memory.

Now we know enough to understand the errors reported for that `join_all` call from back in Listing 17-17. We originally tried to move the futures produced by async blocks into a `Vec<Box<dyn Future<Output = ()>>>`, but as we've seen, those futures may have internal references, so they don't implement `Unpin`. They need to be pinned, and then we can pass the `Pin` type into the `Vec`, confident that the underlying data in the futures will *not* be moved.

`Pin` and `Unpin` are mostly important for building lower-level libraries, or when you're building a runtime itself, rather than for day-to-day Rust code. When you see these traits in error messages, though, now you'll have a better idea of how to fix your code!

> Note: This combination of `Pin` and `Unpin` makes it possible to safely implement a whole class of complex types in Rust that would otherwise prove challenging because they're self-referential. Types that require `Pin` show up most commonly in async Rust today, but every once in a while, you might see them in other contexts, too.
>
> The specifics of how `Pin` and `Unpin` work, and the rules they're required to uphold, are covered extensively in the API documentation for `std::pin`, so if you're interested in learning more, that's a great place to start.
>
> If you want to understand how things work under the hood in even more detail, see Chapters 2 and 4 of *Asynchronous Programming in Rust*.

The `Stream` Trait

Now that you have a deeper grasp on the `Future`, `Pin`, and `Unpin` traits, we can turn our attention to the `Stream` trait. As you learned earlier in the chapter, streams are similar to asynchronous iterators. Unlike `Iterator` and `Future`, however, `Stream` has no definition in the standard library as of this writing, but there *is* a very common definition from the `futures` crate used throughout the ecosystem.

Let’s review the definitions of the `Iterator` and `Future` traits before looking at how a `Stream` trait might merge them together. From `Iterator`, we have the idea of a sequence: its `next` method provides an `Option<Self::Item>`. From `Future`, we have the idea of readiness over time: its `poll` method provides a `Poll<Self::Output>`. To represent a sequence of items that become ready over time, we define a `Stream` trait that puts those features together:

```
use std::pin::Pin;
use std::task::{Context, Poll};

trait Stream {
    type Item;

    fn poll_next(
        self: Pin<&mut Self>,
        cx: &mut Context<'_>
    ) -> Poll<Option<Self::Item>>;
}
```

The `Stream` trait defines an associated type called `Item` for the type of the items produced by the stream. This is similar to `Iterator`, where there may be zero to many items, and unlike `Future`, where there is always a single `Output`, even if it’s the unit type `()`.

`Stream` also defines a method to get those items. We call it `poll_next`, to make it clear that it polls in the same way `Future::poll` does and produces a sequence of items in the same way `Iterator::next` does. Its return type combines `Poll` with `Option`. The outer type is `Poll`, because it has to be checked for readiness, just as a future does. The inner type is `Option`, because it needs to signal whether there are more messages, just as an iterator does.

Something very similar to this definition will likely end up as part of Rust’s standard library. In the meantime, it’s part of the toolkit of most runtimes, so you can rely on it, and everything we cover next should generally apply!

In the example we saw in the section on streaming, though, we didn't use `poll_next` *or* `Stream`, but instead used `next` and `StreamExt`. We *could* work directly in terms of the `poll_next` API by hand-writing our own `Stream` state machines, of course, just as we *could* work with futures directly via their `poll` method. Using `await` is much nicer, though, and the `StreamExt` trait supplies the `next` method so we can do just that:

```
# use std::pin::Pin;
# use std::task::{Context, Poll};
#
# trait Stream {
#     type Item;
#     fn poll_next(
#         self: Pin<&mut Self>,
#         cx: &mut Context<'_>,
#     ) -> Poll<Option<Self::Item>>;
# }
#
trait StreamExt: Stream {
    async fn next(&mut self) -> Option<Self::Item>
    where
        Self: Unpin;

    // other methods...
}
```

> Note: The actual definition we used earlier in the chapter looks slightly different than this, because it supports versions of Rust that did not yet support using async functions in traits. As a result, it looks like this:
>
> ```
> fn next(&mut self) -> Next<'_, Self> where Self: Unpin;
> ```
>
> That `Next` type is a `struct` that implements `Future` and allows us to name the lifetime of the reference to `self` with `Next<'_, Self>`, so that `await` can work with this method.

The `StreamExt` trait is also the home of all the interesting methods available to use with streams. `StreamExt` is automatically implemented for every type that implements `Stream`, but these traits are defined separately to enable the community to iterate on convenience APIs without affecting the foundational trait.

In the version of `StreamExt` used in the `trpl` crate, the trait not only defines the `next` method but also supplies a default implementation of `next` that correctly handles the details of calling `Stream::poll_next`. This means that even when you need to write your own streaming data type, you *only* have to implement `Stream`, and then anyone who uses your data type can use `StreamExt` and its methods with it automatically.

That's all we're going to cover for the lower-level details on these traits. To wrap up, let's consider how futures (including streams), tasks, and threads all fit together!

Putting It All Together: Futures, Tasks, and Threads

As we saw in Chapter 16, threads provide one approach to concurrency. We've seen another approach in this chapter: using async with futures and streams. If you‘re wondering when to choose method over the other, the answer is: it depends! And in many cases, the choice isn't threads *or* async but rather threads *and* async.

Many operating systems have supplied threading-based concurrency models for decades now, and many programming languages support them as a result. However, these models are not without their tradeoffs. On many operating systems, they use a fair bit of memory for each thread, and they come with some overhead for starting up and shutting down. Threads are also only an option when your operating system and hardware support them. Unlike mainstream desktop and mobile computers, some embedded systems don't have an OS at all, so they also don't have threads.

The async model provides a different—and ultimately complementary—set of tradeoffs. In the async model, concurrent operations don't require their own threads. Instead, they can run on tasks, as when we used `trpl::spawn_task` to kick off work from a synchronous function in the streams section. A task is similar to a thread, but instead of being managed by the operating system, it's managed by library-level code: the runtime.

In the previous section, we saw that we could build a stream by using an async channel and spawning an async task we could call from synchronous code. We can do the exact same thing with a thread. In Listing 17-40, we used `trpl::spawn_task` and `trpl::sleep`. In Listing 17-41, we replace those with the `thread::spawn` and `thread::sleep` APIs from the standard library in the `get_intervals` function.

```
# extern crate trpl; // required for mdbook test
#
# use std::{pin::pin, thread, time::Duration};
#
# use trpl::{ReceiverStream, Stream, StreamExt};

```

```
#
# fn main() {
#     trpl::run(async {
#                                          let    messages    =
get_messages().timeout(Duration::from_millis(200));
#         let intervals = get_intervals()
#             .map(|count| format!("Interval #{count}"))
#             .throttle(Duration::from_millis(500))
#             .timeout(Duration::from_secs(10));
#         let merged = messages.merge(intervals).take(20);
#         let mut stream = pin!(merged);
#
#         while let Some(result) = stream.next().await {
#             match result {
#                 Ok(item) => println!("{item}"),
#                         Err(reason)  =>  eprintln!("Problem:
{reason:?}"),
#             }
#         }
#     });
# }
#
# fn get_messages() -> impl Stream<Item = String> {
#     let (tx, rx) = trpl::channel();
#
#     trpl::spawn_task(async move {
#          let messages = ["a", "b", "c", "d", "e", "f", "g",
"h", "i", "j"];
#
#                              for   (index,   message)   in
messages.into_iter().enumerate() {
#               let time_to_sleep = if index % 2 == 0 { 100 }
else { 300 };
#
trpl::sleep(Duration::from_millis(time_to_sleep)).await;
#
```

```
#                   if let Err(send_error) = tx.send(format!
("Message: '{message}'")) {
#                   eprintln!("Cannot send message '{message}':
{send_error}");
#                   break;
#               }
#           }
#     });
#
#     ReceiverStream::new(rx)
# }
#
fn get_intervals() -> impl Stream<Item = u32> {
    let (tx, rx) = trpl::channel();

    // This is *not* `trpl::spawn` but `std::thread::spawn`!
    thread::spawn(move || {
        let mut count = 0;
        loop {
                // Likewise, this is *not* `trpl::sleep` but
`std::thread::sleep`!
            thread::sleep(Duration::from_millis(1));
            count += 1;

            if let Err(send_error) = tx.send(count) {
                eprintln!("Could not send interval {count}:
{send_error}");
                break;
            };
        }
    });

    ReceiverStream::new(rx)
}
```

If you run this code, the output is identical to that of Listing 17-40. And notice how little changes here from the perspective of the calling code. What's more, even though one of our functions spawned an async task on the runtime and the other spawned an OS thread, the resulting streams were unaffected by the differences.

Despite their similarities, these two approaches behave very differently, although we might have a hard time measuring it in this very simple example. We could spawn millions of async tasks on any modern personal computer. If we tried to do that with threads, we would literally run out of memory!

However, there's a reason these APIs are so similar. Threads act as a boundary for sets of synchronous operations; concurrency is possible *between* threads. Tasks act as a boundary for sets of *asynchronous* operations; concurrency is possible both *between* and *within* tasks, because a task can switch between futures in its body. Finally, futures are Rust's most granular unit of concurrency, and each future may represent a tree of other futures. The runtime—specifically, its executor—manages tasks, and tasks manage futures. In that regard, tasks are similar to lightweight, runtime-managed threads with added capabilities that come from being managed by a runtime instead of by the operating system.

This doesn't mean that async tasks are always better than threads (or vice versa). Concurrency with threads is in some ways a simpler programming model than concurrency with `async`. That can be a strength or a weakness. Threads are somewhat "fire and forget"; they have no native equivalent to a future, so they simply run to completion without being interrupted except by the operating system itself. That is, they have no built-in support for *intratask concurrency* the way futures do. Threads in Rust also have no mechanisms for cancellation—a subject we haven't covered explicitly in this chapter but was implied by the fact that whenever we ended a future, its state got cleaned up correctly.

These limitations also make threads harder to compose than futures. It's much more difficult, for example, to use threads to build helpers such as the `timeout` and `throttle` methods we built earlier in this chapter. The fact that futures are richer data structures means they can be composed together more naturally, as we have seen.

Tasks, then, give us *additional* control over futures, allowing us to choose where and how to group them. And it turns out that threads and tasks often work very well together, because tasks can (at least in some runtimes) be moved around between threads. In fact, under the hood, the runtime we've been using—including the `spawn_blocking` and `spawn_task` functions—is multithreaded by default! Many runtimes use an approach called *work stealing* to transparently move tasks around between threads, based on how the threads are currently being utilized, to improve the system's overall performance. That approach actually requires threads *and* tasks, and therefore futures.

When thinking about which method to use when, consider these rules of thumb:

- If the work is *very parallelizable*, such as processing a bunch of data where each part can be processed separately, threads are a better choice.
- If the work is *very concurrent*, such as handling messages from a bunch of different sources that may come in at different intervals or different rates, async is a better choice.

And if you need both parallelism and concurrency, you don't have to choose between threads and async. You can use them together freely, letting each one play the part it's best at. For example, Listing 17-42 shows a fairly common example of this kind of mix in real-world Rust code.

```
# extern crate trpl; // for mdbook test
#
use std::{thread, time::Duration};

fn main() {
    let (tx, mut rx) = trpl::channel();

    thread::spawn(move || {
        for i in 1..11 {
            tx.send(i).unwrap();
            thread::sleep(Duration::from_secs(1));
        }
```

```
    });

    trpl::run(async {
        while let Some(message) = rx.recv().await {
            println!("{message}");
        }
    });
}
```

We begin by creating an async channel, then spawn a thread that takes ownership of the sender side of the channel. Within the thread, we send the numbers 1 through 10, sleeping for a second between each. Finally, we run a future created with an async block passed to `trpl::run` just as we have throughout the chapter. In that future, we await those messages, just as in the other message-passing examples we have seen.

To return to the scenario we opened the chapter with, imagine running a set of video encoding tasks using a dedicated thread (because video encoding is compute-bound) but notifying the UI that those operations are done with an async channel. There are countless examples of these kinds of combinations in real-world use cases.

Summary

This isn’t the last you’ll see of concurrency in this book. The project in Chapter 21 will apply these concepts in a more realistic situation than the simpler examples discussed here and compare problem-solving with threading versus tasks more directly.

No matter which of these approaches you choose, Rust gives you the tools you need to write safe, fast, concurrent code—whether for a high-throughput web server or an embedded operating system.

Next, we’ll talk about idiomatic ways to model problems and structure solutions as your Rust programs get bigger. In addition, we’ll discuss how Rust’s idioms relate to those you might be familiar with from object-oriented programming.

Object-Oriented Programming Features

Object-oriented programming (OOP) is a way of modeling programs. Objects as a programmatic concept were introduced in the programming language Simula in the 1960s. Those objects influenced Alan Kay's programming architecture in which objects pass messages to each other. To describe this architecture, he coined the term *object-oriented programming* in 1967. Many competing definitions describe what OOP is, and by some of these definitions Rust is object oriented but by others it is not. In this chapter, we'll explore certain characteristics that are commonly considered object oriented and how those characteristics translate to idiomatic Rust. We'll then show you how to implement an object-oriented design pattern in Rust and discuss the trade-offs of doing so versus implementing a solution using some of Rust's strengths instead.

Characteristics of Object-Oriented Languages

There is no consensus in the programming community about what features a language must have to be considered object oriented. Rust is influenced by many programming paradigms, including OOP; for example, we explored the features that came from functional programming in Chapter 13. Arguably, OOP languages share certain common characteristics, namely objects, encapsulation, and inheritance. Let's look at what each of those characteristics means and whether Rust supports it.

Objects Contain Data and Behavior

The book *Design Patterns: Elements of Reusable Object-Oriented Software* by Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides (Addison-Wesley, 1994), colloquially referred to as *The Gang of Four* book, is a catalog of object-oriented design patterns. It defines OOP 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**.

Using this definition, 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, according to the Gang of Four's definition of objects.

Encapsulation That Hides Implementation Details

Another aspect commonly associated with OOP is the idea of *encapsulation*, which means that the implementation details of an object aren't accessible to code using that object. Therefore, the only way to interact with an object is through its public API; code using the object shouldn't be able to reach into the object's internals and change data or behavior directly. This enables the programmer to change and refactor an object's internals without needing to change the code that uses the object.

We discussed how to control encapsulation in Chapter 7: we can use the `pub` keyword to decide which modules, types, functions, and methods in our code should be public, and by default everything else 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 contains the average of the values in the vector, meaning the average doesn't have to be computed on demand whenever anyone needs it. In other words, `AveragedCollection` will cache the calculated average for us. Listing 18-1 has the definition of the `AveragedCollection` struct:

```
pub struct AveragedCollection {
    list: Vec<i32>,
    average: f64,
}
```

The struct is marked `pub` so that other code can use it, 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, the average is also updated. We do this by implementing `add`, `remove`, and `average` methods on the struct, as shown in Listing 18-2:

```
# pub struct AveragedCollection {
#     list: Vec<i32>,
#     average: f64,
# }
#
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;
    }
}
```

The public methods `add`, `remove`, and `average` are the only ways to access or modify data in an instance of `AveragedCollection`. When an item is added to `list` using the `add` method or removed using the `remove` method, the implementations of each call the private `update_average` method that handles updating the `average` field as well.

We leave the `list` and `average` fields private so there is no way for external code to add or remove items to or from the `list` field directly; otherwise, the `average` field might become out of sync when the `list` changes. The `average` method returns the value in the `average` field, allowing external code to read the `average` but not modify it.

Because we've encapsulated the implementation details of the struct `AveragedCollection`, we can easily change aspects, such as the data structure, in the future. For instance, we could use a `HashSet<i32>` instead of a `Vec<i32>` for the `list` field. As long as the signatures of the `add`, `remove`, and `average` public methods stayed the same, code using `AveragedCollection` wouldn't need to change. If we made `list` public instead, this wouldn't necessarily be the case: `HashSet<i32>` and `Vec<i32>` have different methods for adding and removing items, so the external code would likely have to change if it were modifying `list` directly.

If encapsulation is a required aspect for a language to be considered object oriented, then Rust meets that requirement. The option to use `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 whereby an object can inherit elements from another object's definition, thus gaining the parent object's data and behavior without you having to define them again.

If a language must have inheritance to be object oriented, then Rust is not such a language. There is no way to define a struct that inherits the parent struct's fields and method implementations without using a macro.

However, if you're used to having inheritance in your programming toolbox, you can use other solutions in Rust, depending on your reason for reaching for inheritance in the first place.

You would choose inheritance for two main reasons. One is for reuse of code: you can implement particular behavior for one type, and inheritance enables you to reuse that implementation for a different type. You can do this in a limited way in Rust code using default trait method implementations, which you saw in Listing 10-14 when we added a default implementation of the `summarize` method on the `Summary` trait. Any type implementing the `Summary` trait would have the `summarize` method available on it without any further code. This is similar to a parent class having an implementation of a method and an inheriting child class also having the implementation of the method. We can also override the default implementation of the `summarize` method when we implement the `Summary` trait, which is similar to a child class overriding the implementation of a method inherited from a parent class.

The other reason to use inheritance relates to the type system: to enable a child type to be used in the same places as the parent type. This is also called *polymorphism*, which means that you can substitute multiple objects for each other at runtime if they share certain characteristics.

Polymorphism

To many people, polymorphism is synonymous with inheritance. But it's actually a more general concept that refers to code that can work with data of multiple types. For inheritance, those types are generally subclasses.

Rust instead uses generics to abstract over different possible types and trait bounds to impose constraints on what those types must provide. This is sometimes called *bounded parametric polymorphism*.

Inheritance has recently fallen out of favor as a programming design solution in many programming languages because it's often at risk of sharing more code than necessary. Subclasses shouldn't always share all characteristics of their parent class but will do so with inheritance. This can make a program's design less flexible. It also introduces the possibility of calling methods on subclasses that don't make sense or that cause errors because the methods don't apply to the subclass. In addition, some languages will only allow single inheritance (meaning a subclass can only inherit from one class), further restricting the flexibility of a program's design.

For these reasons, Rust takes the different approach of using trait objects instead of inheritance. Let's look at how trait objects enable polymorphism in Rust.

Using Trait Objects That Allow for Values of Different Types

In Chapter 8, we mentioned that one limitation of vectors is that they can store elements of only one type. We created a workaround in Listing 8-9 where we defined a `SpreadsheetCell` enum that had variants to hold integers, floats, and text. This meant we could store different types of data in each cell and still have a vector that represented a row of cells. This is a perfectly good solution when our interchangeable items are a fixed set of types that we know when our code is compiled.

However, sometimes we want our library user to be able to extend the set of types that are valid in a particular situation. To show how we might achieve this, we'll create an example graphical user interface (GUI) tool that iterates through a list of items, calling a `draw` method on each one to draw it to the screen—a common technique for GUI tools. We'll create a library crate called `gui` that contains the structure of a GUI library. This crate might include some types for people to use, such as `Button` or `TextField`. In addition, `gui` users will want to create their own types that can be drawn: for instance, one programmer might add an `Image` and another might add a `SelectBox`.

We won't implement a full-fledged GUI library for this example but will show how the pieces would fit together. At the time of writing the library, we can't know and define all the types other programmers might want to create. But we do know that `gui` needs to keep track of many values of different types, and it needs to call a `draw` method on each of these differently typed values. It doesn't need to know exactly what will happen when we call the `draw` method, just that the value will have that method available for us to call.

To do this in a language with inheritance, we might define a class named `Component` that has a method named `draw` on it. The other classes, such as `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. But because Rust doesn't have inheritance, we need another way to structure the `gui` library to allow users to extend it with new types.

Defining a Trait for Common Behavior

To implement the behavior we want `gui` to have, we'll define a trait named `Draw` that will have one method named `draw`. Then we can define a vector that takes a trait object. A *trait object* points to both an instance of a type implementing our specified trait and a table used to look up trait methods on that type at runtime. We create a trait object by specifying some sort of pointer, such as an `&` reference or a `Box<T>` smart pointer, then the `dyn` keyword, and then specifying the relevant trait. (We'll talk about the reason trait objects must use a pointer in "Dynamically Sized Types and the `Sized` Trait" in Chapter 20.) We can use trait objects in place of a generic or concrete type. Wherever we use a trait object, Rust's type system will ensure at compile time that any value used in that context will implement the trait object's trait. Consequently, we don't need to know all the possible types at compile time.

We've mentioned that, in Rust, we refrain from calling structs and enums "objects" to distinguish them from other languages' objects. In a struct or enum, the data in the struct fields and the behavior in `impl` blocks are separated, whereas in other languages, the data and behavior combined into one concept is often labeled an object. However, trait objects *are* more like objects in other languages in the sense that they combine data and behavior. But trait objects differ from traditional objects in that we can't add data to a trait object. Trait objects aren't as generally useful as objects in other languages: their specific purpose is to allow abstraction across common behavior.

Listing 18-3 shows how to define a trait named `Draw` with one method named `draw`.

```
pub trait Draw {
    fn draw(&self);
}
```

This syntax should look familiar from our discussions on how to define traits in Chapter 10. Next comes some new syntax: Listing 18-4 defines a struct named `Screen` that holds a vector named `components`. This vector is of type `Box<dyn Draw>`, which is a trait object; it's a stand-in for any type inside a `Box` that implements the `Draw` trait.

```
# pub trait Draw {
#     fn draw(&self);
# }
#
pub struct Screen {
    pub components: Vec<Box<dyn Draw>>,
}
```

On the `Screen` struct, we'll define a method named `run` that will call the `draw` method on each of its `components`, as shown in Listing 18-5.

```
# pub trait Draw {
#     fn draw(&self);
# }
#
# pub struct Screen {
#     pub components: Vec<Box<dyn Draw>>,
# }
#
impl Screen {
    pub fn run(&self) {
        for component in self.components.iter() {
            component.draw();
        }
    }
}
```

This works differently from defining a struct that uses a generic type parameter with trait bounds. A generic type parameter can be substituted with only one concrete type at a time, whereas 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 18-6:

```
# pub trait Draw {
#     fn draw(&self);
# }
#
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();
        }
    }
}
```

This restricts us to a `Screen` instance that has a list of components all of type `Button` or all of type `TextField`. If you'll only ever have homogeneous collections, using generics and trait bounds is preferable because the definitions will be monomorphized at compile time to use the concrete types.

On the other hand, with the method using trait objects, one `Screen` instance can hold a `Vec<T>` that contains a `Box<Button>` as well as a `Box<TextField>`. Let's look at how this works, and then we'll talk about the runtime performance implications.

Implementing the Trait

Now we'll add some types that implement the `Draw` trait. We'll provide the `Button` type. Again, actually implementing a GUI library is beyond the 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 18-7:

```
# pub trait Draw {
#     fn draw(&self);
# }
#
# pub struct Screen {
#     pub components: Vec<Box<dyn Draw>>,
# }
#
# impl Screen {
#     pub fn run(&self) {
#         for component in self.components.iter() {
#             component.draw();
#         }
#     }
# }
#
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
    }
}
```

The `width`, `height`, and `label` fields on `Button` will differ from the fields on other components; for example, a `TextField` type might have those same fields plus a `placeholder` field. Each of the types we want to draw on the screen will implement the `Draw` trait but will use different code in the `draw` method to define how to draw that particular type, as `Button` has here (without the actual GUI code, as mentioned). The `Button` type, for instance, might have an additional `impl` block containing methods related to what happens when a user clicks the button. These kinds of methods won't apply to types like `TextField`.

If someone using our library decides to implement a `SelectBox` struct that has `width`, `height`, and `options` fields, they would implement the `Draw` trait on the `SelectBox` type as well, as shown in Listing 18-8.

```
use 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
    }
}
#
# fn main() {}
```

Our library's user can now write their `main` function to create a `Screen` instance. To the `Screen` instance, they can add a `SelectBox` and a `Button` 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 18-9 shows this implementation:

```
# use 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
#     }
# }
#
use gui::{Button, Screen};

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();
}
```

When we wrote the library, we didn’t know that someone might add the `SelectBox` type, but our `Screen` implementation was able to operate on the new type and draw it because `SelectBox` implements the `Draw` trait, which means it implements the `draw` method.

This concept—of being concerned only with the messages a value responds to rather than the value's concrete type—is similar to the concept of *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 18-5, `run` doesn't need to know what the concrete type of each component is. It doesn't check whether a component is an instance of a `Button` or a `SelectBox`, it just calls the `draw` method on the component. By specifying `Box<dyn Draw>` as the type of the values in the `components` vector, we've defined `Screen` to need values that we can call the `draw` method on.

The advantage of using trait objects and Rust's type system to write code similar to code using duck typing is that we never have to check whether 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 anyway. Rust won't compile our code if the values don't implement the traits that the trait objects need.

For example, Listing 18-10 shows what happens if we try to create a `Screen` with a `String` as a component.

```
use gui::Screen;

fn main() {
    let screen = Screen {
        components: vec![Box::new(String::from("Hi"))],
    };

    screen.run();
}
```

We'll get this error because `String` doesn't implement the `Draw` trait:

```
$ cargo run
   Compiling gui v0.1.0 (file:///projects/gui)
error[E0277]: the trait bound `String: Draw` is not satisfied
```

```
 --> src/main.rs:5:26
  |
5 |         components: vec![Box::new(String::from("Hi"))],
  |                          ^^^^^^^^^^^^^^^^^^^^^^^^^^^^ the
trait `Draw` is not implemented for `String`
  |
  = help: the trait `Draw` is implemented for `Button`
  = note: required for the cast from `Box<String>` to `Box<dyn
Draw>`

For more information about this error, try `rustc --explain
E0277`.
error: could not compile `gui` (bin "gui") due to 1 previous
error
```

This error lets us know that either we're passing something to `Screen` that we didn't mean to pass and so 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 "Performance of Code Using Generics" in Chapter 10 our discussion on the monomorphization process performed on generics by the compiler: the compiler generates nongeneric 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*, which is when the compiler knows what method you're calling at compile time. This is opposed to *dynamic dispatch*, which is when the compiler can't tell at compile time which method you're calling. In dynamic dispatch cases, the compiler emits code that at runtime will figure out which method to call.

When we use trait objects, Rust must use dynamic dispatch. The compiler doesn't know all the types that might be used with the code that's using trait objects, so it doesn't know which method implemented on which type to call. Instead, at runtime, Rust uses the pointers inside the trait object to know which method to call. This lookup incurs a runtime cost that doesn’t occur with static dispatch. Dynamic dispatch also prevents the compiler from choosing to inline a method’s code, which in turn prevents some optimizations, and Rust has some rules, called *dyn compatibility*, about where you can and cannot use dynamic dispatch. Those rules are beyond the scope of this discussion, but you can read more about them in the reference. However, we did get extra flexibility in the code that we wrote in Listing 18-5 and were able to support in Listing 18-9, so it’s a trade-off to consider.

Implementing an Object-Oriented Design Pattern

The *state pattern* is an object-oriented design pattern. The crux of the pattern is that we define a set of states a value can have internally. The states are represented by a set of *state objects*, and the value's behavior changes based on its state. We're going to work through an example of a blog post struct that has a field to hold its state, which will be a state object from the set "draft", "review", or "published".

The state objects share functionality: in Rust, of course, we use structs and traits rather than objects and inheritance. Each state object is responsible for its own behavior and for governing when it should change into another state. The value that holds a state object knows nothing about the different behavior of the states or when to transition between states.

The advantage of using the state pattern is that, when the business requirements of the program 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.

First we're going to implement the state pattern in a more traditional object-oriented way, then we'll use an approach that's a bit more natural in Rust. Let's dig in to incrementally implement a blog post workflow using the state pattern.

The final functionality will look like this:

1. A blog post starts as an empty draft.
2. When the draft is done, a review of the post is requested.
3. When the post is approved, it gets published.
4. Only published blog posts return content to print, so unapproved posts can't accidentally be published.

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 remain an unpublished draft.

Listing 18-11 shows this workflow in code form: this is an example usage of the API we'll implement in a library crate named `blog`. This won't compile yet because we haven't implemented the `blog` crate.

```
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());
}
```

We want to allow the user to create a new draft blog post with `Post::new`. We want to allow text to be added to the blog post. If we try to get the post's content immediately, before approval, we shouldn't get any text because the post is still a draft. We've added `assert_eq!` in the code for demonstration purposes. An excellent unit test for this would be to assert that a draft blog post returns an empty string from the `content` method, but we're not going to write tests for this example.

Next, we want to enable a request for a review of the post, and we want `content` to return an empty string while waiting for the review. When the post receives approval, it should get published, meaning the text of the post will be returned when `content` is called.

Notice that the only type we're interacting with from the crate is the `Post` type. This type will use the state pattern and will hold a value that will be one of three state objects representing the various states a post can be in—draft, review, or published. Changing from one state to another will be managed internally within the `Post` type. The states change in response to the methods called by our library's users on the `Post` instance, but they don't have to manage the state changes directly. Also, users can't make a mistake with the states, such as publishing a post before it's reviewed.

Defining `Post` and Creating a New Instance in the Draft State

Let's get started on the implementation of the library! We know we need a public `Post` struct that holds some content, so we'll start with the definition of the struct and an associated public `new` function to create an instance of `Post`, as shown in Listing 18-12. We'll also make a private `State` trait that will define the behavior that all state objects for a `Post` must have.

Then `Post` will hold a trait object of `Box<dyn State>` inside an `Option<T>` in a private field named `state` to hold the state object. You'll see why the `Option<T>` is necessary in a bit.

```
pub struct Post {
    state: Option<Box<dyn 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 {}
```

The `State` trait defines the behavior shared by different post states. The state objects are `Draft`, `PendingReview`, and `Published`, and they will all implement the `State` trait. For now, the trait doesn't have any methods, and we'll start by defining just the `Draft` state because that is the state we want a post to start in.

When we create a new `Post`, we set its `state` field to a `Some` value that holds a `Box`. This `Box` points to a new instance of the `Draft` struct. This ensures that whenever we create a new instance of `Post`, it will start out as a draft. Because the `state` field of `Post` is private, there is no way to create a `Post` in any other state! In the `Post::new` function, we set the `content` field to a new, empty `String`.

Storing the Text of the Post Content

We saw in Listing 18-11 that we want to be able to call a method named `add_text` and pass it a `&str` that is then added as the text content of the blog post. We implement this as a method, rather than exposing the `content` field as `pub`, so that later we can implement a method that will control how the `content` field's data is read. The `add_text` method is pretty straightforward, so let's add the implementation in Listing 18-13 to the `impl Post` block.

```
# pub struct Post {
#     state: Option<Box<dyn State>>,
#     content: String,
# }
#
impl Post {
    // --snip--
#     pub fn new() -> Post {
#         Post {
#             state: Some(Box::new(Draft {})),
#             content: String::new(),
#         }
#     }
```

```
#
    pub fn add_text(&mut self, text: &str) {
        self.content.push_str(text);
    }
}
#
# trait State {}
#
# struct Draft {}
#
# impl State for Draft {}
```

The `add_text` method takes a mutable reference to `self` because 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 behavior doesn't depend on the state the post is in, so it's not part of the state pattern. The `add_text` method doesn't interact with the `state` field at all, but it is part of the behavior we want to support.

Ensuring the Content of a Draft Post Is Empty

Even 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 because the post is still in the draft state, as shown on line 7 of Listing 18-11. For now, let's implement the `content` method with the simplest thing that will fulfill this requirement: always returning an empty string slice. We'll change this later once we implement the ability to change a post's state so it can be published. So far, posts can only be in the draft state, so the post content should always be empty. Listing 18-14 shows this placeholder implementation.

```
# pub struct Post {
#     state: Option<Box<dyn State>>,
#     content: String,
# }
#
```

```
impl Post {
    // --snip--
#     pub fn new() -> Post {
#         Post {
#             state: Some(Box::new(Draft {})),
#             content: String::new(),
#         }
#     }
#
#     pub fn add_text(&mut self, text: &str) {
#         self.content.push_str(text);
#     }
#
    pub fn content(&self) -> &str {
        ""
    }
}
#
# trait State {}
#
# struct Draft {}
#
# impl State for Draft {}
```

With this added `content` method, everything in Listing 18-11 up to line 7 works as intended.

Requesting a Review Changes the Post’s State

Next, we need to add functionality to request a review of a post, which should change its state from `Draft` to `PendingReview`. Listing 18-15 shows this code.

```
# pub struct Post {
#     state: Option<Box<dyn State>>,
#     content: String,
# }
#
```

```
impl Post {
    // --snip--
#     pub fn new() -> Post {
#         Post {
#             state: Some(Box::new(Draft {})),
#             content: String::new(),
#         }
#     }
#
#     pub fn add_text(&mut self, text: &str) {
#         self.content.push_str(text);
#     }
#
#     pub fn content(&self) -> &str {
#         ""
#     }
#
    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<dyn State>;
}

struct Draft {}

impl State for Draft {
    fn request_review(self: Box<Self>) -> Box<dyn State> {
        Box::new(PendingReview {})
    }
}
```

```
struct PendingReview {}

impl State for PendingReview {
    fn request_review(self: Box<Self>) -> Box<dyn State> {
        self
    }
}
```

We give `Post` a public method named `request_review` that will take a mutable reference to `self`. Then we call an internal `request_review` method on the current state of `Post`, and this second `request_review` method consumes the current state and returns a new state.

We add 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>`, invalidating the old state so the state value of the `Post` can transform into a new state.

To consume the old state, the `request_review` method needs to take ownership of the state value. This is where the `Option` in the `state` field of `Post` comes in: we call the `take` method to take the `Some` value out of the `state` field and leave a `None` in its place because Rust doesn’t let us have unpopulated fields in structs. This lets us move the `state` value out of `Post` rather than borrowing it. Then we’ll set the post’s `state` value to the result of this operation.

We need to set `state` to `None` temporarily rather than setting it directly with code like `self.state = self.state.request_review();` to get ownership of the `state` value. This ensures `Post` can’t use the old `state` value after we’ve transformed it into a new state.

The `request_review` method on `Draft` returns a new, boxed instance of a new `PendingReview` struct, which represents the state when a post is waiting for a review. The `PendingReview` struct also implements the `request_review` method but doesn't do any transformations. Rather, it returns itself because when we request a review on a post already in the `PendingReview` state, it 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 its `state` value. Each state is responsible for its own rules.

We'll leave the `content` method on `Post` as is, returning an empty string slice. We can now have a `Post` in the `PendingReview` state as well as in the `Draft` state, but we want the same behavior in the `PendingReview` state. Listing 18-11 now works up to line 10!

Adding `approve` to Change the Behavior of `content`

The `approve` method will be similar to the `request_review` method: it will set `state` to the value that the current state says it should have when that state is approved, as shown in Listing 18-16:

```
# pub struct Post {
#     state: Option<Box<dyn State>>,
#     content: String,
# }
#
impl Post {
    // --snip--
#     pub fn new() -> Post {
#         Post {
#             state: Some(Box::new(Draft {})),
#             content: String::new(),
#         }
#     }
#
#     pub fn add_text(&mut self, text: &str) {
#         self.content.push_str(text);
#     }
```

```
#
#     pub fn content(&self) -> &str {
#         ""
#     }
#
#     pub fn request_review(&mut self) {
#         if let Some(s) = self.state.take() {
#             self.state = Some(s.request_review())
#         }
#     }
#
    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<dyn State>;
    fn approve(self: Box<Self>) -> Box<dyn State>;
}

struct Draft {}

impl State for Draft {
    // --snip--
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         Box::new(PendingReview {})
#     }
#
    fn approve(self: Box<Self>) -> Box<dyn State> {
        self
    }
}
```

```
struct PendingReview {}

impl State for PendingReview {
    // --snip--
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
#
    fn approve(self: Box<Self>) -> Box<dyn State> {
        Box::new(Published {})
    }
}

struct Published {}

impl State for Published {
    fn request_review(self: Box<Self>) -> Box<dyn State> {
        self
    }

    fn approve(self: Box<Self>) -> Box<dyn State> {
        self
    }
}
```

We add the `approve` method to the `State` trait and add a new struct that implements `State`, the `Published` state.

Similar to the way `request_review` on `PendingReview` works, if we call the `approve` method on a `Draft`, it will have no effect because `approve` 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, because the post should stay in the `Published` state in those cases.

Now we need to update the `content` method on `Post`. We want the value returned from `content` to depend on the current state of the `Post`, so we're going to have the `Post` delegate to a `content` method defined on its `state`, as shown in Listing 18-17:

```
# pub struct Post {
#     state: Option<Box<dyn State>>,
#     content: String,
# }
#
impl Post {
    // --snip--
#     pub fn new() -> Post {
#         Post {
#             state: Some(Box::new(Draft {})),
#             content: String::new(),
#         }
#     }
#
#     pub fn add_text(&mut self, text: &str) {
#         self.content.push_str(text);
#     }
#
    pub fn content(&self) -> &str {
        self.state.as_ref().unwrap().content(self)
    }
    // --snip--
#
#     pub fn request_review(&mut self) {
#         if let Some(s) = self.state.take() {
#             self.state = Some(s.request_review())
#         }
#     }
#
#     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<dyn State>;
#     fn approve(self: Box<Self>) -> Box<dyn State>;
# }
#
# struct Draft {}
#
# impl State for Draft {
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         Box::new(PendingReview {})
#     }
#
#     fn approve(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
# }
#
# struct PendingReview {}
#
# impl State for PendingReview {
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
#
#     fn approve(self: Box<Self>) -> Box<dyn State> {
#         Box::new(Published {})
#     }
# }
#
# struct Published {}
#
```

```
# impl State for Published {
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
#
#     fn approve(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
# }
```

Because the goal is to keep all of these rules inside the structs that implement `State`, we call a `content` method on the value in `state` and pass the post instance (that is, `self`) as an argument. Then we return the value that's returned from using the `content` method on the `state` value.

We call the `as_ref` method on the `Option` because we want a reference to the value inside the `Option` rather than ownership of the value. Because `state` is an `Option<Box<dyn State>>`, when we call `as_ref`, an `Option<&Box<dyn State>>` is returned. If we didn't call `as_ref`, we would get an error because we can't move `state` out of the borrowed `&self` of the function parameter.

We then call the `unwrap` method, which we know will never panic, because we know the methods on `Post` ensure that `state` will always contain a `Some` value when those methods are done. This is one of the cases we talked about in "Cases in Which You Have More Information Than the Compiler" in Chapter 9 when we know that a `None` value is never possible, even though the compiler isn't able to understand that.

At this point, when we call `content` on the `&Box<dyn State>`, deref coercion will take effect on the `&` and the `Box` so the `content` method will ultimately be called on the type that implements the `State` trait. That means we need to add `content` to the `State` trait definition, and that is where we'll put the logic for what content to return depending on which state we have, as shown in Listing 18-18:

```
# pub struct Post {
#     state: Option<Box<dyn State>>,
#     content: String,
# }
#
# impl Post {
#     pub fn new() -> Post {
#         Post {
#             state: Some(Box::new(Draft {})),
#             content: String::new(),
#         }
#     }
#
#     pub fn add_text(&mut self, text: &str) {
#         self.content.push_str(text);
#     }
#
#     pub fn content(&self) -> &str {
#         self.state.as_ref().unwrap().content(self)
#     }
#
#     pub fn request_review(&mut self) {
#         if let Some(s) = self.state.take() {
#             self.state = Some(s.request_review())
#         }
#     }
#
#     pub fn approve(&mut self) {
#         if let Some(s) = self.state.take() {
#             self.state = Some(s.approve())
#         }
#     }
# }
#
trait State {
```

```
    // --snip--
#     fn request_review(self: Box<Self>) -> Box<dyn State>;
#     fn approve(self: Box<Self>) -> Box<dyn State>;
#
    fn content<'a>(&self, post: &'a Post) -> &'a str {
        ""
    }
}

// --snip--
#
# struct Draft {}
#
# impl State for Draft {
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         Box::new(PendingReview {})
#     }
#
#     fn approve(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
# }
#
# struct PendingReview {}
#
# impl State for PendingReview {
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
#
#     fn approve(self: Box<Self>) -> Box<dyn State> {
#         Box::new(Published {})
#     }
# }
#
struct Published {}
```

```
impl State for Published {
    // --snip--
#     fn request_review(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
#
#     fn approve(self: Box<Self>) -> Box<dyn State> {
#         self
#     }
#
    fn content<'a>(&self, post: &'a Post) -> &'a str {
        &post.content
    }
}
```

We add a default implementation for the `content` method that returns an empty string slice. That means we don't need to implement `content` on the `Draft` and `PendingReview` structs. The `Published` struct will override the `content` method and return the value in `post.content`.

Note that we need lifetime annotations on this method, as we discussed in Chapter 10. We're taking a reference to a `post` as an argument and returning a reference to part of that `post`, so the lifetime of the returned reference is related to the lifetime of the `post` argument.

And we're done—all of Listing 18-11 now works! We've implemented the state pattern with the rules of the blog post workflow. The logic related to the rules lives in the state objects rather than being scattered throughout `Post`.

Why Not An Enum?

You may have been wondering why we didn't use an `enum` with the different possible post states as variants. That's certainly a possible solution; try it and compare the end results to see which you prefer! One disadvantage of using an enum is that every place that checks the value of the enum will need a `match` expression or similar to handle

> every possible variant. This could get more repetitive than this trait object solution.

Trade-offs of the State Pattern

We've shown that Rust is capable of implementing the object-oriented state pattern to encapsulate the different kinds of behavior a post should have in each state. The methods on `Post` know nothing about the various behaviors. The way we organized the code, we have to look in only one place to know the different ways a published post can behave: the implementation of the `State` trait on the `Published` struct.

If we were to create an alternative implementation that didn't use the state pattern, we might instead use `match` expressions in the methods on `Post` or even in the `main` code that checks the state of the post and changes behavior in those places. That would mean we would have to look in several places to understand all the implications of a post being in the published state! This would only increase the more states we added: each of those `match` expressions would need another arm.

With the state pattern, the `Post` methods and the places we use `Post` don't need `match` expressions, and to add a new state, we would only need to add a new struct and implement the trait methods on that one struct.

The implementation using the state pattern is easy to extend to add more functionality. To see the simplicity of maintaining code that uses the state pattern, try a few of these suggestions:

- Add a `reject` method that changes the post's state from `PendingReview` back to `Draft`.
- Require two calls to `approve` before the state can be changed to `Published`.
- Allow users to add text content only when a post is in the `Draft` state. Hint: have the state object responsible for what might change about the content but not responsible for modifying the `Post`.

One downside of the state pattern is that, because the states implement the transitions between 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 less work if `PendingReview` didn't need to change with the addition of a new state, but that would mean switching to another design pattern.

Another downside is that we've duplicated some logic. To eliminate some of the duplication, we might try to make default implementations for the `request_review` and `approve` methods on the `State` trait that return `self`; however, this wouldn't work: when using `State` as a trait object, the trait doesn't know what the concrete `self` will be exactly, so the return type isn't known at compile time. (This is one of the dyn compatibility rules mentioned earlier.)

Other duplication includes the similar implementations of the `request_review` and `approve` methods on `Post`. Both methods use `Option::take` with the `state` field of `Post`, and if `state` is `Some`, they delegate to the wrapped value's implementation of the same method 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 "Macros" in Chapter 20).

By implementing the state pattern exactly as it's defined for object-oriented languages, we're not taking as full advantage of Rust's strengths as we could. Let's look at some changes we can make to the `blog` crate that can make invalid states and transitions into compile-time errors.

Encoding States and Behavior as Types

We'll show you how to rethink the state pattern to get a different set of trade-offs. Rather than encapsulating the states and transitions completely so outside code has no knowledge of them, we'll encode the states into different types. Consequently, Rust's type checking system will prevent attempts to use draft posts where only published posts are allowed by issuing a compiler error.

Let's consider the first part of `main` in Listing 18-11:

```
# 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());
}
```

We still enable the creation of new posts in the draft state using `Post::new` and the ability 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'll make it so 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 telling us the method doesn't exist. As a result, it will be impossible for us to accidentally display draft post content in production because that code won't even compile. Listing 18-19 shows the definition of a `Post` struct and a `DraftPost` struct, as well as methods on each.

```
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);
    }
}
```

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 because we're moving the encoding of the state to the types of the structs. The `Post` struct 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`. Because `content` is private and there aren't any functions that return `Post`, it's not possible to create an instance of `Post` right now.

The `DraftPost` struct has an `add_text` method, so we can add text to `content` as before, but note that `DraftPost` does not have a `content` method defined! So now the program ensures 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 result in a compiler error.

Implementing Transitions as Transformations into Different Types

So how do we get a published post? We want to enforce the rule 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 18-20.

```
# 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 {
    // --snip--
#     pub fn add_text(&mut self, text: &str) {
#         self.content.push_str(text);
#     }
#
    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,
        }
    }
}
```

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 lingering `DraftPost` instances after we've called `request_review` on them, and so forth. The `PendingReviewPost` struct doesn't have a `content` method defined on it, so attempting to read its content results in a compiler error, as 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.

But we also have to make some small changes to `main`. The `request_review` and `approve` methods return new instances rather than modifying the struct they're called on, so 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 posts' contents be empty strings, 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 18-21.

```
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());
}
```

The changes we needed to make to `main` to reassign `post` mean that this implementation doesn't quite follow the object-oriented state pattern anymore: the transformations between the states are no longer encapsulated entirely within the `Post` implementation. However, our gain is that invalid states are now impossible because of the type system and the type checking that happens at compile time! This ensures that certain bugs, such as display of the content of an unpublished post, will be discovered before they make it to production.

Try the tasks suggested at the start of this section on the `blog` crate as it is after Listing 18-21 to see what you think about the design of this version of the code. Note that some of the tasks might be completed already in this design.

We've seen that even though Rust is capable of implementing object-oriented design patterns, other patterns, such as encoding state into the type system, are also available in Rust. These patterns have different trade-offs. Although you might be very familiar with object-oriented patterns, rethinking the problem to take advantage of Rust's features can provide benefits, such as preventing some bugs at compile time. Object-oriented patterns won’t always be the best solution in Rust due to certain features, like ownership, that object-oriented languages don’t have.

Summary

Regardless of whether you think Rust is an object-oriented language after reading this chapter, you now know that you can use trait objects to get some object-oriented features in Rust. Dynamic dispatch can give your code some flexibility in exchange for a bit of runtime performance. You can use this flexibility to implement object-oriented patterns that can help your code's maintainability. Rust also has other features, like ownership, that object-oriented languages don't have. An object-oriented pattern won't always be the best way to take advantage of Rust's strengths, but it is an available option.

Next, we'll look at patterns, which are another of Rust's features that enable lots of flexibility. We've looked at them briefly throughout the book but haven't seen their full capability yet. Let's go!

Patterns and Matching

Patterns are a special syntax in Rust for matching against the structure of types, both complex and simple. Using patterns in conjunction with `match` expressions and other constructs gives you more control over a program's control flow. A pattern consists of some combination of the following:

- Literals
- Destructured arrays, enums, structs, or tuples
- Variables
- Wildcards
- Placeholders

Some example patterns include `x`, `(a, 3)`, and `Some(Color::Red)`. In the contexts in which patterns are valid, these components describe the shape of data. Our program then matches values against the patterns to determine whether it has the correct shape of data to continue running a particular piece of code.

To use a pattern, we compare it to some value. If the pattern matches the value, we use the value parts in our code. Recall the `match` expressions in Chapter 6 that used patterns, such as the coin-sorting machine example. If the value fits the shape of the pattern, we can use the named pieces. If it doesn't, the code associated with the pattern won't run.

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. By the end of the chapter, you'll know how to use patterns to express many concepts in a clear way.

All the Places Patterns Can Be Used

Patterns pop up in a number of places in Rust, and you’ve been using them a lot without realizing it! This section discusses all the places where patterns are valid.

`match` Arms

As discussed in Chapter 6, we use patterns 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, like this:

```
match VALUE {
    PATTERN => EXPRESSION,
    PATTERN => EXPRESSION,
    PATTERN => EXPRESSION,
}
```

For example, here's the `match` expression from Listing 6-5 that matches on an `Option<i32>` value in the variable `x`:

```
match x {
    None => None,
    Some(i) => Some(i + 1),
}
```

The patterns in this `match` expression are the `None` and `Some(i)` to the left of each arrow.

One requirement for `match` expressions is that they need to be *exhaustive* in the sense that all possibilities for the value in the `match` expression must be accounted for. One way to ensure you’ve covered every possibility is to have a catchall pattern for the last arm: for example, a variable name matching any value can never fail and thus covers every remaining case.

The particular pattern `_` will match anything, but it never binds to a variable, so it’s often used in the last match arm. The `_` pattern can be useful when you want to ignore any value not specified, for example. We'll cover the `_` pattern in more detail in "Ignoring Values in a Pattern" later in this chapter.

Conditional `if let` Expressions

In Chapter 6, we discussed how to use `if let` expressions mainly as a shorter way to write the equivalent of a `match` that only matches one case. Optionally, `if let` can have a corresponding `else` containing code to run if the pattern in the `if let` doesn't match.

Listing 19-1 shows that it's also possible to mix and match `if let`, `else if`, and `else if let` expressions. Doing so gives us more flexibility than a `match` expression in which we can express only one value to compare with the patterns. Also, Rust doesn't require that the conditions in a series of `if let`, `else if`, `else if let` arms relate to each other.

The code in Listing 19-1 determines what color to make your background based on a series of checks for several conditions. For this example, we've created variables with hardcoded values that a real program might receive from user input.

```
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, {color}, as the
background");
    } 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");
    }
}
```

If the user specifies a favorite color, that color is used as the background. If no favorite color is specified and today is Tuesday, the background color is green. Otherwise, if the user specifies their age as a string and we can parse it as a number successfully, the color is either purple or orange depending on the value of the number. If none of these conditions apply, the background color is blue.

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`.

You can see that `if let` can also introduce new variables that shadow existing variables in the same way that `match` arms can: the line `if let Ok(age) = age` introduces a new `age` variable that contains the value inside the `Ok` variant, shadowing the existing `age` variable. This means we need to place the `if age > 30` condition within that block: we can't combine these two conditions into `if let Ok(age) = age && age > 30`. The new `age` we want to compare to 30 isn't valid until the new scope starts with the curly bracket.

The downside of using `if let` expressions is that the compiler doesn't check for exhaustiveness, whereas with `match` expressions it does. If we omitted the last `else` block and therefore missed handling some cases, the compiler would not alert us to the possible logic bug.

`while let` Conditional Loops

Similar in construction to `if let`, the `while let` conditional loop allows a `while` loop to run for as long as a pattern continues to match. In Listing 19-2 we show a `while let` loop that waits on messages sent between threads, but in this case checking a `Result` instead of an `Option`.

```
# fn main() {
    let (tx, rx) = std::sync::mpsc::channel();
    std::thread::spawn(move || {
        for val in [1, 2, 3] {
            tx.send(val).unwrap();
        }
    });

    while let Ok(value) = rx.recv() {
        println!("{value}");
    }
# }
```

This example prints `1`, `2`, and then `3`. The `recv` method takes the first message out of the receiver side of the channel and returns an `Ok(value)`. When we first saw `recv` back in Chapter 16, we unwrapped the error directly, or interacted with it as an iterator using a `for` loop. As Listing 19-2 shows, though, we can also use `while let`, because the `recv` method returns `Ok` each time a message arrives, as long as the sender exists, and then produces an `Err` once the sender side disconnects.

`for` Loops

In a `for` loop, the value that directly follows the keyword `for` is a pattern. For example, in `for x in y`, the `x` is the pattern. Listing 19-3 demonstrates how to use a pattern in a `for` loop to destructure, or break apart, a tuple as part of the `for` loop.

```
# fn main() {
    let v = vec!['a', 'b', 'c'];

    for (index, value) in v.iter().enumerate() {
        println!("{value} is at index {index}");
    }
# }
```

The code in Listing 19-3 will print the following:

```
$ cargo run
   Compiling patterns v0.1.0 (file:///projects/patterns)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.52s
     Running `target/debug/patterns`
a is at index 0
b is at index 1
c is at index 2
```

We adapt an iterator using the `enumerate` method so it produces a value and the index for that value, placed into a tuple. The first value produced is the tuple `(0, 'a')`. When this value is matched to the pattern `(index, value)`, `index` will be `0` and `value` will be `'a'`, printing the first line of the output.

`let` Statements

Prior to this chapter, we had only explicitly discussed using patterns with `match` and `if let`, but in fact, we've used patterns in other places as well, including in `let` statements. For example, consider this straightforward variable assignment with `let`:

```
let x = 5;
```

Every time you've used a `let` statement like this you've been using patterns, although you might not have realized it! More formally, a `let` statement looks like this:

```
let PATTERN = EXPRESSION;
```

In statements like `let x = 5;` with a variable name in the *`PATTERN`* slot, the variable name is just a particularly simple form of a pattern. Rust compares the expression against the pattern and assigns any names it finds. So, in the `let x = 5;` example, `x` is a pattern that means "bind what matches here to the variable `x`." Because 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` more clearly, consider Listing 19-4, which uses a pattern with `let` to destructure a tuple.

```
# fn main() {
    let (x, y, z) = (1, 2, 3);
# }
```

Here, we match a tuple against a pattern. Rust compares the value `(1, 2, 3)` to the pattern `(x, y, z)` and sees that the value matches the pattern, in that the number of elements is the same in both, so Rust binds `1` to `x`, `2` to `y`, and `3` to `z`. You can think of this tuple pattern as nesting three individual variable patterns inside it.

If the number of elements in the pattern doesn’t match the number of elements in the tuple, the overall type won’t match and we’ll get a compiler error. For example, Listing 19-5 shows an attempt to destructure a tuple with three elements into two variables, which won’t work.

```
# fn main() {
    let (x, y) = (1, 2, 3);
# }
```

Attempting to compile this code results in this type error:

```
$ cargo run
   Compiling patterns v0.1.0 (file:///projects/patterns)
error[E0308]: mismatched types
 --> src/main.rs:2:9
  |
2 |     let (x, y) = (1, 2, 3);
  |         ^^^^^^   --------- this expression has type
`({integer}, {integer}, {integer})`
  |         |
  |         expected a tuple with 3 elements, found one with 2
elements
  |
  = note: expected tuple `({integer}, {integer}, {integer})`
```

```
            found tuple `(_, _)`

For more information about this error, try `rustc --explain E0308`.
error: could not compile `patterns` (bin "patterns") due to 1 previous error
```

To fix the error, we could ignore one or more of the values in the tuple using `_` or `..`, as you'll see in the "Ignoring Values in a Pattern" section. If the problem is that we have too many variables in the pattern, the solution is to make the types match by removing variables so the number of variables equals the number of elements in the tuple.

Function Parameters

Function parameters can also be patterns. The code in Listing 19-6, which declares a function named `foo` that takes one parameter named `x` of type `i32`, should by now look familiar.

```
fn foo(x: i32) {
    // code goes here
}
#
# fn main() {}
```

The `x` part is a pattern! As we did with `let`, we could match a tuple in a function's arguments to the pattern. Listing 19-7 splits the values in a tuple as we pass it to a function.

```
fn print_coordinates(&(x, y): &(i32, i32)) {
    println!("Current location: ({x}, {y})");
}

fn main() {
    let point = (3, 5);
    print_coordinates(&point);
}
```

This code prints `Current location: (3, 5)`. The values `&(3, 5)` match the pattern `&(x, y)`, so `x` is the value `3` and `y` is the value `5`.

We can also use patterns in closure parameter lists in the same way as in function parameter lists because closures are similar to functions, as discussed in Chapter 13.

At this point, you’ve seen several ways to use patterns, but patterns don’t work the same in every place we can use them. In some places, the patterns must be irrefutable; in other circumstances, they can be refutable. We’ll discuss these two concepts next.

Refutability: Whether a Pattern Might Fail to Match

Patterns come in two forms: refutable and irrefutable. Patterns that will match for any possible value passed are *irrefutable*. An example would be `x` in the statement `let x = 5;` because `x` matches anything and therefore cannot fail to match. Patterns that can fail to match for some possible value are *refutable*. An example would be `Some(x)` in the expression `if let Some(x) = a_value` because if the value in the `a_value` variable is `None` rather than `Some`, the `Some(x)` pattern will not match.

Function parameters, `let` statements, and `for` loops can only accept irrefutable patterns because the program cannot do anything meaningful when values don't match. The `if let` and `while let` expressions and the `let...else` statement accept refutable and irrefutable patterns, but the compiler warns against irrefutable patterns because, by definition, they're intended to handle possible failure: the functionality of a conditional is in its ability to perform differently depending on success or failure.

In general, you shouldn't have to worry about the distinction between refutable and irrefutable patterns; however, you do need to be familiar with the concept of refutability so you can respond when you see it in an error message. In those cases, you'll need to change either the pattern or the construct you're using the pattern with, depending on the intended behavior of the code.

Let's look at an example of what happens when we try to use a refutable pattern where Rust requires an irrefutable pattern and vice versa. Listing 19-8 shows a `let` statement, but for the pattern, we've specified `Some(x)`, a refutable pattern. As you might expect, this code will not compile.

```
# fn main() {
#     let some_option_value: Option<i32> = None;
    let Some(x) = some_option_value;
# }
```

If `some_option_value` were a `None` value, it would fail to match the pattern `Some(x)`, meaning the pattern is refutable. However, the `let` statement can only accept an irrefutable pattern because there is nothing valid the code can do with a `None` value. At compile time, Rust will complain that we've tried to use a refutable pattern where an irrefutable pattern is required:

```
$ cargo run
   Compiling patterns v0.1.0 (file:///projects/patterns)
error[E0005]: refutable pattern in local binding
 --> src/main.rs:3:9
  |
3 |     let Some(x) = some_option_value;
  |         ^^^^^^^ pattern `None` not covered
  |
  = note: `let` bindings require an "irrefutable pattern", like a `struct` or an `enum` with only one variant
  = note: for more information, visit https://doc.rust-lang.org/book/ch19-02-refutability.html
  = note: the matched value is of type `Option<i32>`
help: you might want to use `let else` to handle the variant that isn't matched
  |
3 |     let Some(x) = some_option_value else { todo!() };
  |                                     ++++++++++++++++

For more information about this error, try `rustc --explain E0005`.
error: could not compile `patterns` (bin "patterns") due to 1 previous error
```

Because we didn't cover (and couldn't cover!) every valid value with the pattern `Some(x)`, Rust rightfully produces a compiler error.

If we have a refutable pattern where an irrefutable pattern is needed, we can fix it by changing the code that uses the pattern: instead of using `let`, we can use `if let`. Then if the pattern doesn't match, the code will just skip the code in the curly brackets, giving it a way to continue validly. Listing 19-9 shows how to fix the code in Listing 19-8.

```
# fn main() {
#     let some_option_value: Option<i32> = None;
    let Some(x) = some_option_value else {
        return;
    };
# }
```

We've given the code an out! This code is perfectly valid now. However, if we give `if let` an irrefutable pattern (a pattern that will always match), such as `x`, as shown in Listing 19-10, the compiler will give a warning.

```
# fn main() {
    let x = 5 else {
        return;
    };
# }
```

Rust complains that it doesn't make sense to use `if let` with an irrefutable pattern:

```
$ cargo run
   Compiling patterns v0.1.0 (file:///projects/patterns)
warning: irrefutable `let...else` pattern
 --> src/main.rs:2:5
  |
2 |     let x = 5 else {
  |     ^^^^^^^^^
  |
  = note: this pattern will always match, so the `else` clause
is useless
  = help: consider removing the `else` clause
  = note: `#[warn(irrefutable_let_patterns)]` on by default

warning: `patterns` (bin "patterns") generated 1 warning
    Finished `dev` profile [unoptimized + debuginfo] target(s)
```

```
in 0.39s
     Running `target/debug/patterns`
```

For this reason, match arms must use refutable patterns, except for the last arm, which should match any remaining values with an irrefutable pattern. Rust allows us to use an irrefutable pattern in a `match` with only one arm, but this syntax isn't particularly useful and could be replaced with a simpler `let` statement.

Now that you know where to use patterns and the difference between refutable and irrefutable patterns, let's cover all the syntax we can use to create patterns.

Pattern Syntax

In this section, we gather all the syntax that is valid in patterns and discuss why and when you might want to use each one.

Matching Literals

As you saw in Chapter 6, you can match patterns against literals directly. The following code gives some examples:

```
# fn main() {
    let x = 1;

    match x {
        1 => println!("one"),
        2 => println!("two"),
        3 => println!("three"),
        _ => println!("anything"),
    }
# }
```

This code prints `one` because the value in `x` is 1. This syntax is useful when you want your code to take an action if it gets a particular concrete value.

Matching Named Variables

Named variables are irrefutable patterns that match any value, and we've used them many times in this book. However, there is a complication when you use named variables in `match`, `if let`, or `while let` expressions. Because each of these kinds of expression starts a new scope, variables declared as part of a pattern inside the expression will shadow those with the same name outside, as is the case with all variables. In Listing 19-11, we declare a variable named `x` with the value `Some(5)` and a variable `y` with the value `10`. We then create a `match` expression on the value `x`. Look at the patterns in the match arms and `println!` at the end, and try to figure out what the code will print before running this code or reading further.

```
# 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 = {x:?}, y = {y}");
# }
```

Let's walk through what happens when the `match` expression runs. The pattern in the first match arm doesn't match the defined value of `x`, so the code continues.

The pattern in the second match arm introduces a new variable named `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 `y` variable, not the `y` we declared at the beginning with the value `10`. This new `y` binding will match any value inside a `Some`, which is what we have in `x`. Therefore, this new `y` binds to the inner value of the `Some` in `x`. That value is `5`, so the expression for that arm executes and prints `Matched, y = 5`.

If `x` had been a `None` value instead of `Some(5)`, the patterns in the first two arms wouldn't have matched, so the value would have matched to the underscore. We didn't introduce the `x` variable in the pattern of the underscore arm, so the `x` in the expression is still the outer `x` that hasn't been shadowed. In this hypothetical case, the `match` would print `Default case, x = None`.

When the `match` expression is done, its scope ends, and so does the scope of the inner `y`. The last `println!` produces `at the end: x = Some(5), y = 10`.

To create a `match` expression that compares the values of the outer `x` and `y`, rather than introducing a new variable that shadows the existing `y` variable, we would need to use a match guard conditional instead. We'll talk about match guards later in "Extra Conditionals with Match Guards".

Multiple Patterns

You can match multiple patterns using the `|` syntax, which is the pattern *or* operator. For example, in the following code we match the value of `x` against the match arms, the first of which has an *or* option, meaning if the value of `x` matches either of the values in that arm, that arm's code will run:

```
# fn main() {
    let x = 1;

    match x {
        1 | 2 => println!("one or two"),
        3 => println!("three"),
        _ => println!("anything"),
    }
# }
```

This code prints `one or two`.

Matching Ranges of Values with `..=`

The `..=` syntax allows us to match to an inclusive range of values. In the following code, when a pattern matches any of the values within the given range, that arm will execute:

```
# fn main() {
    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. This syntax is more convenient for multiple match values than using the `|` operator to express the same idea; if we were to use `|` we would have to specify `1 | 2 | 3 | 4 | 5`. Specifying a range is much shorter, especially if we want to match, say, any number between 1 and 1,000!

The compiler checks that the range isn't empty at compile time, and because the only types for which Rust can tell if a range is empty or not are `char` and numeric values, ranges are only allowed with numeric or `char` values.

Here is an example using ranges of `char` values:

```
# fn main() {
    let x = 'c';

    match x {
        'a'..='j' => println!("early ASCII letter"),
        'k'..='z' => println!("late ASCII letter"),
        _ => println!("something else"),
    }
# }
```

Rust can tell that `'c'` is within the first pattern's range and prints `early ASCII letter`.

Destructuring to Break Apart Values

We can also use patterns to destructure structs, enums, and tuples to use different parts of these values. Let's walk through each value.

Destructuring Structs

Listing 19-12 shows a `Point` struct with two fields, `x` and `y`, that we can break apart using a pattern with a `let` statement.

```
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);
}
```

This code creates the variables `a` and `b` that match the values of the `x` and `y` fields of the `p` struct. This example shows that the names of the variables in the pattern don't have to match the field names of the struct. However, it's common to match the variable names to the field names to make it easier to remember which variables came from which fields. Because of this common usage, and because writing `let Point { x: x, y: y } = p;` contains a lot of duplication, Rust has a shorthand for patterns that match struct fields: you only need to list the name of the struct field, and the variables created from the pattern will have the same names. Listing 19-13 behaves in the same way as the code in Listing 19-12, but the variables created in the `let` pattern are `x` and `y` instead of `a` and `b`.

```
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);
}
```

This code creates the variables `x` and `y` that match the `x` and `y` fields of the `p` variable. The outcome is that the variables `x` and `y` contain the values from the `p` struct.

We can also destructure with literal values as part of the struct pattern rather than creating variables for all the fields. Doing so allows us to test some of the fields for particular values while creating variables to destructure the other fields.

In Listing 19-14, we have a `match` expression that separates `Point` values into three cases: points that lie directly on the `x` axis (which is true when `y = 0`), on the `y` axis (`x = 0`), or on neither axis.

```
# struct Point {
#     x: i32,
#     y: i32,
# }
#
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})");
        }
    }
}
```

The first arm will match any point that lies on the `x` axis by specifying that the `y` field matches if its value matches the literal `0`. The pattern still creates an `x` variable that we can use in the code for this arm.

Similarly, the second arm matches any point on the `y` axis by specifying that the `x` field matches if its value is `0` and creates a variable `y` for the value of the `y` field. The third arm doesn't specify any literals, so it matches any other `Point` and creates variables for both the `x` and `y` fields.

In this example, the value `p` matches the second arm by virtue of `x` containing a `0`, so this code will print `On the y axis at 7`.

Remember that a `match` expression stops checking arms once it has found the first matching pattern, so even though `Point { x: 0, y: 0}` is on the `x` axis and the `y` axis, this code would only print `On the x axis at 0`.

Destructuring Enums

We've destructured enums in this book (for example, Listing 6-5), but we haven't yet explicitly discussed that the pattern to destructure an enum corresponds to the way the data stored within the enum is defined. As an example, in Listing 19-15 we use the `Message` enum from Listing 6-2 and write a `match` with patterns that will destructure each inner value.

```
enum Message {
    Quit,
    Move { x: i32, y: i32 },
    Write(String),
    ChangeColor(i32, i32, i32),
}

fn main() {
    let msg = Message::ChangeColor(0, 160, 255);

    match msg {
        Message::Quit => {
                    println!("The Quit variant has no data to
destructure.");
        }
        Message::Move { x, y } => {
            println!("Move in the x direction {x} and in the y
direction {y}");
        }
        Message::Write(text) => {
            println!("Text message: {text}");
        }
        Message::ChangeColor(r, g, b) => {
            println!("Change color to red {r}, green {g}, and
```

```
blue {b}");
        }
    }
}
```

This code will print `Change color to red 0, green 160, and blue 255`. Try changing the value of `msg` to see the code from the other arms run.

For enum variants without any data, like `Message::Quit`, we can't destructure the value any further. We can only match on the literal `Message::Quit` value, and no variables are in that pattern.

For struct-like enum variants, such as `Message::Move`, we can use a pattern similar to the pattern we specify to match structs. After the variant name, we place curly brackets and then list the fields with variables so we break apart the pieces to use in the code for this arm. Here we use the shorthand form as we did in Listing 19-13.

For tuple-like enum variants, like `Message::Write` that holds a tuple with one element and `Message::ChangeColor` that holds a tuple with three elements, the pattern is similar to the pattern we specify to match tuples. The number of variables in the pattern must match the number of elements in the variant we're matching.

Destructuring Nested Structs and Enums

So far, our examples have all been matching structs or enums one level deep, but matching can work on nested items too! For example, we can refactor the code in Listing 19-15 to support RGB and HSV colors in the `ChangeColor` message, as shown in Listing 19-16.

```
enum Color {
    Rgb(i32, i32, i32),
    Hsv(i32, i32, i32),
}

enum Message {
    Quit,
    Move { x: i32, y: i32 },
```

```
    Write(String),
    ChangeColor(Color),
}

fn main() {
    let msg = Message::ChangeColor(Color::Hsv(0, 160, 255));

    match msg {
        Message::ChangeColor(Color::Rgb(r, g, b)) => {
             println!("Change color to red {r}, green {g}, and
blue {b}");
        }
        Message::ChangeColor(Color::Hsv(h, s, v)) => {
            println!("Change color to hue {h}, saturation {s},
value {v}");
        }
        _ => (),
    }
}
```

The pattern of the first arm in the `match` expression matches a `Message::ChangeColor` enum variant that contains a `Color::Rgb` variant; then the pattern binds to the three inner `i32` values. The pattern of the second arm also matches a `Message::ChangeColor` enum variant, but the inner enum matches `Color::Hsv` instead. We can specify these complex conditions in one `match` expression, even though two enums are involved.

Destructuring Structs and Tuples

We can mix, match, and nest destructuring patterns in even more complex ways. The following example shows a complicated destructure where we nest structs and tuples inside a tuple and destructure all the primitive values out:

```
# fn main() {
#     struct Point {
#         x: i32,
```

```
#         y: i32,
#     }
#
     let ((feet, inches), Point { x, y }) = ((3, 10), Point {
x: 3, y: -10 });
# }
```

This code lets us break complex types into their component parts so we can use the values we're interested in separately.

Destructuring with patterns is a convenient way to use pieces of values, such as the value from each field in a struct, separately from each other.

Ignoring Values in a Pattern

You've seen that it's sometimes useful to ignore values in a pattern, such as in the last arm of a `match`, to get a catchall that doesn't actually do anything but does account for all remaining possible values. There are a few ways to ignore entire values or parts of values in a pattern: using the `_` pattern (which you've seen), using the `_` pattern within another pattern, using a name that starts with an underscore, or using `..` to ignore remaining parts of a value. Let's explore how and why to use each of these patterns.

An Entire Value with _

We've used the underscore as a wildcard pattern that will match any value but not bind to the value. This is especially useful as the last arm in a `match` expression, but we can also use it in any pattern, including function parameters, as shown in Listing 19-17.

```
fn foo(_: i32, y: i32) {
    println!("This code only uses the y parameter: {y}");
}

fn main() {
    foo(3, 4);
}
```

This code will completely ignore the value `3` passed as the first argument, and will print `This code only uses the y parameter: 4`.

In most cases when you no longer need a particular function parameter, you would change the signature so it doesn't include the unused parameter. Ignoring a function parameter can be especially useful in cases when, for example, you're implementing a trait when you need a certain type signature but the function body in your implementation doesn't need one of the parameters. You then avoid getting a compiler warning about unused function parameters, as you would if you used a name instead.

Parts of a Value with a Nested _

We can also use `_` inside another pattern to ignore just part of a value, for example, when we want to test for only part of a value but have no use for the other parts in the corresponding code we want to run. Listing 19-18 shows code responsible for managing a setting's value. The business requirements are that the user should not be allowed to overwrite an existing customization of a setting but can unset the setting and give it a value if it is currently unset.

```
# fn main() {
    let mut setting_value = Some(5);
    let new_setting_value = Some(10);

    match (setting_value, new_setting_value) {
        (Some(_), Some(_)) => {
             println!("Can't overwrite an existing customized
value");
        }
        _ => {
            setting_value = new_setting_value;
        }
    }

    println!("setting is {setting_value:?}");
# }
```

This code will print `Can't overwrite an existing customized value` and then `setting is Some(5)`. In the first match arm, we don't need to match on or use the values inside either `Some` variant, but we do need to test for the case when `setting_value` and `new_setting_value` are the `Some` variant. In that case, we print the reason for not changing `setting_value`, and it doesn't get changed.

In all other cases (if either `setting_value` or `new_setting_value` is `None`) expressed by the `_` pattern in the second arm, we want to allow `new_setting_value` to become `setting_value`.

We can also use underscores in multiple places within one pattern to ignore particular values. Listing 19-19 shows an example of ignoring the second and fourth values in a tuple of five items.

```
# fn main() {
    let numbers = (2, 4, 8, 16, 32);

    match numbers {
        (first, _, third, _, fifth) => {
            println!("Some numbers: {first}, {third}, {fifth}");
        }
    }
# }
```

This code will print `Some numbers: 2, 8, 32`, and the values `4` and `16` will be ignored.

An Unused Variable by Starting Its Name with _

If you create a variable but don't use it anywhere, Rust will usually issue a warning because an unused variable could be a bug. However, sometimes it's useful to be able to create a variable you won't use yet, such as when you're prototyping or just starting a project. In this situation, you can tell Rust not to warn you about the unused variable by starting the name of the variable with an underscore. In Listing 19-20, we create two unused variables, but when we compile this code, we should only get a warning about one of them.

```
fn main() {
    let _x = 5;
    let y = 10;
}
```

Here, we get a warning about not using the variable `y`, but we don't get a warning about not using `_x`.

Note that there is a subtle difference between using only `_` and using a name that starts with an underscore. The syntax `_x` still binds the value to the variable, whereas `_` doesn't bind at all. To show a case where this distinction matters, Listing 19-21 will provide us with an error.

```
# fn main() {
    let s = Some(String::from("Hello!"));

    if let Some(_s) = s {
        println!("found a string");
    }

    println!("{s:?}");
# }
```

We'll receive an error because the `s` value will still be moved into `_s`, which prevents us from using `s` again. However, using the underscore by itself doesn't ever bind to the value. Listing 19-22 will compile without any errors because `s` doesn't get moved into `_`.

```
# fn main() {
    let s = Some(String::from("Hello!"));

    if let Some(_) = s {
        println!("found a string");
    }
```

```
    println!("{s:?}");
# }
```

This code works just fine because we never bind `s` to anything; it isn't moved.

Remaining Parts of a Value with `..`

With values that have many parts, we can use the `..` syntax to use specific parts and ignore the rest, avoiding the need to list underscores for each ignored value. The `..` pattern ignores any parts of a value that we haven't explicitly matched in the rest of the pattern. In Listing 19-23, we have a `Point` struct that holds a coordinate in three-dimensional space. In the `match` expression, we want to operate only on the `x` coordinate and ignore the values in the `y` and `z` fields.

```
# fn main() {
    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}"),
    }
# }
```

We list the `x` value and then just include the `..` pattern. This is quicker than having to list `y: _` and `z: _`, particularly when we're working with structs that have lots of fields in situations where only one or two fields are relevant.

The syntax `..` will expand to as many values as it needs to be. Listing 19-24 shows how to use `..` with a tuple.

```
fn main() {
    let numbers = (2, 4, 8, 16, 32);

    match numbers {
        (first, .., last) => {
            println!("Some numbers: {first}, {last}");
        }
    }
}
```

In this code, the first and last value are matched with `first` and `last`. The `..` will match and ignore everything in the middle.

However, using `..` must be unambiguous. If it is unclear which values are intended for matching and which should be ignored, Rust will give us an error. Listing 19-25 shows an example of using `..` ambiguously, so it will not compile.

```
fn main() {
    let numbers = (2, 4, 8, 16, 32);

    match numbers {
        (.., second, ..) => {
            println!("Some numbers: {second}")
        },
    }
}
```

When we compile this example, we get this error:

```
$ cargo run
   Compiling patterns v0.1.0 (file:///projects/patterns)
error: `..` can only be used once per tuple pattern
 --> src/main.rs:5:22
  |
5 |         (.., second, ..) => {
  |          --          ^^ can only be used once per tuple
pattern
  |          |
```

```
  |          previously used here

error: could not compile `patterns` (bin "patterns") due to 1
previous error
```

It's impossible for Rust to determine how many values in the tuple to ignore before matching a value with `second` and then how many further values to ignore thereafter. This code could mean that we want to ignore `2`, bind `second` to `4`, and then ignore `8`, `16`, and `32`; or that we want to ignore `2` and `4`, bind `second` to `8`, and 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 because using `..` in two places like this is ambiguous.

Extra Conditionals with Match Guards

A *match guard* is an additional `if` condition, specified after the pattern in a `match` arm, that must also match for that arm to be chosen. Match guards are useful for expressing more complex ideas than a pattern alone allows. Note, however, that they are only available in `match` expressions, not in `if let` or `while let` expressions.

The condition can use variables created in the pattern. Listing 19-26 shows a `match` where the first arm has the pattern `Some(x)` and also has a match guard of `if x % 2 == 0` (which will be `true` if the number is even).

```
# fn main() {
    let num = Some(4);

    match num {
         Some(x) if x % 2 == 0 => println!("The number {x} is
even"),
        Some(x) => println!("The number {x} is odd"),
        None => (),
    }
# }
```

This example will print `The number 4 is even`. When `num` is compared to the pattern in the first arm, it matches because `Some(4)` matches `Some(x)`. Then the match guard checks whether the remainder of dividing `x` by 2 is equal to 0, and because it is, the first arm is selected.

If `num` had been `Some(5)` instead, the match guard in the first arm would have been `false` because the remainder of 5 divided by 2 is 1, which is not equal to 0. Rust would then go to the second arm, which would match because the second arm doesn't have a match guard and therefore matches any `Some` variant.

There is no way to express the `if x % 2 == 0` condition within a pattern, so the match guard gives us the ability to express this logic. The downside of this additional expressiveness is that the compiler doesn't try to check for exhaustiveness when match guard expressions are involved.

In Listing 19-11, we mentioned that we could use match guards to solve our pattern-shadowing problem. Recall that we created a new variable inside the pattern in the `match` expression instead of using the variable outside the `match`. That new variable meant we couldn't test against the value of the outer variable. Listing 19-27 shows how we can use a match guard to fix this problem.

```
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 = {x:?}, y = {y}");
}
```

This code will now print `Default case, x = Some(5)`. The pattern in the second match arm doesn't introduce a new variable `y` that would shadow the outer `y`, meaning we can use the outer `y` in the match guard. Instead of specifying the pattern as `Some(y)`, which would have shadowed the outer `y`, we specify `Some(n)`. This creates a new variable `n` that doesn't shadow anything because there is no `n` variable outside the `match`.

The match guard `if n == y` is not a pattern and therefore doesn't introduce new variables. This `y` *is* the outer `y` rather than a new `y` shadowing it, and we can look for a value that has the same value as the outer `y` by comparing `n` to `y`.

You can also use the *or* operator `|` in a match guard to specify multiple patterns; the match guard condition will apply to all the patterns. Listing 19-28 shows the precedence when combining a pattern that uses `|` with a match guard. The important part of this example is that the `if y` match guard applies to `4`, `5`, *and* `6`, even though it might look like `if y` only applies to `6`.

```
# fn main() {
    let x = 4;
    let y = false;

    match x {
        4 | 5 | 6 if y => println!("yes"),
        _ => println!("no"),
    }
# }
```

The match condition states that the arm only matches if the value of `x` is equal to `4`, `5`, or `6` *and* if `y` is `true`. When this code runs, the pattern of the first arm matches because `x` is `4`, but the match guard `if y` is `false`, so the first arm is not chosen. The code moves on to the second arm, which does match, and this program prints `no`. The reason is that the `if` condition applies to the whole pattern `4 | 5 | 6`, not just 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) => ...
```

After running the code, the precedence behavior is evident: if the match guard were applied only to the final value in the list of values specified using the `|` operator, the arm would have matched and the program would have printed `yes`.

`@` Bindings

The *at* operator `@` lets us create a variable that holds a value at the same time we're testing that value for a pattern match. In Listing 19-29, we want to test that a `Message::Hello` `id` field is within the range `3..=7`. We also want to bind the value to the variable `id_variable` so we can use it in the code associated with the arm. We could name this variable `id`, the same as the field, but for this example we'll use a different name.

```
# fn main() {
    enum Message {
        Hello { id: i32 },
    }

    let msg = Message::Hello { id: 5 };

    match msg {
        Message::Hello {
            id: id_variable @ 3..=7,
        } => println!("Found an id in range: {id_variable}"),
        Message::Hello { id: 10..=12 } => {
            println!("Found an id in another range")
        }
         Message::Hello { id } => println!("Found some other
id: {id}"),
    }
# }
```

This example will print `Found an id in range: 5`. By specifying `id_variable @` before the range `3..=7`, we're capturing whatever value matched the range while also testing that the value matched the range pattern.

In the second arm, where we only have a range specified in the pattern, the code associated with the arm doesn't have a variable that contains the actual value of the `id` field. The `id` field's value could have been 10, 11, or 12, but the code that goes with that pattern doesn't know which it is. The pattern code isn't able to use the value from the `id` field, because we haven't saved the `id` value in a variable.

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 in a variable named `id`. The reason is that we've used the struct field shorthand syntax. But we haven't applied any test to the value in the `id` field in this arm, as we did with the first two arms: any value would match this pattern.

Using `@` lets us test a value and save it in a variable within one pattern.

Summary

Rust's patterns are very useful in distinguishing between different kinds of data. When used in `match` expressions, Rust ensures your patterns cover every possible value, or your program won't compile. Patterns in `let` statements and function parameters make those constructs more useful, enabling the destructuring of values into smaller parts at the same time as assigning those parts to variables. We can create simple or complex patterns to suit our needs.

Next, for the penultimate chapter of the book, we'll look at some advanced aspects of a variety of Rust's features.

Advanced Features

By now, you've learned the most commonly used parts of the Rust programming language. Before we do one more project in Chapter 21, we'll look at a few aspects of the language you might run into every once in a while, but may not use every day. You can use this chapter as a reference for when you encounter any unknowns. The features covered here are useful in very specific situations. Although you might not reach for them often, we want to make sure you have a grasp of all the features Rust has to offer.

In this chapter, we'll cover:

- Unsafe Rust: how to opt out of some of Rust's guarantees and take responsibility for manually upholding those guarantees
- Advanced traits: associated types, default type parameters, fully qualified syntax, supertraits, and the newtype pattern in relation to traits
- Advanced types: more about the newtype pattern, type aliases, the never type, and dynamically sized types
- Advanced functions and closures: function pointers and returning closures
- Macros: ways to define code that defines more code at compile time

It's a panoply of Rust features with something for everyone! Let's dive in!

Unsafe Rust

All the code we've discussed so far has had Rust's memory safety guarantees enforced at compile time. However, Rust has a second language hidden inside it that doesn't enforce these memory safety guarantees: it's called *unsafe Rust* and works just like regular Rust, but gives us extra superpowers.

Unsafe Rust exists because, by nature, static analysis is conservative. When the compiler tries to determine whether or not code upholds the guarantees, it's better for it to reject some valid programs than to accept some invalid programs. Although the code *might* be okay, if the Rust compiler doesn't have enough information to be confident, it will reject the code. In these cases, you can use unsafe code to tell the compiler, "Trust me, I know what I'm doing." Be warned, however, that you use unsafe Rust at your own risk: if you use unsafe code incorrectly, problems can occur due to memory unsafety, such as null pointer dereferencing.

Another reason Rust has an unsafe alter ego is that the underlying computer hardware is inherently unsafe. If Rust didn't let you do unsafe operations, you couldn't do certain tasks. Rust needs to allow you to do low-level systems programming, such as directly interacting with the operating system or even writing your own operating system. Working with low-level systems programming is one of the goals of the language. Let's explore what we can do with unsafe Rust and how to do it.

Unsafe Superpowers

To switch to unsafe Rust, use the `unsafe` keyword and then start a new block that holds the unsafe code. You can take five actions in unsafe Rust that you can't in safe Rust, which we call *unsafe superpowers*. Those superpowers include the ability to:

- Dereference a raw pointer
- Call an unsafe function or method
- Access or modify a mutable static variable
- Implement an unsafe trait
- Access fields of a `union`

It’s important to understand that `unsafe` doesn’t turn off the borrow checker or disable any of Rust’s other safety checks: if you use a reference in unsafe code, it will still be checked. The `unsafe` keyword only gives you access to these five features that are then not checked by the compiler for memory safety. You’ll still get some degree of safety inside of an unsafe block.

In addition, `unsafe` does not mean the code inside the block is necessarily dangerous or that it will definitely have memory safety problems: the intent is that as the programmer, you’ll ensure the code inside an `unsafe` block will access memory in a valid way.

People are fallible and mistakes will happen, but by requiring these five unsafe operations to be inside blocks annotated with `unsafe`, you’ll know that any errors related to memory safety must be within an `unsafe` block. Keep `unsafe` blocks small; you’ll be thankful later when you investigate memory bugs.

To isolate unsafe code as much as possible, it’s best to enclose such code within a safe abstraction and provide a safe API, which we’ll discuss later in the chapter when we examine unsafe functions and methods. Parts of the standard library are implemented as safe abstractions over unsafe code that has been audited. Wrapping unsafe code in a safe abstraction prevents uses of `unsafe` from leaking out into all the places that you or your users might want to use the functionality implemented with `unsafe` code, because using a safe abstraction is safe.

Let’s look at each of the five unsafe superpowers in turn. We’ll also look at some abstractions that provide a safe interface to unsafe code.

Dereferencing a Raw Pointer

In “Dangling References” in Chapter 4, we mentioned that the compiler ensures references are always valid. Unsafe Rust has two new types called *raw pointers* that are similar to references. As with references, raw pointers can be immutable or mutable and are written as `*const T` and `*mut T`, respectively. The asterisk isn’t the dereference operator; it’s part of the type name. In the context of raw pointers, *immutable* means that the pointer can’t be directly assigned to after being dereferenced.

Different from references and smart pointers, raw pointers:

- Are allowed to ignore the borrowing rules by having both immutable and mutable pointers 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 cleanup

By opting out of having Rust enforce these guarantees, you can give up guaranteed safety in exchange for greater performance or the ability to interface with another language or hardware where Rust's guarantees don't apply.

Listing 20-1 shows how to create an immutable and a mutable raw pointer.

```
# fn main() {
    let mut num = 5;

    let r1 = &raw const num;
    let r2 = &raw mut num;
# }
```

Notice that we don't include the `unsafe` keyword in this code. We can create raw pointers in safe code; we just can't dereference raw pointers outside an unsafe block, as you'll see in a bit.

We've created raw pointers by using the raw borrow operators: `&raw const num` creates a `*const i32` immutable raw pointer, and `&raw mut num` creates a `*mut i32` mutable raw pointer. Because we created them directly from a local variable, we know these particular raw pointers are valid, but we can't make that assumption about just any raw pointer.

To demonstrate this, next we'll create a raw pointer whose validity we can't be so certain of, using `as` to cast a value instead of using the raw borrow operators. Listing 20-2 shows how to create a raw pointer to an arbitrary location in memory. Trying to use arbitrary memory is undefined: there might be data at that address or there might not, the compiler might optimize the code so there is no memory access, or the program might terminate with a segmentation fault. Usually, there is no good reason to write code like this, especially in cases where you can use a raw borrow operator instead, but it is possible.

```
# fn main() {
    let address = 0x012345usize;
    let r = address as *const i32;
# }
```

Recall that we can create raw pointers in safe code, but we can't *dereference* raw pointers and read the data being pointed to. In Listing 20-3, we use the dereference operator `*` on a raw pointer that requires an `unsafe` block.

```
# fn main() {
    let mut num = 5;

    let r1 = &raw const num;
    let r2 = &raw mut num;

    unsafe {
        println!("r1 is: {}", *r1);
        println!("r2 is: {}", *r2);
    }
# }
```

Creating a pointer does no harm; it's only when we try to access the value that it points at that we might end up dealing with an invalid value.

Note also that in Listing 20-1 and 20-3, we created `*const i32` and `*mut i32` raw pointers that both pointed to the same memory location, where `num` is stored. If we instead tried to create an immutable and a mutable reference to `num`, the code would not have compiled because Rust's ownership rules don't allow a mutable reference at the same time as any immutable references. With raw pointers, we can 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 you ever use raw pointers? One major use case is when interfacing with C code, as you'll see in the next section, “Calling an Unsafe Function or Method.” Another case is when building up safe abstractions that the borrow checker doesn’t understand. We’ll introduce unsafe functions and then look at an example of a safe abstraction that uses unsafe code.

Calling an Unsafe Function or Method

The second type of operation you can perform in an unsafe block is calling unsafe functions. Unsafe functions and methods look exactly like regular functions and methods, but they have an extra `unsafe` before the rest of the definition. The `unsafe` keyword in this context indicates the function has requirements we need to uphold when we call this function, because Rust can’t guarantee we’ve met these requirements. By calling an unsafe function within an `unsafe` block, we’re saying that we’ve read this function’s documentation and we take responsibility for upholding the function’s contracts.

Here is an unsafe function named `dangerous` that doesn’t do anything in its body:

```
# fn main() {
    unsafe fn dangerous() {}

    unsafe {
        dangerous();
    }
# }
```

We must call the `dangerous` function within a separate `unsafe` block. If we try to call `dangerous` without the `unsafe` block, we’ll get an error:

```
$ cargo run
    Compiling unsafe-example v0.1.0 (file:///projects/unsafe-
example)
error[E0133]: call to unsafe function `dangerous` is unsafe
and requires unsafe block
 --> src/main.rs:4:5
  |
4 |     dangerous();
```

```
  |     ^^^^^^^^^^^ call to unsafe function
  |
  = note: consult the function's documentation for information
on how to avoid undefined behavior

For more information about this error, try `rustc --explain
E0133`.
error: could not compile `unsafe-example` (bin "unsafe-
example") due to 1 previous error
```

With the `unsafe` block, we're asserting to Rust that we've read the function's documentation, we understand how to use it properly, and we've verified that we're fulfilling the contract of the function.

To perform unsafe operations in the body of an unsafe function, you still need to use an `unsafe` block, just as within a regular function, and the compiler will warn you if you forget. This helps to keep `unsafe` blocks as small as possible, as unsafe operations may not be needed across the whole function body.

Creating a Safe Abstraction over Unsafe Code

Just because a function contains unsafe code doesn't mean we need to mark the entire function as unsafe. In fact, wrapping unsafe code in a safe function is a common abstraction. As an example, let's study the `split_at_mut` function from the standard library, which requires some unsafe code. We'll explore how we might implement it. This safe method is defined on mutable slices: it takes one slice and makes it two by splitting the slice at the index given as an argument. Listing 20-4 shows how to use `split_at_mut`.

```
# fn main() {
    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]);
# }
```

We can't implement this function using only safe Rust. An attempt might look something like Listing 20-5, which won't compile. For simplicity, we'll implement `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(values: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]) {
    let len = values.len();

    assert!(mid <= len);

    (&mut values[..mid], &mut values[mid..])
}
#
# fn main() {
#     let mut vector = vec![1, 2, 3, 4, 5, 6];
#     let (left, right) = split_at_mut(&mut vector, 3);
# }
```

This function first gets the total length of the slice. Then it asserts that the index given as a parameter is within the slice by checking whether it's less than or equal to the length. The assertion means that if we pass an index that is greater than the length to split the slice 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 original slice to the `mid` index and another from `mid` to the end of the slice.

When we try to compile the code in Listing 20-5, we'll get an error.

```
$ cargo run
    Compiling unsafe-example v0.1.0 (file:///projects/unsafe-example)
error[E0499]: cannot borrow `*values` as mutable more than once at a time
 --> src/main.rs:6:31
```

```
  |
1 | fn split_at_mut(values: &mut [i32], mid: usize) -> (&mut
[i32], &mut [i32]) {
  |                          - let's call the lifetime of this
reference `'1`
...
6 |     (&mut values[..mid], &mut values[mid..])
  |     --------------------------^^^^^^--------
  |     |     |                   |
  |     |     |                   second mutable borrow occurs
here
  |     |     first mutable borrow occurs here
   |        returning  this  value  requires  that  `*values`  is
borrowed for `'1`
  |
  = help: use `.split_at_mut(position)` to obtain two mutable
non-overlapping sub-slices

For more information about this error, try `rustc --explain
E0499`.
error:  could  not  compile  `unsafe-example`  (bin  "unsafe-
example") due to 1 previous error
```

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 because the two slices aren’t overlapping, but Rust isn’t smart enough to know this. When we know code is okay, but Rust doesn’t, it’s time to reach for unsafe code.

Listing 20-6 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(values:  &mut  [i32],  mid:  usize)  ->  (&mut
```

```
[i32], &mut [i32]) {
    let len = values.len();
    let ptr = values.as_mut_ptr();

    assert!(mid <= len);

    unsafe {
        (
            slice::from_raw_parts_mut(ptr, mid),
                slice::from_raw_parts_mut(ptr.add(mid), len -
mid),
        )
    }
}
#
# fn main() {
#     let mut vector = vec![1, 2, 3, 4, 5, 6];
#     let (left, right) = split_at_mut(&mut vector, 3);
# }
```

Recall from “The Slice Type” in Chapter 4 that slices are a pointer to some data and the length of the slice. We use the `len` method to get the length of a slice and the `as_mut_ptr` method to access the raw pointer of a slice. In this case, because 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`.

We keep the assertion that the `mid` index is within the slice. Then we get to the unsafe code: the `slice::from_raw_parts_mut` function takes a raw pointer and a length, and it creates a slice. We use it to create a slice that starts from `ptr` and is `mid` items long. Then we call the `add` 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.

The function `slice::from_raw_parts_mut` is unsafe because it takes a raw pointer and must trust that this pointer is valid. The `add` method on raw pointers is also unsafe because it must trust that the offset location is also a valid pointer. Therefore, we had to put an `unsafe` block around our calls to `slice::from_raw_parts_mut` and `add` so we could call them. By looking at the code and by adding the assertion that `mid` must be less than or equal to `len`, we can tell 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 we don't need to mark the resultant `split_at_mut` function as `unsafe`, and we can call this function from safe Rust. We've created a safe abstraction to the unsafe code with an implementation of the function that uses `unsafe` code in a safe way, because it creates only valid pointers from the data this function has access to.

In contrast, the use of `slice::from_raw_parts_mut` in Listing 20-7 would likely crash when the slice is used. This code takes an arbitrary memory location and creates a slice 10,000 items long.

```
# fn main() {
    use std::slice;

    let address = 0x01234usize;
    let r = address as *mut i32;

    let values: &[i32] = unsafe { slice::from_raw_parts_mut(r,
10000) };
# }
```

We don't own the memory at this arbitrary location, and there is no guarantee that the slice this code creates contains valid `i32` values. Attempting to use `values` as though it's a valid slice results in undefined behavior.

Using `extern` Functions to Call External Code

Sometimes, your Rust code might need to interact with code written in another language. For this, Rust has the keyword `extern` that facilitates the creation and use of a *Foreign Function Interface (FFI)*. An FFI is a way for a programming language to define functions and enable a different (foreign) programming language to call those functions.

Listing 20-8 demonstrates how to set up an integration with the `abs` function from the C standard library. Functions declared within `extern` blocks are generally unsafe to call from Rust code, so `extern` blocks must also be marked `unsafe`. The reason is that other languages don't enforce Rust's rules and guarantees, and Rust can't check them, so responsibility falls on the programmer to ensure safety.

```
unsafe extern "C" {
    fn abs(input: i32) -> i32;
}

fn main() {
    unsafe {
         println!("Absolute value of -3 according to C: {}",
abs(-3));
    }
}
```

Within the `unsafe extern "C"` block, we list the names and signatures of external functions from another language we want to call. The `"C"` part 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. Information about all the ABIs Rust supports is available in [the Rust Reference](#).

Every item declared within an `unsafe extern` block is implicitly `unsafe`. However, some FFI functions *are* safe to call. For example, the `abs` function from C's standard library does not have any memory safety considerations and we know it can be called with any `i32`. In cases like this, we can use the `safe` keyword to say that this specific function is safe to call even though it is in an `unsafe extern` block. Once we make that change, calling it no longer requires an `unsafe` block, as shown in Listing 20-9.

```
unsafe extern "C" {
    safe fn abs(input: i32) -> i32;
}

fn main() {
    println!("Absolute value of -3 according to C: {}", abs(-3));
}
```

Marking a function as `safe` does not inherently make it safe! Instead, it is like a promise you are making to Rust that it *is* safe. It is still your responsibility to make sure that promise is kept!

Calling Rust Functions from Other Languages

We can also use `extern` to create an interface that allows other languages to call Rust functions. Instead of creating a whole `extern` block, we add the `extern` keyword and specify the ABI to use just before the `fn` keyword for the relevant function. We also need to add an `#[unsafe(no_mangle)]` annotation to tell the Rust compiler not to mangle the name of this function. *Mangling* is when a compiler changes the name we've given a function to a different name that contains more information for other parts of the compilation process to consume but is less human readable. Every programming language compiler mangles names slightly differently, so for a Rust function to be nameable by other languages, we must disable the Rust compiler's name mangling. This is unsafe because there might be name collisions across libraries without the built-in mangling, so it is our responsibility to make sure the name we choose is safe to export without mangling.

In the following example, we make the `call_from_c` function accessible from C code, after it's compiled to a shared library and linked from C:

```
#[unsafe(no_mangle)]
pub extern "C" fn call_from_c() {
    println!("Just called a Rust function from C!");
}
```

This usage of `extern` requires `unsafe` only in the attribute, not on the `extern` block.

Accessing or Modifying a Mutable Static Variable

In this book, we've not yet talked about global variables, which Rust does support but can be problematic with Rust's ownership rules. If two threads are accessing the same mutable global variable, it can cause a data race.

In Rust, global variables are called *static* variables. Listing 20-10 shows an example declaration and use of a static variable with a string slice as a value.

```
static HELLO_WORLD: &str = "Hello, world!";

fn main() {
    println!("name is: {HELLO_WORLD}");
}
```

Static variables are similar to constants, which we discussed in "Constants" in Chapter 3. The names of static variables are in `SCREAMING_SNAKE_CASE` by convention. Static variables can only store references with the `'static` lifetime, which means the Rust compiler can figure out the lifetime and we aren't required to annotate it explicitly. Accessing an immutable static variable is safe.

A subtle difference between constants and immutable static variables is that values in a static variable have a fixed address in memory. Using the value will always access the same data. Constants, on the other hand, are allowed to duplicate their data whenever they're used. Another difference is that static variables can be mutable. Accessing and modifying mutable static variables is *unsafe*. Listing 20-11 shows how to declare, access, and modify a mutable static variable named `COUNTER`.

```
static mut COUNTER: u32 = 0;

/// SAFETY: Calling this from more than a single thread at a
time is undefined
/// behavior, so you *must* guarantee you only call it from a
single thread at
/// a time.
unsafe fn add_to_count(inc: u32) {
    unsafe {
        COUNTER += inc;
    }
}

fn main() {
    unsafe {
        // SAFETY: This is only called from a single thread in
`main`.
        add_to_count(3);
        println!("COUNTER: {}", *(&raw const COUNTER));
    }
}
```

As with regular variables, we specify mutability using the `mut` keyword. Any code that reads or writes from `COUNTER` must be within an `unsafe` block. This code compiles and prints `COUNTER: 3` as we would expect because it's single threaded. Having multiple threads access `COUNTER` would likely result in data races, so it is undefined behavior. Therefore, we need to mark the entire function as `unsafe`, and document the safety limitation, so anyone calling the function knows what they are and are not allowed to do safely.

Whenever we write an unsafe function, it is idiomatic to write a comment starting with `SAFETY` and explaining what the caller needs to do to call the function safely. Likewise, whenever we perform an unsafe operation, it is idiomatic to write a comment starting with `SAFETY` to explain how the safety rules are upheld.

Additionally, the compiler will not allow you to create references to a mutable static variable. You can only access it via a raw pointer, created with one of the raw borrow operators. That includes in cases where the reference is created invisibly, as when it is used in the `println!` in this code listing. The requirement that references to static mutable variables can only be created via raw pointers helps make the safety requirements for using them more obvious.

With mutable data that is globally accessible, it's difficult to ensure there are no data races, which is why Rust considers mutable static variables to be unsafe. Where possible, it's preferable to use the concurrency techniques and thread-safe smart pointers we discussed in Chapter 16 so the compiler checks that data access from different threads is done safely.

Implementing an Unsafe Trait

We can use `unsafe` to implement an unsafe trait. A trait is unsafe when at least one of its methods has some invariant that the compiler can't verify. We declare that a trait is `unsafe` by adding the `unsafe` keyword before `trait` and marking the implementation of the trait as `unsafe` too, as shown in Listing 20-12.

```
unsafe trait Foo {
    // methods go here
}

unsafe impl Foo for i32 {
    // method implementations go here
}
#
# fn main() {}
```

By using `unsafe impl`, we're promising that we'll uphold the invariants that the compiler can't verify.

As an example, recall the `Sync` and `Send` marker traits we discussed in "Extensible Concurrency with the `Sync` and `Send` Traits" in Chapter 16: the compiler implements these traits automatically if our types are composed entirely of other types that implement `Send` and `Sync`. If we implement a type that contains a type that does not implement `Send` or `Sync`, such as raw pointers, and we want to mark that type as `Send` or `Sync`, we must use `unsafe`. Rust can't verify that our type upholds the guarantees that it can be safely sent across threads or accessed from multiple threads; therefore, we need to do those checks manually and indicate as such with `unsafe`.

Accessing Fields of a Union

The final action that works only with `unsafe` is accessing fields of a union. A `union` is similar to a `struct`, but only one declared field is used in a particular instance at one time. Unions are primarily used to interface with unions in C code. Accessing union fields is unsafe because Rust can't guarantee the type of the data currently being stored in the union instance. You can learn more about unions in the Rust Reference.

Using Miri to Check Unsafe Code

When writing unsafe code, you might want to check that what you have written actually is safe and correct. One of the best ways to do that is to use Miri, an official Rust tool for detecting undefined behavior. Whereas the borrow checker is a *static* tool that works at compile time, Miri is a *dynamic* tool that works at runtime. It checks your code by running your program, or its test suite, and detecting when you violate the rules it understands about how Rust should work.

Using Miri requires a nightly build of Rust (which we talk about more in Appendix G: How Rust is Made and "Nightly Rust"). You can install both a nightly version of Rust and the Miri tool by typing `rustup +nightly component add miri`. This does not change what version of Rust your project uses; it only adds the tool to your system so you can use it when you want to. You can run Miri on a project by typing `cargo +nightly miri run` or `cargo +nightly miri test`.

For an example of how helpful this can be, consider what happens when we run it against Listing 20-11.

```
$ cargo +nightly miri run
    Compiling unsafe-example v0.1.0 (file:///projects/unsafe-
```

```
example)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.01s
                                                       Running
`file:///home/.rustup/toolchains/nightly/bin/cargo-miri runner
target/miri/debug/unsafe-example`
COUNTER: 3
```

Miri correctly warns us that we have shared references to mutable data. Here, Miri issues only a warning because this is not guaranteed to be undefined behavior in this case, and it does not tell us how to fix the problem. but at least we know there is a risk of undefined behavior and can think about how to make the code safe. In some cases, Miri can also detect outright errors—code patterns that are *sure* to be wrong—and make recommendations about how to fix those errors.

Miri doesn't catch everything you might get wrong when writing unsafe code. Miri is a dynamic analysis tool, so it only catches problems with code that actually gets run. That means you will need to use it in conjunction with good testing techniques to increase your confidence about the unsafe code you have written. Miri also does not cover every possible way your code can be unsound.

Put another way: If Miri *does* catch a problem, you know there's a bug, but just because Miri *doesn't* catch a bug doesn't mean there isn't a problem. It can catch a lot, though. Try running it on the other examples of unsafe code in this chapter and see what it says!

You can learn more about Miri at [its GitHub repository](https://github.com/rust-lang/miri).

When to Use Unsafe Code

Using `unsafe` to use one of the five superpowers just discussed isn't wrong or even frowned upon, but it is trickier to get `unsafe` code correct because the compiler can't help uphold memory safety. When you have a reason to use `unsafe` code, you can do so, and having the explicit `unsafe` annotation makes it easier to track down the source of problems when they occur. Whenever you write unsafe code, you can use Miri to help you be more confident that the code you have written upholds Rust's rules.

For a much deeper exploration of how to work effectively with unsafe Rust, read Rust’s official guide to the subject, the Rustonomicon.

Advanced Traits

We first covered traits in “Traits: Defining Shared Behavior” in Chapter 10, but we didn’t discuss the more advanced details. Now that you know more about Rust, we can get into the nitty-gritty.

Associated Types

Associated types connect 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 instead of the placeholder type for the particular implementation. That way, we can define a trait that uses some types without needing to know exactly what those types are until the trait is implemented.

We’ve described most of the advanced features in this chapter as being rarely needed. Associated types are somewhere in the middle: they’re used more rarely than features explained in the rest of the book but more commonly than many of the other features discussed in this chapter.

One example of a trait with an associated type is the `Iterator` trait that the standard library provides. The associated type is named `Item` and stands in for the type of the values the type implementing the `Iterator` trait is iterating over. The definition of the `Iterator` trait is as shown in Listing 20-13.

```
pub trait Iterator {
    type Item;

    fn next(&mut self) -> Option<Self::Item>;
}
```

The type `Item` is a placeholder, and the `next` method’s definition shows that it will return values of type `Option<Self::Item>`. Implementors of the `Iterator` trait will specify the concrete type for `Item`, and the `next` method will return an `Option` containing a value of that concrete type.

Associated types might seem like a similar concept to generics, in that the latter allow us to define a function without specifying what types it can handle. To examine the difference between the two concepts, we'll look at an implementation of the `Iterator` trait on a type named `Counter` that specifies the `Item` type is `u32`:

```
# struct Counter {
#     count: u32,
# }
#
# impl Counter {
#     fn new() -> Counter {
#         Counter { count: 0 }
#     }
# }
#
impl Iterator for Counter {
    type Item = u32;

    fn next(&mut self) -> Option<Self::Item> {
        // --snip--
#         if self.count < 5 {
#             self.count += 1;
#             Some(self.count)
#         } else {
#             None
#         }
#     }
# }
```

This syntax seems comparable to that of generics. So why not just define the `Iterator` trait with generics, as shown in Listing 20-14?

```
pub trait Iterator<T> {
    fn next(&mut self) -> Option<T>;
```

```
}
```

The difference is that when using generics, as in Listing 20-14, we must annotate the types in each implementation; because we can also implement `Iterator<String> for Counter` or any other type, we could have multiple implementations of `Iterator` for `Counter`. In other words, when a trait has a generic parameter, it can be implemented for a type multiple times, changing the concrete types of the generic type parameters each time. When we use the `next` method on `Counter`, we would have to provide type annotations to indicate which implementation of `Iterator` we want to use.

With associated types, we don't need to annotate types because we can't implement a trait on a type multiple times. In Listing 20-13 with the definition that uses associated types, we can choose what the type of `Item` will be only once, because there can be only 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`.

Associated types also become part of the trait's contract: implementors of the trait must provide a type to stand in for the associated type placeholder. Associated types often have a name that describes how the type will be used, and documenting the associated type in the API documentation is a good practice.

Default Generic Type Parameters and Operator Overloading

When we use generic type parameters, we can specify a default concrete type for the generic type. This eliminates the need for implementors of the trait to specify a concrete type if the default type works. You specify a default type when declaring a generic type with the `<PlaceholderType=ConcreteType>` syntax.

A great example of a situation where this technique is useful is with *operator overloading*, in which you customize the behavior of an operator (such as `+`) in particular situations.

Rust doesn’t allow you to create your own operators or overload arbitrary operators. But you can overload the operations and corresponding traits listed in `std::ops` by implementing the traits associated with the operator. For example, in Listing 20-15 we overload the `+` operator to add two `Point` instances together. We do this by implementing the `Add` trait on a `Point` struct.

```
use std::ops::Add;

#[derive(Debug, Copy, Clone, 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 }
    );
}
```

The `add` method adds the `x` values of two `Point` instances and the `y` values of two `Point` instances to create a new `Point`. The `Add` trait has an associated type named `Output` that determines the type returned from the `add` method.

The default generic type in this code is within the `Add` trait. Here is its definition:

```
trait Add<Rhs=Self> {
    type Output;

    fn add(self, rhs: Rhs) -> Self::Output;
}
```

This code should look generally familiar: a trait with one method and an associated type. The new part is `Rhs=Self`: this syntax is called *default type parameters*. The `Rhs` generic type parameter (short for "right-hand side") defines 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 `Self`, which will be the type we're implementing `Add` on.

When we implemented `Add` for `Point`, we used the default for `Rhs` because we wanted to add two `Point` instances. Let's look at an example of implementing the `Add` trait where we want to customize the `Rhs` type rather than using the default.

We have two structs, `Millimeters` and `Meters`, holding values in different units. This thin wrapping of an existing type in another struct is known as the *newtype pattern*, which we describe in more detail in the "Using the Newtype Pattern to Implement External Traits on External Types" section. We want to add values in millimeters to values in meters and have the implementation of `Add` do the conversion correctly. We can implement `Add` for `Millimeters` with `Meters` as the `Rhs`, as shown in Listing 20-16.

```
use std::ops::Add;

struct Millimeters(u32);
struct Meters(u32);

impl Add<Meters> for Millimeters {
    type Output = Millimeters;

    fn add(self, other: Meters) -> Millimeters {
        Millimeters(self.0 + (other.0 * 1000))
    }
}
```

To add `Millimeters` and `Meters`, we specify `impl Add<Meters>` to set the value of the `Rhs` type parameter instead of using the default of `Self`.

You'll use default type parameters in two main ways:

1. To extend a type without breaking existing code
2. To allow customization in specific cases most users won't need

The standard library's `Add` trait is an example of the second purpose: usually, you'll add two like types, but the `Add` trait provides the ability to customize beyond that. Using a default type parameter in the `Add` trait definition means you don't have to specify the extra parameter most of the time. In other words, a bit of implementation boilerplate isn't needed, making it easier to use the trait.

The first purpose is similar to the second but in reverse: if you want to add a type parameter to an existing trait, you can give it a default to allow extension of the functionality of the trait without breaking the existing implementation code.

Disambiguating Between Methods with the Same Name

Nothing in Rust prevents a trait from having a method with the same name as another trait's method, nor does Rust prevent you from implementing both traits on one type. It's also possible to implement a method directly on the type with the same name as methods from traits.

When calling methods with the same name, you'll need to tell Rust which one you want to use. Consider the code in Listing 20-17 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 already has a method named `fly` implemented on it. Each `fly` method does something different.

```
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*");
```

```
    }
}
#
# fn main() {}
```

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 20-18.

```
# 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*");
#     }
```

```
# }
#
fn main() {
    let person = Human;
    person.fly();
}
```

Running this code will print `*waving arms furiously*`, showing that Rust called the `fly` method implemented on `Human` directly.

To call the `fly` methods from either the `Pilot` trait or the `Wizard` trait, we need to use more explicit syntax to specify which `fly` method we mean. Listing 20-19 demonstrates this syntax.

```
# 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*");
#     }
# }
#
fn main() {
    let person = Human;
    Pilot::fly(&person);
    Wizard::fly(&person);
    person.fly();
}
```

Specifying the trait name before the method name clarifies to Rust which implementation of `fly` we want to call. We could also write `Human::fly(&person)`, which is equivalent to the `person.fly()` that we used in Listing 20-19, but this is a bit longer to write if we don't need to disambiguate.

Running this code prints the following:

```
$ cargo run
    Compiling traits-example v0.1.0 (file:///projects/traits-
example)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.46s
     Running `target/debug/traits-example`
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 could figure out which implementation of a trait to use based on the type of `self`.

However, associated functions that are not methods don’t have a `self` parameter. When there are multiple types or traits that define non-method functions with the same function name, Rust doesn't always know which type you mean unless you use *fully qualified syntax*. For example, in Listing 20-20 we create a trait for an animal shelter that wants to name all baby dogs *Spot*. We make an `Animal` trait with an associated non-method function `baby_name`. The `Animal` trait is implemented for the struct `Dog`, on which we also provide an associated non-method function `baby_name` directly.

```
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());
}
```

We implement the code for naming all puppies Spot 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 call the `Dog::baby_name` function, which calls the associated function defined on `Dog` directly. This code prints the following:

```
$ cargo run
    Compiling traits-example v0.1.0 (file:///projects/traits-example)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.54s
     Running `target/debug/traits-example`
A baby dog is called a Spot
```

This output isn't what we wanted. We want to call the `baby_name` function that is part of the `Animal` trait that we implemented on `Dog` so the code prints `A baby dog is called a puppy`. The technique of specifying the trait name that we used in Listing 20-19 doesn't help here; if we change `main` to the code in Listing 20-21, we'll get a compilation error.

```
# 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   {}",
Animal::baby_name());
}
```

Because `Animal::baby_name` doesn't have a `self` parameter, and there could be other types that implement the `Animal` trait, Rust can't figure out which implementation of `Animal::baby_name` we want. We'll get this compiler error:

```
$ cargo run
    Compiling traits-example v0.1.0 (file:///projects/traits-
example)
error[E0790]: cannot call associated function on trait without
specifying the corresponding `impl` type
  --> src/main.rs:20:43
   |
2  |     fn baby_name() -> String;
   |     ------------------------- `Animal::baby_name` defined
here
...
20  |           println!("A  baby  dog  is  called  a  {}",
Animal::baby_name());
                                                             |
^^^^^^^^^^^^^^^^^^^ cannot call associated function of trait
   |
help:  use  the  fully-qualified  path  to  the  only  available
implementation
   |
20  |        println!("A baby dog is called a {}", <Dog as
Animal>::baby_name());
   |                                          +++++++       +
```

```
For more information about this error, try `rustc --explain E0790`.
error: could not compile `traits-example` (bin "traits-example") due to 1 previous error
```

To disambiguate and tell Rust that we want to use the implementation of `Animal` for `Dog` as opposed to the implementation of `Animal` for some other type, we need to use fully qualified syntax. Listing 20-22 demonstrates how to use fully qualified syntax.

```
# 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 as Animal>::baby_name());
}
```

We’re providing Rust with a type annotation within the angle brackets, which indicates 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:

```
$ cargo run
    Compiling traits-example v0.1.0 (file:///projects/traits-example)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.48s
     Running `target/debug/traits-example`
A baby dog is called a puppy
```

In general, fully qualified syntax is defined as follows:

```
<Type as Trait>::function(receiver_if_method, next_arg, ...);
```

For associated functions that aren’t methods, there would not be a `receiver`: there would only be the list of other arguments. You could use fully qualified syntax everywhere that you call functions or methods. However, you’re allowed to omit any part of this syntax that Rust can figure out from other information in the program. You only need to use this more verbose syntax in cases where there are multiple implementations that use the same name and Rust needs help to identify which implementation you want to call.

Using Supertraits

Sometimes you might write a trait definition that depends on another trait: for a type to implement the first trait, you want to require that type to also implement the second trait. You would do this so that your trait definition can make use of the associated items of the second trait. The trait your trait definition is relying on is called a *supertrait* of your trait.

For example, let’s say we want to make an `OutlinePrint` trait with an `outline_print` method that will print a given value formatted so that it's framed in asterisks. That is, given a `Point` struct that implements the standard library trait `Display` to result in `(x, y)`, when we call `outline_print` on a `Point` instance that has `1` for `x` and `3` for `y`, it should print the following:

```
**********
*        *
* (1, 3) *
*        *
**********
```

In the implementation of the `outline_print` method, we want to use the `Display` trait's functionality. Therefore, we need to specify that the `OutlinePrint` trait will work only 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`. This technique is similar to adding a trait bound to the trait. Listing 20-23 shows an implementation of the `OutlinePrint` trait.

```
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));
    }
}
#
# fn main() {}
```

Because we've specified that `OutlinePrint` requires the `Display` trait, we can use the `to_string` function that is automatically implemented for any type that implements `Display`. If we tried to use `to_string` without adding a colon and specifying the `Display` trait after the trait name, we'd get an error saying that no method named `to_string` was found for the type `&Self` in the current scope.

Let's see what happens when we try to implement `OutlinePrint` on a type that doesn't implement `Display`, such as the `Point` struct:

```
# 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));
#     }
# }
#
struct Point {
    x: i32,
    y: i32,
}

impl OutlinePrint for Point {}
#
# fn main() {
#     let p = Point { x: 1, y: 3 };
#     p.outline_print();
# }
```

We get an error saying that `Display` is required but not implemented:

```
$ cargo run
    Compiling traits-example v0.1.0 (file:///projects/traits-
example)
error[E0277]: `Point` doesn't implement `std::fmt::Display`
  --> src/main.rs:20:23
   |
20 | impl OutlinePrint for Point {}
   |                       ^^^^^ `Point` cannot be formatted
with the default formatter
   |
    = help: the trait `std::fmt::Display` is not implemented
for `Point`
   = note: in format strings you may be able to use `{:?}` (or
{:#?} for pretty-print) instead
note: required by a bound in `OutlinePrint`
  --> src/main.rs:3:21
   |
3  | trait OutlinePrint: fmt::Display {
   |                     ^^^^^^^^^^^^ required by this bound
in `OutlinePrint`

error[E0277]: `Point` doesn't implement `std::fmt::Display`
  --> src/main.rs:24:7
   |
24 |     p.outline_print();
   |       ^^^^^^^^^^^^^ `Point` cannot be formatted with the
default formatter
   |
    = help: the trait `std::fmt::Display` is not implemented
for `Point`
   = note: in format strings you may be able to use `{:?}` (or
{:#?} for pretty-print) instead
note: required by a bound in `OutlinePrint::outline_print`
  --> src/main.rs:3:21
   |
```

```
3  | trait OutlinePrint: fmt::Display {
   |                        ^^^^^^^^^^^^ required by this bound
in `OutlinePrint::outline_print`
4  |     fn outline_print(&self) {
    |            ------------- required by a bound in this
associated function

For more information about this error, try `rustc --explain
E0277`.
error: could not compile `traits-example` (bin "traits-
example") due to 2 previous errors
```

To fix this, we implement `Display` on `Point` and satisfy the constraint that `OutlinePrint` requires, like so:

```
# 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));
#     }
# }
#
# struct Point {
#     x: i32,
#     y: i32,
# }
#
# impl OutlinePrint for Point {}
#
use std::fmt;
```

```
impl fmt::Display for Point {
    fn fmt(&self, f: &mut fmt::Formatter) -> fmt::Result {
        write!(f, "({}, {})", self.x, self.y)
    }
}
#
# fn main() {
#     let p = Point { x: 1, y: 3 };
#     p.outline_print();
# }
```

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.

Using the Newtype Pattern to Implement External Traits on External Types

In “Implementing a Trait on a Type” in Chapter 10, we mentioned the orphan rule that states we’re only allowed to implement a trait on a type if either the trait or the type, or both, are local to our crate. It’s possible to get around this restriction using the *newtype pattern*, which involves creating a new type in a tuple struct. (We covered tuple structs in “Using Tuple Structs Without Named Fields to Create Different Types” in Chapter 5.) The tuple struct will have one field and be a thin wrapper around the type for which we want to implement a trait. Then the wrapper type is local to our crate, and we can implement the trait on the wrapper. *Newtype* is a term that originates from the Haskell programming language. There is no runtime performance penalty for using this pattern, and the wrapper type is elided at compile time.

As an example, let’s say we want to implement `Display` on `Vec<T>`, which the orphan rule prevents us from doing directly because the `Display` trait and the `Vec<T>` type are defined outside our crate. We can make a `Wrapper` struct that holds an instance of `Vec<T>`; then we can implement

`Display` on `Wrapper` and use the `Vec<T>` value, as shown in Listing 20-24.

```
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}");
}
```

The implementation of `Display` uses `self.0` to access the inner `Vec<T>`, because `Wrapper` is a tuple struct and `Vec<T>` is the item at index 0 in the tuple. Then we can use the functionality of the `Display` trait on `Wrapper`.

The downside of using this technique is that `Wrapper` is a new type, so it doesn't have the methods of the value it's holding. We would have to implement all the methods of `Vec<T>` directly on `Wrapper` such that the methods delegate to `self.0`, which would allow us to treat `Wrapper` exactly like a `Vec<T>`. If we wanted the new type to have every method the inner type has, implementing the `Deref` trait on the `Wrapper` to return the inner type would be a solution (we discussed implementing the `Deref` trait in "Treating Smart Pointers Like Regular References with the `Deref` Trait" in Chapter 15). If we didn't want the `Wrapper` type to have all the methods of the inner type—for example, to restrict the `Wrapper` type's behavior—we would have to implement just the methods we do want manually.

This newtype pattern is also useful even when traits are not involved. Let's switch focus and look at some advanced ways to interact with Rust's type system.

Advanced Types

The Rust type system has some features that we've so far mentioned but haven't yet discussed. We'll start by discussing newtypes in general as we examine why newtypes are useful as types. Then we'll move on to type aliases, a feature similar to newtypes but with slightly different semantics. We'll also discuss the `!` type and dynamically sized types.

Using the Newtype Pattern for Type Safety and Abstraction

This section assumes you've read the earlier section "Using the Newtype Pattern to Implement External Traits on External Types." The newtype pattern is also useful for tasks beyond those we've discussed so far, including statically enforcing that values are never confused and indicating the units of a value. You saw an example of using newtypes to indicate units in Listing 20-16: recall that the `Millimeters` and `Meters` structs wrapped `u32` values in a newtype. If we wrote a function with a parameter of type `Millimeters`, we wouldn't be able to compile a program that accidentally tried to call that function with a value of type `Meters` or a plain `u32`.

We can also use the newtype pattern to abstract away some implementation details of a type: the new type can expose a public API that is different from the API of the private inner type.

Newtypes can also hide internal implementation. For example, we could provide a `People` type to wrap 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; 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, which we discussed in "Encapsulation That Hides Implementation Details" in Chapter 18.

Creating Type Synonyms with Type Aliases

Rust provides the ability to declare a *type alias* to give an existing type another name. For this we use the `type` keyword. For example, we can create the alias `Kilometers` to `i32` like so:

```
# fn main() {
    type Kilometers = i32;
#
#     let x: i32 = 5;
#     let y: Kilometers = 5;
#
#     println!("x + y = {}", x + y);
# }
```

Now, the alias `Kilometers` is a *synonym* for `i32`; unlike the `Millimeters` and `Meters` types we created in Listing 20-16, `Kilometers` is not a separate, new type. Values that have the type `Kilometers` will be treated the same as values of type `i32`:

```
# fn main() {
    type Kilometers = i32;

    let x: i32 = 5;
    let y: Kilometers = 5;

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

Because `Kilometers` and `i32` are the same type, we can add values of both types and we can pass `Kilometers` values to functions that take `i32` parameters. However, using this method, we don't get the type-checking benefits that we get from the newtype pattern discussed earlier. In other words, if we mix up `Kilometers` and `i32` values somewhere, the compiler will not give us an error.

The main use case for type synonyms is to reduce repetition. For example, we might have a lengthy type like this:

```
Box<dyn Fn() + Send + 'static>
```

Writing this lengthy type in function signatures and as type annotations all over the code can be tiresome and error prone. Imagine having a project full of code like that in Listing 20-25.

```
# fn main() {
      let f: Box<dyn Fn() + Send + 'static> = Box::new(||
println!("hi"));

    fn takes_long_type(f: Box<dyn Fn() + Send + 'static>) {
        // --snip--
    }

    fn returns_long_type() -> Box<dyn Fn() + Send + 'static> {
        // --snip--
#         Box::new(|| ())
    }
# }
```

A type alias makes this code more manageable by reducing the repetition. In Listing 20-26, we've introduced an alias named `Thunk` for the verbose type and can replace all uses of the type with the shorter alias `Thunk`.

```
# fn main() {
    type Thunk = Box<dyn Fn() + Send + 'static>;

    let f: Thunk = Box::new(|| println!("hi"));

    fn takes_long_type(f: Thunk) {
        // --snip--
    }

    fn returns_long_type() -> Thunk {
        // --snip--
#         Box::new(|| ())
    }
# }
```

This code is much easier to read and write! Choosing a meaningful 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).

Type aliases are also commonly used with the `Result<T, E>` type for reducing repetition. Consider the `std::io` module in the standard library. I/O operations often return a `Result<T, E>` to handle situations when operations fail to work. This library has a `std::io::Error` struct that represents all 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::fmt;
use std::io::Error;

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>;
}
```

The `Result<..., Error>` is repeated a lot. As such, `std::io` has this type alias declaration:

```
# use std::fmt;
#
type Result<T> = std::result::Result<T, std::io::Error>;
#
# 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:  fmt::Arguments)  ->
Result<()>;
# }
```

Because this declaration is in the `std::io` module, we can use the fully qualified alias `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:

```
# use std::fmt;
#
# type Result<T> = std::result::Result<T, std::io::Error>;
#
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:  fmt::Arguments)  ->
Result<()>;
}
```

The type alias helps in two ways: it makes code easier to write *and* it gives us a consistent interface across all of `std::io`. Because it's an alias, it's just another `Result<T, E>`, which means we can use any methods that work on `Result<T, E>` with it, as well as special syntax like the `?` operator.

The Never Type That Never Returns

Rust has a special type named `!` that's known in type theory lingo as the *empty type* because it has no values. We prefer to call it the *never type* because it stands in the place of the return type when a function will never return. Here is an example:

```
fn bar() -> ! {
    // --snip--
```

```
#     panic!();
}
```

This code is read as “the function `bar` returns never.” Functions that return never are called *diverging functions*. We can’t create values of the type `!` so `bar` can never possibly return.

But what use is a type you can never create values for? Recall the code from Listing 2-5, part of the number-guessing game; we’ve reproduced a bit of it here in Listing 20-27.

```
# use std::cmp::Ordering;
# use std::io;
#
# use rand::Rng;
#
# fn main() {
#     println!("Guess the number!");
#
#     let secret_number = rand::thread_rng().gen_range(1..=100);
#
#     println!("The secret number is: {secret_number}");
#
#     loop {
#         println!("Please input your guess.");
#
#         let mut guess = String::new();
#
#         // --snip--
#
#         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}");
#
#         // --snip--
#
#         match guess.cmp(&secret_number) {
#             Ordering::Less => println!("Too small!"),
#             Ordering::Greater => println!("Too big!"),
#             Ordering::Equal => {
#                 println!("You win!");
#                 break;
#             }
#         }
#     }
# }
```

At the time, we skipped over some details in this code. In “The `match` Control Flow Operator” in Chapter 6, we discussed that `match` arms must all return the same type. So, for example, the following code doesn’t work:

```
# fn main() {
#     let guess = "3";
    let guess = match guess.trim().parse() {
        Ok(_) => 5,
        Err(_) => "hello",
    };
# }
```

The type of `guess` in this code would have to be an integer *and* a string, and Rust requires that `guess` have only one type. So what does `continue` return? How were we allowed to return a `u32` from one arm and have another arm that ends with `continue` in Listing 20-27?

As you might have guessed, `continue` has a `!` value. That is, when Rust computes the type of `guess`, it looks at both match arms, the former with a value of `u32` and the latter with a `!` value. Because `!` can never have a value, Rust decides that the type of `guess` is `u32`.

The formal way of describing this behavior is that expressions of type `!` can be coerced into any other type. We're allowed to end this `match` arm with `continue` because `continue` doesn't return a value; instead, it moves control back to the top of the loop, so in the `Err` case, we never assign a value to `guess`.

The never type is useful with the `panic!` macro as well. Recall the `unwrap` function that we call on `Option<T>` values to produce a value or panic with this definition:

```
# enum Option<T> {
#     Some(T),
#     None,
# }
#
# use crate::Option::*;
#
impl<T> Option<T> {
    pub fn unwrap(self) -> T {
        match self {
            Some(val) => val,
               None => panic!("called `Option::unwrap()` on a
`None` value"),
        }
    }
}
```

In this code, the same thing happens as in the `match` in Listing 20-27: Rust sees that `val` has the type `T` and `panic!` has the type `!`, so the result of the overall `match` expression is `T`. This code 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`:

```
# fn main() {
    print!("forever ");

    loop {
        print!("and ever ");
    }
# }
```

Here, the loop never ends, so `!` is the value of the expression. However, this wouldn't be true if we included a `break`, because the loop would terminate when it got to the `break`.

Dynamically Sized Types and the `Sized` Trait

Rust needs to know certain details about its types, such as how much space to allocate for a value of a particular type. This leaves one corner of its type system a little confusing at first: the concept of *dynamically sized types*. Sometimes referred to as *DSTs* or *unsized types*, these types let us write code using values whose size we can know only at runtime.

Let's dig into the details of a dynamically sized type called `str`, which we've been using throughout the book. That's right, not `&str`, but `str` on its own, is a DST. We can't know how long the string is until runtime, meaning we can't create a variable of type `str`, nor can we take an argument of type `str`. Consider the following code, which does not work:

```
# fn main() {
    let s1: str = "Hello there!";
    let s2: str = "How's it going?";
# }
```

Rust needs to know how much memory to allocate for any value of a particular type, and all values of a type must use the same amount of memory. If Rust allowed us to write this code, these two `str` values would need to take up the same amount of space. 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 do we do? In this case, you already know the answer: we make the types of `s1` and `s2` a `&str` rather than a `str`. Recall from "String Slices" in Chapter 4 that the slice data structure just stores the starting position and the length of the slice. So although 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 its length. As such, we can know the size of a `&str` value at compile time: it's twice the length of a `usize`. That is, we always know the size of a `&str`, no matter how long the string it refers to is. In general, this is the 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. The golden rule of dynamically sized types is that we must always put values of dynamically sized types behind a pointer of some kind.

We can combine `str` with all kinds of pointers: for example, `Box<str>` or `Rc<str>`. In fact, you've 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 "Using Trait Objects That Allow for Values of Different Types" in Chapter 18, we mentioned that to use traits as trait objects, we must put them behind a pointer, such as `&dyn Trait` or `Box<dyn Trait>` (`Rc<dyn Trait>` would work too).

To work with DSTs, Rust provides the `Sized` trait to determine whether or not a type's size is known at compile time. This trait is automatically implemented for everything whose size is known 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 though we had written this:

```
fn generic<T: Sized>(t: T) {
    // --snip--
}
```

By default, generic functions will work only on types that have a known size at compile time. However, you can use the following special syntax to relax this restriction:

```
fn generic<T: ?Sized>(t: &T) {
    // --snip--
}
```

A trait bound on `?Sized` means "`T` may or may not be `Sized`" and this notation overrides the default that generic types must have a known size at compile time. The `?Trait` syntax with this meaning is only available for `Sized`, not any other traits.

Also note that we switched the type of the `t` parameter from `T` to `&T`. Because 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, we'll talk about functions and closures!

Advanced Functions and Closures

This section explores some advanced features related to functions and closures, including function pointers and returning closures.

Function Pointers

We've talked about how to pass closures to functions; you can also pass regular functions to functions! This technique is useful when you want to pass a function you've already defined rather than defining a new closure. Functions coerce to the type `fn` (with a lowercase *f*), not to be confused with the `Fn` closure trait. The `fn` type is called a *function pointer*. Passing functions with function pointers will allow you to use functions as arguments to other functions.

The syntax for specifying that a parameter is a function pointer is similar to that of closures, as shown in Listing 20-28, where we've defined a function `add_one` that adds 1 to its parameter. The function `do_twice` takes two parameters: a function pointer to any function that takes an `i32` parameter and returns an `i32`, and one `i32` value. The `do_twice` function calls the function `f` twice, passing it the `arg` value, then adds the two function call results together. The `main` function calls `do_twice` with the arguments `add_one` and `5`.

```
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}");
}
```

This code 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`), meaning you can always pass a function pointer as an argument for a function that expects a closure. It's best to write functions using a generic type and one of the closure traits so your functions can accept either functions or closures.

That said, one example of where you would want to only accept `fn` and not closures is when interfacing with external code that doesn't have closures: C functions can accept functions as arguments, but C doesn't have closures.

As an example of where you could use either a closure defined inline or a named function, let's look at a use of the `map` method provided by the `Iterator` trait in the standard library. To use the `map` method to turn a vector of numbers into a vector of strings, we could use a closure, as in Listing 20-29.

```
# fn main() {
    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. Listing 20-30 shows what this would look like.

```
# fn main() {
    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 must use the fully qualified syntax that we talked about in "Advanced Traits" 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`.

Recall from "Enum values" in Chapter 6 that the name of each enum variant that we define also becomes an initializer function. We can use these initializer functions as function pointers that implement the closure traits, which means we can specify the initializer functions as arguments for methods that take closures, as seen in Listing 20-31.

```
# fn main() {
    enum Status {
        Value(u32),
        Stop,
    }

                  let     list_of_statuses:     Vec<Status>     =
(0u32..20).map(Status::Value).collect();
# }
```

Here we create `Status::Value` instances using each `u32` value in the range that `map` is called on by using the initializer function of `Status::Value`. Some people prefer this style and some people prefer to use closures. They compile to the same code, so use whichever style is clearer to you.

Returning Closures

Closures are represented by traits, which means you can't return closures directly. In most cases where you might want to return a trait, you can instead use the concrete type that implements the trait as the return value of the function. However, you can't usually do that with closures because they don't have a concrete type that is returnable. You're not allowed to use the function pointer `fn` as a return type if the closure captures any values from its scope, for example.

Instead, you will normally use the `impl Trait` syntax we learned about in Chapter 10. You can return any function type, using `Fn`, `FnOnce` and `FnMut`. For example, the code in Listing 20-32 will work just fine.

```
fn returns_closure() -> impl Fn(i32) -> i32 {
    |x| x + 1
}
```

However, as we noted in [“Closure Type Inference and Annotation”]() in Chapter 13, each closure is also its own distinct type. If you need to work with multiple functions that have the same signature but different implementations, you will need to use a trait object for them. Consider what happens if you write code like that shown in Listing 20-33.

```
fn main() {
                let    handlers    =    vec![returns_closure(),
returns_initialized_closure(123)];
    for handler in handlers {
        let output = handler(5);
        println!("{output}");
```

```
    }
}

fn returns_closure() -> impl Fn(i32) -> i32 {
    |x| x + 1
}

fn returns_initialized_closure(init: i32) -> impl Fn(i32) ->
i32 {
    move |x| x + init
}
```

Here we have two functions, `returns_closure` and `returns_initialized_closure`, which both return `impl Fn(i32) -> i32`. Notice that he closures that they return are different, even though they implement the same type. If we try to compile this, Rust lets us know that it won’t work:

```
$ cargo build
   Compiling functions-example v0.1.0
(file:///projects/functions-example)
error[E0308]: mismatched types
  --> src/main.rs:2:44
   |
2  |     let handlers = vec![returns_closure(),
returns_initialized_closure(123)];
   |
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ expected opaque type, found a
different opaque type
...
9  | fn returns_closure() -> impl Fn(i32) -> i32 {
   |                         ------------------- the expected
opaque type
...
13 | fn returns_initialized_closure(init: i32) -> impl Fn(i32)
```

```
-> i32 {
   |                                              ------------
------- the found opaque type
   |
   = note: expected opaque type `impl Fn(i32) -> i32` (opaque
type at <src/main.rs:9:25>)
              found opaque type `impl Fn(i32) -> i32` (opaque
type at <src/main.rs:13:46>)
   = note: distinct uses of `impl Trait` result in different
opaque types

For more information about this error, try `rustc --explain
E0308`.
error: could not compile `functions-example` (bin "functions-
example") due to 1 previous error
```

The error message tells us that whenever we return an `impl Trait` Rust creates a unique *opaque type*, a type where we cannot see into the details of what Rust constructs for us. So even though these functions both return closures that implements the same trait, `Fn(i32) -> i32`, the opaque types Rust generates for each are distinct. (This is similar to how Rust produces different concrete types for distinct async blocks even when they have the same output type, as we saw in “Working with Any Number of Futures” in Chapter 17. We have seen a solution to this problem a few times now: we can use a trait object, as in Listing 20-34.

```
# fn main() {
#     let handlers = vec![returns_closure(),
returns_initialized_closure(123)];
#     for handler in handlers {
#         let output = handler(5);
#         println!("{output}");
#     }
# }
#
fn returns_closure() -> Box<dyn Fn(i32) -> i32> {
```

```
    Box::new(|x| x + 1)
}

fn returns_initialized_closure(init: i32) -> Box<dyn Fn(i32) -
> i32> {
    Box::new(move |x| x + init)
}
```

This code will compile just fine. For more about trait objects, refer to the section “Using Trait Objects That Allow for Values of Different Types” in Chapter 18.

Next, let’s look at macros!

Macros

We've used macros like `println!` throughout this book, but we haven't fully explored what a macro is and how it works. The term *macro* refers to a family of features in Rust: *declarative* macros with `macro_rules!` and three kinds of *procedural* macros:

- Custom `#[derive]` macros that specify code added with the `derive` attribute used on structs and enums
- Attribute-like macros that define custom attributes usable on any item
- Function-like macros that look like function calls but operate on the tokens specified as their argument

We'll talk about each of these in turn, but first, let's look at why we even need macros when we already have functions.

The Difference Between Macros and Functions

Fundamentally, macros are a way of writing code that writes other code, which is known as *metaprogramming*. In Appendix C, we discuss the `derive` attribute, which generates an implementation of various traits for you. We've also used the `println!` and `vec!` macros throughout the book. All of these macros *expand* to produce more code than the code you've written manually.

Metaprogramming is useful for reducing the amount of code you have to write and maintain, which is also one of the roles of functions. However, macros have some additional powers that functions don't have.

A function signature must declare the number and type of parameters the function has. Macros, on the other hand, can take a variable number of parameters: we can call `println!("hello")` with one argument or `println!("hello {}", name)` with two arguments. Also, macros are expanded before the compiler interprets the meaning of the code, so a macro can, for example, implement a trait on a given type. A function can't, because it gets called at runtime and a trait needs to be implemented at compile time.

The downside to implementing a macro instead of a function is that macro definitions are more complex than function definitions because you're writing Rust code that writes Rust code. Due to this indirection, macro definitions are generally more difficult to read, understand, and maintain than function definitions.

Another important difference between macros and functions is that you must define macros or bring them into scope *before* you call them in a file, as opposed to functions you can define anywhere and call anywhere.

Declarative Macros with `macro_rules!` for General Metaprogramming

The most widely used form of macros in Rust is the *declarative macro*. These are also sometimes referred to as "macros by example," "`macro_rules!` macros," or just plain "macros." At their core, declarative macros allow you to write something similar to a Rust `match` expression. As discussed in Chapter 6, `match` expressions are control structures that take an expression, compare the resultant value of the expression to patterns, and then run the code associated with the matching pattern. Macros also compare a value to patterns that are associated with particular code: in this situation, the value is the literal Rust source code passed to the macro; the patterns are compared with the structure of that source code; and the code associated with each pattern, when matched, replaces the code passed to the macro. This all happens during compilation.

To define a macro, you use the `macro_rules!` construct. Let's explore how to use `macro_rules!` by looking at how the `vec!` macro is defined. Chapter 8 covered how we can use the `vec!` macro to create a new vector with particular values. For example, the following macro creates a new vector containing three integers:

```
let v: Vec<u32> = vec![1, 2, 3];
```

We could also use the `vec!` macro to make a vector of two integers or a vector of five string slices. We wouldn't be able to use a function to do the same because we wouldn't know the number or type of values up front.

Listing 20-35 shows a slightly simplified definition of the `vec!` macro.

```
#[macro_export]
macro_rules! vec {
    ( $( $x:expr ),* ) => {
        {
            let mut temp_vec = Vec::new();
            $(
                temp_vec.push($x);
            )*
            temp_vec
        }
    };
}
```

> Note: The actual definition of the `vec!` macro in the standard library includes code to pre-allocate the correct amount of memory up front. That code is an optimization that we don't include here, to make the example simpler.

The `#[macro_export]` annotation indicates that this macro should be made available whenever the crate in which the macro is defined is brought into scope. Without this annotation, the macro can't be brought into scope.

We then start the macro definition with `macro_rules!` and the name of the macro we're defining *without* the exclamation mark. The name, in this case `vec`, is followed by curly brackets denoting the body of the macro definition.

The structure in the `vec!` body is similar to the structure of a `match` expression. Here we have one arm with the pattern `( $( $x:expr ),* )`, followed by `=>` and the block of code associated with this pattern. If the pattern matches, the associated block of code will be emitted. Given that this is the only pattern in this macro, there is only one valid way to match; any other pattern will result in an error. More complex macros will have more than one arm.

Valid pattern syntax in macro definitions is different from the pattern syntax covered in Chapter 19 because macro patterns are matched against Rust code structure rather than values. Let's walk through what the pattern pieces in Listing 20-29 mean; for the full macro pattern syntax, see the Rust Reference.

First we use a set of parentheses to encompass the whole pattern. We use a dollar sign (`$`) to declare a variable in the macro system that will contain the Rust code matching the pattern. The dollar sign makes it clear this is a macro variable as opposed to a regular Rust variable. Next comes a set of parentheses that captures values that match the pattern within the parentheses for use in the replacement code. Within `$()` is `$x:expr`, which matches any Rust expression and gives the expression the name `$x`.

The comma following `$()` indicates that a literal comma separator character must appear between each instance of the code that matches the code within `$()`. The `*` specifies that the pattern matches zero or more of whatever precedes the `*`.

When we call this macro with `vec![1, 2, 3];`, the `$x` pattern matches three times with the three expressions `1`, `2`, and `3`.

Now let's look at the pattern in the body of the code associated with this arm: `temp_vec.push()` within `$()*` is generated for each part that matches `$()` in the pattern zero or more times depending on how many times the pattern matches. The `$x` is replaced with each expression matched. When we call this macro with `vec![1, 2, 3];`, the code generated that replaces this macro call will be the following:

```
{
    let mut temp_vec = Vec::new();
    temp_vec.push(1);
    temp_vec.push(2);
    temp_vec.push(3);
    temp_vec
}
```

We've defined a macro that can take any number of arguments of any type and can generate code to create a vector containing the specified elements.

To learn more about how to write macros, consult the online documentation or other resources, such as "The Little Book of Rust

Macros” started by Daniel Keep and continued by Lukas Wirth.

Procedural Macros for Generating Code from Attributes

The second form of macros is the procedural macro, which acts more like a function (and is a type of procedure). *Procedural macros* accept some code as an input, operate on that code, and produce some code as an output rather than matching against patterns and replacing the code with other code as declarative macros do. The three kinds of procedural macros are custom `derive`, attribute-like, and function-like, and all work in a similar fashion.

When creating procedural macros, the definitions must reside in their own crate with a special crate type. This is for complex technical reasons that we hope to eliminate in the future. In Listing 20-36, we show how to define a procedural macro, where `some_attribute` is a placeholder for using a specific macro variety.

```
use proc_macro;

#[some_attribute]
pub fn some_name(input: TokenStream) -> TokenStream {
}
```

The function that defines a procedural macro takes a `TokenStream` as an input and produces a `TokenStream` as an output. The `TokenStream` type is defined by the `proc_macro` crate that is included with Rust and represents a sequence of tokens. This is the core of the macro: the source code that the macro is operating on makes up the input `TokenStream`, and the code the macro produces is the output `TokenStream`. The function also has an attribute attached to it that specifies which kind of procedural macro we’re creating. We can have multiple kinds of procedural macros in the same crate.

Let’s look at the different kinds of procedural macros. We’ll start with a custom `derive` macro and then explain the small dissimilarities that make the other forms different.

How to Write a Custom `derive` Macro

Let’s create a crate named `hello_macro` that defines a trait named `HelloMacro` with one associated function named `hello_macro`. Rather than making our users implement the `HelloMacro` trait for each of their types, we’ll provide a procedural macro so users can annotate their type with `#[derive(HelloMacro)]` to get a default implementation of the `hello_macro` function. The default implementation will print `Hello, Macro! My name is TypeName!` where `TypeName` is the name of the type on which this trait has been defined. In other words, we’ll write a crate that enables another programmer to write code like Listing 20-37 using our crate.

```
use hello_macro::HelloMacro;
use hello_macro_derive::HelloMacro;

#[derive(HelloMacro)]
struct Pancakes;

fn main() {
    Pancakes::hello_macro();
}
```

This code will print `Hello, Macro! My name is Pancakes!` when we’re done. The first step is to make a new library crate, like this:

```
$ cargo new hello_macro --lib
```

Next, we’ll define the `HelloMacro` trait and its associated function:

```
pub trait HelloMacro {
    fn hello_macro();
}
```

We have a trait and its function. At this point, our crate user could implement the trait to achieve the desired functionality, as in Listing 20-39.

```
use hello_macro::HelloMacro;

struct Pancakes;
```

```
impl HelloMacro for Pancakes {
    fn hello_macro() {
        println!("Hello, Macro! My name is Pancakes!");
    }
}

fn main() {
    Pancakes::hello_macro();
}
```

However, they would need to write the implementation block for each type they wanted to use with `hello_macro`; we want to spare them from having to do this work.

Additionally, we can't yet provide the `hello_macro` function with default implementation that will print the name of the type the trait is implemented on: Rust doesn't have reflection capabilities, so it can't look up the type's name at runtime. We need a macro to generate code at compile time.

The next step is to define the procedural macro. At the time of this writing, procedural macros need to be in their own crate. Eventually, this restriction might be lifted. The convention for structuring crates and macro crates is as follows: for a crate named `foo`, a custom `derive` procedural macro crate is called `foo_derive`. Let's start a new crate called `hello_macro_derive` inside our `hello_macro` project:

```
$ cargo new hello_macro_derive --lib
```

Our two crates are tightly related, so we create the procedural macro crate within the directory of our `hello_macro` crate. If we change the trait definition in `hello_macro`, we'll have to change the implementation of the procedural macro in `hello_macro_derive` as well. The two crates will need to be published separately, and programmers using these crates will need to add both as dependencies and bring them both into scope. We could instead have the `hello_macro` crate use `hello_macro_derive` as a dependency and re-export the procedural macro code. However, the way we’ve structured the project makes it possible for programmers to use `hello_macro` even if they don’t want the `derive` functionality.

We need to declare the `hello_macro_derive` crate as a procedural macro crate. We’ll also need functionality from the `syn` and `quote` crates, as you’ll see in a moment, so we need to add them as dependencies. Add the following to the *Cargo.toml* file for `hello_macro_derive`:

```
[lib]
proc-macro = true

[dependencies]
syn = "2.0"
quote = "1.0"
```

To start defining the procedural macro, place the code in Listing 20-40 into your *src/lib.rs* file for the `hello_macro_derive` crate. Note that this code won’t compile until we add a definition for the `impl_hello_macro` function.

```
use proc_macro::TokenStream;
use quote::quote;

#[proc_macro_derive(HelloMacro)]
pub fn hello_macro_derive(input: TokenStream) -> TokenStream {
    // Construct a representation of Rust code as a syntax tree
    // that we can manipulate.
    let ast = syn::parse(input).unwrap();

    // Build the trait implementation.
    impl_hello_macro(&ast)
}
```

Notice that we’ve split the code into the `hello_macro_derive` function, which is responsible for parsing the `TokenStream`, and the `impl_hello_macro` function, which is responsible for transforming the syntax tree: this makes writing a procedural macro more convenient. The code in the outer function (`hello_macro_derive` in this case) will be the same for almost every procedural macro crate you see or create. The code you specify in the body of the inner function (`impl_hello_macro` in this case) will be different depending on your procedural macro's purpose.

We've introduced three new crates: `proc_macro`, `syn`, and `quote`. The `proc_macro` crate comes with Rust, so we didn't need to add that to the dependencies in *Cargo.toml*. The `proc_macro` crate is the compiler's API that allows us to read and manipulate Rust code from our code.

The `syn` crate parses Rust code from a string into a data structure that we can perform operations on. The `quote` crate turns `syn` data structures back into Rust code. These crates make it much simpler to parse any sort of Rust code we might want to handle: writing a full parser for Rust code is no simple task.

The `hello_macro_derive` function will be called when a user of our library specifies `#[derive(HelloMacro)]` on a type. This is possible because we've annotated the `hello_macro_derive` function here with `proc_macro_derive` and specified the name `HelloMacro`, which matches our trait name; this is the convention most procedural macros follow.

The `hello_macro_derive` function first converts the `input` from a `TokenStream` to a data structure that we can then interpret and perform operations on. This is where `syn` comes into play. The `parse` function in `syn` takes a `TokenStream` and returns a `DeriveInput` struct representing the parsed Rust code. Listing 20-41 shows the relevant parts of the `DeriveInput` struct we get from parsing the `struct Pancakes;` string.

```
DeriveInput {
    // --snip--

    ident: Ident {
        ident: "Pancakes",
        span: #0 bytes(95..103)
    },
    data: Struct(
        DataStruct {
```

```
            struct_token: Struct,
            fields: Unit,
            semi_token: Some(
                Semi
            )
        }
    )
}
```

The fields of this struct show that the Rust code we've parsed is a unit struct with the `ident` (*identifier*, meaning the name) of `Pancakes`. There are more fields on this struct for describing all sorts of Rust code; check the [`syn` documentation for `DeriveInput`] for more information.

Soon we'll define the `impl_hello_macro` function, which is where we'll build the new Rust code we want to include. But before we do, note that the output for our `derive` macro is also a `TokenStream`. The returned `TokenStream` is added to the code that our crate users write, so when they compile their crate, they'll get the extra functionality that we provide in the modified `TokenStream`.

You might have noticed that we're calling `unwrap` to cause the `hello_macro_derive` function to panic if the call to the `syn::parse` function fails here. It's necessary for our procedural macro to panic on errors because `proc_macro_derive` functions must return `TokenStream` rather than `Result` to conform to the procedural macro API. We've simplified this example by using `unwrap`; in production code, you should provide more specific error messages about what went wrong by using `panic!` or `expect`.

Now that we have the code to turn the annotated Rust code from a `TokenStream` into a `DeriveInput` instance, let's generate the code that implements the `HelloMacro` trait on the annotated type, as shown in Listing 20-42.

```
# use proc_macro::TokenStream;
# use quote::quote;
#
```

```
# #[proc_macro_derive(HelloMacro)]
# pub fn hello_macro_derive(input: TokenStream) -> TokenStream
{
#     // Construct a representation of Rust code as a syntax
tree
#     // that we can manipulate
#     let ast = syn::parse(input).unwrap();
#
#     // Build the trait implementation
#     impl_hello_macro(&ast)
# }
#
fn impl_hello_macro(ast: &syn::DeriveInput) -> TokenStream {
    let name = &ast.ident;
    let generated = quote! {
        impl HelloMacro for #name {
            fn hello_macro() {
                println!("Hello, Macro! My name is {}!",
stringify!(#name));
            }
        }
    };
    generated.into()
}
```

We get an `Ident` struct instance containing the name (identifier) of the annotated type using `ast.ident`. The struct in Listing 20-33 shows that when we run the `impl_hello_macro` function on the code in Listing 20-31, the `ident` we get will have the `ident` field with a value of `"Pancakes"`. Thus, the `name` variable in Listing 20-34 will contain an `Ident` struct instance that, when printed, will be the string `"Pancakes"`, the name of the struct in Listing 20-37.

The `quote!` macro lets us define the Rust code that we want to return. The compiler expects something different to the direct result of the `quote!` macro's execution, so we need to convert it to a `TokenStream`. We do this by calling the `into` method, which consumes this intermediate representation and returns a value of the required `TokenStream` type.

The `quote!` macro also provides some very cool templating mechanics: we can enter `#name`, and `quote!` will replace it with the value in the variable `name`. You can even do some repetition similar to the way regular macros work. Check out [the `quote` crate's docs] for a thorough introduction.

We want our procedural macro to generate an implementation of our `HelloMacro` trait for the type the user annotated, which we can get by using `#name`. The trait implementation has the one function `hello_macro`, whose body contains the functionality we want to provide: printing `Hello, Macro! My name is` and then the name of the annotated type.

The `stringify!` macro used here is built into Rust. It takes a Rust expression, such as `1 + 2`, and at compile time turns the expression into a string literal, such as `"1 + 2"`. This is different from `format!` or `println!`, macros which evaluate the expression and then turn the result into a `String`. There is a possibility that the `#name` input might be an expression to print literally, so we use `stringify!`. Using `stringify!` also saves an allocation by converting `#name` to a string literal at compile time.

At this point, `cargo build` should complete successfully in both `hello_macro` and `hello_macro_derive`. Let's hook up these crates to the code in Listing 20-31 to see the procedural macro in action! Create a new binary project in your *projects* directory using `cargo new pancakes`. We need to add `hello_macro` and `hello_macro_derive` as dependencies in the `pancakes` crate's *Cargo.toml*. If you're publishing your versions of `hello_macro` and `hello_macro_derive` to [crates.io], they would be regular dependencies; if not, you can specify them as `path` dependencies as follows:

```
hello_macro = { path = "../hello_macro" }
hello_macro_derive = { path = "../hello_macro/hello_macro_derive" }
```

Put the code in Listing 20-37 into *src/main.rs*, and run `cargo run`: it should print `Hello, Macro! My name is Pancakes!` The implementation of the `HelloMacro` trait from the procedural macro was included without the `pancakes` crate needing to implement it; the `#[derive(HelloMacro)]` added the trait implementation.

Next, let's explore how the other kinds of procedural macros differ from custom `derive` macros.

Attribute-Like macros

Attribute-like macros are similar to custom `derive` macros, but instead of generating code for the `derive` attribute, they allow you to create new attributes. They're also more flexible: `derive` only works for structs and enums; attributes can be applied to other items as well, such as functions. Here's an example of using an attribute-like macro. Say you have an attribute named `route` that annotates functions when using a web application framework:

```
#[route(GET, "/")]
fn index() {
```

This `#[route]` attribute would be defined by the framework as a procedural macro. The signature of the macro definition function would look like this:

```
#[proc_macro_attribute]
pub fn route(attr: TokenStream, item: TokenStream) ->
TokenStream {
```

Here, we have two parameters of type `TokenStream`. The first is for the contents of the attribute: the `GET, "/"` part. The second is the body of the item the attribute is attached to: in this case, `fn index() {}` and the rest of the function's body.

Other than that, attribute-like macros work the same way as custom `derive` macros: you create a crate with the `proc-macro` crate type and implement a function that generates the code you want!

Function-Like macros

Function-like macros define macros that look like function calls. Similarly to `macro_rules!` macros, they're more flexible than functions; for example, they can take an unknown number of arguments. However, `macro_rules!` macros can only be defined using the match-like syntax we discussed in "Declarative Macros with `macro_rules!` for General Metaprogramming" earlier. Function-like macros take a `TokenStream` parameter and their definition manipulates that `TokenStream` using Rust code as the other two types of procedural macros do. An example of a function-like macro is an `sql!` macro that might be called like so:

```
let sql = sql!(SELECT * FROM posts WHERE id=1);
```

This macro would parse the SQL statement inside it and check that it's syntactically correct, which is much more complex processing than a `macro_rules!` macro can do. The `sql!` macro would be defined like this:

```
#[proc_macro]
pub fn sql(input: TokenStream) -> TokenStream {
```

This definition is similar to the custom `derive` macro's signature: we receive the tokens that are inside the parentheses and return the code we wanted to generate.

Summary

Whew! Now you have some Rust features in your toolbox that you likely won’t use often, but you’ll know they’re available in very particular circumstances. We’ve introduced several complex topics so that when you encounter them in error message suggestions or in other people’s code, you’ll be able to recognize these concepts and syntax. Use this chapter as a reference to guide you to solutions.

Next, we’ll put everything we’ve discussed throughout the book into practice and do one more project!

Final Project: Building a Multithreaded Web Server

It's been a long journey, but we've reached the end of the book. In this chapter, we'll build one more project together to demonstrate some of the concepts we covered in the final chapters, as well as recap some earlier lessons.

For our final project, we'll make a web server that says "hello" and looks like Figure 21-1 in a web browser.

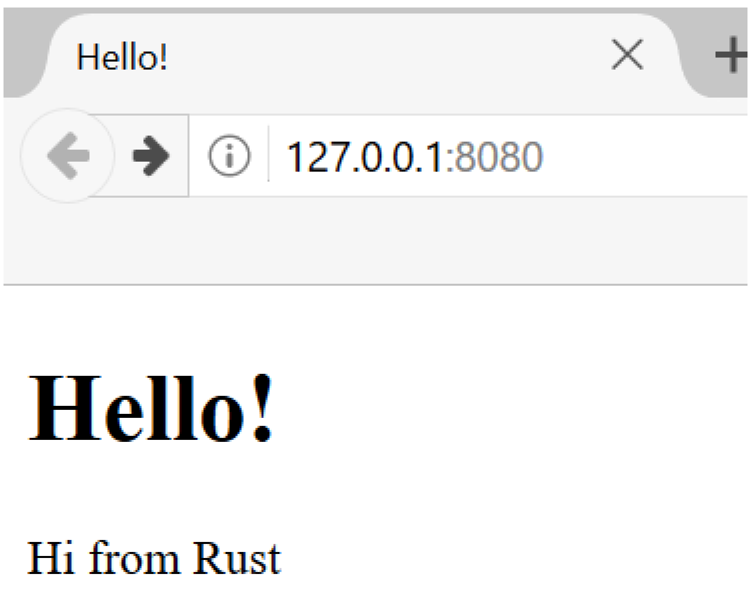


Figure 21-1: Our final shared project

Here is our plan for building the web server:

1. Learn a bit about TCP and HTTP.
2. Listen for TCP connections on a socket.
3. Parse a small 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, we should mention two details. First, the method we'll use won't be the best way to build a web server with Rust.

Community members have published a number of production-ready crates available on crates.io that provide more complete web server and thread pool implementations than we'll build. However, our intention in this chapter is to help you learn, not to take the easy route. Because Rust is a systems programming language, we can choose the level of abstraction we want to work with and can go to a lower level than is possible or practical in other languages.

Second, we will not be using async and await here. Building a thread pool is a big enough challenge on its own, without adding in building an async runtime! However, we will note how async and await might be applicable to some of the same problems we will see in this chapter. Ultimately, as we noted back in Chapter 17, many async runtimes use thread pools for managing their work.

We'll therefore write the basic HTTP server and thread pool manually so you can learn the general ideas and techniques behind the crates you might use in the future.

Building a Single-Threaded Web Server

We'll start by getting a single-threaded web server working. Before we begin, let's look at a quick overview of the protocols involved in building web servers. The details of these protocols are beyond the scope of this book, but a brief overview will give you the information you need.

The two main protocols involved in web servers are *Hypertext Transfer Protocol (HTTP)* and *Transmission Control Protocol (TCP)*. Both protocols are *request-response* protocols, meaning a *client* initiates requests and a *server* listens to the requests and provides a response to the client. The contents of those requests and responses are defined by the protocols.

TCP is the lower-level protocol that describes the details of how information gets from one server to another but doesn't specify what that information is. HTTP builds on top of TCP by defining the contents of the requests and responses. It's technically possible to use HTTP with other protocols, but in the vast majority of cases, HTTP sends its data over TCP. We'll work with the raw bytes of TCP and HTTP requests and responses.

Listening to the TCP Connection

Our web server needs to listen to a TCP connection, so that's the first part we'll work on. The standard library offers a `std::net` module that lets us do this. Let's make a new project in the usual fashion:

```
$ cargo new hello
     Created binary (application) `hello` project
$ cd hello
```

Now enter the code in Listing 21-1 in *src/main.rs* to start. This code will listen at the local address `127.0.0.1:7878` for incoming TCP streams. When it gets an incoming stream, it will print `Connection established!`.

```
use std::net::TcpListener;

fn main() {
    let listener = TcpListener::bind("127.0.0.1:7878").unwrap();
```

```
    for stream in listener.incoming() {
        let stream = stream.unwrap();

        println!("Connection established!");
    }
}
```

Using `TcpListener`, we can listen for TCP connections at the address `127.0.0.1:7878`. In the address, the section before the colon is an IP address representing your computer (this is the same on every computer and doesn't represent the authors' computer specifically), and `7878` is the port. We've chosen this port for two reasons: HTTP isn't normally accepted on this port so our server is unlikely to conflict with any other web server you might have running on your machine, and 7878 is *rust* typed on a telephone.

The `bind` function in this scenario works like the `new` function in that it will return a new `TcpListener` instance. The function is called `bind` because, in networking, connecting to a port to listen to is known as "binding to a port."

The `bind` function returns a `Result<T, E>`, which indicates that it's possible for binding to fail. For example, connecting to port 80 requires administrator privileges (non-administrators can listen only on ports higher than 1023), so if we tried to connect to port 80 without being an administrator, binding wouldn't work. Binding also wouldn't work, for example, if we ran two instances of our program and so had two programs listening to the same port. Because we're writing a basic server just for learning purposes, we won't worry about handling these kinds of errors; instead, we use `unwrap` to stop the program if errors happen.

The `incoming` method on `TcpListener` returns an iterator that gives us a sequence of streams (more specifically, streams of type `TcpStream`). A single *stream* represents an open connection between the client and the server. A *connection* is the name for the full request and response process in which a client connects to the server, the server generates a response, and the server closes the connection. As such, we will read from the `TcpStream` to see what the client sent and then write our response to the stream to send data back to the client. Overall, this `for` loop will process each connection in turn and produce a series of streams for us to handle.

For now, our handling of the stream consists of calling `unwrap` to terminate our program if the stream has any errors; if there aren't any errors, the program prints a message. We'll add more functionality for the success case in the next listing. The reason we might receive errors from the `incoming` method when a client connects to the server is that we're not actually iterating over connections. Instead, we're iterating over *connection attempts*. The connection might not be successful 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 they can support; new connection attempts beyond that number will produce an error until some of the open connections are closed.

Let's try running this code! Invoke `cargo run` in the terminal and then load *127.0.0.1:7878* in a web browser. The browser should show an error message like "Connection reset" because the server isn't currently sending back any data. But when you look at your terminal, you should see several messages that were printed when the browser connected to the server!

```
     Running `target/debug/hello`
Connection established!
Connection established!
Connection established!
```

Sometimes you'll see multiple messages printed for one browser request; the reason might be that the browser is making a request for the page as well as a request for other resources, like the *favicon.ico* icon that appears in the browser tab.

It could also be that the browser is trying to connect to the server multiple times because the server isn't responding with any data. When `stream` goes out of scope and is dropped at the end of the loop, the connection is closed as part of the `drop` implementation. Browsers sometimes deal with closed connections by retrying, because the problem might be temporary.

Browsers also sometimes open multiple connections to the server without sending any requests, so that if they *do* later send requests, they can happen faster. When this happens, our server will see each connection, regardless of whether there are any requests over that connection. Many versions of Chrome-based browsers do this, for example; you can disable that optimization by using = private browsing mode or use a different browser.

The important factor is that we've successfully gotten a handle to a TCP connection!

Remember to stop the program by pressing `ctrl-c` when you're done running a particular version of the code. Then restart the program by invoking the `cargo run` command after you've made each set of code changes to make sure you're running the newest code.

Reading the Request

Let's implement the functionality to read the request from the browser! To separate the concerns of first getting a connection and then taking some action with the connection, we'll start a new function for processing connections. In this new `handle_connection` function, we'll read data from the TCP stream and print it so we can see the data being sent from the browser. Change the code to look like Listing 21-2.

```
use std::{
    io::{BufReader, prelude::*},
    net::{TcpListener, TcpStream},
};

fn main() {
    let listener = TcpListener::bind("127.0.0.1:7878").unwrap();

    for stream in listener.incoming() {
        let stream = stream.unwrap();

        handle_connection(stream);
```

```
    }
}

fn handle_connection(mut stream: TcpStream) {
    let buf_reader = BufReader::new(&stream);
    let http_request: Vec<_> = buf_reader
        .lines()
        .map(|result| result.unwrap())
        .take_while(|line| !line.is_empty())
        .collect();

    println!("Request: {http_request:#?}");
}
```

We bring `std::io::prelude` and `std::io::BufReader` into scope to get access to traits and types that let us read from and write to the stream. In the `for` loop in the `main` function, instead of printing a message that says we made a connection, we now call the new `handle_connection` function and pass the `stream` to it.

In the `handle_connection` function, we create a new `BufReader` instance that wraps a reference to the `stream`. The `BufReader` adds buffering by managing calls to the `std::io::Read` trait methods for us.

We create a variable named `http_request` to collect the lines of the request the browser sends to our server. We indicate that we want to collect these lines in a vector by adding the `Vec<_>` type annotation.

`BufReader` implements the `std::io::BufRead` trait, which provides the `lines` method. The `lines` method returns an iterator of `Result<String, std::io::Error>` by splitting the stream of data whenever it sees a newline byte. To get each `String`, we map and `unwrap` each `Result`. The `Result` might be an error if the data isn't valid UTF-8 or if there was a problem reading from the stream. Again, a production program should handle these errors more gracefully, but we're choosing to stop the program in the error case for simplicity.

The browser signals the end of an HTTP request by sending two newline characters in a row, so to get one request from the stream, we take lines until we get a line that is the empty string. Once we've collected the lines into the vector, we're printing them out using pretty debug formatting so we can take a look at the instructions the web browser is sending to our server.

Let's try this code! Start the program and make a request in a web browser again. Note that we'll still get an error page in the browser, but our program's output 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 0.42s
     Running `target/debug/hello`
Request: [
    "GET / HTTP/1.1",
    "Host: 127.0.0.1:7878",
    "User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X 10.15;
rv:99.0) Gecko/20100101 Firefox/99.0",
                                                      "Accept:
text/html,application/xhtml+xml,application/xml;q=0.9,image/av
if,image/webp,*/*;q=0.8",
    "Accept-Language: en-US,en;q=0.5",
    "Accept-Encoding: gzip, deflate, br",
    "DNT: 1",
    "Connection: keep-alive",
    "Upgrade-Insecure-Requests: 1",
    "Sec-Fetch-Dest: document",
    "Sec-Fetch-Mode: navigate",
    "Sec-Fetch-Site: none",
    "Sec-Fetch-User: ?1",
    "Cache-Control: max-age=0",
]
```

Depending on your browser, you might get slightly different output. Now that we're printing the request data, we can see why we get multiple connections from one browser request by looking at the path after `GET` in the first line of the request. If the repeated connections are all requesting /, we know the browser is trying to fetch / repeatedly because it's not getting a response from our program.

Let's break down this request data to understand what the browser is asking of our program.

A Closer Look at an HTTP Request

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 the *request line* that holds information about what the client is requesting. The first part of the request line indicates the *method* being used, such as `GET` or `POST`, which describes how the client is making this request. Our client used a `GET` request, which means it is asking for information.

The next part of the request line is /, which indicates the *uniform resource identifier (URI)* the client is requesting: a URI is almost, but not quite, the same as a *uniform resource locator (URL)*. The difference between URIs and URLs isn't important for our purposes in this chapter, but the HTTP spec uses the term URI, so we can just mentally substitute *URL* for *URI* here.

The last part is the HTTP version the client uses, and then the request line ends in a CRLF sequence. (CRLF stands for *carriage return* and *line feed*, which are terms from the typewriter days!) The CRLF sequence can also be written as `\r\n`, where `\r` is a carriage return and `\n` is a line feed. The *CRLF sequence* separates the request line from the rest of the request data. Note that when the CRLF is printed, we see a new line start rather than `\r\n`.

Looking at the request line data we received from running our program so far, we see that `GET` is the method, / is the request URI, and `HTTP/1.1` is the version.

After the request line, 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, such as *127.0.0.1:7878/test*, to see how the request data changes.

Now that we know what the browser is asking for, let's send back some data!

Writing a Response

We're going to implement sending data in response to a client request. Responses have the following format:

```
HTTP-Version Status-Code Reason-Phrase CRLF
headers CRLF
message-body
```

The first line is a *status line* that 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 are any headers, another CRLF sequence, and the body of the response.

Here is an example response that uses HTTP version 1.1, and has a status code of 200, an OK reason phrase, no headers, and no body:

```
HTTP/1.1 200 OK\r\n\r\n
```

The status code 200 is the standard success response. The text is a tiny successful HTTP response. Let's write this to the stream as our response to a successful request! From the `handle_connection` function, remove the `println!` that was printing the request data and replace it with the code in Listing 21-3.

```
# use std::{
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
# };
#
# fn main() {
#     let listener = TcpListener::bind("127.0.0.1:7878").unwrap();
#
```

```
#     for stream in listener.incoming() {
#         let stream = stream.unwrap();
#
#         handle_connection(stream);
#     }
# }
#
fn handle_connection(mut stream: TcpStream) {
    let buf_reader = BufReader::new(&stream);
    let http_request: Vec<_> = buf_reader
        .lines()
        .map(|result| result.unwrap())
        .take_while(|line| !line.is_empty())
        .collect();

    let response = "HTTP/1.1 200 OK\r\n\r\n";

    stream.write_all(response.as_bytes()).unwrap();
}
```

The first new line defines the `response` variable that holds the success message's data. Then we call `as_bytes` on our `response` to convert the string data to bytes. The `write_all` method on `stream` takes a `&[u8]` and sends those bytes directly down the connection. Because the `write_all` operation could fail, we use `unwrap` on any error result as before. Again, in a real application you would add error handling here.

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 other than the output from Cargo. When you load *127.0.0.1:7878* in a web browser, you should get a blank page instead of an error. You've just handcoded receiving an HTTP request and sending a response!

Returning Real HTML

Let's implement the functionality for returning more than a blank page. Create the new file *hello.html* in the root of your project directory, not in the *src* directory. You can input any HTML you want; Listing 21-4 shows one possibility.

```
<!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>
```

This is a minimal HTML5 document with a heading and some text. To return this from the server when a request is received, we'll modify `handle_connection` as shown in Listing 21-5 to read the HTML file, add it to the response as a body, and send it.

```
use std::{
    fs,
    io::{BufReader, prelude::*},
    net::{TcpListener, TcpStream},
};
// --snip--

# fn main() {
#     let listener = TcpListener::bind("127.0.0.1:7878").unwrap();
#
#     for stream in listener.incoming() {
#         let stream = stream.unwrap();
#
#         handle_connection(stream);
#     }
# }
```

```
#
fn handle_connection(mut stream: TcpStream) {
    let buf_reader = BufReader::new(&stream);
    let http_request: Vec<_> = buf_reader
        .lines()
        .map(|result| result.unwrap())
        .take_while(|line| !line.is_empty())
        .collect();

    let status_line = "HTTP/1.1 200 OK";
    let contents = fs::read_to_string("hello.html").unwrap();
    let length = contents.len();

    let response =
                     format!("{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}");

    stream.write_all(response.as_bytes()).unwrap();
}
```

We've added `fs` to the `use` statement to bring the standard library's filesystem module into scope. The code for reading the contents of a file to a string should look familiar; we used it when we read the contents of a file for our I/O project in Listing 12-4.

Next, we use `format!` to add the file's contents as the body of the success response. To ensure a valid HTTP response, we add the `Content-Length` header which is set to the size of our response body, in this case the size of `hello.html`.

Run this code with `cargo run` and load *127.0.0.1:7878* in your browser; you should see your HTML rendered!

Currently, we're ignoring the request data in `http_request` and just sending back the contents of the HTML file unconditionally. That means if you try requesting *127.0.0.1:7878/something-else* in your browser, you'll still get back this same HTML response. At the moment, our server is very limited and does not do what most web servers do. We want to customize our responses depending on 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 add functionality to check that the browser is requesting / before returning the HTML file and return an error if the browser requests anything else. For this we need to modify `handle_connection`, as shown in Listing 21-6. This new code checks the content of the request received against what we know a request for / looks like and adds `if` and `else` blocks to treat requests differently.

```
# use std::{
#     fs,
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
# };
#
# fn main() {
#     let listener = TcpListener::bind("127.0.0.1:7878").unwrap();
#
#     for stream in listener.incoming() {
#         let stream = stream.unwrap();
#
#         handle_connection(stream);
#     }
# }
// --snip--

fn handle_connection(mut stream: TcpStream) {
    let buf_reader = BufReader::new(&stream);
    let request_line = buf_reader.lines().next().unwrap().unwrap();
```

```
    if request_line == "GET / HTTP/1.1" {
        let status_line = "HTTP/1.1 200 OK";
                                        let     contents     =
fs::read_to_string("hello.html").unwrap();
        let length = contents.len();

        let response = format!(
                             "{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}"
        );

        stream.write_all(response.as_bytes()).unwrap();
    } else {
        // some other request
    }
}
```

We're only going to be looking at the first line of the HTTP request, so rather than reading the entire request into a vector, we're calling `next` to get the first item from the iterator. The first `unwrap` takes care of the `Option` and stops the program if the iterator has no items. The second `unwrap` handles the `Result` and has the same effect as the `unwrap` that was in the `map` added in Listing 21-2.

Next, we check the `request_line` to see if it equals the request line of a GET request to the */* path. If it does, the `if` block returns the contents of our HTML file.

If the `request_line` does *not* equal the GET request to the */* path, it means we've received some other request. We'll add code to the `else` block in a moment to respond to all other requests.

Run this code now and request *127.0.0.1:7878*; you should get the HTML in *hello.html*. If you make any other request, such as *127.0.0.1:7878/something-else*, you'll get a connection error like those you saw when running the code in Listing 21-1 and Listing 21-2.

Now let’s add the code in Listing 21-7 to the `else` block to return a response with the status code 404, which signals that the content for the request was not found. We’ll also return some HTML for a page to render in the browser indicating the response to the end user.

```
# use std::{
#     fs,
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
# };
#
# fn main() {
#     let listener = TcpListener::bind("127.0.0.1:7878").unwrap();
#
#     for stream in listener.incoming() {
#         let stream = stream.unwrap();
#
#         handle_connection(stream);
#     }
# }
#
# fn handle_connection(mut stream: TcpStream) {
#     let buf_reader = BufReader::new(&stream);
#     let request_line = buf_reader.lines().next().unwrap().unwrap();
#
#     if request_line == "GET / HTTP/1.1" {
#         let status_line = "HTTP/1.1 200 OK";
#         let contents = fs::read_to_string("hello.html").unwrap();
#         let length = contents.len();
#
#         let response = format!(
#             "{status_line}\r\nContent-Length: {length}\r\n\r\n{contents}"
```

```
#         );
#
#         stream.write_all(response.as_bytes()).unwrap();
    // --snip--
    } else {
        let status_line = "HTTP/1.1 404 NOT FOUND";
                                            let     contents     =
fs::read_to_string("404.html").unwrap();
        let length = contents.len();

        let response = format!(
                             "{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}"
        );

        stream.write_all(response.as_bytes()).unwrap();
    }
# }
```

Here, our response has a status line with status code 404 and the reason phrase `NOT FOUND`. The body of the response will be the HTML in the file *404.html*. You'll need to create a *404.html* file next to *hello.html* for the error page; again feel free to use any HTML you want or use the example HTML in Listing 21-8.

```
<!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>
```

With these changes, run your server again. Requesting *127.0.0.1:7878* should return the contents of *hello.html*, and any other request, like *127.0.0.1:7878/foo*, should return the error HTML from *404.html*.

A Touch of Refactoring

At the moment, the `if` and `else` blocks have a lot of repetition: they're both reading files and writing the contents of the files to the stream. The only differences are the status line and the filename. Let's make the code more concise by pulling out those differences into separate `if` and `else` lines 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. Listing 21-9 shows the resultant code after replacing the large `if` and `else` blocks.

```
# use std::{
#     fs,
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
# };
#
# fn main() {
#                                    let       listener       =
TcpListener::bind("127.0.0.1:7878").unwrap();
#
#     for stream in listener.incoming() {
#         let stream = stream.unwrap();
#
#         handle_connection(stream);
#     }
# }
// --snip--

fn handle_connection(mut stream: TcpStream) {
    // --snip--
#     let buf_reader = BufReader::new(&stream);
#                                 let      request_line      =
```

```
buf_reader.lines().next().unwrap().unwrap();

     let (status_line, filename) = if request_line == "GET / HTTP/1.1" {
        ("HTTP/1.1 200 OK", "hello.html")
    } else {
        ("HTTP/1.1 404 NOT FOUND", "404.html")
    };

    let contents = fs::read_to_string(filename).unwrap();
    let length = contents.len();

    let response =
                     format!("{status_line}\r\nContent-Length: {length}\r\n\r\n{contents}");

    stream.write_all(response.as_bytes()).unwrap();
}
```

Now the `if` and `else` blocks only 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, as discussed in Chapter 19.

The previously duplicated code is now outside the `if` and `else` blocks and uses the `status_line` and `filename` variables. This makes it easier to see the difference between the two cases, and it means we have only one place to update the code if we want to change how the file reading and response writing work. The behavior of the code in Listing 21-9 will be the same as that in Listing 21-7.

Awesome! We now have a simple web server in approximately 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.

Currently, our server runs in a single thread, meaning it can only serve one request at a time. Let’s examine how that can be a problem by simulating some slow requests. Then we’ll fix it so our server can handle multiple requests at once.

Turning Our Single-Threaded Server into a Multithreaded Server

Right now, the server will process each request in turn, meaning it won't process a second connection until the first is finished processing. If the server received more and more requests, this serial execution would be less and less optimal. If the server receives a request that takes a long time to process, subsequent requests will have to wait until the long request is finished, even if the new requests can be processed quickly. We'll need to fix this, but first we'll look at the problem in action.

Simulating a Slow Request in the Current Server Implementation

We'll look at how a slow-processing request can affect other requests made to our current server implementation. Listing 21-10 implements handling a request to */sleep* with a simulated slow response that will cause the server to sleep for five seconds before responding.

```
use std::{
    fs,
    io::{BufReader, prelude::*},
    net::{TcpListener, TcpStream},
    thread,
    time::Duration,
};
// --snip--
#
# fn main() {
#     let listener = TcpListener::bind("127.0.0.1:7878").unwrap();
#
#     for stream in listener.incoming() {
#         let stream = stream.unwrap();
#
#         handle_connection(stream);
```

```
#     }
# }

fn handle_connection(mut stream: TcpStream) {
    // --snip--

#     let buf_reader = BufReader::new(&stream);
#                                  let      request_line      =
buf_reader.lines().next().unwrap().unwrap();
#
    let (status_line, filename) = match &request_line[..] {
        "GET / HTTP/1.1" => ("HTTP/1.1 200 OK", "hello.html"),
        "GET /sleep HTTP/1.1" => {
            thread::sleep(Duration::from_secs(5));
            ("HTTP/1.1 200 OK", "hello.html")
        }
        _ => ("HTTP/1.1 404 NOT FOUND", "404.html"),
    };

    // --snip--
#
#     let contents = fs::read_to_string(filename).unwrap();
#     let length = contents.len();
#
#     let response =
#                     format!("{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}");
#
#     stream.write_all(response.as_bytes()).unwrap();
}
```

We switched from `if` to `match` now that we have three cases. We need to explicitly match on a slice of `request_line` to pattern match against the string literal values; `match` doesn't do automatic referencing and dereferencing, like the equality method does.

The first arm is the same as the `if` block from Listing 21-9. The second arm matches a request to */sleep*. When that request is received, the server will sleep for five seconds before rendering the successful HTML page. The third arm is the same as the `else` block from Listing 21-9.

You can see how primitive our server is: real libraries would handle the recognition of multiple requests in a much less verbose way!

Start the server using `cargo run`. Then open two browser windows: one for *http://127.0.0.1:7878/* and the other for *http://127.0.0.1:7878/sleep*. If you enter the */* URI a few times, as before, you'll see it respond quickly. But if you enter */sleep* and then load */*, you'll see that */* waits until `sleep` has slept for its full five seconds before loading.

There are multiple techniques we could use to avoid requests backing up behind a slow request, including using async as we did Chapter 17; the one we'll implement is a thread pool.

Improving Throughput with a Thread Pool

A *thread pool* is a group of spawned threads that are waiting and ready to handle a task. When the program receives a new task, it assigns one of the threads in the pool to the task, and that thread will process the task. 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's returned to the pool of idle threads, ready to handle a new task. A thread pool allows you to process connections concurrently, increasing the throughput of your server.

We'll limit the number of threads in the pool to a small number to protect us from DoS attacks; if we had our program create a new thread for each request as it came in, someone making 10 million requests to our server could create havoc by using up all our server's resources and grinding the processing of requests to a halt.

Rather than spawning unlimited threads, then, we'll have a fixed number of threads waiting in the pool. Requests that come in are sent to the pool for processing. The pool will maintain a queue of incoming requests. Each of the threads in the pool will pop off a request from this queue, handle the request, and then ask the queue for another request. With this design, we can process up to `N` requests concurrently, where `N` is the number of threads. If each thread is responding to a long-running request, subsequent requests can still back up in the queue, but we've increased the number of long-running requests we can handle before reaching that point.

This technique is just one of many ways to improve the throughput of a web server. Other options you might explore are the fork/join model, the single-threaded async I/O model, and the multithreaded async I/O model. If you're interested in this topic, you can read more about other solutions and try to implement them; with a low-level language like Rust, all of these options are possible.

Before we begin implementing a thread pool, let's talk about what using the pool should look like. When you're trying to design code, writing the client interface first can help guide your design. Write the API of the code so it's structured in the way you want to call it; then implement the functionality within that structure rather than implementing the functionality and then designing the public API.

Similar to how we used test-driven development in the project in Chapter 12, we'll use compiler-driven development here. We'll write the code that calls the functions we want, and then we'll look at errors from the compiler to determine what we should change next to get the code to work. Before we do that, however, we'll explore the technique we're not going to use as a starting point.

Spawning a Thread for Each Request

First, let's explore how our code might look if it did create a new thread for every connection. As mentioned earlier, this isn't our final plan due to the problems with potentially spawning an unlimited number of threads, but it is a starting point to get a working multithreaded server first. Then we'll add the thread pool as an improvement, and contrasting the two solutions will be easier. Listing 21-11 shows the changes to make to `main` to spawn a new thread to handle each stream within the `for` loop.

```
# use std::{
#     fs,
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
```

```
#     thread,
#     time::Duration,
# };
#
fn main() {
                                  let        listener        =
TcpListener::bind("127.0.0.1:7878").unwrap();

    for stream in listener.incoming() {
        let stream = stream.unwrap();

        thread::spawn(|| {
            handle_connection(stream);
        });
    }
}
#
# fn handle_connection(mut stream: TcpStream) {
#     let buf_reader = BufReader::new(&stream);
#                                 let      request_line      =
buf_reader.lines().next().unwrap().unwrap();
#
#     let (status_line, filename) = match &request_line[..] {
#                  "GET  /  HTTP/1.1"  =>  ("HTTP/1.1  200  OK",
"hello.html"),
#         "GET /sleep HTTP/1.1" => {
#             thread::sleep(Duration::from_secs(5));
#             ("HTTP/1.1 200 OK", "hello.html")
#         }
#         _ => ("HTTP/1.1 404 NOT FOUND", "404.html"),
#     };
#
#     let contents = fs::read_to_string(filename).unwrap();
#     let length = contents.len();
#
#     let response =
```

```
#                     format!("{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}");
#
#     stream.write_all(response.as_bytes()).unwrap();
# }
```

As you learned in Chapter 16, `thread::spawn` will create a new thread and then run the code in the closure in the new thread. If you run this code and load */sleep* in your browser, then */* in two more browser tabs, you'll indeed see that the requests to */* don't have to wait for */sleep* to finish. However, as we mentioned, this will eventually overwhelm the system because you'd be making new threads without any limit.

You may also recall from Chapter 17 that this is exactly the kind of situation where async and await really shine! Keep that in mind as we build the thread pool and think about how things would look different or the same with async.

Creating a Finite Number of Threads

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 that uses our API. Listing 21-12 shows the hypothetical interface for a `ThreadPool` struct we want to use instead of `thread::spawn`.

```
# use std::{
#     fs,
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
#     thread,
#     time::Duration,
# };
#
fn main() {
                                  let        listener        =
TcpListener::bind("127.0.0.1:7878").unwrap();
    let pool = ThreadPool::new(4);

    for stream in listener.incoming() {
```

```
        let stream = stream.unwrap();

        pool.execute(|| {
            handle_connection(stream);
        });
    }
}
#
# fn handle_connection(mut stream: TcpStream) {
#     let buf_reader = BufReader::new(&stream);
#                                let      request_line      =
buf_reader.lines().next().unwrap().unwrap();
#
#     let (status_line, filename) = match &request_line[..] {
#                 "GET  /  HTTP/1.1"  =>  ("HTTP/1.1  200  OK",
"hello.html"),
#         "GET /sleep HTTP/1.1" => {
#             thread::sleep(Duration::from_secs(5));
#             ("HTTP/1.1 200 OK", "hello.html")
#         }
#         _ => ("HTTP/1.1 404 NOT FOUND", "404.html"),
#     };
#
#     let contents = fs::read_to_string(filename).unwrap();
#     let length = contents.len();
#
#     let response =
#                     format!("{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}");
#
#     stream.write_all(response.as_bytes()).unwrap();
# }
```

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` has a similar interface as `thread::spawn` in that it takes a closure the pool should run for each stream. We need to implement `pool.execute` so it takes the closure and gives it to a thread in the pool to run. This code won't yet compile, but we'll try so the compiler can guide us in how to fix it.

Building `ThreadPool` Using Compiler Driven Development

Make the changes in Listing 21-12 to *src/main.rs*, and then let's use the compiler errors from `cargo check` to drive our development. Here is the first error we get:

```
$ cargo check
    Checking hello v0.1.0 (file:///projects/hello)
error[E0433]: failed to resolve: use of undeclared type
`ThreadPool`
  --> src/main.rs:11:16
   |
11 |     let pool = ThreadPool::new(4);
   |                ^^^^^^^^^^ use of undeclared type
`ThreadPool`

For more information about this error, try `rustc --explain
E0433`.
error: could not compile `hello` (bin "hello") due to 1
previous error
```

Great! This error tells us we need a `ThreadPool` type or module, so we'll build one now. Our `ThreadPool` implementation will be independent of the kind of work our web server is doing. So let's switch the `hello` crate from a binary crate to a library crate to hold our `ThreadPool` implementation. After we change to a library crate, we could also use the separate thread pool library for any work we want to do using a thread pool, not just for serving web requests.

Create a *src/lib.rs* file that contains the following, which is the simplest definition of a `ThreadPool` struct that we can have for now:

```
pub struct ThreadPool;
```

Then edit *main.rs* file to bring `ThreadPool` into scope from the library crate by adding the following code to the top of *src/main.rs*:

```
use hello::ThreadPool;
# use std::{
#     fs,
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
#     thread,
#     time::Duration,
# };
#
# fn main() {
#                                    let       listener       =
TcpListener::bind("127.0.0.1:7878").unwrap();
#     let pool = ThreadPool::new(4);
#
#     for stream in listener.incoming() {
#         let stream = stream.unwrap();
#
#         pool.execute(|| {
#             handle_connection(stream);
#         });
#     }
# }
#
# fn handle_connection(mut stream: TcpStream) {
#     let buf_reader = BufReader::new(&stream);
#                                 let      request_line      =
buf_reader.lines().next().unwrap().unwrap();
#
#     let (status_line, filename) = match &request_line[..] {
#                 "GET  /  HTTP/1.1"  =>  ("HTTP/1.1  200  OK",
"hello.html"),
#         "GET /sleep HTTP/1.1" => {
#             thread::sleep(Duration::from_secs(5));
```

```
#             ("HTTP/1.1 200 OK", "hello.html")
#         }
#         _ => ("HTTP/1.1 404 NOT FOUND", "404.html"),
#     };
#
#     let contents = fs::read_to_string(filename).unwrap();
#     let length = contents.len();
#
#     let response =
#                      format!("{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}");
#
#     stream.write_all(response.as_bytes()).unwrap();
# }
```

This code still won't work, but let's check it again to get the next error that we need to address:

```
$ cargo check
    Checking hello v0.1.0 (file:///projects/hello)
error[E0599]: no function or associated item named `new` found
for struct `ThreadPool` in the current scope
  --> src/main.rs:12:28
   |
12 |     let pool = ThreadPool::new(4);
   |                               ^^^ function or associated
item not found in `ThreadPool`

For more information about this error, try `rustc --explain
E0599`.
error: could not compile `hello` (bin "hello") due to 1
previous error
```

This error indicates that next we need 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 should return a

`ThreadPool` instance. Let's implement the simplest `new` function that will have those characteristics:

```
pub struct ThreadPool;

impl ThreadPool {
    pub fn new(size: usize) -> ThreadPool {
        ThreadPool
    }
}
```

We chose `usize` as the type of the `size` parameter because we know that a negative number of threads doesn't make any sense. We also know we'll use this `4` as the number of elements in a collection of threads, which is what the `usize` type is for, as discussed in "Integer Types" in Chapter 3.

Let's check the code again:

```
$ cargo check
    Checking hello v0.1.0 (file:///projects/hello)
error[E0599]: no method named `execute` found for struct
`ThreadPool` in the current scope
  --> src/main.rs:17:14
   |
17 |         pool.execute(|| {
   |         -----^^^^^^^ method not found in `ThreadPool`

For more information about this error, try `rustc --explain
E0599`.
error: could not compile `hello` (bin "hello") due to 1
previous error
```

Now the error occurs because we don't have an `execute` method on `ThreadPool`. Recall from "Creating a Finite Number of Threads" that we decided our thread pool should have an interface similar to `thread::spawn`. In addition, we'll implement the `execute` function so it takes the closure it's given and gives it to an idle thread in the pool to run.

We'll define the `execute` method on `ThreadPool` to take a closure as a parameter. Recall from [“Moving Captured Values Out of the Closure and the `Fn` Traits”] in Chapter 13 that we can take closures as parameters with three different traits: `Fn`, `FnMut`, and `FnOnce`. We need to decide which kind of closure to use here. We know we'll end up doing something similar to the standard library `thread::spawn` implementation, so we can look at what bounds the signature of `thread::spawn` has on its parameter. The documentation shows us the following:

```
pub fn spawn<F, T>(f: F) -> JoinHandle<T>
    where
        F: FnOnce() -> T,
        F: Send + 'static,
        T: Send + 'static,
```

The `F` type parameter is the one we're concerned with here; the `T` type parameter is related to the return value, and we're not concerned with that. We can see that `spawn` uses `FnOnce` as the trait bound on `F`. This is probably what we want as well, because we'll eventually pass the argument we get in `execute` to `spawn`. We can be further confident that `FnOnce` is the trait we want to use because the thread for running a request will only execute that request's closure one time, which matches the `Once` in `FnOnce`.

The `F` type parameter also has the trait bound `Send` and the lifetime bound `'static`, which are useful in 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 take to execute. Let's create an `execute` method on `ThreadPool` that will take a generic parameter of type `F` with these bounds:

```
# pub struct ThreadPool;
#
impl ThreadPool {
    // --snip--
#     pub fn new(size: usize) -> ThreadPool {
#         ThreadPool
```

```
#     }
#
    pub fn execute<F>(&self, f: F)
    where
        F: FnOnce() + Send + 'static,
    {
    }
}
```

We still use the `()` after `FnOnce` because this `FnOnce` represents a closure that takes no parameters and returns the unit type `()`. 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, this is the simplest implementation of the `execute` method: it does nothing, but we're only trying to make our code compile. Let's check it again:

```
$ cargo check
    Checking hello v0.1.0 (file:///projects/hello)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.24s
```

It compiles! But note that if you try `cargo run` and make a request in the browser, you'll see the errors in the browser that we saw at the beginning of the chapter. Our library isn't actually calling the closure passed to `execute` yet!

> Note: A saying you might hear about languages with strict compilers, such as Haskell and Rust, is "if the code compiles, it works." But this saying is not universally true. Our project compiles, but it does absolutely nothing! If we were building a real, complete project, this would be a good time to start writing unit tests to check that the code compiles *and* has the behavior we want.

Consider: what would be different here if we were going to execute a *future* instead of a closure?

Validating the Number of Threads in `new`

We aren't doing anything with the parameters to `new` and `execute`. Let's implement the bodies of these functions with the behavior we want. To start, let's think about `new`. Earlier we chose an unsigned type for the `size` parameter because 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 `usize`. We'll add code to check that `size` is greater than zero before we return a `ThreadPool` instance and have the program panic if it receives a zero by using the `assert!` macro, as shown in Listing 21-13.

```
# pub struct ThreadPool;
#
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);

        ThreadPool
    }

    // --snip--
#     pub fn execute<F>(&self, f: F)
#     where
#         F: FnOnce() + Send + 'static,
#     {
#     }
}
```

We've also added some documentation for our `ThreadPool` with doc comments. Note that we followed good documentation practices by adding a section that calls out the situations in which our function can panic, as discussed in Chapter 14. Try running `cargo doc --open` and clicking the `ThreadPool` struct to see what the generated docs for `new` look like!

Instead of adding the `assert!` macro as we've done here, we could change `new` into `build` and return a `Result` like we did with `Config::build` 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 function named `build` with the following signature to compare with the `new` function:

```
pub fn build(size: usize) -> Result<ThreadPool, PoolCreationError> {
```

Creating Space to Store the Threads

Now that we have a way to know we have a valid number of threads to store in the pool, we can create those threads and store them in the `ThreadPool` struct before returning the struct. But how do we "store" a thread? Let's take another look at the `thread::spawn` signature:

```
pub fn spawn<F, T>(f: F) -> JoinHandle<T>
    where
        F: FnOnce() -> T,
        F: Send + 'static,
        T: Send + 'static,
```

The `spawn` function returns a `JoinHandle<T>`, where `T` is the type that the closure returns. 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 `()`.

The code in Listing 21-14 will compile but doesn't create any threads yet. 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.

```
use std::thread;

pub struct ThreadPool {
    threads: Vec<thread::JoinHandle<()>>,
}

impl ThreadPool {
    // --snip--
#     /// 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 mut threads = Vec::with_capacity(size);

        for _ in 0..size {
            // create some threads and store them in the
vector
        }

        ThreadPool { threads }
    }
    // --snip--
#
#     pub fn execute<F>(&self, f: F)
#     where
#         F: FnOnce() + Send + 'static,
#     {
#     }
}
```

We've brought `std::thread` into scope in the library crate because we're using `thread::JoinHandle` as the type of the items in the vector in `ThreadPool`.

Once a valid size is received, our `ThreadPool` creates a new vector that can hold `size` items. The `with_capacity` function performs the same task as `Vec::new` but with an important difference: it pre-allocates space in the vector. Because we know we need to store `size` elements in the vector, doing this allocation up front is slightly more efficient than using `Vec::new`, which resizes itself as elements are inserted.

When you run `cargo check` again, it should succeed.

A `Worker` Struct Responsible for Sending Code from the `ThreadPool` to a Thread

We left a comment in the `for` loop in Listing 21-14 regarding the creation of threads. Here, we'll look at how we actually create threads. The standard library provides `thread::spawn` as a way to create threads, and `thread::spawn` expects to get some code the thread should run as soon as the thread is created. However, in our case, we want to create the threads and have them *wait* for code that we'll send later. The standard library's implementation of threads doesn't include any way to do that; we have to implement it manually.

We'll implement this behavior by introducing a new data structure between the `ThreadPool` and the threads that will manage this new behavior. We'll call this data structure *Worker*, which is a common term in pooling implementations. The `Worker` picks up code that needs to be run and runs the code in the Worker's thread.

Think of people working in the kitchen at a restaurant: the workers wait until orders come in from customers, and then they're responsible for taking those orders and fulfilling them.

Instead of storing a vector of `JoinHandle<()>` instances in the thread pool, we'll store instances of the `Worker` struct. Each `Worker` will store a single `JoinHandle<()>` instance. Then we'll implement a method on `Worker` that will take a closure of code to run and send it to the already running thread for execution. We'll also give each `Worker` an `id` so we can distinguish between the different instances of `Worker` in the pool when logging or debugging.

Here is the new process that will happen when we create a `ThreadPool`. We'll implement the code that sends the closure to the thread after we have `Worker` set up in this way:

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 that holds the `id` and a thread spawned with an empty closure.
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 looking at the code in Listing 21-15.

Ready? Here is Listing 21-15 with one way to make the preceding modifications.

```
use std::thread;

pub struct ThreadPool {
    workers: Vec<Worker>,
}

impl ThreadPool {
    // --snip--
#     /// 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 mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id));
        }

        ThreadPool { workers }
    }
    // --snip--
#
#     pub fn execute<F>(&self, f: F)
#     where
#         F: FnOnce() + Send + 'static,
#     {
#     }
}

struct Worker {
    id: usize,
    thread: thread::JoinHandle<()>,
}

impl Worker {
    fn new(id: usize) -> Worker {
        let thread = thread::spawn(|| {});

        Worker { id, thread }
    }
}
```

We’ve changed the name of the field on `ThreadPool` from `threads` to `workers` because it’s now holding `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`.

External code (like our server in *src/main.rs*) doesn't need to know the implementation details regarding using a `Worker` struct within `ThreadPool`, so we make the `Worker` struct and its `new` function private. The `Worker::new` function uses the `id` we give it and stores a `JoinHandle<()>` instance that is created by spawning a new thread using an empty closure.

> Note: If the operating system can't create a thread because there aren't enough system resources, `thread::spawn` will panic. That will cause our whole server to panic, even though the creation of some threads might succeed. For simplicity's sake, this behavior is fine, but in a production thread pool implementation, you'd likely want to use `std::thread::Builder` and its `spawn` method that returns `Result` instead.

This code will compile and will store the number of `Worker` instances we specified as an argument to `ThreadPool::new`. But we're *still* not processing the closure that we get in `execute`. Let's look at how to do that next.

Sending Requests to Threads via Channels

The next problem we'll tackle is that the closures given to `thread::spawn` do absolutely nothing. Currently, we get the closure we want to execute in the `execute` method. But we need to give `thread::spawn` a closure to run when we create each `Worker` during the creation of the `ThreadPool`.

We want the `Worker` structs that we just created to fetch the code to run from a queue held in the `ThreadPool` and send that code to its thread to run.

The channels we learned about in Chapter 16—a simple way to communicate between two threads—would be perfect for this use case. We'll use a channel to function as the queue of jobs, and `execute` will send a job from the `ThreadPool` to the `Worker` instances, which will send the job to its thread. Here is the plan:

1. The `ThreadPool` will create a channel and hold on to the sender.
2. Each `Worker` will hold on to the receiver.
3. We'll create a new `Job` struct that will hold the closures we want to send down the channel.
4. The `execute` method will send the job it wants to execute through the sender.
5. In its thread, the `Worker` will loop over its receiver and execute the closures of any jobs it receives.

Let's start by creating a channel in `ThreadPool::new` and holding the sender in the `ThreadPool` instance, as shown in Listing 21-16. The `Job` struct doesn't hold anything for now but will be the type of item we're sending down the channel.

```
use std::{sync::mpsc, thread};

pub struct ThreadPool {
    workers: Vec<Worker>,
    sender: mpsc::Sender<Job>,
}

struct Job;

impl ThreadPool {
    // --snip--
#     /// 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 mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id));
        }

        ThreadPool { workers, sender }
    }
    // --snip--
#
#     pub fn execute<F>(&self, f: F)
#     where
#         F: FnOnce() + Send + 'static,
#     {
#     }
}
#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
# impl Worker {
#     fn new(id: usize) -> Worker {
#         let thread = thread::spawn(|| {});
#
#         Worker { id, thread }
#     }
# }
```

In `ThreadPool::new`, we create our new channel and have the pool hold the sender. This will successfully compile.

Let’s try passing a receiver of the channel into each `Worker` as the thread pool creates the channel. We know we want to use the receiver in the thread that the `Worker` instances spawn, so we’ll reference the `receiver` parameter in the closure. The code in Listing 21-17 won’t quite compile yet.

```
# use std::{sync::mpsc, thread};
#
# pub struct ThreadPool {
#     workers: Vec<Worker>,
#     sender: mpsc::Sender<Job>,
# }
#
# struct Job;
#
impl ThreadPool {
    // --snip--
#     /// 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 mut workers = Vec::with_capacity(size);

        for id in 0..size {
            workers.push(Worker::new(id, receiver));
        }

        ThreadPool { workers, sender }
    }
```

```
    // --snip--
#
#     pub fn execute<F>(&self, f: F)
#     where
#         F: FnOnce() + Send + 'static,
#     {
#     }
}

// --snip--

#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
impl Worker {
    fn new(id: usize, receiver: mpsc::Receiver<Job>) -> Worker
{
        let thread = thread::spawn(|| {
            receiver;
        });

        Worker { id, thread }
    }
}
```

We’ve made some small and straightforward changes: we pass the receiver into `Worker::new`, and then we use it inside the closure.

When we try to check this code, we get this error:

```
$ cargo check
    Checking hello v0.1.0 (file:///projects/hello)
error[E0382]: use of moved value: `receiver`
  --> src/lib.rs:26:42
   |
```

```
21 |         let (sender, receiver) = mpsc::channel();
    |                             -------- move occurs because
`receiver` has type `std::sync::mpsc::Receiver<Job>`, which
does not implement the `Copy` trait
...
25 |         for id in 0..size {
   |         ----------------- inside of this loop
26 |             workers.push(Worker::new(id, receiver));
   |                                          ^^^^^^^^ value
moved here, in previous iteration of loop
   |
note: consider changing this parameter type in method `new` to
borrow instead if owning the value isn't necessary
  --> src/lib.rs:47:33
   |
47 |     fn new(id: usize, receiver: mpsc::Receiver<Job>) ->
Worker {
   |        --- in this method       ^^^^^^^^^^^^^^^^^^^ this
parameter takes ownership of the value
help: consider moving the expression out of the loop so it is
only moved once
   |
25 ~         let mut value = Worker::new(id, receiver);
26 ~         for id in 0..size {
27 ~             workers.push(value);
   |

For more information about this error, try `rustc --explain
E0382`.
error: could not compile `hello` (lib) due to 1 previous error
```

The code is trying to pass `receiver` to multiple `Worker` instances. This won’t work, as you’ll recall from Chapter 16: the channel implementation that Rust provides is multiple *producer*, single *consumer*. This means we can’t just clone the consuming end of the channel to fix this code. We also don’t want to send a message multiple times to multiple consumers; we want one list of messages with multiple `Worker` instances such that each message gets processed once.

Additionally, taking a job off the channel queue involves mutating the `receiver`, so the threads need a safe way to share and modify `receiver`; otherwise, we might get race conditions (as covered in Chapter 16).

Recall the thread-safe smart pointers discussed in Chapter 16: to share ownership across multiple threads and allow the threads to mutate the value, we need to use `Arc<Mutex<T>>`. The `Arc` type will let multiple `Worker` instances own the receiver, and `Mutex` will ensure that only one `Worker` gets a job from the receiver at a time. Listing 21-18 shows the changes we need to make.

```
use std::{
    sync::{Arc, Mutex, mpsc},
    thread,
};
// --snip--

# pub struct ThreadPool {
#     workers: Vec<Worker>,
#     sender: mpsc::Sender<Job>,
# }
#
# struct Job;
#
impl ThreadPool {
    // --snip--
#     /// 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 }
    }

    // --snip--
#
#     pub fn execute<F>(&self, f: F)
#     where
#         F: FnOnce() + Send + 'static,
#     {
#     }
}

// --snip--

# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
impl Worker {
                     fn     new(id:     usize,     receiver:
Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
        // --snip--
```

```
#         let thread = thread::spawn(|| {
#             receiver;
#         });
#
#         Worker { id, thread }
    }
}
```

In `ThreadPool::new`, we put the receiver in an `Arc` and a `Mutex`. For each new `Worker`, we clone the `Arc` to bump the reference count so the `Worker` instances can share ownership of the receiver.

With these changes, the code compiles! We're getting there!

Implementing the `execute` Method

Let's finally implement the `execute` method on `ThreadPool`. We'll also change `Job` from a struct to a type alias for a trait object that holds the type of closure that `execute` receives. As discussed in "Creating Type Synonyms with Type Aliases" in Chapter 20, type aliases allow us to make long types shorter for ease of use. Look at Listing 21-19.

```
# use std::{
#     sync::{Arc, Mutex, mpsc},
#     thread,
# };
#
# pub struct ThreadPool {
#     workers: Vec<Worker>,
#     sender: mpsc::Sender<Job>,
# }
#
// --snip--

type Job = Box<dyn FnOnce() + Send + 'static>;

impl ThreadPool {
    // --snip--
```

```
#     /// 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(job).unwrap();
    }
}

// --snip--
#
```

```
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
# impl Worker {
#     fn new(id: usize, receiver:
Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
#         let thread = thread::spawn(|| {
#             receiver;
#         });
#
#         Worker { id, thread }
#     }
# }
```

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` for the case that sending fails. This might happen if, for example, we stop all our threads from executing, meaning the receiving end has stopped receiving new messages. At the moment, we can't stop our threads from executing: our threads continue executing as long as the pool exists. The reason we use `unwrap` is that we know the failure case won't happen, but the compiler doesn't know that.

But we're not quite done yet! In the `Worker`, our closure being passed to `thread::spawn` still 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 21-20 to `Worker::new`.

```
# use std::{
#     sync::{Arc, Mutex, mpsc},
#     thread,
# };
#
# pub struct ThreadPool {
```

```
#     workers: Vec<Worker>,
#     sender: mpsc::Sender<Job>,
# }
#
# type Job = Box<dyn FnOnce() + 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(job).unwrap();
#     }
# }
#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
// --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 {id} got a job; executing.");

                job();
            }
        });

        Worker { id, thread }
    }
}
```

Here, we first call `lock` on the `receiver` to acquire the mutex, and then we call `unwrap` to panic on any errors. Acquiring a lock might fail if the mutex is in a *poisoned* state, which can happen if some other thread panicked while holding the lock rather than releasing the lock. In this situation, calling `unwrap` to have this thread panic is the correct action to take. Feel free to change this `unwrap` to an `expect` with an error message that is meaningful to you.

If we get the lock on the mutex, we call `recv` to receive a `Job` from the channel. A final `unwrap` moves past any errors here as well, which might occur if the thread holding the sender has shut down, similar to how the `send` method returns `Err` if the receiver shuts down.

The call to `recv` blocks, so if there is no job yet, the current thread will wait until a job becomes available. The `Mutex<T>` ensures that only one `Worker` thread at a time is trying to request a job.

Our thread pool is now 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 `workers` is never read
 --> src/lib.rs:7:5
  |
6 | pub struct ThreadPool {
  |            ---------- field in this struct
7 |     workers: Vec<Worker>,
  |     ^^^^^^^
  |
  = note: `#[warn(dead_code)]` on by default

warning: fields `id` and `thread` are never read
  --> src/lib.rs:48:5
   |
47 | struct Worker {
   |        ------ fields in this struct
48 |     id: usize,
   |     ^^
49 |     thread: thread::JoinHandle<()>,
   |     ^^^^^^

warning: `hello` (lib) generated 2 warnings
```

```
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 4.91s
     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 that executes connections asynchronously. There are never more than four threads created, so our system won't get overloaded if the server receives 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.

> Note: If you open */sleep* in multiple browser windows simultaneously, they might load one at a time in five-second intervals. Some web browsers execute multiple instances of the same request sequentially for caching reasons. This limitation is not caused by our web server.

This is a good time to pause and consider how the code in Listings 21-18, 21-19, and 21-20 would be different if we were using futures instead of a closure for the work to be done. What types would change? How would the method signatures be different, if at all? What parts of the code would stay the same?

After learning about the `while let` loop in Chapters 17 and 18, you might be wondering why we didn't write the worker thread code as shown in Listing 21-21.

```
# use std::{
#     sync::{Arc, Mutex, mpsc},
#     thread,
```

```
# };
#
# pub struct ThreadPool {
#     workers: Vec<Worker>,
#     sender: mpsc::Sender<Job>,
# }
#
# type Job = Box<dyn FnOnce() + 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(job).unwrap();
#     }
# }
#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
// --snip--

impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
        let thread = thread::spawn(move || {
            while let Ok(job) = receiver.lock().unwrap().recv() {
                println!("Worker {id} got a job; executing.");

                job();
            }
        });

        Worker { id, thread }
    }
}
```

This code compiles and runs but doesn’t result in the desired threading behavior: a slow request will still cause other requests to wait to be processed. The reason is somewhat subtle: the `Mutex` struct has no public `unlock` method because the ownership of the lock is based on the lifetime of the `MutexGuard<T>` within the `LockResult<MutexGuard<T>>` that the `lock` method returns. At compile time, the borrow checker can then enforce the rule that a resource guarded by a `Mutex` cannot be accessed unless we hold the lock. However, this implementation can also result in the lock being held longer than intended if we aren't mindful of the lifetime of the `MutexGuard<T>`.

The code in Listing 21-20 that uses `let job = receiver.lock().unwrap().recv().unwrap();` works because with `let`, any temporary values used in the expression on the right hand side of the equal sign are immediately dropped when the `let` statement ends. However, `while let` (and `if let` and `match`) does not drop temporary values until the end of the associated block. In Listing 21-21, the lock remains held for the duration of the call to `job()`, meaning other `Worker` instances cannot receive jobs.

Graceful Shutdown and Cleanup

The code in Listing 21-20 is responding to requests asynchronously through the use of a thread pool, as we intended. We get some warnings about the `workers`, `id`, and `thread` fields that we're not using in a direct way that reminds us we're not cleaning up anything. When we use the less elegant `ctrl-c` method to halt the main thread, all other threads are stopped immediately as well, even if they're in the middle of serving a request.

Next, then, we'll implement the `Drop` trait to call `join` on each of the threads in the pool so they can finish the requests they're working on before closing. Then we'll implement a way 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 accept only two requests before gracefully shutting down its thread pool.

One thing to notice as we go: none of this affects the parts of the code that handle executing the closures, so everything here would be just the same if we were using a thread pool for an async runtime.

Implementing the `Drop` Trait on `ThreadPool`

Let's start with implementing `Drop` on our thread pool. When the pool is dropped, our threads should all join to make sure they finish their work. Listing 21-22 shows a first attempt at a `Drop` implementation; this code won't quite work yet.

```
# use std::{
#     sync::{Arc, Mutex, mpsc},
#     thread,
# };
#
# pub struct ThreadPool {
#     workers: Vec<Worker>,
#     sender: mpsc::Sender<Job>,
# }
#
# type Job = Box<dyn FnOnce() + 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(job).unwrap();
#     }
# }
#
```

```
impl Drop for ThreadPool {
    fn drop(&mut self) {
        for worker in &mut self.workers {
            println!("Shutting down worker {}", worker.id);

            worker.thread.join().unwrap();
        }
    }
}
#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
# 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 {id} got a job; executing.");
#
#                 job();
#             }
#         });
#
#         Worker { id, thread }
#     }
# }
```

First, we loop through each of the thread pool `workers`. We use `&mut` for this because `self` is a mutable reference, and we also need to be able to mutate `worker`. For each worker, we print a message saying that this particular `Worker` instance is shutting down, and then we call `join` on that `Worker` instance's thread. If the call to `join` fails, we use `unwrap` to make Rust panic and go into an ungraceful shutdown.

Here is the error we get when we compile this code:

```
$ cargo check
    Checking hello v0.1.0 (file:///projects/hello)
error[E0507]: cannot move out of `worker.thread` which is
behind a mutable reference
  --> src/lib.rs:52:13
   |
52 |             worker.thread.join().unwrap();
   |             ^^^^^^^^^^^^^ ------ `worker.thread` moved
due to this method call
   |             |
   |             move occurs because `worker.thread` has type
`JoinHandle<()>`, which does not implement the `Copy` trait
   |
note: `JoinHandle::<T>::join` takes ownership of the receiver
`self`, which moves `worker.thread`
                                                              -->
/rustc/4eb161250e340c8f48f66e2b929ef4a5bed7c181/library/std/sr
c/thread/mod.rs:1876:17

For more information about this error, try `rustc --explain
E0507`.
error: could not compile `hello` (lib) due to 1 previous error
```

The error tells us we can't call `join` because we only have a mutable borrow of each `worker` and `join` takes ownership of its argument. To solve this issue, we need to move the thread out of the `Worker` instance that owns `thread` so `join` can consume the thread. One way to do this is by taking the same approach we did in Listing 18-15. If `Worker` held an `Option<thread::JoinHandle<()>>`, we could 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 would have a `Some` variant in `thread`, and when we wanted to clean up a `Worker`, we'd replace `Some` with `None` so the `Worker` wouldn't have a thread to run.

However, the *only* time this would come up would be when dropping the `Worker`. In exchange, we'd have to deal with an `Option<thread::JoinHandle<()>>` anywhere we accessed `worker.thread`. Idiomatic Rust uses `Option` quite a bit, but when you find yourself wrapping something you know will always be present in `Option` as a workaround like this, it's a good idea to look for alternative approaches. They can make your code cleaner and less error-prone.

In this case, a better alternative exists: the `Vec::drain` method. It accepts a range parameter to specify which items to remove from the `Vec`, and returns an iterator of those items. Passing the `..` range syntax will remove *every* value from the `Vec`.

So we need to update the `ThreadPool` `drop` implementation like this:

```
# use std::{
#     sync::{Arc, Mutex, mpsc},
#     thread,
# };
#
# pub struct ThreadPool {
#     workers: Vec<Worker>,
#     sender: mpsc::Sender<Job>,
# }
#
# type Job = Box<dyn FnOnce() + 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(job).unwrap();
#     }
# }
#
impl Drop for ThreadPool {
    fn drop(&mut self) {
        for worker in self.workers.drain(..) {
            println!("Shutting down worker {}", worker.id);

            worker.thread.join().unwrap();
```

```
        }
    }
}
#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
# 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  {id}  got  a  job;
executing.");
#
#                 job();
#             }
#         });
#
#         Worker { id, thread }
#     }
# }
```

This resolves the compiler error and does not require any other changes to our code.

Signaling to the Threads to Stop Listening for Jobs

With all the changes we've made, our code compiles without any warnings. However, the bad news is that this code doesn't function the way we want it to yet. The key is the logic in the closures run by the threads of the `Worker` instances: at the moment, we call `join`, but that won't shut down the threads because they `loop` forever looking for jobs. If we try to drop our `ThreadPool` with our current implementation of `drop`, the main thread will block forever, waiting for the first thread to finish.

To fix this problem, we'll need a change in the `ThreadPool` `drop` implementation and then a change in the `Worker` loop.

First we'll change the `ThreadPool` `drop` implementation to explicitly drop the `sender` before waiting for the threads to finish. Listing 21-23 shows the changes to `ThreadPool` to explicitly drop `sender`. Unlike with the thread, here we *do* need to use an `Option` to be able to move `sender` out of `ThreadPool` with `Option::take`.

```
# use std::{
#     sync::{Arc, Mutex, mpsc},
#     thread,
# };
#
pub struct ThreadPool {
    workers: Vec<Worker>,
    sender: Option<mpsc::Sender<Job>>,
}
// --snip--
#
# type Job = Box<dyn FnOnce() + 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 {
        // --snip--
```

```
#         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: Some(sender),
        }
    }

    pub fn execute<F>(&self, f: F)
    where
        F: FnOnce() + Send + 'static,
    {
        let job = Box::new(f);

        self.sender.as_ref().unwrap().send(job).unwrap();
    }
}

impl Drop for ThreadPool {
    fn drop(&mut self) {
        drop(self.sender.take());

        for worker in self.workers.drain(..) {
            println!("Shutting down worker {}", worker.id);
```

```
            worker.thread.join().unwrap();
        }
    }
}
#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
# 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  {id}  got  a  job;
executing.");
#
#                 job();
#             }
#         });
#
#         Worker { id, thread }
#     }
# }
```

Dropping `sender` closes the channel, which indicates no more messages will be sent. When that happens, all the calls to `recv` that the `Worker` instances do in the infinite loop will return an error. In Listing 21-24, we change the `Worker` loop to gracefully exit the loop in that case, which means the threads will finish when the `ThreadPool` `drop` implementation calls `join` on them.

```
# use std::{
#     sync::{Arc, Mutex, mpsc},
#     thread,
# };
#
# pub struct ThreadPool {
#     workers: Vec<Worker>,
#     sender: Option<mpsc::Sender<Job>>,
# }
#
# type Job = Box<dyn FnOnce() + 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: Some(sender),
#         }
#     }
#
#     pub fn execute<F>(&self, f: F)
#     where
#         F: FnOnce() + Send + 'static,
#     {
#         let job = Box::new(f);
#
#         self.sender.as_ref().unwrap().send(job).unwrap();
#     }
# }
#
# impl Drop for ThreadPool {
#     fn drop(&mut self) {
#         drop(self.sender.take());
#
#         for worker in self.workers.drain(..) {
#             println!("Shutting down worker {}", worker.id);
#
#             worker.thread.join().unwrap();
#         }
#     }
# }
#
# struct Worker {
#     id: usize,
#     thread: thread::JoinHandle<()>,
# }
#
impl Worker {
    fn new(id: usize, receiver: Arc<Mutex<mpsc::Receiver<Job>>>) -> Worker {
        let thread = thread::spawn(move || {
```

```
            loop {
                let message = receiver.lock().unwrap().recv();

                match message {
                    Ok(job) => {
                        println!("Worker {id} got a job; executing.");

                        job();
                    }
                    Err(_) => {
                        println!("Worker {id} disconnected; shutting down.");
                        break;
                    }
                }
            }
        });

        Worker { id, thread }
    }
}
```

To see this code in action, let's modify `main` to accept only two requests before gracefully shutting down the server, as shown in Listing 21-25.

```
# use hello::ThreadPool;
# use std::{
#     fs,
#     io::{BufReader, prelude::*},
#     net::{TcpListener, TcpStream},
#     thread,
#     time::Duration,
# };
#
fn main() {
    let listener =
```

```
TcpListener::bind("127.0.0.1:7878").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 buf_reader = BufReader::new(&stream);
#     let request_line =
buf_reader.lines().next().unwrap().unwrap();
#
#     let (status_line, filename) = match &request_line[..] {
#         "GET / HTTP/1.1" => ("HTTP/1.1 200 OK",
"hello.html"),
#         "GET /sleep HTTP/1.1" => {
#             thread::sleep(Duration::from_secs(5));
#             ("HTTP/1.1 200 OK", "hello.html")
#         }
#         _ => ("HTTP/1.1 404 NOT FOUND", "404.html"),
#     };
#
#     let contents = fs::read_to_string(filename).unwrap();
#     let length = contents.len();
#
#     let response =
#         format!("{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}");
#
```

```
#     stream.write_all(response.as_bytes()).unwrap();
# }
```

You wouldn't want a real-world web server to shut down after serving only two requests. This code just demonstrates that the graceful shutdown and cleanup is in working order.

The `take` method is defined in the `Iterator` trait and limits the iteration to the first two items at most. The `ThreadPool` will go out of scope at the end of `main`, and the `drop` implementation will run.

Start the server with `cargo run`, and make three requests. The third request should error, and in your terminal you should see output similar to this:

```
$ cargo run
   Compiling hello v0.1.0 (file:///projects/hello)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
in 0.41s
     Running `target/debug/hello`
Worker 0 got a job; executing.
Shutting down.
Shutting down worker 0
Worker 3 got a job; executing.
Worker 1 disconnected; shutting down.
Worker 2 disconnected; shutting down.
Worker 3 disconnected; shutting down.
Worker 0 disconnected; shutting down.
Shutting down worker 1
Shutting down worker 2
Shutting down worker 3
```

You might see a different ordering of `Worker` IDs and messages printed. We can see how this code works from the messages: `Worker` instances 0 and 3 got the first two requests. The server stopped accepting connections after the second connection, and the `Drop` implementation on `ThreadPool` starts executing before `Worker` 3 even starts its job. Dropping the `sender` disconnects all the `Worker` instances and tells them to shut down. The

`Worker` instances each print a message when they disconnect, and then the thread pool calls `join` to wait for each `Worker` thread to finish.

Notice one interesting aspect of this particular execution: the `ThreadPool` dropped the `sender`, and before any `Worker` received an error, we tried to join `Worker` 0. `Worker` 0 had not yet gotten an error from `recv`, so the main thread blocked waiting for `Worker` 0 to finish. In the meantime, `Worker` 3 received a job and then all threads received an error. When `Worker` 0 finished, the main thread waited for the rest of the `Worker` instances to finish. At that point, they had all exited their loops and stopped.

Congrats! We've now completed our project; 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:

```
use hello::ThreadPool;
use std::{
    fs,
    io::{BufReader, prelude::*},
    net::{TcpListener, TcpStream},
    thread,
    time::Duration,
};

fn main() {
    let listener = TcpListener::bind("127.0.0.1:7878").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 buf_reader = BufReader::new(&stream);
                               let        request_line        =
buf_reader.lines().next().unwrap().unwrap();

    let (status_line, filename) = match &request_line[..] {
        "GET / HTTP/1.1" => ("HTTP/1.1 200 OK", "hello.html"),
        "GET /sleep HTTP/1.1" => {
            thread::sleep(Duration::from_secs(5));
            ("HTTP/1.1 200 OK", "hello.html")
        }
        _ => ("HTTP/1.1 404 NOT FOUND", "404.html"),
    };

    let contents = fs::read_to_string(filename).unwrap();
    let length = contents.len();

    let response =
                     format!("{status_line}\r\nContent-Length:
{length}\r\n\r\n{contents}");

    stream.write_all(response.as_bytes()).unwrap();
}
use std::{
    sync::{Arc, Mutex, mpsc},
    thread,
};

pub struct ThreadPool {
    workers: Vec<Worker>,
    sender: Option<mpsc::Sender<Job>>,
```

```
}

type Job = Box<dyn FnOnce() + 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: Some(sender),
        }
    }

    pub fn execute<F>(&self, f: F)
    where
        F: FnOnce() + Send + 'static,
    {
```

```
        let job = Box::new(f);

        self.sender.as_ref().unwrap().send(job).unwrap();
    }
}

impl Drop for ThreadPool {
    fn drop(&mut self) {
        drop(self.sender.take());

        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<Job>>>) -> Worker {
        let thread = thread::spawn(move || {
            loop {
                let message = receiver.lock().unwrap().recv();

                match message {
                    Ok(job) => {
                        println!("Worker {id} got a job;
executing.");
```

```
                        job();
                    }
                    Err(_) => {
                           println!("Worker {id} disconnected;
shutting down.");
                        break;
                    }
                }
            }
        });

        Worker {
            id,
            thread: Some(thread),
        }
    }
}
```

We could do more here! If you want 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 task other than serving web requests.
- Find a thread pool crate on crates.io and implement a similar web server using the crate instead. Then 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 want to thank you for joining us on this tour of Rust. You’re now ready to implement your own Rust projects and help with other people’s projects. Keep in mind that there is a welcoming 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 list contains keywords that are reserved for current or future use by the Rust language. As such, they cannot be used as identifiers (except as raw identifiers as we'll discuss in the "Raw Identifiers" section). Identifiers are names of functions, variables, parameters, struct fields, modules, crates, constants, macros, static values, attributes, types, traits, or lifetimes.

Keywords Currently in Use

The following is a list of keywords currently in use, with their functionality described.

- `as` - perform primitive casting, disambiguate the specific trait containing an item, or rename items in `use` statements
- `async` - return a `Future` instead of blocking the current thread
- `await` - suspend execution until the result of a `Future` is ready
- `break` - exit a loop immediately
- `const` - define constant items or constant raw pointers
- `continue` - continue to the next loop iteration
- `crate` - in a module path, refers to the crate root
- `dyn` - dynamic dispatch to a trait object
- `else` - fallback for `if` and `if let` control flow constructs
- `enum` - define an enumeration
- `extern` - link an external function or variable
- `false` - Boolean false literal
- `fn` - define a function or the function pointer type
- `for` - loop over items from an iterator, implement a trait, or specify a higher-ranked lifetime
- `if` - branch based on the result of a conditional expression
- `impl` - implement inherent or trait functionality
- `in` - part of `for` loop syntax
- `let` - bind a variable

- `loop` - loop unconditionally
- `match` - match a value to patterns
- `mod` - define a module
- `move` - make a closure take ownership of all its captures
- `mut` - denote mutability in references, raw pointers, or pattern bindings
- `pub` - denote public visibility in struct fields, `impl` blocks, or modules
- `ref` - bind by reference
- `return` - return from function
- `Self` - a type alias for the type we are defining or implementing
- `self` - method subject or current module
- `static` - global variable or lifetime lasting the entire program execution
- `struct` - define a structure
- `super` - parent module of the current module
- `trait` - define a trait
- `true` - Boolean true literal
- `type` - define a type alias or associated type
- `union` - define a union; is only a keyword when used in a union declaration
- `unsafe` - denote unsafe code, functions, traits, or implementations
- `use` - bring symbols into scope; specify precise captures for generic and lifetime bounds
- `where` - denote clauses that constrain a type
- `while` - loop conditionally based on the result of an expression

Keywords Reserved for Future Use

The following keywords do not yet have any functionality but are reserved by Rust for potential future use.

- `abstract`
- `become`
- `box`
- `do`

- `final`
- `gen`
- `macro`
- `override`
- `priv`
- `try`
- `typeof`
- `unsized`
- `virtual`
- `yield`

Raw Identifiers

Raw identifiers are the syntax that lets you use keywords where they wouldn't normally be allowed. You use a raw identifier by prefixing a keyword with `r#`.

For example, `match` is a keyword. If you try to compile the following function that uses `match` as its name:

Filename: src/main.rs

```
fn match(needle: &str, haystack: &str) -> bool {
    haystack.contains(needle)
}
```

you'll get this error:

```
error: expected identifier, found keyword `match`
 --> src/main.rs:4:4
  |
4 | fn match(needle: &str, haystack: &str) -> bool {
  |    ^^^^^ expected identifier, found keyword
```

The error shows that you can't use the keyword `match` as the function identifier. To use `match` as a function name, you need to use the raw identifier syntax, like this:

Filename: src/main.rs

```
fn r#match(needle: &str, haystack: &str) -> bool {
    haystack.contains(needle)
}

fn main() {
    assert!(r#match("foo", "foobar"));
}
```

This code will compile without any errors. Note the `r#` prefix on the function name in its definition as well as where the function is called in `main`.

Raw identifiers allow you to use any word you choose as an identifier, even if that word happens to be a reserved keyword. This gives us more freedom to choose identifier names, as well as lets us integrate with programs written in a language where these words aren't keywords. In addition, raw identifiers allow you to use libraries written in a different Rust edition than your crate uses. For example, `try` isn't a keyword in the 2015 edition but is in the 2018, 2021, and 2024 editions. If you depend on a library that is written using the 2015 edition and has a `try` function, you'll need to use the raw identifier syntax, `r#try` in this case, to call that function from your code on later editions. See Appendix E for more information on editions.

Appendix B: Operators and Symbols

This appendix contains a glossary of Rust's syntax, including operators and other symbols that appear by themselves or in the context of paths, generics, trait bounds, macros, attributes, comments, tuples, and brackets.

Operators

Table B-1 contains the operators in Rust, an example of how the operator would appear in context, a short explanation, and whether that operator is overloadable. If an operator is overloadable, the relevant trait to use to overload that operator is listed.

Table B-1: Operators

Operator	Example	Explanation	Overloadable?
`!`	`ident!(...)`, `ident!{...}`, `ident![...]`	Macro expansion	
`!`	`!expr`	Bitwise or logical complement	`Not`
`!=`	`expr != expr`	Nonequality comparison	`PartialEq`
`%`	`expr % expr`	Arithmetic remainder	`Rem`
`%=`	`var %= expr`	Arithmetic remainder and assignment	`RemAssign`
`&`	`&expr`, `&mut expr`	Borrow	

Operator	Example	Explanation	Overloadable?
`&`	`&type`, `&mut type`, `&'a type`, `&'a mut type`	Borrowed pointer type	
`&`	`expr & expr`	Bitwise AND	`BitAnd`
`&=`	`var &= expr`	Bitwise AND and assignment	`BitAndAssign`
`&&`	`expr && expr`	Short-circuiting logical AND	
`*`	`expr * expr`	Arithmetic multiplication	`Mul`
`*=`	`var *= expr`	Arithmetic multiplication and assignment	`MulAssign`
`*`	`*expr`	Dereference	`Deref`
`*`	`*const type`, `*mut type`	Raw pointer	
`+`	`trait + trait`, `'a + trait`	Compound type constraint	
`+`	`expr + expr`	Arithmetic addition	`Add`

Operator	Example	Explanation	Overloadable?
`+=`	`var += expr`	Arithmetic addition and assignment	`AddAssign`
`,`	`expr, expr`	Argument and element separator	
`-`	`- expr`	Arithmetic negation	`Neg`
`-`	`expr - expr`	Arithmetic subtraction	`Sub`
`-=`	`var -= expr`	Arithmetic subtraction and assignment	`SubAssign`
`->`	`fn(...) -> type`, `|...| -> type`	Function and closure return type	
`.`	`expr.ident`	Field access	
`.`	`expr.ident(expr, ...)`	Method call	
`.`	`expr.0`, `expr.1`, etc.	Tuple indexing	
`..`	`..`, `expr..`, `..expr`, `expr..expr`	Right-exclusive range literal	`PartialOrd`

Operator	Example	Explanation	Overloadable?
`..=`	`..=expr`, `expr..=expr`	Right-inclusive range literal	`PartialOrd`
`..`	`..expr`	Struct literal update syntax	
`..`	`variant(x, ..)`, `struct_type { x, .. }`	“And the rest” pattern binding	
`...`	`expr...expr`	(Deprecated, use `..=` instead) In a pattern: inclusive range pattern	
`/`	`expr / expr`	Arithmetic division	`Div`
`/=`	`var /= expr`	Arithmetic division and assignment	`DivAssign`
`:`	`pat: type`, `ident: type`	Constraints	
`:`	`ident: expr`	Struct field initializer	
`:`	`'a: loop {...}`	Loop label	
`;`	`expr;`	Statement and item terminator	

Operator	Example	Explanation	Overloadable?
`;`	`[...; len]`	Part of fixed-size array syntax	
`<<`	`expr << expr`	Left-shift	`Shl`
`<<=`	`var <<= expr`	Left-shift and assignment	`ShlAssign`
`<`	`expr < expr`	Less than comparison	`PartialOrd`
`<=`	`expr <= expr`	Less than or equal to comparison	`PartialOrd`
`=`	`var = expr`, `ident = type`	Assignment/equivalence	
`==`	`expr == expr`	Equality comparison	`PartialEq`
`=>`	`pat => expr`	Part of match arm syntax	
`>`	`expr > expr`	Greater than comparison	`PartialOrd`
`>=`	`expr >= expr`	Greater than or equal to comparison	`PartialOrd`
`>>`	`expr >> expr`	Right-shift	`Shr`
`>>=`	`var >>= expr`	Right-shift and assignment	`ShrAssign`
`@`	`ident @ pat`	Pattern binding	

Operator	Example	Explanation	Overloadable?
`^`	`expr ^ expr`	Bitwise exclusive OR	`BitXor`
`^=`	`var ^= expr`	Bitwise exclusive OR and assignment	`BitXorAssign`
`|`	`pat | pat`	Pattern alternatives	
`|`	`expr | expr`	Bitwise OR	`BitOr`
`|=`	`var |= expr`	Bitwise OR and assignment	`BitOrAssign`
`||`	`expr || expr`	Short-circuiting logical OR	
`?`	`expr?`	Error propagation	

Non-operator Symbols

The following list contains all symbols that don't function as operators; that is, they don't behave like a function or method call.

Table B-2 shows symbols that appear on their own and are valid in a variety of locations.

Table B-2: Stand-Alone Syntax

Symbol	Explanation
`'ident`	Named lifetime or loop label
`...u8`, `...i32`, `...f64`, `...usize`, etc.	Numeric literal of specific type
`"..."`	String literal
`r"..."`, `r#"..."#`, `r##"..."##`, etc.	Raw string literal, escape characters not processed

<table>
<tr><th>Symbol</th><th>Explanation</th></tr>
<tr><td>b"..."</td><td>Byte string literal; constructs an array of bytes instead of a string</td></tr>
<tr><td>br"...", br#"..."#, br##"..."##, etc.</td><td>Raw byte string literal, combination of raw and byte string literal</td></tr>
<tr><td>'...'</td><td>Character literal</td></tr>
<tr><td>b'...'</td><td>ASCII byte literal</td></tr>
<tr><td>|...| expr</td><td>Closure</td></tr>
<tr><td>!</td><td>Always empty bottom type for diverging functions</td></tr>
<tr><td>_</td><td>“Ignored” pattern binding; also used to make integer literals readable</td></tr>
</table>

Table B-3 shows symbols that appear in the context of a path through the module hierarchy to an item.

Table B-3: Path-Related Syntax

Symbol	Explanation
ident::ident	Namespace path
::path	Path relative to the extern prelude, where all other crates are rooted (i.e., an explicitly absolute path including crate name)
self::path	Path relative to the current module (i.e., an explicitly relative path).
super::path	Path relative to the parent of the current module
type::ident, <type as trait>::ident	Associated constants, functions, and types
<type>::...	Associated item for a type that cannot be directly named (e.g., <&T>::..., <[T]>::..., etc.)

Symbol	Explanation
`trait::method(...)`	Disambiguating a method call by naming the trait that defines it
`type::method(...)`	Disambiguating a method call by naming the type for which it’s defined
`<type as trait>::method(...)`	Disambiguating a method call by naming the trait and type

Table B-4 shows symbols that appear in the context of using generic type parameters.

Table B-4: Generics

Symbol	Explanation
`path<...>`	Specifies parameters to generic type in a type (e.g., `Vec<u8>`)
`path::<...>`, `method::<...>`	Specifies parameters to generic type, function, or method in an expression; often referred to as turbofish (e.g., `"42".parse::<i32>()`)
`fn ident<...> ...`	Define generic function
`struct ident<...> ...`	Define generic structure
`enum ident<...> ...`	Define generic enumeration
`impl<...> ...`	Define generic implementation

Symbol	Explanation
`for<...> type`	Higher-ranked lifetime bounds
`type<ident=type>`	A generic type where one or more associated types have specific assignments (e.g., `Iterator<Item=T>`)

Table B-5 shows symbols that appear in the context of constraining generic type parameters with trait bounds.

Table B-5: Trait Bound Constraints

Symbol	Explanation
`T: U`	Generic parameter `T` constrained to types that implement `U`
`T: 'a`	Generic type `T` must outlive lifetime `'a` (meaning the type cannot transitively contain any references with lifetimes shorter than `'a`)
`T: 'static`	Generic type `T` contains no borrowed references other than `'static` ones
`'b: 'a`	Generic lifetime `'b` must outlive lifetime `'a`
`T: ?Sized`	Allow generic type parameter to be a dynamically sized type
`'a + trait`, `trait + trait`	Compound type constraint

Table B-6 shows symbols that appear in the context of calling or defining macros and specifying attributes on an item.

Table B-6: Macros and Attributes

Symbol	Explanation

Symbol	Explanation
`#[meta]`	Outer attribute
`#![meta]`	Inner attribute
`$ident`	Macro substitution
`$ident:kind`	Macro capture
`$(…)…`	Macro repetition
`ident!(...)`, `ident!{...}`, `ident![...]`	Macro invocation

Table B-7 shows symbols that create comments.

Table B-7: Comments

Symbol	Explanation
`//`	Line comment
`//!`	Inner line doc comment
`///`	Outer line doc comment
`/*...*/`	Block comment
`/*!...*/`	Inner block doc comment
`/**...*/`	Outer block doc comment

Table B-8 shows the contexts in which parentheses are used.

Table B-8: Parentheses

Symbol	Explanation
`()`	Empty tuple (aka unit), both literal and type
`(expr)`	Parenthesized expression
`(expr,)`	Single-element tuple expression
`(type,)`	Single-element tuple type
`(expr, ...)`	Tuple expression

Symbol	Explanation
`(type, ...)`	Tuple type
`expr(expr, ...)`	Function call expression; also used to initialize tuple `struct`s and tuple `enum` variants

Table B-9 shows the contexts in which curly braces are used.

Table B-9: Curly Brackets

Context	Explanation
`{...}`	Block expression
`Type {...}`	`struct` literal

Table B-10 shows the contexts in which square brackets are used.

Table B-10: Square Brackets

Context	Explanation
`[...]`	Array literal
`[expr; len]`	Array literal containing `len` copies of `expr`
`[type; len]`	Array type containing `len` instances of `type`
`expr[expr]`	Collection indexing. Overloadable (`Index`, `IndexMut`)
`expr[..]`, `expr[a..]`, `expr[..b]`, `expr[a..b]`	Collection indexing pretending to be collection slicing, using `Range`, `RangeFrom`, `RangeTo`, or `RangeFull` as the "index"

Appendix C: Derivable Traits

In various places in the book, we've discussed the `derive` attribute, which you can apply to a struct or enum definition. The `derive` attribute generates code that will implement a trait with its own default implementation on the type you've annotated with the `derive` syntax.

In this appendix, we provide a reference of all the traits in the standard library that you can use with `derive`. Each section covers:

- What operators and methods deriving this trait will enable
- What the implementation of the trait provided by `derive` does
- What implementing the trait signifies about the type
- The conditions in which you're allowed or not allowed to implement the trait
- Examples of operations that require the trait

If you want different behavior from that provided by the `derive` attribute, consult the standard library documentation for each trait for details on how to manually implement them.

The traits listed here are the only ones defined by the standard library that can be implemented on your types using `derive`. Other traits defined in the standard library don't have sensible default behavior, so it's up to you to implement them in the way that makes sense for what you're trying to accomplish.

An example of a trait that can't be derived is `Display`, which handles formatting for end users. You should always consider the appropriate way to display a type to an end user. What parts of the type should an end user be allowed to see? What parts would they find relevant? What format of the data would be most relevant to them? The Rust compiler doesn't have this insight, so it can't provide appropriate default behavior for you.

The list of derivable traits provided in this appendix is not comprehensive: libraries can implement `derive` for their own traits, making the list of traits you can use `derive` with truly open-ended.

Implementing `derive` involves using a procedural macro, which is covered in the "Macros" section of Chapter 20.

`Debug` for Programmer Output

The `Debug` trait enables debug formatting in format strings, which you indicate by adding `:?` within `{}` placeholders.

The `Debug` trait allows you to print instances of a type for debugging purposes, so you and other programmers using your type can inspect an instance at a particular point in a program's execution.

The `Debug` trait is required, for example, in the use of the `assert_eq!` macro. This macro prints the values of instances given as arguments if the equality assertion fails so programmers can see why the two instances weren't equal.

`PartialEq` and `Eq` for Equality Comparisons

The `PartialEq` trait allows you to compare instances of a type to check for equality and enables use of the `==` and `!=` operators.

Deriving `PartialEq` implements the `eq` method. When `PartialEq` is derived on structs, two instances are equal only if *all* fields are equal, and the instances are not equal if any fields are not equal. When derived on enums, each variant is equal to itself and not equal to the other variants.

The `PartialEq` trait is required, for example, with the use of the `assert_eq!` macro, which needs to be able to compare two instances of a type for equality.

The `Eq` trait has no methods. Its purpose is to signal that for every value of the annotated type, the value is equal to itself. The `Eq` trait can only be applied to types that also implement `PartialEq`, although not all types that implement `PartialEq` can implement `Eq`. One example of this is floating point number types: the implementation of floating point numbers states that two instances of the not-a-number (`NaN`) value are not equal to each other.

An example of when `Eq` is required is for keys in a `HashMap<K, V>` so the `HashMap<K, V>` can tell whether two keys are the same.

`PartialOrd` and `Ord` for Ordering Comparisons

The `PartialOrd` trait allows you to compare instances of a type for sorting purposes. A type that implements `PartialOrd` can be used with the `<`, `>`, `<=`, and `>=` operators. You can only apply the `PartialOrd` trait to types that also implement `PartialEq`.

Deriving `PartialOrd` implements the `partial_cmp` method, which returns an `Option<Ordering>` that will be `None` when the values given don't produce an ordering. An example of a value that doesn't produce an ordering, even though most values of that type can be compared, is the not-a-number (`NaN`) floating point value. Calling `partial_cmp` with any floating-point number and the `NaN` floating-point value will return `None`.

When derived on structs, `PartialOrd` compares two instances by comparing the value in each field in the order in which the fields appear in the struct definition. When derived on enums, variants of the enum declared earlier in the enum definition are considered less than the variants listed later.

The `PartialOrd` trait is required, for example, for the `gen_range` method from the `rand` crate that generates a random value in the range specified by a range expression.

The `Ord` trait allows you to know that for any two values of the annotated type, a valid ordering will exist. The `Ord` trait implements the `cmp` method, which returns an `Ordering` rather than an `Option<Ordering>` because a valid ordering will always be possible. You can only apply the `Ord` trait to types that also implement `PartialOrd` and `Eq` (and `Eq` requires `PartialEq`). When derived on structs and enums, `cmp` behaves the same way as the derived implementation for `partial_cmp` does with `PartialOrd`.

An example of when `Ord` is required is when storing values in a `BTreeSet<T>`, a data structure that stores data based on the sort order of the values.

`Clone` and `Copy` for Duplicating Values

The `Clone` trait allows you to explicitly create a deep copy of a value, and the duplication process might involve running arbitrary code and copying heap data. See Variables and Data Interacting with Clone" in Chapter 4 for more information on `Clone`.

Deriving `Clone` implements the `clone` method, which when implemented for the whole type, calls `clone` on each of the parts of the type. This means all the fields or values in the type must also implement `Clone` to derive `Clone`.

An example of when `Clone` is required is when calling the `to_vec` method on a slice. The slice doesn't own the type instances it contains, but the vector returned from `to_vec` will need to own its instances, so `to_vec` calls `clone` on each item. Thus the type stored in the slice must implement `Clone`.

The `Copy` trait allows you to duplicate a value by only copying bits stored on the stack; no arbitrary code is necessary. See "Stack-Only Data: Copy" in Chapter 4 for more information on `Copy`.

The `Copy` trait doesn't define any methods to prevent programmers from overloading those methods and violating the assumption that no arbitrary code is being run. That way, all programmers can assume that copying a value will be very fast.

You can derive `Copy` on any type whose parts all implement `Copy`. A type that implements `Copy` must also implement `Clone`, because a type that implements `Copy` has a trivial implementation of `Clone` that performs the same task as `Copy`.

The `Copy` trait is rarely required; types that implement `Copy` have optimizations available, meaning you don't have to call `clone`, which makes the code more concise.

Everything possible with `Copy` you can also accomplish with `Clone`, but the code might be slower or have to use `clone` in places.

`Hash` for Mapping a Value to a Value of Fixed Size

The `Hash` trait allows you to take an instance of a type of arbitrary size and map that instance to a value of fixed size using a hash function. Deriving `Hash` implements the `hash` method. The derived implementation of the `hash` method combines the result of calling `hash` on each of the parts of the type, meaning all fields or values must also implement `Hash` to derive `Hash`.

An example of when `Hash` is required is in storing keys in a `HashMap<K, V>` to store data efficiently.

`Default` for Default Values

The `Default` trait allows you to create a default value for a type. Deriving `Default` implements the `default` function. The derived implementation of the `default` function calls the `default` function on each part of the type, meaning all fields or values in the type must also implement `Default` to derive `Default`.

The `Default::default` function is commonly used in combination with the struct update syntax discussed in "Creating Instances from Other Instances with Struct Update Syntax" in Chapter 5. You can customize a few fields of a struct and then set and use a default value for the rest of the fields by using `..Default::default()`.

The `Default` trait is required when you use the method `unwrap_or_default` on `Option<T>` instances, for example. If the `Option<T>` is `None`, the method `unwrap_or_default` will return the result of `Default::default` for the type `T` stored in the `Option<T>`.

Appendix D - Useful Development Tools

In this appendix, we talk about some useful development tools that the Rust project provides. We'll look at automatic formatting, quick ways to apply warning fixes, a linter, and integrating with IDEs.

Automatic Formatting with `rustfmt`

The `rustfmt` tool reformats your code according to the community code style. Many collaborative projects use `rustfmt` to prevent arguments about which style to use when writing Rust: everyone formats their code using the tool.

Rust installations include rustfmt by default, so you should already have the programs `rustfmt` and `cargo-fmt` on your system. These two commands are analogous to `rustc` and `cargo` in that `rustfmt` allows finer-grained control and `cargo-fmt` understands conventions of a project that uses Cargo. To format any Cargo project, enter the following:

```
$ cargo fmt
```

Running this command reformats all the Rust code in the current crate. This should only change the code style, not the code semantics.

This command gives you `rustfmt` and `cargo-fmt`, similar to how Rust gives you both `rustc` and `cargo`. To format any Cargo project, enter the following:

```
$ cargo fmt
```

Running this command reformats all the Rust code in the current crate. This should only change the code style, not the code semantics. For more information on `rustfmt`, see its documentation.

Fix Your Code with `rustfix`

The `rustfix` tool is included with Rust installations and can automatically fix compiler warnings that have a clear way to correct the problem that's likely what you want. It's likely you've seen compiler warnings before. For example, consider this code:

Filename: src/main.rs

```
fn main() {
    let mut x = 42;
    println!("{x}");
}
```

Here, we're defining the variable `x` as mutable, but we never actually mutate it. Rust warns us about that:

```
$ cargo build
   Compiling myprogram v0.1.0 (file:///projects/myprogram)
warning: variable does not need to be mutable
 --> src/main.rs:2:9
  |
2 |     let mut x = 0;
  |         ----^
  |         |
  |         help: remove this `mut`
  |
  = note: `#[warn(unused_mut)]` on by default
```

The warning suggests that we remove the `mut` keyword. We can automatically apply that suggestion using the `rustfix` tool by running the command `cargo fix`:

```
$ cargo fix
    Checking myprogram v0.1.0 (file:///projects/myprogram)
      Fixing src/main.rs (1 fix)
    Finished dev [unoptimized + debuginfo] target(s) in 0.59s
```

When we look at *src/main.rs* again, we'll see that `cargo fix` has changed the code:

Filename: src/main.rs

```
fn main() {
    let x = 42;
    println!("{x}");
}
```

The `x` variable is now immutable, and the warning no longer appears.

You can also use the `cargo fix` command to transition your code between different Rust editions. Editions are covered in Appendix E.

More Lints with Clippy

The Clippy tool is a collection of lints to analyze your code so you can catch common mistakes and improve your Rust code. Clippy is included with standard Rust installations.

To run Clippy's lints on any Cargo project, enter the following:

```
$ cargo clippy
```

For example, say you write a program that uses an approximation of a mathematical constant, such as pi, as this program does:

```
fn main() {
    let x = 3.1415;
    let r = 8.0;
    println!("the area of the circle is {}", x * r * r);
}
```

Running `cargo clippy` on this project results in this error:

```
error: approximate value of `f{32, 64}::consts::PI` found
 --> src/main.rs:2:13
  |
2 |     let x = 3.1415;
  |             ^^^^^^
  |
  = note: `#[deny(clippy::approx_constant)]` on by default
  = help: consider using the constant directly
    = help: for further information visit https://rust-lang.github.io/rust-clippy/master/index.html#approx_constant
```

This error lets you know that Rust already has a more precise `PI` constant defined, and that your program would be more correct if you used the constant instead. You would then change your code to use the `PI` constant. The following code doesn't result in any errors or warnings from Clippy:

```
fn main() {
    let x = std::f64::consts::PI;
    let r = 8.0;
    println!("the area of the circle is {}", x * r * r);
}
```

For more information on Clippy, see its documentation.

IDE Integration Using `rust-analyzer`

To help IDE integration, the Rust community recommends using `rust-analyzer`. This tool is a set of compiler-centric utilities that speaks the Language Server Protocol, which is a specification for IDEs and programming languages to communicate with each other. Different clients can use `rust-analyzer`, such as the Rust analyzer plug-in for Visual Studio Code.

Visit the `rust-analyzer` project's home page for installation instructions, then install the language server support in your particular IDE. Your IDE will gain abilities such as autocompletion, jump to definition, and inline errors.

Appendix E - Editions

In Chapter 1, you saw that `cargo new` adds a bit of metadata to your *Cargo.toml* file about an edition. This appendix talks about what that means!

The Rust language and compiler have a six-week release cycle, meaning users get a constant stream of new features. Other programming languages release larger changes less often; Rust releases smaller updates more frequently. After a while, all of these tiny changes add up. But from release to release, it can be difficult to look back and say, “Wow, between Rust 1.10 and Rust 1.31, Rust has changed a lot!”

Every three years or so, the Rust team produces a new Rust *edition*. Each edition brings together the features that have landed into a clear package with fully updated documentation and tooling. New editions ship as part of the usual six-week release process.

Editions serve different purposes for different people:

- For active Rust users, a new edition brings together incremental changes into an easy-to-understand package.
- For non-users, a new edition signals that some major advancements have landed, which might make Rust worth another look.
- For those developing Rust, a new edition provides a rallying point for the project as a whole.

At the time of this writing, four Rust editions are available: Rust 2015, Rust 2018, Rust 2021, and Rust 2024. This book is written using Rust 2024 edition idioms.

The `edition` key in *Cargo.toml* indicates which edition the compiler should use for your code. If the key doesn’t exist, Rust uses `2015` as the edition value for backward compatibility reasons.

Each project can opt in to an edition other than the default 2015 edition. Editions can contain incompatible changes, such as including a new keyword that conflicts with identifiers in code. However, unless you opt in to those changes, your code will continue to compile even as you upgrade the Rust compiler version you use.

All Rust compiler versions support any edition that existed prior to that compiler's release, and they can link crates of any supported editions together. Edition changes only affect the way the compiler initially parses code. Therefore, if you're using Rust 2015 and one of your dependencies uses Rust 2018, your project will compile and be able to use that dependency. The opposite situation, where your project uses Rust 2018 and a dependency uses Rust 2015, works as well.

To be clear: most features will be available on all editions. Developers using any Rust edition will continue to see improvements as new stable releases are made. However, in some cases, mainly when new keywords are added, some new features might only be available in later editions. You will need to switch editions if you want to take advantage of such features.

For more details, the *Edition Guide* is a complete book about editions that enumerates the differences between editions and explains how to automatically upgrade your code to a new edition via `cargo fix`.

Appendix F: Translations of the Book

For resources in languages other than English. Most are still in progress; see the Translations label to help or let us know about a new translation!

- Português (BR)
- Português (PT)
- : KaiserY/trpl-zh-cn, gnu4cn/rust-lang-Zh_CN
-
- Українська
- Español, alternate, Español por RustLangES
- Русский
-
-
- Français
- Polski
- Cebuano
- Tagalog
- Esperanto
- ελληνική
- Svenska
- Farsi, Persian (FA)
- Deutsch
-
-
- Danske

Appendix G - How Rust is Made and “Nightly Rust”

This appendix is about how Rust is made and how that affects you as a Rust developer.

Stability Without Stagnation

As a language, Rust cares a *lot* about the stability of your code. We want Rust to be a rock-solid foundation you can build on, and if things were constantly changing, that would be impossible. At the same time, if we can’t experiment with new features, we may not find out important flaws until after their release, when we can no longer change things.

Our solution to this problem is what we call “stability without stagnation”, and our guiding principle is this: you should never have to fear upgrading to a new version of stable Rust. Each upgrade should be painless, but should also bring you new features, fewer bugs, and faster compile times.

Choo, Choo! Release Channels and Riding the Trains

Rust development operates on a *train schedule*. That is, all development is done on the `master` branch of the Rust repository. Releases follow a software release train model, which has been used by Cisco IOS and other software projects. There are three *release channels* for Rust:

- Nightly
- Beta
- Stable

Most Rust developers primarily use the stable channel, but those who want to try out experimental new features may use nightly or beta.

Here’s an example of how the development and release process works: let’s assume that the Rust team is working on the release of Rust 1.5. That release happened in December of 2015, but it will provide us with realistic version numbers. A new feature is added to Rust: a new commit lands on the `master` branch. Each night, a new nightly version of Rust is produced. Every day is a release day, and these releases are created by our release infrastructure automatically. So as time passes, our releases look like this, once a night:

```
nightly: * - - * - - *
```

Every six weeks, it's time to prepare a new release! The `beta` branch of the Rust repository branches off from the `master` branch used by nightly. Now, there are two releases:

```
nightly: * - - * - - *
                     |
beta:                *
```

Most Rust users do not use beta releases actively, but test against beta in their CI system to help Rust discover possible regressions. In the meantime, there's still a nightly release every night:

```
nightly: * - - * - - * - - * - - *
                     |
beta:                *
```

Let's say a regression is found. Good thing we had some time to test the beta release before the regression snuck into a stable release! The fix is applied to `master`, so that nightly is fixed, and then the fix is backported to the `beta` branch, and a new release of beta is produced:

```
nightly: * - - * - - * - - * - - * - - *
                     |
beta:                * - - - - - - - - *
```

Six weeks after the first beta was created, it's time for a stable release! The `stable` branch is produced from the `beta` branch:

```
nightly: * - - * - - * - - * - - * - - * - * - *
                     |
beta:                * - - - - - - - - *
                                       |
stable:                                *
```

Hooray! Rust 1.5 is done! However, we've forgotten one thing: because the six weeks have gone by, we also need a new beta of the *next* version of Rust, 1.6. So after `stable` branches off of `beta`, the next version of `beta` branches off of `nightly` again:

```
nightly: * - - * - - * - - * - - * - - * - * - *
                     |                         |
beta:                * - - - - - - - - *       *
                                       |
stable:                                *
```

This is called the "train model" because every six weeks, a release "leaves the station", but still has to take a journey through the beta channel before it arrives as a stable release.

Rust releases every six weeks, like clockwork. If you know the date of one Rust release, you can know the date of the next one: it's six weeks later. A nice aspect of having releases scheduled every six weeks is that the next train is coming soon. If a feature happens to miss a particular release, there's no need to worry: another one is happening in a short time! This helps reduce pressure to sneak possibly unpolished features in close to the release deadline.

Thanks to this process, you can always check out the next build of Rust and verify for yourself that it's easy to upgrade to: if a beta release doesn't work as expected, you can report it to the team and get it fixed before the next stable release happens! Breakage in a beta release is relatively rare, but `rustc` is still a piece of software, and bugs do exist.

Maintenance time

The Rust project supports the most recent stable version. When a new stable version is released, the old version reaches its end of life (EOL). This means each version is supported for six weeks.

Unstable Features

There's one more catch with this release model: unstable features. Rust uses a technique called "feature flags" to determine what features are enabled in a given release. If a new feature is under active development, it lands on `master`, and therefore, in nightly, but behind a *feature flag*. If you, as a user, wish to try out the work-in-progress feature, you can, but you must be using a nightly release of Rust and annotate your source code with the appropriate flag to opt in.

If you're using a beta or stable release of Rust, you can't use any feature flags. This is the key that allows us to get practical use with new features before we declare them stable forever. Those who wish to opt into the bleeding edge can do so, and those who want a rock-solid experience can stick with stable and know that their code won't break. Stability without stagnation.

This book only contains information about stable features, as in-progress features are still changing, and surely they'll be different between when this book was written and when they get enabled in stable builds. You can find documentation for nightly-only features online.

Rustup and the Role of Rust Nightly

Rustup makes it easy to change between different release channels of Rust, on a global or per-project basis. By default, you'll have stable Rust installed. To install nightly, for example:

```
$ rustup toolchain install nightly
```

You can see all of the *toolchains* (releases of Rust and associated components) you have installed with `rustup` as well. Here's an example on one of your authors' Windows computer:

```
> rustup toolchain list
stable-x86_64-pc-windows-msvc (default)
beta-x86_64-pc-windows-msvc
nightly-x86_64-pc-windows-msvc
```

As you can see, the stable toolchain is the default. Most Rust users use stable most of the time. You might want to use stable most of the time, but use nightly on a specific project, because you care about a cutting-edge feature. To do so, you can use `rustup override` in that project's directory to set the nightly toolchain as the one `rustup` should use when you're in that directory:

```
$ cd ~/projects/needs-nightly
$ rustup override set nightly
```

Now, every time you call `rustc` or `cargo` inside of *~/projects/needs-nightly*, `rustup` will make sure that you are using nightly Rust, rather than your default of stable Rust. This comes in handy when you have a lot of Rust projects!

The RFC Process and Teams

So how do you learn about these new features? Rust's development model follows a *Request For Comments (RFC) process*. If you'd like an improvement in Rust, you can write up a proposal, called an RFC.

Anyone can write RFCs to improve Rust, and the proposals are reviewed and discussed by the Rust team, which is comprised of many topic subteams. There's a full list of the teams on Rust's website, which includes teams for each area of the project: language design, compiler implementation, infrastructure, documentation, and more. The appropriate team reads the proposal and the comments, writes some comments of their own, and eventually, there's consensus to accept or reject the feature.

If the feature is accepted, an issue is opened on the Rust repository, and someone can implement it. The person who implements it very well may not be the person who proposed the feature in the first place! When the implementation is ready, it lands on the `master` branch behind a feature gate, as we discussed in the "Unstable Features" section.

After some time, once Rust developers who use nightly releases have been able to try out the new feature, team members will discuss the feature, how it's worked out on nightly, and decide if it should make it into stable Rust or not. If the decision is to move forward, the feature gate is removed, and the feature is now considered stable! It rides the trains into a new stable release of Rust.