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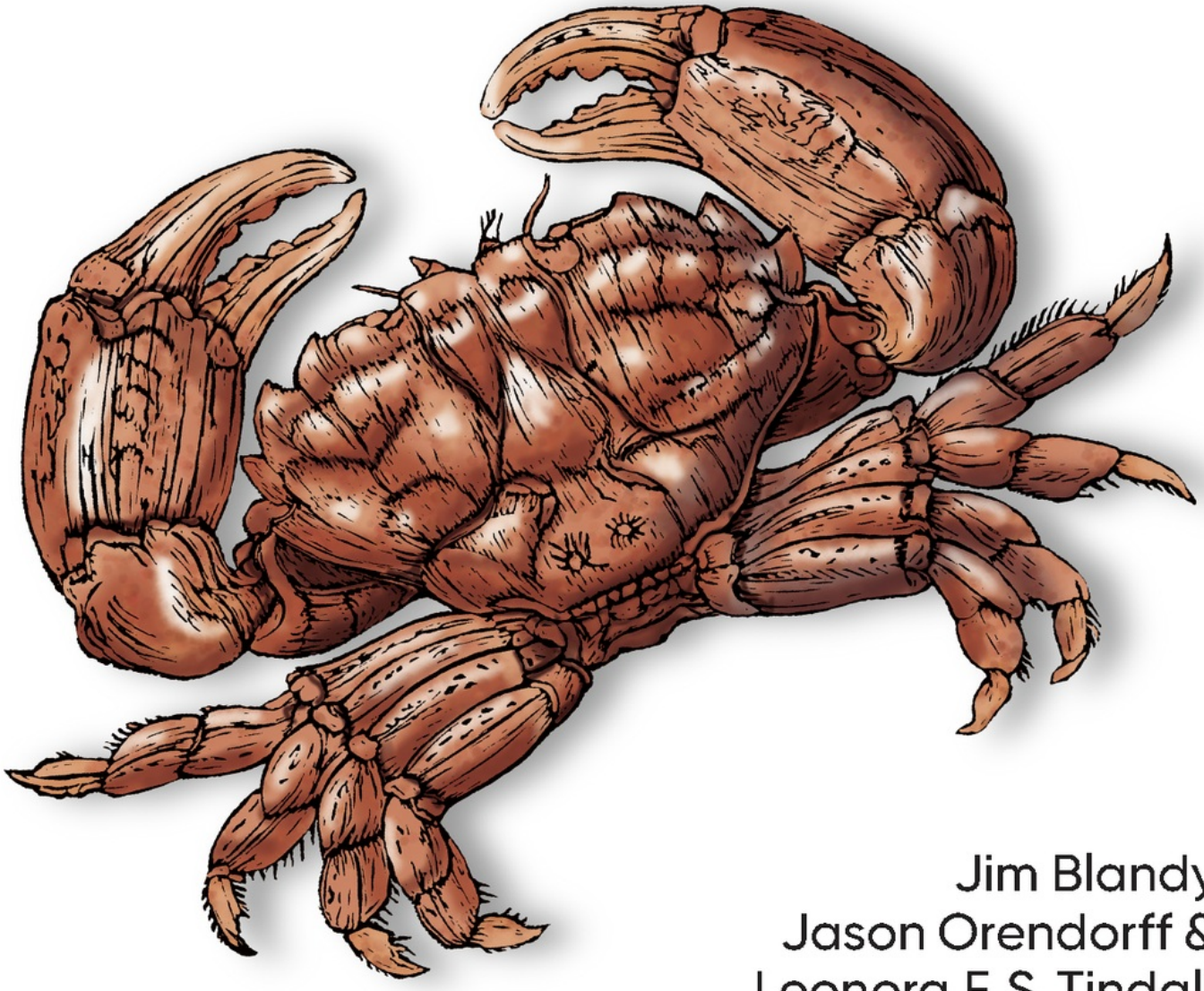
# Programming Rust

## Fast, Safe Systems Development



Jim Blandy,
Jason Orendorff &
Leonora F. S. Tindall

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THIRD EDITION

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**Jim Blandy, Jason Orendorff, and Leonora F. S. Tindall**

**Programming Rust**

by Jim Blandy, Jason Orendorff, and Leonora F. S. Tindall

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[LSI]

# Preface

Rust is a language for systems programming.

This bears some explanation these days, as systems programming is unfamiliar to most working programmers. Yet it underlies everything we do.

You close your laptop. The operating system detects this, suspends all the running programs, turns off the screen, and puts the computer to sleep. Later, you open the laptop: the screen and other components are powered up again, and each program is able to pick up where it left off. We take this for granted. But systems programmers wrote a lot of code to make that happen.

Systems programming is for:

- Operating systems
- Device drivers of all kinds
- Filesystems
- Databases
- Code that runs in very cheap devices, or devices that must be extremely reliable
- Cryptography
- Media codecs (software for reading and writing audio, video, and image files)
- Media processing (for example, speech recognition or photo editing software)
- Memory management (for example, implementing a garbage collector)

- Text rendering (the conversion of text and fonts into pixels)
- Implementing higher-level programming languages (like JavaScript and Python)
- Networking
- Virtualization and software containers
- Scientific simulations
- Games

In short, systems programming is *resource-constrained* programming. It is programming when every byte and every CPU cycle counts.

The amount of systems code involved in supporting a basic app is staggering.

This book will not teach you systems programming. In fact, this book covers many details of memory management that might seem unnecessarily abstruse at first if you haven't already done some systems programming on your own. But if you are a seasoned systems programmer, you'll find that Rust is something exceptional: a new tool that eliminates major, well-understood problems that have plagued a whole industry for decades.

## Who Should Read This Book

If you're already a systems programmer and you're ready for an alternative to C++, this book is for you. If you're an experienced developer in any programming language, whether C#, Java, Python, JavaScript, or something else, this book is for you too.

However, you don't just need to learn Rust. To get the most out of the language, you also need to gain some experience with systems programming. We recommend reading this book while also implementing some systems programming side projects in Rust. Build something you've never built before, something that takes advantage of Rust's speed,

concurrency, and safety. The list of topics at the beginning of this preface should give you some ideas.

## Why We Wrote This Book

We set out to write the book we wished we had when we started learning Rust. Our goal was to tackle the big, new concepts in Rust up front and head-on, presenting them clearly and in depth so as to minimize learning by trial and error.

## Navigating This Book

The first two chapters of this book introduce Rust and provide a brief tour before we move on to the fundamental data types in Chapter 3. Chapters 4 and 5 address the core concepts of ownership and references. We recommend reading these first five chapters through in order.

Chapters 6 through 10 cover the basics of the language: expressions (Chapter 6), error handling (Chapter 7), crates and modules (Chapter 8), structs (Chapter 9), and enums and patterns (Chapter 10). It's all right to skim a little here, but don't skip the chapter on error handling. Trust us.

Chapter 11 covers traits and generics, the last two big concepts you need to know. Traits are like interfaces in Java or C#. They're also the main way Rust supports integrating your types into the language itself. Chapter 12 shows how traits support operator overloading, and Chapter 13 covers many more utility traits.

Understanding traits and generics unlocks the rest of the book. Closures and iterators, two key power tools that you won't want to miss, are covered in Chapters 14 and 15, respectively. You can read the remaining chapters in any order, or just dip into them as needed. They cover the rest of the language: collections (Chapter 16), strings and text (Chapter 17), input and output (Chapter 18), threads (Chapter 19), asynchronous programming

(Chapters 20 and 21), macros (Chapter 22), unsafe code (Chapter 23), and calling functions in other languages (Chapter 24).

## Conventions Used in This Book

The following typographical conventions are used in this book:

*Italic*

Indicates new terms, URLs, and filenames.

`Constant width`

Used for program listings, as well as within paragraphs to refer to program elements such as variable or function names, databases, data types, environment variables, statements, and keywords.

> **NOTE**
>
> This icon signifies a general note.

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Supplemental material (code examples, exercises, etc.) is available for download at *https://github.com/ProgrammingRust*.

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# Chapter 1. Systems Programmers Can Have Nice Things

*In certain contexts—for example the context Rust is targeting—being 10x or even 2x faster than the competition is a make-or-break thing. It decides the fate of a system in the market, as much as it would in the hardware market.*

—Graydon Hoare

*All computers are now parallel...*
*Parallel programming **is** programming.*

—Michael McCool et al., *Structured Parallel Programming*

*TrueType parser flaw used by nation-state attacker for surveillance; all software is security-sensitive.*

—Andy Wingo

We chose to open our book with these three quotes for a reason. But let's start with a mystery. What does the following C program do?

```
int main(int argc, char **argv) {
  unsigned long a[1];
  a[3] = 0x7ffff7d48a38UL;
  return 0;
}
```

On Jason's laptop this morning, this program printed:

```
undef: Error: .netrc file is readable by others.
undef: Remove 'password' line or make file unreadable by others.
```

Then it crashed. If you try it on your machine, it may do something else. What's going on here?

The program is flawed. The array `a` is only one element long, so using `a[3]` is, according to the C programming language standard, *undefined behavior*:

> *Behavior, upon use of a nonportable or erroneous program construct or of erroneous data, for which this International Standard imposes no requirements.*

Undefined behavior doesn't just have an unpredictable result: the standard explicitly permits the program to do *anything at all*. In our case, storing this particular value in the fourth element of this particular array happens to corrupt the function call stack such that returning from the `main` function, instead of exiting the program gracefully as it should, jumps into the midst of code from the C standard library for retrieving a password from a file in the user's home directory. It doesn't go well.

C and C++ have hundreds of rules for avoiding undefined behavior. They're mostly common sense: don't access memory you shouldn't, don't let arithmetic operations overflow, don't divide by zero, and so on. But the compiler does not enforce these rules; it has no obligation to detect even blatant violations. The responsibility for avoiding undefined behavior falls entirely on you, the programmer.

Empirically speaking, we programmers do not have a great track record in this regard. While a student at the University of Utah, researcher Peng Li modified C and C++ compilers to make the programs they translated report whether they executed certain forms of undefined behavior. He found that nearly all programs do, including those from well-respected projects that hold their code to high standards. Assuming that you can avoid undefined behavior in C and C++ is like assuming you can win a game of chess simply because you know the rules.

The occasional strange message or crash may be a quality issue, but inadvertent undefined behavior has also been a major cause of security

flaws since the 1988 Morris Worm used a variation of the technique shown earlier to propagate from one computer to another on the early internet.

So C and C++ put programmers in an awkward position: those languages are the industry standards for systems programming, but the demands they place on programmers all but guarantee a steady stream of crashes and security problems. Answering our mystery just raises a bigger question: can't we do any better?

## Rust Shoulders the Load for You

Our answer is framed by our three opening quotes. The third quote refers to reports that Stuxnet, a computer worm found breaking into industrial control equipment in 2010, gained control of the victims' computers using, among many other techniques, undefined behavior in code that parsed TrueType fonts embedded in word processing documents.

It's a safe bet that the authors of that code were not expecting it to be used this way, illustrating that it's not just operating systems and servers that need to worry about security: any software that might handle data from an untrusted source could be the target of an exploit.

The Rust language makes you a simple promise: if your program passes the compiler's checks, it is free of undefined behavior. Dangling pointers, double-frees, and null pointer dereferences are all caught at compile time. Array references are secured with a mix of compile-time and run-time checks, so there are no buffer overruns: the Rust equivalent of our unfortunate C program exits safely with an error message.

Further, Rust aims to be both *safe* and *pleasant to use*. To make stronger guarantees about your program's behavior, Rust imposes more restrictions on your code than C and C++ do, and these restrictions take practice and experience to get used to. But overall the language is flexible and expressive. This is attested to by the breadth of code written in Rust and the range of application areas to which it is being applied.

In our experience, being able to trust the language to catch more mistakes encourages us to try more ambitious projects. Modifying large, complex programs is less risky when you know that issues of memory management and pointer validity are taken care of. And debugging is much simpler when the potential consequences of a bug don't include corrupting unrelated parts of your program.

Of course, there are still plenty of bugs that Rust cannot detect. But in practice, taking undefined behavior off the table substantially changes the character of development for the better.

## Parallel Programming Is Tamed

Concurrency is notoriously difficult to use correctly in C and C++. Developers usually turn to concurrency only when single-threaded code has proven unable to achieve the performance they need. But the second opening quote argues that parallelism is too important to modern machines to treat as a method of last resort.

As it turns out, the same restrictions that ensure memory safety in Rust also ensure that Rust programs are free of data races. You can share data freely between threads, as long as it isn't changing. Data that does change can only be accessed using synchronization primitives. All the traditional concurrency tools are available: mutexes, condition variables, channels, atomics, and so on. Rust simply checks that you're using them properly.

This makes Rust an excellent language for multithreaded programming. The Rust ecosystem offers libraries that go beyond the usual concurrency primitives and help you distribute complex loads evenly across pools of processors, use lock-free synchronization mechanisms, and more.

## And Yet Rust Is Still Fast

This, finally, is our first opening quote. Rust shares the ambitions Bjarne Stroustrup articulates for C++ in his paper "Abstraction and the C++

Machine Model”:

> *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.*

Systems programming is often concerned with pushing the machine to its limits. For games, the entire machine should be devoted to creating the best experience for the player. For web browsers, the efficiency of the browser sets the ceiling on what content authors can do. Within the machine’s inherent limitations, as much memory and processor attention as possible must be left to the content itself. The same principle applies to operating systems: the kernel should make the machine’s resources available to user programs, not consume them itself.

But when we say Rust is “fast,” what does that really mean? One can write slow code in any general-purpose language. It would be more precise to say that, if you are ready to make the investment to design your program to make the best use of the underlying machine’s capabilities, Rust supports you in that effort. The language is designed with efficient defaults and gives you the ability to control how memory gets used and how the processor’s attention is spent.

## Rust Makes Collaboration Easier

We hid a fourth quote in the title of this chapter: “Systems programmers can have nice things.” Robert O’Callahan wrote this, referring to Rust’s support for code sharing and reuse.

Rust’s package manager and build tool, Cargo, makes it easy to use libraries published by others on Rust’s public package repository, the crates.io website. You simply add the library’s name and required version number to a file, and Cargo takes care of downloading the library, along with whatever other libraries it uses in turn, compiling everything, and linking the whole lot together. You can think of Cargo as Rust’s answer to NPM or

RubyGems, with an emphasis on sound version management and reproducible builds.

There are popular Rust libraries providing everything from off-the-shelf serialization to HTTP clients and servers and modern graphics APIs. The language's traits and generics let library interfaces offer just the right degree of flexibility. And Rust's standard library provides a common vocabulary of basic types to help plug everything together.

The next chapter aims to make concrete the broad claims we've made in this chapter, with a tour of several small Rust programs that show off the language's strengths.

# Chapter 2. A Tour of Rust

Rust presents the authors of a book like this one with a challenge: what gives the language its character is not some specific, amazing feature that we can show off on the first page, but rather, the way all its parts are designed to work together smoothly in service of the goals we laid out in the previous chapter: safe, performant systems programming. Each part of the language is best justified in the context of all the rest.

So rather than tackle one language feature at a time, we've prepared a tour of a few small but complete programs, each of which introduces some more features of the language, in context:

- As a warm-up, we have a program that does a simple calculation on its command-line arguments, with unit tests. This shows Rust's core types and basic syntax.
- Next, we build a web server. We'll use a third-party library to handle the details of HTTP and introduce string handling, closures, and error handling.
- Our last program plots a beautiful fractal, distributing the computation across multiple threads for speed. This includes an example of a generic function, illustrates how to handle something like a buffer of pixels, and shows off Rust's support for concurrency.

Rust's promise to prevent undefined behavior with minimal impact on performance influences the design of every part of the system, from the standard data structures like vectors and strings to the way Rust programs use third-party libraries. The details of how this is managed are covered throughout the book. But for now, we want to show you that Rust is a capable and pleasant language to use.

First, of course, you need to install Rust on your computer.

## rustup and Cargo

The best way to install Rust is to use `rustup`. Go to *https://rustup.rs* and follow the instructions there.

You can, alternatively, go to the Rust website to get pre-built packages for Linux, macOS, and Windows. Rust is also included in some operating system distributions. We prefer `rustup` because it's a tool for managing Rust installations, like RVM for Ruby or NVM for Node. For example, when a new version of Rust is released, you'll be able to upgrade with zero clicks by typing `rustup update`.

In any case, once you've completed the installation, you should have a few new commands available at your command line:

```
$ cargo --version
cargo 1.95.0 (f2d3ce0bd 2026-03-21)
$ rustc --version
rustc 1.95.0 (59807616e 2026-04-14)
$ rustdoc --version
rustdoc 1.95.0 (59807616e 2026-04-14)
```

Here, the `$` is the command prompt; on Windows, this would be `PS C:\>` or something similar. In this transcript we run the three commands we installed, asking each to report which version it is. Taking each command in turn:

- `cargo` is Rust's compilation manager, package manager, and general-purpose tool. You can use Cargo to start a new project, build and run your program, and manage any external libraries your code depends on.
- `rustc` is the Rust compiler. Usually we let Cargo invoke the compiler for us, but sometimes it's useful to run it directly.
- `rustdoc` is the Rust documentation tool. If you write documentation in comments of the appropriate form in your program's source code, `rustdoc` can build nicely formatted

HTML from them. Like `rustc`, we usually let Cargo run `rustdoc` for us.

As a convenience, Cargo can create a new Rust package for us, with some standard metadata arranged appropriately:

```
$ cargo new hello
    Creating binary (application) `hello` package
```

This command creates a new package directory named *hello*, ready to build a command-line executable.

Looking inside the package's top-level directory:

```
$ cd hello
$ ls -la
total 24
drwxrwxr-x.  4 jimb jimb 4096 Sep 22 21:09 .
drwx------. 62 jimb jimb 4096 Sep 22 21:09 ..
drwxrwxr-x.  6 jimb jimb 4096 Sep 22 21:09 .git
-rw-rw-r--.  1 jimb jimb    7 Sep 22 21:09 .gitignore
-rw-rw-r--.  1 jimb jimb   88 Sep 22 21:09 Cargo.toml
drwxrwxr-x.  2 jimb jimb 4096 Sep 22 21:09 src
```

We can see that Cargo has created a file *Cargo.toml* to hold metadata for the package. At the moment this file doesn't contain much:

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

[dependencies]
```

If our program ever acquires dependencies on other libraries, we can record them in this file, and Cargo will take care of downloading, building, and updating those libraries for us. We'll cover the *Cargo.toml* file in detail in Chapter 8.

Cargo has set up our package for use with the `git` version control system, creating a *.git* metadata subdirectory and a *.gitignore* file. You can tell Cargo to skip this step by passing `--vcs none` to `cargo new` on the command line.

The *src* subdirectory contains the actual Rust code:

```
$ cd src
$ ls -l
total 4
-rw-rw-r--. 1 jimb jimb 45 Sep 22 21:09 main.rs
```

It seems that Cargo has begun writing the program on our behalf. The *main.rs* file contains the text:

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

In Rust, you don't even need to write your own "Hello, World!" program. And this is the extent of the boilerplate for a new Rust program: two files, totaling nine lines.

We can invoke the `cargo run` command from any directory in the package to build and run our program:

```
$ cargo run
   Compiling hello v0.1.0 (/home/jimb/rust/hello)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.28s
     Running `/home/jimb/rust/hello/target/debug/hello`
Hello, world!
```

Cargo has invoked the Rust compiler, `rustc`, and then run the executable it produced. Cargo places the executable in the *target* subdirectory at the top of the package:

```
$ ls -l ../target/debug
total 580
drwxrwxr-x. 2 jimb jimb   4096 Sep 22 21:37 build
```

```
drwxrwxr-x. 2 jimb jimb   4096 Sep 22 21:37 deps
drwxrwxr-x. 2 jimb jimb   4096 Sep 22 21:37 examples
-rwxrwxr-x. 1 jimb jimb 576632 Sep 22 21:37 hello
-rw-rw-r--. 1 jimb jimb    198 Sep 22 21:37 hello.d
drwxrwxr-x. 2 jimb jimb     68 Sep 22 21:37 incremental
$ ../target/debug/hello
Hello, world!
```

When we're through, Cargo can clean up the generated files for us:

```
$ cargo clean
     Removed 21 files, 8.4MiB total
$ ../target/debug/hello
bash: ../target/debug/hello: No such file or directory
```

# Rust Functions

Rust's syntax is deliberately unoriginal. If you are familiar with C, C++, Java, or JavaScript, you can probably find your way through the general structure of a Rust program. Here is a function that computes the greatest common divisor of two integers, using Euclid's algorithm. You can add this code to the end of *src/main.rs*:

```
fn gcd(mut n: u64, mut m: u64) -> u64 {
    while m != 0 {
        if m < n {
            let t = m;
            m = n;
            n = t;
        }
        m = m % n;
    }
    n
}
```

The `fn` keyword (pronounced "fun") introduces a function. Here, we're defining a function named `gcd`, which takes two parameters `n` and `m`, each of which is of type `u64`, an unsigned 64-bit integer. The `->` token precedes the return type: our function returns a `u64` value. Four-space indentation is standard Rust style.

Rust's machine integer type names reflect their size and signedness: `i32` is a signed 32-bit integer; `u8` is an unsigned 8-bit integer (used for "byte" values); and so on. The `isize` and `usize` types hold pointer-sized signed and unsigned integers, 32 bits long on 32-bit platforms, and 64 bits long on 64-bit platforms. Rust also has two floating-point types, `f32` and `f64`, which are the IEEE single- and double-precision floating-point types, like `float` and `double` in C and C++.

By default, once a variable is initialized, its value can't be changed, but placing the `mut` keyword (pronounced "mute," short for *mutable*) before the parameters `n` and `m` allows our function body to assign to them. In practice, most variables don't get reassigned; the `mut` keyword on those that do can be a helpful hint when reading code.

The heart of our function is a `while` loop containing an `if` statement and an assignment. Unlike C and C++, Rust does not require parentheses around the conditional expressions, but it does require curly braces around the statements they control.

A `let` statement declares a local variable, like `t` in our function. We don't need to write out `t`'s type, as long as Rust can infer it from how the variable is used. In our function, the only type that works for `t` is `u64`, matching `m` and `n`. Rust only infers types within function bodies: you must write out the types of function parameters and return values, as we did before. If we wanted to spell out `t`'s type, we could write:

```
let t: u64 = m;
```

Rust has a `return` statement, but the `gcd` function doesn't need one. If a function body ends with an expression that is *not* followed by a semicolon, that's the function's return value. In fact, any block surrounded by curly braces can function as an expression. For example, this is an expression that prints a message and then yields `x.cos()` as its value:

```
{
    println!("evaluating cos x");
```

```
    x.cos()
}
```

It's typical in Rust to use this form to establish the function's value when control "falls off the end" of the function and use `return` statements only for explicit early returns from the midst of a function.

## Writing and Running Unit Tests

Rust has simple support for testing built into the language. To test our `gcd` function, we can add this code at the end of *src/main.rs*:

```
#[test]
fn test_gcd() {
    assert_eq!(gcd(14, 15), 1);
    assert_eq!(gcd(2 * 3 * 54321, 5 * 7 * 54321), 54321);
    assert_eq!(gcd(0, 0), 0);
}
```

Here we define a function named `test_gcd`, which calls `gcd` and checks that it returns correct values. The `#[test]` atop the definition marks `test_gcd` as a test function, to be skipped in normal compilations, but included and called automatically if we run our program with the `cargo test` command. We can have test functions scattered throughout our source tree, placed next to the code they exercise, and `cargo test` will automatically gather them up and run them all.

The `#[test]` marker is an example of an *attribute*. Attributes are an open-ended system for marking functions and other declarations with extra information, like attributes in C++ and C#, or annotations in Java. They're used to control compiler warnings and code style checks, include code conditionally (like `#ifdef` in C and C++), tell Rust how to interact with code written in other languages, and so on. We'll see more examples of attributes as we go.

The body of our test consists of several calls to the `assert_eq!` macro, testing the results of a few `gcd` test cases. The `!` character marks these as a

macro calls, not function calls. During compilation, macro calls are "expanded" to Rust code. Our first use of `assert_eq!` expands to a bit of code that checks whether `gcd(14, 15)` is equal to `1`. If not, it prints a helpful error message, including the two values and the source location of the failing check. Then it terminates the program, or, in this case, the test. This kind of abrupt termination is called a *panic*.

There's also an `assert!(condition);` macro that checks a Boolean condition. Like the `assert` macro in C and C++, Rust's `assert!` and `assert_eq!` macros are commonly used to check invariants in regular code, not only in tests. Unlike C and C++, in which assertions can be skipped, Rust always checks assertions regardless of how the program was compiled. There are also `debug_assert!` and `debug_assert_eq!` macros, whose assertions are skipped when the program is compiled for speed.

With our `gcd` and `test_gcd` definitions added to the *hello* package we created at the beginning of the chapter, and our current directory somewhere within the package's subtree, we can run the tests as follows:

```
$ cargo test
   Compiling hello v0.1.0 (/home/jimb/rust/hello)
    Finished `test` profile [unoptimized + debuginfo] target(s)
in 0.35s
     Running unittests src/main.rs
(.../hello/target/debug/deps/hello-2375...)

running 1 test
test test_gcd ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out;
    finished in 0.00s
```

## Handling Command-Line Arguments

For our program to take a series of numbers as command-line arguments and print their greatest common divisor, we can replace the `main` function

in *src/main.rs* with:

```
use std::str::FromStr;
use std::env;

fn main() {
    let mut numbers = Vec::new();

    for arg in env::args().skip(1) {
        numbers.push(u64::from_str(&arg).expect("error parsing
argument"));
    }

    if numbers.len() == 0 {
        eprintln!("Usage: gcd NUMBER ...");
        std::process::exit(1);
    }

    let mut d = numbers[0];
    for m in &numbers[1..] {
        d = gcd(d, *m);
    }

    println!("The greatest common divisor of {numbers:?} is
{d}");
}
```

This is a large block of code, so let's take it piece by piece:

```
use std::str::FromStr;
use std::env;
```

The first `use` declaration brings the standard library *trait* `FromStr` into scope. A trait is a collection of function signatures that types can implement, like an interface in Java or C#. Any type that implements the `FromStr` trait has a `from_str` method that tries to parse a value of that type from a string. The `u64` type implements `FromStr`, and we'll call `u64::from_str` to parse our command-line arguments. Although we never use the name `FromStr` elsewhere in the program, a trait must be in scope to use its methods. We'll cover traits in detail in Chapter 11.

The second `use` declaration brings in the `std::env` module, which provides several useful functions and types for interacting with the execution environment, including the `args` function, which gives us access to the program's command-line arguments.

Moving on to the program's `main` function:

```
fn main() {
```

Our `main` function doesn't return a value, so we can simply omit the `->` and return type that would normally follow the parameter list.

```
    let mut numbers = Vec::new();
```

We declare a mutable local variable `numbers` and initialize it to an empty vector. `Vec` is Rust's growable vector type, analogous to C++'s `std::vector`, a Python list, or a JavaScript array. Even though vectors are designed to be grown and shrunk dynamically, we must still mark the variable `mut` for Rust to let us push numbers onto the end of it.

The type of `numbers` is `Vec<u64>`, a vector of `u64` values, but as before, we don't need to write that out. Rust will infer it for us, in part because what we push onto the vector are `u64` values, but also because we pass the vector's elements to `gcd`, which accepts only `u64` values.

```
    for arg in env::args().skip(1) {
```

Here we use a `for` loop to process our command-line arguments, setting the variable `arg` to each argument in turn and evaluating the loop body.

The `std::env` module's `args` function returns an *iterator* over the command-line arguments. That is, its return type implements the `Iterator` trait, which provides methods for looping over a sequence of values. Iterators are ubiquitous in Rust; the standard library includes other iterators that produce the elements of a vector, the lines of a file, messages received on a communications channel, and almost anything else that makes

sense to loop over. Rust's iterators are very efficient: the compiler is usually able to translate them into the same code as a handwritten loop. We'll show how this works and give examples in Chapter 15.

Beyond their use with `for` loops, iterators include a broad selection of methods you can use directly. For example, the first value produced by the iterator returned by `args` is always the name of the program being run. We want to skip that, so we call the iterator's `skip` method to produce a new iterator that omits that first value.

```
numbers.push(u64::from_str(&arg).expect("error parsing
argument"));
```

Here we call `u64::from_str` to attempt to parse our command-line argument `arg` as an unsigned 64-bit integer. Rather than a method we're invoking on a particular `u64` value, `u64::from_str` is a function associated with the `u64` type, akin to a static method in C++ or Java.

The `from_str` function doesn't return a `u64` directly, but rather a `Result` value that indicates whether the parse succeeded or failed. A `Result` value is one of two variants:

- A value written `Ok(v)`, indicating that the parse succeeded and `v` is the value produced
- A value written `Err(e)`, indicating that the parse failed and `e` is an error value explaining why

Functions that do anything that might fail, such as doing input or output or otherwise interacting with the operating system, can return `Result` types whose `Ok` variants carry successful results—the count of bytes transferred, the file opened, and so on—and whose `Err` variants carry an error code indicating what went wrong. Unlike most modern languages, Rust does not have exceptions: all errors are handled using either `Result` or panic, as outlined in Chapter 7.

We use `Result`'s `expect` method to check the success of our parse. If the result is an `Err(e)`, `expect` prints a message that includes a description of `e` and exits the program immediately. However, if the result is `Ok(v)`, `expect` simply returns `v` itself, which we are finally able to push onto the end of our vector of numbers.

```
if numbers.len() == 0 {
    eprintln!("Usage: gcd NUMBER ...");
    std::process::exit(1);
}
```

There's no greatest common divisor of an empty set of numbers, so we check that our vector has at least one element and exit the program with an error if it doesn't. We use the `eprintln!` macro to write our error message to the standard error output stream.

```
let mut d = numbers[0];
for m in &numbers[1..] {
    d = gcd(d, *m);
}
```

This loop uses `d` as its running value, updating it to stay the greatest common divisor of all the numbers we've processed so far. As before, we must mark `d` as mutable so that we can assign to it in the loop.

The `for` loop has two surprising bits to it. First, we wrote `for m in &numbers[1..]`; what is the `&` operator for? Second, we wrote `gcd(d, *m)`; what is the `*` in `*m` for? These two details are complementary to each other.

Up to this point, our code has operated only on simple values like integers that fit in fixed-size blocks of memory. But now we're about to iterate over a vector, which could be of any size whatsoever—possibly very large. Rust is cautious when handling such values: it wants to leave the programmer in control over memory consumption, making it clear how long each value lives, while still ensuring memory is freed promptly when no longer needed.

So when we iterate, we want to tell Rust that *ownership* of the vector should remain with `numbers`; we are merely *borrowing* its elements for the loop. The `&` operator in `&numbers[1..]` borrows a *reference* to the vector's elements from the second onward. The `for` loop iterates over the referenced elements, letting `m` borrow each element in succession. The `*` operator in `*m` *dereferences* `m`, yielding the value it refers to; this is the next `u64` we want to pass to `gcd`. Finally, since `numbers` owns the vector, Rust automatically frees it when `numbers` goes out of scope at the end of `main`.

Rust's rules for ownership and references are key to Rust's memory management and safe concurrency; we discuss them in detail in Chapters 4 and 5. You'll need to be comfortable with those rules to be comfortable in Rust, but for this introductory tour, all you need to know is that `&x` borrows a reference to `x` and that `*r` is the value that the reference `r` refers to.

Continuing our walk through the program:

```
println!("The greatest common divisor of {numbers:?} is {d}");
```

Having iterated over the elements of `numbers`, the program prints the results. The `println!` macro takes a format string, replaces the parts in braces `{...}` with the specified values, and writes the result to the standard output stream.

When we reach the end of our `main` function and return normally, the process exits with an exit status of 0, indicating success. Alternatively, we could have our `main` function return a `std::process::ExitCode` or a `Result`, in which case the return value would determine the exit status. In the case of an error `Result`, Rust would also print the debug form of the error to `stderr`.

The `cargo run` command allows us to pass arguments to our program.

This command allows us to try command-line handling:

```
$ cargo run 42 56
   Compiling hello v0.1.0 (/home/jimb/rust/hello)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.22s
     Running `/home/jimb/rust/hello/target/debug/hello 42 56`
The greatest common divisor of [42, 56] is 14
$ cargo run 799459 28823 27347
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.02s
     Running `/home/jimb/rust/hello/target/debug/hello 799459
28823 27347`
The greatest common divisor of [799459, 28823, 27347] is 41
$ cargo run 83
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.02s
     Running `/home/jimb/rust/hello/target/debug/hello 83`
The greatest common divisor of [83] is 83
$ cargo run
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.02s
     Running `/home/jimb/rust/hello/target/debug/hello`
Usage: gcd NUMBER ...
```

We've used a few features from Rust's standard library in this section. If you're curious about what else is available, we strongly encourage you to try Rust's online documentation. It has a live search feature that makes exploration easy and even includes links to the source code. The `rustup` command automatically installs a copy on your computer when you install Rust itself. You can view the standard library documentation on the Rust website or in your browser with the command:

```
$ rustup doc --std
```

## Serving Pages to the Web

One of Rust's strengths is the collection of freely available library packages published on the website crates.io. The `cargo` command makes it easy for your code to use a crates.io package: it will download the right version of the package, build it, and update it as requested. A Rust package, whether a library or an executable, is called a *crate*; Cargo and crates.io both derive

their names from this term. To show how this works, we'll put together a simple web server using the `actix-web` web framework crate, the `serde` serialization crate, and various other crates on which they depend. As shown in Figure 2-1, our website will prompt the user for two numbers and compute their greatest common divisor.

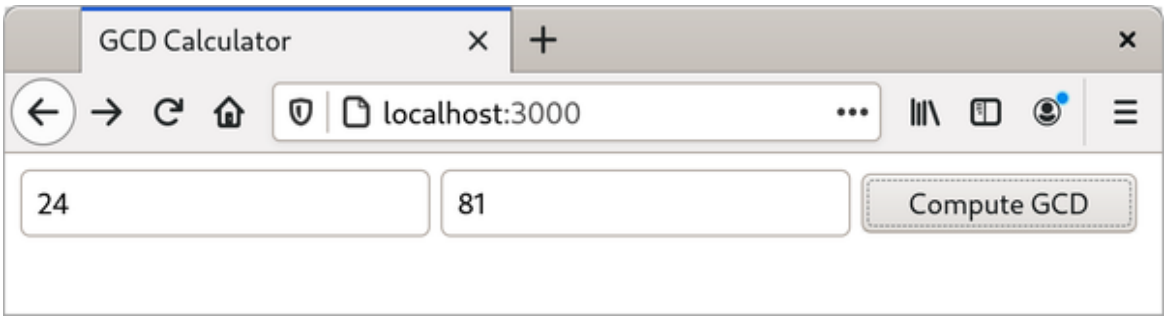


*Figure 2-1. Web page offering to compute GCD*

First, we'll have Cargo create a new package for us, named `actix-gcd`:

```
$ cargo new actix-gcd
    Creating binary (application) `actix-gcd` package
$ cd actix-gcd
```

Then, we'll tell Cargo which packages we want to use:

```
$ cargo add actix-web@4.13.0
    Updating crates.io index
      Adding actix-web v4.13.0 to dependencies
    ...
$ cargo add serde@1.0.228 --features derive
    Updating crates.io index
      Adding serde v1.0.228 to dependencies
    ...
```

We've included version numbers in these commands to ensure that the crates you get are compatible with the ones we used during testing. In practice, you'll usually omit the version numbers, and `cargo add` will use the latest version. These commands add entries to our new project's *Cargo.toml* file, which now looks like this:

```
[package]
name = "actix-gcd"
version = "0.1.0"
edition = "2024"

[dependencies]
actix-web = "4.13.0"
serde = { version = "1.0.228", features = ["derive"] }
```

Instead of using `cargo add`, you could simply open *Cargo.toml* in your editor and add the last two lines yourself. From now on, we'll show *Cargo.toml* snippets instead of `cargo add` commands, as that is a bit easier to copy and paste and includes the version numbers for each package we're using.

Each line in the `[dependencies]` section of *Cargo.toml* gives the name of a crate on crates.io, and the version of that crate we would like to use. New versions of these crates are published frequently. By default, whenever we build this project from scratch on a new machine or run `cargo update`, Cargo will download the latest compatible version of these packages, perhaps Actix 4.15.1 and Serde 1.0.253. We'll discuss version management in more detail in Chapter 8.

Crates can have optional *features*: parts of the interface or implementation that not all users need and that are therefore excluded from the build by default. The `serde` crate offers a wonderfully terse way to handle data from web forms, but according to `serde`'s documentation, it is available only if we select the crate's `derive` feature, so we've requested it in our *Cargo.toml* file, as shown.

Note that we need only name those crates we'll use directly; `cargo` takes care of bringing in whatever other crates those need in turn.

For our first iteration, we'll keep the web server simple: it will serve only the page that prompts the user for numbers to compute with. We'll replace the contents of *actix-gcd/src/main.rs* with the following:

```
use actix_web::{App, HttpResponse, HttpServer, web};
```

```
#[actix_web::main]
async fn main() {
    let server = HttpServer::new(|| {
        App::new()
            .route("/", web::get().to(get_index))
    });

    println!("Serving on http://localhost:3000...");
    server
        .bind("127.0.0.1:3000")
        .expect("error binding server to address")
        .run()
        .await
        .expect("error running server");
}

async fn get_index() -> HttpResponse {
    HttpResponse::Ok()
        .content_type("text/html")
        .body(
            r#"
                <title>GCD Calculator</title>
                <form action="/gcd" method="post">
                <input type="text" name="n"/>
                <input type="text" name="m"/>
                <button type="submit">Compute GCD</button>
                </form>
            "#
        )
}
```

We start with a `use` declaration to make some of the `actix-web` crate's definitions easier to get at. When we write `use actix_web::{...}`, each of the names listed inside the curly brackets becomes directly usable in our code; instead of having to spell out the full name `actix_web::HttpResponse` each time we use it, we can simply refer to it as `HttpResponse`. (We'll get to the `serde` crate in a bit.)

This time our `main` function is an `async fn`, marked with the attribute `#[actix_web::main]`. Actix is written using *asynchronous code* to support serving thousands of connections at a time without spawning thousands of system threads. Rust's `async` and `await` features are in the same general family as `async/await` in C# and JavaScript, or the

lightweight processes in Erlang. They're a way to deal with tasks that don't need the CPU all the time—perhaps because, as in our case, they will spend a lot of time waiting for the network. A single CPU core can keep many concurrent `async` tasks running responsively without the overhead of system threads. We'll explain in Chapter 20.

The body of our `main` function is simple: it calls `HttpServer::new` to create a server that responds to requests for a single path, `"/"`; prints a message reminding us how to connect to it; and then sets it listening on TCP port 3000 on the local machine.

The argument we pass to `HttpServer::new` is the Rust *closure* expression `|| { App::new() ... }`. A closure is a value that can be called as if it were a function. This closure takes no arguments, but if it did, their names would appear between the `||` vertical bars. The `{ ... }` is the body of the closure. When we start our server, Actix starts a pool of threads to handle incoming requests. Each thread calls our closure to get a fresh copy of the `App` value that tells it how to route and handle requests.

The closure calls `App::new` to create a new, empty `App` and then calls its `route` method to add a single route for the path `"/"`. The handler provided for that route, `web::get().to(get_index)`, treats HTTP `GET` requests by calling the function `get_index`. The `route` method returns the same `App` it was invoked on, now enhanced with the new route. Since there's no semicolon at the end of the closure's body, the `App` is the closure's return value, ready for the `HttpServer` thread to use.

The `get_index` function builds an `HttpResponse` value representing the response to an HTTP `GET /` request. `HttpResponse::Ok()` represents an HTTP `200 OK` status, indicating that the request succeeded. We call its `content_type` and `body` methods to fill in the details of the response; each call returns the `HttpResponse` it was applied to, with the modifications made. Finally, the return value from `body` serves as the return value of `get_index`.

Since the response text contains a lot of double quotes, we write it using the Rust "raw string" syntax: the letter `r`, zero or more hash marks (that is, the `#` character), a double quote, and then the contents of the string, terminated by another double quote followed by the same number of hash marks. Any character may occur within a raw string without being escaped, including double quotes; in fact, no escape sequences like `\"` are recognized. We can always ensure the string ends where we intend by using more hash marks around the quotes than ever appear in the text.

Having written *main.rs*, we can use the `cargo run` command to do everything needed to set it running: fetching the needed crates, compiling them, building our own program, linking everything together, and starting it up:

```
$ cargo run
    Updating crates.io index
 Downloading crates ...
  Downloaded serde v1.0.100
  Downloaded actix-web v1.0.8
  Downloaded serde_derive v1.0.100
...
   Compiling serde_json v1.0.40
   Compiling actix-router v0.1.5
   Compiling actix-http v0.2.10
   Compiling awc v0.2.7
   Compiling actix-web v1.0.8
   Compiling gcd v0.1.0 (/home/jimb/rust/actix-gcd)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
1m 24s
     Running `/home/jimb/rust/actix-gcd/target/debug/actix-gcd`
Serving on http://localhost:3000...
```

At this point, we can visit the given URL in our browser and see the page shown earlier in Figure 2-1.

Unfortunately, clicking Compute GCD doesn't do anything, other than navigate our browser to a blank page. Let's fix that next by adding another route to our `App` to handle the `POST` request from our form.

It's finally time to use the `serde` crate we listed in our *Cargo.toml* file: it provides a handy tool that will help us process the form data. First, we'll need to add the following `use` declaration to the top of *src/main.rs*:

```
use serde::Deserialize;
```

Rust programmers typically gather all their `use` declarations together toward the top of the file, but this isn't strictly necessary: Rust allows declarations to occur in any order, as long as they appear at the appropriate level of nesting.

Let's define a Rust structure type that represents the values we expect from our form:

```
#[derive(Deserialize)]
struct GcdParameters {
    n: u64,
    m: u64,
}
```

This defines a new type named `GcdParameters` that has two fields, `n` and `m`, each of which is a `u64`—the argument type our `gcd` function expects.

The annotation above the `struct` definition is an attribute, like the `#[test]` attribute we used earlier to mark test functions. Placing a `#[derive(Deserialize)]` attribute above a type definition tells the `serde` crate to examine the type when the program is compiled and automatically generate code to parse a value of this type from data in the format that HTML forms use for `POST` requests.

In fact, that attribute is sufficient to let you parse a `GcdParameters` value from almost any sort of structured data: JSON, YAML, TOML, or any one of a number of other textual and binary formats. The `serde` crate also provides a `Serialize` attribute that generates code to do the reverse, taking Rust values and writing them out in a structured format.

The comma after `m: u64` is optional, since it's the last field. Rust consistently permits an extra trailing comma everywhere commas are used, and it is the standard style to include it whenever a list spans multiple lines. This includes array elements and function arguments. Using the same syntax on every line means less fiddling with punctuation when things change, and it makes for cleaner diffs.

With this definition in place, we can write our handler function quite easily:

```
async fn post_gcd(form: web::Form<GcdParameters>) -> HttpResponse
{
    if form.n == 0 || form.m == 0 {
        return HttpResponse::BadRequest()
            .content_type("text/html")
            .body("Computing the GCD with zero is boring.");
    }

    let response = format!(
        "The greatest common divisor of the numbers {} and {} \
            is <b>{}</b>\n",
        form.n,
        form.m,
        gcd(form.n, form.m),
    );

    HttpResponse::Ok()
        .content_type("text/html")
        .body(response)
}
```

For a function to serve as an Actix request handler, its arguments must all have types Actix knows how to extract from an HTTP request. Our `post_gcd` function takes one argument, `form`, whose type is `web::Form<GcdParameters>`. Actix knows how to extract a value of any type `web::Form<T>` from an HTTP request if, and only if, `T` can be deserialized from HTML form `POST` data. Since we've placed the `#[derive(Deserialize)]` attribute on our `GcdParameters` type definition, Actix can deserialize it from form data, so request handlers can expect a `web::Form<GcdParameters>` value as a parameter. These relationships between types and functions are all worked out at compile

time; if you write a handler function with an argument type that Actix doesn't know how to handle, the Rust compiler lets you know of your mistake immediately.

Looking inside `post_gcd`, the function first returns an HTTP 400 Bad Request error if either parameter is zero, since our `gcd` function will panic if they are. Then, it constructs a response to the request using the `format!` macro. The `format!` macro is just like the `println!` macro, except that instead of writing the text to the standard output, it returns it as a string.

In this example, since the values we want to print are not simple variable names, we must use empty braces, `{}`, to mark the place where we want to insert them and then pass the values as extra arguments. Once it has obtained the text of the response, `post_gcd` wraps it up in an HTTP `200 OK` response, sets its content type, and returns it to be delivered to the sender.

We also have to register `post_gcd` as the handler for the form. We'll replace our `main` function with this version:

```
#[actix_web::main]
async fn main() {
    let server = HttpServer::new(|| {
        App::new()
            .route("/", web::get().to(get_index))
            .route("/gcd", web::post().to(post_gcd))
    });

    println!("Serving on http://localhost:3000...");
    server
        .bind("127.0.0.1:3000")
        .expect("error binding server to address")
        .run()
        .await
        .expect("error running server");
}
```

The only change here is that we've added another call to `route`, establishing `web::post().to(post_gcd)` as the handler for the path `"/gcd"`.

The last remaining piece is the `gcd` function we wrote earlier, in "Rust Functions". Add that code to the *actix-gcd/src/main.rs* file. With that in place, you can interrupt any servers you might have left running and rebuild and restart the program:

```
$ cargo run
   Compiling actix-gcd v0.1.0 (/home/jimb/rust/actix-gcd)
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.0 secs
     Running `target/debug/actix-gcd`
Serving on http://localhost:3000...
```

This time, by visiting *http://localhost:3000*, entering some numbers, and clicking the Compute GCD button, you should actually see some results (Figure 2-2).

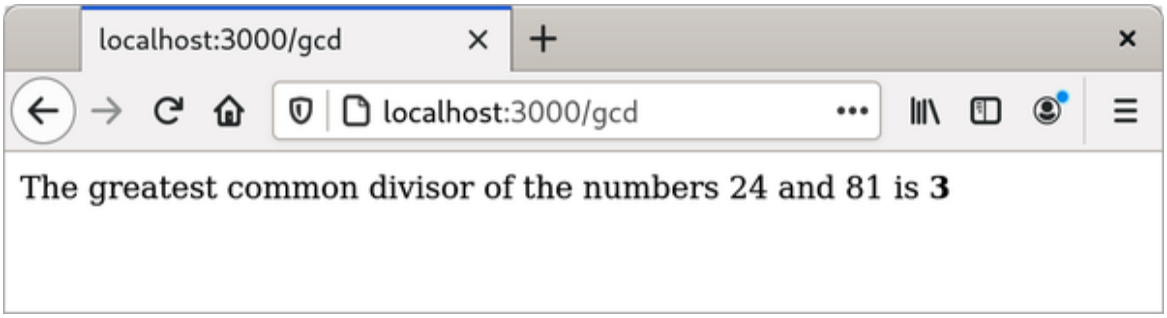


*Figure 2-2. Web page showing results of computing GCD*

# Concurrency

One of Rust's great strengths is its support for concurrent programming. The same rules that ensure Rust programs are free of memory errors also ensure threads can share memory only in ways that avoid data races. For example:

- If you use a mutex to coordinate threads making changes to a shared data structure, Rust ensures that you can't access the data except when you're holding the lock and releases the lock automatically when you're done. In C and C++, the relationship between a mutex and the data it protects is left to the comments.

- If you want to share read-only data among several threads, Rust ensures that you cannot modify the data accidentally. In C and C++, the type system can help with this, but it's easy to get it wrong.
- If you transfer ownership of a data structure from one thread to another, Rust makes sure you have indeed relinquished all access to it. In C and C++, it's up to you to check that nothing on the sending thread will ever touch the data again. If you don't get it right, the effects can depend on what happens to be in the processor's cache and how many writes to memory you've done recently. Not that we're bitter.

In this section, we'll walk you through the process of writing your second multi-threaded program. You've already written your first: the Actix web framework you used to implement the Greatest Common Divisor server uses a pool of threads to run request handler functions. If the server receives simultaneous requests, it may run the `get_index` and `post_gcd` functions in several threads at once. That may come as a bit of a shock, since we certainly didn't have concurrency in mind when we wrote those functions. But Rust guarantees this is safe to do, no matter how elaborate your server gets: if your program compiles, it is free of data races. All Rust functions are thread-safe.

This section's program plots the Mandelbrot set, a fractal produced by iterating a simple function on complex numbers. Plotting the Mandelbrot set is often called an *embarrassingly parallel* algorithm, because the pattern of communication between the threads is so simple. We'll cover more complex patterns in Chapter 19, but this task demonstrates some of the essentials.

To get started, we'll create a fresh Rust project:

```
$ cargo new mandelbrot
    Creating binary (application) `mandelbrot` package
$ cd mandelbrot
```

All the code will go in *mandelbrot/src/main.rs*, and we'll add some dependencies to *mandelbrot/Cargo.toml*. Before we get into the concurrent Mandelbrot implementation, we need to describe the computation we're going to perform.

## What the Mandelbrot Set Actually Is

When reading code, it's helpful to have a concrete idea of what it's trying to do, so let's take a short excursion into some pure mathematics. We'll start with a simple case and then add complicating details until we arrive at the calculation at the heart of the Mandelbrot set.

Here's an infinite loop, written using Rust's dedicated syntax for that, a `loop` statement:

```
fn square_loop(mut x: f64) {
    loop {
        x = x * x;
    }
}
```

In real life, Rust can see that `x` is never used for anything and so might not bother computing its value. But for the time being, assume the code runs as written. What happens to the value of `x`? Squaring any number between 0 and 1 makes it smaller, so it approaches zero; squaring 1 yields 1; squaring a number larger than 1 makes it larger, so it approaches infinity; and squaring a negative number makes it positive, after which it behaves like one of the prior cases (Figure 2-3).

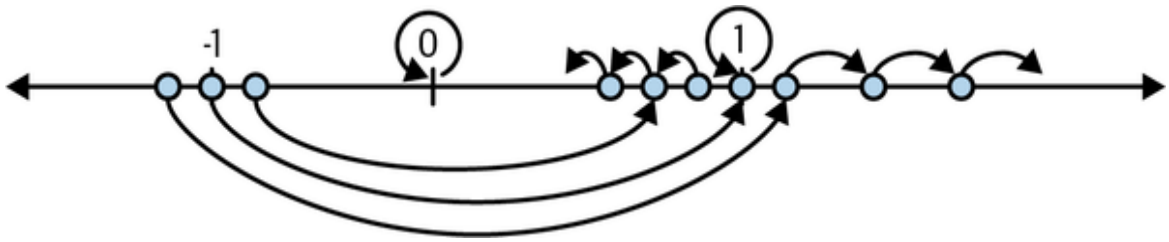


*Figure 2-3. Effects of repeatedly squaring a number*

So depending on the value you pass to `square_loop`, `x` stays at either zero or one, approaches zero, or approaches infinity.

Now consider a slightly different loop:

```
fn square_add_loop(c: f64) {
    let mut x = 0.0;
    loop {
        x = x * x + c;
    }
}
```

This time, `x` starts at zero, and we tweak its progress in each iteration by adding in `c` after squaring it. This makes it harder to see how `x` fares, but some experimentation shows that if `c` is greater than 0.25 or less than −2.0, then `x` eventually becomes infinitely large; otherwise, it stays somewhere in the neighborhood of zero.

The next wrinkle: instead of using `f64` values, consider the same loop using complex numbers. The `num` crate on crates.io provides a complex number type we can use, so we must add a line for `num` to the `[dependencies]` section in our program's *Cargo.toml* file.

While we're here, we can add the `image` crate, which we'll use later:

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

[dependencies]
num = "0.4.3"
image = "0.25.10"
```

Now we can write the penultimate version of our loop:

```
use num::Complex;

fn complex_square_add_loop(c: Complex<f64>) {
    let mut z = Complex { re: 0.0, im: 0.0 };
    loop {
        z = z * z + c;
    }
}
```

It's traditional to use `z` for complex numbers, so we've renamed our looping variable. The expression `Complex { re: 0.0, im: 0.0 }` is the way we write complex zero using the `num` crate's `Complex` type. `Complex` is a Rust structure type (or *struct*), defined like:

```
struct Complex<T> {
    /// Real portion of the complex number
    re: T,

    /// Imaginary portion of the complex number
    im: T,
}
```

The preceding code defines a struct named `Complex`, with two fields, `re` and `im`. `Complex` is a *generic* structure: you can read the `<T>` after the type name as "for any type `T`." For example, `Complex<f64>` is a complex number whose `re` and `im` fields are `f64` values, `Complex<f32>` would use 32-bit floats, and so on. Given this definition, an expression like `Complex { re: 0.24, im: 0.3 }` produces a `Complex` value with its `re` field initialized to 0.24, and its `im` field initialized to 0.3.

The `num` crate arranges for `*`, `+`, and other arithmetic operators to work on `Complex` values, so the rest of the function works just like the prior version, except that it operates on points on the complex plane, not just points along the real number line. We'll explain how you can make Rust's operators work with your own types in Chapter 12.

Finally, we've reached the destination of our pure math excursion. The Mandelbrot set is defined as the set of complex numbers `c` for which `z` does not fly out to infinity. Our original simple squaring loop was predictable enough: any number greater than 1 or less than −1 flies away.

Throwing a `+ c` into each iteration makes the behavior a little harder to anticipate: as we said earlier, values of `c` greater than 0.25 or less than −2 cause `z` to fly away. But expanding the game to complex numbers produces truly bizarre and beautiful patterns, which are what we want to plot.

Since a complex number `c` has both real and imaginary components `c.re` and `c.im`, we'll treat these as the `x` and `y` coordinates of a point on the Cartesian plane and color the point black if `c` is in the Mandelbrot set, or a lighter color otherwise. So for each pixel in our image, we must run the preceding loop on the corresponding point on the complex plane, see whether it escapes to infinity or orbits around the origin forever, and color it accordingly.

The infinite loop takes a while to run, but there are two tricks for the impatient. First, if we give up on running the loop forever and just try some limited number of iterations, it turns out that we still get a decent approximation of the set. How many iterations we need depends on how precisely we want to plot the boundary.

Second, it's been shown that, if `z` ever once leaves the circle of radius 2 centered at the origin, it will definitely fly infinitely far away from the origin eventually. So here's the final version of our loop, and the heart of our program:

```
use num::Complex;

/// Tries to determine if `c` is in the Mandelbrot set, using at
most `limit`
/// iterations to decide.
///
/// If `c` is not a member, this returns `Some(i)`, where `i` is
the number of
/// iterations it took for `c` to leave the circle of radius 2
centered on the
/// origin. If `c` seems to be a member (more precisely, if we
reached the
/// iteration limit without being able to prove that `c` is not a
member),
/// this returns `None`.
fn escape_time(c: Complex<f64>, limit: usize) -> Option<usize> {
    let mut z = Complex { re: 0.0, im: 0.0 };
    for i in 0..limit {
        if z.norm_sqr() > 4.0 {
            return Some(i);
        }
        z = z * z + c;
    }
```

```
        None
    }
```

This function takes the complex number `c` that we want to test for membership in the Mandelbrot set and a limit on the number of iterations to try before giving up and declaring `c` to probably be a member.

The function's return value is an `Option<usize>`. Rust's standard library defines the `Option` type as follows:

```
enum Option<T> {
    None,
    Some(T),
}
```

`Option` is an *enumerated type*, often called an *enum*, because its definition enumerates several variants that a value of this type could be: for any type `T`, a value of type `Option<T>` is either `Some(v)`, where `v` is a value of type `T`, or `None`, indicating no `T` value is available. Like the `Complex` type we discussed earlier, `Option` is a generic type: you can use `Option<T>` to represent an optional value of any type `T` you like.

In our case, `escape_time` returns an `Option<usize>` to indicate whether `c` is in the Mandelbrot set—and if it's not, how long we had to iterate to find that out. If `c` is not in the set, `escape_time` returns `Some(i)`, where `i` is the number of the iteration at which `z` left the circle of radius 2. Otherwise, `c` is apparently in the set, and `escape_time` returns `None`.

```
    for i in 0..limit {
```

The earlier examples showed `for` loops iterating over command-line arguments and vector elements; this `for` loop simply iterates over the range of integers starting with `0` and up to (but not including) `limit`.

The `z.norm_sqr()` method call returns the square of `z`'s distance from the origin. To decide whether `z` has left the circle of radius 2, instead of computing a square root, we just compare the squared distance with 4.0, which is faster.

You may have noticed that we use `///` to mark the comment lines above the function definition; the comments above the members of the `Complex` structure start with `///` as well. These are *documentation comments*; the `rustdoc` utility knows how to parse them, together with the code they describe, and produce online documentation. The documentation for Rust's standard library is written in this form. We describe documentation comments in detail in Chapter 8.

The rest of the program is concerned with deciding which portion of the set to plot at what resolution and distributing the work across several threads to speed up the calculation.

## Parsing Pair Command-Line Arguments

The program takes several command-line arguments controlling the resolution of the image we'll write and the portion of the Mandelbrot set the image shows.

Since these command-line arguments follow a common form, here's a function to parse them:

```
use std::str::FromStr;

/// Parses the string `s` as a coordinate pair, like `"400x600"`
or `"1.0,0.5"`.
///
/// Specifically, `s` should have the form <left><sep><right>,
where <sep> is
/// the character given by the `separator` argument, and <left>
and <right> are
/// both strings that can be parsed by `T::from_str`. `separator`
must be an
/// ASCII character.
///
/// If `s` has the proper form, this returns `Some<(x, y)>`. If
```

```
it doesn't parse
/// correctly, this returns `None`.
fn parse_pair<T: FromStr>(s: &str, separator: char) -> Option<(T,
T)> {
    match s.find(separator) {
        None => None,
        Some(index) => {
            match (T::from_str(&s[..index]), T::from_str(&s[index
+ 1..])) {
                (Ok(l), Ok(r)) => Some((l, r)),
                _ => None,
            }
        }
    }
}

#[test]
fn test_parse_pair() {
    assert_eq!(parse_pair::<i32>("",         ','), None);
    assert_eq!(parse_pair::<i32>("10,",      ','), None);
    assert_eq!(parse_pair::<i32>(",10",      ','), None);
    assert_eq!(parse_pair::<i32>("10,20",    ','), Some((10,
20)));
    assert_eq!(parse_pair::<i32>("10,20xy", ','), None);
    assert_eq!(parse_pair::<f64>("0.5x",     'x'), None);
    assert_eq!(parse_pair::<f64>("0.5x1.5", 'x'), Some((0.5,
1.5)));
}
```

The definition of `parse_pair` is a *generic function*:

```
fn parse_pair<T: FromStr>(s: &str, separator: char) -> Option<(T,
T)> {
```

You can read the clause `<T: FromStr>` aloud as, "For any type `T` that implements the `FromStr` trait...." This effectively lets us define an entire family of functions at once: `parse_pair::<i32>` is a function that parses pairs of `i32` values, `parse_pair::<f64>` parses pairs of floating-point values, and so on. This is very much like a function template in C++. A Rust programmer would call `T` a *type parameter* of `parse_pair`. When you use a generic function, Rust will often be able to

infer type parameters for you, and you won't need to write them out as we did in the test code.

Our return type is `Option<(T, T)>`: either `None` or a value `Some((v1, v2))`, where `(v1, v2)` is a tuple of two values, both of type `T`.

The `parse_pair` function doesn't use an explicit return statement, so its return value is the value of the last (and the only) expression in its body:

```
match s.find(separator) {
    None => None,
    Some(index) => {
        ...
    }
}
```

The `String` type's `find` method searches the string for a character that matches `separator`. If `find` returns `None`, meaning that the separator character doesn't occur in the string, the entire `match` expression evaluates to `None`, indicating that the parse failed.

Otherwise, we take `index` to be the separator's position in the string:

```
match (T::from_str(&s[..index]), T::from_str(&s[index + 1..])) {
    (Ok(l), Ok(r)) => Some((l, r)),
    _ => None,
}
```

This begins to show off the power of the `match` expression. The argument to the match is this tuple expression:

```
(T::from_str(&s[..index]), T::from_str(&s[index + 1..]))
```

The expressions `&s[..index]` and `&s[index + 1..]` are slices of the string, preceding and following the separator. The type parameter `T`'s associated `from_str` function takes each of these and tries to parse them

as a value of type `T`, producing a tuple of results. This is what we match against:

```
(Ok(l), Ok(r)) => Some((l, r)),
```

This pattern matches only if both `Results` are `Ok` variants, indicating that both parses succeeded. If so, `Some((l, r))` is the value of the match expression and hence the return value of the function.

```
_ => None
```

The wildcard pattern `_` matches anything and ignores its value. If we reach this point, then `parse_pair` has failed, so we evaluate to `None`, again providing the return value of the function.

Now that we have `parse_pair`, it's easy to write a function to parse a pair of floating-point coordinates and return them as a `Complex<f64>` value:

```
/// Parses a pair of floating-point numbers separated by a comma
as a
/// complex number.
fn parse_complex(s: &str) -> Option<Complex<f64>> {
    match parse_pair(s, ',') {
        Some((re, im)) => Some(Complex { re, im }),
        None => None,
    }
}

#[test]
fn test_parse_complex() {
    assert_eq!(
        parse_complex("1.25,-0.0625"),
        Some(Complex { re: 1.25, im: -0.0625 }),
    );
    assert_eq!(parse_complex(",-0.0625"), None);
}
```

The `parse_complex` function calls `parse_pair`, builds a `Complex` value if the coordinates were parsed successfully, and passes failures along

to its caller.

If you were reading closely, you may have noticed that we used a shorthand notation to build the `Complex` value. It's common to initialize a struct's fields with variables of the same name, so rather than forcing you to write `Complex { re: re, im: im }`, Rust lets you simply write `Complex { re, im }`. This is modeled on similar notations in JavaScript and Haskell.

## Mapping from Pixels to Complex Numbers

The program needs to work in two related coordinate spaces: each pixel in the output image corresponds to a point on the complex plane. The relationship between these two spaces depends on which portion of the Mandelbrot set we're going to plot and the resolution of the image requested, as determined by command-line arguments. The following function converts from *image space* to *complex number space*:

```
/// Computes the point on the complex plane that corresponds to a
given
/// pixel in the output image.
///
/// `bounds` is a pair giving the width and height of the image
in pixels.
/// `pixel` is a (column, row) pair indicating a particular pixel
in that image.
/// The `upper_left` and `lower_right` parameters are points on
the complex
/// plane designating the area our image covers.
fn pixel_to_point(
    bounds: (usize, usize),
    pixel: (usize, usize),
    upper_left: Complex<f64>,
    lower_right: Complex<f64>,
) -> Complex<f64> {
    let (width, height) = (
        lower_right.re - upper_left.re,
        upper_left.im - lower_right.im
    );
    Complex {
        re: upper_left.re + pixel.0 as f64 * width  / bounds.0 as
f64,
```

```
            im: upper_left.im - pixel.1 as f64 * height / bounds.1 as
f64,
            // Why subtraction here? pixel.1 increases as we go down,
            // but the imaginary component increases as we go up.
        }
    }

    #[test]
    fn test_pixel_to_point() {
        assert_eq!(
            pixel_to_point(
                (100, 200),
                (25, 175),
                Complex { re: -1.0, im: 1.0 },
                Complex { re: 1.0, im: -1.0 },
            ),
            Complex { re: -0.5, im: -0.75 },
        );
    }
```

Figure 2-4 illustrates the calculation `pixel_to_point` performs.

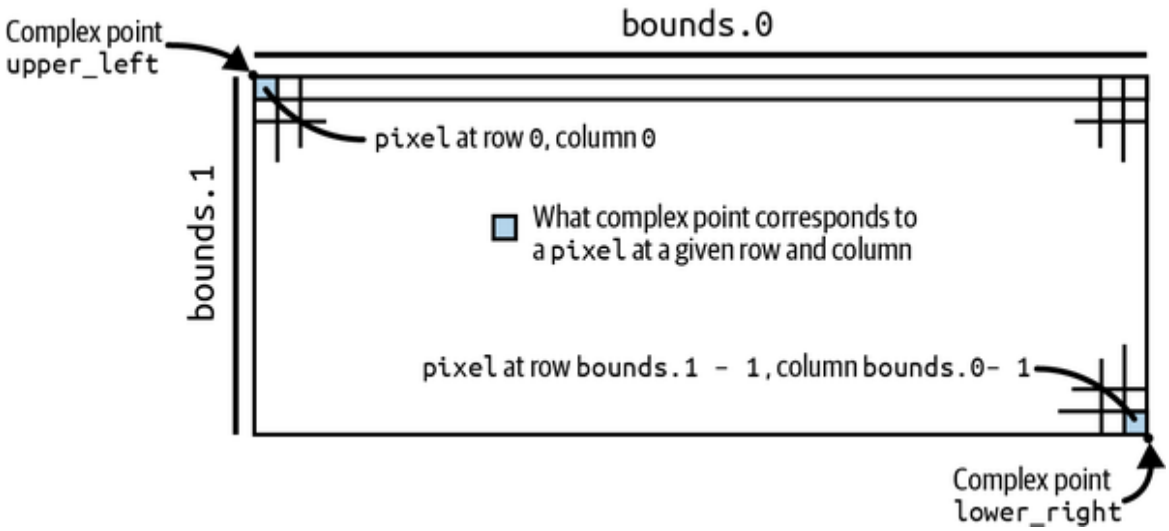


*Figure 2-4. The relationship between the complex plane and the image's pixels*

The code of `pixel_to_point` is simply calculation, so we won't explain it in detail. However, there are a few things to point out. Expressions with this form refer to tuple fields:

```
pixel.0
```

This refers to the first field of the tuple `pixel`.

```
pixel.0 as f64
```

This is Rust's syntax for a type conversion: this converts `pixel.0` to an `f64` value. Unlike C and C ++, Rust generally refuses to convert between numeric types implicitly; you must write out the conversions you need. This can be tedious, but being explicit about which conversions occur, and when, is surprisingly helpful. Implicit integer conversions seem innocent enough, but historically they have been a frequent source of bugs and security holes in real-world C and C++ code.

## Plotting the Set

To plot the Mandelbrot set, for every pixel in the image, we simply apply `escape_time` to the corresponding point on the complex plane and color the pixel depending on the result:

```
/// Renders a rectangle of the Mandelbrot set into a buffer of
pixels.
///
/// The `bounds` argument gives the width and height of the
buffer `pixels`,
/// which holds one grayscale pixel per byte. The `upper_left`
and `lower_right`
/// arguments specify points on the complex plane corresponding
to the upper-
/// left and lower-right corners of the pixel buffer.
fn render(
    pixels: &mut [u8],
    bounds: (usize, usize),
    upper_left: Complex<f64>,
    lower_right: Complex<f64>,
) {
    assert!(pixels.len() == bounds.0 * bounds.1);

    for row in 0..bounds.1 {
        for column in 0..bounds.0 {
            let point =
                pixel_to_point(bounds, (column, row), upper_left,
lower_right);
```

```
                pixels[row * bounds.0 + column] =
                    match escape_time(point, 255) {
                        None => 0,
                        Some(count) => 255 - count as u8,
                    };
            }
        }
    }
```

The type of the first argument, `pixels`, is `&mut [u8]`. In English, that's a mutable reference, `&mut`, to a slice of unsigned 8-bit integers, `[u8]`. Think of a *slice* as an array or vector; `pixels` will refer to a slab of contiguous memory, typically millions of `u8` bytes. We need a *mutable reference* to write to the buffer, since Rust references are read-only by default.

```
pixels[row * bounds.0 + column] =
    match escape_time(point, 255) {
        None => 0,
        Some(count) => 255 - count as u8,
    };
```

If `escape_time` says that `point` belongs to the set, `render` colors the corresponding pixel black (`0`). Otherwise, `render` assigns darker colors to the numbers that took longer to escape the circle.

## Writing Image Files

The `image` crate provides functions for reading and writing a wide variety of image formats, along with some basic image manipulation functions. In particular, it includes an encoder for the PNG image file format, which this program uses to save the final results of the calculation:

```
use image::{ExtendedColorType, ImageEncoder, ImageError};
use image::codecs::png::PngEncoder;
use std::fs::File;

/// Writes the buffer `pixels`, whose dimensions are given by
`bounds`, to the
/// file named `filename`.
```

```
fn write_image(
    filename: &str,
    pixels: &[u8],
    bounds: (usize, usize),
) -> Result<(), ImageError> {
    let output = File::create(filename)?;

    let encoder = PngEncoder::new(output);
    encoder.write_image(
        pixels,
        bounds.0 as u32,
        bounds.1 as u32,
        ExtendedColorType::L8,
    )?;

    Ok(())
}
```

The operation of this function is pretty straightforward: it opens a file and tries to write the image to it. The `write_image` method is provided by the `image::ImageEncoder` trait, which we import on the first line of the example. We pass the encoder the actual pixel data from `pixels`, pass its width and height from `bounds`, and then pass a final argument that says how to interpret the bytes in `pixels`. The value `ExtendedColorType::L8` indicates that each byte is an eight-bit grayscale value.

That's all simple enough. What's interesting about this function is how it copes when something goes wrong. If we encounter an error, we need to report that back to our caller. As we've mentioned, fallible functions in Rust should return a `Result` value, which is either `Ok(s)` on success, where `s` is the successful value, or `Err(e)` on failure, where `e` is an error code. So what are `write_image`'s success and error types?

When all goes well, our `write_image` function has no useful value to return; it wrote everything interesting to the file. So its success type is the *unit* type `()`, so called because it has only one value, also written `()`. The unit type is akin to `void` in C and C++.

When an error occurs, it's because either `File::create` wasn't able to create the file or `encoder.encode` wasn't able to write the image to it; the I/O operation returned an error code.

The return type of `File::create` is `Result<std::fs::File, std::io::Error>`, while that of `encoder.encode` is `Result<(), std::io::Error>`, so both share the same error type, `std::io::Error`. It makes sense for our `write_image` function to do the same. In either case, failure should result in an immediate return, passing along the `std::io::Error` value describing what went wrong.

One way to handle the `File::create` result would be to `match` on its return value, like this:

```
let output = match File::create(filename) {
    Ok(f) => f,
    Err(e) => {
        return Err(e);
    }
};
```

On success, let `output` be the `File` carried in the `Ok` value. On failure, pass the error along to our own caller.

This kind of `match` statement is such a common pattern in Rust that the language provides the `?` operator as shorthand for the whole thing.

So, rather than writing out this logic explicitly in `write_image`, we used the following equivalent and much more legible statement:

```
let output = File::create(filename)?;
```

If `File::create` fails, the `?` operator returns from `write_image`, passing along the error. Otherwise, `output` holds the successfully opened `File`.

## A Concurrent Mandelbrot Program

All the pieces are in place, and we can show you the `main` function, where we can put concurrency to work for us. First, a nonconcurrent version for simplicity:

```
use std::env;

fn main() {
    let args: Vec<String> = env::args().collect();

    if args.len() != 5 {
        let program = &args[0];
        eprintln!("Usage: {program} FILE PIXELS LEFT,TOP
RIGHT,BOTTOM");
        eprintln!("Example: {program} mandel.png 1000x750
-1.20,0.35 -1,0.20");
        std::process::exit(1);
    }

    let bounds: (usize, usize) = parse_pair(&args[2], 'x')
        .expect("error parsing image dimensions");
    let upper_left = parse_complex(&args[3])
        .expect("error parsing upper left corner point");
    let lower_right = parse_complex(&args[4])
        .expect("error parsing lower right corner point");

    let mut pixels = vec![0; bounds.0 * bounds.1];

    render(&mut pixels, bounds, upper_left, lower_right);

    write_image(&args[1], &pixels, bounds)
        .expect("error writing PNG file");
}
```

After collecting the command-line arguments into a vector of `Strings`, we parse each one and then begin calculations.

```
let mut pixels = vec![0; bounds.0 * bounds.1];
```

A macro call `vec![v; n]` creates a vector `n` elements long whose elements are initialized to `v`, so the preceding code creates a vector of zeros whose length is `bounds.0 * bounds.1`, where `bounds` is the image resolution parsed from the command line. We'll use this vector as a

rectangular array of one-byte grayscale pixel values, as shown in Figure 2-5.

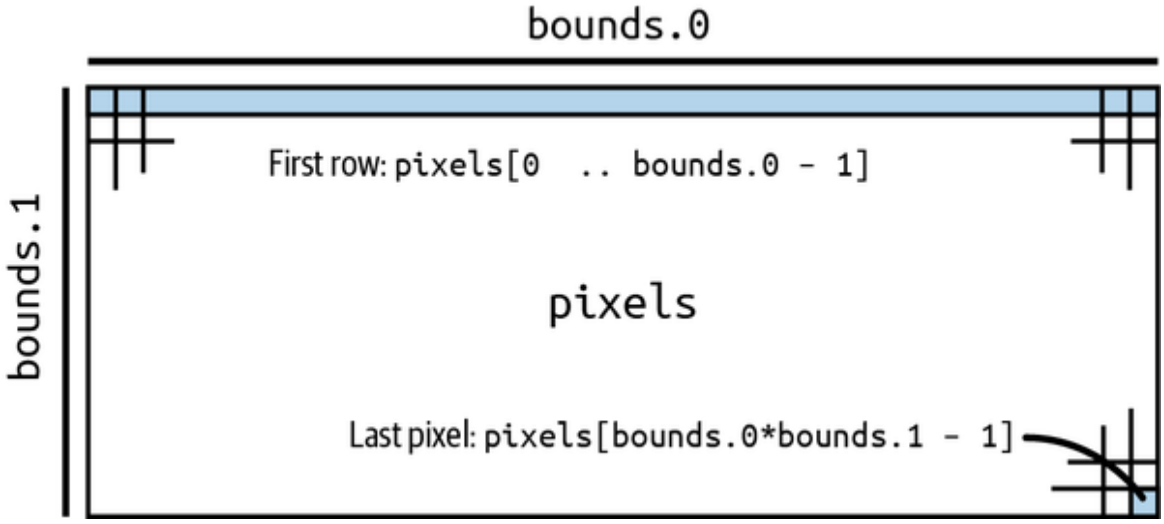


*Figure 2-5. Using a vector as a rectangular array of `pixels`*

The next line of interest is this:

```
render(&mut pixels, bounds, upper_left, lower_right);
```

This calls the `render` function to actually compute the image. The expression `&mut pixels` borrows a mutable reference to our pixel buffer, allowing `render` to fill it with computed grayscale values, even while `pixels` remains the vector's owner. The remaining arguments pass the image's dimensions and the rectangle of the complex plane we've chosen to plot.

```
write_image(&args[1], &pixels, bounds)
    .expect("error writing PNG file");
```

Finally, we write the pixel buffer out to disk as a PNG file. In this case, we pass a shared (nonmutable) reference to the buffer, since `write_image` should have no need to modify the buffer's contents.

At this point, we can build and run the program in release mode, which enables many powerful compiler optimizations, and after several seconds, it will write a beautiful image to the file *mandel.png*:

```
$ cargo build --release
    Updating crates.io index
   ...
   Compiling image v0.25.5
   Compiling mandelbrot v0.1.0 ($RUSTBOOK/mandelbrot)
    Finished `release` profile [optimized] target(s) in 25.36s
$ time target/release/mandelbrot mandel.png 4000x3000 -1.20,0.35
-1,0.20
real    0m4.678s
user    0m4.661s
sys     0m0.008s
```

On Windows, instead run this command in PowerShell: `measure-command { .\target\release\mandelbrot mandel.png 4000x3000 -1.20,0.35 -1,0.20 }`.

This command should create a file called *mandel.png*, which you can view with your system's image viewing program or in a web browser. If all has gone well, it should look like Figure 2-6.

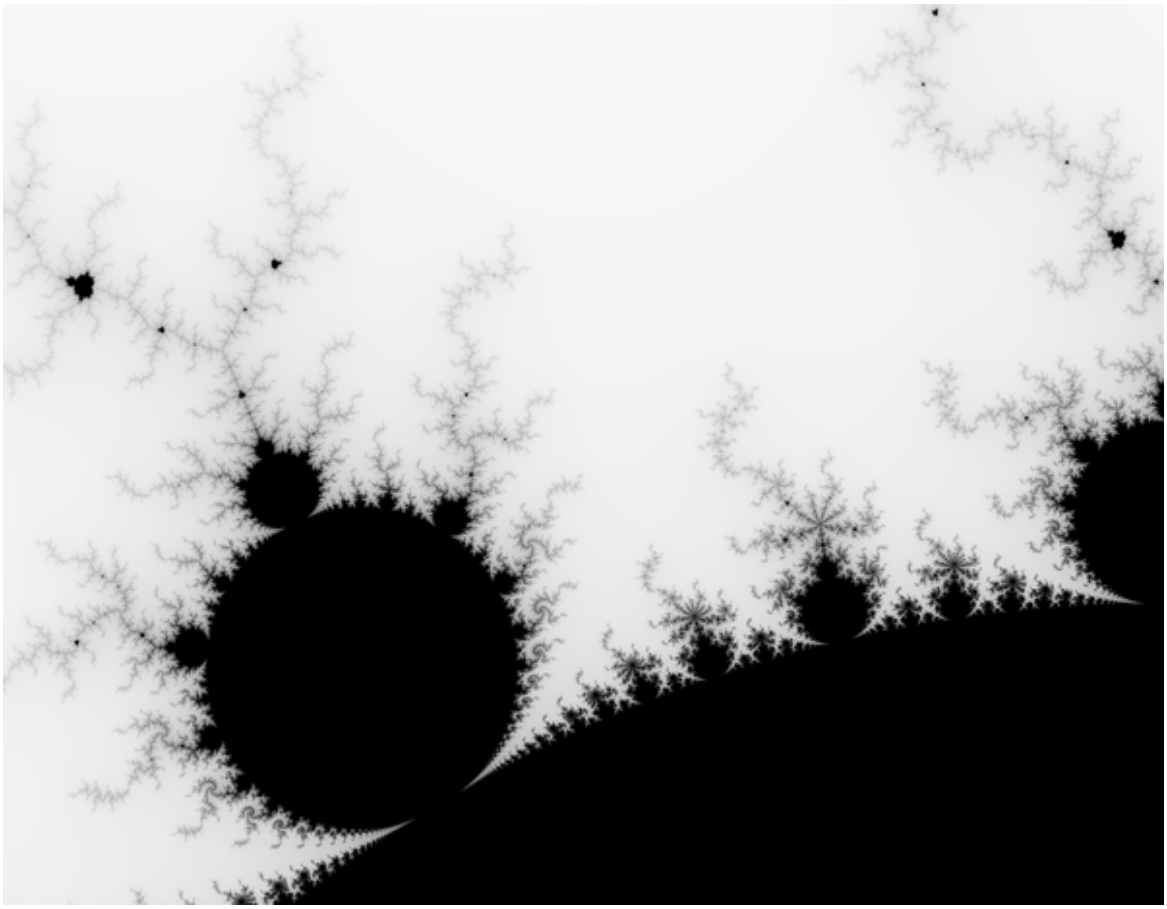

*Figure 2-6. Results from the Mandelbrot program*

In the previous transcript, we used the Unix `time` program to analyze the running time of the program: it took about five seconds total to run the Mandelbrot computation on each pixel of the image. But almost all modern machines have multiple processor cores, and this program used only one. If we could distribute the work across all the computing resources the machine has to offer, we should be able to complete the image much more quickly.

To this end, we'll divide the image into sections, one per processor, and let each processor color the pixels assigned to it. For simplicity, we'll break it into horizontal bands, as shown in Figure 2-7. When all processors have finished, we can write out the pixels to disk.

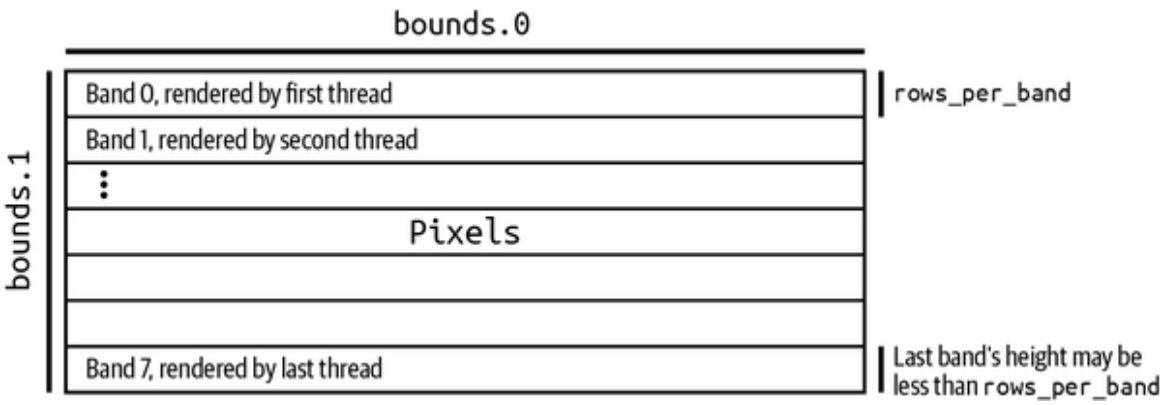


*Figure 2-7. Dividing the pixel buffer into bands for parallel rendering*

Rust offers a *scoped thread* facility that does exactly what we need here. To use it, we need to take out the single line calling `render` and replace it with the following:

```
let threads = std::thread::available_parallelism()
    .expect("error querying CPU count")
    .get();
let rows_per_band = bounds.1.div_ceil(threads);

let bands = pixels.chunks_mut(rows_per_band * bounds.0);
std::thread::scope(|spawner| {
    for (i, band) in bands.enumerate() {
        let top = rows_per_band * i;
        let height = band.len() / bounds.0;
        let band_bounds = (bounds.0, height);
        let band_upper_left =
            pixel_to_point(bounds, (0, top), upper_left,
lower_right);
        let band_lower_right =
            pixel_to_point(bounds, (bounds.0, top + height),
                           upper_left, lower_right);

        spawner.spawn(move || {
            render(band, band_bounds, band_upper_left,
band_lower_right);
        });
    }
});
```

Breaking this down in the usual way:

```
let threads = std::thread::available_parallelism()
    .expect("error querying CPU count")
    .get();
```

We start by asking the system how many threads we should create, using `std::thread::available_parallelism()`. This function returns a `Result<NonZero<usize>>`: either an error or an `Ok` value containing a `usize` that is guaranteed to be nonzero. We use `.expect()` to dispense with the error case and the `get` method of the `NonZero` type to convert it to a plain `usize`.

```
let rows_per_band = bounds.1.div_ceil(threads);
```

Next we compute how many rows of pixels each band should have. We divide the number of rows by the number of threads, rounding upward so that the bands will cover the entire image even if the height isn't a multiple of `threads`. Rust's numeric types provide dozens of methods, including `div_ceil` for integer division rounding up. In another language, we might write `(bounds.1 + threads - 1) / threads`, but calling `div_ceil` is shorter, more expressive, and just as fast. (The method is also correct in corner cases where the addition would overflow, although that's unlikely here!)

```
let bands = pixels.chunks_mut(rows_per_band * bounds.0);
```

Here we divide the pixel buffer into bands. The buffer's `chunks_mut` method returns an iterator producing mutable, nonoverlapping slices of the buffer, each of which encloses `rows_per_band * bounds.0` pixels—in other words, `rows_per_band` complete rows of pixels. The last slice that `chunks_mut` produces may contain fewer rows, but each row will contain the same number of pixels.

Now we can put some threads to work:

```
std::thread::scope(|spawner| {
    ...
```

```
    });
```

The argument `|spawner| { ... }` is a Rust closure that expects a single argument, `spawner`. Note that, unlike functions declared with `fn`, we don't need to declare the types of a closure's arguments; Rust will infer them, along with its return type. In this case, `std::thread::scope` calls the closure, passing as the `spawner` argument a value the closure can use to create new threads. The `std::thread::scope` function waits for all such threads to finish execution before returning itself. This behavior allows Rust to be sure that such threads will not access their portions of `pixels` after it has gone out of scope and allows us to be sure that when `std::thread::scope` returns, the computation of the image is complete.

```
    for (i, band) in bands.enumerate() {
```

Here we iterate over the pixel buffer's bands. Each band is a mutable slice of the image, providing exclusive access to one band, ensuring that only one thread can write to it at a time. We explain how this works in detail in Chapter 5. The `enumerate` adapter produces tuples pairing each vector element with its index.

```
        let top = rows_per_band * i;
        let height = band.len() / bounds.0;
        let band_bounds = (bounds.0, height);
        let band_upper_left =
            pixel_to_point(bounds, (0, top), upper_left, lower_right);
        let band_lower_right =
            pixel_to_point(bounds, (bounds.0, top + height),
                           upper_left, lower_right);
```

Given the index and the actual size of the band (recall that the last one might be shorter than the others), we can produce a bounding box of the sort `render` requires, but one that refers only to this band of the buffer, not the entire image. Similarly, we repurpose the renderer's

`pixel_to_point` function to find where the band's upper-left and lower-right corners fall on the complex plane.

```
    spawner.spawn(move || {
        render(band, band_bounds, band_upper_left, band_lower_right);
    });
```

Finally, we create a thread, running the closure `move || { ... }`. The `move` keyword at the front indicates that this closure takes ownership of the variables it uses; in particular, only the closure may use the mutable slice `band`.

As we mentioned earlier, the `std::thread::scope` call ensures that all threads have completed before it returns, meaning that it is safe to save the image to a file, which is our next action.

With all that in place, we can build and run the multithreaded program:

```
$ cargo build --release
   Compiling mandelbrot v0.1.0 ($RUSTBOOK/mandelbrot)
    Finished `release` profile [optimized] target(s) in #.## secs
$ time target/release/mandelbrot mandel.png 4000x3000 -1.20,0.35
-1,0.20
real    0m1.436s
user    0m4.922s
sys     0m0.011s
```

Here, we've used `time` again to see how long the program took to run; note that even though we still spent almost 5 seconds of processor time, the elapsed real time was only about 1.5 seconds. You can verify that a portion of that time is spent writing the image file by commenting out the code that does so and measuring again. On the laptop where this code was tested, the concurrent version reduces the Mandelbrot calculation time proper by a factor of almost four. We'll show how to substantially improve on this in Chapter 19.

As before, this program will have created a file called *mandel.png*. With this faster version, you can more easily explore the Mandelbrot set by changing the command-line arguments to your liking.

## Safety Is Invisible

In the end, the parallel program we ended up with is not substantially different from what we might write in any other language: we apportion pieces of the pixel buffer out among the processors, let each one work on its piece separately, and when they've all finished, present the result. So what is so special about Rust's concurrency support?

What we haven't shown here is all the Rust programs we *cannot* write. The code we looked at in this chapter partitions the buffer among the threads correctly, but there are many small variations on that code that do not (and thus introduce data races); not one of those variations will pass the Rust compiler's static checks. A C or C++ compiler will cheerfully help you explore the vast space of programs with subtle data races; Rust tells you, up front, when something could go wrong.

In Chapters 4 and 5, we'll describe Rust's rules for memory safety. Chapter 19 explains how these rules also ensure proper concurrency hygiene. But for those to make sense, it's essential to get a grounding in Rust's fundamental types, which we'll cover in the next chapter.

# Chapter 3. Fundamental Types

> *The first principles of the universe are atoms and empty space; everything else is merely thought to exist.*
>
> —Democritus

This chapter covers Rust's fundamental types for representing values: integer and floating-point numbers, strings and characters, vectors and arrays, and so on. These source-level types have concrete machine-level counterparts with predictable costs and performance.

Compared to a dynamically typed language like JavaScript or Python, Rust requires more planning from you up front. You must spell out the types of function arguments and return values, struct fields, and a few other constructs. For the rest, Rust's *type inference* will generally figure out the types for you. For example, you could spell out every type in a function, like this:

```
fn grade_cutoffs(tier_size: u32) -> Vec<u32> {
    let mut cutoffs: Vec<u32> = Vec::<u32>::new();
    for tier in 1u32..5u32 {
        cutoffs.push(100u32 - tier * tier_size);
    }
    cutoffs
}
```

But this is cluttered and repetitive. Given the function's return type, it's obvious that `cutoffs` must be a `Vec<u32>`, a vector of 32-bit signed integers; no other type would work. And from that it follows that each element of the vector must be a `u32`, and therefore all the numbers being multiplied and subtracted must be `u32` as well.

This is exactly the sort of reasoning Rust's type inference applies, allowing you to instead write:

```
fn grade_cutoffs(tier_size: u32) -> Vec<u32> {
    let mut cutoffs = Vec::new();
    for tier in 1..5 {
        cutoffs.push(100 - tier * tier_size);
    }
    cutoffs
}
```

These two definitions are exactly equivalent, and Rust will generate the same machine code either way. Type inference gives back much of the legibility of dynamically typed languages, while still catching type errors at compile time.

The rest of this chapter covers Rust's types from the bottom up. Table 3-1 offers a sample of the sorts of types you'll see in Rust. It shows Rust's primitive types, some very common types from the standard library, and some examples of user-defined types.

*Table 3-1. Examples of types in Rust*

| Type | Description | Values |
|---|---|---|
| `i8`, `i16`, `i32`, `i64`, `i128`<br>`u8`, `u16`, `u32`, `u64`, `u128` | Signed and unsigned integers, of given bit width | `42`, `-5i8`, `0x400u16`, `0o100i16`, `20_922_789_888_000u64`, `b'*'` (`u8` byte literal) |
| `isize`, `usize` | Signed and unsigned integers, the same size as an address on the machine (usually 64 bits) | `137`, `-0b0101_0010_isize`, `0xffff_fc00_usize` |
| `f32`, `f64` | IEEE floating-point numbers, single and double precision | `1.0`, `3.14159f32`, `6.0221e23` |
| `bool` | Boolean | `true`, `false` |
| `(char, u8, i32)` | Tuple: mixed types allowed | `('%', 0x7f, -1)` |
| `()` | “Unit” (empty tuple) | `()` |
| `struct S {`<br>`  x: f32,`<br>`  y: f32,`<br>`}` | Named-field struct | `S { x: 120.0, y: 209.0 }` |
| `struct T(i32, char);` | Tuple struct | `T(120, 'X')` |

| Type | Description | Values |
| --- | --- | --- |
| `struct E;` | Unit-like struct; has no fields | `E` |
| `enum Attend { OnTime, Late(u32) }` | Enumeration, algebraic data type | `Attend::Late(5)`, `Attend::OnTime` |
| `Box<Attend>` | Box: owning pointer to value in heap | `Box::new(Late(15))` |
| `&i32`, `&mut i32` | Shared and mutable references: non-owning pointers that must not outlive their referent | `&s.y`, `&mut v` |
| `String` | UTF-8 string, dynamically sized | `"ラーメン: ramen".to_string()` |
| `&str` | Reference to `str`: non-owning pointer to UTF-8 text | `"そば: soba"`, `&s[0..12]` |
| `char` | Unicode character, 32 bits wide | `'*'`, `'\n'`, `'字'`, `'\x7f'`, `'\u{CA0}'` |
| `[f64; 4]`, `[u8; 256]` | Array, fixed length; elements all of same type | `[1.0, 0.0, 0.0, 1.0]`, `[b' '; 256]` |

| Type | Description | Values |
| --- | --- | --- |
| `Vec<f64>` | Vector, varying length; elements all of same type | `vec![0.367, 2.718, 7.389]` |
| `&[u8]`, `&mut [u8]` | Reference to slice: reference to a portion of an array or vector, comprising pointer and length | `&v[10..20]`, `&mut a[..]` |
| `Option<&str>` | Optional value: either `None` (absent) or `Some(v)` (present, with value `v`) | `Some("Dr.")`, `None` |
| `Result<u64, Error>` | Result of operation that may fail: either a success value `Ok(v)`, or an error `Err(e)` | `Ok(4096)`, `Err(Error::last_os_error())` |
| `&dyn Error`, `&mut dyn Read` | Reference to trait object: any value that implements a given set of methods | `&err as &dyn Error`, `&mut file as &mut dyn Read` |
| `fn(&str) -> bool` | Function pointer | `str::is_empty` |
| (Closure types have no written form) | Closure | `\|a, b\| { a*a + b*b }` |

Most of these types are covered in this chapter, except for the following:

- We give `struct` types their own chapter, Chapter 9.
- We give enumerated types their own chapter, Chapter 10.
- We describe trait objects in Chapter 11.
- We describe essentials of `String` and `&str` here but provide details in Chapter 17.
- We cover function and closure types in Chapter 14.

## Numeric Types

The foundation of Rust's type system is a collection of fixed-width numeric types, chosen to match the types that almost all modern processors implement directly in hardware. Fixed-width numeric types can overflow or lose precision, but they are adequate for most applications and can be thousands of times faster than representations like arbitrary-precision integers and exact rationals. If you need those sorts of numeric representations, they are available in the `num` crate.

The names of Rust's numeric types follow a regular pattern, spelling out their width in bits and the representation they use (Table 3-2).

*Table 3-2. Rust numeric types*

| Size (bits) | Unsigned integer | Signed integer | Floating point |
|---|---|---|---|
| 8 | `u8` | `i8` | |
| 16 | `u16` | `i16` | |
| 32 | `u32` | `i32` | `f32` |
| 64 | `u64` | `i64` | `f64` |
| 128 | `u128` | `i128` | |
| Machine word | `usize` | `isize` | |

Here, a *machine word* is a value the size of an address on the machine the code runs on: 32 or 64 bits.

## Integer Types

Rust's unsigned integer types use their full range to represent positive values and zero (Table 3-3).

*Table 3-3. Rust unsigned integer types*

| Type | Range |
|---|---|
| `u8` | 0 to $2^8$–1 (0 to 255) |
| `u16` | 0 to $2^{16}$–1 (0 to 65,535) |
| `u32` | 0 to $2^{32}$–1 (0 to 4,294,967,295) |
| `u64` | 0 to $2^{64}$–1 (0 to 18,446,744,073,709,551,615, or 18 quintillion) |
| `u128` | 0 to $2^{128}$–1 (0 to around $3.4\times10^{38}$) |
| `usize` | 0 to either $2^{32}$–1 or $2^{64}$–1 |

Rust's signed integer types use the two's complement representation, using the same bit patterns as the corresponding unsigned type to cover a range of positive and negative values (Table 3-4).

*Table 3-4. Rust signed integer types*

| Type | Range |
|---|---|
| `i8` | $-2^7$ to $2^7-1$ (–128 to 127) |
| `i16` | $-2^{15}$ to $2^{15}-1$ (–32,768 to 32,767) |
| `i32` | $-2^{31}$ to $2^{31}-1$ (–2,147,483,648 to 2,147,483,647) |
| `i64` | $-2^{63}$ to $2^{63}-1$ (–9,223,372,036,854,775,808 to 9,223,372,036,854,775,807) |
| `i128` | $-2^{127}$ to $2^{127}-1$ (roughly $-1.7\times10^{38}$ to $+1.7\times10^{38}$) |
| `isize` | Either $-2^{31}$ to $2^{31}-1$, or $-2^{63}$ to $2^{63}-1$ |

Rust uses the `u8` type for byte values. For example, reading data from a binary file or socket yields a stream of `u8` values.

C/C++ programmers should note that there is no single "character" type used for both text and binary data in Rust. As we'll see when we discuss strings and characters later in this chapter, Rust's `char` type is a Unicode character type, not an integer type, and is quite different from C's `char`.

The `usize` and `isize` types are analogous to `size_t` and `ptrdiff_t` in C and C++. Their precision matches the size of the address space on the target machine: they are 32 bits long on 32-bit architectures, and 64 bits long on 64-bit architectures. Rust requires array indices to be `usize` values. Values representing the sizes of arrays or vectors or counts of the number of elements in some data structure also generally have the `usize` type.

Integer literals in Rust can take a suffix indicating their type: `42u8` is a `u8` value, and `1729isize` is an `isize`. If an integer literal lacks a type

suffix, Rust puts off determining its type until it finds the value being used in a way that pins it down: stored in a variable of a particular type, passed to a function that expects a particular type, compared with another value of a particular type, or something like that. If the code provides no such clues, Rust defaults to `i32`.

The prefixes `0x`, `0o`, and `0b` designate hexadecimal, octal, and binary literals.

To make long numbers more legible, you can insert underscores among the digits. For example, you can write the largest `u32` value as `4_294_967_295`. The exact placement of the underscores is not significant, so you can break hexadecimal or binary numbers into groups of four digits rather than three, as in `0xffff_ffff`, or set off the type suffix from the digits, as in `127_u8`.

You can convert from one integer type to another using the `as` operator:

```
assert_eq!(10_i8 as u16, 10_u16);
assert_eq!(0xcafedad_u64 as u8, 0xad_u8);  // value too big for
u8, truncated
```

The standard library provides some operations as methods on integers. For example:

```
assert_eq!(2_u16.pow(4), 16);               // exponentiation
assert_eq!((-4_i32).abs(), 4);              // absolute value
assert_eq!(0b101101_u8.count_ones(), 4);    // population count
assert_eq!(12_i32.max(37), 37);             // maximum of two
values
```

There are dozens of these. You can find them in the online documentation under “Primitive Type `i32`” and friends.

In real code, you usually won’t need to write out the type suffixes as we’ve done here, because the context will determine the type. When it doesn’t, however, the error messages can be surprising.

For example, the following doesn’t compile:

```
println!("{}", (-4).abs());
```

Rust complains:

```
error: can't call method `abs` on ambiguous numeric type
`{integer}`
```

In cases like this where the type of an integer is unclear, Rust usually defaults to `i32`. In the particular case where we're calling a method, though, it's an error. Rust always needs to know the type of a value before looking up its methods. The solution is to spell out which type you intend, either with a suffix or by using a specific type's function:

```
println!("{}", (-4_i32).abs());
println!("{}", i32::abs(-4));
```

Note that method calls have a higher precedence than unary prefix operators, so be careful when applying methods to negated values. Without the parentheses around `-4_i32` in the first statement, `-4_i32.abs()` would apply the `abs` method to the positive value `4`, producing positive `4`, and then negate that, producing `-4`.

## Handling Integer Overflow

Integer arithmetic can *overflow*, producing results that are outside the range of Rust's integer types.

For example, the following function has a surprising bug:

```
fn midpoint(lo: i32, hi: i32) -> i32 {
    (lo + hi) / 2
}

// panic: attempt to add with overflow (in debug builds only!)
let m = midpoint(7, i32::MAX);
```

The `midpoint` function looks about right, but when called with large enough arguments, `(lo + hi)` produces a result that is outside of `i32`'s

range. In Java, that would “wrap around” to a negative number instead. The function would then divide that by two and return an incorrect result. In C or C++, integer overflow is undefined behavior.

In Rust, debug builds check the addition and panic on overflow, giving you a chance to notice and fix the problem. (In this case, you could cast the arguments to `i64`, do the math, and cast the result back to `i32`; or just use the built-in method `lo.midpoint(hi)`.) In release builds, for speed, the checks are disabled by default, and integer arithmetic wraps around, as in Java.

This conditional behavior isn’t always ideal, so the integer types provide methods that let you spell out exactly what you want. These integer arithmetic methods fall into five general categories:

- *Wrapping* operations return the value equivalent to the mathematically correct result modulo the range of the value:

  ```
  // The first product can be represented as a u16;
  // the second cannot, so we get 250000 modulo 2¹⁶.
  assert_eq!(100_u16.wrapping_mul(200), 20000);
  assert_eq!(500_u16.wrapping_mul(500), 53392);

  // Operations on signed types may wrap to negative
  values.
  assert_eq!(500_i16.wrapping_mul(500), -12144);
  ```

  This is exactly how the `*` operator behaves in release builds. The advantage of the `wrapping` methods is that they behave the same way in all builds.

- *Strict* operations provide the debug-mode behavior in all builds. They always panic on overflow:

  ```
  let x = usize::MAX.strict_mul(2);  // panic (in all
  builds)
  ```

- *Checked* operations return an `Option` of the result: `Some(v)` if the mathematically correct result can be represented as a value of that type, or `None` if it cannot. For example:

```
// The sum 10 + 20 fits in a u8, but 100 + 200 doesn't.
assert_eq!(10_u8.checked_add(20), Some(30));
assert_eq!(100_u8.checked_add(200), None);

// Oddly, signed division can overflow too, in one
particular case.
// A signed n-bit type can represent -2ⁿ⁻¹, but not 2ⁿ⁻¹.
assert_eq!((-128_i8).checked_div(-1), None);
```

- *Saturating* operations return the representable value that is closest to the mathematically correct result. In other words, the result is "clamped" to the maximum and minimum values the type can represent:

  ```
  assert_eq!(32760_i16.saturating_add(10), 32767);
  assert_eq!((-32760_i16).saturating_sub(10), -32768);
  ```

- *Overflowing* operations return a tuple `(result, overflowed)`, where `result` is what the wrapping version of the function would return, and `overflowed` is a `bool` indicating whether an overflow occurred:

  ```
  assert_eq!(255_u8.overflowing_sub(2), (253, false));
  assert_eq!(255_u8.overflowing_add(2), (1, true));
  ```

The bit-shifting operations `shl` (shift left, <<) and `shr` (shift right, >>) deviate from the pattern. For these operations it is the shift distance, not the result, that can be out of range (again causing undefined behavior in C++). So the "checking," "wrapping," or "overflowing" for these methods applies to the shift distance argument:

```
assert_eq!(10_u64.wrapping_shl(65), 20);
assert_eq!(10_u64.checked_shr(65), None);
```

## Floating-Point Types

Rust provides the usual single- and double-precision floating-point types (Table 3-5). Rust's `f32` and `f64` correspond to the `float` and `double` types in C/C++ and Java, or `float32` and `float64` in Go. Both types follow the IEEE 754 floating-point standard. They include positive and

negative infinities, distinct positive and negative zero values, and a *not-a-number* value.

*Table 3-5. Floating-point types*

| Type | Precision | Range |
|---|---|---|
| `f32` | IEEE single precision (at least 6 decimal digits) | Roughly $\pm 3.4 \times 10^{38}$ |
| `f64` | IEEE double precision (at least 15 decimal digits) | Roughly $\pm 1.8 \times 10^{308}$ |

Floating-point literals have the general form diagrammed in Figure 3-1.

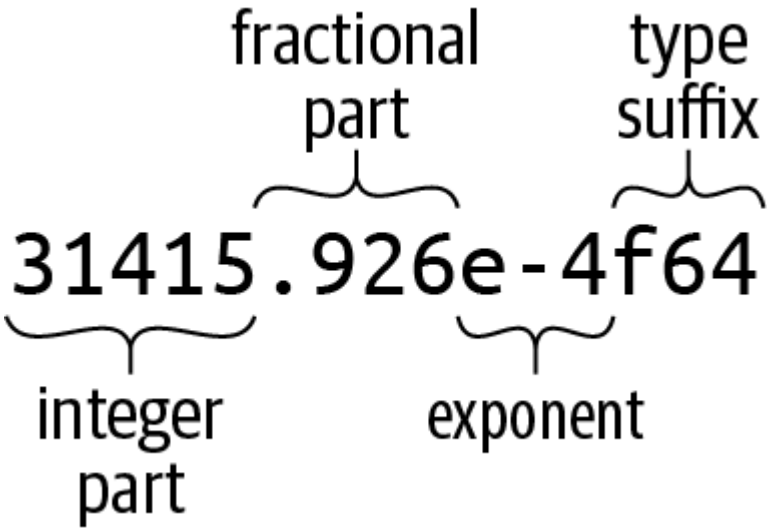


*Figure 3-1. A floating-point literal*

Every part of a floating-point number after the integer part is optional, but at least one of the fractional part, exponent, or type suffix must be present to distinguish it from an integer literal. Rust never assigns a floating-point type to a integer literal, or vice versa.

The fractional part may consist of a lone decimal point, so `5.` is a valid floating-point constant.

If a floating-point literal lacks a type suffix, Rust checks the context to see how the value is used, much as it does for integer literals. The default is `f64`.

The types `f32` and `f64` have associated constants for the IEEE-required special values like `INFINITY`, `NEG_INFINITY` (negative infinity), `NAN` (the not-a-number value), and `MIN` and `MAX` (the largest and smallest finite values):

```
assert!((-1. / f32::INFINITY).is_sign_negative());
assert_eq!(-f32::MIN, f32::MAX);
```

The `f32` and `f64` types provide a full complement of methods for mathematical calculations; for example, `2f64.sqrt()` is the double-precision square root of two. Some examples include:

```
assert_eq!(5f32.sqrt() * 5f32.sqrt(), 5.);  // exactly 5.0, per
IEEE
assert_eq!((-1.01f64).floor(), -2.0);
```

These methods are documented under "Primitive Type `f32`" and "Primitive Type `f64`." The separate modules `std::f32::consts` and `std::f64::consts` provide various commonly used mathematical constants like `E`, `PI`, and the square root of two. As with integers, you usually won't need to write out type suffixes on floating-point literals in real code, but when you do, putting a type on either the literal or the function will suffice:

```
println!("{}", (2.0_f64).sqrt());
println!("{}", f64::sqrt(2.0));
```

Unlike C and C++, Rust does not perform numeric conversions implicitly. If a function expects an `f64` argument, it's an error to pass an `i32` value as the argument. In fact, Rust won't even implicitly convert an `i16` value to an `i32` value, even though every `i16` value is in the range of `i32`. But you

can always write out *explicit* conversions using the `as` operator: `i as f64`, or `x as i32`.

The lack of implicit conversions sometimes makes a Rust expression more verbose than the analogous C or C++ code would be. However, implicit integer conversions have a well-established record of causing bugs and security holes, especially when the integers in question represent the size of something in memory and an unanticipated overflow occurs. In our experience, the act of writing out numeric conversions in Rust has alerted us to problems we would otherwise have missed. We explain exactly how conversions behave in "Type Casts".

## The bool Type

Rust's Boolean type, `bool`, has the usual two values for such types, `true` and `false`. Comparison operators like == and < produce `bool` results: the value of `2 < 5` is `true`.

Many languages are lenient about using values of other types in contexts that require a Boolean value: C and C++ implicitly convert characters, integers, floating-point numbers, and pointers to Boolean values, so they can be used directly as the condition in an `if` or `while` statement. Python and JavaScript permit any value at all in an `if` condition, with language-specific rules to determine which values are treated as `true` there and which are `false`. Rust, however, is very strict: control structures like `if` and `while` require their conditions to be `bool` expressions, as do the short-circuiting logical operators `&&` and `||`. You must write `if x != 0 { ... }`, not simply `if x { ... }`.

Rust's `as` operator can convert `bool` values to integer types:

```
assert_eq!(false as i32, 0);
assert_eq!(true  as i32, 1);
```

However, `as` won't convert in the other direction, from numeric types to `bool`. Instead, you must write out an explicit comparison like `x != 0`.

Although a `bool` needs only a single bit to represent it, Rust uses an entire byte for a `bool` value in memory, so you can create a pointer to it.

## Tuples

A *tuple* is a pair, or triple, quadruple, quintuple, etc. (hence, *n-tuple*, or *tuple*), of values of assorted types. You can write a tuple as a sequence of values, separated by commas and surrounded by parentheses. For example, `(1984_i32, false)` is a tuple whose first field is an integer and whose second is a boolean; its type is `(i32, bool)`. Given a tuple value `t`, you can access its fields as `t.0`, `t.1`, and so on.

Tuples are very different from arrays. For one thing, each field of a tuple can have a different type, whereas an array's elements must all be the same type. Further, while accessing elements by a variable index, `arr[i]`, is practically the defining feature of arrays, there is no way to do this with a tuple. You can access a field by its numeric "name", `t.1`, but you can't write `t.i` or `t[i]` to get the `i`th field.

Rust code often uses tuple types to return multiple values from a function. For example, the `split_at` method on string slices, which divides a string into two halves and returns them both, is declared like this:

```
fn split_at(&self, mid: usize) -> (&str, &str);
```

The return type `(&str, &str)` is a tuple of two string slices. You can use pattern-matching syntax to assign each field of the return value to a different variable:

```
let text = "I see the eigenvalue in thine eye";
let (head, tail) = text.split_at(21);
assert_eq!(head, "I see the eigenvalue ");
assert_eq!(tail, "in thine eye");
```

This is more legible than the equivalent:

```
let text = "I see the eigenvalue in thine eye";
let temp = text.split_at(21);
let head = temp.0;
let tail = temp.1;
assert_eq!(head, "I see the eigenvalue ");
assert_eq!(tail, "in thine eye");
```

You'll also see tuples used as a sort of minimal-drama struct type. For example, in the Mandelbrot program in Chapter 2, we needed to pass the width and height of the image to the functions that plot it and write it to disk. We could declare a struct with `width` and `height` members, but that's pretty heavy notation for something so obvious, so we just used a tuple:

```
/// Writes the buffer `pixels`, whose dimensions are given by
`bounds`, to the
/// file named `filename`.
fn write_image(
    filename: &str,
    pixels: &[u8],
    bounds: (usize, usize),
) -> Result<(), std::io::Error> {
    ...
}
```

The type of the `bounds` parameter is `(usize, usize)`, a tuple of two `usize` values. Admittedly, we could just as well write out separate `width` and `height` parameters, and the machine code would be about the same either way. It's a matter of clarity. We think of the size as one value, not two, and using a tuple lets us write what we mean.

The other commonly used tuple type is the zero-tuple `()`. This is traditionally called the *unit type* because it has only one value, also written `()`. Rust uses the unit type where there's no meaningful value to carry, but context requires some sort of type nonetheless.

For example, a function that returns no value has a return type of `()`. The standard library's `std::thread::sleep` function has no meaningful

value to return; it just pauses the program for a while. The declaration for `std::thread::sleep` reads:

```
fn sleep(duration: Duration);
```

The signature omits the function's return type altogether, which is shorthand for returning the unit type:

```
fn sleep(duration: Duration) -> ();
```

Similarly, the `write_image` example we mentioned before has a return type of `Result<(), std::io::Error>`, meaning that the function returns a `std::io::Error` value if something goes wrong but returns no value on success.

## Pointer Types

Rust has several types that represent memory addresses.

This is unusual in modern programming languages for two reasons. First, in many languages, values do not nest. In Java, for example, if `class Rectangle` contains a field `Vector2D upperLeft;`, then `upperLeft` is a reference to another separately created `Vector2D` object. Objects never physically contain other objects in Java. The language doesn't need pointer types because every Java object type is implicitly a pointer type.

Rust is different. The language is designed to help keep allocations to a minimum, so values nest by default. The value `((0, 0), (1440, 900))` is stored as four adjacent integers. If you store it in a local variable, you've got a local variable four integers wide. Nothing is allocated in the heap. This is great for memory efficiency, but as a consequence, whenever a Rust program needs one value to point to another, it must say so by using a pointer type explicitly.

The second reason Rust needs several pointer types is that there's no garbage collector to manage memory for us. It turns out memory still needs to be managed. Rust programs must decide when to allocate memory, how much to allocate, and when it's safe to deallocate it. In Rust, these memory management policies are written out in the pointer types themselves. Here are some Rust pointer types and the policies they represent. Don't worry if this is a bit bewildering at first; we explain all of these types fully in later chapters.

`&T` *and* `&mut T`

We showed a few examples of references already in Chapter 2. References refer to "borrowed" values without taking on any responsibility for cleanup. Therefore, references have no memory management overhead at all.

`Box<T>`

This is a pointer type that points to a value of type `T` stored in the heap. Memory is allocated when the program calls `Box::new(value)`. When the box is "dropped"—for example, when the variable holding the box goes out of scope—the memory is freed. Boxes are not needed every day, but they're the most basic way to override the default nesting of values, which is occasionally useful.

`std::rc::Rc<T>` *and* `std::sync::Arc<T>`

These are Rust's support for reference counting. Unlike `Box<T>` pointers, multiple `Rc<T>` pointers can point to the same heap-allocated `T`. This is useful when, say, multiple parts of a program all need access to a shared component. Rust tracks how many `Rc`s point to each shared value. The memory for the `T` is freed when the last `Rc` pointing to it is

dropped. `Arc<T>` is the same, but it uses an atomic reference count, so `Arc`s can be shared across multiple threads.

`*const T` *and* `*mut T`

These are Rust's raw pointer types, the equivalent of C pointers. They can be dereferenced only in `unsafe` blocks, code that explicitly opts out of Rust's safety guarantees. Raw pointers can be necessary when calling into a C library, or behind the scenes when implementing a new kind of data structure from scratch. We won't discuss them again until Chapter 23.

All of these types point to a value of type `T`; they differ only in memory management strategies and corresponding rules about mutability and thread safety.

Java doesn't need all this variety: the garbage collector provides a convenient, one-size-fits-all strategy for managing memory. C++ programmers, however, will recognize these as *smart pointer* types, similar to those in the C++ standard library: `Box<T>` is like C++'s `std::unique_ptr<T>`, and `Arc<T>` is like C++'s `std::shared_ptr<T>`.

Except for raw pointers, Rust pointer types are non-nullable. Use `Option` for optional pointers, with `None` representing `null`. There's no extra memory cost; an `Option<&T>` is the same size as a `&T`.

## Arrays, Vectors, and Slices

Rust has three types for representing a sequence of values in memory:

- The type `Vec<T>`, called a *vector of `T`s*, is a dynamically allocated, growable sequence of values of type `T`. A vector's

elements live in the heap, so you can resize vectors at will: push new elements onto them, append other vectors to them, delete elements, and so on.

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- The types `&[T]` and `&mut [T]` are reference types that refer to a *slice*, a contiguous subsequence, of a vector or array's elements.

Given a value `v` of any of these three types, the expression `v.len()` gives the number of elements in `v`, and `v[i]` refers to the `i`th element of `v`. The first element is `v[0]`, and the last element is `v[v.len() - 1]`. Rust checks that `i` always falls within this range; if it doesn't, the expression panics. The length of `v` may be zero, in which case any attempt to index it will panic. `i` must be a `usize` value; you can't use any other integer type as an index.

## Arrays

There are several ways to write array values. The simplest is to write a series of values within square brackets:

```
let lazy_caterer: [u32; 6] = [1, 2, 4, 7, 11, 16];
let taxonomy = ["Animalia", "Arthropoda", "Insecta"];

assert_eq!(lazy_caterer[3], 7);
assert_eq!(taxonomy.len(), 3);
```

For the common case of a long array filled with some value, you can write `[V; N]`, where *`V`* is the value each element should have, and *`N`* is the length.

For example, `[true; 10000]` is an array of 10,000 `bool` elements, all set to `true`:

```
let mut sieve = [true; 10000];
for i in 2..100 {
    if sieve[i] {
        let mut j = i * i;
        while j < 10000 {
            sieve[j] = false;
            j += i;
        }
    }
}

assert!(sieve[211]);
assert!(!sieve[9876]);
```

You'll see this syntax used for fixed-size buffers: `[0u8; 1024]` is a one-kilobyte buffer, filled with zeros. Rust has no notation for an uninitialized array. (In general, Rust ensures that code can never access uninitialized memory.)

An array's length is part of its type, fixed at compile time. If `n` is a variable, you can't write `[true; n]` to get an array of `n` elements. You might think, in light of this severe limitation, that arrays don't sound very useful. For most use cases, you'd be right! Arrays are efficient: small arrays can be stored on the stack or inside a struct without allocating more heap memory. An array of 8 bytes can fit in a single machine register! But in day-to-day programming, most lists have a variable length. For that, you need a vector.

## Vectors

A vector `Vec<T>` is a resizable array of elements of type `T`, allocated in the heap.

There are several ways to create vectors. The simplest is to use the `vec!` macro, which gives us a syntax for vectors that looks very much like an array literal:

```
let mut primes = vec![2, 3, 5, 7];
assert_eq!(primes.iter().product::<i32>(), 210);
```

But of course, this is a vector, not an array, so we can add elements to it dynamically:

```
primes.push(11);
primes.push(13);
assert_eq!(primes.iter().product::<i32>(), 30030);
```

You can also build a vector by repeating a given value a certain number of times, again using a syntax that imitates array literals:

```
fn new_pixel_buffer(rows: usize, cols: usize) -> Vec<u8> {
    vec![0; rows * cols]
}
```

The `vec!` macro is equivalent to calling `Vec::new` to create a new, empty vector and then pushing the elements onto it:

```
let mut pal = Vec::new();
pal.push("step");
pal.push("on");
pal.push("no");
pal.push("pets");
assert_eq!(pal, vec!["step", "on", "no", "pets"]);
```

Another possibility is to build a vector from the values produced by an iterator:

```
let v: Vec<i32> = (0..5).collect();
assert_eq!(v, [0, 1, 2, 3, 4]);
```

You'll often need to supply the type when using `collect` (as we've done here), because it can build many different sorts of collections, not just vectors. By specifying the type of `v`, we've made it unambiguous which sort of collection we want.

`Vec` is an essential type in Rust—it's used almost anywhere one needs a list of dynamic size—so there are many other methods that construct new vectors or extend existing ones. We'll cover them in Chapter 16.

A `Vec<T>` consists of three values: a pointer to the heap-allocated buffer for the elements, which is created and owned by the `Vec<T>`; the number of elements that buffer has the capacity to store; and the number it actually contains now (in other words, its length). When the buffer has reached its capacity, adding another element to the vector entails allocating a larger buffer, copying the present contents into it, updating the vector's pointer and capacity to describe the new buffer, and finally freeing the old one.

If you know the number of elements a vector will need in advance, instead of `Vec::new`, you can call `Vec::with_capacity` to create a vector with a buffer large enough to hold them all, right from the start; then, you can add the elements to the vector one at a time without causing reallocation. The `vec!` macro uses a trick like this, since it knows how many elements the final vector will have. Note this only establishes the vector's initial size; if you exceed your estimate, the vector simply enlarges its storage as usual.

Many library functions look for the opportunity to use `Vec::with_capacity` instead of `Vec::new`. For example, in the `collect` example, the iterator `0..5` knows in advance that it will yield five values, and the `collect` function takes advantage of this to pre-allocate the vector it returns with the correct capacity. We'll see how this works in Chapter 15.

Just as a vector's `len` method returns the number of elements it contains now, its `capacity` method returns the number of elements it could hold without reallocation:

```
let mut v = Vec::with_capacity(2);
assert_eq!(v.len(), 0);
assert_eq!(v.capacity(), 2);

v.push(1);
v.push(2);
```

```
assert_eq!(v.len(), 2);
assert_eq!(v.capacity(), 2);

v.push(3);
assert_eq!(v.len(), 3);
// Typically prints "capacity is now 4":
println!("capacity is now {}", v.capacity());
```

The capacity printed at the end isn't guaranteed to be exactly 4, but it will be at least 3, since the vector is holding three values.

You can insert and remove elements wherever you like in a vector, although these operations shift all the elements after the affected position forward or backward, so they may be slow if the vector is long:

```
let mut v = vec![10, 20, 30, 40, 50];

// Make the element at index 3 be 35.
v.insert(3, 35);
assert_eq!(v, [10, 20, 30, 35, 40, 50]);

// Remove the element at index 1.
v.remove(1);
assert_eq!(v, [10, 30, 35, 40, 50]);
```

You can use the `pop` method to remove the last element and return it. More precisely, popping a value from a `Vec<T>` returns an `Option<T>`: `None` if the vector was already empty, or `Some(v)` if its last element was `v`:

```
let mut v = vec!["Snow Puff", "Glass Gem"];
assert_eq!(v.pop(), Some("Glass Gem"));
assert_eq!(v.pop(), Some("Snow Puff"));
assert_eq!(v.pop(), None);
```

You can use a `for` loop to iterate over a vector:

```
// Get our command-line arguments as a vector of Strings.
let languages: Vec<String> = std::env::args().skip(1).collect();
for l in languages {
    println!(
        "{l}: {}",
        if l.len() % 2 == 0 {
```

```
            "functional"
        } else {
            "imperative"
        },
    );
}
```

Running this program with a list of programming languages is illuminating:

```
$ cargo run Lisp Scheme C C++ Fortran
   Compiling proglangs v0.1.0 (/home/jimb/rust/proglangs)
    Finished dev [unoptimized + debuginfo] target(s) in 0.36s
     Running `target/debug/proglangs Lisp Scheme C C++ Fortran`
Lisp: functional
Scheme: functional
C: imperative
C++: imperative
Fortran: imperative
$
```

Finally, a satisfying definition for the term *functional language*. Despite its fundamental role, `Vec` is an ordinary type defined in Rust, not built into the language. We'll cover the techniques needed to implement such types in Chapter 23.

## Slices

A slice, written `[T]` without specifying the length, is a region of an array or vector. Since a slice can be any length, slices can't be stored directly in variables or passed as function arguments. They are always passed by reference. This being the case, it's extremely common to refer to references of type `&[T]` as "slices," using the shorter name for the more common concept. We'll do the same later, but in this section, we'll call values of type `&[T]` "slice references" to avoid ambiguity.

A slice reference is a *fat pointer*: a two-word value comprising a pointer to the slice's first element, and the number of elements in the slice.

Suppose you run the following code:

```
let v: Vec<f64> = vec![0.0,  0.707,  1.0,  0.707];
let a: [f64; 4] =     [0.0, -0.707, -1.0, -0.707];

let sv: &[f64] = &v;
let sa: &[f64] = &a;
```

In the last two lines, Rust automatically converts the `&Vec<f64>` reference and the `&[f64; 4]` reference to slice references that point directly to the data.

By the end, memory looks like Figure 3-2.

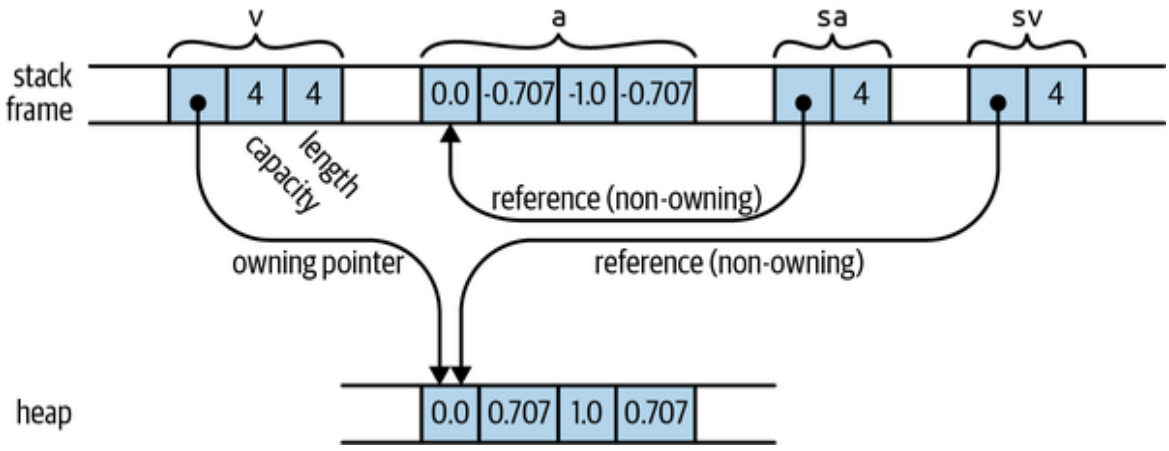


*Figure 3-2. A vector `v` and an array `a` in memory, with slices `sa` and `sv` referring to each*

An ordinary reference points to one value; a slice reference points to several values stored side-by-side in memory. Since slice references can point to data whether it's located in an array or a vector, they're a good choice when you want to write a function that can operate on either one.

For example, here's a function that prints a slice of numbers, one per line:

```
fn print_nums(n: &[f64]) {
    for elt in n {
        println!("{elt}");
    }
}

print_nums(&a);  // works on arrays
print_nums(&v);  // works on vectors
```

Just as in the previous example, Rust automatically converts `&a` and `&v` to slice references. You can get a reference to a slice of an array or vector, or a slice of an existing slice, by indexing it with a range:

```
print_nums(&v[0..2]);     // print the first two elements of v
print_nums(&a[2..]);      // print elements of a starting with
a[2]
print_nums(&sv[1..3]);    // print v[1] and v[2]
```

As with ordinary array accesses, Rust checks that the indices are valid. Trying to borrow a slice that extends past the end of the data results in a panic.

If our `print_nums` function took its argument as a `&Vec<f64>`, it would be unnecessarily limited to full vectors only; `&v[0..2]` and so on would not be valid arguments. Where possible, functions should accept slice references rather than vector or array references, for generality.

For the same reason, many of the useful standard library methods you'd like to see on arrays and vectors—searching, sorting, filling, reversing, and so on—are implemented as methods on slices:

```
let mut chaos = vec![3, 5, 4, 1, 2];
chaos.sort();
assert_eq!(chaos, [1, 2, 3, 4, 5]);
```

In this example, the `sort` method is actually defined on the slice type `[i32]`, not `Vec<i32>`. Rust once again automatically creates a slice reference to the vector's elements, and calls `sort` on that. It would work the same with an array.

## String and Character Types

Programmers familiar with C++ will recall that there are two string types in the standard library. The type `std::string_view` is a read-only reference to some text. It can refer to any string anywhere, including string

literals. The standard library also offers a class, `std::string`, for dynamically creating strings at run time.

Rust has a similar design. The reference type `&str` refers to some text anywhere in memory. The type `String` is for building strings dynamically. In the sections that follow, we'll briefly introduce these types, as well as the Unicode character type, `char`. For much more about strings and text processing, see Chapter 17.

## String and Character Literals

String literals are enclosed in double quotes.

```
let quote = "Editing is a rewording activity.";  // Alan Perlis
```

The type of a string literal is `&str`.

Character literals are enclosed in single quotes, like `'8'` or `'!'`. They have the type `char`, which can represent any single Unicode character: `'錆'` is a `char` literal representing the Japanese kanji for *sabi* (rust).

A string may span multiple lines:

```
println!(
    "In the room the women come and go,
    Singing of Mount Abora"
);
```

The newline character in that string literal is included in the string and therefore in the output. So are the spaces at the beginning of the second line. (Windows-style line endings do not affect the string's content. A line break in a string is always treated as a single newline character, `'\n'`.)

If one line of a string ends with a backslash, then the newline character and the leading whitespace on the next line are dropped:

```
println!(
    "It was a bright, cold day in April, and \
    there were four of us—\
```

```
        more or less."
);
```

This prints a single line of text. The string contains a single space between "and" and "there" because there is a space before the backslash in the program and no space between the em dash and "more." As in many other languages, *escape sequences* stand for special characters (Table 3-6).

*Table 3-6. Character escape sequences*

| Character | Escape sequence |
|---|---|
| Single quote, `'` | `\'` |
| Backslash, `\` | `\\` |
| Newline | `\n` |
| Carriage return | `\r` |
| Tab | `\t` |
| Any ASCII character (0 to 127) | `\x` exactly two hex digits |
| Any character | `\u{` up to six hex digits `}` |

You can write any character as `\u{HHHHHH}`, where `HHHHHH` is the code point as a hexadecimal number of up to six digits, with underscores allowed for grouping as usual. For example, the character literal `'\u{CA0}'` represents the character "ಠ", a Kannada letter used in the Unicode Look of Disapproval, "ಠ_ಠ". The same literal could also be simply written as `'ಠ'`.

In a few cases, the need to double every backslash in a string is a nuisance. (The classic examples are regular expressions and Windows paths.) For these cases, Rust offers *raw strings*. A raw string is tagged with the lowercase letter `r`. All backslashes and whitespace characters inside a raw

string are included verbatim in the string. No escape sequences are recognized:

```
let default_win_install_path = r"C:\Program Files\Gorillas";

let pattern = Regex::new(r"\d+(\.\d+)*");
```

You can't include a double-quote character in a raw string simply by putting a backslash in front of it—remember, we said *no* escape sequences are recognized. However, there is a cure for that too. The start and end of a raw string can be marked with pound signs:

```
println!(
    r###"
    This raw string started with 'r###"'.
    Therefore it does not end until we reach a quote mark ('"')
    followed immediately by three pound signs ('###'):
    "###
);
```

You can add as few or as many pound signs as needed to make it clear where the raw string ends.

## Characters and Strings in Memory

Rust's character type `char` represents a single Unicode character by its code point. Each `char` value takes up four bytes of memory, the same as a `u32`.

Rust strings are sequences of Unicode characters, but they are not stored in memory as arrays of `char`s. Instead, they are stored using UTF-8, a variable-width encoding. Each ASCII character in a string is stored in one byte. Other characters take up multiple bytes.

Figure 3-3 shows the `String` and `&str` values created by the following code:

```
let noodles = "noodles".to_string();
let oodles = &noodles[1..];
```

```
let disapproodles = "ಠ_ಠ";
```

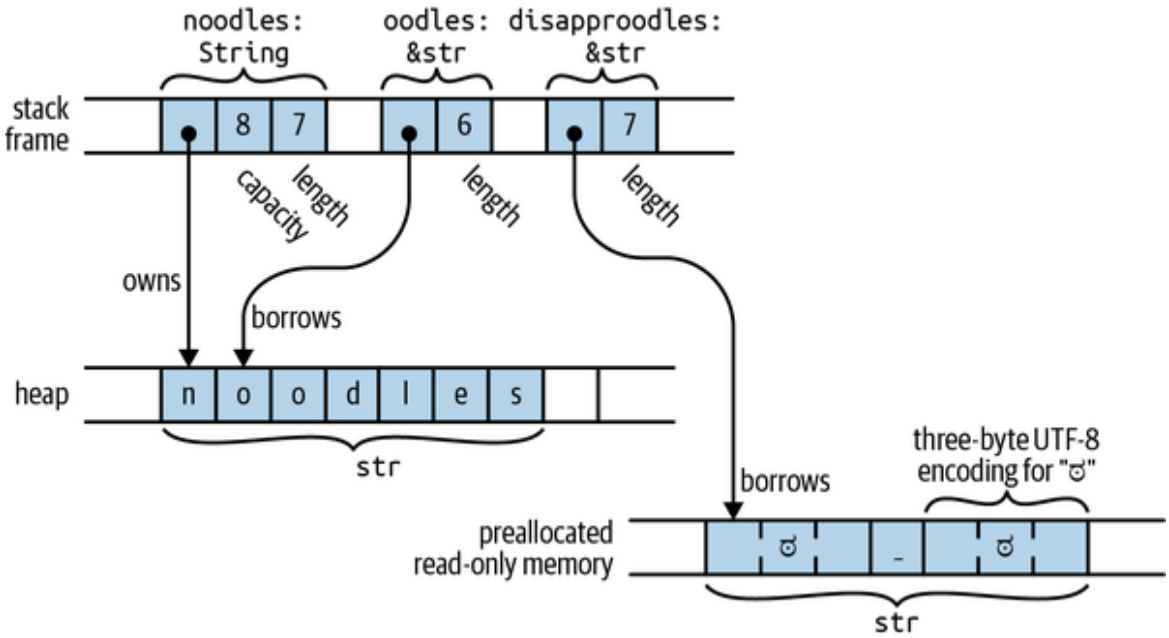


*Figure 3-3. `String`, `&str`, and `str`*

A `String` has a resizable buffer holding UTF-8 text. The buffer is allocated in the heap, so it can be resized as needed. In the figure, `noodles` is a `String` that owns an eight-byte buffer, of which seven are in use. You can think of a `String` as a `Vec<u8>` that is guaranteed to hold well-formed UTF-8; in fact, this is how `String` is implemented.

A `&str` (pronounced "stir" or "string slice") is a reference to a run of UTF-8 text owned by someone else: it "borrows" the text. In the example, `oodles` is a `&str` referring to the last six bytes of the text belonging to `noodles`, so it represents the text `"oodles"`. Like other slice references, a `&str` is a fat pointer, containing both the address of the actual data and its length.

You can think of a `&str` as being nothing more than a `&[u8]` that is guaranteed to hold well-formed UTF-8. Likewise, a `char` is essentially a `u32` that is guaranteed to hold a valid Unicode scalar value. They are types with *invariants*: rules about their values that are enforced by the implementation, that can't be broken except by abusing unsafe code, and that programs can therefore rely on.

A string literal is a `&str` that refers to preallocated text, typically stored in read-only memory along with the program's machine code. In the preceding example, `"ಠ_ಠ"` is a string literal, pointing to seven bytes that are loaded into memory when the program begins execution and that last until it exits.

A `String` or `&str`'s `.len()` method returns its length. The length is measured in bytes, not characters:

```
assert_eq!("ಠ_ಠ".len(), 7);
assert_eq!("ಠ_ಠ".chars().count(), 3);
```

It is impossible to modify a `&str`:

```
let mut s = "hello";
s[0] = 'c';     // error: `&str` cannot be modified, and other
reasons
s.push('\n');  // error: no method named `push` found for
reference `&str`
```

To create new strings at run time, use `String`.

## String

`&str` is very much like `&[T]`: a fat pointer to some data. `String` is analogous to `Vec<T>`, as described in Table 3-7.

*Table 3-7. `Vec<T>` and `String` comparison*

| | Vec<T> | String |
|---|---|---|
| Automatically frees buffers | Yes | Yes |
| Growable | Yes | Yes |
| `::new()` and `::with_capacity()` associated functions | Yes | Yes |
| Consists of pointer, capacity, and length | Yes | Yes |
| `.push()` and `.pop()` methods | Yes | Yes |
| Range syntax `&v[start..stop]` | Yes, returns `&[T]` | Yes, returns `&str` |
| Automatic conversion | `&Vec<T>` to `&[T]` | `&String` to `&str` |
| Inherits methods | From `&[T]` | From `&str` |

Like a `Vec`, each `String` has its own heap-allocated buffer that isn't shared with any other `String`. The `String` automatically frees this memory when it is dropped, just like a `Vec` or `Box`.

There are several ways to create `String`s:

- The `.to_string()` method converts a `&str` to a `String`. This copies the string:
  ```
  let error_message = "too many pets".to_string();
  ```
- `String::new()` returns an empty string. You can then build up the new string piece by piece using the += operator. The value to

the right of += can be a `&str` or `&String`:

```
let mut s = String::new();
s += "You can see:\n";
for item in game.items() {
    if item.location == player.location {
        s += "    ";
        s += &item.name;
        s += "\n";
    }
}
```

- The `format!()` macro works just like `println!()`, except that it returns a new `String` instead of writing text to standard out, and it doesn't automatically add a newline at the end:

  ```
  let place = "Portland";
  assert_eq!(format!("Hello, {place}!"), "Hello,
  Portland!".to_string());
  ```

  The first argument to `format!()` or `println!()` is called a *format string*. The bits in curly braces are called *format specifiers*, and in the output, each format specifier is replaced with some value. Values can be passed as additional arguments to the macro or, for single identifiers only, included in the format specifier itself:

  ```
  assert_eq!(
      format!("from {} to {}", start, end),
      format!("from {start} to {end}"),
  );
  ```

  A format specifier of `{}` or `{`*`name`*`}` renders a value in `Display` format, for end users; `{:?}` or `{`*`name`*`:?}` renders it in `Debug` format, for debugging. An example of the difference is that if `s` is a string, `println!("{s}")` prints the content of the string verbatim, whereas `println!("{s:?}")` adds double quotes around it and renders any special characters in `s` as escape sequences. Not all types support `Display` format, but almost everything supports `Debug`. You'll need `{:?}` to print a tuple, slice, `Vec`, or `Option`.

To include an actual curly brace in the output, double it: `println!("{{")`.

That should be enough to get on with. Rust format strings offer many more features for fine-tuning the output. We cover them in "Formatting Values".

- To concatenate a list of strings, use `.concat()` or `.join(sep)`:

```
let bits = vec!["veni", "vidi", "vici"];
assert_eq!(bits.concat(), "venividivici");
assert_eq!(bits.join(", "), "veni, vidi, vici");
```

  These methods are defined for slices of type `[&str]` and `[String]` and are therefore available on arrays and vectors as well.

The choice sometimes arises of which type to use: `&str` or `String`. Chapter 5 addresses this question in detail. For now it will suffice to point out that a `&str` can refer to any slice of any string, so as with slices versus vectors, `&str` is usually preferable to `String` for function arguments.

## Using Strings

Strings support the == and != operators. Two strings are equal if they contain the same characters in the same order, regardless of whether they point to the same location in memory:

```
assert!("ONE".to_lowercase() == "one");
```

Strings also support the comparison operators <, <=, >, and >=, as well as many useful methods and functions that you can find in the online documentation under "Primitive Type `str`" or the "`std::str`" module (or just flip to Chapter 17). Here are a few examples:

```
assert!("peanut".contains("nut"));
assert_eq!("ಠ_ಠ".replace("ಠ", "■"), "■_■");
```

```
assert_eq!("    clean\n".trim(), "clean");

for word in "veni, vidi, vici".split(", ") {
    assert!(word.starts_with("v"));
}
```

Characters have some methods of their own, for classification and conversions. They are documented under “Primitive Type `char`” (and in “Characters (char)”):

```
assert_eq!('β'.is_alphabetic(), true);
assert_eq!(char::from_u32(0x1f642), Some('🙂'));
assert_eq!('🙂'.len_utf8(), 4);
assert_eq!('1'.to_digit(10), Some(1));
assert_eq!(char::from_digit(2, 10), Some('2'));
```

## Other String-Like Types

Rust guarantees that strings are valid UTF-8. Sometimes a program really needs to be able to deal with strings that are *not* valid Unicode. This usually happens when a Rust program has to interoperate with some other system that doesn’t enforce any such rules. For example, in most operating systems it’s easy to create a file with a filename that isn’t valid Unicode. What should happen when a Rust program comes across this sort of filename?

Rust’s solution is to offer a few string-like types for these situations:

- For ordinary text, use `String` and `&str`.
- When working with filenames, use `PathBuf` and `&Path` instead. You can import them from `std::path`.
- When working with environment variable names and command-line arguments, if you need to handle non-UTF-8 values, use `OsString` and `&OsStr` from `std::ffi`. But this is rarely necessary. Most programs just use `String`, as we did when handling command-line arguments in Chapter 2.

- When working with binary data that isn't UTF-8 encoded at all, use `Vec<u8>` and `&[u8]`.
- When interoperating with C libraries that use null-terminated strings, use `CString` and `&CStr` from `std::ffi`.

For those last two situations, Rust has special syntax:

```
let elf_magic = b"\x7fELF";    // a byte string (not UTF-8)
assert_eq!(elf_magic, &[127u8, b'E', b'L', b'F']);

let branch = c"main";  // a C string (null-terminated)
assert_eq!(branch,
CStr::from_bytes_with_nul(b"main\0").unwrap());
```

A string literal prefixed with `b` is a *byte string*. For example, `b"\x7fELF"` is a byte string; its type is `&[u8; 4]`, a reference to an immutable array of bytes. Since a byte string represents bytes, not characters, it does not have to be valid UTF-8. (This particular example is the "magic number" that appears as the first four bytes of practically every Linux executable, including the ones you've been building with `cargo build`, if you've been working through the examples in this book on Linux.)

Similarly, a *byte literal* is a character-like literal prefixed with `b`. It has the type `u8`. For example, since the ASCII code for `A` is 65, the literals `b'A'` and `65u8` are exactly equivalent. Byte strings and byte literals can't contain arbitrary Unicode characters; they must make do with ASCII and `\xHH` escape sequences.

The string `c"main"` is a *C string*. It is like the regular string `"main"` except it is *null-terminated*; that is, it's stored with an extra 0 byte to indicate the end of the string, as required by many C APIs. Its type is `&std::ffi::CStr`.

You won't use these features every day, but we will show example code using a byte string in Chapter 23 and a C string in Chapter 24.

## Type Aliases

The `type` keyword can be used like `typedef` in C++ to declare a new name for an existing type:

```
type Bytes = Vec<u8>;
```

The type `Bytes` that we're declaring here is shorthand for this particular kind of `Vec`:

```
fn encode(image: &Bitmap) -> Bytes {  // returns a Vec<u8>
    ...
}
```

## Beyond the Basics

Types are a central part of Rust. We'll continue talking about types and introducing new ones throughout the book. In particular, Rust's user-defined types give the language much of its flavor, because that's where methods are defined. There are three kinds of user-defined types, and we'll cover them in three successive chapters: structs in Chapter 9, enums in Chapter 10, and traits in Chapter 11.

Functions and closures have their own types, covered in Chapter 14. And the types that make up the standard library are covered throughout the book. For example, Chapter 16 presents the standard collection types.

All of that will have to wait, though. Before we move on, it's time to tackle the concepts that are at the heart of Rust's safety rules.

# Chapter 4. Ownership and Moves

When it comes to managing memory, there are two characteristics we'd like from our programming languages:

- We'd like memory to be freed promptly, at a time of our choosing. This gives us control over the program's memory consumption.
- We never want to use a pointer to an object after it's been freed. This would be undefined behavior, leading to crashes and security holes.

But these seem to be mutually exclusive: freeing a value while pointers exist to it necessarily leaves those pointers dangling.

Almost all major programming languages fall into one of two camps, depending on which of the two qualities they give up on:

- The "Safety First" camp uses garbage collection to manage memory, automatically freeing objects when all reachable pointers to them are gone. This eliminates dangling pointers by simply keeping the objects around until there are no pointers to them left to dangle. Most modern languages fall in this camp from Python, JavaScript, and Ruby to languages like Java, C#, and Haskell.

  Relying on garbage collection means relinquishing control over exactly when objects get freed to the collector. In general, garbage collectors are surprising beasts, and understanding why memory wasn't freed when you expected can be challenging.

- The "Control First" camp leaves you in charge of freeing memory. Your program's memory consumption is entirely in your hands, but

avoiding dangling pointers also becomes your concern. C and C++ are the only mainstream languages in this camp.

This is great if you never make mistakes, but evidence suggests that eventually you will. Pointer misuse has been a common culprit in reported security problems for as long as that data has been collected.

Rust aims to be both safe and performant, so neither of these compromises is acceptable. But if reconciliation were easy, someone would have done it long before now. Something fundamental had to change.

Rust breaks the deadlock in a surprising way: by imposing some rules restricting how your programs can use pointers, the net effect of which is to bring just enough order to the chaos to allow Rust's compile-time checks to verify that your program is free of memory safety errors. At compile time, Rust records where and when values are created and used, tracking the ownership of each value as it moves through the program to prevent the use of uninitialized values and free them exactly once, and only when they are no longer needed, avoiding double-free bugs. The compiler also analyzes references to those values to prevent the use of dangling pointers. At run time, your pointers are simple addresses in memory, just as they would be in C and C++. The difference is that your code has been proven to use them safely. This chapter and the next are devoted to explaining exactly what these restrictions are and why they work.

These same rules also form the basis of Rust's support for safe concurrent programming. Using Rust's carefully designed threading primitives, the rules that ensure your code uses memory correctly also serve to prove that it is free of data races. A bug in a Rust program cannot cause one thread to corrupt another's data, introducing hard-to-reproduce failures in unrelated parts of the system. The nondeterministic behavior inherent in multithreaded code is isolated to those features designed to handle it—mutexes, message channels, atomic values, and so on—rather than appearing in ordinary memory references. Multithreaded code in C and C++ has earned its ugly reputation, but Rust rehabilitates it quite nicely.

Rust's radical wager, the claim on which it stakes its success and that forms the root of the language, is that even with these restrictions in place, you'll find the language more than flexible enough for almost every task, and that the benefits—the elimination of broad classes of memory management and concurrency bugs—will justify the adaptations you'll need to make to your style. The authors of this book are bullish on Rust exactly because of our extensive experience with C and C++. For us, Rust's deal is a no-brainer.

Rust's rules are probably unlike what you've seen in other programming languages. Learning how to work with them and turn them to your advantage is, in our opinion, the central challenge of learning Rust.

In this chapter, we'll first provide insight into the logic and intent behind Rust's rules by showing how the same underlying issues play out in other languages. Then, we'll explain Rust's rules in detail, looking at what ownership means at a conceptual and mechanical level, how changes in ownership are tracked in various scenarios, and types that bend or break some of these rules in order to provide more flexibility.

## Ownership

If you've read much C or C++ code, you've probably come across a comment saying that an instance of some class *owns* some other object that it points to. This generally means that the owning object gets to decide when to free the owned object: when the owner is destroyed, it destroys its possessions along with it.

For example, suppose you write the following C++ code:

```
std::string s = "frayed knot";
```

The string `s` is represented in memory roughly as shown in Figure 4-1.

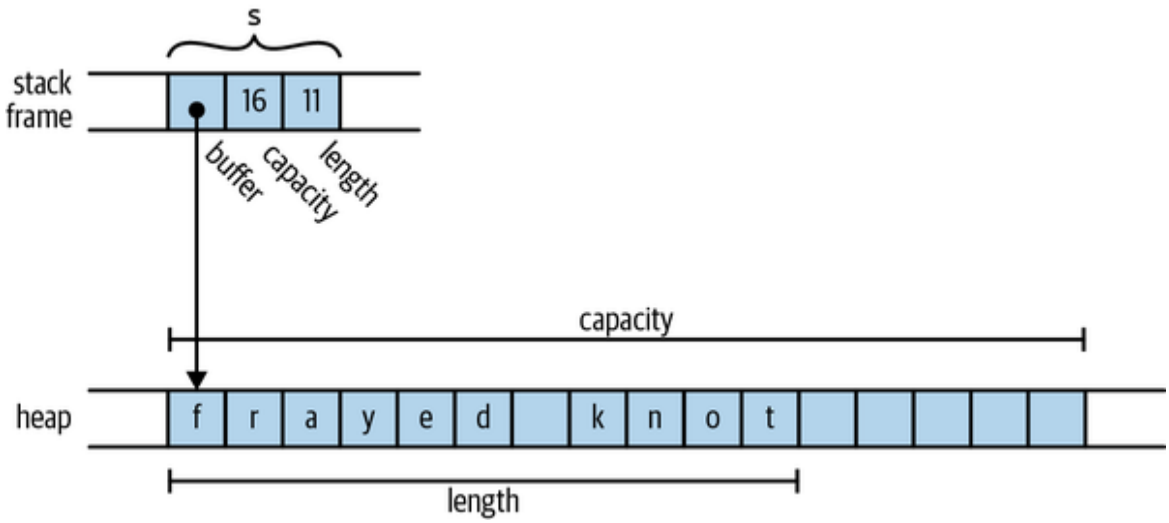


*Figure 4-1. A C++ `std::string` value on the stack, pointing to its heap-allocated buffer*

Here, the actual `std::string` object has a fixed size of three machine words. It comprises a pointer to a heap-allocated buffer, the buffer's overall capacity (that is, how large the text can grow before the string must allocate a larger buffer to hold it), and the length of the text it holds now. These are fields private to the `std::string` class, not accessible to the string's users.

A `std::string` owns its buffer: when the program destroys the string, the string's destructor frees the buffer. In the past, some C++ libraries shared a single buffer among several `std::string` values, using a reference count to decide when the buffer should be freed. Newer versions of the C++ specification effectively preclude that representation; all modern C++ libraries use the approach shown here.

In these situations it's generally understood that although it's fine for other code to create temporary pointers to the owned memory, it is that code's responsibility to make sure its pointers are gone before the owner decides to destroy the owned object. You can create a pointer to a character living in a `std::string`'s buffer, but when the string is destroyed, your pointer becomes invalid, and it's up to you to make sure you don't use it anymore. The owner determines the lifetime of the owned, and everyone else must respect its decisions.

We've used `std::string` here as an example of what ownership looks like in C++: it's just a convention that the standard library generally follows, and although the language encourages you to follow similar practices, how you design your own types is ultimately up to you.

In Rust, however, the concept of ownership is built into the language itself and enforced by compile-time checks. Every value has a single owner that determines its lifetime. When the owner is freed—*dropped*, in Rust terminology—the owned value is dropped too. These rules are meant to make it easy for you to find any given value's lifetime simply by inspecting the code, giving you the control over its lifetime that a systems language should provide.

A variable owns its value. When control leaves the block in which the variable is declared, the variable is dropped, so its value is dropped along with it. For example:

```
fn print_padovan() {
    let mut padovan = vec![1, 1, 1];  // allocated here
    for i in 3..10 {
        let next = padovan[i - 3] + padovan[i - 2];
        padovan.push(next);
    }
    println!("P(1..10) = {padovan:?}");
}                                     // dropped here
```

The type of the variable `padovan` is `Vec<i32>`, a vector of 32-bit integers. In memory, the final value of `padovan` will look something like Figure 4-2.

This is similar to the C++ `std::string` we showed earlier, except that the elements in the buffer are 32-bit values, not characters. Note that the words holding `padovan`'s pointer, capacity, and length live directly in the stack frame of the `print_padovan` function; only the vector's buffer is allocated in the heap.

As with the string `s` earlier, the vector owns the buffer holding its elements. When the variable `padovan` goes out of scope at the end of the function,

the program drops the vector. And since the vector owns its buffer, the buffer goes with it.

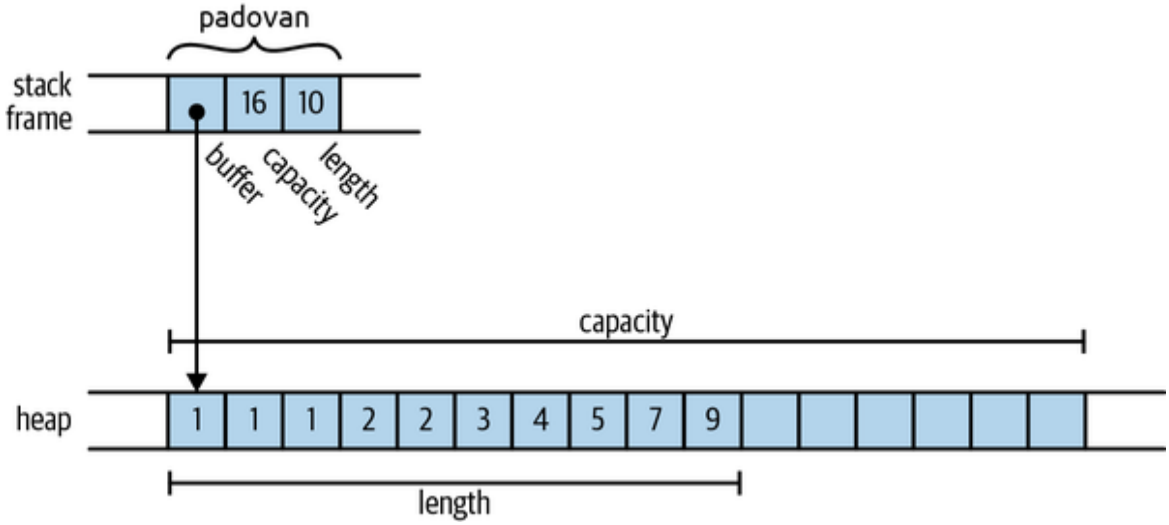


*Figure 4-2. A `Vec<i32>` on the stack, pointing to its buffer in the heap*

Rust's `Box` type serves as another example of ownership. A `Box<T>` is a pointer to a value of type `T` stored in the heap. Calling `Box::new(v)` allocates some heap space, moves the value `v` into it, and returns a `Box` pointing to the heap space. Since a `Box` owns the space it points to, when the `Box` is dropped, it frees the space too.

For example, you can allocate a tuple in the heap like so:

```
{
    let point = Box::new((0.625, 0.5));  // point allocated here
    let label = format!("{point:?}");    // label allocated here
    assert_eq!(label, "(0.625, 0.5)");
}                                        // both dropped here
```

When the program calls `Box::new`, it allocates space for a tuple of two `f64` values in the heap, moves its argument `(0.625, 0.5)` into that space, and returns a pointer to it. By the time control reaches the call to `assert_eq!`, the stack frame looks like Figure 4-3.

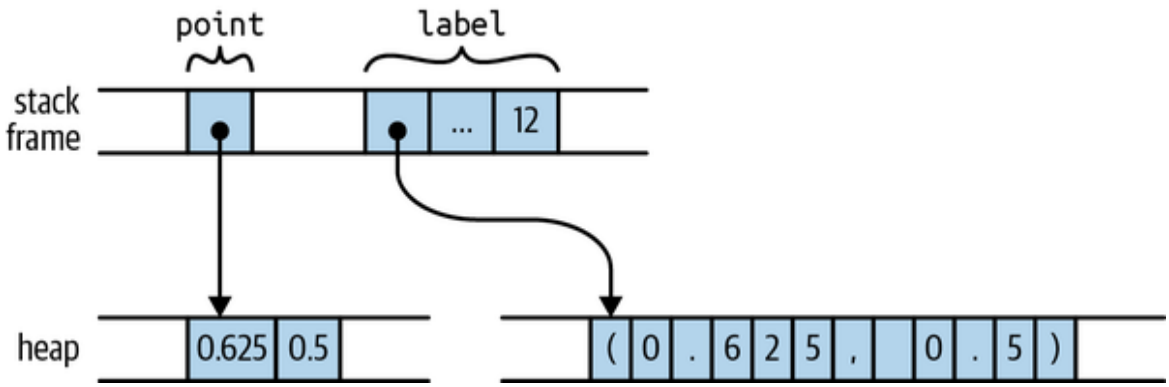


*Figure 4-3. Two local variables, each owning memory in the heap*

The stack frame itself holds the variables `point` and `label`, each of which refers to a heap allocation that it owns. When they are dropped, the allocations they own are freed along with them.

Just as variables own their values, structs and tuples own their fields, and arrays and vectors own their elements:

```
struct Person {
    name: String,
    birth: i32,
}

let mut composers = Vec::new();
composers.push(Person {
    name: "Palestrina".to_string(),
    birth: 1525,
});
composers.push(Person {
    name: "Dowland".to_string(),
    birth: 1563,
});
composers.push(Person {
    name: "Lully".to_string(),
    birth: 1632,
});
for composer in &composers {
    println!("{}, born {}", composer.name, composer.birth);
}
```

Here, `composers` is a `Vec<Person>`, a vector of structs, each of which holds a string and a number. In memory, the final value of `composers`

looks like Figure 4-4.

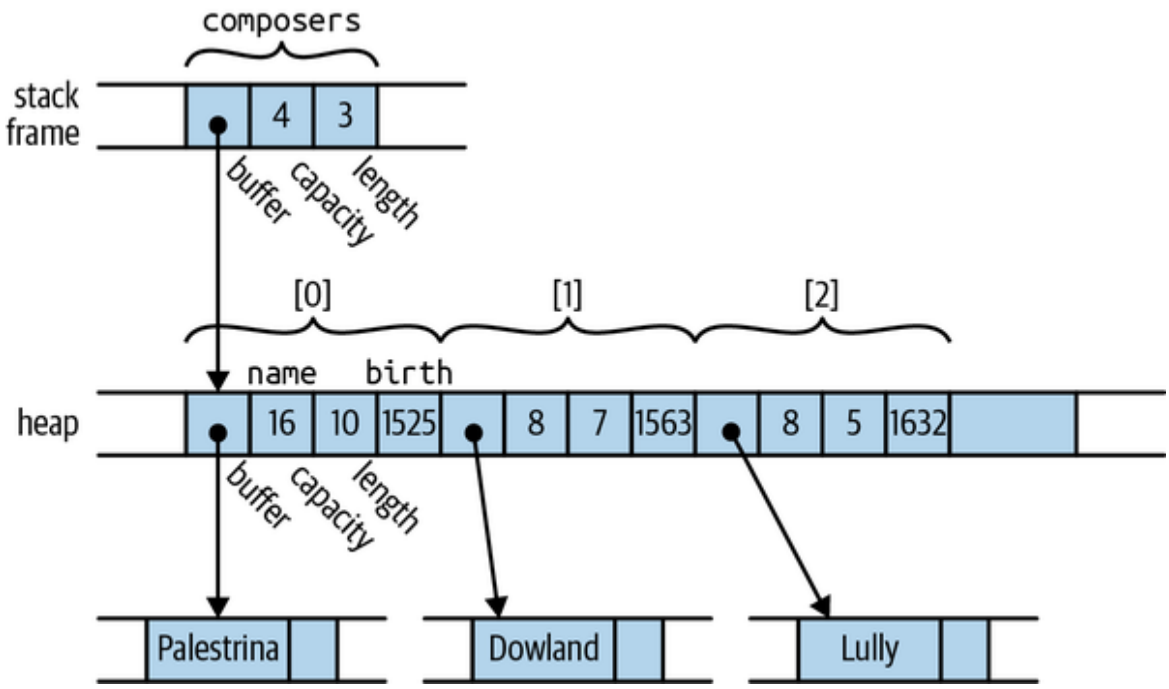


*Figure 4-4. A more complex tree of ownership*

There are many ownership relationships here, but each one is pretty straightforward: `composers` owns a vector; the vector owns its elements, each of which is a `Person` structure; each structure owns its fields; and the string field owns its text. When control leaves the scope in which `composers` is declared, the program drops its value and takes the entire arrangement with it. If there were other sorts of collections in the picture—a `HashMap`, perhaps, or a `BTreeSet`—the story would be the same.

At this point, take a step back and consider the consequences of the ownership relations we've presented so far. Every value has a single owner, making it easy to decide when to drop it. But a single value may own many other values: for example, the vector `composers` owns all of its elements. And those values may own other values in turn: each element of `composers` owns a string, which owns its text.

It follows that the owners and their owned values form *trees*: your owner is your parent, and the values you own are your children. And at the ultimate root of each tree is a variable; when that variable goes out of scope, the

entire tree goes with it. We can see such an ownership tree in the diagram for `composers`: it's not a "tree" in the sense of a search tree data structure, or an HTML document made from DOM elements. Rather, we have a tree built from a mixture of types, with Rust's single-owner rule forbidding any rejoining of structure that could make the arrangement more complex than a tree. Every value in a Rust program is a member of some tree, rooted in some variable.

Rust programs don't usually explicitly drop values at all, in the way C and C++ programs would use `free` and `delete`. The way to drop a value in Rust is to remove it from the ownership tree somehow: by leaving the scope of a variable, deleting an element from a vector, or something of that sort. At that point, Rust ensures the value is properly dropped, along with everything it owns.

In a certain sense, Rust is less powerful than other languages: every other practical programming language lets you build arbitrary graphs of objects that point to each other in whatever way you see fit. But it is exactly because Rust is less powerful that the analyses the language can carry out on your programs can be more powerful. Rust's safety guarantees are possible exactly because the relationships it may encounter in your code are more tractable. This is part of Rust's "radical wager" we mentioned earlier: in practice, Rust claims, there is usually more than enough flexibility in how one goes about solving a problem to ensure that at least a few perfectly fine solutions fall within the restrictions the language imposes.

That said, concept of ownership as we've explained it so far is too rigid to be useful for even relatively simple programs. Rust's design addresses this inflexibility in a few ways:

- You can move values from one owner to another. This allows you to build, rearrange, and tear down the tree.
- Very simple types like integers, floating-point numbers, and characters are excused from the ownership rules. These are called `Copy` types.

- The standard library provides the reference-counted pointer types `Rc` and `Arc`, which allow values to have multiple owners, under some restrictions.
- You can "borrow a reference" to a value; references are non-owning pointers, with limited lifetimes.

Each of these strategies contributes flexibility to the ownership model, while still upholding Rust's promises. We'll explain each one in turn, with references covered in the next chapter.

## Moves

In Rust, for most types, operations like assigning a value to a variable, passing it to a function, or returning it from a function don't copy the value: they *move* it. The source relinquishes ownership of the value to the destination and becomes uninitialized; the destination now controls the value's lifetime. Rust programs build up and tear down complex structures one value at a time, one move at a time.

You may be surprised that Rust would change the meaning of such fundamental operations; surely assignment is something that should be pretty well nailed down at this point in history. However, if you look closely at how different languages have chosen to handle assignment, you'll see that there's actually significant variation from one school to another. The comparison also makes the meaning and consequences of Rust's choice easier to see.

Consider the following Python code:

```
s = ['udon', 'ramen', 'soba']
t = s
u = s
```

Each Python object carries a reference count, tracking the number of values that are currently referring to it. So after the assignment to `s`, the state of the program looks like Figure 4-5 (note that some fields are left out). Since

only `s` is pointing to the list, the list's reference count is 1; and since the list is the only object pointing to the strings, each of their reference counts is also 1.

What happens when the program executes the assignments to `t` and `u`? Python implements assignment simply by making the destination point to the same object as the source and incrementing the object's reference count. So the final state of the program is something like Figure 4-6.

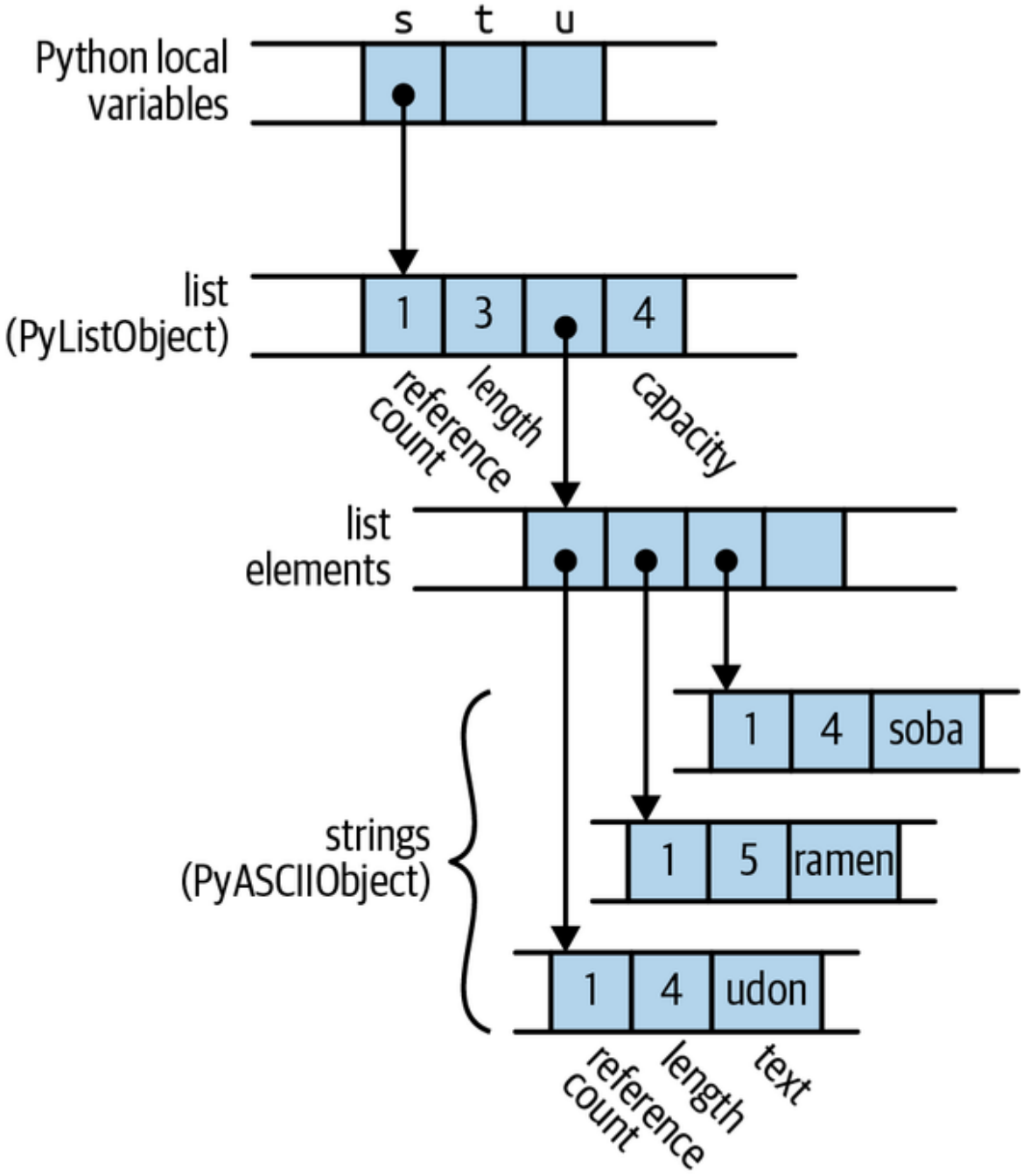


*Figure 4-5. How Python represents a list of strings in memory*

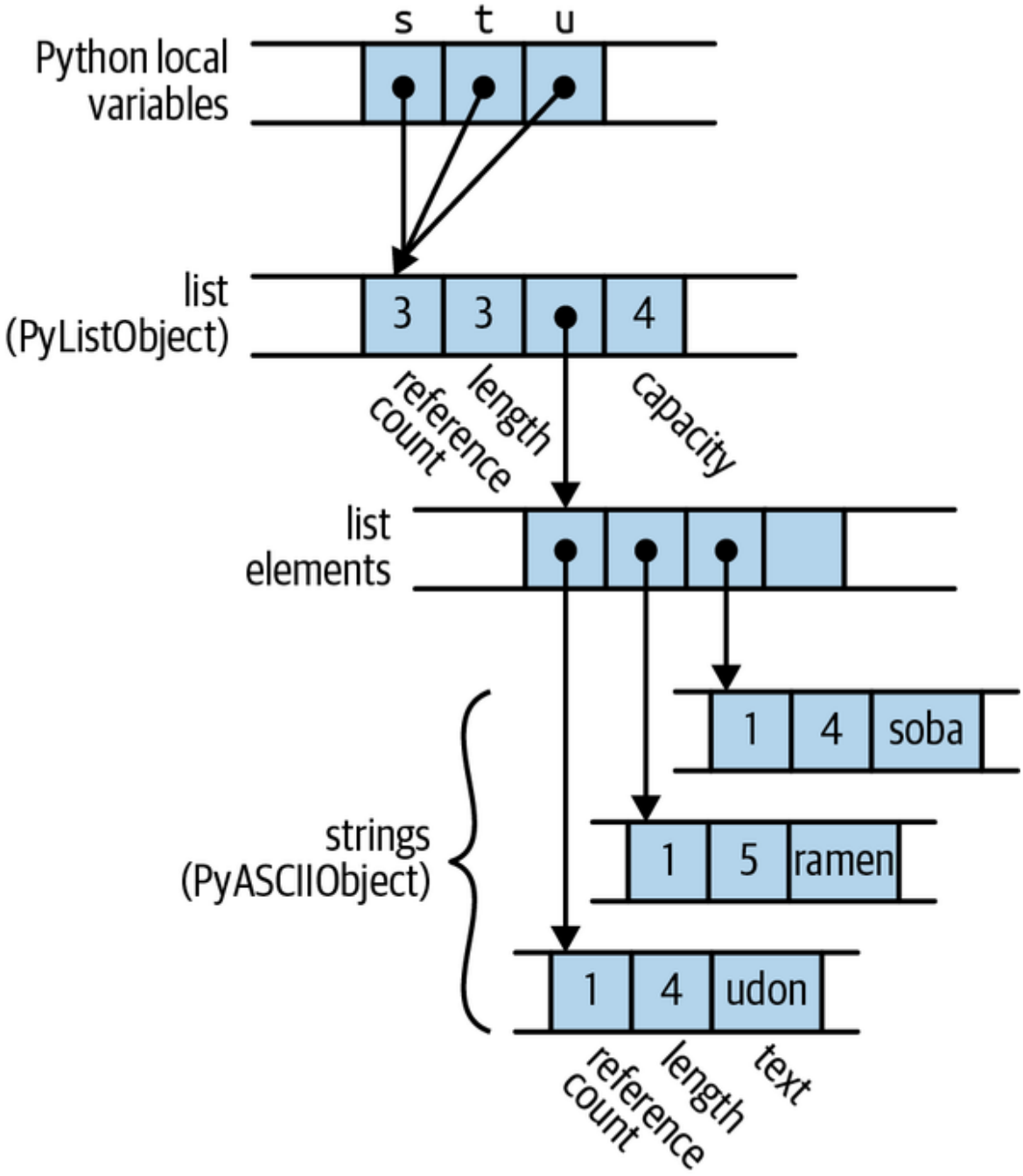


*Figure 4-6. The result of assigning `s` to both `t` and `u` in Python*

Python has copied the pointer from `s` into `t` and `u` and updated the list's reference count to 3. Assignment in Python is cheap, but because it creates a new reference to the object, we must maintain reference counts to know when we can free the value.

Now consider the analogous C++ code:

```
using namespace std;
vector<string> s = { "udon", "ramen", "soba" };
vector<string> t = s;
vector<string> u = s;
```

The original value of `s` looks like Figure 4-7 in memory.

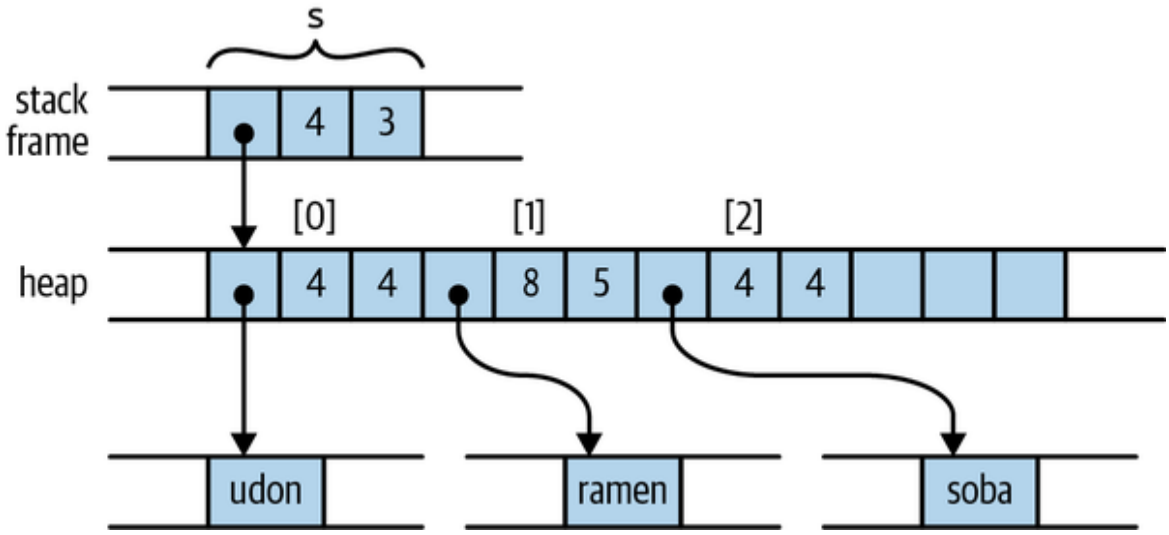


*Figure 4-7. How C++ represents a vector of strings in memory*

What happens when the program assigns `s` to `t` and `u`? Assigning a `std::vector` produces a copy of the vector in C++; `std::string` behaves similarly. So by the time the program reaches the end of this code, it has actually allocated three vectors and nine strings (Figure 4-8).

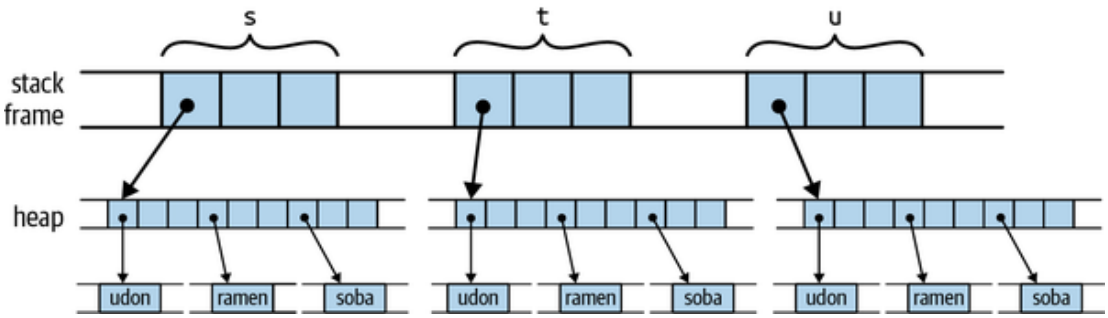


*Figure 4-8. The result of assigning `s` to both `t` and `u` in C++*

Depending on the values involved, assignment in C++ can consume unbounded amounts of memory and processor time. The advantage,

however, is that it's easy for the program to decide when to free all this memory: when the variables go out of scope, everything allocated here gets cleaned up automatically.

In a sense, C++ and Python have chosen opposite trade-offs: Python makes assignment cheap, at the expense of requiring reference counting (and in the general case, garbage collection). C++ keeps the ownership of all the memory clear, at the expense of making assignment carry out a deep copy of the object. C++ programmers are often less than enthusiastic about this choice: deep copies can be expensive, and there are usually more practical alternatives.

So what would the analogous program do in Rust? Here's the code:

```
let s = vec!["udon".to_string(), "ramen".to_string(),
"soba".to_string()];
let t = s;
let u = s;
```

Like C and C++, Rust puts plain string literals like `"udon"` in read-only memory, so for a clearer comparison with the C++ and Python examples, we call `to_string` here to get heap-allocated `String` values. After carrying out the initialization of `s`, since Rust and C++ use similar representations for vectors and strings, the situation looks just as it did in C++ (Figure 4-9).

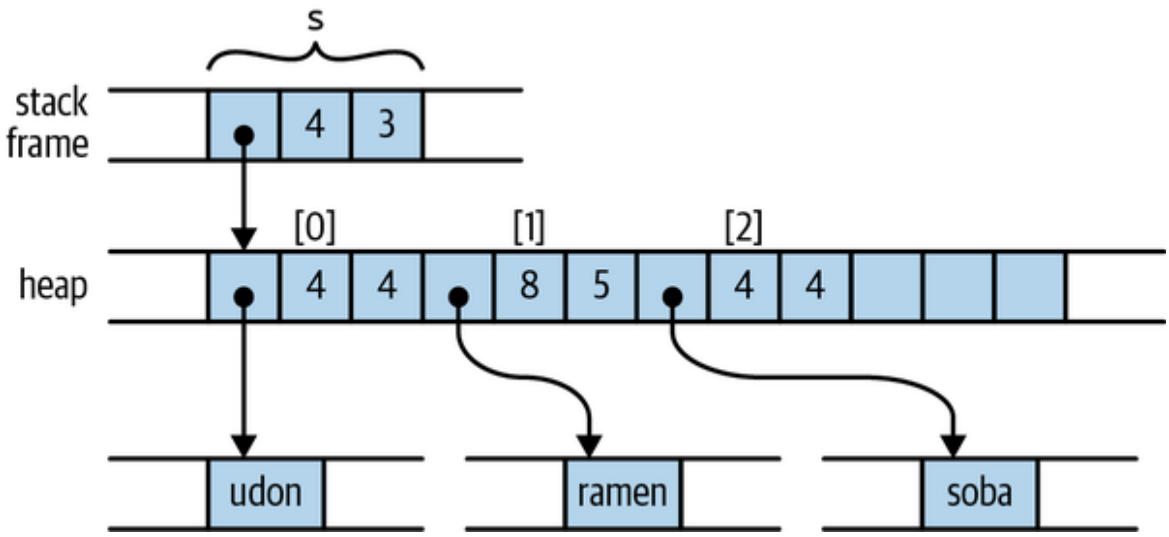


*Figure 4-9. How Rust represents a vector of strings in memory*

But recall that, in Rust, assignments of most types *move* the value from the source to the destination, leaving the source uninitialized. So after initializing `t`, the program's memory looks like Figure 4-10.

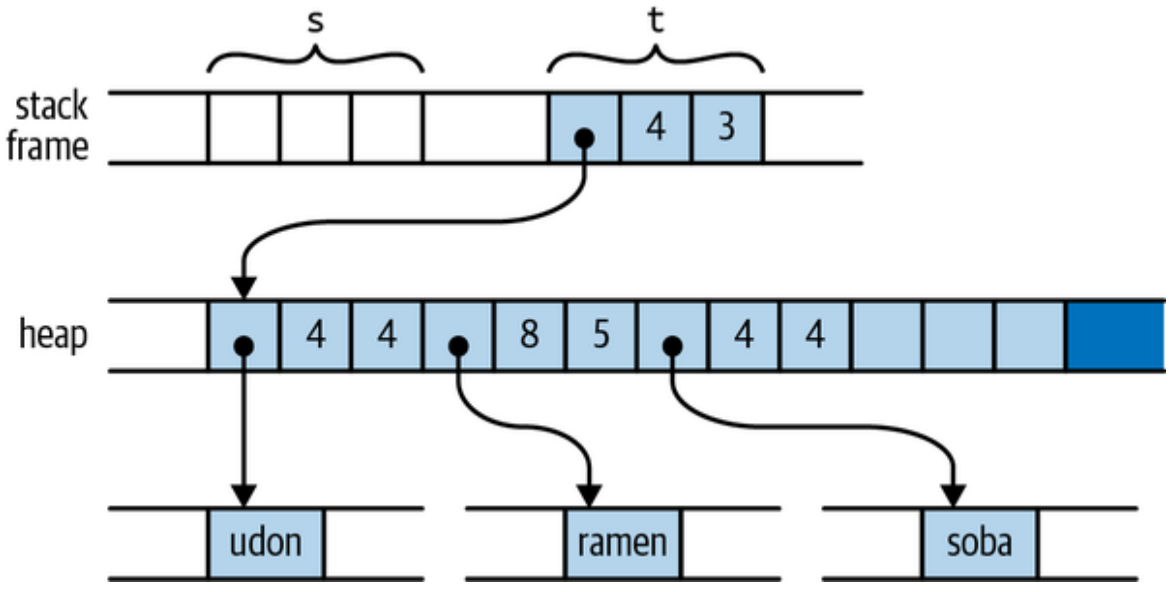


*Figure 4-10. The result of assigning `s` to `t` in Rust*

What has happened here? The initialization `let t = s;` moved the vector's three header fields from `s` to `t`; now `t` owns the vector. The vector's elements stayed just where they were, and nothing happened to the strings either. Every value still has a single owner, although one has

changed hands. There were no reference counts to be adjusted. And the compiler now considers `s` uninitialized.

So what happens when we reach the initialization `let u = s;`? This would assign the uninitialized value `s` to `u`. Rust prudently prohibits using uninitialized values, so the compiler rejects this code with the following error:

```
error: use of moved value: `s`
  |
7 |     let s = vec!["udon".to_string(), "ramen".to_string(),
"soba".to_string()];
  |         - move occurs because `s` has type `Vec<String>`,
  |           which does not implement the `Copy` trait
8 |     let t = s;
  |             - value moved here
9 |     let u = s;
  |             ^ value used here after move
```

Consider the consequences of Rust's use of a move here. Like Python, the assignment is cheap: the program simply moves the three-word header of the vector from one spot to another. But like C++, ownership is always clear: the program doesn't need reference counting or garbage collection to know when to free the vector elements and string contents.

The price you pay is that you must explicitly ask for copies when you want them. If you want to end up in the same state as the C++ program in Figure 4-8, with each variable holding an independent copy of the structure, you must call the vector's `clone` method.

This method performs a deep copy of the vector and its elements:

```
let s = vec!["udon".to_string(), "ramen".to_string(),
"soba".to_string()];
let t = s.clone();
let u = s.clone();
```

You could also re-create Python's behavior (Figure 4-6) by using Rust's reference-counted pointer types; we'll discuss those shortly in "Rc and Arc: Shared Ownership".

## More Operations That Move

In the examples thus far, we've shown initializations, providing values for variables as they come into scope in a `let` statement. Assigning to a variable is slightly different, in that if you move a value into a variable that was already initialized, Rust drops the variable's prior value. For example:

```
let mut s = "Govinda".to_string();
s = "Siddhartha".to_string();  // value "Govinda" dropped here
```

In this code, when the program assigns the string `"Siddhartha"` to `s`, its prior value `"Govinda"` gets dropped first. But consider the following:

```
let mut s = "Govinda".to_string();
let t = s;
s = "Siddhartha".to_string();  // nothing is dropped here
```

This time, `t` has taken ownership of the original string from `s` so that by the time we assign to `s`, it is uninitialized. In this scenario, no string is dropped.

We've used initializations and assignments in the examples here because they're simple, but Rust applies move semantics to almost any use of a value. Passing arguments to functions moves ownership to the function's parameters; returning a value from a function moves ownership to the caller. Building a tuple moves the values into the tuple. And so on.

You may now have better insight into what's really going on in the examples we offered in the previous section. For example, when we were constructing our vector of composers, we wrote:

```
struct Person {
    name: String,
    birth: i32,
}

let mut composers = Vec::new();
composers.push(Person {
    name: "Palestrina".to_string(),
    birth: 1525,
});
```

This code shows places where moves occur, beyond initialization and assignment:

*Returning values from a function*

> The call `Vec::new()` constructs a new vector and returns not a pointer to the vector but the vector itself: its ownership moves from `Vec::new` to the variable `composers`. Similarly, the `to_string` call returns a fresh `String` instance.

*Constructing new values*

> The `name` field of the new `Person` structure is initialized with the return value of `to_string`. The structure takes ownership of the string.

*Passing values to a function*

> The entire `Person` structure, not a pointer to it, is passed to the vector's `push` method, which moves it onto the end of the vector. The vector takes ownership of the `Person` and thus becomes the indirect owner of the name `String` as well.

Moving values around like this may sound inefficient, but there are two things to keep in mind. First, the moves always apply to the value proper, not the heap storage they own. For vectors and strings, the *value proper* is the three-word header alone; the potentially large element arrays and text buffers sit where they are in the heap. Second, the Rust compiler's code generation is good at "seeing through" all these moves; in practice, the machine code often stores the value directly where it belongs.

## Moves and Control Flow

The previous examples all have very simple control flow; how do moves interact with more complicated code? The general principle is that, if it's possible for a variable to have had its value moved away and it hasn't

definitely been given a new value since, it's considered uninitialized. For example:

```
let x = vec![10, 20, 30];
if c {
    f(x);  // ok to move from x here
}
h(x);  // bad: x may have been moved
```

For similar reasons, moving from a variable in a loop is forbidden:

```
let x = vec![10, 20, 30];
while f() {
    g(x);  // bad: x would be moved in first iteration,
           // uninitialized in second
}
```

That is, unless we've definitely given it a new value by the next iteration:

```
let mut x = vec![10, 20, 30];
while f() {
    g(x);           // move from x
    x = h();        // give x a fresh value
}
e(x);
```

## Moves and Indexed Content

We've mentioned that a move leaves its source uninitialized, as the destination takes ownership of the value. But not every kind of value owner is prepared to become uninitialized. For example, consider the following code:

```
// Build a vector of the strings "101", "102", ... "105"
let mut v = Vec::new();
for i in 101..106 {
    v.push(i.to_string());
}

// Pull out random elements from the vector.
```

```
let third = v[2];  // error: Cannot move out of index of Vec
let fifth = v[4];  // here too
```

For this to work, Rust would somehow need to remember that the third and fifth elements of the vector have become uninitialized and track that information until the vector is dropped. In the most general case, vectors would need to carry around extra information with them to indicate which elements are live and which have become uninitialized. That is clearly not the right behavior for a systems programming language; a vector should be nothing but a vector. In fact, Rust rejects the preceding code with the following error:

```
error: cannot move out of index of `Vec<String>`
   |
14 |     let third = v[2];
   |                 ^^^^
   |                 |
   |                 move occurs because value has type `String`,
   |                 which does not implement the `Copy` trait
   |                 help: consider borrowing here: `&v[2]`
```

It also makes a similar complaint about the move to `fifth`. In the error message, Rust suggests using a reference, in case you want to access the element without moving it. This is often what you want.

But what if you really do want to move an element out of a vector? You need to find a method that does so in a way that respects the limitations of the type. Here are three possibilities:

```
// Build a vector of the strings "101", "102", ... "105"
let mut v = Vec::new();
for i in 101..106 {
    v.push(i.to_string());
}

// 1. Pop a value off the end of the vector:
let fifth = v.pop().expect("vector empty!");
assert_eq!(fifth, "105");

// 2. Move a value out of a given index in the vector,
// and move the last element into its spot:
```

```
let second = v.swap_remove(1);
assert_eq!(second, "102");

// 3. Swap in another value for the one we're taking out:
let third = std::mem::replace(&mut v[2],
"substitute".to_string());
assert_eq!(third, "103");

// Let's see what's left of our vector.
assert_eq!(v, vec!["101", "104", "substitute"]);
```

Each one of these methods moves an element out of the vector but does so in a way that leaves the vector in a state that is fully populated, if perhaps smaller.

Collection types like `Vec` also generally offer methods to consume all their elements in a loop:

```
let v = vec![
    "liberté".to_string(),
    "égalité".to_string(),
    "fraternité".to_string(),
];

for mut s in v {
    s.push('!');
    println!("{s}");
}
```

When we pass the vector to the loop directly, as in `for ... in v`, this *moves* the vector out of `v`, leaving `v` uninitialized. The `for` loop's internal machinery takes ownership of the vector and dissects it into its elements. At each iteration, the loop moves another element to the variable `s`. Since `s` now owns the string, we're able to modify it in the loop body before printing it. And since the vector itself is no longer visible to the code, nothing can observe it mid-loop in some partially emptied state.

If you do find yourself needing to move a value out of an owner that the compiler can't track, you might consider changing the owner's type to something that can dynamically track whether it has a value or not. For example, here's a variant on the earlier example:

```
struct Person {
    name: Option<String>,
    birth: i32,
}

let mut composers = Vec::new();
composers.push(Person {
    name: Some("Palestrina".to_string()),
    birth: 1525,
});
```

You can't do this:

```
let first_name = composers[0].name;
```

That will just elicit the same "cannot move out of index" error shown earlier. But because you've changed the type of the `name` field from `String` to `Option<String>`, that means that `None` is a legitimate value for the field to hold, so this works:

```
let first_name = std::mem::replace(&mut composers[0].name, None);
assert_eq!(first_name, Some("Palestrina".to_string()));
assert_eq!(composers[0].name, None);
```

The `replace` call moves out the value of `composers[0].name`, leaving `None` in its place, and passes ownership of the original value to its caller. In fact, using `Option` this way is common enough that the type provides a `take` method for this very purpose. You could write the preceding manipulation more legibly as follows:

```
let first_name = composers[0].name.take();
```

This call to `take` has the same effect as the earlier call to `replace`.

## Copy Types: The Exception to Moves

The examples we've shown so far of values being moved involve vectors, strings, and other types that could potentially use a lot of memory and be

expensive to copy. Moves keep ownership of such types clear and assignment cheap. But for simpler types like integers or characters, this sort of careful handling really isn't necessary.

Compare what happens in memory when we assign a `String` with what happens when we assign an `i32` value:

```
let string1 = "somnambulance".to_string();
let string2 = string1;

let num1: i32 = 36;
let num2 = num1;
```

After running this code, memory looks like Figure 4-11.

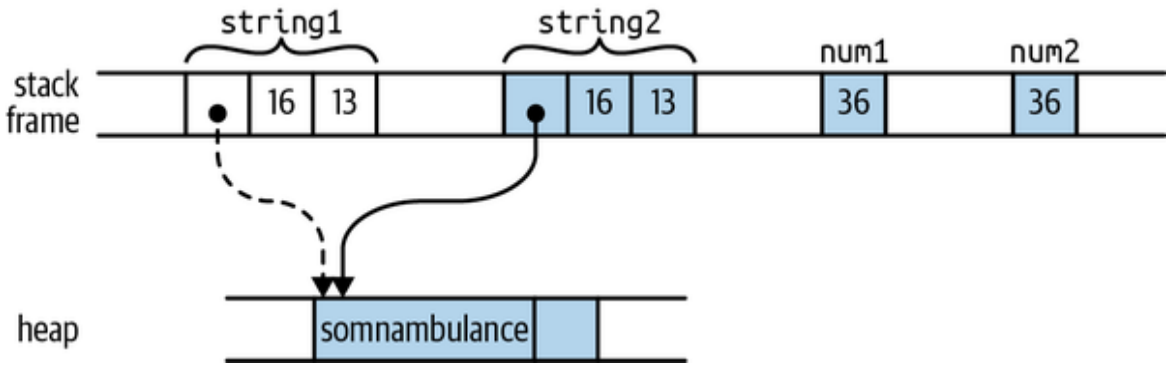


*Figure 4-11. Assigning a `String` moves the value, whereas assigning an `i32` copies it*

As with the vectors earlier, assignment *moves* `string1` to `string2` so that we don't end up with two strings responsible for freeing the same buffer. However, the situation with `num1` and `num2` is different. An `i32` is simply a pattern of bits in memory; it doesn't own any heap resources or really depend on anything other than the bytes it comprises. By the time we've moved its bits to `num2`, we've made a completely independent copy of `num1`.

Moving a value leaves the source of the move uninitialized. But whereas it serves an essential purpose to treat `string1` as valueless, treating `num1` that way is pointless; no harm could result from continuing to use it. The advantages of a move don't apply here, and it's inconvenient.

Earlier we were careful to say that *most* types are moved; now we've come to the exceptions, the types Rust designates as *`Copy` types*. Assigning a value of a `Copy` type copies the value, rather than moving it. The source of the assignment remains initialized and usable, with the same value it had before. Passing `Copy` types to functions and constructors behaves similarly.

The standard `Copy` types include all the machine integer and floating-point numeric types, the `char` and `bool` types, and a few others. A tuple or fixed-size array of `Copy` types is itself a `Copy` type.

Only types for which a simple bit-for-bit copy suffices can be `Copy`. As we've already explained, `String` is not a `Copy` type, because it owns a heap-allocated buffer. For similar reasons, `Box<T>` is not `Copy`; it owns its heap-allocated referent. The `File` type, representing an operating system file handle, is not `Copy`; duplicating such a value would entail asking the operating system for another file handle. Similarly, the `MutexGuard` type, representing a locked mutex, isn't `Copy`: this type isn't meaningful to copy at all, as only one thread may hold a mutex at a time.

As a rule of thumb, any type that needs to do something special when a value is dropped cannot be `Copy`: a `Vec` needs to free its elements, a `File` needs to close its file handle, a `MutexGuard` needs to unlock its mutex, and so on. Bit-for-bit duplication of such types would leave it unclear which value was now responsible for the original's resources.

What about types you define yourself? By default, `struct` and `enum` types are not `Copy`:

```
struct Label {
    number: u32,
}

fn print_label(l: Label) {
    println!("STAMP: {}", l.number);
}

let l = Label { number: 3 };
print_label(l);
println!("My label number is: {}", l.number);
```

This won't compile; Rust complains:

```
error: borrow of moved value: `l`
   |
10 |     let l = Label { number: 3 };
   |         - move occurs because `l` has type `main::Label`,
   |           which does not implement the `Copy` trait
11 |     print_label(l);
   |                 - value moved here
12 |     println!("My label number is: {}", l.number);
   |                                        ^^^^^^^^
   |                  value borrowed here after move
```

Since `Label` is not `Copy`, passing it to `print_label` moved ownership of the value to the `print_label` function, which then dropped it before returning. But this is silly; a `Label` is nothing but a `u32` with pretensions. There's no reason passing `l` to `print_label` should move the value.

But user-defined types being non-`Copy` is only the default. If all the fields of your struct are themselves `Copy`, then you can make the type `Copy` as well by placing the attribute `#[derive(Copy, Clone)]` above the definition, like so:

```
#[derive(Copy, Clone)]
struct Label {
    number: u32,
}
```

With this change, the preceding code compiles without complaint. However, if we try this on a type whose fields are not all `Copy`, it doesn't work. Suppose we compile the following code:

```
#[derive(Copy, Clone)]
struct StringLabel {
    name: String,
}
```

It elicits this error:

```
error: the trait `Copy` cannot be implemented for this type
  |
7 | #[derive(Copy, Clone)]
  |          ---- in this derive macro expansion
8 | struct StringLabel {
  |        ^^^^^^^^^^^
9 |     name: String,
  |     ------------ this field does not implement `Copy`
```

Why aren't user-defined types automatically `Copy`, assuming they're eligible? Whether a type is `Copy` or not has a big effect on how code is allowed to use it: `Copy` types are more flexible, since assignment and related operations don't leave the original uninitialized.

But for a type's implementer, the opposite is true: `Copy` types are very limited in which types they can contain, whereas non-`Copy` types can use heap allocation and own other sorts of resources. So making a type `Copy` represents a serious commitment on the part of the implementer: if it's necessary to change it to non-`Copy` later, much of the code that uses it will probably need to be adapted.

While C++ lets you overload assignment operators and define specialized copy and move constructors, Rust doesn't permit this sort of customization. In Rust, every move is a byte-for-byte, shallow copy that leaves the source uninitialized. Copies are the same, except that the source remains initialized. This does mean that C++ classes can provide convenient interfaces that Rust types cannot, where ordinary-looking code implicitly adjusts reference counts, puts off expensive copies for later, or uses other sophisticated implementation tricks.

But the effect of this flexibility on C++ as a language is to make basic operations like assignment, passing parameters, and returning values from functions less predictable. For example, earlier in this chapter we showed how assigning one variable to another in C++ can require arbitrary amounts of memory and processor time. One of Rust's principles is that costs should be apparent to the programmer. Basic operations must remain simple. Potentially expensive operations should be explicit, like the calls to `clone`

in the earlier example that make deep copies of vectors and the strings they contain.

In this section, we've talked about `Copy` and `Clone` in vague terms as characteristics a type might have. They are actually examples of *traits*, Rust's open-ended facility for categorizing types based on what you can do with them. We describe traits in general in Chapter 11, and `Copy` and `Clone` in particular in Chapter 13.

## Rc and Arc: Shared Ownership

Although most values have unique owners in typical Rust code, in some cases it's difficult to find every value a single owner that has the lifetime you need; you'd like the value to simply live until everyone's done using it. For these cases, Rust provides the reference-counted pointer types `Rc` and `Arc`. As you would expect from Rust, these are entirely safe to use: you cannot forget to adjust the reference count, create other pointers to the referent that Rust doesn't notice, or stumble over any of the other sorts of problems that accompany reference-counted pointer types in C++.

The `Rc` and `Arc` types are very similar; the only difference between them is that an `Arc` is safe to share between threads directly—the name `Arc` is short for *atomic reference count*—whereas a plain `Rc` uses faster non-thread-safe code to update its reference count.

If you don't need to share the pointers between threads, there's no reason to pay the performance penalty of an `Arc`, so you should use `Rc`; Rust will prevent you from accidentally passing one across a thread boundary. The two types are otherwise equivalent, so for the rest of this section, we'll only talk about `Rc`.

Earlier we showed how Python uses reference counts to manage its values' lifetimes. You can use `Rc` to get a similar effect in Rust. Consider the following code:

```
use std::rc::Rc;

// Rust can infer all these types; written out for clarity
let s: Rc<String> = Rc::new("shirataki".to_string());
let t: Rc<String> = s.clone();
let u: Rc<String> = s.clone();
```

For any type `T`, an `Rc<T>` value is a pointer to a heap-allocated `T` that has had a reference count affixed to it. Cloning an `Rc<T>` value does not copy the `T`; instead, it simply creates another pointer to it and increments the reference count. So the preceding code produces the situation illustrated in Figure 4-12 in memory.

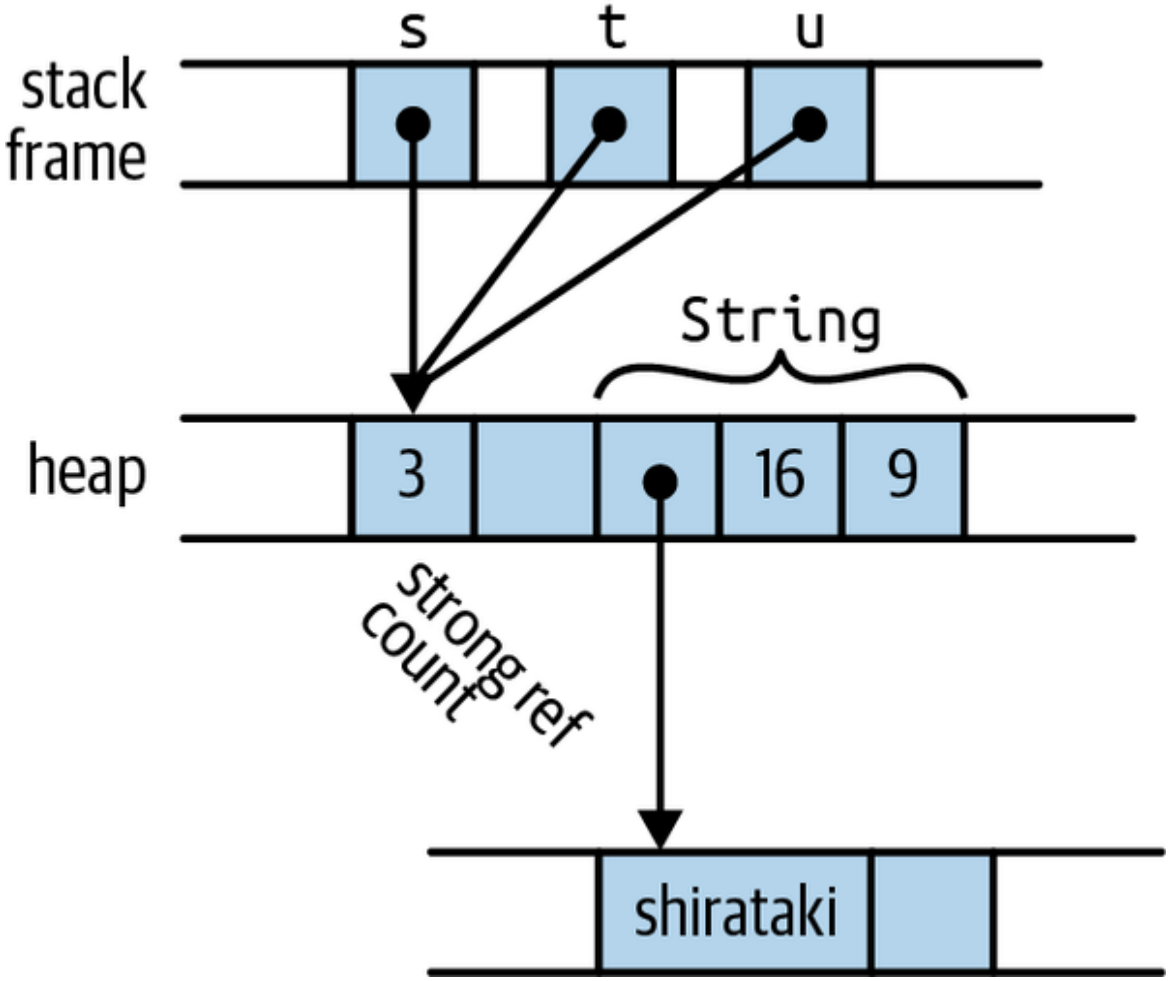


*Figure 4-12. A reference-counted string with three references*

Each of the three `Rc<String>` pointers is referring to the same block of memory, which holds a reference count and space for the `String`. The

usual ownership rules apply to the `Rc` pointers themselves, and when the last extant `Rc` is dropped, Rust drops the `String` as well.

You can use any of `String`'s usual methods directly on an `Rc<String>`:

```
assert!(s.contains("shira"));
assert_eq!(t.find("taki"), Some(5));
println!("{u} are quite chewy, almost bouncy, but lack flavor");
```

A value owned by an `Rc` pointer is immutable. Suppose you try to add some text to the end of the string:

```
s.push_str(" noodles");
```

Rust will decline:

```
error: cannot borrow data in an `Rc` as mutable
   |
13 |     s.push_str(" noodles");
   |     ^ cannot borrow as mutable
   |
```

Rust's memory and thread-safety guarantees depend on ensuring that no value is ever simultaneously shared and mutable. Rust assumes the referent of an `Rc` pointer might in general be shared, so it must not be mutable. We explain why this restriction is important in Chapter 5.

One well-known problem with using reference counts to manage memory is that, if there are ever two reference-counted values that point to each other, each will hold the other's reference count above zero, so the values will never be freed (Figure 4-13).

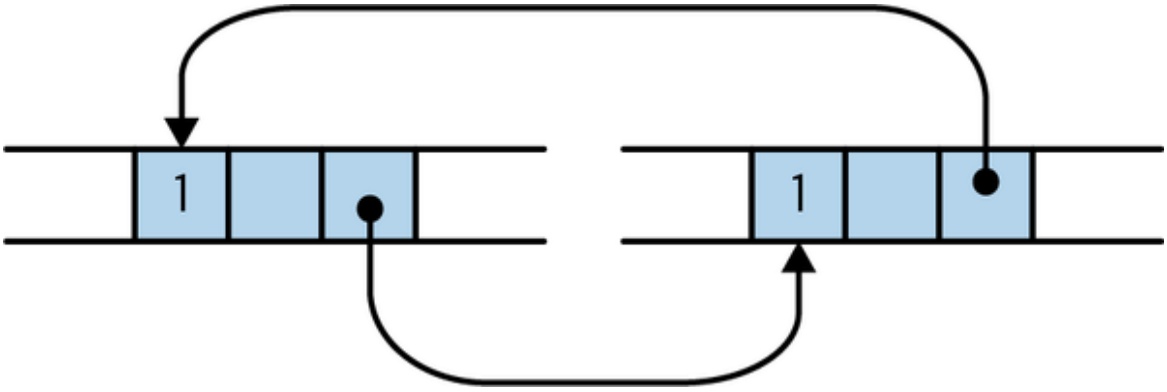


*Figure 4-13. A reference-counting loop; these objects will not be freed*

It is possible to leak values in Rust this way, but such situations are rare. You cannot create a cycle without, at some point, making an older value point to a newer value. This obviously requires the older value to be mutable. Since `Rc` pointers hold their referents immutable, it's not normally possible to create a cycle. However, Rust does provide ways to create mutable portions of otherwise immutable values; this is called *interior mutability*, and we cover it in "Interior Mutability". If you combine those techniques with `Rc` pointers, you can create a cycle and leak memory.

You can sometimes avoid creating cycles of `Rc` pointers by using *weak pointers*, `std::rc::Weak`, for some of the links instead. However, we won't cover those in this book; see the standard library's documentation for details.

Moves and reference-counted pointers are two ways to relax the rigidity of the ownership tree. In the next chapter, we'll look at a third way: borrowing references to values. Once you have become comfortable with both ownership and borrowing, you will have climbed the steepest part of Rust's learning curve, and you'll be ready to take advantage of Rust's unique strengths.

# Chapter 5. References

*Libraries cannot provide new inabilities.*

—Mark Miller

In the previous chapter, we discussed the types `Box<T>`, `Vec<T>`, and `String`, all of which contain a pointer to some data in the heap, which they *own*. A value's owner is responsible for cleaning up after it: dropping a `Box<T>` drops the `T` as well. Rust also has non-owning pointer types called *references*, which have no effect on their referents' lifetimes.

A reference points to a value and grants read or read-write access to it, usually temporary access. It does not grant ownership. Rust refers to creating a reference as *borrowing*: what you have borrowed, you must eventually return to its owner.

The references themselves are nothing special—under the hood, they're just addresses. But the rules that keep them safe are novel to Rust; outside of research languages, you won't have seen anything like them before. And although these rules are the part of Rust that requires the most effort to master, the breadth of classic, absolutely everyday bugs they prevent is surprising, and their effect on multithreaded programming is liberating. This is Rust's radical wager, again.

In this chapter, we'll walk through how references work in Rust; show how references, functions, and user-defined types all incorporate lifetime information to ensure that they're used safely; and illustrate some common categories of bugs that these efforts prevent, at compile time and without run-time performance penalties.

## Reference Basics

As an example, let's suppose we're going to build a table of murderous Renaissance artists and the works they're known for. Rust's standard library

includes a hash table type, so we can define our type like this:

```
use std::collections::HashMap;

type Table = HashMap<String, Vec<String>>;
```

In other words, this is a hash table that maps `String` values to `Vec<String>` values, taking the name of an artist to a list of the names of their works. You can iterate over the entries of a `HashMap` with a `for` loop, so we can write a function to print out a `Table`:

```
fn show(table: Table) {
    for (artist, works) in table {
        println!("works by {artist}:");
        for work in works {
            println!("  {work}");
        }
    }
}
```

Constructing and printing the table is straightforward:

```
fn main() {
    let mut table = Table::new();
    table.insert("Gesualdo".to_string(),
                 vec!["many madrigals".to_string(),
                      "Tenebrae Responsoria".to_string()]);
    table.insert("Caravaggio".to_string(),
                 vec!["The Musicians".to_string(),
                      "The Calling of St. Matthew".to_string()]);
    table.insert("Cellini".to_string(),
                 vec!["Perseus with the head of
Medusa".to_string(),
                      "a salt cellar".to_string()]);

    show(table);
}
```

And it all works fine:

```
$ cargo run
     Running
```

```
`/home/jimb/rust/book/fragments/target/debug/fragments`
works by Gesualdo:
  many madrigals
  Tenebrae Responsoria
works by Cellini:
  Perseus with the head of Medusa
  a salt cellar
works by Caravaggio:
  The Musicians
  The Calling of St. Matthew
$
```

But if you've read the previous chapter's section on moves, this definition for `show` should raise a few questions. In particular, `HashMap` is not `Copy`—it can't be, since it owns a dynamically allocated table. So when the program calls `show(table)`, the whole structure gets moved to the function, leaving the variable `table` uninitialized. (It also iterates over its contents in no specific order, so if you've gotten a different order, don't worry.)

If the calling code tries to use `table` now, it'll run into trouble:

```
...
show(table);
assert_eq!(table["Gesualdo"][0], "many madrigals");
```

Rust complains that `table` isn't available anymore:

```
error: borrow of moved value: `table`
   |
20 |     let mut table = Table::new();
   |         --------- move occurs because `table` has type
   |                   `HashMap<String, Vec<String>>`,
   |                   which does not implement the `Copy` trait
...
31 |     show(table);
   |          ----- value moved here
32 |     assert_eq!(table["Gesualdo"][0], "many madrigals");
   |                ^^^^^ value borrowed here after move
note: consider changing this parameter type in function `show` to
borrow instead
      if owning the value isn't necessary
   |
```

```
7  | fn show(table: Table) {
   |    ----        ^^^^^ this parameter takes ownership of the
value
   |    |
   |    in this function
help: consider cloning the value if the performance cost is
acceptable
   |
35 |     show(table.clone());
   |               ++++++++
```

In fact, if we look into the definition of `show`, the outer `for` loop takes ownership of the hash table and consumes it entirely; and the inner `for` loop does the same to each of the vectors. (We saw this behavior earlier, in the "liberté, égalité, fraternité" example.) Because of move semantics, we've completely destroyed the entire structure simply by trying to print it out. Thanks, Rust!

The compiler helpfully suggests that we could either create a reference or clone the value to avoid this problem. In this case, the right solution is to use references, which let you access a value without affecting its ownership. References come in two kinds:

- A *shared reference* lets you read but not modify its referent. However, you can have as many shared references to a particular value at a time as you like. The expression `&e` yields a shared reference to `e`'s value; if `e` has the type `T`, then `&e` has the type `&T`, pronounced "ref `T`." Shared references are `Copy`.
- If you have a *mutable reference* to a value, you may both read and modify the value. However, you may not have any other references of any sort to that value active at the same time. The expression `&mut e` yields a mutable reference to `e`'s value; you write its type as `&mut T`, which is pronounced "ref mute `T`." Mutable references are not `Copy`.

You can think of the distinction between shared and mutable references as a way to enforce a *multiple readers or single writer* rule at compile time. In

fact, this rule doesn't apply only to references; it covers the borrowed value's owner as well. As long as there are shared references to a value, not even its owner can modify it; the value is locked down. Nobody can modify `table` while `show` is working with it. Similarly, if there is a mutable reference to a value, it has exclusive access to the value; you can't use the owner at all until the mutable reference goes away. Keeping sharing and mutation fully separate turns out to be essential to memory safety, for reasons we'll go into later.

The printing function in our example doesn't need to modify the table, just read its contents. The caller should be able to pass it a shared reference to the table, as follows:

```
show(&table);
```

References are non-owning pointers, so the `table` variable remains the owner of the entire structure; `show` has just borrowed it for a bit. Naturally, we'll need to adjust the definition of `show` to match, but you'll have to look closely to see the difference:

```
fn show(table: &Table) {
    for (artist, works) in table {
        println!("works by {artist}:");
        for work in works {
            println!("  {work}");
        }
    }
}
```

The type of `show`'s parameter `table` has changed from `Table` to `&Table`: instead of passing the table by value (and hence moving ownership into the function), we're now passing a shared reference. That's the only textual change. But how does this play out as we work through the body?

Whereas our original outer `for` loop took ownership of the `HashMap` and consumed it, in our new version it receives a shared reference to the

`HashMap`. Iterating over a shared reference to a `HashMap` is defined to produce shared references to each entry's key and value: `artist` has changed from a `String` to a `&String`, and `works` from a `Vec<String>` to a `&Vec<String>`.

The inner loop is changed similarly. Iterating over a shared reference to a vector is defined to produce shared references to its elements, so `work` is now a `&String`. No ownership changes hands anywhere in this function; it's just passing around non-owning references.

Now, if we wanted to write a function to alphabetize the works of each artist, a shared reference doesn't suffice, since shared references don't permit modification. Instead, the sorting function needs to take a mutable reference to the table:

```
fn sort_works(table: &mut Table) {
    for (_artist, works) in table {
        works.sort();
    }
}
```

And we need to pass it one:

```
sort_works(&mut table);
```

This mutable borrow grants `sort_works` the ability to read and modify our structure, as required by the vectors' `sort` method.

When we pass a value to a function in a way that moves ownership of the value to the function, we say that we have passed it *by value*. If we instead pass the function a reference to the value, we say that we have passed the value *by reference*.

For example, we fixed our `show` function by changing it to accept the table by reference, rather than by value. Many languages draw this distinction, but it's especially important in Rust, because it spells out how ownership is affected.

# Working with References

The preceding example shows a pretty typical use for references: allowing functions to access or manipulate a structure without taking ownership. But references are more flexible than that, so let's look at some examples to get a more detailed view of what's going on.

## Implicit and Explicit References

If you're familiar with references in C++, you'll have noticed Rust references are quite similar. Most importantly, they're both just addresses at the machine level. The syntax is a bit different, though.

In C++, references are created implicitly by conversion and dereferenced implicitly:

```
// C++ code!
int x = 10;
int& r = x;            // initialization creates reference
implicitly
assert(r == 10);       // implicitly dereference r to see x's
value
r = 20;                // stores 20 in x, r itself still points to
x
```

In Rust, references are created explicitly with the `&` operator and dereferenced explicitly with the `*` operator:

```
// Back to Rust code from this point onward.
let x = 10;
let r = &x;            // &x is a shared reference to x
assert_eq!(*r, 10);    // explicitly dereference r
```

To create a mutable reference, use the `&mut` operator:

```
let mut y = 32;
let m = &mut y;        // &mut y is a mutable reference to y
*m += 32;              // explicitly dereference m to set y's
value
assert_eq!(*m, 64);    // or to get y's current value
```

But you might recall that, when we fixed the `show` function to take the table of artists by reference instead of by value, we never had to use the `&` or `*` operator. In fact, the body of the function didn't have to change at all. Why is that?

Since references are so widely used in Rust, the language often supports using a reference in place of a value. For example, printing a reference is the same as printing its value, so `println!("works by {artist}:");` does the same thing whether `artist` is a `String` or a reference to one. As we already mentioned, a `for` loop over a reference produces references to the values inside. No explicit `*` is needed in either case.

The `.` operator also implicitly dereferences its left operand, if needed:

```
let aria = Anime {
    name: "Aria: The Animation",
    bechdel_pass: true,
};
let anime_ref = &aria;
assert_eq!(anime_ref.name, "Aria: The Animation");

// Equivalent to the above, but with the dereference written out:
assert_eq!((*anime_ref).name, "Aria: The Animation");
```

The `.` operator can also implicitly borrow a reference to its left operand, if needed for a method call. For example, `Vec`'s `sort` method takes a mutable reference to the vector, so these two calls are equivalent:

```
let mut v = vec![1973, 1968];
v.sort();           // implicitly borrows a mutable reference to
v
(&mut v).sort();    // equivalent, but more verbose
```

In short, Rust automatically creates references and dereferences them in a few places, for convenience. Everywhere else, the `&` and `*` operators are required, for clarity.

## Assigning References

Assigning a reference to a variable makes that variable point somewhere new:

```
let x = 10;
let y = 20;
let mut r = &x;

if b {
    r = &y;
}

assert!(*r == 10 || *r == 20);
```

The reference `r` initially points to `x`. But if `b` is true, the code points it at `y` instead, as illustrated in Figure 5-1.

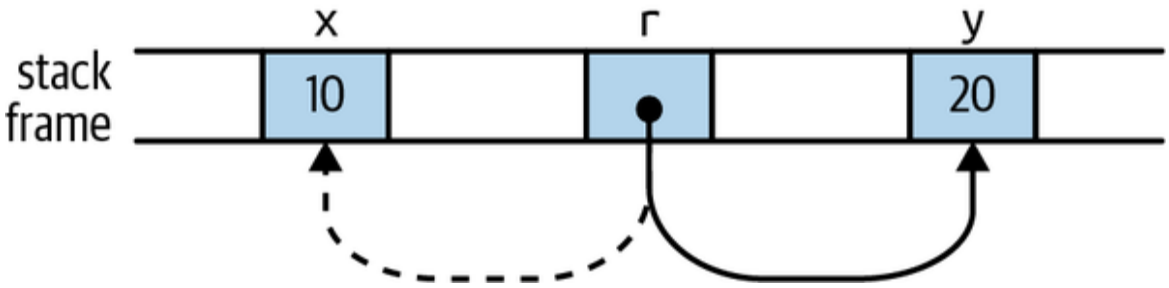


*Figure 5-1. The reference `r`, now pointing to `y` instead of `x`*

This behavior may seem too obvious to be worth mentioning: of course `r` now points to `y`, since we stored `&y` in it. But we point this out because C++ references behave very differently: as shown earlier, assigning a value to a reference in C++ stores the value in its referent. Once a C++ reference has been initialized, there's no way to make it point at anything else.

## References to References

Rust permits references to references:

```
struct Point {
    x: i32,
    y: i32,
```

```
}

let point = Point { x: 1000, y: 729 };
let r: &Point = &point;
let rr: &&Point = &r;
let rrr: &&&Point = &rr;
```

(We've written out the reference types for clarity, but you could omit them; there's nothing here Rust can't infer for itself.) The `.` operator follows as many references as it takes to find its target:

```
assert_eq!(rrr.y, 729);
```

In memory, the references are arranged as shown in Figure 5-2.

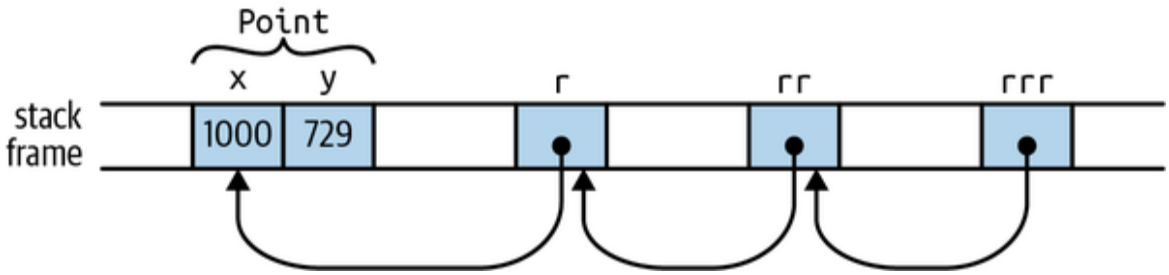


*Figure 5-2. A chain of references to references*

So the expression `rrr.y`, guided by the type of `rrr`, actually traverses three references to get to the `Point` before fetching its `y` field.

## Comparing References

Like the `.` operator, Rust's comparison operators "see through" any number of references:

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

let rx = &x;
let ry = &y;

let rrx = &rx;
let rry = &ry;
```

```
assert!(rrx <= rry);
assert!(rrx == rry);
```

The final assertion here succeeds, even though `rrx` and `rry` point at different values (namely, `rx` and `ry`), because the == operator follows all the references and performs the comparison on their final targets, `x` and `y`. This is almost always the behavior you want, especially when writing generic functions. If you actually want to know whether two references point to the same memory, you can use `std::ptr::eq`, which compares them as addresses:

```
assert!(rx == ry);                // their referents are equal
assert!(!std::ptr::eq(rx, ry));   // but occupy different
addresses
```

Note that the operands of a comparison must have exactly the same type, including the references:

```
assert!(rx == rrx);   // error: type mismatch: `&i32` vs `&&i32`
assert!(rx == *rrx);  // this is okay
```

## References Are Never Null

Rust references are never null. There's no analogue to C's `NULL` or C++'s `nullptr`. There is no default initial value for a reference (you can't use any variable until it's been initialized, regardless of its type), and Rust won't convert integers to references (outside of `unsafe` code), so you can't convert zero into a reference.

C and C++ code often uses a null pointer to indicate the absence of a value: for example, the `malloc` function returns either a pointer to a new block of memory or `nullptr` if there isn't enough memory available to satisfy the request. In Rust, if you need a value that is either a reference to something or not, use the type `Option<&T>`. At the machine level, Rust represents `None` as a null pointer and `Some(r)`, where `r` is a `&T` value, as the nonzero address, so `Option<&T>` is just as efficient as a nullable pointer

in C or C++, even though it's safer: its type requires you to check whether it's `None` before you can use it.

## Borrowing References to Arbitrary Expressions

Whereas C and C++ only let you apply the `&` operator to certain kinds of expressions, Rust lets you borrow a reference to the value of any sort of expression at all:

```
fn factorial(n: usize) -> usize {
    (1..n + 1).product()
}
let r = &factorial(6);
// Arithmetic operators can see through one level of references.
assert_eq!(r + &1009, 1729);
```

In situations like this, Rust simply creates an anonymous variable to hold the expression's value and makes the reference point to that. The lifetime of this anonymous variable depends on what you do with the reference:

- If you immediately assign the reference to a variable in a `let` statement (or make it part of some struct or array that is being immediately assigned), then Rust makes the anonymous variable live as long as the variable the `let` initializes. In the preceding example, Rust would do this for the referent of `r`.
- Otherwise, the anonymous variable lives to the end of the enclosing statement. In our example, the anonymous variable created to hold `1009` lasts only to the end of the `assert_eq!` statement.

If you're used to C or C++, this may sound error-prone. But remember that Rust will never let you write code that would produce a dangling reference. If the reference could ever be used beyond the anonymous variable's lifetime, Rust will always report the problem to you at compile time. You can then fix your code to keep the referent in a named variable with an appropriate lifetime.

### Fat Pointers

The references we've shown so far are all simple addresses. A reference to a slice is slightly different. It contains both the starting address of the slice and its length. Because slice references have these two fields, they are larger than other references. They are called *fat pointers*.

There is one other kind of fat pointer in Rust: pointers to trait objects, using the `dyn` keyword. We'll cover those in "Using dyn".

Aside from carrying a little extra data, slice and trait object references behave just like the other sorts of references we've shown so far in this chapter: they don't own their referents, they are not allowed to outlive their referents, they may be mutable or shared, and so on.

## Reference Safety

As we've presented them so far, references look pretty much like ordinary pointers in C or C++. But those are unsafe; how does Rust keep its references under control? Perhaps the best way to see the rules in action is to try to break them.

To convey the fundamental ideas, we'll start with the simplest cases, showing how Rust ensures references are used properly within a single function body. Then we'll look at passing references between functions and storing them in data structures. This entails giving said functions and data types *lifetime parameters*, which we'll explain. Finally, we'll present some shortcuts that Rust provides to simplify common usage patterns. Throughout, we'll be showing how Rust points out broken code and often suggests solutions.

### Borrowing a Local Variable

Here's a pretty obvious case. You can't borrow a reference to a local variable and take it out of the variable's scope:

```
{
    let r;
    {
        let x = 1;
        r = &x;
    }
    assert_eq!(*r, 1);  // bad: reads memory `x` used to occupy
}
```

The Rust compiler rejects this program, with a detailed error message:

```
error: `x` does not live long enough
   |
7  |          r = &x;
   |              ^^ borrowed value does not live long enough
8  |      }
   |      - `x` dropped here while still borrowed
9  |      assert_eq!(*r, 1);  // bad: reads memory `x` used to
occupy
   |      ----------------- borrow later used here
```

Rust's complaint is that `x` lives only until the end of the inner block, whereas the reference to it is used later, in the outer block, which is verboten.

While it's obvious to a human reader that this program is broken, it's worth looking at how Rust itself reached that conclusion. Even this simple example shows the logical tools Rust uses to check much more complex code.

Rust tries to assign each reference in your program a *lifetime* that meets the constraints imposed by how it is used. A lifetime is some stretch of your program for which a reference could be safe to use: a statement, an expression, the scope of some variable, or the like.

There is only one reference borrowed in this code: the reference we borrow to `x` and store in `r`. Rust will try to assign a valid lifetime to that reference. If it succeeds, the code is valid. However, there are two constraints on this lifetime. First, the reference to `x` must not outlive `x` itself, as shown in Figure 5-3.

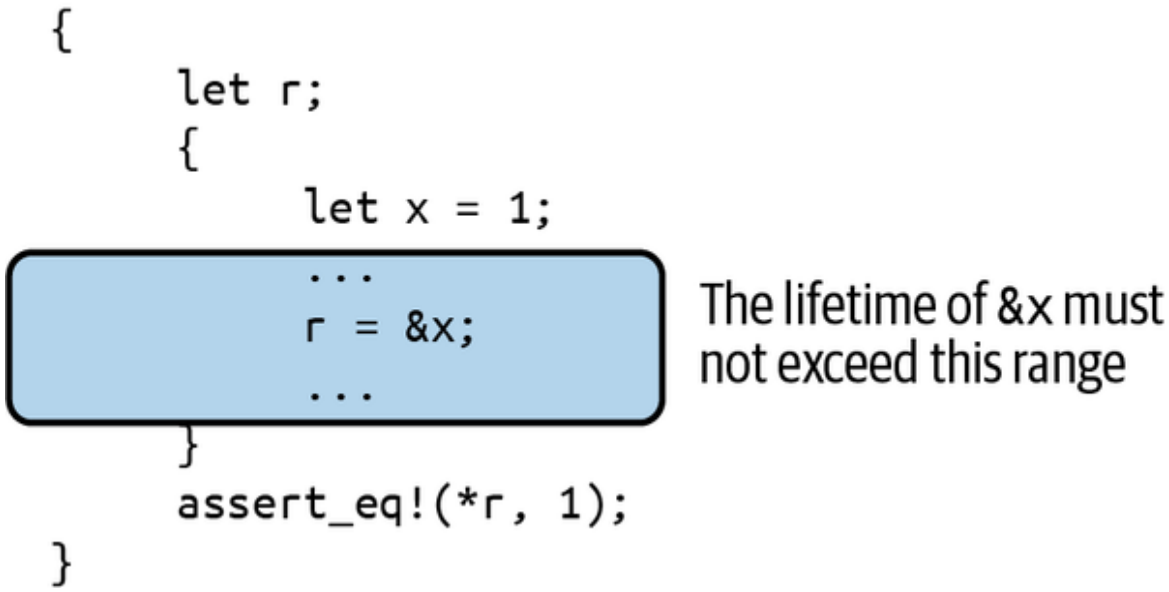


*Figure 5-3. Permissible lifetimes for `&x`*

Beyond the point where `x` goes out of scope, the reference becomes a dangling pointer. We say that the variable's lifetime must *contain* or *enclose* that of the reference borrowed from it. Second, the reference's lifetime must last all the way to its last use, as shown in Figure 5-4.

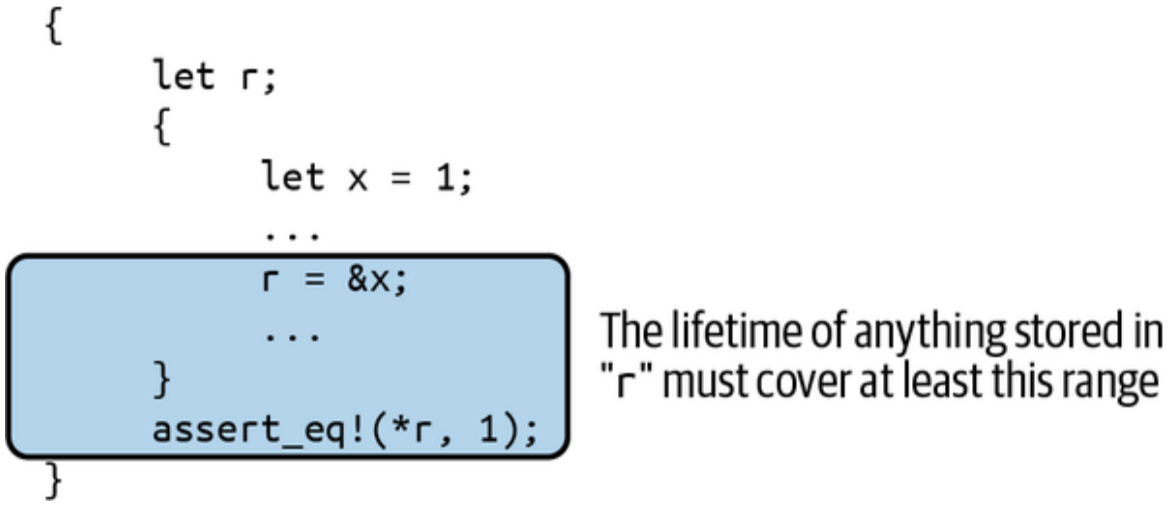


*Figure 5-4. Permissible lifetimes for reference stored in `r`*

When we dereference `r` at the end of the example, Rust concludes that the lifetime must extend to that point. We say that the reference's lifetime must contain or enclose all its uses.

The first kind of constraint limits how large a reference's lifetime can be, while the second kind limits how small it can be. Rust simply tries to find a lifetime for each reference that satisfies all these constraints. In our example, however, there is no such lifetime, as shown in Figure 5-5.

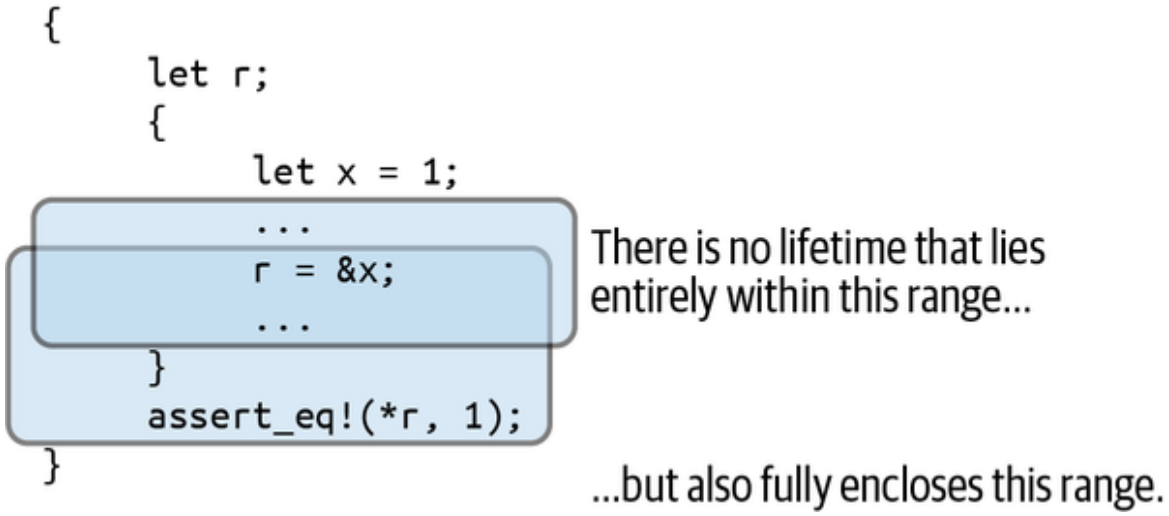


*Figure 5-5. A reference with contradictory constraints on its lifetime*

Let's now consider a different example where things do work out. We have the same kinds of constraints: the reference's lifetime must be contained by `x`'s but fully enclose `r`'s. But because `r`'s last use is inside the scope of `x` now, there is a lifetime that meets the constraints, as shown in Figure 5-6.

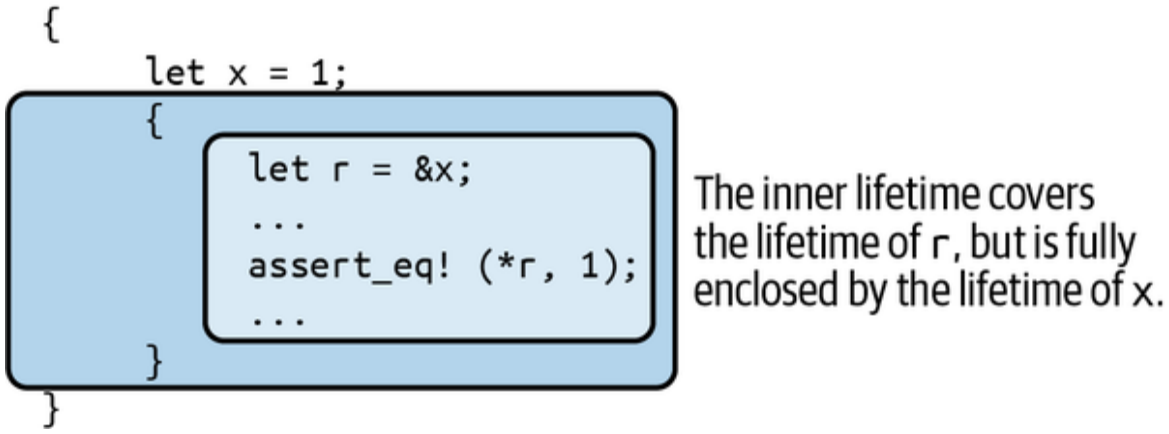


*Figure 5-6. A reference with a lifetime enclosing `r`'s scope, but within `x`'s scope*

These rules apply in a natural way when you borrow a reference to some part of some larger data structure, like an element of a vector:

```
let v = vec![1, 2, 3];
let r = &v[1];
```

Since `v` owns the vector, which owns its elements, the lifetime of `v` must enclose that of the reference `&v[1]`. Similarly, if you store a reference in some data structure, its lifetime must enclose that of the data structure. For example, if you build a vector of references, all of them must have lifetimes enclosing that of the variable that owns the vector.

Note that lifetimes are strictly a compile-time concept. They are figments of the Rust compiler's imagination:

*Lifetimes don't take up space at run time.*

> They have no in-memory representation. At run time, a reference is nothing but an address.

*Lifetimes don't control how long values last.*

> A value in a variable is dropped when you assign a different value to it or the variable goes out of scope. Lifetimes can't change that.

*Lifetimes don't affect the compiled code.*

> The Rust compiler uses them to check that your code is safe, then discards them.

The process we've described in this section is essentially the way the Rust borrow checker validates all code. Bringing more language features into the picture—e.g., data structures and function calls—introduces new sorts of constraints, but the principle remains the same: first, understand the constraints arising from the way the program uses references; then, find lifetimes that satisfy those constraints. This is not so different from the process C and C++ programmers impose on themselves; the difference is that Rust knows the rules and enforces them.

## Receiving References as Function Arguments

When we pass a reference to a function, how does Rust make sure the function uses it safely? Suppose we have a function `f` that takes a reference and stores it in a global variable. We'll need to make a few revisions to this, but here's a first cut:

```
// This code has several problems, and doesn't compile.
static mut STASH: &i32;
fn f(p: &i32) {
    STASH = p;
}
```

Rust's equivalent of a global variable is called a *static*: it's a value that's created when the program starts and lasts until it terminates. (Like any other declaration, Rust's module system controls where statics are visible, so they're only "global" in their lifetime, not their visibility.) We cover statics in Chapter 8, but for now we'll just call out a few rules that the code just shown doesn't follow:

- Every static must be initialized.
- Mutable statics are inherently not thread-safe (after all, any thread can access a static at any time), and even in single-threaded programs, they can fall prey to other sorts of reentrancy problems. For these reasons, you may access a mutable static only within an `unsafe` block. In this example we're not concerned with those particular problems, so we'll just throw in an `unsafe` block and move on.

With those revisions made, we now have the following:

```
static mut STASH: &i32 = &128;
fn f(p: &i32) {  // still not good enough
    unsafe {
        STASH = p;
    }
}
```

We're almost done. To see the remaining problem, we need to write out a few things that Rust is helpfully letting us omit. The signature of `f` as written here is actually shorthand for the following:

```
fn f<'a>(p: &'a i32) { ... }
```

Here, the lifetime `'a` (pronounced "tick A") is a *lifetime parameter* of `f`. You can read `<'a>` as "for any lifetime `'a`" so when we write `fn f<'a>(p: &'a i32)`, we're defining a function that takes a reference to an `i32` with any given lifetime `'a`.

Since we must allow `'a` to be any lifetime, things had better work out if it's the smallest possible lifetime: one just enclosing the call to `f`. This assignment then becomes a point of contention:

```
STASH = p;
```

Since `STASH` lives for the program's entire execution, the reference type it holds must have a lifetime of the same length; Rust calls this the *`'static` lifetime*. But the lifetime of `p`'s reference is some `'a`, which could be anything, as long as it encloses the call to `f`. So, Rust rejects our code:

```
error: lifetime may not live long enough
  |
3 | fn f(p: &i32) {  // still not good enough
  |         - let's call the lifetime of this reference `'1`
...
5 |         STASH = p;
  |         ^^^^^^^^^ assignment requires that `'1` must outlive
`'static`
```

At this point, it's clear that our function can't accept just any reference as an argument. But as Rust points out, it ought to be able to accept a reference that has a `'static` lifetime: storing such a reference in `STASH` can't create a dangling pointer. And indeed, the following code compiles just fine:

```
static mut STASH: &i32 = &10;

fn f(p: &'static i32) {
    unsafe {
        STASH = p;
    }
}
```

This time, `f`'s signature spells out that `p` must be a reference with lifetime `'static`, so there's no longer any problem storing that in `STASH`. We can only apply `f` to references to other statics, but that's the only thing that's certain not to leave `STASH` dangling anyway. So we can write:

```
static WORTH_POINTING_AT: i32 = 1000;
f(&WORTH_POINTING_AT);
```

Since `WORTH_POINTING_AT` is a static, the type of `&WORTH_POINTING_AT` is `&'static i32`, which is safe to pass to `f`.

Take a step back, though, and notice what happened to `f`'s signature as we amended our way to correctness: the original `f(p: &i32)` ended up as `f(p: &'static i32)`. In other words, we were unable to write a function that stashed a reference in a global variable without reflecting that intention in the function's signature. In Rust, a function's signature always exposes the body's behavior.

Conversely, if we do see a function with a signature like `g(p: &i32)` (or with the lifetimes written out, `g<'a>(p: &'a i32)`), we can tell that it *does not* stash its argument `p` anywhere that will outlive the call. There's no need to look into `g`'s definition; the signature alone tells us what `g` can and can't do with its argument. This fact ends up being very useful when you're trying to establish the safety of a call to the function.

## Passing References to Functions

Now that we've shown how a function's signature relates to its body, let's examine how it relates to the function's callers. Suppose you have the following code:

```
// This could be written more briefly: fn g(p: &i32),
// but let's write out the lifetimes for now.
fn g<'a>(p: &'a i32) { ... }

let x = 10;
g(&x);
```

From `g`'s signature alone, Rust knows it will not save `p` anywhere that might outlive the call: any lifetime that encloses the call must work for `'a`. So Rust chooses the smallest possible lifetime for `&x`: that of the call to `g`. This meets all constraints: it doesn't outlive `x`, and it encloses the entire call to `g`. So this code passes muster.

Note that although `g` takes a lifetime parameter `'a`, we didn't need to mention it when calling `g`. You only need to worry about lifetime parameters when defining functions and types; when using them, Rust infers the lifetimes for you.

What if we tried to pass `&x` to function `f` from earlier that stores its argument in a static?

```
fn f(p: &'static i32) { ... }

let x = 10;
f(&x);
```

This fails to compile: the reference `&x` must not outlive `x`, but by passing it to `f`, we constrain it to live at least as long as `'static`. There's no way to satisfy everyone here, so Rust rejects the code.

## Returning References

It's common for a function to take a reference to some data structure and then return a reference into some part of that structure. For example, here's a function that returns a reference to the smallest element of a slice:

```
// v should have at least one element.
fn smallest(v: &[i32]) -> &i32 {
    let mut s = &v[0];
```

```
    for r in &v[1..] {
        if *r < *s {
            s = r;
        }
    }
    s
}
```

We've omitted lifetimes from that function's signature in the usual way. When a function takes a single reference as an argument and returns a single reference, Rust assumes that the two have the same lifetime. Writing this out explicitly would give us:

```
fn smallest<'a>(v: &'a [i32]) -> &'a i32 { ... }
```

Suppose we call `smallest` like this:

```
let s;
{
    let parabola = [9, 4, 1, 0, 1, 4, 9];
    s = smallest(&parabola);
}
assert_eq!(*s, 0);  // bad: points to element of dropped array
```

From `smallest`'s signature, we can see that its argument and return value must have the same lifetime, `'a`. In our call, the argument `&parabola` must not outlive `parabola` itself, yet `smallest`'s return value must live at least as long as `s`.

There's no possible lifetime `'a` that can satisfy both constraints. Rust rejects the code:

```
error: `parabola` does not live long enough
   |
10 |         let parabola = [9, 4, 1, 0, 1, 4, 9];
   |             -------- binding `parabola` declared here
11 |         s = smallest(&parabola);
   |                      -------- borrowed value does not live
long enough
12 |     }
   |     - `parabola` dropped here while still borrowed
```

```
13 |     assert_eq!(*s, 0);  // bad: points to element of dropped
array
   |     ----------------- borrow later used here
```

Moving `s` so that its lifetime is clearly contained within `parabola`'s fixes the problem:

```
{
    let parabola = [9, 4, 1, 0, 1, 4, 9];
    let s = smallest(&parabola);
    assert_eq!(*s, 0);  // fine: parabola still alive
}
```

Lifetimes in function signatures let Rust assess the relationships between the references you pass to the function and those the function returns, and they ensure they're being used safely.

## Structs Containing References

How does Rust handle references stored in data structures? Here's the same erroneous program we looked at earlier, except that we've put the reference inside a structure:

```
// This does not compile.
struct S {
    r: &i32,
}

let s;
{
    let x = 10;
    s = S { r: &x };
}
assert_eq!(*s.r, 10);  // bad: reads from dropped `x`
```

The safety constraints Rust places on references can't magically disappear just because we hid the reference inside a struct. Somehow, those constraints must end up applying to `S` as well. Indeed, Rust is skeptical:

```
error: missing lifetime specifier
  |
7 |         r: &i32
  |            ^ expected named lifetime parameter
```

Whenever a reference type appears inside another type's definition, you must write out its lifetime. You can write this:

```
struct S {
    r: &'static i32,
}
```

This says that `r` can only refer to `i32` values that will last for the lifetime of the program, which is rather limiting. The alternative is to give the type a lifetime parameter `'a` and use that for `r`:

```
struct S<'a> {
    r: &'a i32,
}
```

Now the `S` type has a lifetime, just as reference types do. Each value you create of type `S` gets a fresh lifetime `'a`, which becomes constrained by how you use the value. The lifetime of any reference you store in `r` had better enclose `'a`, and `'a` must outlast the lifetime of wherever you store the `S`.

Turning back to the preceding code, the expression `S { r: &x }` creates a fresh `S` value with some lifetime `'a`. When you store `&x` in the `r` field, you constrain `'a` to lie entirely within `x`'s lifetime.

The assignment `s = S { ... }` stores this `S` in a variable whose lifetime extends to the end of the example, constraining `'a` to outlast the lifetime of `s`. And now Rust has arrived at the same contradictory constraints as before: `'a` must not outlive `x` yet must live at least as long as `s`. No satisfactory lifetime exists, and Rust rejects the code. Disaster averted!

How does a type with a lifetime parameter behave when placed inside some other type?

```
struct D {
    s: S,  // not adequate
}
```

Rust is skeptical, just as it was when we tried placing a reference in `S` without specifying its lifetime:

```
error: missing lifetime specifier
  |
8 |     s: S,  // not adequate
  |        ^ expected named lifetime parameter
  |
```

We can't leave off `S`'s lifetime parameter here: Rust needs to know how `D`'s lifetime relates to that of the reference in its `S` in order to apply the same checks to `D` that it does for `S` and plain references.

We could give `s` the `'static` lifetime. This works:

```
struct D {
    s: S<'static>,
}
```

With this definition, the `s` field may only borrow values that live for the entire execution of the program. That's somewhat restrictive, but it does mean that `D` can't possibly borrow a local variable; there are no special constraints on `D`'s lifetime.

The error message from Rust suggests another approach, which is more general:

```
help: consider introducing a named lifetime parameter
  |
7 | struct D<'a> {
8 |     s: S<'a>,
  |
```

Here, we give `D` its own lifetime parameter and pass that to `S`:

```
struct D<'a> {
    s: S<'a>,
}
```

By taking a lifetime parameter `'a` and using it in `s`'s type, we've allowed Rust to relate `D` value's lifetime to that of the reference its `S` holds.

We showed earlier how a function's signature exposes what it does with the references we pass it. Now we've shown something similar about types: a type's lifetime parameters always reveal whether it contains references with interesting (that is, non-`'static`) lifetimes and what those lifetimes can be.

For example, suppose we have a parsing function that takes a slice of bytes and returns a structure holding the results of the parse:

```
fn parse_record<'i>(input: &'i [u8]) -> Record<'i> { ... }
```

Without looking into the definition of the `Record` type at all, we can tell that, if we receive a `Record` from `parse_record`, whatever references it contains must point into the input buffer we passed in, and nowhere else (except perhaps at `'static` values).

In fact, this exposure of internal behavior is the reason Rust requires types that contain references to take explicit lifetime parameters. There's no reason Rust couldn't simply make up a distinct lifetime for each reference in the struct and save you the trouble of writing them out. Early versions of Rust actually behaved this way, but developers found it confusing: it is helpful to know when one value borrows something from another value, especially when working through errors.

It's not just references and types like `S` that have lifetimes. Every type in Rust has a lifetime, including `i32` and `String`. Most are simply `'static`, meaning that values of those types can live for as long as you like; for example, a `Vec<i32>` is self-contained and needn't be dropped

before any particular variable goes out of scope. But a type like `Vec<&'a i32>` has a lifetime that must be enclosed by `'a`: it must be dropped while its referents are still alive.

## Distinct Lifetime Parameters

Suppose you've defined a structure containing two references like this:

```
struct S<'a> {
    x: &'a i32,
    y: &'a i32,
}
```

Both references use the same lifetime `'a`. This could be a problem if your code wants to do something like this:

```
let x = 10;
let r;
{
    let y = 20;
    {
        let s = S { x: &x, y: &y };
        r = s.x;
    }
}
println!("{r}");
```

This code doesn't create any dangling pointers. The reference to `y` stays in `s`, which goes out of scope before `y` does. The reference to `x` ends up in `r`, which doesn't outlive `x`.

If you try to compile this, however, Rust will complain that `y` does not live long enough, even though it clearly does. Why is Rust worried? If you work through the code carefully, you can follow its reasoning:

- Both fields of `S` are references with the same lifetime `'a`, so Rust must find a single lifetime that works for both `s.x` and `s.y`.
- We assign `r = s.x`, requiring `'a` to enclose `r`'s lifetime.

- We initialized `s.y` with `&y`, requiring `'a` to be no longer than `y`'s lifetime.

These constraints are impossible to satisfy: no lifetime is shorter than `y`'s scope but longer than `r`'s. Rust balks. The problem arises because both references in `S` have the same lifetime `'a`. Changing the definition of `S` to let each reference have a distinct lifetime fixes everything:

```
struct S<'a, 'b> {
    x: &'a i32,
    y: &'b i32,
}
```

With this definition, `s.x` and `s.y` have independent lifetimes. What we do with `s.x` has no effect on what we store in `s.y`, so it's easy to satisfy the constraints now: `'a` can simply be `r`'s lifetime, and `'b` can be `s`'s. (`y`'s lifetime would work too for `'b`, but Rust tries to choose the smallest lifetime that works.) Everything ends up fine.

Function signatures can have similar effects. Suppose we have a function like this:

```
fn f<'a>(r: &'a i32, s: &'a i32) -> &'a i32 { r }  // perhaps too
tight
```

Here, both reference parameters use the same lifetime `'a`, which can unnecessarily constrain the caller in the same way we've shown previously. If this is a problem, you can let parameters' lifetimes vary independently:

```
fn f<'a, 'b>(r: &'a i32, s: &'b i32) -> &'a i32 { r }  // looser
```

The downside to this is that adding lifetimes can make types and function signatures harder to read. Your authors tend to try the simplest possible definition first and then loosen restrictions until the code compiles. Since Rust won't permit the code to run unless it's safe, simply waiting to be told when there's a problem is a perfectly acceptable tactic.

## Omitting Lifetime Parameters

We've shown plenty of functions so far in this book that return references or take them as parameters, but we've usually not needed to spell out which lifetime is which. The lifetimes are there; Rust is just letting us omit them when it's reasonably obvious what they should be.

In the simplest cases, you may never need to write out lifetimes for your parameters. Rust just assigns a distinct lifetime to each spot that needs one. For example:

```
struct S<'a, 'b> {
    x: &'a i32,
    y: &'b i32,
}

fn sum_r_xy(r: &i32, s: S) -> i32 {
    r + s.x + s.y
}
```

This function's signature is shorthand for:

```
fn sum_r_xy<'a, 'b, 'c>(r: &'a i32, s: S<'b, 'c>) -> i32
```

If you do return references or other types with lifetime parameters, Rust still tries to make the unambiguous cases easy. If there's only a single lifetime that appears among your function's parameters, then Rust assumes any lifetimes in your return value must be that one:

```
fn first_third(point: &[i32; 3]) -> (&i32, &i32) {
    (&point[0], &point[2])
}
```

With all the lifetimes written out, the equivalent would be:

```
fn first_third<'a>(point: &'a [i32; 3]) -> (&'a i32, &'a i32)
```

If there are multiple lifetimes among your parameters, then there's no natural reason to prefer one over the other for the return value, and Rust

makes you spell out what's going on.

If your function is a method on some type and takes its `self` parameter by reference, then that breaks the tie: Rust assumes that `self`'s lifetime is the one to give everything in your return value. (A `self` parameter refers to the value the method is being called on. It's Rust's equivalent of `this` in C++, Java, or JavaScript, or `self` in Python. We'll cover methods in "Defining Methods with impl".)

For example, you can write the following:

```
struct StringTable {
    elements: Vec<String>,
}

impl StringTable {
    fn find_by_prefix(&self, prefix: &str) -> Option<&String> {
        for i in 0..self.elements.len() {
            if self.elements[i].starts_with(prefix) {
                return Some(&self.elements[i]);
            }
        }
        None
    }
}
```

The `find_by_prefix` method's signature is shorthand for:

```
fn find_by_prefix<'a, 'b>(&'a self, prefix: &'b str) ->
Option<&'a String>
```

Rust assumes that whatever you're borrowing, you're borrowing from `self`. Again, these are just abbreviations, meant to be helpful without introducing surprises. When they're not what you want, you can always write the lifetimes out explicitly.

## Sharing Versus Mutation

So far, we've discussed how Rust ensures no reference will ever point to a variable that has gone out of scope. But there are other ways to introduce dangling pointers. Here's an easy case:

```
let v = vec![4, 8, 19, 27, 34, 10];
let r = &v;
let aside = v;  // move vector to aside
r[0];           // bad: uses `v`, which is now uninitialized
```

The assignment to `aside` moves the vector, leaving `v` uninitialized, and turns `r` into a dangling pointer, as shown in Figure 5-7.

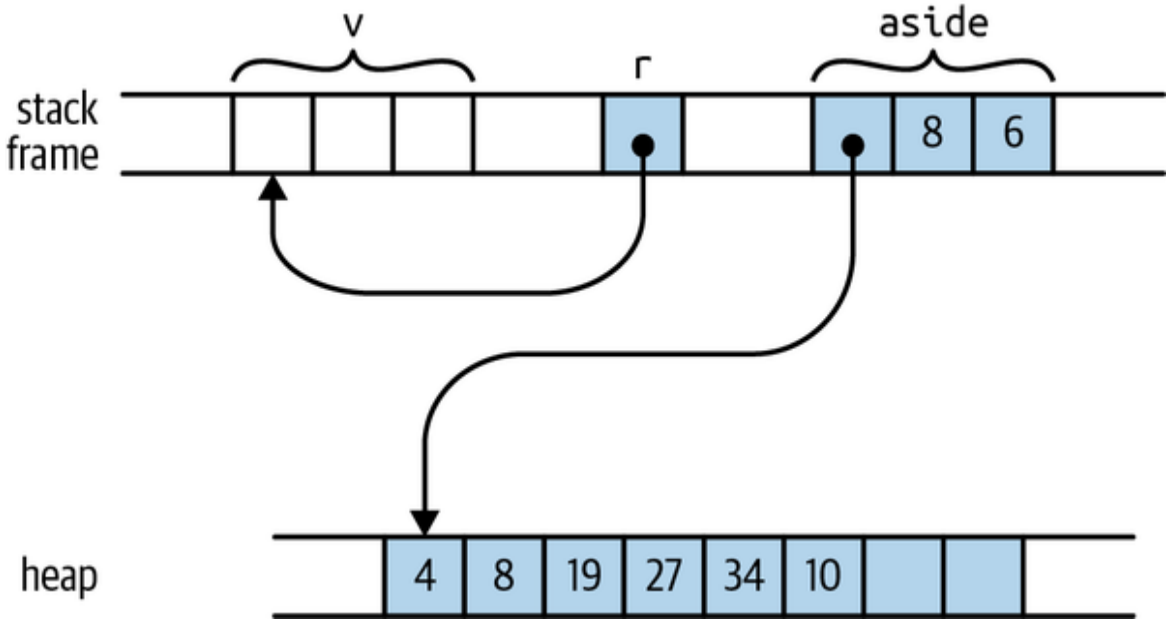


*Figure 5-7. A reference to a vector that has been moved away*

Although `v` stays in scope for `r`'s entire lifetime, the problem here is that `v`'s value gets moved elsewhere, leaving `v` uninitialized while `r` still refers to it. Naturally, Rust catches the error:

```
error: cannot move out of `v` because it is borrowed
   |
 9 |     let v = vec![4, 8, 19, 27, 34, 10];
   |         - binding `v` declared here
10 |     let r = &v;
   |             -- borrow of `v` occurs here
11 |     let aside = v;  // move vector to aside
   |                 ^ move out of `v` occurs here
```

```
12 |     r[0];           // bad: uses `v`, which is now
uninitialized
   |     - borrow later used here
```

Throughout its lifetime, a shared reference makes its referent read-only: you may not assign to the referent or move its value elsewhere. In this code, `r`'s lifetime contains the attempt to move the vector, so Rust rejects the program. If you change the program as shown here, there's no problem:

```
let v = vec![4, 8, 19, 27, 34, 10];
{
    let r = &v;
    r[0];       // ok: vector is still there
}
let aside = v;
```

In this version, `r` goes out of scope earlier, the reference's lifetime ends before `v` is moved aside, and all is well.

Here's a different way to wreak havoc. Suppose we have a handy function to extend a vector with the elements of a slice:

```
fn extend(vec: &mut Vec<f64>, slice: &[f64]) {
    for elt in slice {
        vec.push(*elt);
    }
}
```

This is a less flexible (and much less optimized) version of the standard library's `extend_from_slice` method on vectors. We can use it to build up a vector from slices of other vectors or arrays:

```
let mut wave = Vec::new();
let head = vec![0.0, 1.0];
let tail = [0.0, -1.0];

extend(&mut wave, &head);    // extend wave with another vector
extend(&mut wave, &tail);    // extend wave with an array

assert_eq!(wave, vec![0.0, 1.0, 0.0, -1.0]);
```

So we've built up one period of a sine wave here. If we want to add another undulation, can we append the vector to itself?

```
extend(&mut wave, &wave);
assert_eq!(wave, vec![0.0, 1.0, 0.0, -1.0, 0.0, 1.0, 0.0, -1.0]);
```

This may look fine on casual inspection. But remember that when we add an element to a vector, if its buffer is full, it must allocate a new buffer with more space. Suppose `wave` starts with space for four elements and so must allocate a larger buffer when `extend` tries to add a fifth. Memory ends up looking like Figure 5-8.

The `extend` function's `vec` argument borrows `wave` (owned by the caller), which has allocated itself a new buffer with space for eight elements. But `slice` continues to point to the old four-element buffer, which has been dropped.

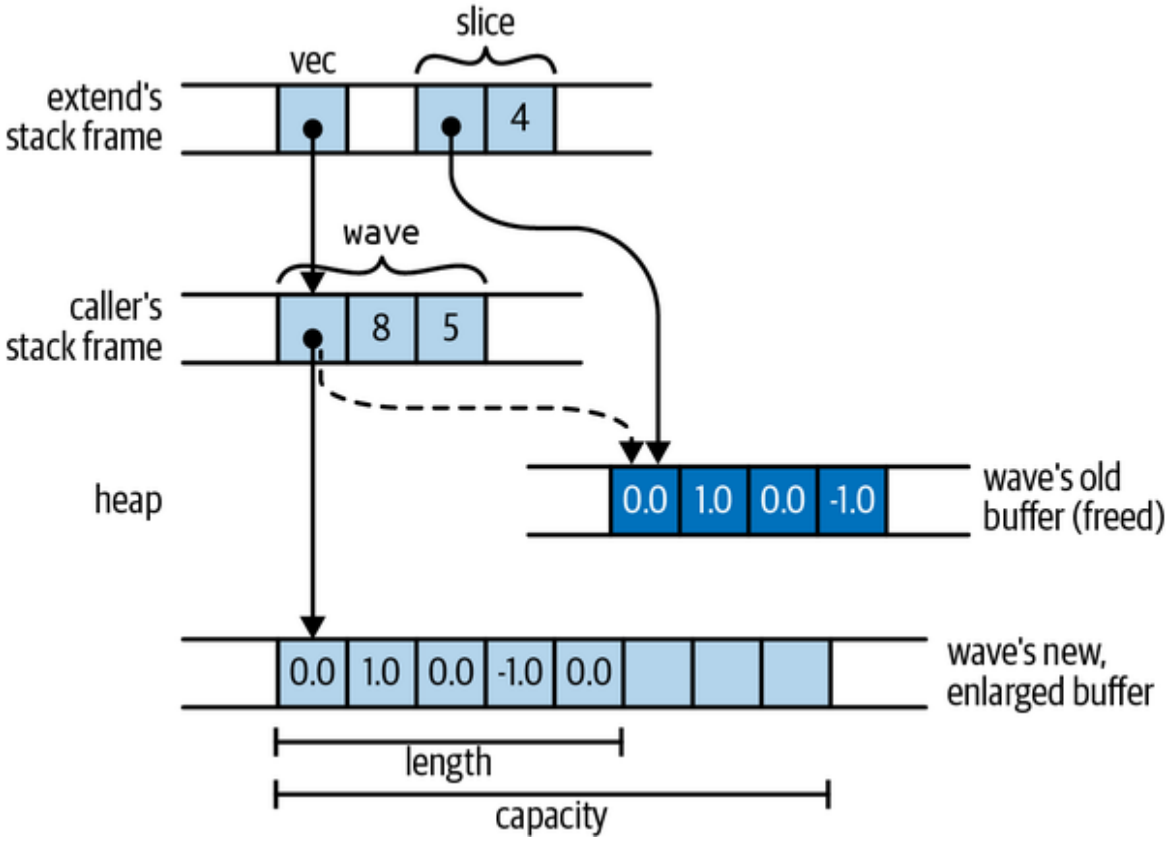


*Figure 5-8. A slice turned into a dangling pointer by a vector reallocation*

This sort of problem isn't unique to Rust: modifying collections while pointing into them is delicate territory in many languages. In C++, the `std::vector` specification cautions you that "reallocation [of the vector's buffer] invalidates all the references, pointers, and iterators referring to the elements in the sequence." Similarly, Java says, of modifying a `java.util.Hashtable` object:

> *If the Hashtable is structurally modified at any time after the iterator is created, in any way except through the iterator's own remove method, the iterator will throw a `ConcurrentModificationException`.*

What's especially difficult about this sort of bug is that it doesn't happen all the time. In testing, your vector might always happen to have enough space, the buffer might never be reallocated, and the problem might never come to light.

Rust, however, reports the problem with our call to `extend` at compile time:

```
error: cannot borrow `wave` as immutable because it is also
       borrowed as mutable
  |
9 |     extend(&mut wave, &wave);
  |     ------ ---------  ^^^^^ immutable borrow occurs here
  |     |      |
  |     |      mutable borrow occurs here
  |     mutable borrow later used by call
```

In other words, we may borrow a mutable reference to the vector, and we may borrow a shared reference to its elements, but those two references' lifetimes must not overlap. In our case, both references' lifetimes contain the call to `extend`, so Rust rejects the code.

These errors both stem from violations of Rust's rules for mutation and sharing:

*Shared access is read-only access.*

> Values borrowed by shared references are read-only. Across the lifetime of a shared reference, neither its referent, nor anything reachable from

that referent, can be changed *by anything*. There exist no live mutable references to anything in that structure, its owner is held read-only, and so on. It's really frozen.

*Mutable access is exclusive access.*

A value borrowed by a mutable reference is reachable exclusively via that reference. Across the lifetime of a mutable reference, there is no other usable path to its referent or to any value reachable from there. The only references whose lifetimes may overlap with a mutable reference are those you borrow from the mutable reference itself.

Rust reported the `extend` example as a violation of the second rule: since we've borrowed a mutable reference to `wave`, that mutable reference must be the only way to reach the vector or its elements. The shared reference to the slice is itself another way to reach the elements, violating the second rule.

But Rust could also have treated our bug as a violation of the first rule: since we've borrowed a shared reference to `wave`'s elements, the elements and the `Vec` itself are all read-only. You can't borrow a mutable reference to a read-only value.

Each kind of reference affects what we can do with the values along the owning path to the referent and the values reachable from the referent (Figure 5-9).

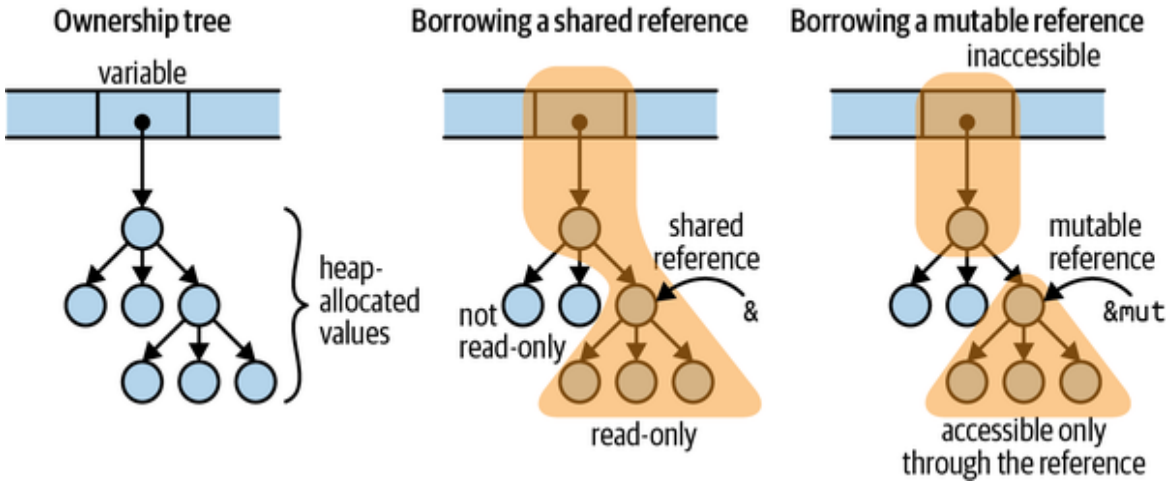


*Figure 5-9. Borrowing a reference affects what you can do with other values in the same ownership tree*

Note that in both cases, the path of ownership leading to the referent cannot be changed for the reference's lifetime. For a shared borrow, the path is read-only; for a mutable borrow, it's completely inaccessible. So there's no way for the program to do anything that will invalidate the reference.

Paring these principles down to the simplest possible examples:

```
let mut x = 10;
let r1 = &x;
let r2 = &x;      // ok: multiple shared borrows permitted
x += 10;          // error: cannot assign to `x` because it is
borrowed
let m = &mut x;   // error: cannot borrow `x` as mutable because
it is
                  // also borrowed as immutable
println!("{r1}, {r2}, {m}");  // the references are used here,
                              // so their lifetimes must last
                              // at least this long

let mut y = 20;
let m1 = &mut y;
let m2 = &mut y;  // error: cannot borrow as mutable more than
once
let z = y;         // error: cannot use `y` because it was mutably
borrowed
println!("{m1}, {m2}, {z}");  // references are used here
```

It is OK to reborrow a shared reference from a shared reference:

```
let mut w = (107, 109);
let r = &w;
let r0 = &r.0;          // ok: reborrowing shared as shared
let m1 = &mut r.1;      // error: can't reborrow shared as mutable
println!("{r0}");       // r0 gets used here
```

You can reborrow from a mutable reference:

```
let mut v = (136, 139);
let m = &mut v;
let m0 = &mut m.0;      // ok: reborrowing mutable from mutable
*m0 = 137;
let r1 = &m.1;          // ok: reborrowing shared from mutable,
                        // and doesn't overlap with m0
v.1;                    // error: access through other paths
still forbidden
println!("{r1}");       // r1 gets used here
```

These restrictions are pretty tight. Turning back to our attempted call `extend(&mut wave, &wave)`, there's no quick and easy way to fix up the code to work the way we'd like. And Rust applies these rules everywhere: if we borrow, say, a shared reference to a key in a `HashMap`, we can't borrow a mutable reference to the `HashMap` until the shared reference's lifetime ends.

But there's good justification for this: designing collections to support unrestricted, simultaneous iteration and modification is difficult and often precludes simpler, more efficient implementations. Java's `Hashtable` and C++'s `vector` don't bother, and neither Python dictionaries nor JavaScript objects define exactly how such access behaves. Other collection types in JavaScript do but require heavier implementations as a result. C++'s `std::map` promises that inserting new entries doesn't invalidate pointers to other entries in the map, but by making that promise, the standard precludes more cache-efficient designs like Rust's `BTreeMap`, which stores multiple entries in each node of the tree. Here's another example of the kind of bug these rules catch.

An old-school classic mistake in C++ is incorrectly overloading the assignment operator:

```
// Copy assignment. C++ calls this when user code assigns `obj1 =
obj2;`.
MyObject& operator=(const MyObject& other) {
  // Clean up some resource held by this object...
  freeResource(m_resource);
  // ...then put a new resource in its place.
  m_resource = allocCopyOfResource(other.m_resource);

  return *this;
}
```

This looks reasonable enough, but what happens if the user assigns an object to itself, as in `myobj = myobj`? Then `this` and `other` point to the same object. So the resource freed on the first line is the same resource we try to copy on the next line. It's a use-after-free, a bad bug, and easy to miss during testing.

In Rust, this can't happen. There's no way to overload the = operator in Rust. But more fundamentally, even if a Rust type did have an `assign` method, carrying out exactly the same steps as this C++ code, the compiler would not allow the call `myobj.assign(&myobj)`. That would require having a `mut` reference and a non-`mut` reference to the same variable at the same time, and Rust flags that as an error:

```
error: cannot borrow `myobj` as mutable because it is also
borrowed as immutable
   |
22 |     myobj.assign(&myobj);
   |     ^^^^^ ------ ------
   |     |     |      |
   |     |     |      immutable borrow occurs here
   |     |     immutable borrow later used by call
   |     mutable borrow occurs here
```

This should look familiar. It turns out that two classic C++ bugs—failure to cope with self-assignment and using invalidated iterators—are the same underlying kind of bug! In both cases, code assumes it is modifying one value while consulting another, when in fact they're both the same value. If you've ever accidentally let the source and destination of a call to `memcpy` or `strcpy` overlap in C or C++, that's yet another form the bug can take.

By requiring mutable access to be exclusive, Rust has fended off a wide class of everyday mistakes.

The immiscibility of shared and mutable references really demonstrates its value when writing concurrent code. A data race is possible only when some value is both mutable and shared between threads—which is exactly what Rust's reference rules eliminate. A concurrent Rust program that avoids `unsafe` code is free of data races *by construction*. We'll cover this aspect in more detail when we talk about concurrency in Chapter 19, but in summary, concurrency is much easier to use in Rust than in most other languages.

## RUST'S SHARED REFERENCES VERSUS C'S POINTERS TO CONST

On first inspection, Rust's shared references seem to closely resemble C and C++'s pointers to `const` values. However, Rust's rules for shared references are much stricter. For example, consider the following C code:

```
int x = 42;               // int variable, not const
const int *p = &x;        // pointer to const int
assert(*p == 42);
x++;                      // change variable directly
assert(*p == 43);         // "constant" referent's value has
changed
```

The fact that `p` is a `const int *` means that you can't modify its referent via `p` itself: `(*p)++` is forbidden. But you can also get at the referent directly as `x`, which is not `const`, and change its value that way. The C family's `const` keyword has its uses, but constant it is not.

In Rust, a shared reference forbids all modifications to its referent, until its lifetime ends:

```
let mut x = 42;           // non-const i32 variable
let p = &x;               // shared reference to i32
assert_eq!(*p, 42);
x += 1;                   // error: cannot assign to x because
it is borrowed
assert_eq!(*p, 42);       // if you take out the assignment,
this is true
```

To ensure a value is constant, we need to keep track of all possible paths to that value and make sure that they either don't permit modification or cannot be used at all. C and C++ pointers are too unrestricted for the compiler to check this. Rust's references are always tied to a particular lifetime, making it feasible to check them at compile time.

# Taking Arms Against a Sea of Objects

Since the rise of automatic memory management in the 1990s, the default architecture of all programs has been the *sea of objects*, shown in Figure 5-10.

This is what happens if you have garbage collection and you start writing a program without designing anything. We've all built systems that look like this.

This architecture has many advantages that don't show up in the diagram: initial progress is rapid, it's easy to hack stuff in, and a few years down the road, you'll have no difficulty justifying a complete rewrite. (Cue AC/DC's "Highway to Hell.")

Of course, there are disadvantages too. When everything depends on everything else like this, it's hard to test, evolve, or even think about any component in isolation.

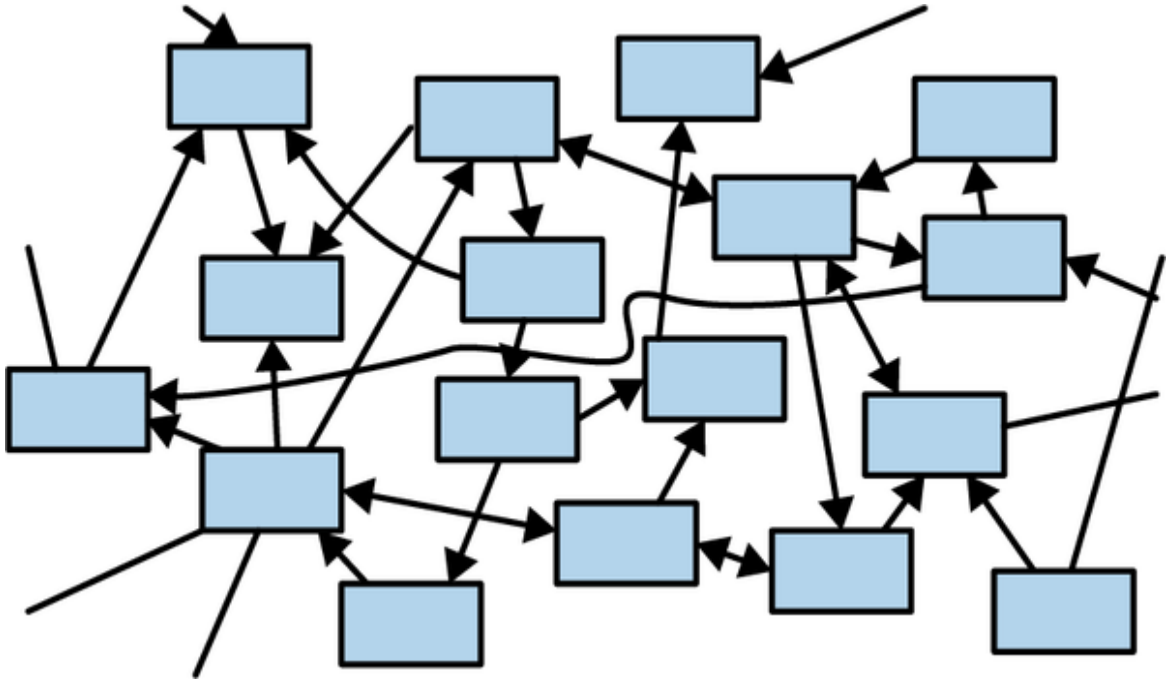

*Figure 5-10. A sea of objects*

One fascinating thing about Rust is that the ownership model puts a speed bump on the highway to hell. It takes a bit of effort to make a cycle in Rust —two values such that each one contains a reference pointing to the other.

You have to use a smart pointer type, such as `Rc`, and interior mutability—a topic we haven't even covered yet. Rust prefers for pointers, ownership, and data flow to pass through the system in one direction, as shown in Figure 5-11.

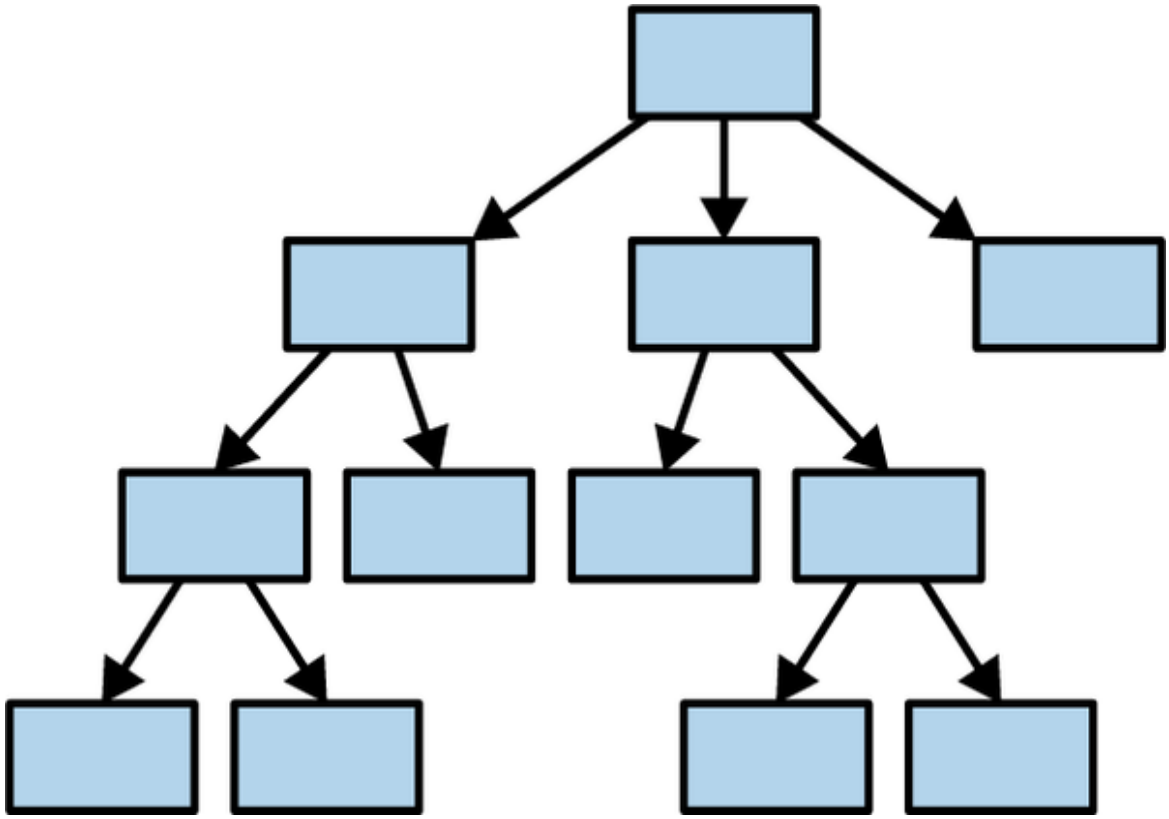

*Figure 5-11. A tree of values*

The reason we bring this up right now is that it would be natural, after reading this chapter, to want to run right out and create a "sea of structs," all tied together with `Rc` smart pointers, and re-create all the object-oriented antipatterns you're familiar with. This won't work for you right away. Rust's ownership model will give you some trouble. The cure is to do some up-front design and build a better program.

Rust is all about transferring the pain of understanding your program from the future to the present. It works unreasonably well: not only can Rust force you to understand why your program is thread-safe, it can even require some amount of high-level architectural design.

# Chapter 6. Expressions

*LISP programmers know the value of everything, but the cost of nothing.*

—Alan Perlis, epigram #55

In this chapter, we'll cover the *expressions* of Rust, the building blocks that make up the body of Rust functions and thus the majority of Rust code. We'll cover control flow, including `if` and `match` expressions, loops, and function calls, which in Rust are all expressions, and we'll examine how Rust's foundational operators work in isolation and in combination.

A few concepts that technically fall into this category, such as closures and iterators, are deep enough that we will dedicate a whole chapter to them later. For now, we aim to cover as much syntax as possible in a few pages.

## An Expression Language

Rust visually resembles the C family of languages, but this is a bit of a ruse. In C, there is a sharp distinction between *expressions,* bits of code that look something like this:

```
5 * (fahr-32) / 9
```

and *statements,* which look more like this:

```
for (; begin != end; ++begin) {
    if (*begin == target)
        break;
}
```

Expressions have values. Statements don't.

Rust is what is called an *expression language*. This means it follows an older tradition, dating back to Lisp, where expressions do all the work.

In C, `if` and `switch` are statements. They don't produce a value, and they can't be used in the middle of an expression. In Rust, `if` and `match` *can* produce values. We already saw a `match` expression that produces a numeric value in Chapter 2:

```
pixels[row * bounds.0 + column] =
    match escape_time(point, 255) {
        None => 0,
        Some(count) => 255 - count as u8,
    };
```

An `if` expression can be used to initialize a variable:

```
let status =
    if cpu.temperature <= MAX_TEMP {
        HttpStatus::Ok
    } else {
        HttpStatus::ServerError  // server melted
    };
```

A `match` expression can be passed as an argument to a function or macro:

```
println!(
    "Inside the vat, you see {}.",
    match vat.contents {
        Some(brain) => brain.desc(),
        None => "nothing of interest",
    }
);
```

This explains why Rust does not have C's ternary operator (`expr1 ? expr2 : expr3`). In C, it is a handy expression-level analogue to the `if` statement. It would be redundant in Rust: the `if` expression handles both cases.

Most of the control flow tools in C are statements. In Rust, they are all expressions.

Table 6-1 summarizes Rust's control flow expressions. We will discuss all of these constructs in the first half of this chapter, before turning to other

kinds of expressions, like function calls and arithmetic.

*Table 6-1. Block and control flow expressions*

| Expression type | Example |
|---|---|
| Block | `{ f(); g() }` |
| `if` expressions | `if ok { f() }` |
| | `if ok { 1 } else { 0 }` |
| | `if let Some(x) = f() { x } else { 0 }` |
| Pattern matching | `match x { None => 0, _ => 1 }` |
| Loops | `for v in e { f(v); }` |
| | `while ok { ok = f(); }` |
| | `while let Some(x) = it.next() { f(x); }` |
| | `loop { next_event(); }` |
| Jumps in control flow | `break` |
| | `continue` |
| | `return 0` |
| Compile-time evaluation | `const { PI / 6.0 }` |
| Enable unsafe features | `unsafe { *ptr = 0; }` |

# Blocks

Blocks are the glue of Rust expressions. As in many other languages, they are delimited by curly braces, can contain any number of declarations and expressions, and simply execute line by line from top to bottom.

A block produces a value and can be used anywhere a value is needed:

```
let display_name = match post.author() {
    Some(author) => author.name(),
    None => {
        let network_info = post.get_network_metadata()?;
        let ip = network_info.client_address();
        ip.to_string()
    }
};
```

The code after `Some(author) =>` is the simple expression `author.name()`. The code after `None =>` is a block expression. It makes no difference to Rust. The value of the block is the value of its last expression, `ip.to_string()`.

Note that there is no semicolon after the `ip.to_string()` method call. Most lines of Rust code do end with either a semicolon or curly braces, just like C or Java. And if a block looks like C code, with semicolons in all the familiar places, then it will run just like a C block, and its value will be `()`. As we mentioned in Chapter 2, when you leave the semicolon off the last line of a block, that makes the value of the block the value of its final expression, rather than the usual `()`.

In some languages, particularly JavaScript, you're allowed to omit semicolons, and the language simply fills them in for you—a minor convenience. This is different. In Rust, the semicolon actually means something:

```
let msg = {
    // let-declaration: semicolon is always required
    let dandelion_control = puffball.open();

    // expression + semicolon: method is called, return value
dropped
    dandelion_control.release_all_seeds(launch_codes);

    // expression with no semicolon: method is called,
    // return value stored in `msg`
    dandelion_control.get_status()
};
```

This ability of blocks to contain declarations and also produce a value at the end is a neat feature, one that quickly comes to feel natural. The one drawback is that it leads to an odd error message when you leave out a semicolon by accident:

```
...
if preferences.changed() {
    page.compute_size()  // oops, missing semicolon
}
...
```

If you made this mistake in a C or Java program, the compiler would simply point out that you're missing a semicolon. Here's what Rust says:

```
error: mismatched types
21 | /     if preferences.changed() {
22 | |         page.compute_size()  // oops, missing semicolon
   | |         ^^^^^^^^^^^^^^^^^^^ expected `()`, found `(u32,
u32)`
23 | |     }
   | |_____- `if` expressions without `else` arms expect their
   |           inner expression to be `()`
   |
   = note: expected unit type `()`
                  found tuple `(u32, u32)`
help: consider using a semicolon here
   |
22 |         page.compute_size();  // oops, missing semicolon
   |                            +
```

Rust eventually suggests a semicolon, but only after explaining in detail why the code can't work as written. In languages where the semicolon is always required, the compiler has less explaining to do.

## Declarations

In addition to expressions and semicolons, a block may contain any number of declarations. The most common are `let` declarations, which declare local variables:

```
let name: type = expr;
```

The type and initializer are optional. The semicolon is required. Like all identifiers in Rust, variable names must start with a letter or underscore and can contain digits only after that first character. Rust has a broad definition of “letter”: it includes Greek letters, accented Latin characters, and many more symbols—anything that Unicode Standard Annex #31 declares suitable. Emoji aren’t allowed.

A `let` declaration can declare a variable without initializing it. The variable can then be initialized with a later assignment. This is occasionally useful, because sometimes a variable should be initialized from the middle of some sort of control flow construct:

```
let name;
if user.has_nickname() {
    name = user.nickname();
} else {
    name = generate_unique_name();
    user.register(&name);
}
```

Here there are two different ways the local variable `name` might be initialized, but either way it will be initialized exactly once, so `name` does not need to be declared `mut`.

It’s an error to use a variable before it’s initialized. (This is closely related to the error of using a value after it’s been moved. Rust really wants you to use values only while they exist!)

You may occasionally see code that seems to redeclare an existing variable, like this:

```
for line in file.lines() {
    let line = line?;
    ...
}
```

The `let` declaration creates a new, second variable, of a different type. The type of the first variable `line` is `Result<String, io::Error>`. The second `line` is a `String`. Its definition supersedes the first's for the rest of the block. This is called *shadowing* and is very common in Rust programs. The code is equivalent to:

```
for line_result in file.lines() {
    let line = line_result?;
    ...
}
```

In this book, we'll stick to using a `_result` suffix in such situations so that the variables have distinct names. In real-world code, however, shadowing is helpful. It communicates that we're definitely done with the old variable and makes it impossible to use it again by mistake.

A block can also contain *item declarations*. An item is simply any declaration that could appear globally in a program or module, such as a `fn`, `struct`, or `use`.

Later chapters will cover items in detail. For now, `fn` makes a sufficient example. Any block may contain a `fn`:

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

fn show_files() -> io::Result<()> {
    let mut v = vec![];
    ...

    fn cmp_by_timestamp_then_name(a: &FileInfo, b: &FileInfo) ->
Ordering {
        a.timestamp
            .cmp(&b.timestamp)          // first, compare
timestamps
            .reverse()                  // newest file first
            .then(a.path.cmp(&b.path))  // compare paths to break
ties
    }

    v.sort_by(cmp_by_timestamp_then_name);
```

```
    ...
}
```

When a `fn` is declared inside a block, its scope is the entire block—that is, it can be *used* throughout the enclosing block. But a nested `fn` cannot access local variables or arguments that happen to be in scope. For example, the function `cmp_by_timestamp_then_name` could not use `v` directly. (Rust also has closures, which do see into enclosing scopes. See Chapter 14.)

A block can even contain a whole module. This may seem a bit much—do we really need to be able to nest *every* piece of the language inside every other piece?—but programmers (and particularly programmers using macros) have a way of finding uses for every scrap of orthogonality the language provides.

## if and match

The form of an `if` expression is familiar:

```
if condition1 {
    block1
} else if condition2 {
    block2
} else {
    block_n
}
```

Each `condition` must be an expression of type `bool`; true to form, Rust does not implicitly convert numbers or pointers to Boolean values. Unlike C, parentheses are not required around conditions. In fact, `rustc` will emit a warning if unnecessary parentheses are present. The curly braces, however, are required.

The `else if` blocks, as well as the final `else`, are optional. An `if` expression with no `else` block behaves exactly as though it had an empty `else` block.

`match` expressions are something like the C `switch` statement, but more flexible. An example:

```
match code {
    0 => println!("OK"),
    1 => println!("Wires Tangled"),
    2 => println!("User Asleep"),
    _ => println!("Unrecognized Error {code}"),
}
```

This is something a `switch` statement could do. Exactly one of the four arms of this `match` expression will execute, depending on the value of `code`. The wildcard pattern `_` matches everything. This is like the `default:` case in a `switch` statement, except that it must come last; placing a `_` pattern before other patterns means that it will have precedence over them. Those patterns will never match anything (and the compiler will warn you about it). The compiler can optimize this kind of `match` using a jump table, just like a `switch` statement in C++. A similar optimization is applied when each arm of a `match` produces a constant value.

In that case, the compiler builds an array of those values, and the `match` is compiled into an array access. Apart from a bounds check, there is no branching at all in the compiled code. The versatility of `match` stems from the variety of supported *patterns* that can be used to the left of => in each arm. Each pattern is simply a constant integer. We've also shown `match` expressions that distinguish the two kinds of `Option` values:

```
match params.get("name") {
    Some(name) => println!("Hello, {name}!"),
    None => println!("Greetings, stranger."),
}
```

This is only a hint of what patterns can do. A pattern can match a range of values. It can unpack tuples. It can match against individual fields of structs. It can chase references, borrow parts of a value, and more. Rust's patterns are a mini-language of their own. We'll dedicate several pages to them in Chapter 10. The general form of a `match` expression is:

```
match value {
    pattern => expr,
    ...
}
```

The comma after an arm may be dropped if the `expr` is a block.

Rust checks the given `value` against each pattern in turn, starting with the first. When a pattern matches, the corresponding `expr` is evaluated, and the `match` expression is complete; no further patterns are checked. At least one of the patterns must match. Rust prohibits `match` expressions that do not cover all possible values:

```
let score = match card.rank {
    Jack => 10,
    Queen => 10,
    Ace => 11,
};  // error: nonexhaustive patterns
```

All branches of an `if` or `match` expression must produce values of the same type:

```
let favorite_number =
    if likes_primes { 31 } else { 57 };  // ok, both i32

let favorite_number =
    if user.is_hobbit() { "eleventy-one" } else { 9 };  // error

let suggested_pet = match favorites.element {
    Fire => Pet::RedPanda,
    Air => Pet::Buffalo,
    Water => Pet::Orca,
    _ => None,  // error: incompatible types
};

let best_sports_team =
    if is_hockey_season() { "Predators" };  // error
```

(The last example is an error because in July, the result would be `()`.)

## if let

An `if` expression can incorporate pattern matching using the `let` keyword:

```
if let pattern = expr {
    block1
} else {
    block2
}
```

The given `expr` either matches the `pattern`, in which case `block1` runs, or doesn't match, and `block2` runs. This is often a nice way to get data out of an `Option` or `Result`:

```
if let Some(cookie) = request.session_cookie {
    return restore_session(cookie);
}

if let Err(err) = show_cheesy_anti_robot_task() {
    log_robot_attempt(err);
    politely_accuse_user_of_being_a_robot();
} else {
    session.mark_as_human();
}
```

Note that in the previous example, the variable `err` is in scope throughout the `if` block, but not in the `else` block. If we get there, the pattern failed to match.

Multiple conditions can be chained using `&&`, like so:

```
if let Some(session) = sessions.get(cookie)
    && session.is_encrypted()
    && let Some(user) = session.logged_in_user()
    && user.is_admin()
{
    ... show admin controls ...
}
```

Each condition can be either an expression of type `bool`, satisfied if the value is `true`; or a `let` condition, satisfied if the pattern matches. The

names introduced by each `let` condition are in scope for the subsequent conditions.

It's never strictly *necessary* to use `if let`, because `match` can do everything `if let` can do. A simple `if let` expression is shorthand for a `match` with just one pattern:

```
match expr {
    pattern => { block1 }
    _ => { block2 }
}
```

More complex `if let` expressions, with multiple conditions, can be written as nested `match` expressions.

## let else

When there is only one acceptable pattern, Rust provides a convenient shorthand, the `let...else` declaration:

```
let pattern: type = expr else {
    divergent block
};
```

For instance, application code often needs to look something up in a table, and exit if it isn't found. With `let...else`, this can be written concisely as:

```
let Some(team) = teams.get(team_name) else {
    return Err(Error::TeamNotFound);
};
for player in team {
    ...
}
```

The `else` block must always be something that ends the flow of execution, such as a panic, `return`, `break`, or `continue`. (This is called "diverging" and is discussed in "Why Rust Has loop".) `let...else` is

convenient for many common control flow patterns, but like `if let`, it is always possible to do the same thing via `match`:

```
match teams.get(team_name) {
    Some(team) => {
        // ...the rest of the block following the let-else
        for player in team {
            ...
        }
    }
    _ => {
        return Err(Error::TeamNotFound);
    }
}
```

## Loops

There are four looping expressions:

```
while condition {
    block
}

while let pattern = expr {
    block
}

loop {
    block
}

for pattern in iterable {
    block
}
```

Loops are expressions in Rust, but the value of a `while` or `for` loop is always `()`, so their value isn't very useful. A `loop` expression can produce a value via the `break` keyword, as we'll see in the next section.

A `while` loop behaves exactly like the C equivalent, except that, again, the `condition` must be of the exact type `bool`.

The `while let` loop is analogous to `if let`. At the beginning of each loop iteration, the value of `expr` either matches the given `pattern`, in which case the block runs, or doesn't, in which case the loop exits. Multiple conditions can be chained with `&&`, just as for `if` expressions.

Use `loop` to write infinite loops. It executes the `block` repeatedly forever (or until a `break` or `return` is reached or the thread panics).

A `for` loop evaluates the `iterable` expression and then evaluates the `block` once for each value in the resulting iterator. Many types can be iterated over, including all the standard collections like `Vec` and `HashMap`. The standard C `for` loop:

```
for (int i = 0; i < 20; i++) {
    printf("%d\n", i);
}
```

is written like this in Rust:

```
for i in 0..20 {
    println!("{i}");
}
```

As in C, the last number printed is `19`.

The `..` operator produces a *range*, a simple struct with two fields: `start` and `end`. `0..20` is the same as `std::ops::Range { start: 0, end: 20 }`. Ranges can be used with `for` loops because `Range` is an iterable type: it implements the `std::iter::IntoIterator` trait, which we'll discuss in Chapter 15. The standard collections are all iterable, as are arrays and slices.

In keeping with Rust's move semantics, a `for` loop over a value consumes the value:

```
let strings: Vec<String> = error_messages();
for s in strings {          // each String is moved into s
here...
    println!("{s}");
```

```
}                               // ...and dropped here
println!("{} error(s)", strings.len());  // error: use of moved
value
```

This can be inconvenient. The easy remedy is to loop over a reference to the collection instead. The loop variable, then, will be a reference to each item in the collection:

```
for s in &strings {             // `strings` is only borrowed here...
    println!("{s}");
}                               // ...nothing is moved or deallocated
println!("{} error(s)", strings.len());  // ok
```

Here, the type of `&strings` is `&Vec<String>`, and the type of `s` is `&String`.

Iterating over a `mut` reference provides a `mut` reference to each element:

```
let mut strings = error_messages();
for s in &mut strings {         // the type of s is &mut String
    s.push('\n');               // add a newline to each string
}
```

Chapter 15 covers `for` loops in greater detail and shows many other ways to use iterators.

## break and continue Expressions

A `break` expression exits an enclosing loop. (In many languages, `break` also has a special role in `switch` statements, but not in Rust.)

Within a `loop` expression, `break expr` exits the `loop` and gives it a value. This feature is easier to show than explain:

```
// Prompt the user repeatedly until they enter a number.
let party_size = loop {
    let line = input_line("how many?> ");
    if let Ok(num) = line.trim().parse::<u64>() {
        break num;
```

```
    }
};
```

When this example reaches `break num`, the value of `num` becomes the value of the whole `loop`.

If a `loop` has multiple `break` expressions, they must all supply values of the same type. This syntax doesn't work with `for` or `while` loops, as those can finish normally, without breaking, producing the value `()`.

A `continue` expression jumps to the next loop iteration:

```
// Read some data, one line at a time.
for line in input_lines {
    let trimmed = trim_comments_and_whitespace(line);
    if trimmed.is_empty() {
        // Jump back to the top of the loop and
        // move on to the next line of input.
        continue;
    }
    ...
}
```

In a `for` loop, `continue` advances to the next value in the collection. If there are no more values, the loop exits. Similarly, in a `while` loop, `continue` rechecks the loop condition. If it's now false, the loop exits.

A loop can be *labeled* with a lifetime. In the following example, `'search:` is a label for the outer `for` loop. Thus, `break 'search` exits that loop, not the inner loop:

```
'search: for room in apartment {
    for spot in room.hiding_spots() {
        if spot.contains(keys) {
            println!("Your keys are {spot} in the {room}.");
            break 'search;
        }
    }
}
```

Labels can also be used with `continue`.

In the rare case that a `break` needs both a label and a value, it's written as `break 'label value`.

## Labeled Blocks

The `break` expression has one other function. It can be used to exit early from a block.

A block can be labeled with a lifetime, just like a loop. Then the label can be used with `break` to break out of the block early. In the following example, `'trim` is a label for the overall block. `break` exits the named block immediately, providing its value:

```
let trimmed = 'trim: {
    if string.chars().last() != Some('\n') {
        break 'trim None;
    }
    string.pop();
    if string.chars().last() != Some('\r') {
        break 'trim Some(Newline::Unix);
    }
    string.pop();
    Some(Newline::Windows)
};
```

The same logic could be written with nested `if` expressions instead, but arguably this version reads better, the same way a function sometimes reads better with a few early `return`s.

## return Expressions

A `return` expression exits the current function, returning a value to the caller.

`return` without a value is shorthand for `return ()`:

```
fn f() {     // return type omitted: defaults to ()
    return;  // return value omitted: defaults to ()
}
```

Functions don't have to have an explicit `return` expression. The body of a function works like a block expression: if the last expression isn't followed by a semicolon, its value is the function's return value. In fact, this is the preferred way to supply a function's return value in Rust. The `return` keyword is only necessary when exiting a function early.

In Chapter 2, we noted that the `?` operator is shorthand for a common kind of early `return`: bailing out when an error happens. We'll cover `?` fully in Chapter 7.

## Why Rust Has loop

Several pieces of the Rust compiler analyze the flow of control through your program:

- Rust checks that every path through a function returns a value of the expected return type. To do this correctly, it needs to know whether it's possible to reach the end of the function.
- Rust checks that local variables are never used uninitialized. This entails checking every path through a function to make sure there's no way to reach a place where a variable is used without having already passed through code that initializes it.
- Rust warns about unreachable code. Code is unreachable if *no* path through the function reaches it.

These are called *flow-sensitive* analyses. They are nothing new; Java has had a "definite assignment" analysis, similar to Rust's, for years.

When enforcing this sort of rule, a language must strike a balance between simplicity, which makes it easier for programmers to figure out what the compiler is talking about sometimes, and cleverness, which can help eliminate false warnings and cases where the compiler rejects a perfectly safe program. Rust went for simplicity. Its flow-sensitive analyses do not examine loop conditions at all, instead simply assuming that any condition in a program can be either true or false.

This causes Rust to reject some safe programs:

```
fn wait_for_process(process: &mut Process) -> i32 {
    while true {
        if process.wait() {
            return process.exit_code();
        }
    }
}  // error: mismatched types: expected i32, found ()
```

The error here is bogus. This function exits only via the `return` expression, so the fact that the `while` loop doesn't produce an `i32` is irrelevant.

However, if you replace `while true` with `loop`, the code compiles fine. Rust doesn't worry about reaching the end of the function without having produced an `i32` value. It knows the end can't be reached. Control will never flow past the end of the `loop`.

There's another way control flow influences Rust's type checking. Earlier we said that all branches of an `if` expression must have the same type. But it would be silly to enforce this rule on blocks that end with a `break` or `return` expression, an infinite `loop`, or a call to `panic!()` or `std::process::exit()`. What all those expressions have in common is that they never finish in the usual way and produce a value. A `break` or `return` exits the current block abruptly, an infinite `loop` never finishes at all, and so on.

So in Rust, these expressions don't have a normal type. Expressions that don't finish normally are assigned the special type `!`, and they're exempt from the rules about types having to match. You can see `!` in the function signature of `std::process::exit()`:

```
fn exit(code: i32) -> !
```

The `!` means that `exit()` never returns. It's a *divergent function*.

You can write divergent functions of your own using the same syntax, and this is perfectly natural in some cases:

```
fn serve_forever(socket: ServerSocket, handler: ServerHandler) ->
! {
    socket.listen();
    loop {
        let s = socket.accept();
        handler.handle(s);
    }
}
```

Of course, Rust then considers it an error if the function can return normally.

## const and unsafe Blocks

Finally, there are two more Rust keywords that can be attached to blocks: `const` and `unsafe`. These are comparatively rare, so we'll be brief.

A `const` block is like a regular block, but it runs at compile time instead of run time. In most cases, it's clearer to declare a constant:

```
let angle = const { PI / 6.0 };  // const block

const ANGLE: f64 = PI / 6.0;     // constant
```

Both values are guaranteed to be computed at compile time, but `ANGLE` can be declared globally and used throughout your code. Local variables can't. Nor are `const` blocks widely useful as a performance feature. The compiler optimizes away wasteful run-time calculations without needing to be told; in this example, the division would happen at compile time even without a `const` block, even in debug builds.

The interesting thing about `const` blocks is that the compiler checks that the code finishes successfully. If a `const` block panics, it's treated as a compile-time error, not a run-time panic. This makes `const` blocks useful for compile-time assertions:

```
fn allocate_memory<T>(alloc: &mut MyAlloc, value: T) -> MyBox<T>
{
    const {
        // Enforce some limitations of the allocator.
        // Compilation fails if either assertion fails.
        assert!(size_of::<T>() > 0);
        assert!(size_of::<T>() <= MyAlloc::MAX_SIZE);
    }
    ...
}
```

Lastly, `unsafe` blocks are used to opt out of Rust's safety guarantees and opt in to sharp-edged language and library features, such as raw pointers. We will discuss unsafe code in Chapter 23.

With all the building blocks of Rust control flow in place, we can move on to the finer-grained expressions typically used within that flow, like arithmetic operators and function calls.

# Operators

Table 6-2 lists Rust's operators, the symbols that express the language's most basic operations. The operators are grouped by precedence and listed from highest precedence to lowest. (Like most programming languages, Rust has *operator precedence* to determine the order of operations when an expression contains multiple adjacent operators. For example, in `limit < 2 * broom.size + 1`, the `.` operator has the highest precedence, so the field access happens first.)

The arithmetic and bitwise operations and their associated compound assignments can be overloaded with arbitrary behavior for user-defined types, as discussed in Chapter 12.

All of the operators that can usefully be chained are left-associative. That is, a chain of operations such as `a - b - c` is grouped as `(a - b) - c`, not `a - (b - c)`. The operators that can be chained in this way are all the ones you might expect:

```
*   /   %   +   -   <<   >>   &   ^   |   &&   ||   as
```

The comparison operators, the assignment operators, and the range operators `..` and `..=` can't be chained at all.

*Table 6-2. Rust operators*

| Expression type | Example |
|---|---|
| Grouping | `(2 + 2)` |
| Array literal | `[1, 2, 3]` |
| Repeat array literal | `[0; 50]` |
| Tuple | `(6, "crullers")` |
| Path | `std::f64::consts::PI` |
| Struct literal | `Point {x: 0, y: 0}` |
| Tuple field access | `pair.0` |
| Struct field access | `point.x` |
| Method call | `point.translate(50, 50)` |
| Function call | `stdin()` |
| Macro invocation | `println!("ok")` |
| Index | `arr[0]` |
| `Err`/`None` early return | `create_dir("tmp")?` |
| Logical/bitwise NOT | `!ok` |
| Negation | `-num` |
| Dereference | `*ptr` |
| Borrow | `&val` |

| Expression type | Example |
| --- | --- |
| Multiplication, division, remainder (modulus) | `n * 2`, `n / 2`, `n % 2` |
| Addition and subtraction | `n + 1`, `n - 1` |
| Bit shifts | `n << 1`, `n >> 1` |
| Bitwise AND | `n & 1` |
| Bitwise exclusive OR | `n ^ 1` |
| Bitwise OR | `n \| 1` |
| Comparisons | `a == b`, `a != b`, `a < b`, `a <= b`, `a > b`, `a >= b` |
| Logical AND | `x.ok && y.ok` |
| Logical OR | `x.ok \|\| backup.ok` |
| Ranges | `start..end`, `start..=end` |
| Assignment | `x = val` |
| Compound assignment | `x += 1` (also `*= /= %= -= <<= >>= &= ^= \|=`) |
| Type cast | `x as u32` |
| Closure | `\|x, y\| x + y` |

## Function and Method Calls

The syntax for calling functions and methods is the same in Rust as in many other languages:

```
let x = gcd(1302, 462);  // function call

let room = player.location();  // method call
```

In the second example here, `player` is a variable of the made-up type `Player`, which has a made-up `.location()` method. (We'll show how to define your own methods when we start talking about user-defined types in Chapter 9.)

Rust usually makes a sharp distinction between references and the values they refer to. If you pass a `&i32` to a function that expects an `i32`, that's a type error. You'll notice that the `.` operator relaxes those rules a bit. In the method call `player.location()`, `player` might be a `Player`, a reference of type `&Player`, or a smart pointer of type `Box<Player>` or `Rc<Player>`. The `.location()` method might take the player either by value or by reference. The same `.location()` syntax works in all cases, because Rust's `.` operator automatically dereferences `player` or borrows a reference to it as needed.

A third syntax is used for calling associated functions, like `Vec::new()`:

```
let mut numbers = Vec::new();  // associated function call
```

These are similar to static methods in object-oriented languages: ordinary methods are called on values (like `my_vec.len()`), and associated functions are called on types (like `Vec::new()`).

Naturally, method calls can be chained:

```
// From the Actix-based web server in Chapter 2:
server
    .bind("127.0.0.1:3000")
    .expect("error binding server to address")
    .run()
```

```
        .await
        .expect("error running server");
```

One quirk of Rust syntax is that in a function call or method call, the usual syntax for generic types, `Vec<T>`, does not work:

```
return Vec<i32>::with_capacity(1000);  // error: something about
chained comparisons

let ramp = (0..n).collect<Vec<i32>>();  // same error
```

The problem is that in expressions, < is the less-than operator. The Rust compiler helpfully suggests writing `::<T>` instead of `<T>` in this case, and that solves the problem:

```
return Vec::<i32>::with_capacity(1000);  // ok, using ::<

let ramp = (0..n).collect::<Vec<i32>>();  // ok, using ::<
```

The symbol `::<...>` is affectionately known in the Rust community as the *turbofish*.

Alternatively, it is often possible to drop the type parameters and let Rust infer them:

```
return Vec::with_capacity(10);  // ok, if the fn return type is
Vec<i32>

let ramp: Vec<i32> = (0..n).collect();  // ok, variable's type is
given
```

It's considered good style to omit the types whenever they can be inferred.

## Fields and Elements

The fields of a struct are accessed using familiar syntax. Tuples are the same except that their fields have numbers rather than names:

```
game.black_pawns    // struct field
coords.1            // tuple field
```

If the value to the left of the dot is a reference or smart pointer type, it is automatically dereferenced, just as for method calls.

Square brackets access the elements of an array, slice, or vector:

```
pieces[i]           // array element
```

The value to the left of the brackets is automatically dereferenced.

Extracting a slice from an array or vector is straightforward:

```
let second_half = &game_moves[midpoint..end];
```

Here `game_moves` may be an array, slice, or vector; the result, regardless, is a borrowed slice of length `end - midpoint`. All of `game_moves` is considered borrowed for the lifetime of `second_half`.

The `..` operator allows either operand to be omitted; it produces up to four different types of object depending on which operands are present:

```
..      // RangeFull
a..     // RangeFrom { start: a }
..b     // RangeTo { end: b }
a..b    // Range { start: a, end: b }
```

The latter two forms are *exclusive* (or *half-open*): the end value is not included in the range represented. For example, the range `0..3` includes the numbers `0`, `1`, and `2`.

The `..=` operator produces *inclusive* (or *closed*) ranges, which do include the end value:

```
..=b     // RangeToInclusive { end: b }
a..=b    // RangeInclusive::new(a, b)
```

For example, the range `0..=3` includes the numbers `0`, `1`, `2`, and `3`.

Only ranges that include a start value are iterable, since a loop must have somewhere to start. But in array slicing, all six forms are useful. If the start or end of the range is omitted, it defaults to the start or end of the data being sliced.

So an implementation of quicksort, the classic divide-and-conquer sorting algorithm, might look, in part, like this:

```
fn quicksort<T: Ord>(slice: &mut [T]) {
    if slice.len() <= 1 {
        return;  // Nothing to sort.
    }

    // Partition the slice into two parts, front and back.
    let pivot_index = partition(slice);

    // Recursively sort the front half of `slice`.
    quicksort(&mut slice[..pivot_index]);

    // And the back half.
    quicksort(&mut slice[pivot_index + 1..]);
}
```

## Reference Operators

The address-of operators, `&` and `&mut`, are covered in Chapter 5.

The unary `*` operator is used to access the value pointed to by a reference. As we've seen, Rust automatically follows references when you use the `.` operator to access a field or method, so the `*` operator is necessary only when we want to read or write the entire value that the reference points to.

For example, sometimes an iterator produces references, but the program needs the underlying values:

```
let padovan: Vec<u64> = compute_padovan_sequence(n);
for elem in &padovan {
    draw_triangle(turtle, *elem);
}
```

In this example, the type of `elem` is `&u64`, so `*elem` is a `u64`.

## Arithmetic, Bitwise, Comparison, and Logical Operators

Rust's binary operators are like those in many other languages. To save time, we assume familiarity with one of those languages and focus on the few points where Rust departs from tradition. Rust has the usual arithmetic operators, `+`, `-`, `*`, `/`, and `%`. As mentioned in Chapter 3, integer overflow is detected, and causes a panic, in debug builds. The standard library provides methods like `a.wrapping_add(b)` for unchecked arithmetic.

Integer division rounds toward zero, and dividing an integer by zero triggers a panic even in release builds. Integers have a method `a.checked_div(b)` that returns an `Option` (`None` if `b` is zero) and never panics.

Unary `-` negates a number. It is supported for all the numeric types except unsigned integers. There is no unary `+` operator:

```
println!("{}", -100);      // -100
println!("{}", -100u32);   // error: can't apply unary `-` to type
`u32`
println!("{}", +100);      // error: leading `+` is not supported
```

As in C, `a % b` computes the signed remainder, or modulus, of division rounding toward zero. The result has the same sign as the lefthand operand. Note that `%` can be used on floating-point numbers as well as integers:

```
let x = 1234.567 % 10.0;  // approximately 4.567
```

Rust also inherits C's bitwise integer operators, `&`, `|`, `^`, `<<`, and `>>`. However, Rust uses `!` instead of ~ for bitwise NOT:

```
let hi: u8 = 0xe0;
let lo = !hi;  // 0x1f
```

This means that `!n` can't be used on an integer `n` to mean "n is zero." For that, write `n == 0`.

Bit shifting is always sign-extending on signed integer types and zero-extending on unsigned integer types. Since Rust has unsigned integers, it does not need an unsigned shift operator, like Java's >>> operator.

Bitwise operations have higher precedence than comparisons, unlike C, so if you write `x & BIT != 0`, that means `(x & BIT) != 0`, as you probably intended. This is much more useful than C's interpretation, `x & (BIT != 0)`, which tests the wrong bit!

Rust's comparison operators are ==, `!=`, <, <=, >, and >=. Like the arithmetic operators, these can be applied to two numbers only if they're the same type. Strings, tuples, arrays, slices, and vectors are ordered lexicographically. Comparing two references is the same as comparing their referents.

Rust also has the two short-circuiting logical operators `&&` and `||`. Both operands must have the exact type `bool`.

## Assignment

The = operator can be used to assign to `mut` variables and their fields or elements. But assignment is not as common in Rust as in other languages, since variables are immutable by default.

As described in Chapter 4, if the value has a non-`Copy` type, assignment *moves* it into the destination. Ownership of the value is transferred from the source to the destination. The destination's prior value, if any, is dropped.

Compound assignment is supported:

```
total += item.price;
```

This is equivalent to `total = total + item.price;`. Other operators are supported too: `-=`, `*=`, and so forth. The full list is given in Table 6-2, earlier in this chapter.

Unlike C, Rust doesn't support chaining assignment: you can't write `a = b = 3` to assign the value `3` to both `a` and `b`. Assignment is rare enough in

Rust that you won't miss this shorthand.

Rust does not have C's increment and decrement operators `++` and `--`.

## Type Casts

You can convert a value from one type to another using the `as` keyword. This is called a *type cast*:

```
let x = 17;               // x is type i32
let index = x as usize;   // cast to usize
```

Several kinds of casts are permitted:

- Numbers may be cast from any of the built-in numeric types to any other.

  Casting an integer to another integer type is always well-defined. Converting to a narrower type results in truncation. A signed integer cast to a wider type is sign-extended, an unsigned integer is zero-extended, and so on. In short, there are no surprises.

  Converting from a floating-point type to an integer type rounds toward zero: the value of `-1.99 as i32` is `-1`. If the value is too large to fit in the integer type, the cast produces the closest value that the integer type can represent: the value of `1e6 as u8` is `255`.

- Values of type `bool` or `char`, or of a C-like `enum` type, may be cast to any integer type. (We'll cover enums in Chapter 10.)

  Casting in the other direction is not allowed, as `bool`, `char`, and `enum` types all have restrictions on their values that would have to be enforced with run-time checks. For example, casting a `u16` to type `char` is banned because some `u16` values, like `0xd800`, correspond to Unicode surrogate code points and therefore would not make valid `char` values. There is a standard method, `char::from_u32()`, which performs the run-time check and

returns an `Option<char>`; but more to the point, the need for this kind of conversion has grown rare. We typically convert whole strings or streams at once, and algorithms on Unicode text are often nontrivial and best left to libraries.

As an exception, a `u8` may be cast to type `char`, since all integers from 0 to 255 are valid Unicode code points for `char` to hold.

- Some casts involving raw pointer types are also allowed. See "Raw Pointers".

A few conversions involving reference types are so straightforward that the language performs them even without a cast. One trivial example is converting a `mut` reference to a non-`mut` reference.

Several more significant automatic conversions can happen, though:

- Values of type `&String` auto-convert to type `&str` without a cast.
- Values of type `&Vec<i32>` auto-convert to `&[i32]`.
- Values of type `&Box<Chessboard>` auto-convert to `&Chessboard`.

These are called *deref coercions*, because they apply to types that implement the `Deref` built-in trait. The purpose of `Deref` coercion is to make smart pointer types, like `Box`, behave as much like the underlying value as possible. Using a `Box<Chessboard>` is mostly just like using a plain `Chessboard`, thanks to `Deref`.

User-defined types can implement the `Deref` trait, too. When you need to write your own smart pointer type, see "Deref and DerefMut".

## Closures

Rust has *closures*, lightweight function-like values. A closure usually consists of an argument list, given between vertical bars, followed by an

expression:

```
let is_even = |x| x % 2 == 0;

assert_eq!(is_even(14), true);
```

Rust infers the closure's argument types and return type. You can also write them out explicitly, as you would for a function. If you do specify a return type, then the body of the closure must be a block, for the sake of syntactic sanity:

```
let is_even = |x: u64| -> bool x % 2 == 0;   // error

let is_even = |x: u64| -> bool { x % 2 == 0 };   // ok
```

Closures are one of Rust's most delightful features, and there is a great deal more to be said about them. We shall say it in Chapter 14.

## Onward

Expressions are what we think of as "running code." They're the part of a Rust program that compiles to machine instructions. Yet they are a small fraction of the whole language.

The same is true in most programming languages. The first job of a program is to run, but that's not its only job. Programs have to communicate. They have to be testable. They have to stay organized and flexible so that they can continue to evolve. They have to interoperate with code and services built by other teams. And even just to run, programs in a statically typed language like Rust need some more tools for organizing data than just tuples and arrays.

Coming up, we'll spend several chapters talking about features in this area: modules and crates, which give your program structure, and then structs and enums, which do the same for your data.

Next, we'll dedicate a few pages to the important topic of what to do when things go wrong.

# Chapter 7. Error Handling

*I knew if I stayed around long enough, something like this would happen.*

—George Bernard Shaw on dying

Rust's approach to error handling is unusual enough to warrant a short chapter on the topic. There aren't any difficult ideas here, just ideas that might be new to you. This chapter covers the two different kinds of error handling in Rust: panic and `Results`.

Ordinary errors are handled using the `Result` type. `Results` typically represent problems caused by things outside the program, like erroneous input, a network outage, or a permissions problem. That such situations occur is not up to us; even a bug-free program will encounter them from time to time. Most of this chapter is dedicated to that kind of error. We'll cover panic first, though, because it's the simpler of the two.

Panic is for the other kind of error, the kind that *should never happen*.

## Panic

A program panics when it encounters something so messed up that there must be a bug in the program itself. Something like:

- Out-of-bounds array access
- Integer division by zero
- Calling `.expect()` on a `Result` that happens to be `Err`
- Assertion failure

There's also the macro `panic!()`, for cases where your own code discovers that it has gone wrong, and you therefore need to trigger a panic

directly. `panic!()` accepts optional `println!()`-style arguments for building an error message.

What these conditions have in common is that they are all—not to put too fine a point on it—the programmer's fault. A good rule of thumb is: "Don't panic."

But we all make mistakes. When these errors that shouldn't happen do happen—what then? Remarkably, Rust gives you a choice. Rust can either unwind the stack when a panic happens or abort the process. Unwinding is the default.

## Unwinding

When pirates divvy up the booty from a raid, the captain gets half of the loot. Ordinary crew members earn equal shares of the other half. (Pirates hate fractions, so if either division does not come out even, the result is rounded down, with the remainder going to the ship's parrot.)

```
fn pirate_share(total: u64, crew_size: usize) -> u64 {
    let half = total / 2;
    half / crew_size as u64
}
```

This may work fine for centuries until one day it transpires that the captain is the sole survivor of a raid. If we pass a `crew_size` of zero to this function, it will divide by zero. In C++, this would be undefined behavior. In Rust, it triggers a panic, which typically proceeds as follows:

- An error message is printed to the terminal:

  ```
  thread 'main' panicked at pirates.rs:3780:9:
  attempt to divide by zero
  note: Run with `RUST_BACKTRACE=1` for a backtrace.
  ```

  If you set the `RUST_BACKTRACE` environment variable, as the messages suggests, Rust will also dump the stack at this point.

- The stack is unwound. This is a lot like C++ exception handling.

Any temporary values, local variables, or arguments that the current function was using are dropped. Dropping a value simply means cleaning up after it: any `String`s or `Vec`s the program was using are freed, any open `File`s are closed, and so on. User-defined `drop` methods are called too; see "Drop". In the particular case of `pirate_share()`, there's nothing to clean up.

Once the current function call is cleaned up, we move on to its caller, dropping its variables and arguments the same way. Then we move to *that* function's caller, and so on up the stack.

- Finally, the thread exits. If the panicking thread was the main thread, then the whole process exits (with a nonzero exit code).

Perhaps *panic* is a misleading name for this orderly process. A panic is not a crash. It's not undefined behavior. It's more like a `RuntimeException` in Java or a `std::logic_error` in C++. The behavior is well-defined; but it shouldn't be happening.

Panic is safe. It doesn't violate any of Rust's safety rules; even if you manage to panic in the middle of a standard library method, it will never leave a dangling pointer or a half-initialized value in memory. The idea is that Rust catches the invalid array access, or whatever it is, *before* anything bad happens. It would be unsafe to proceed, so Rust unwinds the stack. But the rest of the process can continue running.

Panic is per thread. One thread can be panicking while other threads are going on about their normal business. In Chapter 19, we'll show how a parent thread can find out when a child thread panics and handle the error gracefully.

There is also a way to *catch* stack unwinding, allowing the thread to survive and continue running. The standard library function `std::panic::catch_unwind()` does this. We won't cover how to use it, but this is the mechanism used by Rust's test harness to recover when an assertion fails in a test. (It can also be necessary when writing Rust code

that can be called from C or C++, because unwinding across non-Rust code causes the process to immediately abort; see Chapter 24.)

You can use threads and `catch_unwind()` to handle panic, making your program more robust. One important caveat is that these tools only catch panics that unwind the stack. Not every panic proceeds this way.

## Aborting

Stack unwinding is the default panic behavior, but there are a few circumstances in which Rust does not try to unwind the stack:

*Stack overflow*

> A program with runaway recursion will eventually run out of stack space. This is fatal. Rust prints a message and aborts the whole process.
>
> On Linux, for example, Rust installs a `SIGSEGV` handler that detects when the program tries to write to the guard page just past the end of the stack. For functions with abnormally large stack frames, where an ordinary variable access could skip over the guard page, the compiler emits "stack probing" code to ensure this technique still works.

*Out of memory*

> This situation is not normally under Rust's control. When your program asks for memory, most operating systems virtually always say yes, even when there's not enough physical memory free to satisfy the request. Then, if memory runs low, the system frees up resources by looking around for large processes and terminating them. If your program uses too much memory, it will simply be killed. There's nothing Rust can do about it.
>
> In the rare case that memory allocation does fail, Rust aborts the process. If there are particular points in your program where you need to handle allocation failure, you can use a fallible method like `Vec::try_reserve`, described in "Growing and Shrinking Vectors".

*Double panic*

If a `.drop()` method triggers a second panic while Rust is still trying to clean up after the first, Rust aborts the process.

`panic=abort`

Rust's panic behavior is customizable. If you compile with `-C panic=abort`, the *first* panic in your program aborts the process. (With this option, Rust does not need to know how to unwind the stack, so this can reduce the size of your compiled code.)

## The Panic Hook

The first thing a panicking thread does, before unwinding or aborting, is call the *panic hook*, a function that can be configured by calling `std::panic::set_hook()`. The default panic hook writes its message and (depending on `RUST_BACKTRACE`) a stack trace to `stderr`.

If your program has a log file, it's a good idea to set a panic hook that ensures all panic messages are logged. Otherwise, panics might easily go unreported by accident, especially panics in nonmain threads and asynchronous tasks. In a project that uses the `tracing` crate for logging, the panic hook might look like this:

```
use std::backtrace::Backtrace;
use std::panic::PanicHookInfo;

/// Panic hook to log panic info using the `tracing` crate,
/// instead of the default behavior of printing to stderr.
fn report_panic(panic_info: &PanicHookInfo) {
    let stack = Backtrace::force_capture();
    tracing::error!("{panic_info}\n\n{stack}");
}

fn main() {
    setup_logging();
    std::panic::set_hook(Box::new(report_panic));
    ...
}
```

The standard `Backtrace` type captures the call stack. It supports `Display` and `Debug` formatting, and so far not much else. Note that Rust makes no guarantees about backtrace completeness or accuracy. What's captured can depend on your build profile, hardware platform, and many other factors.

Calling `set_hook` once sets the panic hook for the whole process.

## Other Panic Macros

Rust offers a few more macros that unconditionally panic, with optional format string arguments, just like `panic!()`. Each adds a different short prefix to the panic message, but the real difference between them is in what they mean to programmers:

`todo!(message...)`

> A placeholder for code you'll write in a minute. If you see this in a code review, it's probably a simple mistake; the author presumably meant to finish writing the code before requesting a review. The panic message is `not yet implemented`.

`unimplemented!(message...)`

> This is like `todo!()` but suggests that the omission is on purpose. The panic message is `not implemented`.

`unreachable!(message...)`

> This is for places in your code that control can't reach, such as after a `for` loop when you know the iterator produces values forever. The panic message is `internal error: entered unreachable code`.

This concludes our discussion of panic in Rust. There is not much to say, because ordinary Rust code has no obligation to handle panic. Even if you do use threads, `catch_unwind()`, or a panic hook, all your panic-

handling code will likely be concentrated in a few places. It's unreasonable to expect every function in a program to anticipate and cope with bugs in its own code. Errors caused by other factors are another kettle of fish.

# Result

Rust doesn't have exceptions. Rather, functions that fail have a return type that says so:

```
fn get_weather(location: LatLng) -> Result<WeatherReport,
io::Error>
```

The `Result` type indicates possible failure. When we call the `get_weather()` function, it will return either a *success result* `Ok(weather)`, where `weather` is a new `WeatherReport` value, or an *error result* `Err(error_value)`, where `error_value` is an `io::Error` explaining what went wrong.

Rust requires us to write some kind of error handling whenever we call this function. We can't get at the `WeatherReport` without doing *something* to the `Result`, and you'll get a compiler warning if a `Result` value isn't used.

In Chapter 10, we'll see how the standard library defines `Result` and how you can define your own similar types. For now, we'll take a "cookbook" approach and focus on how to use `Results` to get the error-handling behavior you want. We'll look at how to catch, propagate, and report errors, as well as common patterns for organizing and working with `Result` types.

## Catching Errors

The most thorough way of dealing with a `Result` is the way we showed in Chapter 2: use a `match` expression:

```
match get_weather(hometown) {
    Ok(report) => {
        display_weather(hometown, &report);
    }
    Err(err) => {
        eprintln!("error querying the weather: {err}");
        schedule_weather_retry();
    }
}
```

This is Rust's equivalent of `try/catch` in other languages. It's what you use when you want to handle errors head-on, not pass them on to your caller.

## Printing Errors

Sometimes the only way to handle an error is by dumping it to the terminal and moving on. The previous example showed one way to do this:

```
eprintln!("error querying the weather: {err}");
```

The standard library defines several error types with boring names: `std::io::Error`, `std::fmt::Error`, `std::str::Utf8Error`, and so on. All of them implement a common interface, the `std::error::Error` trait, which means they share the following features and methods:

`println!()`, *etc.*

> All error types support the `Display` and `Debug` traits, so they can be used with any of the macros that use format strings, including `println!()`, `eprintln!()`, `format!()`, and `panic!()`. Printing an error with the `{}` format specifier typically displays only a brief error message. Alternatively, you can print with the `{:?}` format specifier to get a `Debug` view of the error. This is less human-friendly but sometimes includes extra technical information.

```
// result of `eprintln!("error: {err}");`
error: No such file or directory (os error 2)

// result of `eprintln!("error: {err:?}");`
error: Os { code: 2, kind: NotFound, message: "No such file or
directory" }
```

`err.to_string()`

Returns an error message as a `String`. This is equivalent to `format!("{err}")`.

`err.source()`

Returns an `Option` of the underlying error, if any, that caused `err`. For example, a networking error might cause a banking transaction to fail, which could in turn cause your boat to be repossessed. If `err.to_string()` is `"boat was repossessed"`, then `err.source()` might return an error about the failed transaction. That error's `.to_string()` might be `"failed to transfer $300 to United Yacht Supply"`, and its `.source()` might be an `io::Error` with details about the specific network outage that caused all the fuss. This third error is the root cause, so its `.source()` method would return `None`. Since the standard library only includes rather low-level features, the source of errors returned from the standard library is usually `None`.

Printing an error value does not also print out its source. If you want to be sure to print all the available information, use this function:

```
use std::error::Error;
use std::io::{self, Write};

/// Dumps an error message to `stderr`.
```

```
///
/// If another error happens while building the error message or
/// writing to `stderr`, it is ignored.
fn print_error(mut err: &dyn Error) {
    let _ = writeln!(io::stderr(), "error: {err}");
    while let Some(source) = err.source() {
        let _ = writeln!(io::stderr(), "caused by: {source}");
        err = source;
    }
}
```

The `writeln!` macro works like `println!`, except that it writes the data to a stream of your choice. Here, we write the error messages to the standard error stream, `std::io::stderr`. We could use the `eprintln!` macro to do the same thing, but `eprintln!` panics if an error occurs. In `print_error`, we want to ignore errors that arise while writing the message; we explain why in "Ignoring Errors", later in the chapter.

Most Rust error types do not include a stack trace, since the cost of capturing a trace is not always negligible. However, the popular `anyhow` crate provides a ready-made error type that includes a stack if `RUST_BACKTRACE` is set.

## Propagating Errors

In most places where we try something that could fail, we don't want to catch and handle the error immediately. It is simply too much code to use a 10-line `match` statement every place where something could go wrong.

Instead, if an error occurs, we usually want to let our caller deal with it. We want errors to *propagate* up the call stack.

Rust has a `?` operator that does this. You can add a `?` to any expression that produces a `Result`, such as the result of a function call:

```
let weather = get_weather(hometown)?;
```

The behavior of `?` depends on whether this function returns a success result or an error result:

- On success, it unwraps the `Result` to get the success value inside. The type of `weather` here is not `Result<WeatherReport, io::Error>` but simply `WeatherReport`.
- On error, it immediately returns from the enclosing function, passing the error result up the call chain. To ensure that this works, `?` can only be used on a `Result` in functions that have a `Result` return type.

There's nothing magical about the `?` operator. You can express the same thing using a `match` expression, although it's much wordier:

```
let weather = match get_weather(hometown) {
    Ok(success_value) => success_value,
    Err(err) => return Err(err),
};
```

The only differences between this and the `?` operator are some fine points involving types and conversions. We'll cover those details in the next section.

It's easy to forget just how pervasive the possibility of errors is in a program, particularly in code that interfaces with the operating system. The `?` operator sometimes shows up on almost every line of a function:

```
use std::fs;
use std::io;
use std::path::Path;

fn move_all(src: &Path, dst: &Path) -> Result<(), io::Error> {
    for entry_result in src.read_dir()? {  // opening dir could
fail
        let entry = entry_result?;         // reading dir could
fail
        let dst_file = dst.join(entry.file_name());
        fs::rename(entry.path(), dst_file)?;  // renaming could
fail
```

```
        }
        Ok(())  // phew!
    }
```

`?` also works similarly with the `Option` type. In a function that returns `Option`, you can use `?` to unwrap a value and return early in the case of `None`:

```
    // If reports.get() returns an Option<&WeatherReport>...
    let weather = reports.get(hometown)?;
    // ...then `weather` is a &WeatherReport.
```

## Result Methods

One can only propagate errors for so long. Ultimately, somewhere, they must be properly handled.

We showed how this can be done using `match` expressions, handling the error in the `Err(err) =>` arm. However, it would be a bit wordy to do that in every case, so the `Result` type offers a few methods for common error-handling patterns. Each of these methods has a `match` expression in its implementation. (For the full list of `Result` methods, consult the online documentation. The methods listed here are the ones we use the most.)

`result.is_ok()`, `result.is_err()`

Return a `bool` telling if `result` is a success result or an error result.

`result.ok()`

Returns the success value, if any, as an `Option<T>`. If `result` is a success result, this returns `Some(success_value)`; otherwise, it returns `None`, discarding the error value.

`result.err()`

Returns the error value, if any, as an `Option<E>`.

`result.unwrap_or(fallback)`

Returns the success value, if `result` is a success result. Otherwise, it returns `fallback`, discarding the error value.

```
// A fairly safe prediction for Southern California.
const THE_USUAL: WeatherReport = WeatherReport::Sunny(72);


// Get a real weather report, if possible.
// If not, fall back on the usual.
let report = get_weather(los_angeles).unwrap_or(THE_USUAL);
display_weather(los_angeles, &report);
```

This is a nice alternative to `.ok()` because the return type is `T`, not `Option<T>`. Of course, it works only when there's an appropriate fallback value.

`result.unwrap_or_else(fallback_fn)`

This is the same, but instead of passing a fallback value directly, you pass a function or closure. This is for cases where it would be wasteful to compute a fallback value if you're not going to use it. The `fallback_fn` is called only if we have an error result:

```
let report = get_weather(hometown)
    .unwrap_or_else(|_err| vague_prediction(hometown));
```

(Chapter 14 covers closures in detail.)

`result.unwrap()`

Also returns the success value if `result` is a success result. However, if `result` is an error result, this method panics. This method has its uses; we'll talk more about it later.

`result.expect(message)`

This the same as `.unwrap()`, but lets you provide a message that it prints in case of panic.

`result.map(convert_fn)`

This method provides a way to change the value in the `Result` only if it's an `Ok` value. The argument is usually a closure, which will be called only if the result is `Ok`. If it's an `Err` result, `map` returns it unchanged:

```
reqwest::blocking::get(url)              // do an HTTP
request...
    .map(|response| response.status())  // ...but we only care
about the status code
```

In this example, `reqwest::blocking::get(url)` returns a `Result<Response, reqwest::Error>`. We use `.map()` to transform that into a `Result<StatusCode, reqwest::Error>`.

`result.map_err(convert_fn)`

The `map_err` method is the mirror image of `map`. It transforms only `Err` values and thus the result's error type. This can be handy when working with errors of multiple types, as we'll see in a few pages.

Lastly, methods for working with references in a `Result`:

`result.as_ref()`

Converts a `Result<T, E>` to a `Result<&T, &E>`.

`result.as_mut()`

This is the same, but borrows a mutable reference. The return type is `Result<&mut T, &mut E>`.

One reason these last two methods are useful is that all of the other methods listed here, except `.is_ok()` and `.is_err()`, *consume* the `result` they operate on. That is, they take the `self` argument by value. Sometimes it's quite handy to access data inside a `result` without destroying it, and this is what `.as_ref()` and `.as_mut()` do for us. For example, suppose you'd like to call `result.ok()`, but you need `result` to be left intact. You can write `result.as_ref().ok()`, which merely borrows `result`, returning an `Option<&T>` rather than an `Option<T>`.

## Result Type Aliases

Sometimes you'll see Rust documentation that seems to omit the error type of a `Result`:

```
fn remove_file(path: &Path) -> Result<()>
```

This means that a `Result` type alias is being used. A type alias is a kind of shorthand for type names. Modules often define a `Result` type alias to avoid having to repeat an error type that's used consistently by almost every function in the module. For example, the standard library's `std::io` module includes this line of code:

```
pub type Result<T> = result::Result<T, Error>;
```

This defines a public type `std::io::Result<T>`. It's an alias for `Result<T, E>`, but hardcodes `std::io::Error` as the error type. If you write `use std::io;`, then Rust will understand `io::Result<String>` as shorthand for `Result<String, io::Error>`.

When something like `Result<()>` appears in the online documentation, you can click on the identifier `Result` to see which type alias is being

used and learn the error type. In practice, it's usually obvious from context.

## Working with Multiple Error Types

Often, more than one thing could go wrong. Suppose we are simply reading numbers from a text file:

```
use std::io::{self, BufRead};

/// Reads integers from a text file.
/// The file should have one number on each line.
fn read_numbers(file: &mut dyn BufRead) -> io::Result<Vec<i64>> {
    let mut numbers = vec![];
    for line_result in file.lines() {
        let line = line_result?;          // reading lines can
fail
        numbers.push(line.parse()?);      // parsing integers can
fail
    }
    Ok(numbers)
}
```

Rust gives us a compiler error:

```
error: `?` couldn't convert the error to `std::io::Error`
   |
 8 | fn read_numbers(file: &mut dyn BufRead) ->
io::Result<Vec<i64>> {
   |                                           -----------------
---
   |                       expected `std::io::Error` because of
this
...
12 |     numbers.push(line.parse()?);     // parsing integers can
fail
   |                       -------^ the trait
`From<ParseIntError>` is
   |                       |        not implemented for
`std::io::Error`
   |                       |
   |                       this can't be annotated with `?`
because
   |                       it has type `Result<_, ParseIntError>`
   |
```

```
    = note: the question mark operation (`?`) implicitly performs
a
      conversion on the error value using the `From` trait
```

The terms in this error message will make more sense when we reach Chapter 11, which covers traits. For now, just note that Rust is complaining that the `?` operator can't convert a `std::num::ParseIntError` value to the type `std::io::Error`.

The problem here is that reading a line from a file and parsing an integer produce two different potential error types. The type of `line_result` is `Result<String, std::io::Error>`. The type of `line.parse()` is `Result<i64, std::num::ParseIntError>`. The return type of our `read_numbers()` function only accommodates `io::Errors`. Rust tries to cope with the `ParseIntError` by converting it to a `io::Error`, but there's no such conversion, so we get a type error. We need a single error type. One way to achieve this is by converting all other errors to `std::io::Error` manually:

```
let num = line
    .parse()
    .map_err(|err| io::Error::other(err))?;
numbers.push(num);
```

The `.map_err()` method calls the closure only if `line.parse()` returns an error. Here we are using it to convert the type of the error, from a `ParseIntError` into an `io::Error`. The method therefore returns a `Result<i64, std::io::Error>`. We can then dispense with the error in the usual way, using the `?` operator.

In this case, since `io::Error::other` is already a function that takes the error as an argument, we don't need to write a closure. We can simplify this to:

```
let num = line.parse().map_err(io::Error::other)?;
numbers.push(num);
```

But calling `.map_err()` is still awkward busywork, and bogus lines of data in the file aren't what we normally think of as I/O errors. If we applied this technique too freely, the code would become cluttered, and our use of `io::Error` would become rather deceptive. The Rust ecosystem has settled on two other solutions to this problem. Both are implemented as open source crates.

## A Universal Error Type: anyhow

The `anyhow` crate defines a single error type, `anyhow::Error`, that supports conversions from all error types. We must add the crate as a dependency in our *Cargo.toml* file:

```
[dependencies]
anyhow = "1.0.102"
```

With `anyhow`, we don't need to call `.map_err()`. We simply change the return type to use the `anyhow::Result` type alias, as shown next. The `?` operators we already had in the code will then automatically convert either type of error to an `anyhow::Error` as needed:

```
fn read_numbers(file: &mut dyn BufRead) ->
anyhow::Result<Vec<i64>> {
    ...
        let line = line_result?;      // converts io::Error to
anyhow::Error
        numbers.push(line.parse()?);  // same for ParseIntError
    ...
}
```

Using `anyhow` is not the only way to get this functionality. A similar type is built into the Rust standard library. All types that implement the `std::error::Error` trait can be automatically converted to `Box<dyn std::error::Error + Send + Sync + 'static>`. This type is a bit of a mouthful, but `dyn std::error::Error` represents "any error," and `+ Send + Sync + 'static` narrows it down to types that

are safe to pass between threads. Therefore, a rough approximation of `anyhow` in one line of code would look like this:

```
type AnyError = Box<dyn std::error::Error + Send + Sync +
'static>;
```

However, `anyhow` offers some features that this one-liner does not provide:

- Printing an `anyhow::Error` automatically prints the `source` chain.
- `anyhow::Context` provides a convenient way for your program to add information about what it was trying to do when an error occurred, for better error messages.
- The `anyhow::bail!()` and `anyhow::ensure!()` macros provide convenient ways to return an error without having to declare a new type. Like `panic!()` and `assert!()`, they take string formatting arguments, but instead of panicking, they simply return an error result.
- When an `anyhow::Error` is created, it automatically captures a backtrace if the `RUST_BACKTRACE` environment variable is set. (Note, however, that this captures the stack where the error is converted to an `anyhow` error, not where the error initially happened. For some programs, these backtraces are expensive to capture and not very helpful. They can be disabled by setting `RUST_LIB_BACKTRACE=0`.)

The `anyhow` crate documentation covers these features in more detail.

The downside of the `anyhow` approach is that the return type no longer communicates precisely what kinds of errors the caller can expect. The caller must be ready for anything.

If you're writing code to handle an `anyhow::Error` and you want to handle one particular kind of error but let all others propagate out, use the

generic method `err.downcast_ref::<T>()`. It borrows a reference to the error, *if* it happens to be the particular type of error you're looking for:

```
loop {
    match compile_project() {
        Ok(()) => return Ok(()),
        Err(err) => {
            if let Some(mse) = err.downcast_ref::
<MissingSemicolonError>() {
                insert_semicolon_in_source_code(mse.file(),
mse.line())?;
                continue;  // try again!
            }
            return Err(err);
        }
    }
}
```

`anyhow` is ideal for code close to `main`, at the top levels of an executable. Using it in the public API of a library has some drawbacks. First, it effectively imposes an extra dependency on your users, forcing them to accommodate `anyhow::Error` in their own codebase. Second, it obscures the actual types of errors that can occur. When you return an error created by `anyhow::bail!`, or by a third-party crate you're using that isn't part of your public API, your users can't downcast to that specific error: there's no public type that pinpoints the kind of error they want. They'll fall back on running regular expressions on the error messages, like barbarians. Nobody wants that. Lastly, if the `anyhow` crate ever made a breaking change to its API, users would have to reconcile different crates' usage of incompatible versions of `anyhow`, a dependency nightmare. This last concern, at least, has never materialized. `anyhow` has remained at 1.0, publishing only backward-compatible point releases, since 2019. Still, it's generally recommended to use `anyhow` only in applications, not in libraries.

## Defining Custom Error Types

Rather than use `anyhow::Error` for everything, crates usually define a custom error type for use in their public API. The `reqwest` HTTP client crate has `reqwest::Error`, the `sqlx` crate for accessing SQL databases has `sqlx::Error`, `regex` has `regex::Error`, and so on.

We haven't covered user-defined types yet; that's coming up in a few chapters. But error types are handy, so we'll include a bit of a sneak preview here.

For our `read_numbers` function, we need an error type that can contain either an `io::Error` or a `ParseIntError`. In Rust, this can be written as an `enum`:

```
use std::io;
use std::num::ParseIntError;

#[derive(Debug)]
pub enum NumberFileError {
    Io(io::Error),
    Parse(ParseIntError),
}
```

To make the `?` operator work, we must define how to convert each of the two types to a `NumberFileError`:

```
impl From<io::Error> for NumberFileError {
    fn from(err: io::Error) -> NumberFileError {
        NumberFileError::Io(err)
    }
}

impl From<ParseIntError> for NumberFileError {
    fn from(err: ParseIntError) -> NumberFileError {
        NumberFileError::Parse(err)
    }
}
```

This is enough to go on. Changing the return type of `read_numbers` to `Result<Vec<i64>, NumberFileError>` again suffices to make the

example compile. However, if you want your error type to be printable, like the standard error types, then you have a bit more work to do:

```
use std::fmt::{self, Display, Formatter};

// Errors should be printable.
impl Display for NumberFileError {
    fn fmt(&self, f: &mut Formatter) -> fmt::Result {
        let msg = match self {
            NumberFileError::Io(_) => "error reading config
file",
            NumberFileError::Parse(_) => "invalid data in config
file",
        };
        write!(f, "{msg}")
    }
}

// Errors should implement the std::error::Error trait.
impl std::error::Error for NumberFileError {
    fn source(&self) -> Option<&(dyn std::error::Error +
'static)> {
        match self {
            NumberFileError::Io(err) => Some(err),
            NumberFileError::Parse(err) => Some(err),
        }
    }
}
```

It's not important to understand every line of this. All the unfamiliar syntax will be explained in the next few chapters. We mainly want to show that error types can be written out by hand—it's not magic—but it's a lot of boilerplate code. The `thiserror` crate can generate most of this for you.

```
[dependencies]
thiserror = "2.0.18"
```

With `thiserror`, the same error type can be implemented in a few lines:

```
#[derive(Debug, thiserror::Error)]
pub enum NumberFileError {
    #[error("error reading config file")]
    Io(#[from] io::Error),
```

```
        #[error("invalid data in config file")]
        Parse(#[from] ParseIntError),
    }
```

Several attributes direct `thiserror`'s implementation of the new error type:

- `#[derive(Debug, thiserror::Error)]` tells Rust that in addition to the usual `Debug` formatting for this type, we also want some code generated by the `thiserror::Error` derive macro. The Rust compiler generates the code for `Debug`, and the `thiserror` library generates the code for `Error`. (If you like, you can view the generated code using `cargo expand`, as described in "Debugging Macros". Note, however, that generated code is usually a little strange-looking, for reasons we'll explore in that chapter.)
- `#[error(...)]` tells `thiserror` how we would like each variant to appear in `Display` formatting. The string argument is a kind of format string, able to access fields of the error object. For details, see the `thiserror` documentation.
- `#[from]` tells `thiserror` which type conversions to generate and how to implement the `source` method.

You can use `thiserror` to define a crate's public error types without requiring the crate's users to know about `thiserror` or add it to their own dependencies. `thiserror` does all its work by generating code for you, and it never generates anything you couldn't write yourself.

## Dealing with Errors That "Can't Happen"

Sometimes we just *know* that an error can't happen. For example, suppose we're writing code to parse a configuration file, and at one point we find that the next thing in the file is a string of digits:

```
if next_char.is_ascii_digit() {
    let start = current_index;
    current_index = skip_digits(line, current_index);
    let digits = &line[start..current_index];
    ...
```

We want to convert this string of digits to an actual number. There's a standard method that does this:

```
let num = digits.parse::<u64>();
```

Now the problem: the `str.parse::<u64>()` method doesn't return a `u64`. It returns a `Result`. It can fail because some strings aren't numeric:

```
"bleen".parse::<u64>()  // ParseIntError: invalid digit
```

But we happen to know that, in this case, `digits` consists entirely of digits. What should we do?

If the code we're writing already returns an `anyhow::Result`, we can tack on a `?` and forget about it. Otherwise, we face the irritating prospect of having to write error-handling code for an error that can't happen. The best choice then would be to use `.unwrap()`, a `Result` method that panics if the result is an `Err` but simply returns the success value of an `Ok`:

```
let num = digits.parse::<u64>().unwrap();
```

This is just like `?` except that if we're wrong about this error, if it *can* happen, then in that case we would panic.

In fact, we are wrong about this particular case. If the input contains a long enough string of digits, the number will be too big to fit in a `u64`:

```
"99999999999999999999".parse::<u64>()    // overflow error
```

Using `.unwrap()` in this particular case would therefore be a bug. Bogus input shouldn't cause a panic.

That said, situations do come up where a `Result` value truly can't be an error. For example, in Chapter 18, you'll see that the `Write` trait defines a common set of methods (`.write()` and others) for text and binary output. All of those methods return `io::Results`, but if you happen to be writing to a `Vec<u8>`, they can't fail. In such cases, it's acceptable to use `.unwrap()` or `.expect(message)` to dispense with the `Results`.

These methods are also useful when an error would indicate a condition so severe or bizarre that panic is exactly how you want to handle it:

```
fn print_file_age(filename: &Path, last_modified: SystemTime) {
    let age = last_modified.elapsed().expect("system clock
drift");
    ...
}
```

Here, the `.elapsed()` method can fail only if the system time is *earlier* than when the file was created. This can happen if the file was created recently, and the system clock was adjusted backward while our program was running. Depending on how this code is used, it's a reasonable judgment call to panic in that case, rather than handle the error or propagate it to the caller.

## Ignoring Errors

Occasionally we just want to ignore an error altogether. For example, in our `print_error()` function, we had to handle the unlikely situation where printing the error triggers another error. This could happen, for example, if `stderr` is piped to another process and that process is killed. The original error we were trying to report is probably more important to propagate, so we just want to ignore the troubles with `stderr`, but the Rust compiler warns about unused `Result` values:

```
writeln!(io::stderr(), "error: {err}");  // warning: unused
result
```

The idiom `let _ = ...` is used to silence this warning:

```
let _ = writeln!(io::stderr(), "error: {err}");  // ok, ignore result
```

## Handling Errors in main()

In most places where a `Result` is produced, letting the error bubble up to the caller is the right behavior. This is why `?` is a single character in Rust. As we've seen, in some programs it's used on many lines of code in a row.

But if you propagate an error long enough, eventually it reaches `main()`, and something has to be done with it. Normally, `main()` can't use `?` because its return type is not `Result`:

```
fn main() {
    calculate_tides()?;  // error: can't pass the buck any further
}
```

The simplest way to handle errors in `main()` is to use `.expect()`:

```
fn main() {
    calculate_tides().expect("error");  // the buck stops here
}
```

If `calculate_tides()` returns an error result, the `.expect()` method panics. Panicking in the main thread prints an error message and then exits with a nonzero exit code, which is roughly the desired behavior. We use this all the time for tiny programs. It's a start.

The error message is a little intimidating, though:

```
$ tidecalc --planet mercury
thread 'main' panicked at src/main.rs:2:23:
error: "moon not found"
note: run with `RUST_BACKTRACE=1` environment variable to display a backtrace
```

The error message is lost in the noise. Also, `RUST_BACKTRACE=1` is bad advice in this particular case.

However, you can also change the type signature of `main()` to return a `Result` type, so you can use `?`:

```
fn main() -> Result<(), TideCalcError> {
    let tides = calculate_tides()?;
    print_tides(tides);
    Ok(())
}
```

The `main` function can return any type that implements the `std::process::Termination` trait. This trait has a single `report()` method that Rust calls just after `main` returns. For `()`, the `report` method does nothing and returns the default exit code of 0. For error `Results`, it prints the `Debug` form of the error and returns a nonzero exit code, indicating failure.

This prints a somewhat nicer error message, but still not exactly human-friendly:

```
$ tidecalc --planet mercury
Error: TideCalcError { error_type: NoMoon, message: "moon not
found" }
```

If you care about the finer details of how errors are presented, there's no substitute for reporting the error yourself:

```
fn main() {
    if let Err(err) = calculate_tides() {
        print_error(&err);
        std::process::exit(1);
    }
}
```

This code uses an `if let` expression to print the error message only if the call to `calculate_tides()` returns an error result. For details about `if`

`let` expressions, see Chapter 10. The `print_error` function is listed in "Printing Errors".

Now the output is nice and tidy:

```
$ tidecalc --planet mercury
error: moon not found
```

## Why Results?

Now we know enough to understand what Rust is getting at by choosing `Results` over exceptions. Here are the key points of the design:

- Rust requires the programmer to make some sort of decision, and record it in the code, at every point where an error could occur. This is good because otherwise it's easy to get error handling wrong through neglect.
- The most common decision is to allow errors to propagate, and that's written with a single character, `?`. Thus, error plumbing does not clutter up your code the way it does in C and Go. Yet it's still visible: you can look at a chunk of code and see at a glance all places where errors are propagated.
- Since the possibility of errors is part of every function's return type, it's clear which functions can fail and which can't. If you change a function to be fallible, you're changing its return type, so the compiler will make you update that function's downstream users.
- Rust checks that `Result` values are used, so you can't accidentally let an error pass silently (a common mistake in C).
- Since `Result` is a data type like any other, it's easy to store success and error results in the same collection. This makes it easy to model partial success. For example, if you're writing a program that loads millions of records from a text file and you need a way to cope with the likely outcome that most will succeed, but some

will fail, you can represent that situation in memory using a vector of `Results`.

The cost is that you'll find yourself thinking about and engineering error handling more in Rust than you would in other languages. As in many other areas, Rust's take on error handling is wound just a little tighter than what you're used to. For systems programming, it's worth it.

# Chapter 8. Crates and Modules

> *This is one note in a Rust theme: systems programmers can have nice things.*
>
> —Robert O'Callahan, "Random Thoughts on Rust: crates.io and IDEs"

Suppose you're writing a program that simulates the growth of ferns, from the level of individual cells on up. Your program, like a fern, will start out very simple, with all the code, perhaps, in a single file—just the spore of an idea. As it grows, it will start to have internal structure. Different pieces will have different purposes. It will branch out into multiple files. It may cover a whole directory tree. In time it may become a significant part of a whole software ecosystem. For any program that grows beyond a few data structures or a few hundred lines, some organization is necessary.

This chapter covers the features of Rust that help keep your program organized: crates and modules. We'll also cover other topics related to the structure and distribution of a Rust crate, including how to document and test Rust code, how to silence unwanted compiler warnings, how to use Cargo to manage project dependencies and versioning, how to publish open source libraries on Rust's public crate repository, crates.io, how Rust evolves through language editions, and more, using the fern simulator as our running example.

## Crates

Rust programs are made of *crates*. Each crate is a complete, cohesive unit: all the source code for a single library or executable, plus any associated tests, examples, tools, configuration, and other junk. For your fern simulator, you might use third-party libraries for 3D graphics, bioinformatics, parallel computation, and so on. These libraries are distributed as crates (see Figure 8-1).

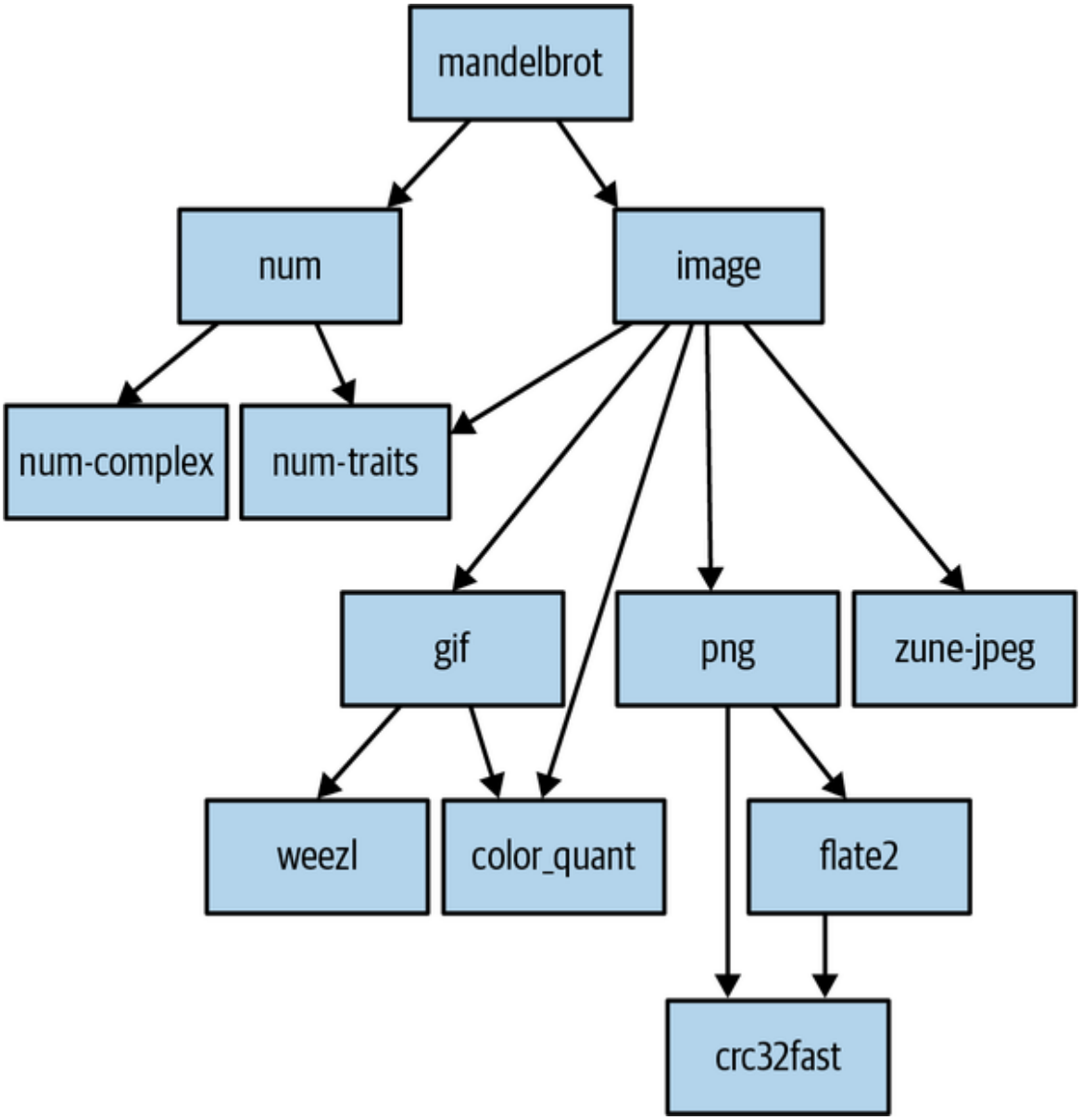


*Figure 8-1. A crate and its dependencies*

The easiest way to see what crates are and how they work together is to use `cargo build` with the `--verbose` flag to build an existing project that has some dependencies. We did this using "A Concurrent Mandelbrot Program" as our example. The results are shown here:

```
$ cd mandelbrot
$ cargo clean    # delete previously compiled code
$ cargo build --verbose
    Updating registry `https://github.com/rust-lang/crates.io-
index`
```

```
 Downloading autocfg v1.0.0
 Downloading semver-parser v0.7.0
 Downloading gif v0.9.0
 Downloading png v0.7.0

... (downloading and compiling many more crates)

   Compiling png v0.17.14
     Running `.../rustc
        --crate-name png
        --edition=2018
        .../png-0.17.14/src/lib.rs
        ...`
   ...
   Compiling image v0.25.5
     Running `.../rustc
        --crate-name image
        --edition=2024
        .../image-0.25.5/src/lib.rs
       --extern png=.../libpng-5661ec35ed9edb7d.rmeta
       ...`
   Compiling mandelbrot v0.1.0 (/tmp/rustbook-test-
files/mandelbrot)
     Running `.../rustc
        --crate-name mandelbrot
        --edition=2024
        src/main.rs
        ...
        -L dependency=.../target/debug/deps
        --extern image=.../libimage-9e7904bb08b4f62d.rlib
        --extern num=.../libnum-f102695dfa84058c.rlib`
    Finished dev [unoptimized + debuginfo] target(s) in 16.94s
$
```

We reformatted the `rustc` command lines for readability, and we deleted a lot of compiler options that aren't relevant to our discussion, replacing them with an ellipsis (`...`).

You might recall that by the time we were done, the Mandelbrot program's *main.rs* contained several `use` declarations for items from other crates:

```
use num::Complex;
// ...
use image::ColorType;
use image::png::PNGEncoder;
```

We also specified in our *Cargo.toml* file which version of each crate we wanted:

```
[dependencies]
num = "0.4.3"
image = "0.25.10"
```

The word *dependencies* here just means other crates this project uses: code we're depending on. We found these crates on crates.io, the Rust community's site for open source crates. For example, we found out about the `image` library by going to crates.io and searching for an image library. Each crate's page on crates.io shows its *README.md* file and links to documentation and source, as well as a line of configuration like `image = "0.25.10"` that you can copy and add to your *Cargo.toml*. The version numbers shown here are simply the latest versions of these three packages at the time we wrote the program.

The Cargo transcript tells the story of how this information is used. When we run `cargo build`, Cargo starts by downloading source code for the specified versions of these crates from crates.io. Then, it reads those crates' *Cargo.toml* files, downloads *their* dependencies, and so on recursively.

For example, the source code for version 0.25.10 of the `image` crate contains a *Cargo.toml* file that includes dependencies on other crates, including `gif`, `zune-jpeg`, and `png`. Seeing this, Cargo knows that before it can use `image`, it must fetch these crates as well. Later we'll see how to tell Cargo to fetch source code from a Git repository or the local filesystem rather than crates.io.

Since `mandelbrot` depends on these crates indirectly, through its use of the `image` crate, we call them *transitive* dependencies of `mandelbrot`. The collection of all these dependency relationships, which tells Cargo everything it needs to know about what crates to build and in what order, is known as the *dependency graph* of the crate. Cargo's automatic handling of the dependency graph and transitive dependencies is a huge win in terms of programmer time and effort.

Once it has the source code, Cargo compiles all the crates. It runs `rustc`, the Rust compiler, once for each crate in the project's dependency graph. When compiling libraries, Cargo uses the `--crate-type lib` option. This tells `rustc` not to look for a `main()` function but instead to produce an *.rlib* file containing compiled code that can be used to create binaries and other *.rlib* files.

When compiling a program, Cargo uses `--crate-type bin`, and the result is a binary executable for the target platform: *mandelbrot.exe* on Windows, for example.

With each `rustc` command, Cargo passes `--extern` options, giving the filename of each library the crate will use. That way, when `rustc` sees a line of code like `use image::png::PNGEncoder`, it can figure out that `image` is the name of another crate, and thanks to Cargo, it knows where to find that compiled crate on disk. The Rust compiler needs access to these *.rlib* files because they contain the compiled code of the library. Rust will statically link that code into the final executable. The *.rlib* also contains type information so Rust can check that the library features we're using in our code actually exist in the crate and that we're using them correctly. It also contains a copy of the crate's public inline functions, generics, and macros, features that can't be fully compiled to machine code until Rust sees how we use them.

`cargo build` supports all sorts of options, most of which are beyond the scope of this book, but we will mention one here: `cargo build --release` produces an optimized build. Release builds run faster, but they take longer to compile, they don't check for integer overflow, they skip `debug_assert!()` assertions, and the stack traces they generate on panic are generally less reliable.

## Editions

Rust has extremely strong compatibility guarantees. Any code that compiled on Rust 1.0 must compile just as well on Rust 1.99 or, if it's ever released, Rust 1.9000.

But sometimes there are compelling proposals for extensions to the language that would cause older code to no longer compile. For example, in 2018, after much discussion, Rust settled on a syntax for asynchronous programming that would use two new keywords, `async` and `await` (see Chapter 20). This language change would break any existing code using `async` or `await` as a variable name.

To support this kind of change with full backward compatibility, Rust introduced *editions*. The most important thing to know about Rust editions is that they are not a big deal. An edition is simply a backward compatibility option in the Rust compiler. Each crate's *Cargo.toml* file contains a line in the `[package]` section that tells Cargo which `--edition` flag to pass to `rustc`:

```
edition = "2024"
```

For new code, it's best to use the latest edition. `cargo new` creates new projects on the latest edition by default. This book uses the 2024 edition throughout.

The choice of which edition to use is truly low-stakes, though. Rust promises that the compiler will always accept all extant editions of the language, and programs can freely mix crates written in different editions. It's even fine for a 2015 edition crate to depend on a 2024 edition crate. In other words, a crate's edition only affects how its source code is construed; edition distinctions are gone by the time the code has been compiled. This means there's no pressure to update old crates just to continue to participate in the modern Rust ecosystem. Similarly, there's no pressure to keep your crate on an older edition to avoid inconveniencing its users. You only need to change editions when you want to use new language features in your own code.

Nor are old editions frozen in time. The new language and library features introduced in each release of Rust are generally available across all editions. Old editions only miss out on features that would break old code.

So far, new editions have been released about every three years. They are *not* announced with great fanfare and a raft of exciting new features. The focus is on the specific incompatible changes, which inevitably seem small or obscure. They are designed to be small. Small changes can unlock significant future language features:

- The aforementioned new keywords `async` and `await` in Rust 2018 unlocked Rust's asynchronous code features (released in December 2023).
- Minor syntax changes affecting macros in Rust 2021 unlocked C string literals (February 2024).
- Changes to the lifetimes of some temporary values in Rust 2024 unlocked `if let` chaining (June 2025).
- The new keyword `gen` in Rust 2024 could unlock Python-style generators in a future version of Rust.

Editions have also been used to introduce minor new features, such as iterability for arrays in Rust 2021, and tighten up Rust's safety story, as when Rust 2024 marked the `set_env` standard library function as `unsafe`. (It had been non-thread-safe all along.)

The *Rust Edition Guide* covers the changes introduced in each edition in detail and explains step-by-step how to upgrade a crate to a new edition.

## Rust Versions

Most new Rust features don't require breaking changes and therefore aren't recorded in editions. So it's often useful to write down the specific versions of Rust that your code supports. Both Cargo and Rustup consume Rust version information, but they do so in different ways and to different ends, and many projects provide both.

Cargo checks the `[package]` section of your *Cargo.toml* for the minimum Rust version required to build your code:

```
rust-version = "1.79.0"
```

You can only specify "regular" versions in the `rust-version` field; Cargo ignores modifiers like `-nightly` here.

This is for the benefit of downstream users of your crate. Cargo knows its own version number and the `rust-version` of all the crates it encounters. Armed with this information, `cargo build` can warn users about any incompatibilities, and commands like `cargo add` and `cargo update` won't try to update crate dependencies to versions that require a newer compiler.

Rustup, on the other hand, can change the actual version of Rust being used. If you publish a crate that supports a specific minimum version of Rust, it's a good idea to test your code with that version, even if you usually develop it using the latest compiler. Rustup makes it easy to do that on a one-off basis by checking your calls to `cargo`, `rustc`, and so forth for an argument starting with a plus sign that specifies a version. For instance, running `cargo +1.79.0 test` will build and run your tests with the 1.79.0 toolchain, while `cargo +stable build` will use the latest stable version.

If you want to specify a default version of Rust that Rustup should use for your project, you can use a *rust-toolchain.toml* file in any directory in your project:

```
[toolchain]
channel = "nightly-2026-06-01"
components = [ "clippy" ]
```

The `channel` can be a stable version like `1.95.0`, a particular nightly build of Rust, or just a channel name like `stable`. Unlike `rust-version`, this information isn't used in dependency resolution; instead, any `cargo` or `rustc` commands in this directory automatically select the specified toolchain. By default, Rustup even downloads a toolchain if it's not already installed, so all developers on your project will automatically

get Rust upgrades when they pull changes to *toolchain.toml*. (If this is a little too automatic for your taste, you can disable it with `rustup set auto-install disable` and then manage toolchains explicitly with `rustup toolchain install`.)

## Build Profiles

There are several configuration settings you can put in your *Cargo.toml* file that affect the `rustc` command lines that `cargo` generates (Table 8-1).

*Table 8-1. Cargo.toml configuration setting sections*

| Command line | Cargo.toml section used |
|---|---|
| `cargo build` | `[profile.dev]` |
| `cargo build --release` | `[profile.release]` |
| `cargo test` | `[profile.test]` |

The defaults are usually fine, but one wrinkle is that release builds do not produce good stack traces by default. This matters when you're debugging panic backtraces in release builds or when you want to use a profiler—a tool that measures where your program is spending its CPU time. In these cases, you need both optimizations (usually enabled only in release builds) and debug symbols (usually enabled only in debug builds). To enable both, add this to your *Cargo.toml*:

```
[profile.release]
debug = "limited"  # enable some debug symbols in release builds
```

The `debug` setting controls the `-C debuginfo` option to `rustc`. With this configuration, when you type `cargo build --release`, you'll get a binary with all the debug symbols needed for good backtraces and profiling. The optimization settings are unaffected.

This is off by default because the debug symbols are large. This may quadruple the size of the executable.

The Cargo documentation lists many other settings you can adjust in *Cargo.toml*.

## Modules

Whereas crates are about code sharing between projects, *modules* are about code organization *within* a project. They act as Rust's namespaces, containers for the functions, types, constants, and so on that make up your Rust program or library. A module looks like this:

```
mod spores {
    use cells::{Cell, Gene};

    /// A cell made by an adult fern. It disperses on the wind as
part of
    /// the fern life cycle. A spore grows into a prothallus -- a
whole
    /// separate organism, up to 5mm across -- which produces the
zygote
    /// that grows into a new fern. (Plant sex is complicated.)
    pub struct Spore {
        ...
    }

    /// Simulates the production of a spore by meiosis.
    pub fn produce_spore(factory: &mut Sporangium) -> Spore {
        ...
    }

    /// Extracts the genes in a particular spore.
    pub(crate) fn genes(spore: &Spore) -> Vec<Gene> {
        ...
    }

    /// Mixes genes to prepare for meiosis (part of interphase).
    fn recombine(parent: &mut Cell) {
        ...
    }
```

```
    ...
}
```

A module is a collection of *items*, named features like the `Spore` struct and the three functions in this example. The `pub` keyword makes an item public, so it can be accessed from outside the module.

One function is marked `pub(crate)`, meaning that it is available anywhere inside this crate but isn't exposed as part of the external interface. It can't be used by other crates, and it won't show up in this crate's documentation.

Anything that isn't marked `pub` is private and can be used only in the same module in which it is defined, or any child modules:

```
let s = spores::produce_spore(&mut factory);  // ok

spores::recombine(&mut cell);  // error: `recombine` is private
```

Marking an item as `pub` is often known as "exporting" that item.

The rest of this section covers the details you'll need to know to make full use of modules:

- We show how to nest modules and distribute them across different files and directories, if needed.
- We explain the path syntax Rust uses to refer to items from other modules and show how to import items so that you can use them without having to write out their full paths.
- We touch on Rust's fine-grained control for struct fields.
- We introduce *prelude* modules, which reduce boilerplate by gathering together common imports that almost any user will need.
- We present *constants* and *statics*, two ways to define named values, for clarity and consistency.

## Nested Modules

Modules can nest, and it's fairly common to see a module that's just a collection of submodules:

```
mod plant_structures {
    pub mod roots {
        ...
    }
    pub mod stems {
        ...
    }
    pub mod leaves {
        ...
    }
}
```

If you want an item in a nested module to be visible to other crates, be sure to mark it *and all enclosing modules* as public. Otherwise you may see a warning like this:

```
warning: function `is_square` is never used
   |
49 |         pub fn is_square(root: &Root) -> bool {
   |                ^^^^^^^^^
```

Perhaps this function really is dead code at the moment. But if you meant to use it in other crates, Rust is letting you know that it's not actually visible to them. You should make sure its enclosing modules are all `pub` as well.

It's also possible to specify `pub(super)`, making an item visible to the parent module only, and `pub(in <path>)`, which makes it visible in a specific parent module and its descendants. This is especially useful with deeply nested modules:

```
mod plant_structures {
    pub mod roots {
        pub mod products {
            pub(in crate::plant_structures::roots) struct
Cytokinin {
                ...
```

```
            }
        }

        use products::Cytokinin;  // ok: in `roots` module
    }

    use roots::products::Cytokinin;  // error: `Cytokinin` is
private
}

// error: `Cytokinin` is private
use plant_structures::roots::products::Cytokinin;
```

In this way, we could write out a whole program, with a huge amount of code and a whole hierarchy of modules, related in whatever ways we wanted, all in a single source file.

Actually working that way is a pain, though, so there's an alternative.

## Modules in Separate Files

A module can also be written like this:

```
mod spores;
```

Earlier, we included the body of the `spores` module, wrapped in curly braces. Here, we're instead telling the Rust compiler that the `spores` module lives in a separate file, called *spores.rs*:

```
// spores.rs

/// A cell made by an adult fern...
pub struct Spore {
    ...
}

/// Simulates the production of a spore by meiosis.
pub fn produce_spore(factory: &mut Sporangium) -> Spore {
    ...
}

/// Extracts the genes in a particular spore.
```

```
pub(crate) fn genes(spore: &Spore) -> Vec<Gene> {
    ...
}

/// Mixes genes to prepare for meiosis (part of interphase).
fn recombine(parent: &mut Cell) {
    ...
}
```

*spores.rs* contains only the items that make up the module. It doesn't need any kind of boilerplate to declare that it's a module.

The location of the code is the *only* difference between this `spores` module and the version we showed in the previous section. The rules about what's public and what's private are exactly the same either way. And Rust never compiles modules separately, even if they're in separate files: when you build a Rust crate, you're recompiling all of its modules.

A module can have its own directory. When Rust sees `mod spores;`, it checks for both *spores.rs* and *spores/mod.rs*; if neither file exists, or both exist, that's an error. For this example, we used *spores.rs* because the `spores` module did not have any submodules.

But, consider the `plant_structures` module we wrote out earlier. If we decide to split that module and its three submodules into their own files, the resulting project would look like this:

```
fern-sim/
├── Cargo.toml
└── src/
    ├── main.rs
    ├── spores.rs
    └── plant_structures/
        ├── mod.rs
        ├── leaves.rs
        ├── roots.rs
        └── stems.rs
```

In *main.rs*, we declare the `plant_structures` module:

```
pub mod plant_structures;
```

This causes Rust to load *plant_structures/mod.rs*, which declares three submodules:

```
// in plant_structures/mod.rs
pub mod roots;
pub mod stems;
pub mod leaves;
```

The content of those three modules is stored in separate files named *leaves.rs*, *roots.rs*, and *stems.rs*, located alongside *mod.rs* in the *plant_structures* directory.

It's also possible to use a file and directory with the same name to make up a module. For instance, if `stems` needed to include modules called `xylem` and `phloem`, we could choose to keep `stems` in *plant_structures/stems.rs* and add a *stems* directory:

```
fern-sim/
├── Cargo.toml
└── src/
    ├── main.rs
    ├── spores.rs
    └── plant_structures/
        ├── mod.rs
        ├── leaves.rs
        ├── roots.rs
        ├── stems/
        │   ├── phloem.rs
        │   └── xylem.rs
        └── stems.rs
```

Then, in *stems.rs*, we declare the two new submodules:

```
// in plant_structures/stems.rs
pub mod xylem;
pub mod phloem;
```

These three options give the module system enough flexibility to support almost any project structure you might desire:

- Modules in their own file

- Modules in their own directory with a *mod.rs*
- Modules in their own file with a supplementary directory containing submodules

## Paths and Imports

The `::` operator is used to access features of a module. Code anywhere in your project can refer to any standard library feature by writing out its path:

```
if s1 > s2 {
    std::mem::swap(&mut s1, &mut s2);
}
```

`std` is the name of the standard library. The path `std` refers to the top-level module of the standard library. `std::mem` is a submodule within the standard library, and `std::mem::swap` is a public function in that module.

You could write all your code this way, spelling out `std::f64::consts::PI` and `std::collections::HashMap::new` every time you want a circle or a dictionary, but it would be tedious to type and hard to read. The alternative is to *import* features into the modules where they're used:

```
use std::mem;

if s1 > s2 {
    mem::swap(&mut s1, &mut s2);
}
```

The `use` declaration causes the name `mem` to be a local alias for `std::mem` throughout the enclosing block or module.

We could write `use std::mem::swap;` to import the `swap` function itself instead of the `mem` module. However, what we did earlier is generally considered the best style: import types, traits, and modules (like

`std::mem`), and then use relative paths to access the functions, constants, and other members within.

Several names can be imported at once:

```
use std::collections::{HashMap, HashSet};  // import both

use std::fs::{self, File};  // import both `std::fs` and
`std::fs::File`.

use std::io::prelude::*;  // import everything
```

This is just shorthand for writing out all the individual imports:

```
use std::collections::HashMap;
use std::collections::HashSet;

use std::fs;
use std::fs::File;

// all the public items in std::io::prelude:
use std::io::prelude::Read;
use std::io::prelude::Write;
use std::io::prelude::BufRead;
use std::io::prelude::Seek;
```

You can use `as` to import an item but give it a different name locally:

```
use std::io::Result as IOResult;

// This return type is just another way to write
`std::io::Result<()>`:
fn save_spore(spore: &Spore) -> IOResult<()>
...
```

Modules do *not* automatically inherit names from their parent modules. For example, suppose we have this in our *proteins/mod.rs*:

```
// proteins/mod.rs
pub enum AminoAcid { ... }
pub mod synthesis;
```

Then the code in *synthesis.rs* does not automatically see the type `AminoAcid`:

```
// proteins/synthesis.rs
pub fn synthesize(seq: &[AminoAcid])  // error: can't find type
`AminoAcid`
    ...
```

Instead, each module starts with a blank slate and must import the names it uses:

```
// proteins/synthesis.rs
use super::AminoAcid;  // explicitly import from parent

pub fn synthesize(seq: &[AminoAcid])  // ok
    ...
```

By default, paths are relative to the current module:

```
// in proteins/mod.rs

// import from a submodule
use synthesis::synthesize;
```

`self` is also a synonym for the current module, so we could write either:

```
// in proteins/mod.rs

// import names from an enum,
// so we can write `Lys` for lysine, rather than `AminoAcid::Lys`
use self::AminoAcid::*;
```

or simply:

```
// in proteins/mod.rs

use AminoAcid::*;
```

(The `AminoAcid` example here is, of course, a departure from the style rule we mentioned earlier about only importing types, traits, and modules.

If our program includes long amino acid sequences, this is justified under Orwell's Sixth Rule: "Break any of these rules sooner than say anything outright barbarous.")

The keywords `super` and `crate` have a special meaning in paths: `super` refers to the parent module, and `crate` refers to the crate containing the current module.

Using paths relative to the crate root rather than the current module makes it easier to move code around the project, since all the imports won't break if the path of the current module changes. For example, we could write *synthesis.rs* using `crate`:

```
// proteins/synthesis.rs
use crate::proteins::AminoAcid;  // explicitly import relative to
crate root

pub fn synthesize(seq: &[AminoAcid])  // ok
    ...
```

Submodules can access private items in their parent modules with `use super::*`.

If you have a module with the same name as a crate that you are using, then referring to their contents takes some care. For example, if your program lists the `image` crate as a dependency in its *Cargo.toml* file but also has a module named `image`, then paths starting with `image` are ambiguous:

```
mod image {
    pub struct Sampler {
        ...
    }
}

// error: Does this refer to our `image` module, or the `image`
crate?
use image::Pixels;
```

Even though the `image` module has no `Pixels` type, the ambiguity is still considered an error: it would be confusing if adding such a definition later

could silently change what paths elsewhere in the program refer to.

To resolve the ambiguity, Rust has a special kind of path called an *absolute path*, starting with `::`, which always refers to an external crate. To refer to the `Pixels` type in the `image` crate, you can write:

```
use ::image::Pixels;        // the `image` crate's `Pixels`
```

To refer to your own module's `Sampler` type, you can write:

```
use self::image::Sampler;   // the `image` module's `Sampler`
```

Modules aren't the same thing as files, but there is a natural analogy between modules and the files and directories of a Unix filesystem. The `use` keyword creates aliases, just as the `ln` command creates links. Paths, like filenames, come in absolute and relative forms. `self` and `super` are like the `.` and `..` special directories.

## The Standard Prelude

We said a moment ago that each module starts with a "blank slate," as far as imported names are concerned. But the slate is not *completely* blank. For one thing, the standard library `std` is linked with every project by default, so `std` is automatically in scope. Without importing anything, you can use standard library features by their full path, like `std::mem::swap`.

Furthermore, a few particularly handy names, like `Vec` and `Result`, are included in the *standard prelude* and automatically imported. The 2024 edition of Rust behaves as though every module, including the root module, started with the following import:

```
use std::prelude::rust_2024::*;
```

The standard prelude contains a few dozen commonly used traits, types, functions, and macros. You can see the full list by looking up `std::prelude` in the standard library documentation.

Older editions of the language use slightly different standard preludes. For example, the `Future` trait used in asynchronous programming was added to the prelude in Rust 2024.

Libraries sometimes provide a module named `prelude` as a convention to tell users the module is meant to be imported using `*`. But the standard prelude is the only one that is ever imported automatically.

## Making use Declarations pub

Even though `use` declarations are just aliases, they can be public:

```
// in plant_structures/mod.rs
...
pub use self::leaves::Leaf;
pub use self::roots::Root;
```

This means that `Leaf` and `Root` are public items of the `plant_structures` module. They are still simple aliases for `plant_structures::leaves::Leaf` and `plant_structures::roots::Root`.

The standard prelude is written as just such a series of `pub` imports.

## Making Struct Fields pub

A module can include user-defined struct types, introduced using the `struct` keyword. We cover these in detail in Chapter 9, but this is a good point to mention how modules interact with the visibility of struct fields.

A simple struct looks like this:

```
pub struct Fern {
    pub roots: RootSet,
    pub stems: StemSet,
}
```

A struct's fields, even private fields, are accessible throughout the module where the struct is declared, and its submodules. Outside the module, only public fields are accessible.

It turns out that enforcing access control by module, rather than by class as in Java or C++, is surprisingly helpful for software design. It cuts down on boilerplate "getter" and "setter" methods, and it largely eliminates the need for anything like C++ `friend` declarations. A single module can define several types that work closely together, such as perhaps `frond::LeafMap` and `frond::LeafMapIter`, accessing each other's private fields as needed, while still hiding those implementation details from the rest of your program.

## Constants and Statics

In addition to functions, types, and nested modules, modules can define *constants* and *statics*.

The `const` keyword introduces a constant. The syntax is just like `let` except that it may be marked `pub`, and the type is required. Also, `UPPERCASE_NAMES` are conventional for constants:

```
pub const ROOM_TEMPERATURE: f64 = 20.0;  // degrees Celsius
```

The `static` keyword introduces a global variable, which is not quite the same thing:

```
pub static ROOM_TEMPERATURE: f64 = 68.0;  // degrees Fahrenheit
```

A constant is a bit like a C++ `#define`: the value is compiled into your code every place it's used. A static is a variable that's set up before your program starts running, has a single location in memory, and lasts until it exits. Use constants for magic numbers and strings in your code. Use statics for larger amounts of data, or any time you need to borrow a reference to the constant value.

There are no `mut` constants. Statics can be marked `mut`, but as discussed in Chapter 5, Rust has no way to enforce its rules about exclusive access on `mut` statics. They are, therefore, inherently non-thread-safe, and safe code can't use them at all:

```
static mut PACKETS_SERVED: usize = 0;

println!("{PACKETS_SERVED} served");  // error: use of mutable
static
```

Rust discourages global mutable state. For a discussion of the alternatives, see "Global Variables".

# Turning a Program into a Library

As your fern simulator starts to take off, you decide you need more than a single program. Suppose you've got one command-line program that runs the simulation and saves results in a file. Now, you want to write other programs for performing scientific analysis of the saved results, displaying 3D renderings of the growing plants in real time, rendering photorealistic pictures, and so on. All these programs need to share the basic fern simulation code. You need to make a library.

The first step is to factor your existing project into two parts: a library crate, which contains all the shared code, and an executable, which contains the code that's only needed for your existing command-line program. To show how you can do this, let's use a grossly simplified example program:

```
struct Fern {
    size: f64,
    growth_rate: f64,
}

impl Fern {
    /// Simulates a fern growing for one day.
    fn grow(&mut self) {
        self.size *= 1.0 + self.growth_rate;
    }
```

```
}

/// Runs a fern simulation for some number of days.
fn run_simulation(fern: &mut Fern, days: usize) {
    for _ in 0..days {
        fern.grow();
    }
}

fn main() {
    let mut fern = Fern {
        size: 1.0,
        growth_rate: 0.001,
    };
    run_simulation(&mut fern, 1000);
    println!("final fern size: {}", fern.size);
}
```

We'll assume that this program has a trivial *Cargo.toml* file:

```
[package]
name = "fern-sim"
version = "0.1.0"
authors = ["You <you@example.com>"]
edition = "2024"
```

Turning this program into a library is easy. Here are the steps:

1. Rename the file *src/main.rs* to *src/lib.rs*.
2. Add the `pub` keyword to items in *src/lib.rs* that will be public features of our library.
3. Move the `main` function to a temporary file somewhere. We'll come back to it.

The resulting *src/lib.rs* file looks like this:

```
pub struct Fern {
    pub size: f64,
    pub growth_rate: f64,
}

impl Fern {
```

```
    /// Simulates a fern growing for one day.
    pub fn grow(&mut self) {
        self.size *= 1.0 + self.growth_rate;
    }
}

/// Runs a fern simulation for some number of days.
pub fn run_simulation(fern: &mut Fern, days: usize) {
    for _ in 0..days {
        fern.grow();
    }
}
```

Note that we didn't need to change anything in *Cargo.toml*. This is because our minimal *Cargo.toml* file leaves Cargo to its default behavior. By default, `cargo build` looks at the files in our source directory and figures out what to build. When it sees the file *src/lib.rs*, it knows to build a library.

The code in *src/lib.rs* forms the *root module* of the library. Other crates that use our library can only access the public items of this root module.

## The src/bin Directory

Getting the original command-line `fern-sim` program working again is also straightforward: Cargo has some built-in support for small programs that live in the same crate as a library.

In fact, Cargo itself is written this way. The bulk of the code is in a Rust library. The `cargo` command-line program that we've been using throughout this book is a thin wrapper program that calls out to the library for all the heavy lifting. Both the library and the command-line program live in the same source repository.

We can keep our program and our library in the same crate, too. Put this code into a file named *src/bin/efern.rs*:

```
use fern_sim::Fern;

fn main() {
```

```
    let mut fern = Fern {
        size: 1.0,
        growth_rate: 0.001,
    };
    fern_sim::run_simulation(&mut fern, 1000);
    println!("final fern size: {}", fern.size);
}
```

The `main` function is the one we set aside earlier. We've added a `use` declaration to import the `Fern` type from the `fern-sim` crate, and further down we call `fern_sim::run_simulation`. In other words, we're using that crate as a library.

Because we've put this file into *src/bin*, Cargo will compile both the `fern-sim` library and this program the next time we run `cargo build`. We can run the `efern` program using `cargo run --bin efern`. Here's what it looks like, using `--verbose` to show the commands Cargo is running:

```
$ cargo build --verbose
   Compiling fern-sim v0.1.0 (/.../fern-sim)
     Running `rustc --crate-name fern-sim ... src/lib.rs ...`
     Running `rustc --crate-name efern ... src/bin/efern.rs ...`
$ cargo run --verbose --bin efern
       Fresh fern-sim v0.1.0 (/.../fern-sim)
     Running `target/debug/efern`
final fern size: 2.7169239322355985
```

We still didn't have to make any changes to *Cargo.toml* because, again, Cargo's default is to look at your source files and figure things out. It automatically treats *.rs* files in *src/bin* as extra programs to build.

We can also build larger programs in the *src/bin* directory using subdirectories. Suppose we want to provide a second program that draws a fern on the screen, but the drawing code is large and modular, so it belongs in its own file. We can give the second program its own subdirectory:

```
fern-sim/
├── Cargo.toml
└── src/
```

```
└── bin/
    ├── efern.rs
    └── draw-fern/
        ├── main.rs
        └── draw.rs
```

This has the advantage of letting larger binaries have their own submodules without cluttering up either the library code or the *src/bin* directory.

Of course, now that `fern-sim` is a library, we also have another option. We could have put this program in its own isolated project, in a completely separate directory, with its own *Cargo.toml* listing `fern-sim` as a dependency:

```
[dependencies]
fern-sim = { path = "../fern-sim" }
```

Perhaps that is what you'll do for other fern-simulating programs down the road. The *src/bin* directory is just right for simple programs like `efern` and `draw-fern`.

## Attributes

Any item in a Rust program can be decorated with *attributes*. Attributes are Rust's catchall syntax for writing miscellaneous instructions and advice to the compiler. For example, suppose you're getting this warning:

```
warning: type `git_revspec` should have an upper camel case name
   |
83 | pub struct git_revspec {
   |            ^^^^^^^^^^^ help: convert the identifier to
   |                         upper camel case: `GitRevspec`
   |
  = note: `#[warn(non_camel_case_types)]` on by default
```

But you chose this name for a reason, and you wish Rust would shut up about it. You can disable the warning by adding an `#[allow]` attribute on the type:

```
#[allow(non_camel_case_types)]
pub struct git_revspec {
    ...
}
```

Other warning-related attributes include `#[deny]`, to treat specified warnings as errors, and `#[expect]`, which is like `#[allow]` except that it's an error if an expected warning *isn't* triggered. The point is to remind you to remove the attribute later if it's no longer needed.

Another typical example of an attribute is `#[inline]`, which is used to micromanage the inline expansion of functions:

```
/// Adjusts levels of ions etc. in two adjacent cells
/// due to osmosis between them.
#[inline]
fn do_osmosis(c1: &mut Cell, c2: &mut Cell) {
    ...
}
```

Inlining is an optimization that we're usually happy to leave to the compiler, but there's one situation where inlining *won't* happen without `#[inline]`. When a function defined in one crate is called in another crate, Rust won't inline it unless it's generic (it has type parameters) or it's explicitly marked `#[inline]`.

Otherwise, the compiler treats `#[inline]` as a suggestion. Rust also supports the more insistent `#[inline(always)]`, to request that a function be expanded inline at every call site, and `#[inline(never)]`, to ask that a function never be inlined.

Some attributes, like `#[allow]`, can be attached to a whole module and apply to everything in it. Others, like `#[test]` and `#[inline]`, must be attached to individual items. As you might expect for a catchall feature, each attribute is custom-made and has its own set of supported arguments. The *Rust Reference* documents the full set of supported attributes in detail.

To attach an attribute to a whole crate, add it at the top of the *main.rs* or *lib.rs* file, before any items, and write `#!` instead of `#`, like this:

```
// libgit2_sys/lib.rs
#![allow(non_camel_case_types)]

pub struct git_revspec {
    ...
}

pub struct git_error {
    ...
}
```

The `#!` tells Rust to attach an attribute to the enclosing item rather than whatever comes next. In this case, the `#![allow]` attribute attaches to the whole `libgit2_sys` crate, not just `struct git_revspec`.

`#!` can also be used inside functions, structs, and so on, but it's only typically used at the beginning of a file, to attach an attribute to the whole module or crate. Some attributes always use the `#!` syntax because they can only be applied to a whole crate.

For example, the `#![feature]` attribute is used to turn on *unstable* features of the Rust language and libraries: features that are experimental and therefore might have bugs or might be changed or removed in the future. For instance, as we're writing this, Rust has experimental support for `f16`, a floating point type whose finite range is ±65,504:

```
#![feature(f16)]

fn main() {
    println!("{}", std::f16::consts::PI);  // 3.14
}
```

Experimental features are available only in nightly builds of Rust, not in the official stable releases. Over time, the Rust team sometimes *stabilizes* an experimental feature so that it becomes a standard part of the language. The `#![feature]` attribute then becomes superfluous, and Rust generates a warning advising you to remove it.

## Conditional Compilation

The `#[cfg]` attribute is used to mark code that should be conditionally compiled. It can be used on any declaration, even a module:

```
// Only include this module in the project if we're building for
Android.
#[cfg(target_os = "android")]
mod mobile;
```

The full syntax of `#[cfg]` is specified in the *Rust Reference*. Table 8-2 lists the most commonly used options.

*Table 8-2. Most commonly used `#[cfg]` options*

| `#[cfg(...)]` option | Enabled when |
|---|---|
| `test` | Tests are enabled (compiling with `cargo test` or `rustc --test`). |
| `debug_assertions` | Debug assertions are enabled (typically in nonoptimized builds). |
| `unix` | Compiling for Unix, including macOS. |
| `windows` | Compiling for Windows. |
| `target_pointer_width = "64"` | Targeting a 64-bit platform. The other possible value is `"32"`. |
| `target_arch = "x86_64"` | Targeting x86-64 in particular. Other values: `"x86"`, `"arm"`, `"aarch64"`, `"powerpc"`, `"powerpc64"`, `"mips"`. |
| `target_os = "macos"` | Compiling for macOS. Other values: `"windows"`, `"ios"`, `"android"`, `"linux"`, `"freebsd"`, `"openbsd"`, `"netbsd"`, `"dragonfly"`. |
| `feature = "robots"` | The user-defined feature named `"robots"` is enabled (compiling with `cargo build --feature robots` or `rustc --cfg feature='"robots"'`). Features are declared in the `[features]` section of *Cargo.toml*. |
| `not(`*A*`)` | *A* is not satisfied. To provide two different implementations of a function, mark one with `#[cfg(X)]` and the other with `#[cfg(not(X))]`. |
| `all(`*A*`,`*B*`)` | Both *A* and *B* are satisfied (the equivalent of `&&`). |

| `#[cfg(...)]` option | Enabled when |
|---|---|
| `any(`*A*`,`*B*`)` | Either *A* or *B* is satisfied (the equivalent of `\|\|`). |
| `false` | Never. This can be used to comment out an item. |

The `#[cfg]` attribute can be used on functions, types, imports, and even individual blocks of code.

Rust also supports a built-in macro, `cfg!(...)`, that returns `true` if the current build configuration matches the condition in parentheses, and `false` otherwise. The macro supports the same syntax as the `#[cfg(...)]` attribute. For example, `cfg!(debug_assertions)` is true if you're compiling with debug assertions enabled.

## The Build Environment

The `env!("VAR_NAME")` macro offers another way for a Rust crate to adapt to build configuration. It returns a string: the value of the specified environment variable at compile time. If the variable doesn't exist, it's a compilation error.

Cargo sets several interesting environment variables when it compiles a crate. For example, to get your crate's current version string, you can write:

```
const MY_VERSION: &str = env!("CARGO_PKG_VERSION");
```

A full list of these environment variables is included in the Cargo documentation.

The `option_env!("VAR_NAME")` macro is the same as `env!` except that it returns an `Option<&str>` that is `None` if the specified variable is not set.

## Including Files

Three more built-in macros let you bring in code or data from another file:

`include!("file.rs")`

Expands to the contents of the specified file, which must be valid Rust code—either an expression or a sequence of items.

`include_str!("file.txt")`

Expands to a `&'static str` containing the text of the specified file. You can use it like this:

```
const COMPOSITOR_SHADER: &str =
    include_str!("../resources/compositor.glsl");
```

If the file doesn't exist or is not valid UTF-8, you'll get a compilation error.

`include_bytes!("file.dat")`

This is the same except the file is treated as binary data, not UTF-8 text. The result is a `&'static [u8]`.

Like all macros, these are processed at compile time. If the file doesn't exist or can't be read, compilation fails. They can't fail at run time. In all cases, if the filename is a relative path, it's resolved relative to the directory that contains the current file.

## Tests and Documentation

As we saw in "Writing and Running Unit Tests", a simple unit testing framework is built into Rust. Tests are ordinary functions marked with the `#[test]` attribute:

```
#[test]
fn math_works() {
    let x: i32 = 1;
    assert!(x.is_positive());
    assert_eq!(x + 1, 2);
}
```

`cargo test` runs all the tests in your project:

```
$ cargo test
   Compiling math_test v0.1.0 (/home/jimb/rust/math_test)
    Finished `test` profile [unoptimized + debuginfo] target(s)
in 0.49s
     Running unittests src/lib.rs (target/debug/deps/math_test-
dfc7...)

running 1 test
test math_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out;
    finished in 0.00s
```

(You'll also see some output about "doc-tests," which we'll get to in a minute.)

This works the same whether your crate is an executable or a library. You can run specific tests by passing arguments to Cargo: `cargo test math` runs all tests that contain `math` somewhere in their name.

Tests commonly use the `assert!` and `assert_eq!` macros from the Rust standard library. `assert!(expr)` succeeds if `expr` is true. Otherwise, it panics, which causes the test to fail. `assert_eq!(v1, v2)` is just like `assert!(v1 == v2)` except that if the assertion fails, the error message shows both values.

You can use these macros in ordinary code, to check invariants, but note that `assert!` and `assert_eq!` are included even in release builds. Use `debug_assert!` and `debug_assert_eq!` instead to write assertions that are checked only in debug builds. To test error cases, add the `#[should_panic]` attribute to your test:

```
/// This test passes only if division by zero causes a panic,
/// as we claimed in the previous chapter.
#[test]
#[allow(unconditional_panic, unused_must_use)]
#[should_panic(expected = "divide by zero")]
fn test_divide_by_zero_error() {
    1 / 0;  // should panic!
}
```

In this case, we also need to add an `allow` attribute to tell the compiler to let us do things that it can statically prove will panic, and perform divisions and just throw away the answer, because normally, it tries to stop that kind of silliness.

You can also return a `Result<(), E>` from your tests. As long as the error variant is `Debug`, which is usually the case, you can simply return a `Result` by using `?` to throw away the `Ok` variant:

```
use std::num::ParseIntError;

/// This test will pass if "1024" is a valid number, which it is.
#[test]
fn explicit_radix() -> Result<(), ParseIntError> {
    i32::from_str_radix("1024", 10)?;
    Ok(())
}
```

Functions marked with `#[test]` are compiled conditionally. A plain `cargo build` or `cargo build --release` skips the testing code. But when you run `cargo test`, Cargo builds your program twice: once in the ordinary way and once with your tests and the test harness enabled. This means your unit tests can live right alongside the code they test, accessing internal implementation details if they need to, and yet there's no run-time cost.

However, it can result in some warnings. For example:

```
fn roughly_equal(a: f64, b: f64) -> bool {
    (a - b).abs() < 1e-6
}
```

```
#[test]
fn test_circle_area() {
    let circle = Circle::new(1.0);
    assert!(roughly_equal(circle.area(), std::f64::consts::PI));
}
```

In builds that omit the test code, `roughly_equal` appears unused, and Rust will now complain:

```
$ cargo build
   Compiling math_test v0.1.0 (file:///.../math_test)
warning: function `roughly_equal` is never used
  |
7 | fn roughly_equal(a: f64, b: f64) -> bool {
  |    ^^^^^^^^^^^^^
  |
  = note: `#[warn(dead_code)]` (part of `#[warn(unused)]`) on by
default
```

So the convention, when your tests get substantial enough to require support code, is to put them in a `tests` module and declare the whole module to be testing-only using the `#[cfg]` attribute:

```
#[cfg(test)]   // include this module only when testing
mod tests {
    use super::*;  // import everything from the enclosing module

    fn roughly_equal(a: f64, b: f64) -> bool {
        (a - b).abs() < 1e-6
    }

    #[test]
    fn circle_area() {
        let circle = Circle::new(1.0);
        assert!(roughly_equal(circle.area(),
std::f64::consts::PI));
    }
}
```

Cargo does not natively provide support for the automatic or random generation of tests, but several community projects do so very effectively:

- The `rstest` crate provides a simple way to test the same code with many different inputs, automatically generating individual tests with each combination of the provided values.
- The `proptest` crate supports *property-based testing*, automatically generating and minimizing test cases based on more general properties, like "any number between 0 and 100" or "any valid `String`."
- The *Rust Fuzz Book* covers the use of `cargo-fuzz` and `afl.rs` for *fuzzing*, the practice of testing the security and stability guarantees of software by generating random inputs and seeing if something breaks.

Rust's test harness uses multiple threads to run several tests at a time, a nice side benefit of your Rust code being thread-safe by default. To disable this, either run a single test, `cargo test testname`, or run `cargo test -- --test-threads 1`. (The first `--` ensures that `cargo test` passes the `--test-threads` option through to the test executable.) This means that, technically, the Mandelbrot program we showed in Chapter 2 was not the second multithreaded program in that chapter, but the third! The `cargo test` run in "Writing and Running Unit Tests" was the first.

Normally, the test harness only shows the output of tests that failed. To show the output from tests that pass too, run `cargo test -- --nocapture`.

## Integration Tests

Your fern simulator continues to grow. You've decided to put all the major functionality into a library that can be used by multiple executables. It would be nice to have some tests that link with the library the way an end user would, using *fern_sim.rlib* as an external crate.

Also, you have some tests that start by loading a saved simulation from a binary file, and it is awkward having those large test files in your *src* directory. Integration tests help with these two problems.

Integration tests are *.rs* files that live in a *tests* directory alongside your project's *src* directory. When you run `cargo test`, Cargo compiles each integration test as a separate, standalone crate, linked with your library and the Rust test harness. Here is an example:

```
// tests/unfurl.rs - Fiddleheads unfurl in sunlight

use fern_sim::Terrarium;
use std::time::Duration;

#[test]
fn test_fiddlehead_unfurling() {
    let mut world =
Terrarium::load("tests/unfurl_files/fiddlehead.tm");
    assert!(world.fern(0).is_furled());
    let one_hour = Duration::from_secs(60 * 60);
    world.apply_sunlight(one_hour);
    assert!(world.fern(0).is_fully_unfurled());
}
```

Integration tests are valuable in part because they see your crate from the outside, just as a user would. They test the crate's public API.

`cargo test` runs both unit tests and integration tests. To run only the integration tests in a particular file—for example, *tests/unfurl.rs*—use the command `cargo test --test unfurl`.

## Documentation

The command `cargo doc` creates HTML documentation for your library:

```
$ cargo doc --no-deps --open
 Documenting fern-sim v0.1.0 (file:///.../fern-sim)
```

The `--no-deps` option tells Cargo to generate documentation only for `fern-sim` itself, and not for all the crates it depends on. The `--open` option tells Cargo to open the documentation in your browser afterward.

You can see the result in Figure 8-2. Cargo saves the new documentation files in *target/doc*. The starting page is *target/doc/fern_sim/index.html*.

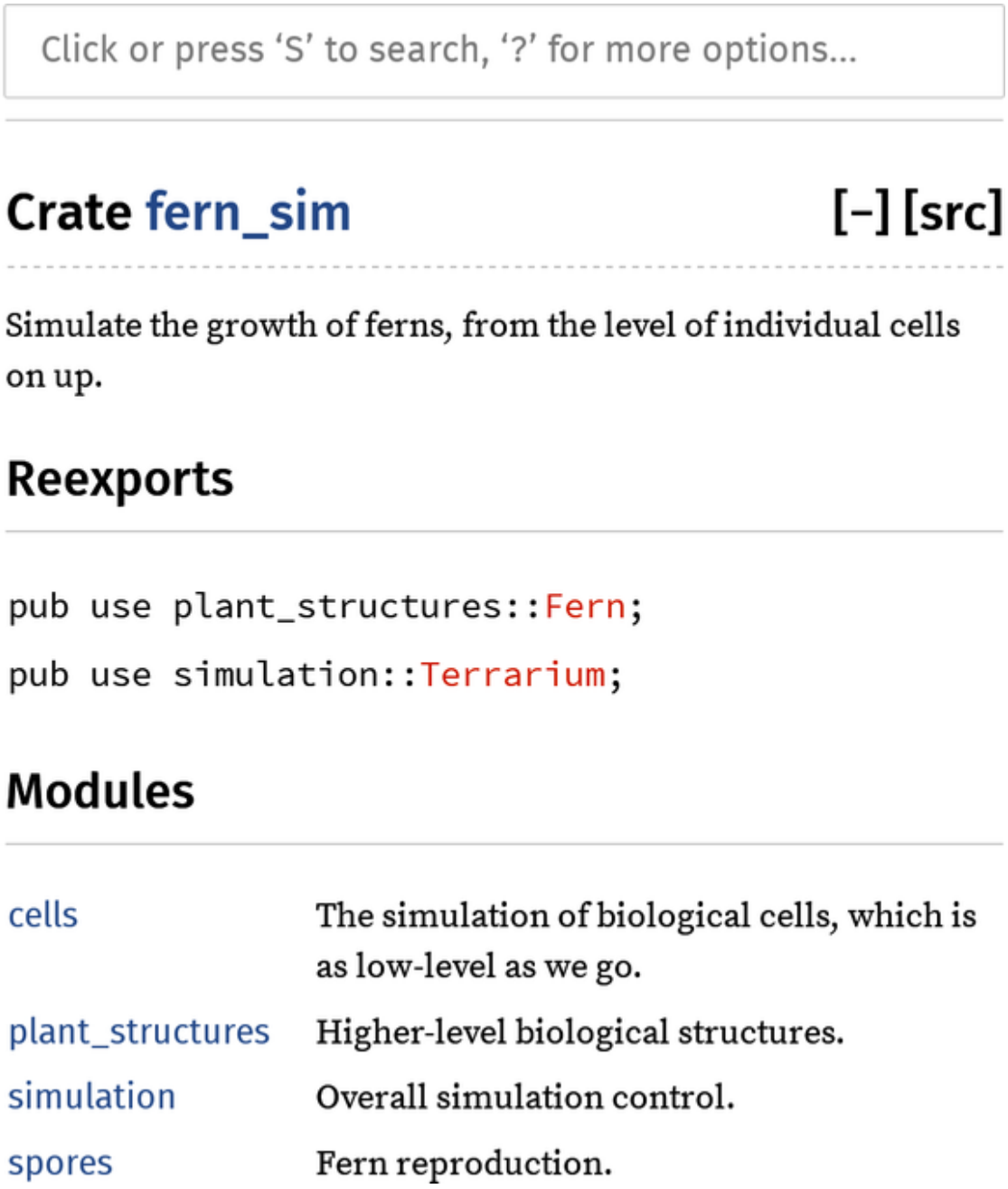


*Figure 8-2. Example of documentation generated by `rustdoc`*

The documentation is generated from the `pub` features of your library, plus any *doc comments* you've attached to them. We've seen a few doc comments in this chapter already. They look like comments:

```
/// Simulates the production of a spore by meiosis.
pub fn produce_spore(factory: &mut Sporangium) -> Spore {
    ...
}
```

But when Rust sees comments that start with three slashes, it treats them as a `#[doc]` attribute instead. Rust treats the preceding example exactly the same as this:

```
#[doc = "Simulates the production of a spore by meiosis."]
pub fn produce_spore(factory: &mut Sporangium) -> Spore {
    ...
}
```

When you compile a library or binary, these attributes don't change anything, but when you generate documentation, doc comments on public features are included in the output.

Likewise, comments starting with `//!` are treated as `#![doc]` attributes and are attached to the enclosing feature, typically a module or crate. For example, your *fern_sim/src/lib.rs* file might begin like this:

```
//! Simulates the growth of ferns, from the level of
//! individual cells on up.
```

The content of a doc comment is treated as Markdown, an easy-to-learn shorthand notation for HTML. The rest of this chapter assumes some familiarity with Markdown. Good tutorials are available on the web.

One special feature of doc comments in Rust is that Markdown links can use Rust item paths, like `leaves::Leaf`, instead of URLs, to indicate what they refer to. Cargo will substitute a link to the right place in the right documentation page. For example, the documentation generated from this code links to the documentation pages for `VascularPath`, `Leaf`, and `Root`:

```
/// Creates a [`VascularPath`] which represents the path of
nutrients
/// from the given [`Root`][r] to the given [`Leaf`]
(leaves::Leaf).
///
/// [r]: roots::Root
pub fn trace_path(leaf: &leaves::Leaf, root: &roots::Root) ->
VascularPath {
```

```
    ...
}
```

You can use `backticks` to set off bits of code in the middle of running text. In the output, these snippets will be formatted in a fixed-width font. Larger code samples can be added by indenting four spaces:

```
/// A block of code in a doc comment:
///
///     if samples::everything().works() {
///         println!("ok");
///     }
```

You can also use Markdown fenced code blocks. This has the same effect as indentation:

```
/// Another snippet, the same code, but written differently:
///
/// ```
/// if samples::everything().works() {
///     println!("ok");
/// }
/// ```
```

Whichever format you use, an interesting thing happens when you include a block of code in a doc comment. Rust automatically turns it into a test.

## Doc-Tests

When you run tests in a Rust library crate, Rust checks that all the code that appears in your documentation actually runs and works. It does this by taking each block of code that appears in a doc comment, compiling it as a separate executable crate, linking it with your library, and running it.

Here is a standalone example of a doc-test. Create a new project by running `cargo new --lib ranges` (the `--lib` flag tells Cargo we're creating a library crate, not an executable crate), and put the following code in *ranges/src/lib.rs*:

```
use std::ops::Range;

/// Returns true if two ranges overlap.
///
///     assert_eq!(ranges::overlap(0..7, 3..10), true);
///     assert_eq!(ranges::overlap(1..5, 101..105), false);
///
/// If either range is empty, they don't count as overlapping.
///
///     assert_eq!(ranges::overlap(0..0, 0..10), false);
///
pub fn overlap(r1: Range<usize>, r2: Range<usize>) -> bool {
    r1.start < r1.end && r2.start < r2.end &&
        r1.start < r2.end && r2.start < r1.end
}
```

The two small blocks of code in the doc comment appear in the documentation generated by `cargo doc`, as shown in Figure 8-3.

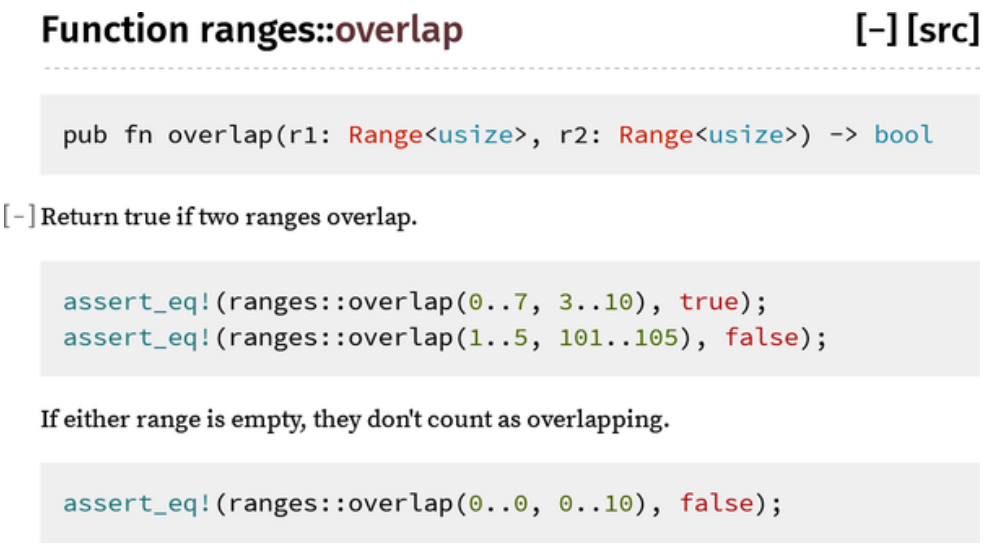


*Figure 8-3. Documentation showing some doc-tests*

They also become two separate tests:

```
$ cargo test
   Compiling ranges v0.1.0 (/home/jimb/rust/ranges)
...
   Doc-tests ranges

running 2 tests
test src/lib.rs - overlap (line 5) ... ok
test src/lib.rs - overlap (line 10) ... ok
```

```
test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured; 0
filtered out;
    finished in 0.29s
```

If you pass the `--verbose` flag to Cargo, you'll see that it's using `rustdoc --test` to run these two tests. `rustdoc` stores each code sample in a separate file, adding a few lines of boilerplate code, to produce two programs.

Here's the first:

```
use ranges;
fn main() {
    assert_eq!(ranges::overlap(0..7, 3..10), true);
    assert_eq!(ranges::overlap(1..5, 101..105), false);
}
```

And here's the second:

```
use ranges;
fn main() {
    assert_eq!(ranges::overlap(0..0, 0..10), false);
}
```

The tests pass if these programs compile and run successfully.

These two code samples contain assertions, but that's just because in this case, the assertions make decent documentation. The idea behind doc-tests is not to put all your tests into comments. Rather, you write the best possible documentation, and Rust makes sure the code samples in your documentation actually compile and run.

Very often a minimal working example includes some details, such as imports or setup code, that are necessary to make the code compile but just aren't important enough to show in the documentation.

To hide a line of a code sample, put a `#` followed by a space at the beginning of that line:

```
/// Lets the sun shine in and runs the simulation for a given
/// amount of time.
///
///     # use fern_sim::Terrarium;
///     # use std::time::Duration;
///     # let mut tm = Terrarium::new();
///     tm.apply_sunlight(Duration::from_secs(60));
///
pub fn apply_sunlight(&mut self, time: Duration) {
    ...
}
```

"

Sometimes it's helpful to show a complete sample program in documentation, including a `main` function. Obviously, if those pieces of code appear in your code sample, you do not also want `rustdoc` to add them automatically. The result wouldn't compile. `rustdoc` therefore treats any code block containing the exact string `fn main` as a complete program and doesn't add anything to it.

Testing can be disabled for specific blocks of code. To tell Rust to compile your example but stop short of running it, use a fenced code block with the `no_run` annotation:

```
/// Uploads all local terrariums to the online gallery.
///
/// ```no_run
/// let mut session = fern_sim::connect();
/// session.upload_all();
/// ```
pub fn upload_all(&mut self) {
    ...
}
```

If the code block isn't Rust code at all, use the name of the language, like `c++` or `sh`, or `text` for plain text (or Rust pseudocode that isn't expected to compile). `rustdoc` doesn't know the names of hundreds of programming languages; rather, it treats any annotation it doesn't recognize as indicating that the code block isn't Rust. This disables code highlighting as well as doc-testing.

# Specifying Dependencies

We've seen one way of telling Cargo where to get source code for crates your project depends on, by version number:

```
image = "0.25.10"
```

There are several ways to specify dependencies, and some rather nuanced things you might want to say about which versions to use, so it's worth spending a few pages on this. First of all, you may want to use dependencies that aren't published on crates.io at all. One way to do this is by specifying a Git repository URL and revision:

```
image = { git = "https://github.com/image-rs/image.git", rev =
"c708281" }
```

This particular crate is open source, hosted on GitHub, but you could just as easily point to a private Git repository hosted on your corporate network. As shown here, you can specify the particular `rev`, `tag`, or `branch` to use. (These are all ways of telling Git which revision of the source code to check out.)

Another alternative is to specify a directory that contains the crate's source code:

```
image = { path = "vendor/image" }
```

This is convenient when your team has a single version control repository that contains source code for several crates, or perhaps the entire dependency graph. Each crate can specify its dependencies using relative paths.

Having this level of control over your dependencies is powerful. If you ever decide that any of the open source crates you use isn't exactly to your liking, you can trivially fork it: just hit the Fork button on GitHub and change one line in your *Cargo.toml* file. Your next `cargo build` will seamlessly use your fork of the crate instead of the official version.

## Versions

When you write something like `image = "0.25"` in your *Cargo.toml* file, Cargo interprets this rather loosely. It uses the most recent version of `image` that is considered compatible with version 0.25. The compatibility rules are adapted from Semantic Versioning":

- A version number that starts with 0.0 is so raw that Cargo never assumes it's compatible with any other version.
- A version number that starts with 0.*x*, where *x* is nonzero, is considered compatible with other point releases in the 0.*x* series. We specified `image` version 0.25, but Cargo would use 0.25.5 if available. (This is not what the Semantic Versioning standard says about 0.*x* version numbers, but the rule proved too useful to leave out.)
- Once a project reaches 1.0, only new major versions break compatibility. So if you ask for version 2.0.1, Cargo might use 2.17.99 instead, but not 3.0.

Version numbers are flexible by default because otherwise the problem of which version to use would quickly become over-constrained. Suppose one library, `libA`, used `num = "0.4.2"` while another, `libB`, used `num = "0.4.3"`. If version numbers required exact matches, no project would be able to use those two libraries together. Allowing Cargo to use any compatible version is a much more practical default.

Still, different projects have different needs when it comes to dependencies and versioning. You can specify an exact version or range of versions by using operators, as illustrated in Table 8-3.

*Table 8-3. Specifying versions in a Cargo.toml file*

| ***Cargo.toml* line** | **Meaning** |
|---|---|
| `image = "=0.10.0"` | Use only the exact version 0.10.0. |
| `image = ">=1.0.5"` | Use 1.0.5 or *any* higher version (even 2.9, if it's available). |
| `image = ">1.0.5 <1.1.9"` | Use a version that's higher than 1.0.5, but lower than 1.1.9. |
| `image = "<=2.7.10"` | Use any version up to 2.7.10. |

Another version specification you'll occasionally see is the wildcard `*`. This tells Cargo that any version will do. Unless some other *Cargo.toml* file contains a more specific constraint, Cargo will use the latest available version. The Cargo documentation at doc.crates.io covers version specifications in even more detail.

Note that the compatibility rules mean that version numbers can't be chosen purely for marketing reasons. They actually mean something. They're a contract between a crate's maintainers and its users. If you maintain a crate that's at version 1.7 and you decide to remove a function or make any other change that isn't fully backward compatible, you must bump your version number to 2.0. If you were to call it 1.8, you'd be claiming that the new version is compatible with 1.7, and your users might find themselves with broken builds.

## Cargo.lock

The version numbers in *Cargo.toml* are deliberately flexible, yet we don't want Cargo to upgrade us to the latest library versions every time we build. Imagine being in the middle of an intense debugging session when suddenly `cargo build` upgrades you to a new version of a library. This could be

incredibly disruptive. Anything changing in the middle of debugging is bad. In fact, when it comes to libraries, there's never a good time for an unexpected change.

Cargo therefore has a built-in mechanism to prevent this. The first time you build a project, Cargo outputs a *Cargo.lock* file that records the exact version of every crate it used. Later builds will consult this file and continue to use the same versions. Cargo upgrades to newer versions only when you tell it to, either by manually bumping up the version number in your *Cargo.toml* file or by running `cargo update`:

```
$ cargo update
    Updating registry `https://github.com/rust-lang/crates.io-
index`
    Updating libc v0.2.7 -> v0.2.11
    Updating png v0.4.2 -> v0.4.3
```

`cargo update` only upgrades to the latest versions that are compatible with what you've specified in *Cargo.toml*. If you've specified `image = "0.25.1"` and you want to upgrade to version 0.26.0, you'll have to change that in *Cargo.toml*. The next time you build, Cargo will update to the new version of the `image` library and store the new version number in *Cargo.lock*.

The preceding example shows Cargo updating two crates that are hosted on crates.io. Something very similar happens for dependencies that are stored in Git. Suppose our *Cargo.toml* file contains this:

```
image = { git = "https://github.com/image-rs/image.git", branch =
"main" }
```

`cargo build` will not pull new changes from the Git repository if it sees that we've got a *Cargo.lock* file. Instead, it reads *Cargo.lock* and uses the same revision as the last time. But `cargo update` will pull from `main` so that our next build uses the latest revision.

*Cargo.lock* is automatically generated for you, and you normally won't edit it by hand. Nonetheless, you should commit *Cargo.lock* to version control,

so your version control history will record your dependency updates alongside code changes.

This is especially valuable when building executables, or in the rare case that your project is a shared library (i.e., the output is a *.dll*, *.dylib*, or *.so* file), because your *Cargo.lock* will be used every time the code is built, ensuring consistent builds. If your project is an ordinary Rust library, your downstream users will have *Cargo.lock* files that contain version information for their entire dependency graph; they will ignore your library's *Cargo.lock* file. Even so, checking in your *Cargo.lock* file in version control makes continuous integration pipelines and tools like `git bisect` easier to use, because it ensures that code is always built with the same dependencies that were used when it was first written.

*Cargo.toml*'s flexible version specifiers make it easy to use Rust libraries in your project and maximize compatibility among libraries. *Cargo.lock*'s bookkeeping supports consistent, reproducible builds across machines. Together, they go a long way toward helping you avoid dependency hell.

## Build Scripts

Cargo allows you add any logic you like to the build process with a *build script*. Before compiling your crate, Cargo checks for a *build.rs* file in the crate root, and if it's there, it compiles and runs that first. For example, this build script makes the current Git commit hash available as an environment variable (to be read with `env!()`):

```
use std::process::Command;

fn main() {
    let output = Command::new("git")
        .args(["rev-parse", "HEAD"])
        .output()
        .unwrap();
    let commit_hash = String::from_utf8(output.stdout).unwrap();
    println!("cargo::rustc-env=COMMIT_HASH={commit_hash}");
}
```

In this case, Cargo sees the `cargo::rustc-env` line in the build script's output and sets the corresponding environment variable during the build process. You can see a list of available configuration commands in *The Cargo Book*.

Build scripts can be much more complex than those presented here, including generating Rust code on the fly and calling out to databases and web APIs. For instance, the `prost` crate uses a build script to generate Rust code based on protocol buffers, a cross-language serialization format; and many crates that depend on C libraries use build scripts to compile them and generate the associated Rust bindings, as in "Using Functions from Libraries".

## Publishing Crates to crates.io

You've decided to publish your fern-simulating library as open source software. Congratulations! This part is easy.

First, make sure Cargo can pack the crate for you:

```
$ cargo package
warning: manifest has no description, license, license-file,
documentation,
homepage or repository. See
http://doc.crates.io/manifest.html#package-metadata
for more info.
   Packaging fern-sim v0.1.0 (file:///.../fern-sim)
   Verifying fern-sim v0.1.0 (file:///.../fern-sim)
   Compiling fern-sim v0.1.0 (file:///.../fern-
sim/target/package/fern-sim-0.1.0)
```

The `cargo package` command creates a file (in this case, *target/package/fern_sim-0.1.0.crate*) containing all your library's source files, including *Cargo.toml*. This is the file that you'll upload to crates.io to share with the world. (You can use `cargo package --list` to see which files are included.) Cargo then double-checks its work by building your library from the *.crate* file, just as your eventual users will.

Cargo warns that the `[package]` section of *Cargo.toml* is missing some information that will be important to downstream users, such as the license under which you're distributing the code. The URL in the warning is an excellent resource, so we won't explain all the fields in detail here.

In short, you can fix the warning by adding a few lines to *Cargo.toml*:

```
[package]
name = "fern-sim"
version = "0.1.0"
edition = "2024"
authors = ["You <you@example.com>"]
license = "MIT"
homepage = "https://fernsim.example.com/"
repository = "https://gitlair.com/sporeador/fern-sim"
documentation = "http://fernsim.example.com/docs"
description = """
Fern simulation, from the cellular level up.
"""
```

> **NOTE**
>
> Once you publish this crate on crates.io, anyone who downloads your crate can see the *Cargo.toml* file. So if the `authors` field contains an email address that you'd rather keep private, now is the time to change it.

Another problem that sometimes arises at this stage is that your *Cargo.toml* file might be specifying the location of other crates by `path`, as shown in "Specifying Dependencies":

```
image = { path = "vendor/image" }
```

For you and your team, this might work fine. But naturally, when other people download the `fern-sim` library, they will not have the same files and directories on their computer that you have. Cargo therefore *ignores* the `path` key in automatically downloaded libraries, and this can cause build errors. The fix, however, is straightforward: if your library is going to be

published on crates.io, its dependencies should be on crates.io too. Specify a version number instead of a `path`:

```
image = "0.25.10"
```

If you prefer, you can specify both a `path`, which takes precedence for your own local builds, and a `version` for all other users:

```
image = { path = "vendor/image", version = "0.25.10" }
```

Of course, in that case it's your responsibility to make sure that the two stay in sync.

Lastly, before publishing a crate, you'll need to log in to crates.io and get an API token. This step is straightforward: once you have an account on crates.io, you can generate a token on your "Account Settings" page, run `cargo login` locally, and paste it in.

The token should be kept secret, like a password. `cargo login` stores it in a configuration file, so run this command only on a computer you control. With that done, the final step is to run `cargo publish`:

```
$ cargo publish
    Updating registry `https://github.com/rust-lang/crates.io-
index`
   Uploading fern-sim v0.1.0 (file:///.../fern-sim)
```

With this, your library joins thousands of others on crates.io.

## Workspaces

As your project continues to grow, you end up writing many crates. They live side by side in a single source repository:

```
fernsoft/
├── .git/...
├── fern-sim/
│   ├── Cargo.toml
```

```
│   ├── Cargo.lock
│   ├── src/...
│   └── target/...
├── fern-img/
│   ├── Cargo.toml
│   ├── Cargo.lock
│   ├── src/...
│   └── target/...
└── fern-video/
    ├── Cargo.toml
    ├── Cargo.lock
    ├── src/...
    └── target/...
```

The way Cargo works, each crate has its own build directory, `target`, which contains a separate build of all that crate's dependencies. These build directories are completely independent. Even if two crates have a common dependency, they can't share any compiled code. This is wasteful.

You can save compilation time and disk space by using a Cargo *workspace*, a collection of crates that share a common build directory and *Cargo.lock* file.

All you need to do is create a *Cargo.toml* file in your repository's root directory and put these lines in it:

```
[workspace]
members = ["fern-sim", "fern-img", "fern-video"]
```

Here, `fern-sim`, etc., are the names of the subdirectories containing your crates. Delete any leftover *Cargo.lock* files and *target* directories that exist in those subdirectories.

Once you've done this, `cargo build` in any crate will automatically create and use a shared build directory under the root directory (in this case, *fernsoft/target*). The command `cargo build --workspace` builds all crates in the current workspace. `cargo test` and `cargo doc` accept the `--workspace` option as well.

Together with the ability to specify dependencies by their `path`, Cargo workspaces make large, multi-crate projects much more ergonomic, especially when managed as a unified version control repository.

## More Nice Things

In case you're not delighted yet, the software ecosystem around Cargo and crates has a few more odds and ends for you:

- When you publish an open source crate on crates.io, your documentation is automatically rendered and hosted on *docs.rs*.
- Since the *Cargo.toml* file tells exactly how to build and test your whole project, setting up continuous integration is easier than in the C++ world. For example, if your project is hosted on GitLab, this *.gitlab-ci.yml* file will get you started:

```
image: "rust:latest"
test:
  script: cargo test
```

- You can automate mundane release tasks like bumping your crate's version number and generating a serviceable changelog with `release-plz`, a Git- and Cargo-aware tool that can run either on your own computer or in CI.
- There are some basic tools for querying your project's dependencies. `cargo tree` shows the dependency graph. `cargo tree -i CRATENAME` shows which crates in project depend on the specified crate. You can run `cargo install cargo-machete` to install the `cargo machete` subcommand, which checks your *Cargo.toml* for stale dependencies that your code is no longer using.
- The Cargo documentation explains in just a few sentences how to run your own package registry, either to host private code or just to avoid relying on crates.io. Alternatively, `cargo vendor` simply

> unzips all your dependencies to a directory in your project. You can then put them in version control and configure Cargo to use that directory, not crates.io, as its package registry.

We could go on.

Rust is new, but it's designed to support large, ambitious projects. It has great tools and an active community. System programmers *can* have nice things.

# Chapter 9. Structs

> *Long ago, when shepherds wanted to see if two herds of sheep were isomorphic, they would look for an explicit isomorphism.*
>
> —John C. Baez and James Dolan, "Categorification"

Rust structs resemble `struct` types in C and C++, classes in Python, and objects in JavaScript. A struct assembles several values of assorted types together into a single value so you can deal with them as a unit. Given a struct, you can read and modify its individual components. And a struct can have methods associated with it that operate on its components.

In this chapter, we'll explain in detail how structs are defined, how they are used, and what they look like in memory. We'll cover how to add methods to them, how to define generic struct types that work with many different component types, and how to ask Rust to generate some handy methods for your structs.

## Defining Structs

The most common way to define a struct type looks like this:

```
/// A rectangle of eight-bit grayscale pixels.
struct GrayscaleMap {
    pixels: Vec<u8>,
    size: (usize, usize),
}
```

This declares a type `GrayscaleMap` with two fields named `pixels` and `size`, of the given types. The convention in Rust is for all types, structs included, to have names that capitalize the first letter of each word, a convention called `UpperCamelCase` . Fields and functions are lowercase, with words separated by underscores. This is called `snake_case`.

You can construct a value of this type with a *struct expression*, like this:

```
let width = 1024;
let height = 576;
let image = GrayscaleMap {
    pixels: vec![0; width * height],
    size: (width, height),
};
```

A struct expression starts with the type name (`GrayscaleMap`) and lists the name and value of each field, all enclosed in curly braces. There's also shorthand for populating fields from local variables or arguments with the same name:

```
fn new_map(size: (usize, usize), pixels: Vec<u8>) -> GrayscaleMap
{
    assert_eq!(pixels.len(), size.0 * size.1);
    GrayscaleMap { pixels, size }
}
```

The struct expression `GrayscaleMap { pixels, size }` is short for `GrayscaleMap { pixels: pixels, size: size }`. You can use `key: value` syntax for some fields and shorthand for others in the same struct expression.

To access a struct's fields, use the familiar `.` operator:

```
assert_eq!(image.size, (1024, 576));
assert_eq!(image.pixels.len(), 1024 * 576);
```

Like all other items, structs are private by default, visible only in the module where they're declared and its submodules. You can make a struct visible outside its module by prefixing its definition with `pub`. The same goes for each of its fields, which are also private by default:

```
/// A rectangle of eight-bit grayscale pixels.
pub struct GrayscaleMap {
    pub pixels: Vec<u8>,
```

```
    pub size: (usize, usize),
}
```

Even if a struct is declared `pub`, its fields can be private:

```
/// A rectangle of eight-bit grayscale pixels.
pub struct GrayscaleMap {
    pixels: Vec<u8>,
    size: (usize, usize),
}
```

Other modules can use this struct and any public associated functions it might have but can't access the private fields by name or use struct expressions to create new `GrayscaleMap` values. That is, creating a struct value requires all the struct's fields to be visible. This is why you can't write a struct expression to create a new `String` or `Vec`. These standard types are structs, but all their fields are private. To create one, you must use public associated functions like `Vec::new()`.

When creating a struct value, you can use another struct of the same type to supply values for fields you omit. In a struct expression, if named fields are followed by `..` and an expression of the same type, any fields not mentioned previously take their values from the given expression. Suppose we have a struct representing a monster in a game:

```
// In this game, brooms are monsters. You'll see.
struct Broom {
    name: String,
    height: u32,
    health: u32,
    position: (f32, f32, f32),
    intent: BroomIntent,
}

/// Two possible alternatives for what a `Broom` could be working
on.
#[derive(Copy, Clone)]
enum BroomIntent {
    FetchWater,
    DumpWater,
}
```

The best fairy tale for programmers is *The Sorcerer's Apprentice*: a novice magician enchants a broom to do his work for him but doesn't know how to stop it when the job is done. Chopping the broom in half with an axe just produces two brooms, each of half the size, but continuing the task with the same blind dedication as the original:

```
// Receive the input Broom by value, taking ownership.
fn chop(b: Broom) -> (Broom, Broom) {
    // Initialize `broom1` mostly from `b`, changing only
`height`. Since
    // `String` is not `Copy`, `broom1` takes ownership of `b`'s
name.
    let mut broom1 = Broom {
        height: b.height / 2,
        ..b
    };

    // Initialize `broom2` mostly from `broom1`. Since `String`
is not
    // `Copy`, we must clone `name` explicitly.
    let mut broom2 = Broom {
        name: broom1.name.clone(),
        ..broom1
    };

    // Give each fragment a distinct name.
    broom1.name.push_str(" I");
    broom2.name.push_str(" II");

    (broom1, broom2)
}
```

With that definition in place, we create a broom, chop it in two, and see what we get:

```
let hokey = Broom {
    name: "Hokey".to_string(),
    height: 60,
    health: 100,
    position: (100.0, 200.0, 0.0),
    intent: BroomIntent::FetchWater,
};

let (hokey1, hokey2) = chop(hokey);
```

```
assert_eq!(hokey1.name, "Hokey I");
assert_eq!(hokey1.height, 30);
assert_eq!(hokey1.health, 100);

assert_eq!(hokey2.name, "Hokey II");
assert_eq!(hokey2.height, 30);
assert_eq!(hokey2.health, 100);
```

The new `hokey1` and `hokey2` brooms have received adjusted names, half the height, and all the health of the original.

# Other Kinds of Structs

Struct types like those previously discussed are called *named-field* structs, and while they are by far the most common struct types Rust programmers will encounter, there are also two simpler kinds of struct types, called *tuple structs* and *unit-like structs*. Both are similar to named-field structs in functionality and in-memory representation.

## Tuple Structs

The second kind of struct type is called a *tuple struct*, because it resembles a tuple:

```
struct Bounds(usize, usize);
```

You construct a value of this type much as you would construct a tuple, except that you must include the struct name:

```
let image_bounds = Bounds(1024, 768);
```

The fields of a tuple struct can be accessed using the usual tuple syntax:

```
assert_eq!(image_bounds.0 * image_bounds.1, 786432);
```

Individual fields of a tuple struct may be public or not:

```
pub struct Bounds(pub usize, pub usize);
```

The expression `Bounds(1024, 768)` looks like a function call, and in fact it is: defining the type also implicitly defines a function:

```
fn Bounds(elem0: usize, elem1: usize) -> Bounds { ... }
```

Tuple structs are good for *newtypes*, structs with a single component that you define to get stricter type checking. For example, if you are working with ASCII-only text, you might define a newtype like this:

```
struct Ascii(Vec<u8>);
```

Using this type for your ASCII strings is much better than simply passing around `Vec<u8>` buffers and explaining what they are in the comments. The newtype helps Rust catch mistakes where some other byte buffer is passed to a function expecting ASCII text. We'll expand on this example in Chapter 23.

Newtypes allow the compiler to type-check your integers:

```
struct StudentId(u32);
struct CourseId(u32);

fn enroll(s: StudentId, c: CourseId) {
    ...
}
```

You could just use `u32` for both arguments in this code, but if you use newtypes, Rust will catch the mistake when a caller accidentally reverses the arguments.

Now a word of caution. Tuple structs are essentially the same thing as regular named-field structs, but with meaningless integers for field names. Except for newtypes, we have found we often regret our tuple structs and change them to named-field structs later:

```
// this seemed fine at first...
struct OldRgbColor(u8, u8, u8);

// ...but ultimately `color.r` reads better than `color.0`
struct NewRgbColor {
    r: u8,
    g: u8,
    b: u8,
}
```

When in doubt, we recommend named-field structs.

## Unit-Like Structs

The third kind of struct declares a type with no fields at all:

```
/// An error type indicating that the server is on fire.
/// No fields -- when this occurs, there's not much to say.
struct ServerOnFireError;
```

A value of such a type occupies no memory, much like the unit type `()`. Rust doesn't bother actually storing unit-like struct values in memory or generating code to operate on them.

But logically, an empty struct is a type with values like any other—or more precisely, a type with *one* value:

```
let err = ServerOnFireError;
```

This is similar to declaring a named-field struct without any fields:

```
struct NoFields {}
let n = NoFields {};
```

You've already encountered a unit-like struct when reading about the `..` range operator in "Fields and Elements". Whereas an expression like `3..5` is shorthand for the struct value `Range { start: 3, end: 5 }`, the expression `..`, a range omitting both endpoints, is shorthand for the unit-like struct value `RangeFull`.

## Struct Layout

In memory, both named-field and tuple structs are the same thing: a collection of values, of possibly mixed types, laid out in a particular way in memory. For example, earlier in the chapter we defined this struct:

```
struct GrayscaleMap {
    pixels: Vec<u8>,
    size: (usize, usize),
}
```

A `GrayscaleMap` value is laid out in memory, as diagrammed in Figure 9-1.

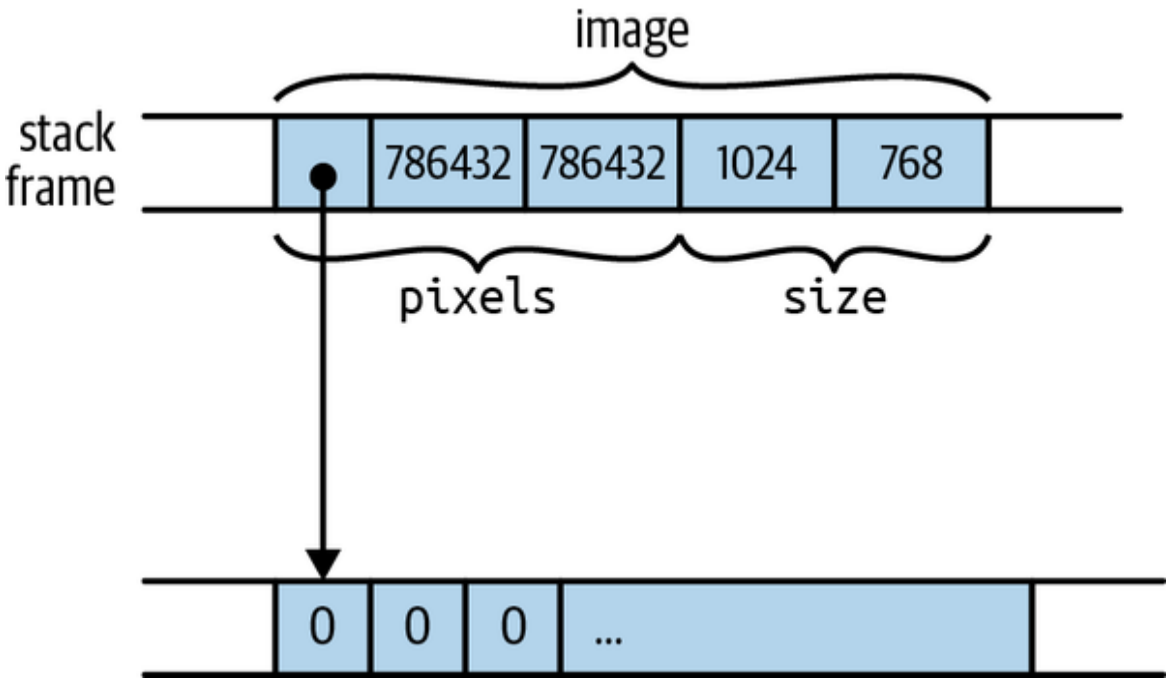


*Figure 9-1. A `GrayscaleMap` struct in memory*

Unlike C and C++, Rust doesn't make specific promises about how it will order a struct's fields in memory; this diagram shows only one possible arrangement. However, Rust does promise to store field values directly in the struct's block of memory. Whereas JavaScript, Python, and Java would put the `pixels` and `size` values each in their own heap-allocated blocks and have `GrayscaleMap`'s fields point at them, Rust embeds `pixels`

and `size` directly in the `GrayscaleMap` value. Only the heap-allocated buffer owned by the `pixels` vector remains in its own block.

You can ask Rust to lay out structs in a way compatible with C and C++, using the `#[repr(C)]` attribute. We'll cover this in detail in Chapter 24.

## Defining Methods with impl

Throughout the book we've been calling methods on all sorts of values. We've pushed elements onto vectors with `v.push(e)`, fetched their length with `v.len()`, checked `Result` values for errors with `r.expect("msg")`, and so on. You can define methods on your own struct types as well. Rather than appearing inside the struct definition, as in C++ or Java, Rust methods appear in a separate `impl` block.

Here, for example, we define a public struct `Queue` and then give it two public methods, `push_back` and `pop_front`:

```
/// A first-in, first-out queue of characters.
pub struct Queue {
    older: Vec<char>,    // older elements, eldest last.
    younger: Vec<char>,  // younger elements, youngest last.
}

impl Queue {
    /// Pushes a character onto the back of a queue.
    pub fn push_back(&mut self, c: char) {
        self.younger.push(c);
    }

    /// Pops a character off the front of a queue. Returns
`Some(c)` if there
    /// was a character to pop, or `None` if the queue was empty.
    pub fn pop_front(&mut self) -> Option<char> {
        if self.older.is_empty() {
            if self.younger.is_empty() {
                return None;
            }

            // Bring the elements in younger over to older, and
put them in
```

```
                // the promised order.
                std::mem::swap(&mut self.older, &mut self.younger);
                self.older.reverse();
            }

            // Now older is guaranteed to have something. Vec's pop
method
            // already returns an Option, so we're set.
            self.older.pop()
        }
    }
```

Functions defined in an `impl` block are called *associated functions*, since they're associated with a specific type. Functions defined anywhere else are sometimes called *free functions*—"free" as in unattached.

Associated functions that have a `self` argument are called *methods*. Associated functions without `self` are like static methods or constructors in other languages; we will cover them in a few pages.

Rust passes a method the value it's being called on as its first argument, which must have the special name `self`. Since `self`'s type is obviously the one named at the top of the `impl` block, or a reference to that, Rust lets you omit the type and write `self`, `&self`, or `&mut self` as shorthand for `self: Queue`, `self: &Queue`, or `self: &mut Queue`. You can use the longhand forms if you like, but almost all Rust code uses shorthand.

In our example, the `push_back` and `pop_front` methods refer to the `Queue`'s fields as `self.older` and `self.younger`. Unlike C++ and Java, where the members of the "this" object are directly visible in method bodies as unqualified identifiers, a Rust method must explicitly use `self` to refer to the value it was called on, similar to the way Python methods use `self` and the way JavaScript methods use `this`.

Since `push_back` and `pop_front` need to modify the `Queue`, they both take `&mut self`. However, when you call a method, you don't need to borrow the mutable reference yourself; the ordinary method call syntax

takes care of that implicitly. So with these definitions in place, you can use `Queue` like this:

```
let mut q = Queue {
    older: Vec::new(),
    younger: Vec::new(),
};

q.push_back('0');
q.push_back('1');
assert_eq!(q.pop_front(), Some('0'));

q.push_back('∞');
assert_eq!(q.pop_front(), Some('1'));
assert_eq!(q.pop_front(), Some('∞'));
assert_eq!(q.pop_front(), None);
```

Simply writing `q.push_back(...)` borrows a mutable reference to `q`, as if you had written `(&mut q).push_back(...)`, since that's what the `push_back` method's `self` requires.

If a method doesn't need to modify its `self`, then you can define it to take a shared reference instead. For example:

```
impl Queue {
    pub fn is_empty(&self) -> bool {
        self.older.is_empty() && self.younger.is_empty()
    }
}
```

Again, the method call expression knows which sort of reference to borrow:

```
assert!(q.is_empty());
q.push_back('⊙');
assert!(!q.is_empty());
```

Or, if a method wants to take ownership of `self`, it can take `self` by value:

```
impl Queue {
    pub fn split(self) -> (Vec<char>, Vec<char>) {
```

```
            (self.older, self.younger)
        }
    }
```

Calling this `split` method looks like the other method calls:

```
let (older, younger) = q.split();
```

But note that since `split` takes its `self` by value, this *moves* the `Queue` out of `q`, meaning that `q` can no longer be used. Since `split`'s `self` now owns the queue, it's able to move the individual vectors out of it and return them to the caller.

Sometimes, taking `self` by value like this, or even by reference, isn't enough, so Rust also lets you pass `self` via smart pointer types.

## Passing Self as a Box, Rc, or Arc

A method's `self` argument can also be a `Box<Self>`, `Rc<Self>`, or `Arc<Self>`. Such a method can only be called on a value of the given pointer type. Calling the method passes ownership of the pointer to it.

You won't usually need to do this. A method that expects `self` by reference works fine when called on any of those pointer types:

```
let mut bq = Box::new(Queue::new());

// `Queue::push_back` expects a `&mut Queue`, but `bq` is a
`Box<Queue>`.
// This is fine: Rust borrows a `&mut Queue` from the `Box` for
the
// duration of the call.
bq.push_back('■');
```

For method calls and field access, Rust automatically borrows a reference from pointer types like `Box`, `Rc`, and `Arc`, so `&self` and `&mut self` are almost always the right thing in a method signature, along with the occasional `self`.

But if it does come to pass that some method needs ownership of a pointer to `self` and its callers have such a pointer handy, Rust will let you pass it as the method's `self` argument. To do so, you must spell out the type of `self`, as if it were an ordinary parameter:

```
impl OrbitComputeJob {
    /// Adds this job to the application-wide list of active
jobs, so that
    /// we'll wait for it to finish on shutdown.
    fn mark_active(self: &Arc<Self>) {
        let new_ref = Arc::clone(self); // bump reference count
        App::add_active_job(new_ref);
    }
}
```

## Nonmethod Associated Functions

An `impl` block can also define associated functions that don't take a `self` argument at all. They're often used to provide constructor functions, like this:

```
impl Queue {
    pub fn new() -> Queue {
        Queue {
            older: Vec::new(),
            younger: Vec::new(),
        }
    }
}
```

This defines the associated function `Queue::new`. Now our example code becomes a bit more svelte:

```
let mut q = Queue::new();

q.push_back('*');
...
```

It's conventional in Rust for constructor functions to be named `new`; we've already seen `Vec::new`, `Box::new`, `HashMap::new`, and others. But

there's nothing special about the name `new`. It's not a keyword, and types often have other associated functions that serve as constructors, like `Vec::with_capacity`.

Although you can have many separate `impl` blocks for a single type, they must all be in the same crate that defines that type. However, Rust does let you attach your own methods to other types; we'll explain how in Chapter 11.

If you're used to C++ or Java, separating a type's methods from its definition may seem unusual, but there are several advantages to doing so:

- It's always easy to find a type's data members. In large C++ class definitions, you might need to skim hundreds of lines of member function definitions to be sure you haven't missed any of the class's data members; in Rust, they're all in one place.
- Although one can imagine fitting methods into the syntax for named-field structs, it's not so neat for tuple and unit-like structs. Pulling methods out into an `impl` block allows a single syntax for all three. In fact, Rust uses this same syntax for defining methods on types that are not structs at all, such as `enum` types and primitive types like `i32`. (The fact that any type can have methods is one reason Rust doesn't use the term *object* much, preferring to call everything a *value*.)
- The same `impl` syntax also serves neatly for implementing traits, which we'll go into in Chapter 11.

## Associated Constants

Another feature of languages like C# and Java that Rust adopts in its type system is the idea of values associated with a type, rather than a specific instance of that type. In Rust, these are known as *associated constants*. As the name implies, associated constants are constant values. They're often used to specify commonly used values of a type. For instance, you could

define a two-dimensional vector for use in linear algebra with an associated unit vector:

```
pub struct Vector2 {
    x: f32,
    y: f32,
}

impl Vector2 {
    const ZERO: Vector2 = Vector2 { x: 0.0, y: 0.0 };
    const UNIT: Vector2 = Vector2 { x: 1.0, y: 0.0 };
}
```

These values are associated with the type itself, and you can use them without referring to another instance of `Vector2`. Much like associated functions, they are accessed by naming the type with which they're associated, followed by their name:

```
let scaled = Vector2::UNIT.scaled_by(2.0);
```

Nor does an associated constant have to be of the same type as the type it's associated with; we could use this feature to add IDs or names to types. For example, if there were several types similar to `Vector2` that needed to be written to a file and then loaded into memory later, an associated constant could be used to add names or numeric IDs that could be written next to the data to identify its type:

```
impl Vector2 {
    const NAME: &'static str = "Vector2";
    const ID: u32 = 18;
}
```

## Generic Structs

Our earlier definition of `Queue` is unsatisfying: it is written to store characters, but there's nothing about its structure or methods that is specific to characters at all. If we were to define another struct that held, say,

`String` values, the code could be identical, except that `char` would be replaced with `String`. That would be a waste of time.

Fortunately, Rust structs can be *generic*, meaning that their definition is a template into which you can plug whatever types you like. For example, here's a definition for `Queue` that can hold values of any type:

```
pub struct Queue<T> {
    older: Vec<T>,
    younger: Vec<T>,
}
```

You can read the `<T>` in `Queue<T>` as "for any element type `T`." So this definition reads, "For any type `T`, a `Queue<T>` is two fields of type `Vec<T>`." For example, in `Queue<String>`, `T` is `String`, so `older` and `younger` have type `Vec<String>`. In `Queue<char>`, `T` is `char`, and we get a struct identical to the `char`-specific definition we started with. In fact, `Vec` itself is a generic struct, defined in just this way.

In generic struct definitions, the type names used in <angle brackets> are called *type parameters*. An `impl` block for a generic struct looks like this:

```
impl<T> Queue<T> {
    pub fn new() -> Queue<T> {
        Queue {
            older: Vec::new(),
            younger: Vec::new(),
        }
    }

    pub fn push_back(&mut self, t: T) {
        self.younger.push(t);
    }

    pub fn is_empty(&self) -> bool {
        self.older.is_empty() && self.younger.is_empty()
    }

    ...
}
```

You can read the line `impl<T> Queue<T>` as something like, “For any type `T`, here are some associated functions available on `Queue<T>`.” Then, you can use the type parameter `T` as a type in the associated function definitions.

The syntax may look a bit redundant, but the `impl<T>` makes it clear that the `impl` block covers any type `T`, which distinguishes it from an `impl` block written for one specific kind of `Queue`, like this one:

```
impl Queue<f64> {
    fn sum(&self) -> f64 {
        ...
    }
}
```

This `impl` block header reads, “Here are some associated functions specifically for `Queue<f64>`.” This gives `Queue<f64>` a `sum` method, available on no other kind of `Queue`. Every `impl` block, generic or not, defines the special type parameter `Self` (note the `CamelCase` name) to be whatever type we’re adding methods to.

In the preceding code, `Self` would be `Queue<T>`, so we can abbreviate `Queue::new`’s definition a bit further:

```
pub fn new() -> Self {
    Queue {
        older: Vec::new(),
        younger: Vec::new(),
    }
}
```

You might have noticed that, in the body of `new`, we didn’t need to write the type parameter in the construction expression; simply writing `Queue { ... }` was good enough. This is Rust’s type inference at work: since there’s only one type that works for that function’s return value—namely, `Queue<T>`—Rust supplies the parameter for us. However, you’ll always need to supply type parameters in function signatures and type definitions.

Rust doesn't infer those; instead, it uses those explicit types as the basis from which it infers types within function bodies.

`Self` can also be used in this way; we could have written `Self { ... }` instead. It's up to you to decide which you find easiest to understand. For associated function calls, you can supply the type parameter explicitly using the `::<>` (turbofish) notation:

```
let mut q = Queue::<char>::new();
```

But in practice, you can usually just let Rust figure it out for you:

```
let mut q = Queue::new();
let mut r = Queue::new();

q.push_back("Marrakesh");   // apparently a Queue<&str>
r.push_back(6798.383);      // apparently a Queue<f64>
```

In fact, this is exactly what we've been doing with `Vec`, another generic struct type, throughout the book.

## Generic Structs with Lifetime Parameters

As we discussed in "Structs Containing References", if a struct type contains references, you must name those references' lifetimes. For example, here's a struct that might hold references to the greatest and least elements of some slice:

```
struct Extrema<'elt> {
    greatest: &'elt i32,
    least: &'elt i32,
}
```

Earlier, we invited you to think of a declaration like `struct Queue<T>` as meaning that, given any specific type `T`, you can make a `Queue<T>` that holds that type. Similarly, you can think of `struct Extrema<'elt>` as

meaning that, given any specific lifetime `'elt`, you can make an `Extrema<'elt>` that holds references with that lifetime.

This function scans a slice and returns an `Extrema` value whose fields refer to its elements:

```
fn find_extrema<'s>(slice: &'s [i32]) -> Extrema<'s> {
    let mut greatest = &slice[0];
    let mut least = &slice[0];

    for i in 1..slice.len() {
        if slice[i] < *least    { least    = &slice[i]; }
        if slice[i] > *greatest { greatest = &slice[i]; }
    }
    Extrema { greatest, least }
}
```

Here, since `find_extrema` borrows elements of `slice`, which has the lifetime `'s`, the `Extrema` struct we return also uses `'s` as the lifetime of its references. Rust always infers lifetime parameters for calls, so calls to `find_extrema` needn't mention them:

```
let a = [0, -3, 0, 15, 48];
let e = find_extrema(&a);
assert_eq!(*e.least, -3);
assert_eq!(*e.greatest, 48);
```

Because it's so common for the return type to use the same lifetime as an argument, Rust lets us abbreviate functions like this by leaving out the lifetime parameter. We can write `find_extrema`'s signature like this, with no change in meaning:

```
fn find_extrema(slice: &[i32]) -> Extrema<'_> {
    ...
}
```

Rust sees that the argument `slice` is a reference and infers that this function has an unwritten lifetime parameter. In the return type, `Extrema<'_>`, the *placeholder lifetime* `'_` refers to this implicit lifetime.

However, for functions with multiple arguments that carry lifetimes, Rust often refuses to guess about lifetimes in the return type and makes you spell everything out.

## Generic Structs with Constant Parameters

A generic struct can also take parameters that are constant values. For example, you could define a type representing polynomials of arbitrary degree like so:

```
/// A polynomial of degree N - 1.
struct Polynomial<const N: usize> {
    /// The coefficients of the polynomial.
    ///
    /// For a polynomial a + bx + cx² + ... + zxⁿ⁻¹,
    /// the `i`'th element is the coefficient of xⁱ.
    coefficients: [f64; N],
}
```

With this definition, `Polynomial<3>` is a quadratic polynomial, for example. The `<const N: usize>` clause says that the `Polynomial` type expects a `usize` value as its generic parameter, which it uses to decide how many coefficients to store.

Unlike `Vec`, which has fields holding its length and capacity and stores its elements in the heap, `Polynomial` stores its coefficients directly in the value, and nothing else. The length is given by the type. (The capacity isn't needed, because `Polynomials` can't grow dynamically.)

We can use the parameter `N` in the type's associated functions:

```
impl<const N: usize> Polynomial<N> {
    fn new(coefficients: [f64; N]) -> Polynomial<N> {
        Polynomial { coefficients }
    }

    /// Evaluates the polynomial at `x`.
    fn eval(&self, x: f64) -> f64 {
        // Horner's method is numerically stable, efficient, and
```

```
simple:
        // c₀ + x(c₁ + x(c₂ + x(c₃ + ... x(c[n-1] + x c[n]))))
        let mut sum = 0.0;
        for i in (0..N).rev() {
            sum = self.coefficients[i] + x * sum;
        }

        sum
    }
}
```

Here, the `new` function accepts an array of length `N` and takes its elements as the coefficients of a fresh `Polynomial` value. The `eval` method iterates over the range `0..N` to find the value of the polynomial at a given point `x`.

As with type and lifetime parameters, Rust can often infer the right values for constant parameters:

```
use std::f64::consts::FRAC_PI_2;   // π/2

// Approximate the `sin` function: sin x ≅ x - 1/6 x³ + 1/120 x⁵
// Around zero, it's pretty accurate!
let sine_poly = Polynomial::new([0.0, 1.0, 0.0, -1.0/6.0, 0.0,
1.0/120.0]);
assert_eq!(sine_poly.eval(0.0), 0.0);
assert!((sine_poly.eval(FRAC_PI_2) - 1.).abs() < 0.005);
```

Since we pass `Polynomial::new` an array with six elements, Rust knows we must be constructing a `Polynomial<6>`. The `eval` method knows how many iterations the `for` loop should run simply by consulting its `Self` type. Since the length is known at compile time, the compiler will probably replace the loop entirely with straight-line code. A `const` generic parameter may be any integer type, `char`, or `bool`. Floating-point numbers, enums, and other types are not permitted.

If the struct takes other kinds of generic parameters, lifetime parameters must come first, followed by types, followed by any `const` values. For example, a type that holds an array of references could be declared like this:

```
struct LumpOfReferences<'a, T, const N: usize> {
    the_lump: [&'a T; N],
}
```

Constant generic parameters are a relatively new addition to Rust, and their use is somewhat restricted for now. For example, it would have been nicer to define `Polynomial` like this:

```
/// A polynomial of degree N.
struct Polynomial<const N: usize> {
    coefficients: [f64; N + 1],
}
```

However, Rust rejects this definition:

```
error: generic parameters may not be used in const operations
  |
6 |     coefficients: [f64; N + 1]
  |                         ^ cannot perform const operation
using `N`
  |
  = help: const parameters may only be used as standalone
arguments
          here, i.e. `N`
```

While it's fine to say `[f64; N]`, a type like `[f64; N + 1]` is apparently too risqué for Rust. But Rust imposes this restriction for the time being to avoid confronting issues like this:

```
struct Ketchup<const N: usize> {
    tomayto: [i32; N & !31],
    tomahto: [i32; N - (N % 32)],
}
```

As it turns out, `N & !31` and `N - (N % 32)` are equal for all values of `N`, so `tomayto` and `tomahto` always have the same type. It should be permitted to assign one to the other, for example. But teaching Rust's type checker the bit-fiddling algebra it would need to be able to recognize this fact risks introducing confusing corner cases to an aspect of the language

that is already quite complicated. Of course, simple expressions like `N + 1` are much more well-behaved, and there is work underway to teach Rust to handle those smoothly.

Since the concern here is with the type checker's behavior, this restriction applies only to constant parameters appearing in types, like the length of an array. In an ordinary expression, you can use `N` however you like: `N + 1` and `N & !31` are perfectly acceptable.

If the value you want to supply for a `const` generic parameter is not simply a literal or a single identifier, then you must wrap it in braces, as in `Polynomial<{5 + 1}>`. This rule allows Rust to report syntax errors more accurately.

## Deriving Common Traits for Struct Types

Structs can be easy to write:

```
struct Point {
    x: f64,
    y: f64,
}
```

However, if you were to start using this `Point` type, you would quickly notice that it's a bit of a pain. As written, `Point` is not copyable or cloneable. You can't print it with `println!("{point:?}");`, and it does not support the == and != operators.

Each of these features has a name in Rust—`Copy`, `Clone`, `Debug`, and `PartialEq`. They are called *traits*. In Chapter 11, we'll show how to implement traits by hand for your own structs. But in the case of these standard traits, and several others, you don't need to implement them by hand unless you want some kind of custom behavior. Rust can automatically implement them for you with mechanical accuracy. Just add a `#[derive]` attribute to the struct:

```
#[derive(Copy, Clone, Debug, PartialEq)]
struct Point {
    x: f64,
    y: f64,
}
```

Each of these traits can be implemented automatically for a struct, provided that each of its fields implements the trait. We can ask Rust to derive `PartialEq` for `Point` because its two fields are both of type `f64`, which already implements `PartialEq`.

Rust can also derive `PartialOrd`, which would add support for the comparison operators <, >, <=, and >=. We haven't done so here, because comparing two points to see if one is "less than" the other is actually a pretty weird thing to do. There's no one conventional order on points. So we choose not to support those operators for `Point` values. Cases like this are one reason that Rust makes us write the `#[derive]` attribute rather than automatically deriving every trait it can. Another reason is that implemented traits are part of a type's public API, so once you've added `Copy` and `Clone`, removing it is a breaking change.

We'll describe Rust's standard traits in detail and explain which ones are `#[derive]`able in Chapter 13.

## Interior Mutability

Mutability is like wasabi: in excess, it causes problems, but you often want just a little bit of it. For example, say your spider robot control system has a central struct, `SpiderRobot`, that contains settings and I/O handles.

It's set up when the robot boots, and the values never change:

```
pub struct SpiderRobot {
    species: String,
    web_enabled: bool,
    leg_devices: [OwnedFd; 8],
    ...
}
```

Every major system of the robot is handled by a different struct, and each one has a pointer back to the `SpiderRobot`:

```
use std::rc::Rc;

pub struct SpiderSenses {
    robot: Rc<SpiderRobot>,  // <-- pointer to settings and I/O
    eyes: [Camera; 32],
    motion: Accelerometer,
    ...
}
```

The structs for web construction, predation, venom flow control, and so forth also all have an `Rc<SpiderRobot>` smart pointer. Recall that `Rc` stands for reference counting, and a value in an `Rc` box is always shared and therefore always immutable. Now suppose you want to add a little logging to the `SpiderRobot` struct, using the standard `File` type. There's a problem: a `File` has to be `mut`. All the methods for writing to it require a `mut` reference.

This sort of situation comes up fairly often. What we need is a little bit of mutable data (a `File`) inside an otherwise immutable value (the `SpiderRobot` struct). This is called *interior mutability*. Rust offers several flavors of it; we'll discuss the two most straightforward types: `Cell<T>` and `RefCell<T>`, both in the `std::cell` module.

A `Cell<T>` is a struct that contains a single private value of type `T`. The only special thing about a `Cell` is that you can get and set the field even if you don't have `mut` access to the `Cell` itself:

`Cell::new(value)`

Creates a new `Cell`, moving the given `value` into it.

`cell.get()`

Returns a copy of the value in the `cell`.

`cell.set(value)`

Stores the given `value` in the `cell`, dropping the previously stored value.

This method takes `self` as a non-`mut` reference:

```
fn set(&self, value: T)    // note: not `&mut self`
```

This is, of course, unusual for methods named `set`. By now, Rust has trained us to expect that we need `mut` access if we want to make changes to data. But by the same token, this one unusual detail is the whole point of `Cell`s. They're simply a safe way of bending the rules on immutability—no more, no less.

Cells also have a few other methods, which you can read about in the documentation.

A `Cell` would be handy if you were adding a simple counter to your `SpiderRobot`. You could write:

```
use std::cell::Cell;

pub struct SpiderRobot {
    ...
    hardware_error_count: Cell<u32>,
    ...
}
```

Then even non-`mut` methods of `SpiderRobot` can access that `u32`, using the `.get()` and `.set()` methods:

```
impl SpiderRobot {
    /// Increases the error count by 1.
    pub fn add_hardware_error(&self) {
        let n = self.hardware_error_count.get();
        self.hardware_error_count.set(n + 1);
    }

    /// True if any hardware errors have been reported.
    pub fn has_hardware_errors(&self) -> bool {
```

```
            self.hardware_error_count.get() > 0
        }
    }
```

This is easy enough, but it doesn't solve our logging problem. `Cell` does *not* let you call `mut` methods on a shared value. The `.get()` method returns a copy of the value in the cell, so it works only if `T` implements the `Copy` trait. For logging, we need a mutable `File`, and `File` isn't copyable.

The right tool in this case is a `RefCell`. Like `Cell<T>`, `RefCell<T>` is a generic type that contains a single value of type `T`.

Unlike `Cell`, `RefCell` supports borrowing references to its `T` value:

`RefCell::new(value)`

: Creates a new `RefCell`, moving `value` into it.

`ref_cell.borrow()`

: Returns a `Ref<T>`, which is essentially just a shared reference to the value stored in `ref_cell`.

  This method panics if the value is already mutably borrowed; see details to follow.

`ref_cell.borrow_mut()`

: Returns a `RefMut<T>`, essentially a mutable reference to the value in `ref_cell`.

  This method panics if the value is already borrowed; see details to follow.

`ref_cell.try_borrow()`, `ref_cell.try_borrow_mut()`

: Work just like `borrow()` and `borrow_mut()`, but return a `Result`. Instead of panicking if the value is already mutably borrowed, they return an `Err` value.

Again, `RefCell` has a few other methods, which you can find in the documentation.

The two `borrow` methods panic only if you try to break the Rust rule that `mut` references are exclusive references. For example, this would panic:

```
use std::cell::RefCell;

let ref_cell: RefCell<String> =
RefCell::new("hello".to_string());

let r = ref_cell.borrow();      // ok, returns a Ref<String>
let count = r.len();            // ok, returns "hello".len()
assert_eq!(count, 5);

let mut w = ref_cell.borrow_mut();  // panic: already borrowed
w.push_str(" world");
```

To avoid panicking, you could put these two borrows into separate blocks. That way, `r` would be dropped before you try to borrow `w`.

This is a lot like how normal references work. The only difference is that normally, when you borrow a reference to a variable, Rust checks *at compile time* to ensure that you're using the reference safely. If the checks fail, you get a compiler error. `RefCell` enforces the same rule using run-time checks. So if you're breaking the rules, you get a panic (or an `Err`, for `try_borrow` and `try_borrow_mut`).

Now we're ready to put `RefCell` to work in our `SpiderRobot` type:

```
pub struct SpiderRobot {
    ...
    log_file: RefCell<File>,
    ...
}

impl SpiderRobot {
    /// Writes a line to the log file.
    pub fn log(&self, message: &str) {
        let mut file = self.log_file.borrow_mut();
        // `writeln!` is like `println!`, but sends
        // output to the given file.
```

```
            writeln!(file, "{message}").unwrap();
        }
    }
```

The variable `file` has type `RefMut<File>`. It can be used just like a mutable reference to a `File`. For details about writing to files, see Chapter 18.

Cells are easy to use. Having to call `.get()` and `.set()` or `.borrow()` and `.borrow_mut()` is slightly awkward, but that's just the price we pay for bending the rules. The other drawback is less obvious and more serious: cells—and any types that contain them—are not thread-safe. Rust, therefore, will not allow multiple threads to access them at once. We'll describe thread-safe flavors of interior mutability in Chapter 19, when we discuss "Mutex<T>", "Atomics", and "Global Variables".

Whether a struct has named fields or is a tuple struct, it is an aggregation of other values: if I have a `SpiderSenses` struct, then I have an `Rc` pointer to a shared `SpiderRobot` struct, I have eyes, I have an accelerometer, and so on. Rust also supports types that are designed to select one among several possible types of values. Such types turn out to be so useful that they're ubiquitous in the language, and they are the subject of the next chapter.

# Chapter 10. Enums and Patterns

> *Surprising how much computer stuff makes sense viewed as tragic deprivation of sum types (cf. deprivation of lambdas).*
>
> —Graydon Hoare

The first topic of this chapter is potent, as old as the hills, happy to help you get a lot done in short order (for a price), and known by many names in many cultures. But it's not the devil. It's a kind of user-defined data type, long known to ML and Haskell hackers as sum types, discriminated unions, or algebraic data types. In Rust, they are called *enumerations*, or simply *enums*. Unlike the devil, they are quite safe, and the price they ask is no great privation.

C++ and C# have enums; you can use them to define your own type whose values are a set of named constants. For example, you might define a type named `Color` with values `Red`, `Orange`, `Yellow`, and so on. This kind of enum works in Rust, too. But Rust takes enums much further. A Rust enum can also contain data, even data of varying types. For example, Rust's `Result<String, io::Error>` type is an enum; such a value is either an `Ok` value containing a `String` or an `Err` value containing an `io::Error`. This is beyond what C++ and C# enums can do. It's more like a C `union`—but unlike unions, Rust enums are type-safe.

Enums are useful whenever a value might be either one thing or another. The "price" of using them is that you must access the data safely, using pattern matching, our topic for the second half of this chapter.

Patterns, too, may be familiar if you've used unpacking in Python or destructuring in JavaScript, but Rust takes patterns further. Rust patterns are like regular expressions for all your data. They're used to test whether a value has a particular desired shape. They can extract several fields from a

struct or tuple into local variables all at once. Like regular expressions, they are concise, typically doing it all in a single line of code.

This chapter starts with the basics of enums, showing how data can be associated with enum variants and how enums are stored in memory. Then we'll show how Rust's patterns and `match` statements can concisely specify logic based on enums, structs, arrays, and slices. Patterns can also include references, moves, and `if` conditions, making them even more capable.

# Enums

Simple, C-style enums are straightforward:

```
enum Ordering {
    Less,
    Equal,
    Greater,
}
```

This declares a type `Ordering` with three possible values, called *variants* or *constructors*: `Ordering::Less`, `Ordering::Equal`, and `Ordering::Greater`. This particular enum is part of the standard library, so Rust code can import it, either by itself:

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

fn compare(n: i32, m: i32) -> Ordering {
    if n < m {
        Ordering::Less
    } else if n > m {
        Ordering::Greater
    } else {
        Ordering::Equal
    }
}
```

or with all its constructors:

```
use std::cmp::Ordering::{self, *};  // `*` to import all children

fn compare(n: i32, m: i32) -> Ordering {
    if n < m {
        Less
    } else if n > m {
        Greater
    } else {
        Equal
    }
}
```

After importing the constructors, we can write `Less` instead of `Ordering::Less`, and so on, but because this is less explicit, it's generally considered better style *not* to import them except when it makes your code much more readable.

In memory, values of C-style enums are stored as integers. Occasionally it's useful to tell Rust which integers to use:

```
enum HttpStatus {
    Ok = 200,
    NotModified = 304,
    NotFound = 404,
    ...
}
```

Otherwise, Rust will assign the numbers for you, starting at 0.

By default, Rust stores C-style enums using the smallest built-in integer type that can accommodate them. Most fit in a single byte:

```
assert_eq!(size_of::<Ordering>(), 1);
assert_eq!(size_of::<HttpStatus>(), 2);  // 404 doesn't fit in a
u8
```

You can override Rust's choice of in-memory representation by adding a `#[repr]` attribute to the enum. For details, see "Finding Common Data Representations".

Casting a C-style enum to an integer is allowed:

```
assert_eq!(HttpStatus::Ok as i32, 200);
```

However, casting in the other direction, from the integer to the enum, is not. Unlike C and C++, Rust guarantees that an enum value is only ever one of the values spelled out in the `enum` declaration. An unchecked cast from an integer type to an enum type could break this guarantee, so it's not allowed. You can either write your own checked conversion:

```
fn http_status_from_u32(n: u32) -> Option<HttpStatus> {
    match n {
        200 => Some(HttpStatus::Ok),
        304 => Some(HttpStatus::NotModified),
        404 => Some(HttpStatus::NotFound),
        ...
        _ => None,
    }
}
```

or use the `enum_primitive` crate. It contains a macro that autogenerates this kind of conversion code for you.

As with structs, the compiler will implement features like the == operator for you, but you have to ask:

```
#[derive(Copy, Clone, Debug, PartialEq, Eq)]
enum TimeUnit {
    Seconds, Minutes, Hours, Days, Months, Years,
}
```

Enums can have methods, just like structs:

```
impl TimeUnit {
    /// Returns the plural noun for this time unit.
    fn plural(self) -> &'static str {
        match self {
            TimeUnit::Seconds => "seconds",
            TimeUnit::Minutes => "minutes",
            TimeUnit::Hours => "hours",
            TimeUnit::Days => "days",
            TimeUnit::Months => "months",
            TimeUnit::Years => "years",
        }
```

```
    }

    /// Returns the singular noun for this time unit.
    fn singular(self) -> &'static str {
        self.plural().trim_end_matches('s')
    }
}
```

Enums are sometimes used in C/C++ to declare a bunch of related integer constants. For example, it's fairly common to use a single integer to store a boolean option per bit, using bitwise AND and OR operations, and sometimes the bits are declared using an `enum`:

```
// C/C++ example
enum open_flags_t {
    READ = 1 << 0,
    WRITE = 1 << 1,
    CREATE = 1 << 2,
    ...
};

int fd = open_file("jokes/dad.txt", WRITE | CREATE);
```

This idiom doesn't translate directly to Rust enums. Instead, use an integer type and constants, as shown next; or check out the `bitflags` crate, which helps you define an integer-wrapping struct for this use case.

```
type OpenFlags = u32;

const READ: OpenFlags = 1 << 0;
const WRITE: OpenFlags = 1 << 1;
const CREATE: OpenFlags = 1 << 2;
...

let flags = WRITE | CREATE;
```

So much for C-style enums. The more interesting sort of Rust enum is the kind whose variants hold data. We'll show how these are stored in memory, how to make them generic by adding type parameters, and how to build complex data structures from enums.

## Enums with Data

Some programs always need to display full dates and times down to the millisecond, but for most applications, it's more user-friendly to use a rough approximation, like "two months ago." We can write an enum to help with that, using the enum defined earlier:

```
/// A timestamp that has been deliberately rounded off, so our
program
/// says "6 months ago" instead of "February 9, 2016, at 9:49
AM".
#[derive(Copy, Clone, Debug, PartialEq)]
enum RoughTime {
    InThePast(TimeUnit, u32),
    JustNow,
    InTheFuture(TimeUnit, u32),
}
```

Two of the variants in this enum, `InThePast` and `InTheFuture`, take arguments. These are called *tuple variants*. Like tuple structs, these constructors are functions that create new `RoughTime` values:

```
let four_score_and_seven_years_ago =
    RoughTime::InThePast(TimeUnit::Years, 4 * 20 + 7);

let three_hours_from_now =
    RoughTime::InTheFuture(TimeUnit::Hours, 3);
```

Enums can also have *struct variants*, which contain named fields, just like ordinary structs:

```
enum Shape {
    Sphere { center: Point3d, radius: f32 },
    Cuboid { corner1: Point3d, corner2: Point3d },
}

let unit_sphere = Shape::Sphere {
    center: ORIGIN,
    radius: 1.0,
};
```

In all, Rust has three kinds of enum variants, echoing the three kinds of structs we showed in the previous chapter. Variants with no data correspond to unit-like structs. Tuple variants look and function just like tuple structs. Struct variants have curly braces and named fields. A single enum can have variants of all three kinds:

```
enum RelationshipStatus {
    Single,
    InARelationship,
    ItsComplicated(Option<String>),
    ItsExtremelyComplicated {
        car: DifferentialEquation,
        cdr: EarlyModernistPoem,
    },
}
```

## Enums in Memory

In memory, enums with data are stored as a small integer *tag*, plus enough memory to hold all the fields of the largest variant. The tag field is for Rust's internal use. It tells which constructor created the value and therefore which fields it has.

As of this writing, `RoughTime` fits in 8 bytes, as shown in Figure 10-1.

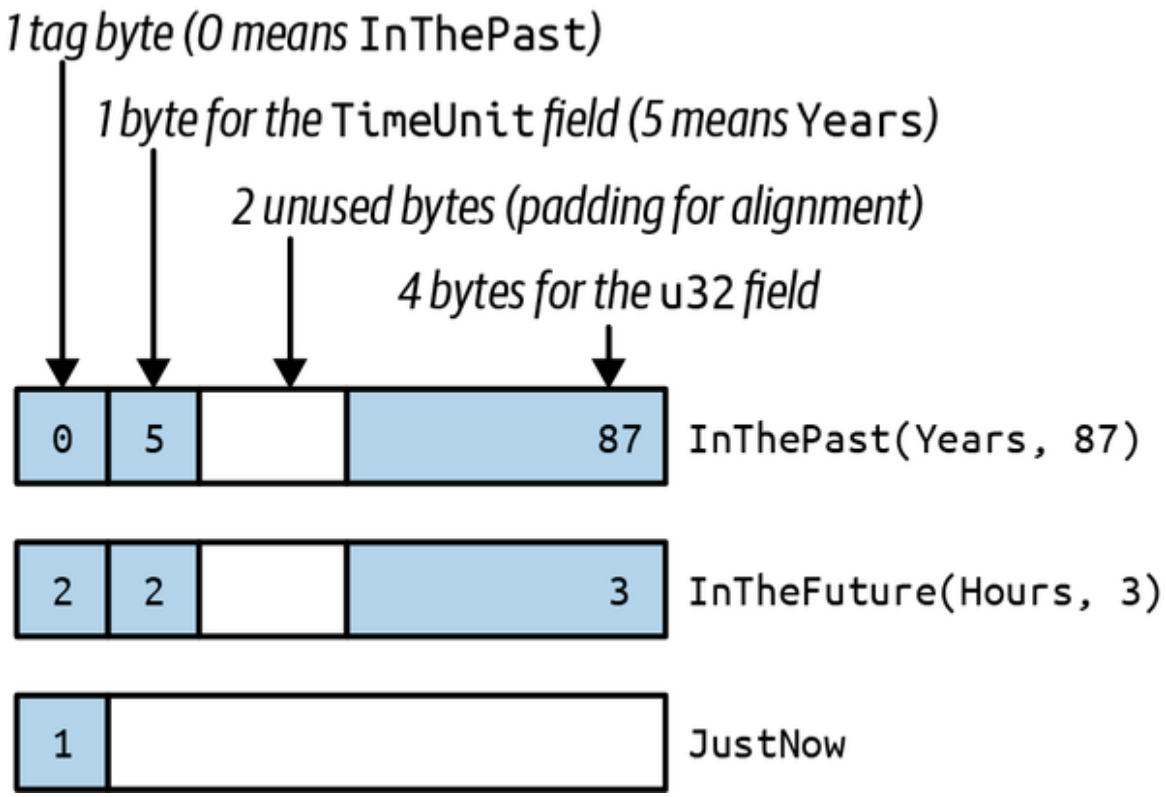


*Figure 10-1. `RoughTime` values in memory*

Rust makes no promises about enum layout, however, to leave the door open for future optimizations. In some cases, it would be possible to pack an enum more efficiently than the figure suggests. For instance, the Rust compiler can optimize away the tag field for some enums, as we'll see later.

## Rich Data Structures Using Enums

Enums are also useful for quickly implementing tree-like data structures. For example, suppose a Rust program needs to work with arbitrary JSON data. In memory, any JSON document can be represented as a value of this Rust type:

```
use std::collections::HashMap;

enum Json {
    Null,
    Boolean(bool),
    Number(f64),
    String(String),
```

```
    Array(Vec<Json>),
    Object(Box<HashMap<String, Json>>),
}
```

The explanation of this data structure in English can't improve much upon the Rust code. The JSON standard specifies the various data types that can appear in a JSON document: `null`, Boolean values, numbers, strings, arrays of JSON values, and objects with string keys and JSON values. The `Json` enum simply spells out these types.

This is not a hypothetical example. A similar enum can be found in `serde_json`, a serialization library for Rust structs that is one of the most downloaded crates on crates.io.

The `Box` around the `HashMap` that represents an `Object` serves only to make all `Json` values more compact. In memory, values of type `Json` take up four machine words. `String` and `Vec` values are three words, and Rust adds a tag byte. `Null` and `Boolean` values don't have enough data in them to use up all that space, but all `Json` values must be the same size. The extra space goes unused. Figure 10-2 shows some examples of how `Json` values actually look in memory.

A `HashMap` is larger still. If we had to leave room for it in every `Json` value, they would be quite large, eight words or so. But a `Box<HashMap>` is a single word: it's just a pointer to heap-allocated data. We could make `Json` even more compact by boxing more fields.

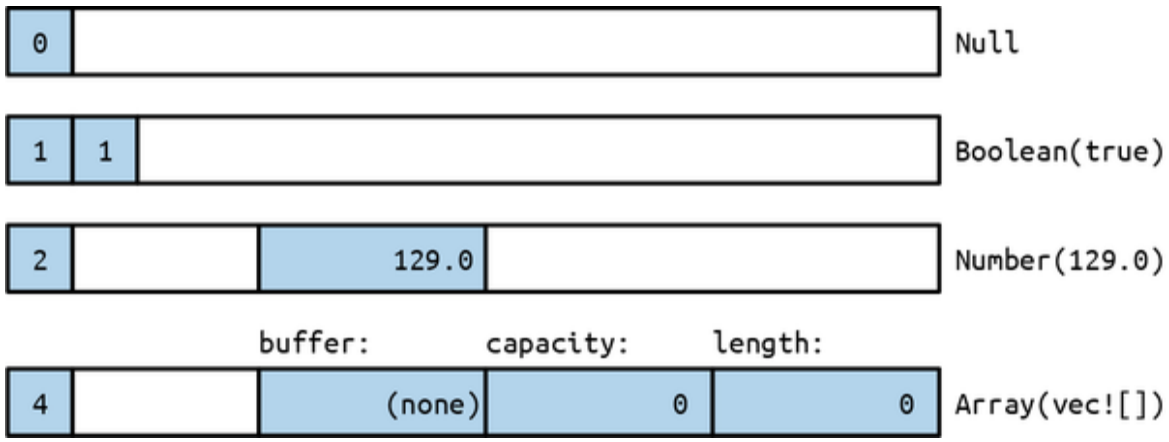


*Figure 10-2. `Json` values in memory*

What's remarkable here is how easy it was to set this up. In C++, one might write a class for this:

```
class JSON {
private:
    enum Tag {
        Null, Boolean, Number, String, Array, Object
    };
    union Data {
        bool boolean;
        double number;
        shared_ptr<string> str;
        shared_ptr<vector<JSON>> array;
        shared_ptr<unordered_map<string, JSON>> object;

        Data() {}
        ~Data() {}
        ...
    };

    Tag tag;
    Data data;

public:
    bool is_null() const { return tag == Null; }
    bool is_boolean() const { return tag == Boolean; }
    bool get_boolean() const {
        assert(is_boolean());
        return data.boolean;
    }
    void set_boolean(bool value) {
        this->~JSON();  // clean up string/array/object value
        tag = Boolean;
        data.boolean = value;
    }
    ...
};
```

At 30 lines of code, we have barely begun the work. This class will need constructors, a destructor, and an assignment operator. An alternative would be to create a class hierarchy with a base class `JSON` and subclasses `JSONBoolean`, `JSONString`, and so on. Either way, when it's done, our C++ JSON library will have more than a dozen methods. It will take a bit of

reading for other programmers to pick it up and use it. The entire Rust enum is eight lines of code.

## Generic Enums

Enums can be generic. Two examples from the standard library are among the most-used data types in the language:

```
enum Option<T> {
    None,
    Some(T),
}

enum Result<T, E> {
    Ok(T),
    Err(E),
}
```

These types are familiar enough by now, and the syntax for generic enums is the same as for generic structs.

One unobvious detail is that Rust can eliminate the tag field of `Option<T>` when the type `T` is a reference, `Box`, or other smart pointer type. Since none of those pointer types is allowed to be zero, Rust can represent `Option<Box<i32>>`, say, as a single machine word: 0 for `None` and nonzero for `Some` pointer. This makes such `Option` types close analogues to C or C++ pointer values that could be null. The difference is that Rust's type system requires you to check that an `Option` is `Some` before you can use its contents. This effectively eliminates null pointer dereferences.

Generic data structures can be built with just a few lines of code. Here is a `BinaryTree` type that can store any number of values of type `T`:

```
// An ordered collection of `T`s.
enum BinaryTree<T> {
    Empty,
    NonEmpty(Box<TreeNode<T>>),
}
```

```
// A part of a BinaryTree.
struct TreeNode<T> {
    element: T,
    left: BinaryTree<T>,
    right: BinaryTree<T>,
}
```

A great deal of information is packed into these two definitions, so we will take the time to translate the code word for word into English. Each `BinaryTree` value is either `Empty` or `NonEmpty`. If it's `Empty`, then it contains no data at all. If `NonEmpty`, then it has a `Box`, a pointer to a heap-allocated `TreeNode`. Each `TreeNode` value contains one actual element, as well as two more `BinaryTree` values. This means a tree can contain subtrees, and thus a `NonEmpty` tree can have any number of descendants.

Figure 10-3 shows a sketch of a value of type `BinaryTree<&str>`. As with `Option<Box<T>>`, Rust eliminates the tag field, so a `BinaryTree` value is just one machine word.

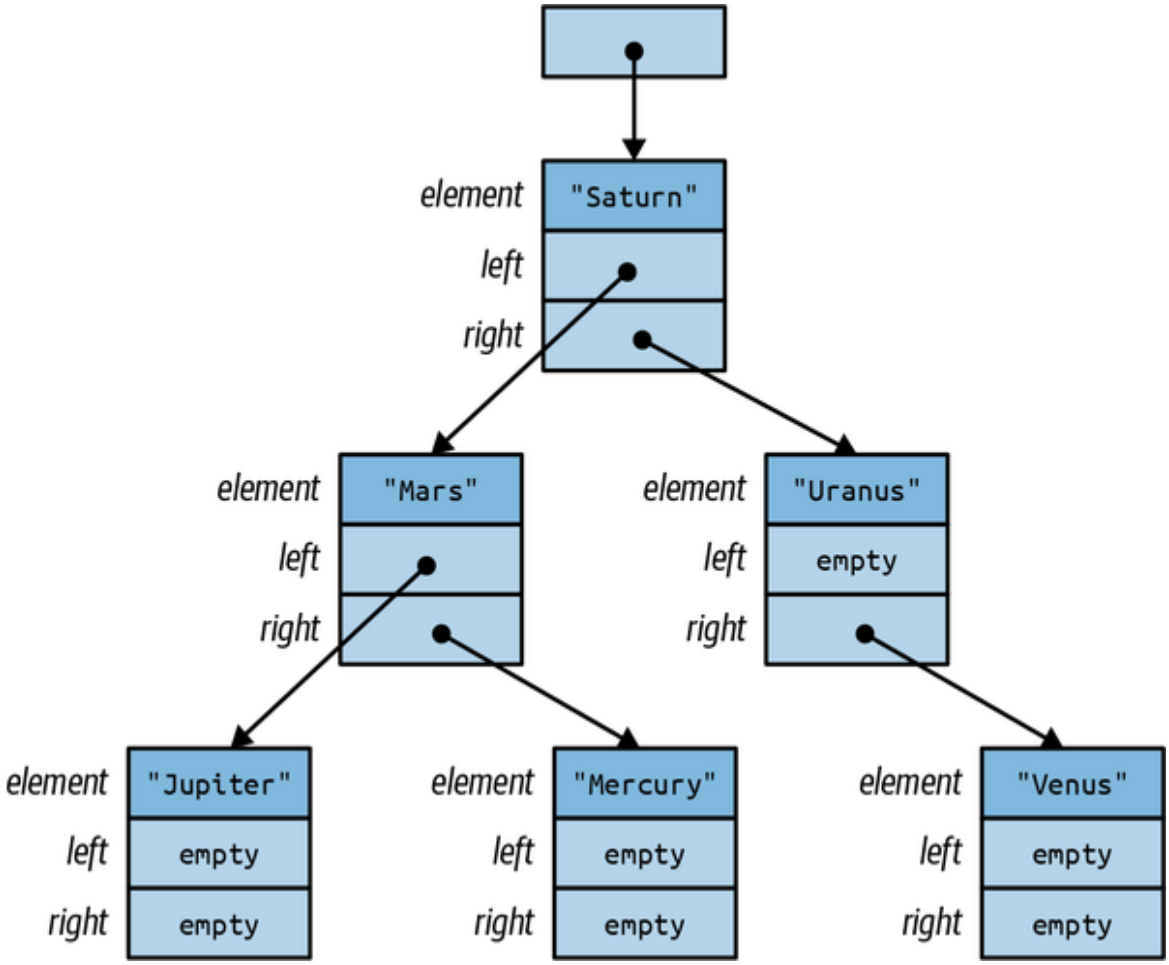


*Figure 10-3. A `BinaryTree` containing six strings*

Building any particular node in this tree is straightforward:

```
use self::BinaryTree::*;
let jupiter_tree = NonEmpty(Box::new(TreeNode {
    element: "Jupiter",
    left: Empty,
    right: Empty,
}));
```

Larger trees can be built from smaller ones:

```
let mars_tree = NonEmpty(Box::new(TreeNode {
    element: "Mars",
    left: jupiter_tree,
    right: mercury_tree,
}));
```

Naturally, this assignment transfers ownership of `jupiter_tree` and `mercury_tree` to their new parent node. The remaining parts of the tree follow the same patterns. The root node is no different from the others:

```
let tree = NonEmpty(Box::new(TreeNode {
    element: "Saturn",
    left: mars_tree,
    right: uranus_tree,
}));
```

Later in this chapter, we'll show how to implement an `add` method on the `BinaryTree` type so that we can instead write:

```
let mut tree = BinaryTree::Empty;
for planet in planets {
    tree.add(planet);
}
```

No matter what language you're coming from, creating data structures like `BinaryTree` in Rust will likely take some practice. It won't be obvious at first where to put the `Box`es. One way to find a design that will work is to draw a picture like Figure 10-3 that shows how you want things laid out in memory. Then work backward from the picture to the code. Each collection of rectangles is a struct or tuple; each arrow is a `Box` or other smart pointer. Figuring out the type of each field is a bit of a puzzle, but a manageable one. The reward for solving the puzzle is control over your program's memory usage.

Now comes the "price" we mentioned in the introduction. The tag field of an enum costs a little memory, up to 8 bytes in the worst case, but that is usually negligible. The real downside to enums (if it can be called that) is that Rust code cannot throw caution to the wind and try to access fields regardless of whether they are actually present in the value:

```
let r = shape.radius;  // error: no field `radius` on type
`Shape`
```

The only way to access the data in an enum is the safe way: using patterns.

## Patterns

Recall the definition of our `RoughTime` type from earlier in this chapter:

```
enum RoughTime {
    InThePast(TimeUnit, u32),
    JustNow,
    InTheFuture(TimeUnit, u32),
}
```

Suppose you have a `RoughTime` value and you'd like to display it on a web page. You need to access the `TimeUnit` and `u32` fields inside the value. Rust doesn't let you access them directly, by writing `rough_time.0` and `rough_time.1`, because, after all, the value might be `RoughTime::JustNow`, which has no fields. But then, how can you get the data out?

You need a `match` expression:

```
 1  fn rough_time_to_english(rt: RoughTime) -> String {
 2      match rt {
 3          RoughTime::InThePast(units, count) => {
 4              format!("{count} {} ago", units.plural())
 5          }
 6          RoughTime::JustNow => {
 7              "just now".to_string()
 8          }
 9          RoughTime::InTheFuture(units, count) => {
10              format!("{count} {} from now", units.plural())
11          }
12      }
13  }
```

`match` performs pattern matching; in this example, the *patterns* are the parts that appear before the => symbol on lines 3, 6, and 9. Patterns that match `RoughTime` values look just like the expressions used to create

`RoughTime` values. This is no coincidence. Expressions *produce* values; patterns *consume* values. The two use a lot of the same syntax.

Let's step through what happens when this `match` expression runs. Suppose `rt` is the value `RoughTime::InTheFuture(TimeUnit::Months, 1)`. Rust first tries to match this value against the pattern on line 3. As you can see in Figure 10-4, it doesn't match.

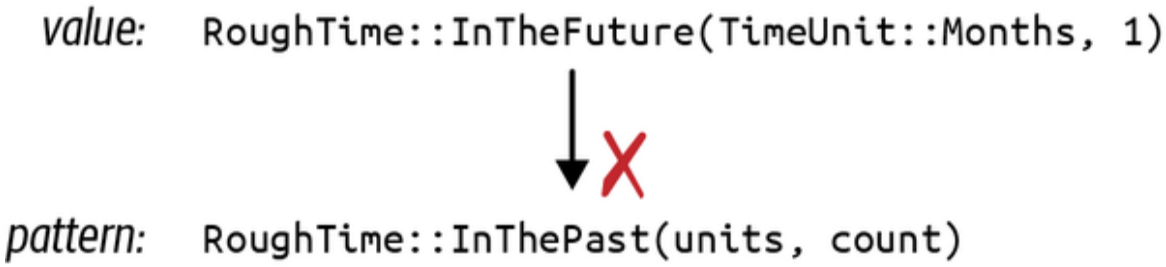


*Figure 10-4. A `RoughTime` value and pattern that do not match*

Pattern matching an enum, struct, or tuple works as though Rust is doing a simple left-to-right scan, checking each component of the pattern to see if the value matches it. If it doesn't, Rust moves on to the next pattern.

The patterns on lines 3 and 6 fail to match. But the pattern on line 9 succeeds (Figure 10-5).

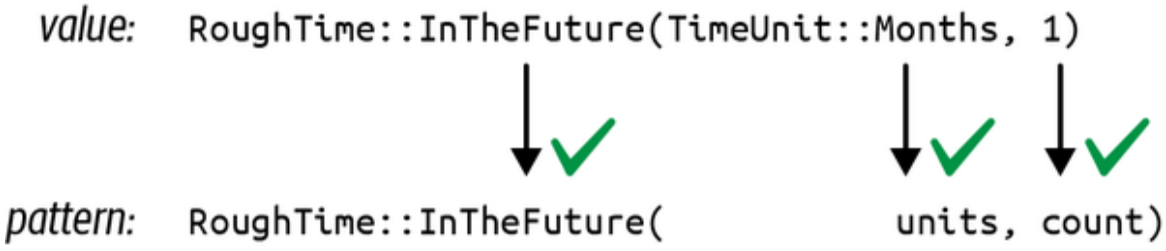


*Figure 10-5. A successful match*

When a pattern contains simple identifiers like `units` and `count`, those become local variables in the code following the pattern. Whatever is present in the value is moved or copied into the new variables. Rust stores `TimeUnit::Months` in `units` and `1` in `count`, runs line 10, and returns the string `"1 months from now"`.

That output has a minor grammatical issue, which can be fixed by adding another arm to the `match`:

```
RoughTime::InTheFuture(unit, 1) => {
    format!("a {} from now", unit.singular())
}
```

This arm matches only if the `count` field is exactly 1. Note that this new code must be added before line 9. If we add it at the end, Rust will never get to it, because the pattern on line 9 matches all `InTheFuture` values. The Rust compiler will warn about an “unreachable pattern” if you make this kind of mistake.

Even with the new code, `RoughTime::InTheFuture(TimeUnit::Hours, 1)` still presents a problem: the result `"a hour from now"` is not quite right. Such is the English language. This too can be fixed by adding another `match` arm. We’ll leave that to you, as an easy exercise.

As this example shows, pattern matching works hand in hand with enums and can even test the data they contain, making `match` a powerful, flexible replacement for C’s `switch` statement. So far, we’ve only seen patterns that match enum values. There’s more to it than that. Rust patterns are their own little language, summarized in Table 10-1. We’ll spend most of this chapter on the features shown in this table.

*Table 10-1. Patterns*

| Pattern type | Example | Notes |
|---|---|---|
| Literal | `100`<br>`"name"` | Matches an exact value; the name of a `const` is also allowed |
| Range | `0..100`<br>`'a'..='z'`<br>`256..` | Matches any value in range |
| Wildcard | `_` | Matches any value and ignores it |
| Variable | `name`<br>`mut count` | Matches any value and moves or copies it into a new local variable |
| `ref` variable | `ref field`<br>`ref mut field` | Borrows a reference to the matched value instead of moving or copying it |
| Binding with subpattern | `val @ 0..=99`<br>`ref circle @ Shape::Circle { .. }` | Matches the pattern to the right of `@`, using the variable name to the left |
| Enum pattern | `Some(value)`<br>`None`<br>`Pet::Orca` | |
| Tuple pattern | `(key, value)`<br>`(r, g, b)` | |
| Array pattern | `[a, b, c, d, e, f, g]`<br>`[heading, carom, correction]` | |

| Pattern type | Example | Notes |
| --- | --- | --- |
| Slice pattern | `[first, second]`<br>`[first, _, third]`<br>`[first, .., last]`<br>`[]` | |
| Struct pattern | `Color(r, g, b)`<br>`Point { x, y }`<br>`Card { suit: Clubs, rank: n }`<br>`Account { id, name, .. }` | |
| Reference | `&value`<br>`&(k, v)` | Matches a reference value and dereferences it |
| Or patterns | `'a' \| 'A'`<br>`Some("left" \| "right" \| "center")` | Matches any of several patterns |
| Guard expression | `x if x * x <= r2` | In `match` only (not valid in `let`, etc.) |

## Literals, Variables, and Wildcards in Patterns

So far, we've shown `match` expressions working with enums. Other types can be matched too. When you need something like a C `switch` statement, use `match` with an integer value. Integer literals like `0` and `1` can serve as patterns:

```
match meadow.count_rabbits() {
    0 => {}  // nothing to say
    1 => println!("A rabbit is nosing around in the clover."),
    n => println!("There are {n} rabbits hopping about in the meadow"),
}
```

The pattern `0` matches if there are no rabbits in the meadow. `1` matches if there is just one. If there are two or more rabbits, we reach the third pattern, `n`. This pattern is just a variable name. It can match any value, and the matched value is moved or copied into a new local variable. So in this case, the value of `meadow.count_rabbits()` is stored in a new local variable `n`, which we then print.

Other literals can be used as patterns too, including Booleans, characters, and even strings:

```
let calendar = match settings.get_string("calendar") {
    "gregorian" => Calendar::Gregorian,
    "chinese" => Calendar::Chinese,
    "ethiopian" => Calendar::Ethiopian,
    other => return parse_error("calendar", other),
};
```

In this example, `other` serves as a catchall pattern like `n` in the previous example. These patterns play the same role as a `default` case in a `switch` statement, matching values that don't match any of the other patterns.

If you need a catchall pattern, but you don't care about the matched value, you can use a single underscore _ as a pattern, the *wildcard pattern*:

```
let caption = match photo.tagged_pet() {
    Pet::Tyrannosaur => "RRRAAAAAHHHHHH",
    Pet::Samoyed => "*dog thoughts*",
    _ => "I'm cute, love me",  // generic caption, works for any
pet
};
```

The wildcard pattern matches any value, but without storing it anywhere. Since Rust requires every `match` expression to handle all possible values, a wildcard is often required at the end. Even if you're sure the remaining cases can't occur, you must at least add a fallback arm, perhaps one that panics:

```
// There are many Shapes, but we only support "selecting"
// either some text, or everything in a rectangular area.
// You can't select an ellipse or trapezoid.
match document.selection() {
    Shape::TextSpan(start, end) => paint_text_selection(start,
end),
    Shape::Rectangle(rect) => paint_rect_selection(rect),
    _ => panic!("unexpected selection type"),
}
```

## Tuple and Struct Patterns

Tuple patterns match tuples. They're useful any time you want to get multiple pieces of data involved in a single `match`:

```
/// Converts an hour AM or PM to the 24-hour convention.
/// For example, "4 P.M." is 16, and "12 A.M." is 0.
fn to_24_hour_time(hour: u32, half: DayHalf) -> u32 {
    match (hour, half) {
        (12, DayHalf::Am) => 0,
        (hour, DayHalf::Am) => hour,
        (12, DayHalf::Pm) => 12,
        (hour, DayHalf::Pm) => 12 + hour,
    }
}
```

Struct patterns use curly braces, just like struct expressions. They contain a subpattern for each field:

```
match balloon.location {
    Point { x: 0, y: height } => {
        println!("straight up {height} meters");
    }
    Point { x: x, y: y } => {
        println!("at ({x}m, {y}m)");
    }
}
```

In this example, if the first arm matches, then `balloon.location.y` is stored in the new local variable `height`.

Suppose `balloon.location` is `Point { x: 30, y: 40 }`. As always, Rust checks each component of each pattern in turn (Figure 10-6).

*Figure 10-6. Pattern matching with structs*

The second arm matches, so the output would be `at (30m, 40m)`.

Patterns like `Point { x: x, y: y }` are common when matching structs, and the redundant names are visual clutter, so Rust has a shorthand for this: `Point {x, y}`. The meaning is the same. This pattern still stores a point's `x` field in a new local `x`, and its `y` field in a new local `y`.

Even with the shorthand, it is cumbersome to match a large struct when we care only about a few fields:

```
match get_account(id) {
    ...
    Some(Account {
        id: _, status: _,
        name, language,  // <--- the 2 things we care about
        address: _, birthday: _, eye_color: _, pet: _,
        security_question: _, hashed_innermost_secret: _,
        is_adamantium_preferred_customer: _,
    }) => language.show_custom_greeting(name),
}
```

To avoid this, use `..` to tell Rust you don't care about any of the other fields:

```
    Some(Account { name, language, .. }) => {
        language.show_custom_greeting(name);
    }
```

## Matching References

As we've seen, matching a noncopyable value moves the value. Continuing with the account example, this code would be invalid:

```
match current_user {
    ...
    Some(Account { name, language, .. }) => {
        ui.greet(&name, &language);
        ui.show_settings(&current_user);  // error: borrow of
moved value
    }
}
```

Here, the two fields `name` and `language` are moved from `current_user` into local variables. The rest of `current_user` is dropped. We can't borrow a reference to it afterward.

If `name` and `language` were both `Copy` values, Rust would copy the fields instead of moving them, and this code would be fine. But suppose these are `String`s. What can we do?

The easiest fix is to match on a reference to `current_user`:

```
match &current_user {  // <-- note: added `&` here
    ...
    Some(Account { name, language, .. }) => {
        ui.greet(name, language);  // <-- note: removed `&`s here
        ui.show_settings(&current_user);  // ok
    }
}
```

Since we're now matching a reference, the variables `name` and `language` become references to the corresponding fields of `current_user`. This is why we removed the two `&`s in the line calling `ui.greet`. In the original, we passed this method references to the `String` variables `name` and `language`. In the new code, those variables are already references—to `String` fields still owned by `current_user`.

Everywhere you could match on a value of some type `T`, you can also match on a `&T` or `&mut T`. No special syntax is needed in the patterns. The

variables in the pattern simply get references to the values they match instead of moves or copies.

## Reference Patterns

Generally speaking, when you have a reference to something you'd like to pattern-match, you'll simply match on the reference, as described in the preceding section. However, Rust also has special syntax for borrowing and dereferencing in patterns, useful in a few specific cases.

A *borrowing pattern* uses the `ref` keyword. Inserting `ref` before any variable in a pattern makes Rust borrow a reference to the matched value instead of moving or copying it. The phrase `ref mut` borrows a `mut` reference. For example, if you're matching a struct with several copyable fields, but you'd also like to match a noncopyable field by reference, you might use a pattern like this:

```
// Copy `id` and `status`, borrow `name`:
Account { id, status, ref name, .. } => ...
```

A *dereferencing pattern* uses the `&` operator. Inserting `&` before any part of a pattern makes it match a reference and dereference it. For example, suppose we have an iterator `chars` over the characters in a string, and it has a method `chars.peek()` that returns an `Option<&char>`: a reference to the next character, if any. (Peekable iterators do in fact return an `Option<&ItemType>`, as we'll see in Chapter 15.) We can use an `&` pattern to get the character as a `char`, not a `&char`:

```
match chars.peek() {
    Some(&c) => println!("coming up: {c:?}"),
    None => println!("end of chars"),
}
```

This syntax is a bit surprising, because Rust is following a pointer here, an action we usually associate with the `*` operator, not the `&` operator. The thing to remember is that patterns and expressions are natural opposites.

Whereas the expression `(x, y)` makes two values into a new tuple, the pattern `(x, y)` does the opposite: it matches a tuple and breaks out the two values. It's the same with `&`. In an expression, `&` creates a reference. In a pattern, `&` matches a reference.

## Array and Slice Patterns

Array patterns match arrays. They're often used to filter out some special-case values and are useful any time you're working with arrays whose values have a different meaning based on position.

For example, when converting hue, saturation, and lightness (HSL) color values to red, green, blue (RGB) color values, colors with zero lightness or full lightness are just black or white. We could use a `match` expression to deal with those cases simply:

```
fn hsl_to_rgb(hsl: [u8; 3]) -> [u8; 3] {
    match hsl {
        [_, _, 0] => [0, 0, 0],
        [_, _, 255] => [255, 255, 255],
        ...
    }
}
```

Slice patterns are similar, but unlike arrays, slices have variable lengths, so slice patterns match not only on values but also on length. `..` in a slice pattern matches any number of elements:

```
fn greet_people(names: &[String]) {
    match names {
        [] => println!("Hello, nobody."),
        [a] => println!("Hello, {a}."),
        [a, b] => println!("Hello, {a} and {b}."),
        [a, .., b] => println!("Hello, everyone from {a} to
{b}."),
    }
}
```

Since `names` is a reference to a slice, the variables `a` and `b` in this example are references to individual elements. Their type is `&String`, not `String`.

Slice patterns work only on slices, not vectors. To match data in a vector, you can write `match &my_vec[..]`, borrowing a reference to the slice containing all of the elements.

## Match Guards

Sometimes a match arm has additional conditions that must be met before it can be considered a match. Suppose we're implementing a board game with hexagonal spaces, and the player just clicked to move a piece. To confirm that the click was valid, we might try something like this:

```
fn check_move(current_hex: Hex, click: Point) ->
game::Result<Hex> {
    match point_to_hex(click) {
        None => {
            Err("That's not a game space.")
        }
        // try to match if user clicked the current_hex
        // (it doesn't work: see explanation below)
        Some(current_hex) => {
            Err("You are already there! You must click somewhere
else.")
        }
        Some(other_hex) => {
            Ok(other_hex)
        }
    }
}
```

This fails because identifiers in patterns introduce *new* variables. The pattern `Some(current_hex)` here creates a new local variable `current_hex`, shadowing the argument `current_hex`. Rust emits several warnings about this code—in particular, the last arm of the `match` is unreachable. One way to fix this is simply to use an `if` expression in the match arm:

```
match point_to_hex(click) {
    None => Err("That's not a game space."),
    Some(hex) => {
        if hex == current_hex {
            Err("You are already there! You must click somewhere
else")
        } else {
            Ok(hex)
        }
    }
}
```

But Rust also provides *match guards*, extra conditions that must be true for a match arm to apply, written as `if CONDITION`, between the pattern and the arm's => token:

```
match point_to_hex(click) {
    None => Err("That's not a game space."),
    Some(hex) if hex == current_hex => {
        Err("You are already there! You must click somewhere
else")
    }
    Some(hex) => Ok(hex),
}
```

If the pattern matches but the condition is false, matching continues with the next arm.

## Matching Multiple Possibilities

A pattern of the form `pat1 | pat2` matches if either subpattern matches:

```
let at_end = match chars.peek() {
    Some('\r' | '\n') | None => true,
    _ => false,
};
```

In an expression, `|` is the bitwise OR operator, but here it works more like the `|` symbol in a regular expression. `at_end` is set to `true` if `chars.peek()` is `None`, or a `Some` holding a carriage return or line feed. Use `..` or `..=` to match a whole range of values:

```
const KILO: usize = 1024;
const MEGA: usize = 1024 * KILO;
const GIGA: usize = 1024 * MEGA;

match num_bytes {
    0..KILO => num_bytes.to_string(),
    KILO..MEGA => format!("{}K", num_bytes / KILO),
    MEGA..GIGA => format!("{}M", num_bytes / MEGA),
    GIGA.. => "big".to_string(),
}
```

Ranges using the `..=` operator include the end value, so `'0'..='9'` matches all the ASCII digits:

```
match next_char {
    '0'..='9' => self.read_number(),
    'a'..='z' | 'A'..='Z' => self.read_word(),
    ' ' | '\t' | '\n' => self.skip_whitespace(),
    _ => self.handle_punctuation(),
}
```

## Binding with @ Patterns

Finally, `x @ pattern` matches exactly like the given `pattern`, but on success, instead of creating variables for parts of the matched value, it creates a single variable `x` and moves or copies the whole value into it. For example, say you have this code:

```
match self.get_selection() {
    Shape::Rect(top_left, bottom_right) => {
        optimized_paint(&Shape::Rect(top_left, bottom_right));
    }
    other_shape => {
        paint_outline(other_shape.get_outline());
    }
}
```

Note that the first case unpacks a `Shape::Rect` value, only to rebuild an identical `Shape::Rect` value on the next line. This can be rewritten to use an `@` pattern:

```
        rect @ Shape::Rect(..) => {
            optimized_paint(&rect);
        }
```

`@` patterns are also useful with ranges:

```
match chars.next() {
    Some(digit @ '0'..='9') => read_number(digit, chars),
    ...
},
```

And they can be used to capture "the rest of the list" in a slice pattern:

```
let [first, second, others @ ..] = &ranked_teams[..] else {
    return Err(TournamentError::NotEnoughTeams);
};
assert_eq!(others, &ranked_teams[2..]);
```

## Where Patterns Are Allowed

Although patterns are most prominent in `match` expressions, they are also allowed in several other places, typically in place of an identifier. The meaning is always the same: instead of just storing a value in a single variable, Rust uses pattern matching to take the value apart.

Patterns can be used to...

```
// ...unpack a struct into three new local variables
let Track { album, track_number, title, .. } = song;

// ...unpack a function argument that's a tuple
fn distance_to((x, y): (f64, f64)) -> f64 { ... }

// ...iterate over keys and values of a HashMap
for (id, document) in &cache_map {
    println!("Document #{id}: {}", document.title);
}

// ...automatically dereference an argument to a closure
// (handy because sometimes other code passes you a reference
// when you'd rather have a copy)
let sum = numbers.fold(0, |a, &num| a + num);
```

Each of these saves two or three lines of boilerplate code. The same concept exists in some other languages: in JavaScript, it's called *destructuring*, while in Python, it's *unpacking*.

Note that in all four examples, we use patterns that are guaranteed to match. The pattern `Point3d { x, y, z }` matches every possible value of the `Point3d` struct type, `(x, y)` matches any `(f64, f64)` pair, and so on. Patterns that always match are special in Rust. They're called *irrefutable patterns*, and they're the only patterns allowed in the four places shown here (after `let`, in function arguments, after `for`, and in closure arguments).

A *refutable pattern* is one that might not match, like `Ok(x)`, which doesn't match an error result, or `'0'..='9'`, which doesn't match the character `'Q'`. Refutable patterns can be used in `match` arms because `match` is designed for them: if one pattern fails to match, it's clear what happens next. The four preceding examples are places in Rust programs where a pattern can be handy, but the language doesn't allow for match failure.

Refutable patterns are also allowed with `if let`, `while let`, and `let ... else`, which can be used to...

```
// ...handle just one enum variant specially
if let RoughTime::InTheFuture(_, _) = user.date_of_birth() {
    user.set_time_traveler(true);
}

// ...run some code only if a table lookup succeeds
if let Some(document) = cache_map.get(&id) {
    return send_cached_response(document);
}

// ...repeatedly try something until it succeeds
while let Err(err) = present_cheesy_anti_robot_task() {
    log_robot_attempt(err);
    // let the user try again (it might still be a human)
}

// ...manually loop over an iterator
while let Some(_) = lines.peek() {
    read_paragraph(&mut lines);
```

```
}

// ... exit early if a lookup fails
let Some(account) = database.get_account(account_id) else {
    return Err(Error::AccountNotFound);
};
```

For details about these constructs, refer to “if let”, “Loops”, and “let else”.

Lastly, the macro `matches!(value, pattern)` simply checks a value against a pattern and returns `true` if it matches. It is shorthand for:

```
match value {
    pattern => true,
    _ => false,
}
```

## Populating a Binary Tree

Earlier we promised to show how to implement a method, `BinaryTree::add()`, that adds a node to a `BinaryTree` of this type:

```
// An ordered collection of `T`s.
enum BinaryTree<T> {
    Empty,
    NonEmpty(Box<TreeNode<T>>),
}

// A part of a BinaryTree.
struct TreeNode<T> {
    element: T,
    left: BinaryTree<T>,
    right: BinaryTree<T>,
}
```

You now know enough about patterns to write this method. An explanation of binary search trees is beyond the scope of this book, but for readers already familiar with the topic, it’s worth seeing how it plays out in Rust:

```
impl<T: Ord> BinaryTree<T> {
    fn add(&mut self, value: T) {
        let mut place = self;
```

```
 4            while let BinaryTree::NonEmpty(node) = place {
 5                if value <= node.element {
 6                    place = &mut node.left;
 7                } else {
 8                    place = &mut node.right;
 9                }
10            }
11            *place = BinaryTree::NonEmpty(Box::new(TreeNode {
12                element: value,
13                left: BinaryTree::Empty,
14                right: BinaryTree::Empty,
15            }));
16        }
17    }
```

Line 1 tells Rust that we're defining a method on `BinaryTrees` of ordered types. This is the same syntax we used to define methods on generic structs in "Defining Methods with impl", but with a new restriction, `T: Ord`, to require `T` to be a type that implements the `Ord` trait. This enables our use of the comparison operator <= on line 5.

The method uses the local variable `place` to point to its current place within the tree. The pattern on line 4 tests whether the current place is `Empty` or `NonEmpty`:

```
while let BinaryTree::NonEmpty(node) = place {
```

If `place` refers to a nonempty subtree, this pattern matches. Since `place` is a mutable reference, `node` is bound to a mutable reference to the `Box<TreeNode<T>>`. We execute the loop body, navigating to either the left or the right child. The loop continues until we reach an `Empty` subtree.

Lastly, lines 11–15 run, changing the `Empty` tree to a `NonEmpty` one. The call to `Box::new()` here allocates a new `TreeNode` in the heap. Its left and right subtrees are both `Empty`.

The new method can be used like this:

```
let mut tree = BinaryTree::Empty;
tree.add("Mercury");
```

```
tree.add("Venus");
...
```

## Public Enums and Compatibility

A public struct can have private fields, but public enums can't. All variants and fields of an enum have the same visibility as the enum itself.

This means that changing a public enum is usually a breaking change. If your crate is published on crates.io, a change as minor as adding a new variant to an `Error` enum can require a major version number bump. This is inconvenient, so Rust offers a partial workaround. You can mark an enum with the `#[non_exhaustive]` attribute to indicate that it may gain new variants in the future. For example, suppose you have this `Error` type in your `fern_sim` crate:

```
#[non_exhaustive]
pub enum Error {
    PhylumNotFound,
    BrackenPipe,
}
```

The Rust compiler then enforces a minor restriction on user code, for forward compatibility. If a downstream user of your crate attempts to match this type *exhaustively*, by listing all variants in a `match` expression, Rust will complain:

```
use fern_sim::Error;

fn should_retry(err: Error) -> bool {
    match err {  // error: non-exhaustive patterns: `_` not
covered
        Error::PhylumNotFound => false,
        Error::BrackenPipe => true,
    }
}
```

The compiler will tell the user to add a catchall arm to the `match`, like `_ => todo!()`. For this particular function, the user must decide whether it

`should_retry` if an unrecognized kind of error occurs.

This rule is a bit odd, but it's exactly what's required to keep new variants from breaking existing code. When you add a variant (perhaps `Error::InsufficientFronds`), all user code will still compile, thanks to the catchall cases your users were forced to write.

The `#[non_exhaustive]` enum can also be used on structs and individual variants of an enum to indicate that future versions may add new fields. This prevents code outside the crate from matching the struct or variant without `..` and from creating new values of those structs or variants using literals (the syntax that looks like `UnitLike`, `TupleLike(v1, v2)`, or `NamedField { f1, f2, f3 }`, all of which would break if new fields were added). For structs, the effect is like adding a private field.

It's a good idea to use `#[non_exhaustive]` on public enums that might grow later. But new variants aren't the only cause of trouble. Practically any change to an enum is a breaking change. The most careful design is to wrap your enum in a public `struct` and keep the enum private. This unfortunately prevents users from taking advantage of pattern matching. You'll have to provide some public methods to compensate.

## The Big Picture

Rust's enums may be new to systems programming, but they are not a new idea. Traveling under various academic-sounding names, like *algebraic data types*, they've been used in functional programming languages for more than 40 years. It's unclear why so few other languages in the C tradition have ever had them. Perhaps it is simply that for a programming language designer, combining variants, references, mutability, and memory safety is extremely challenging. Functional programming languages dispense with mutability. C `unions`, by contrast, have variants, pointers, and mutability—but are so spectacularly unsafe that even in C they're a last resort. Rust's borrow checker is the magic that makes it possible to combine all four without compromise.

Programming is data processing. Getting data into the right shape can be the difference between a small, fast, elegant program and a slow, gigantic tangle of duct tape and virtual method calls.

This is the problem space enums address. They are a design tool for getting data into the right shape. For cases when a value may be one thing or another thing or perhaps nothing at all, enums are better than class hierarchies on every axis: faster, safer, less code, and easier to document.

The limiting factor is flexibility. End users of an enum can't extend it to add new variants. Variants can be added only by changing the enum declaration. And when that happens, existing code breaks. In some cases, trading flexibility for simplicity is just good sense. After all, the structure of JSON is not expected to change. And in some cases, revisiting all uses of an enum when it changes is exactly what we want. For example, when an `enum` is used in a compiler to represent the various operators of a programming language, adding a new operator *should* involve touching all code that handles operators.

But sometimes more flexibility is needed. For those situations, Rust has traits, the topic of our next chapter.

# Chapter 11. Traits and Generics

> *[A] computer scientist tends to be able to deal with nonuniform structures—case 1, case 2, case 3—while a mathematician will tend to want one unifying axiom that governs an entire system.*
>
> —Donald Knuth

One of the great discoveries in programming is that it's possible to write code that operates on values of many different types, *even types that haven't been invented yet.* Here are two examples:

- `Vec<T>` is generic: you can create a vector of any type of value, including types defined in your program that the authors of `Vec` never anticipated.
- Many things have `.write()` methods, including `File`s and `TcpStream`s. Your code can take a writer by reference, any writer, and send data to it. Your code doesn't have to care what type of writer it is. Later, if someone adds a new type of writer, your code will already support it.

Of course, this capability is hardly new with Rust. It's called *polymorphism*, and it was the hot new programming language technology of the 1970s. By now it's effectively universal. Rust supports polymorphism with two related features: traits and generics. These concepts will be familiar to many programmers, but Rust takes a fresh approach inspired by Haskell's typeclasses.

*Traits* are Rust's take on interfaces or abstract base classes. At first, they look just like interfaces in Java or C#. The trait for writing bytes is called `std::io::Write`, and its definition in the standard library starts out like this:

```
trait Write {
    fn write(&mut self, buf: &[u8]) -> Result<usize>;
```

```
    fn flush(&mut self) -> Result<()>;

    fn write_all(&mut self, buf: &[u8]) -> Result<()> { ... }
    ...
}
```

This trait offers several methods; we've shown only the first three.

The standard types `File` and `TcpStream` both implement `std::io::Write`. So does `Vec<u8>`. All three types provide methods named `.write()`, `.flush()`, and so on. Code that uses a writer without caring about its type looks like this:

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

fn say_hello(out: &mut dyn Write) -> std::io::Result<()> {
    out.write_all(b"hello world\n")?;
    out.flush()
}
```

The type of `out` is `&mut dyn Write`, meaning "a mutable reference to any value that implements the `Write` trait." We can pass `say_hello` a mutable reference to any such value:

```
use std::fs::File;
let mut local_file = File::create("hello.txt")?;
say_hello(&mut local_file)?;  // works

let mut bytes = vec![];
say_hello(&mut bytes)?;  // also works
assert_eq!(bytes, b"hello world\n");
```

This chapter begins by showing how traits are used, how they work, and how to define your own. But there is more to traits than we've hinted at so far. We'll use them to add extension methods to existing types, even built-in types like `str` and `bool`. We'll explain why adding a trait to a type costs no extra memory and how to use traits without virtual method call overhead. We'll see that built-in traits are the hook into the language that Rust provides for operator overloading and other features. And we'll cover

the `Self` type, associated functions, and associated types, three features Rust lifted from Haskell that elegantly solve problems that other languages address with workarounds and hacks.

*Generics* are the other flavor of polymorphism in Rust. Like a C++ template, a generic function or type can be used with values of many different types:

```
/// Returns the lesser of two values.
fn min<T: Ord>(value1: T, value2: T) -> T {
    if value1 <= value2 {
        value1
    } else {
        value2
    }
}
```

The `<T: Ord>` in this function means that `min` can be used with arguments of any type `T` that implements the `Ord` trait—that is, any ordered type. A requirement like this is called a *bound*, because it sets limits on which types `T` could possibly be. The compiler generates custom machine code for each type `T` that you actually use.

In Python and JavaScript, all functions work this way naturally: a function can operate on any value that has the properties and methods the function will need. (This is the characteristic often called *duck typing*: if it quacks like a duck, it's a duck.) But it's exactly this flexibility that makes it so difficult for those languages to detect type errors early; testing is often the only way to catch such mistakes. Rust's generics give the language a degree of the same flexibility, while still catching all type errors at compile time.

Despite their flexibility, generic functions are just as efficient as their nongeneric counterparts. There is no inherent performance advantage to be had from writing, say, a specific `min` function for each integer type, over writing a generic one that handles all integers.

Generics and traits are closely related: generic functions use traits in bounds to spell out what types of arguments they can be applied to. So we'll also

talk in this chapter about how `&mut dyn Write` and `<T: Write>` are similar, how they're different, and how to choose between these two ways of using traits.

## Using Traits

A trait is a feature that any given type may or may not support. Most often, a trait represents a capability, something a type can do:

- A value that implements `std::io::Write` can write out bytes.
- A value that implements `std::iter::Iterator` can produce a sequence of values.
- A value that implements `std::clone::Clone` can make clones of itself in memory.
- A value that implements `std::fmt::Debug` can be printed using `println!()` with the `{:?}` format specifier.

Those four traits are all part of Rust's standard library, and many standard types implement them. For example:

- `std::fs::File` implements the `Write` trait; it writes bytes to a local file. `std::net::TcpStream` writes to a network connection. `Vec<u8>` also implements `Write`. Each `.write()` call on a vector of bytes appends some data to the end.
- `Range<i32>` (the type of `0..10`) implements the `Iterator` trait, as do some iterator types associated with slices, hash tables, and so on.
- Most standard library types implement `Clone`. The exceptions are mainly types like `TcpStream` that represent more than just data in memory.
- Likewise, most standard library types support `Debug`.

There is one unusual rule about trait methods: the trait itself must be in scope. Otherwise, all its methods are hidden:

```
let mut buf: Vec<u8> = vec![];
buf.write_all(b"hello")?;  // error: no method named `write_all`
```

In this case, the compiler prints a friendly error message that suggests adding `use std::io::Write;` and indeed that fixes the problem:

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

let mut buf: Vec<u8> = vec![];
buf.write_all(b"hello")?;  // ok
```

Rust has this rule because, as we'll see later in this chapter, you can use traits to add new methods to any type—even standard library types like `u32` and `str`. Third-party crates can do the same thing. Clearly, this could lead to naming conflicts! But since Rust makes you import the traits you plan to use, crates are free to take advantage of this superpower. To get a conflict, you'd have to import two traits that add a method with the same name to the same type. This is rare in practice. (If you do run into a conflict, you can spell out what you want using fully qualified method syntax, covered later in the chapter.)

The reason `Clone` and `Iterator` methods work without any special imports is that they're always in scope by default: they're part of the standard prelude, names that Rust automatically imports into every module. In fact, the prelude is mostly a carefully chosen selection of traits. We'll cover many of them in Chapter 13.

C++ and C# programmers will already have noticed that trait methods are like virtual methods. Still, calls like the one shown above are fast, as fast as any other method call. Simply put, there's no polymorphism here. It's obvious that `buf` is a vector, not a file or a network connection.

The compiler can emit a simple call to `Vec<u8>::write_all()`. It can even inline the method. (C++ and C# will often do the same, although the

possibility of subclassing sometimes precludes this.) Only calls through `&mut dyn Write` incur the overhead of a dynamic dispatch, also known as a virtual method call, which is indicated by the `dyn` keyword in the type.

There are two ways of using traits to write polymorphic code in Rust: `dyn` and generics. We'll present `dyn` first.

## Using dyn

The value that a `dyn` reference refers to is called a *trait object*. For example, the `say_hello` function we showed earlier takes an argument `out` of type `&mut dyn Write`. This argument refers to a trait object of type `dyn Write`, which could be a `Vec<u8>`, a `File`, or any other kind of writer.

Rust doesn't permit variables of type `dyn Write`:

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

let mut buf: Vec<u8> = vec![];
let writer: dyn Write = buf;  // error: size of `dyn Write`
cannot be known
                              // at compilation time
```

A variable's size has to be known at compile time, and types that implement `Write` can be any size.

References have a constant size, and so do `Box`es and other smart pointer types:

```
let mut buf: Vec<u8> = vec![];
let writer: &mut dyn Write = &mut buf;  // ok
let boxed_writer: Box<dyn Write> = Box::new(buf.clone());  // ok
```

Like any other reference, a `dyn` reference points to some value, it has a lifetime, and it can be either `mut` or shared. What makes a `dyn` reference different is that Rust usually doesn't know the type of the referent at compile time. So, a reference to a trait object includes a little extra

information about the referent's type. This is strictly for Rust's own use behind the scenes: when you call `writer.write(data)`, Rust needs the type information to dynamically call the right `write` method depending on the type of `*writer`. You can't query the type information directly, and Rust does not support downcasting from `&mut dyn Write` back to a specific writer type like `&mut Vec<u8>`.

### dyn reference layout

There's nothing fancy about the way a `dyn Write` value is stored in memory. Its layout is exactly the same as a `File` or `Vec<u8>` or whatever type of writer the value actually is. But a *reference* to a `dyn` value is a little different from other references.

In memory, a `dyn` reference is a fat pointer consisting of a pointer to the value, plus a pointer to a table representing that value's type. Each `dyn` reference therefore takes up two machine words, as shown in Figure 11-1.

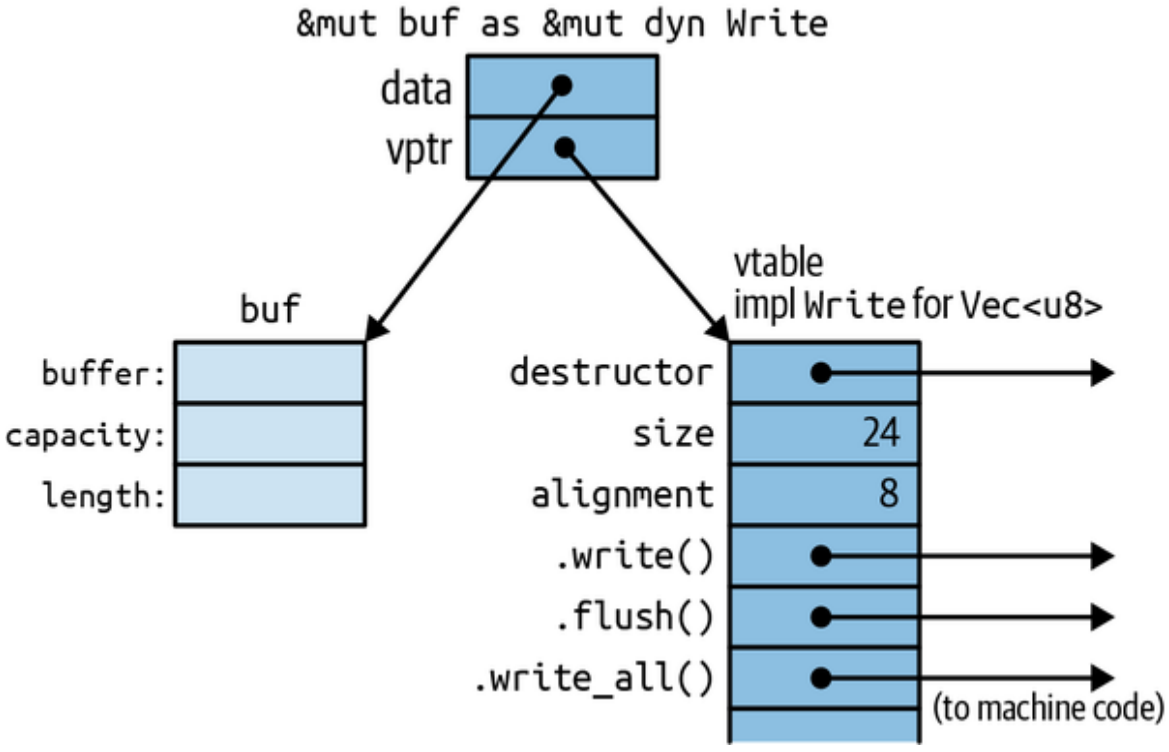


*Figure 11-1. `dyn` references in memory*

C++ has this kind of run-time type information as well. It's called a *virtual table*, or *vtable*. In Rust, as in C++, the vtable is generated once, at compile time, and shared by all objects of the same type. Everything shown in the darker shade in Figure 11-1, including the vtable, is a private implementation detail of Rust. Again, these aren't fields and data structures that you can access directly. Instead, the language automatically uses the vtable when you call a method of a trait object, to determine which implementation to call.

Seasoned C++ programmers will notice that Rust and C++ use memory a bit differently. In C++, the vtable pointer, or *vptr*, is stored as part of the struct. Rust uses fat pointers instead. The struct itself contains nothing but its fields. This way, a struct can implement dozens of traits without containing dozens of vptrs. Even types like `i32`, which aren't big enough to accommodate a vptr, can implement traits.

Rust automatically converts ordinary references into `dyn` references when needed. This is why we're able to pass `&mut local_file` to `say_hello` in this example:

```
let mut local_file = File::create("hello.txt")?;
say_hello(&mut local_file)?;
```

The type of `&mut local_file` is `&mut File`, and the type of the argument to `say_hello` is `&mut dyn Write`. Since a `File` is a kind of writer, Rust allows this, automatically converting the plain reference to a `dyn` reference.

Likewise, Rust will happily convert a `Box<File>` to a `Box<dyn Write>`, a value that owns a writer in the heap:

```
let w: Box<dyn Write> = Box::new(local_file);
```

`Box<dyn Write>`, like `&mut dyn Write`, is a fat pointer: it contains the address of the writer itself and the address of the vtable. The same goes for other pointer types, like `Rc<dyn Write>`.

This kind of conversion is the only way to create a `dyn` pointer. What the compiler is actually doing here is very simple. At the point where the conversion happens, Rust knows the referent's true type (in this case, `File`), so it just adds the address of the appropriate vtable, turning the regular pointer into a fat pointer.

## Generic Functions and Type Parameters

At the beginning of this chapter, we showed a `say_hello()` function that took a `dyn` reference as an argument. Let's rewrite that function as a generic function:

```
fn say_hello<W: Write>(out: &mut W) -> std::io::Result<()> {
    out.write_all(b"hello world\n")?;
    out.flush()
}
```

Only the type signature has changed:

```
fn say_hello(out: &mut dyn Write)      // plain function

fn say_hello<W: Write>(out: &mut W)    // generic function
```

The phrase `<W: Write>` is what makes the function generic. This is a *type parameter*. It means that throughout the body of this function, `W` stands for some type that implements the `Write` trait. Type parameters are usually single uppercase letters, by convention.

Which type `W` stands for depends on how the generic function is used:

```
say_hello(&mut local_file)?;  // calls say_hello::<File>
say_hello(&mut bytes)?;       // calls say_hello::<Vec<u8>>
```

When you pass `&mut local_file` to the generic `say_hello()` function, you're calling `say_hello::<File>()`. Rust generates machine code for this function that calls `File::write_all()` and `File::flush()`. When you pass `&mut bytes`, you're calling

`say_hello::<Vec<u8>>()`. Rust generates separate machine code for this version of the function, calling the corresponding `Vec<u8>` methods. This process is called *monomorphization*, and the compiler handles it all automatically.

In both of these function calls, Rust infers the type `W` from the type of the argument. However, you can always spell out the type parameters:

```
say_hello::<File>(&mut local_file)?;
```

This is seldom necessary, because Rust can usually deduce the type parameters by looking at the arguments. Here, the `say_hello` generic function expects a `&mut W` argument, and we're passing it a `&mut File`, so Rust infers that `W = File`. If the generic function you're calling doesn't have any arguments that provide useful clues, you may have to spell it out:

```
// calling a generic method collect<C>() that takes no arguments
let v1 = (0..1000).collect();  // error: can't infer type
let v2 = (0..1000).collect::<Vec<i32>>();  // ok
```

Sometimes we need multiple abilities from a type parameter. For example, if we want to print out the top 10 most common values in a vector, we'll need for those values to be printable:

```
use std::fmt::Debug;

fn top_ten<T: Debug>(values: &Vec<T>) { ... }
```

But this isn't good enough. How are we planning to determine which values are the most common? The usual way is to use the values as keys in a hash table. That means the values need to support the `Hash` and `Eq` operations. The bounds on `T` must include these as well as `Debug`. The syntax for this uses the + sign:

```
use std::fmt::Debug;
use std::hash::Hash;
```

```
fn top_ten<T: Debug + Hash + Eq>(values: &Vec<T>) { ... }
```

Some types implement `Debug`, some implement `Hash`, some support `Eq`, and a few, like `u32` and `String`, implement all three, as shown in Figure 11-2.

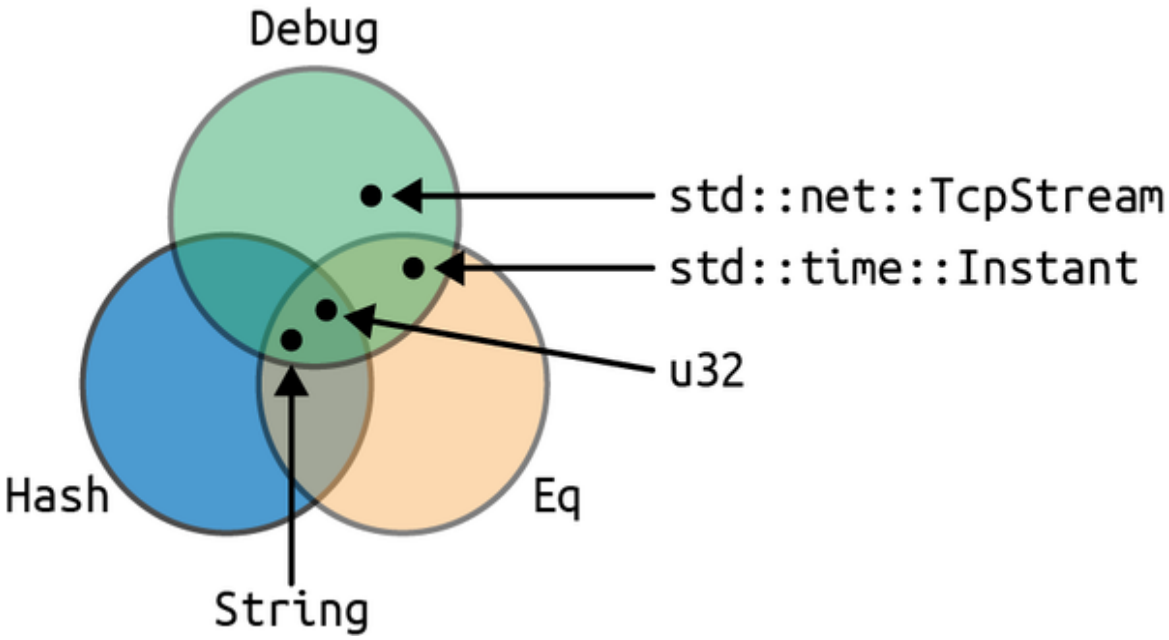


*Figure 11-2. Traits as sets of types*

It's also possible for a type parameter to have no bounds at all, but you can't do much with a value if you haven't specified any bounds for it. You can move it. You can put it into a box or vector. That's about it.

Generic functions can have multiple type parameters:

```
/// Runs a query on a large, partitioned data set.
/// See <http://research.google.com/archive/mapreduce.html>.
fn run_query<M: Mapper + Serialize, R: Reducer + Serialize>(
    data: &DataSet,
    map: M,
    reduce: R,
) -> Results {
    ...
}
```

As this example shows, the bounds can get to be so long that they are hard on the eyes. Rust provides an alternative syntax using the keyword `where`:

```
fn run_query<M, R>(data: &DataSet, map: M, reduce: R) -> Results
where
    M: Mapper + Serialize,
    R: Reducer + Serialize,
{
    ...
}
```

The type parameters `M` and `R` are still declared up front, but the bounds are moved to separate lines. This kind of `where` clause is also allowed on generic structs, enums, type aliases, and methods—anywhere bounds are permitted. Of course, an alternative to `where` clauses is to keep it simple: find a way to write the program without using generics quite so intensively.

"Receiving References as Function Arguments" introduced the syntax for lifetime parameters. A generic function can have both lifetime parameters and type parameters. Lifetime parameters come first:

```
/// Returns a reference to the point in `candidates` that's
/// closest to the `target` point.
fn nearest<'t, 'c, P>(target: &'t P, candidates: &'c [P]) -> &'c
P
where
    P: MeasureDistance,
{
    ...
}
```

This function takes two arguments, `target` and `candidates`. Both are references, and we give them distinct lifetimes `'t` and `'c` (as discussed in "Distinct Lifetime Parameters"). Furthermore, the function works with any type `P` that implements the `MeasureDistance` trait, so we might use it on `Point2d` values in one program and `Point3d` values in another.

Lifetimes never have any impact on machine code. Two calls to `nearest()` using the same type `P`, but different lifetimes, will call the

same compiled function. Only differing types cause Rust to compile multiple copies of a generic function.

In addition to types and lifetimes, generic functions can take constant parameters as well, like the `Polynomial` struct we presented in "Generic Structs with Constant Parameters":

```
fn dot_product<const N: usize>(a: [f64; N], b: [f64; N]) -> f64 {
    let mut sum = 0.;
    for i in 0..N {
        sum += a[i] * b[i];
    }
    sum
}
```

Here, the phrase `<const N: usize>` indicates that the function `dot_product` expects a generic parameter `N`, which must be a `usize`. Given `N`, the function takes two arguments of type `[f64; N]` and adds up the products of their corresponding elements. What distinguishes `N` from an ordinary `usize` argument is that you can use it in the types in `dot_product`'s signature or body.

As with type parameters, you can either provide constant parameters explicitly or let Rust infer them:

```
// Explicitly provide `3` as the value for `N`.
dot_product::<3>([0.2, 0.4, 0.6], [0., 0., 1.])

// Let Rust infer that `N` must be `2`.
dot_product([3., 4.], [-5., 1.])
```

Of course, functions are not the only kind of generic code in Rust:

- We've already covered generic types in "Generic Structs" and "Generic Enums".
- An individual method can be generic, even if the type it's defined on is not generic:

```
impl PancakeStack {
    fn push<T: Topping>(&mut self, goop: T) ->
```

```
        PancakeResult<()> {
                goop.pour(self);
                self.absorb_topping(goop)
            }
        }
```

- Type aliases can be generic, too:
  ```
  type PancakeResult<T> = Result<T, PancakeError>;
  ```

- We'll cover generic traits later in this chapter.

All the features introduced in this section—bounds, `where` clauses, lifetime parameters, and so forth—can be used on all generic items, not just functions.

## Which to Use

The choice of whether to use `dyn` or generics is subtle. Since both features are based on traits, they have a lot in common.

`dyn` is the right choice whenever you need a collection of values of mixed types, all together. It is technically possible to make generic salad:

```
trait Vegetable {
    ...
}

struct Salad<V: Vegetable> {
    veggies: Vec<V>,
}
```

However, this is a rather severe design. Each such salad consists entirely of a single type of vegetable. Not everyone is cut out for this sort of thing. One of your authors once paid $14 for a `Salad<IcebergLettuce>` and has never quite gotten over the experience.

How can we build a better salad? Since `Vegetable` values can be all different sizes, we can't ask Rust for a `Vec<dyn Vegetable>`:

```
struct Salad {
    veggies: Vec<dyn Vegetable>,  // error: size of `dyn
Vegetable` cannot be
                                  // known at compilation time
}
```

The solution is to use a `Box` for each `Vegetable`:

```
struct Salad {
    veggies: Vec<Box<dyn Vegetable>>,
}
```

Each `Box<dyn Vegetable>` can own any type of vegetable, but the box itself has a constant size—two pointers—suitable for storing in a vector. Apart from the unfortunate mixed metaphor of having boxes in one's food, this is precisely what's called for, and it would work out just as well for shapes in a drawing app, monsters in a game, pluggable routing algorithms in a network router, and so on.

Another possible reason to use `dyn` is to reduce the total amount of compiled code. Rust may have to compile a generic function many times, once for each type it's used with. This could make the binary large, a phenomenon called *code bloat* in C++ circles. These days, memory is plentiful, and most of us have the luxury of ignoring code size; but constrained environments do exist.

Outside of situations involving salad or low-resource environments, generics have three important advantages over trait objects, with the result that in Rust, generics are the more common choice.

The first advantage is speed. A `dyn` method call typically consults a vtable, so it's at least a few CPU cycles slower than an ordinary function call. With generics, by contrast, the Rust compiler knows all the types when it generates code. It knows exactly which method will be called, so there is no need to look at a vtable at run time. This shaves a few cycles off every call, and importantly, it unlocks further compiler optimizations.

For instance, the generic `min()` function shown in the introduction is just as fast as if we had written separate functions `min_u8`, `min_i64`, `min_string`, and so on. The compiler can inline it, like any other function, so in a release build, a call to `min::<i32>` is likely just two or three instructions. A call with constant arguments, like `min(5, 3)`, will be even faster: Rust can evaluate it at compile time so that there's no run-time cost at all.

Or consider this generic function call:

```
let mut sink = std::io::sink();
say_hello(&mut sink)?;
```

`std::io::sink()` returns a writer of type `Sink` that quietly discards all bytes written to it.

When Rust generates machine code for this, it could emit code that calls `Sink::write_all`, checks for errors, and then calls `Sink::flush`. That's what the body of the generic function says to do.

Or, Rust could look at the code for those methods and realize the following:

- `Sink::write_all()` does nothing.
- `Sink::flush()` does nothing.
- Neither method ever returns an error.

In short, Rust has all the information it needs to optimize away this function call entirely. Compare that to the behavior with `dyn` references. Rust never knows what type of value a `dyn` reference points to until run time. So even if you pass a `Sink`, the overhead of calling virtual methods and checking for errors still applies.

The second advantage of generics is that not every trait is `dyn` compatible. Traits support several features, such as associated functions, that work only with generics: they rule out `dyn` references entirely. We'll point out these features as we come to them.

The third advantage of generics is that it's easy to bound a generic type parameter with several traits at once, as our `top_ten` function did when it required its `T` parameter to implement `Debug + Hash + Eq`. Unfortunately, `dyn` references can't do this: types like `&mut (dyn Debug + Hash + Eq)` aren't supported in Rust. (You can work around this with subtraits, defined later in this chapter, but it's a bit involved.)

## Defining and Implementing Traits

Defining a trait is simple. Give it a name and list the type signatures of the trait methods. If we're writing a game, we might have a trait like this:

```
/// A trait for characters, items, and scenery -
/// anything in the game world that's visible on screen.
trait Visible {
    /// Renders this object on the given canvas.
    fn draw(&self, canvas: &mut Canvas);

    /// Returns true if clicking at (x, y) should
    /// select this object.
    fn hit_test(&self, x: i32, y: i32) -> bool;
}
```

To implement a trait, use the syntax `impl TraitName for Type`:

```
impl Visible for Broom {
    fn draw(&self, canvas: &mut Canvas) {
        for y in self.y - self.height - 1..self.y {
            canvas.write_at(self.x, y, '|');
        }
        canvas.write_at(self.x, self.y, 'M');
    }

    fn hit_test(&self, x: i32, y: i32) -> bool {
        self.x == x
        && self.y - self.height - 1 <= y
        && y <= self.y
    }
}
```

Note that this `impl` contains an implementation for each method of the `Visible` trait, and nothing else. Everything defined in a trait `impl` must actually be a feature of the trait; if we wanted to add a helper method in support of `Broom::draw()`, we would have to define it in a separate `impl` block:

```
impl Broom {
    /// Helper function used by Broom::draw() below.
    fn broomstick_range(&self) -> Range<i32> {
        self.y - self.height - 1..self.y
    }
}
```

These helper functions can be used within the trait `impl` blocks:

```
impl Visible for Broom {
    fn draw(&self, canvas: &mut Canvas) {
        for y in self.broomstick_range() {
            ...
        }
        ...
    }
    ...
}
```

## Default Methods

The `Sink` writer type we discussed earlier can be implemented in a few lines of code. First, we define the type:

```
/// A Writer that ignores whatever data you write to it.
pub struct Sink;
```

`Sink` is an empty struct, since we don't need to store any data in it. Next, we provide an implementation of the `Write` trait for `Sink`:

```
use std::io::{Result, Write};

impl Write for Sink {
    fn write(&mut self, buf: &[u8]) -> Result<usize> {
```

```
        // Claim to have successfully written the whole buffer.
        Ok(buf.len())
    }

    fn flush(&mut self) -> Result<()> {
        Ok(())
    }
}
```

So far, this is very much like the `Visible` trait. But we have also seen that the `Write` trait has a `write_all` method:

```
let mut out = Sink;
out.write_all(b"hello world\n")?;
```

Why does Rust let us `impl Write for Sink` without defining this method? The answer is that the standard library's definition of the `Write` trait contains a *default implementation* for `write_all`:

```
trait Write {
    fn write(&mut self, buf: &[u8]) -> Result<usize>;
    fn flush(&mut self) -> Result<()>;

    fn write_all(&mut self, buf: &[u8]) -> Result<()> {
        let mut bytes_written = 0;
        while bytes_written < buf.len() {
            bytes_written += self.write(&buf[bytes_written..])?;
        }
        Ok(())
    }

    ...
}
```

The `write` and `flush` methods are the basic methods that every writer must implement. A writer may also implement `write_all`, but if not, the default implementation shown earlier will be used. Your own traits can include default implementations using the same syntax. The most dramatic use of default methods in the standard library is the `Iterator` trait, which

has one required method (`.next()`) and dozens of default methods. Chapter 15 explains why.

## Traits and Other People's Types

Rust lets you implement any trait on any type, as long as either the trait or the type is introduced in the current crate.

This means that any time you want to add a method to any type, you can use a trait to do it:

```
trait IsEmoji {
    fn is_emoji(&self) -> bool;
}

/// Implement IsEmoji for the built-in character type.
impl IsEmoji for char {
    fn is_emoji(&self) -> bool {
        ...
    }
}

assert_eq!('$'.is_emoji(), false);
```

Like any other trait method, this new `is_emoji` method is visible only when `IsEmoji` is in scope.

The sole purpose of this particular trait is to add a method to an existing type, `char`. This is called an *extension trait*. Of course, you can add this trait to other types, too, by writing `impl IsEmoji for str { ... }` and so forth.

You can even use a generic `impl` block to add an extension trait to a whole family of types at once. This trait could be implemented on any type:

```
use std::io::{self, Write};

/// Trait for values to which you can send HTML.
trait WriteHtml {
    fn write_html(&mut self, html: &HtmlDocument) ->
```

```
io::Result<()>;
}
```

Implementing the trait for all writers makes it an extension trait, adding a method to all Rust writers:

```
/// You can write HTML to any std::io writer.
impl<W: Write> WriteHtml for W {
    fn write_html(&mut self, html: &HtmlDocument) ->
io::Result<()> {
        ...
    }
}
```

The line `impl<W: Write> WriteHtml for W` means "for every type `W` that implements `Write`, here's an implementation of `WriteHtml` for `W`."

The `serde` library offers a nice example of how useful it can be to implement user-defined traits on standard types. `serde` is a serialization library. That is, you can use it to write Rust data structures to disk and reload them later.

The library defines a trait, `Serialize`, that's implemented for every data type the library supports. So in the `serde` source code, there is code implementing `Serialize` for `bool`, `i8`, `i16`, `i32`, array and tuple types, and so on, through all the standard data structures like `Vec` and `HashMap`.

The upshot of all this is that `serde` adds a `.serialize()` method to all these types. It can be used like this:

```
use serde::Serialize;

pub fn save_configuration(
    config: &HashMap<String, String>,
) -> std::io::Result<()> {
    // Create a JSON serializer to write the data to a file.
    let writer = File::create(config_filename())?;
    let mut serializer = serde_json::Serializer::new(writer);
```

```
    // The serde `.serialize()` method does the rest.
    config.serialize(&mut serializer)?;

    Ok(())
}
```

We said earlier that when you implement a trait, either the trait or the type must be new in the current crate. This is called the *orphan rule*. It helps Rust ensure that trait implementations are unique. Your code can't `impl Write for u8`, because both `Write` and `u8` are defined in the standard library. If Rust let crates do that, there could be multiple implementations of `Write` for `u8`, in different crates, and Rust would have no reasonable way to decide which implementation to use for a given method call.

(C++ has a similar uniqueness restriction: the One Definition Rule. In typical C++ fashion, it isn't enforced by the compiler, except in the simplest cases, and you get undefined behavior if you break it.)

## Self in Traits

A trait can use the keyword `Self` as a type. The standard `Clone` trait, for example, looks like this (slightly simplified):

```
pub trait Clone {
    fn clone(&self) -> Self;
    ...
}
```

Using `Self` as the return type here means that the type of `x.clone()` is the same as the type of `x`, whatever that might be. If `x` is a `String`, then the type of `x.clone()` is `String`—not `dyn Clone` or any other cloneable type.

Likewise, if we define this trait:

```
pub trait Spliceable {
    fn splice(&self, other: &Self) -> Self;
}
```

with two implementations:

```
impl Spliceable for CherryTree {
    fn splice(&self, other: &Self) -> Self {
        ...
    }
}

impl Spliceable for Mammoth {
    fn splice(&self, other: &Self) -> Self {
        ...
    }
}
```

then inside the first `impl`, `Self` is simply an alias for `CherryTree`, and in the second, it's an alias for `Mammoth`. This means that we can splice together two cherry trees or two mammoths, not that we can create a mammoth-cherry hybrid. The type of `self` and the type of `other` must match.

A trait that uses the `Self` type is not `dyn` compatible:

```
// error: the trait `Spliceable` is not dyn compatible
fn splice_anything(left: &dyn Spliceable, right: &dyn Spliceable)
{
    let combo = left.splice(right);
    // ...
}
```

The reason is something we'll see again and again as we dig into the advanced features of traits. Rust rejects this code because it has no way to type-check the call `left.splice(right)`. The whole point of `dyn` is that the type isn't known until run time. Rust has no way to know at compile time if `left` and `right` will be the same type, as required.

`dyn` references are really intended for the simplest traits, the kind that could be implemented using interfaces in Java or abstract base classes in C++. The more advanced features of traits are useful, but they can't coexist with `dyn` references because with `dyn`, you lose the type information Rust needs to type-check your program.

Now, had we wanted genetically improbable splicing, we could have written:

```
pub trait MegaSpliceable {
    fn splice(&self, other: &dyn MegaSpliceable) -> Box<dyn
MegaSpliceable>;
}
```

This trait is `dyn` compatible. There's no problem type-checking calls to this `.splice()` method because the type of the argument `other` is not required to match the type of `self`, as long as both types are `MegaSpliceable`.

## Subtraits

We can declare that a trait is an extension of another trait:

```
/// Someone in the game world, either the player or some other
/// pixie, gargoyle, squirrel, ogre, etc.
trait Creature: Visible {
    fn position(&self) -> (i32, i32);
    fn facing(&self) -> Direction;
    ...
}
```

The phrase `trait Creature: Visible` means that all creatures are visible. Every type that implements `Creature` must also implement the `Visible` trait:

```
impl Visible for Broom {
    ...
}

impl Creature for Broom {
    ...
}
```

We can implement the two traits in either order, but it's an error to implement `Creature` for a type without also implementing `Visible`.

Here, we say that `Creature` is a *subtrait* of `Visible` and that `Visible` is `Creature`'s *supertrait*.

Subtraits resemble subinterfaces in Java or C#, in that users can assume that any value that implements a subtrait implements its supertrait as well. But in Rust, a subtrait does not inherit the associated items of its supertrait; each trait still needs to be in scope if you want to call its methods.

In fact, Rust's subtraits are really just a shorthand for a bound on `Self`. A definition of `Creature` like this is exactly equivalent to the one shown earlier:

```
trait Creature
where
    Self: Visible,
{
    ...
}
```

## Associated Functions

In most object-oriented languages, interfaces can't include static methods or constructors, but Rust traits are more flexible:

```
trait StringSet {
    /// Returns a new empty set.
    fn new() -> Self;

    /// Returns a set that contains all the strings in `strings`.
    fn from_slice(strings: &[&str]) -> Self;

    /// Returns `true` if this set contains a particular `value`.
    fn contains(&self, string: &str) -> bool;

    /// Adds a string to this set.
    fn add(&mut self, string: &str);
}
```

Every type that implements the `StringSet` trait must implement these four associated functions. The first two, `new()` and `from_slice()`, don't take a `self` argument. They serve as constructors. In nongeneric

code, these functions can be called using `::` syntax, just like any other associated function:

```
// Create sets of two hypothetical types that impl StringSet:
let set1 = SortedStringSet::new();
let set2 = HashedStringSet::new();
```

In generic code, it's the same, except the type is often a type variable, as in the call to `S::new()` shown here:

```
/// Returns the set of words in `document` that aren't in
`wordlist`.
fn unknown_words<S: StringSet>(document: &[String], wordlist: &S)
-> S {
    let mut unknowns = S::new();
    for word in document {
        if !wordlist.contains(word) {
            unknowns.add(word);
        }
    }
    unknowns
}
```

Associated functions that don't take `self` by reference are not `dyn` compatible. If you want to use `&dyn StringSet` references, you must change the trait, adding the bound `where Self: Sized` to the two constructors:

```
trait StringSet {
    fn new() -> Self
    where
        Self: Sized;

    fn from_slice(strings: &[&str]) -> Self
    where
        Self: Sized;

    fn contains(&self, string: &str) -> bool;

    fn add(&mut self, string: &str);
}
```

This bound tells Rust that trait objects are excused from supporting this particular associated function. With these additions, `&dyn StringSet` references are allowed. They don't support `new` or `from_slice`, but you can create them and use them to call `.contains()` and `.add()`. The same trick works for any other associated function that isn't `dyn` compatible. (We will forgo the rather tedious technical explanation of why this works, but the `Sized` trait is covered in Chapter 13.)

## Associated Constants

Like structs and enums, traits can have associated constants. These are declared with the usual `const` syntax, but typically without assigning a value:

```
trait Float {
    const ZERO: Self;
    const ONE: Self;
}
```

The value of the constant is then provided by each `impl`:

```
impl Float for f32 {
    const ZERO: f32 = 0.0;
    const ONE: f32 = 1.0;
}

impl Float for f64 {
    const ZERO: f64 = 0.0;
    const ONE: f64 = 1.0;
}
```

This allows you to write generic code that uses these values:

```
/// Returns `1/x`, or `None` if that would divide by zero.
fn checked_inverse<T>(x: T) -> Option<T>
where
    T: Float + PartialEq + Div<Output = T>,
{
    if x == T::ZERO {
        None
```

```
        } else {
            Some(T::ONE / x)
        }
    }
```

If the trait itself does provide a value for the constant, it's the default value. Implementations can then omit the `const` to use the default value. Associated constants aren't `dyn` compatible.

## Fully Qualified Method Calls

All the ways for calling trait methods we've seen so far rely on Rust filling in some missing pieces for you. For example, suppose you write the following:

```
"hello".to_string()
```

It's understood that `to_string` refers to the `to_string` method of the `ToString` trait, of which we're calling the `str` type's implementation. So there are four players in this game: the trait, the method of that trait, the implementation of that method, and the value to which that implementation is being applied. It's great that we don't have to spell all that out every time we want to call a method. But in some cases you need a way to say exactly what you mean. Fully qualified method calls fit the bill.

First of all, it helps to know that a method is just a special kind of function. These two calls are equivalent:

```
"hello".to_string()

str::to_string("hello")
```

The second form looks exactly like an associated function call. This works even though the `to_string` method takes a `self` argument. Simply pass `self` as the function's first argument.

Since `to_string` is a method of the standard `ToString` trait, there are two more forms you can use:

```
ToString::to_string("hello")

<str as ToString>::to_string("hello")
```

All four of these method calls do exactly the same thing. Most often, you'll just write `value.method()`. The other forms are *qualified* method calls. They specify the type or trait that a method is associated with. The last form, with the angle brackets, specifies both: a *fully qualified* method call.

When you write `"hello".to_string()`, using the `.` operator, you don't say exactly which `to_string` method you're calling. Rust has a method lookup algorithm that figures this out, depending on the types, deref coercions, and so on. With fully qualified calls, you can say exactly which method you mean, and that can help in a few odd cases:

- When two methods have the same name. The classic hokey example is the `Outlaw` with two `.draw()` methods from two different traits, one for drawing it on the screen and one for interacting with the law:

  ```
  outlaw.draw();  // error: draw on screen or draw pistol?

  Visible::draw(&outlaw);  // ok: draw on screen
  HasPistol::draw(&outlaw);  // ok: corral
  ```

  Usually you're better off renaming one of the methods, but sometimes you can't.

- When the type of the `self` argument can't be inferred:

  ```
  let zero = 0;  // type unspecified; could be `i8`, `u8`,
  ...

  zero.abs();  // error: can't call method `abs`
               // on ambiguous numeric type

  i64::abs(zero);  // ok
  ```

- When using the function itself as a function value:

```
let words: Vec<String> =
    line.split_whitespace()  // iterator produces &str
values
        .map(ToString::to_string)  // ok
        .collect();
```

- When calling trait methods in macros. We'll explain in Chapter 22.

Fully qualified syntax also works for associated functions. In the previous section, we wrote `S::new()` to create a new set in a generic function. We could also have written `StringSet::new()` or `<S as StringSet>::new()`.

## Traits That Define Relationships Between Types

So far, every trait we've looked at stands alone: a trait is a set of methods that types can implement. Traits can also be used in situations where there are multiple types that have to work together. They can describe relationships between types:

- The `std::iter::Iterator` trait relates each iterator type with the type of value it produces.
- The `std::ops::Mul` trait relates types that can be multiplied. In the expression `a * b`, the values `a` and `b` can be either the same type or different types.
- The `rand` crate includes both a trait for random number generators (`rand::Rng`) and a trait for types that can be randomly generated (`rand::Distribution`). The traits themselves define exactly how these types work together.

You won't need to create traits like these every day, but you'll come across them throughout the standard library and in third-party crates. In this section, we'll show how each of these examples is implemented, picking up

relevant Rust language features as we need them. The key skill here is the ability to read traits and method signatures and figure out what they say about the types involved.

## Associated Types (or How Iterators Work)

We'll start with iterators. By now every object-oriented language has some sort of built-in support for iterators, objects that represent the traversal of some sequence of values.

Rust has a standard `Iterator` trait, defined like this:

```
pub trait Iterator {
    type Item;

    fn next(&mut self) -> Option<Self::Item>;
    ...
}
```

The first feature of this trait, `type Item;`, is an *associated type*. Each type that implements `Iterator` must specify what type of item it produces.

The second feature, the `next()` method, uses the associated type in its return value. `next()` returns an `Option<Self::Item>`: either `Some(item)`, the next value in the sequence, or `None` when there are no more values to visit. The type is written as `Self::Item`, not just plain `Item`, because `Item` is a feature of each type of iterator, not a standalone type. As always, `self` and the `Self` type show up explicitly in the code everywhere their fields, methods, and so on are used.

Here's what it looks like to implement `Iterator` for a type:

```
// (code from the std::env standard library module)
impl Iterator for Args {
    type Item = String;

    fn next(&mut self) -> Option<String> {
        ...
```

```
    }
    ...
}
```

`std::env::Args` is the type of iterator returned by the standard library function `std::env::args()` that we used in Chapter 2 to access command-line arguments. It produces `String` values, so the `impl` declares `type Item = String;`.

Generic code can use associated types:

```
/// Loops over an iterator, storing the values in a new vector.
fn collect_into_vector<I: Iterator>(iter: I) -> Vec<I::Item> {
    let mut results = Vec::new();
    for value in iter {
        results.push(value);
    }
    results
}
```

Inside the body of this function, Rust infers the type of `value` for us, which is nice; but we must spell out the return type of `collect_into_vector`, and the `Item` associated type is the only way to do that. (`Vec<I>` would be simply wrong: we would be claiming to return a vector of iterators!)

The preceding example is not code that you would write out yourself, because after reading Chapter 15, you'll know that iterators already have a standard method that does this: `iter.collect()`. So let's look at one more example before moving on:

```
/// Prints out all the values produced by an iterator.
fn dump<I>(iter: I)
where
    I: Iterator,
{
    for (index, value) in iter.enumerate() {
        println!("{index}: {value:?}");   // error
    }
}
```

This almost works. There is just one problem: `value` might not be a printable type.

```
error: `<I as Iterator>::Item` doesn't implement `Debug`
  |
8 |         println!("{index}: {value:?}");   // error
  |                            ^^^^^^^^^
  |                   `<I as Iterator>::Item` cannot be formatted
using `{:?}`
  |                   because it doesn't implement `Debug`
  |
  = help: the trait `Debug` is not implemented for `<I as
Iterator>::Item`
help: consider further restricting the associated type
  |
5 |     where I: Iterator, <I as Iterator>::Item: Debug
  |                        ^^^^^^^^^^^^^^^^^^^^^^^^^^^^
```

The error message is slightly obfuscated by Rust's use of the syntax `<I as Iterator>::Item`, which is an explicit but verbose way of saying `I::Item`. This is valid Rust syntax, but you'll rarely actually need to write a type out that way.

The gist of the error message is that to make this generic function compile, we must ensure that `I::Item` implements the `Debug` trait, the trait for formatting values with `{:?}`. As the error message suggests, we can do this by placing a bound on `I::Item`:

```
use std::fmt::Debug;

fn dump<I>(iter: I)
where
    I: Iterator,
    I::Item: Debug,
{
    ...
}
```

Or, we could write, "`I` must be an iterator over `String` values":

```
fn dump<I>(iter: I)
where
    I: Iterator<Item = String>,
{
    ...
}
```

`Iterator<Item = String>` is itself a trait. If you think of `Iterator` as the set of all iterator types, then `Iterator<Item = String>` is a subset of `Iterator`: the set of iterator types that produce `String`s. This syntax can be used anywhere the name of a trait can be used, including `dyn` types:

```
fn dump(iter: &mut dyn Iterator<Item = String>) {
    for (index, s) in iter.enumerate() {
        println!("{index}: {s:?}");
    }
}
```

Traits with associated types, like `Iterator`, are `dyn` compatible, but only if all the associated types are spelled out, as shown here. Otherwise, the type of `s` could be anything, and again, Rust would have no way to type-check this code.

We've shown a lot of examples involving iterators. It's hard not to; they're by far the most prominent use of associated types. But associated types are generally useful whenever a trait needs to cover more than just methods:

- In a thread pool library, a `Task` trait, representing a unit of work, could have an associated `Output` type.
- A `Pattern` trait, representing a way of searching a string, could have an associated `Match` type, representing all the information gathered by matching the pattern to the string:

```
trait Pattern {
    type Match;

    fn search(&self, string: &str) ->
Option<Self::Match>;
}
```

```
/// You can search a string for a particular character.
impl Pattern for char {
    /// A "match" is just the location where the
    /// character was found.
    type Match = usize;

    fn search(&self, string: &str) -> Option<usize> {
        ...
    }
}
```

If you're familiar with regular expressions, it's easy to see how `impl Pattern for RegExp` would have a more elaborate `Match` type, probably a struct that would include the start and length of the match, the locations where parenthesized groups matched, and so on.

- A library working with relational databases might have a `DatabaseConnection` trait with associated types representing transactions, cursors, prepared statements, and so on.

Associated types are perfect for cases where each implementation has *one* specific related type: each type of `Task` produces a particular type of `Output`; each type of `Pattern` looks for a particular type of `Match`. However, as we'll see, some relationships among types are not like this.

## Generic Traits (or How Operator Overloading Works)

Multiplication in Rust uses this trait:

```
/// std::ops::Mul, the trait for types that support `*`.
pub trait Mul<RHS> {
    /// The resulting type after applying the `*` operator
    type Output;

    /// The method for the `*` operator
    fn mul(self, rhs: RHS) -> Self::Output;
}
```

`Mul` is a generic trait. The type parameter, `RHS`, is short for *righthand side*.

The type parameter here means the same thing that it means on a struct or function: `Mul` is a generic trait, and its instances `Mul<f64>`, `Mul<String>`, `Mul<Size>`, etc., are all different traits, just as `min::<i32>` and `min::<String>` are different functions and `Vec<i32>` and `Vec<String>` are different types.

A single type—say, `WindowSize`—can implement both `Mul<f64>` and `Mul<i32>`, and many more. You would then be able to multiply a `WindowSize` by many other types. Each implementation would have its own associated `Output` type.

Generic traits get a special dispensation when it comes to the orphan rule: you can implement a foreign trait for a foreign type, so long as one of the trait's type parameters is a type defined in the current crate. So, if you've defined `WindowSize` yourself, you can implement `Mul<WindowSize>` for `f64`, even though you didn't define either `Mul` or `f64`.

These implementations can even be generic, such as `impl<T> Mul<WindowSize> for Vec<T>`. This works because there's no way any other crate could define `Mul<WindowSize>` on anything and thus no way a conflict among implementations could arise. (We introduced the orphan rule back in "Traits and Other People's Types".) This is how crates like `nalgebra` define arithmetic operations on vectors.

The trait shown earlier is missing one minor detail. The real `Mul` trait looks like this:

```
pub trait Mul<RHS = Self> {
    ...
}
```

The syntax `RHS = Self` means that `RHS` defaults to `Self`. If I write `impl Mul for Complex`, without specifying `Mul`'s type parameter, it means `impl Mul<Complex> for Complex`. In a bound, if I write `where T: Mul`, it means `where T: Mul<T>`. In Rust, the expression

`lhs * rhs` is shorthand for `Mul::mul(lhs, rhs)`. So overloading the `*` operator in Rust is as simple as implementing the `Mul` trait. We'll show examples in the next chapter.

In the previous two sections, we've shown different ways traits can describe relationships between types. All of these can also be seen as ways of avoiding virtual method overhead and downcasts, since they allow Rust to know more concrete types at compile time.

## impl Trait

Some Rust libraries get a lot of mileage out of generics, letting users piece together custom-built types just by calling a few methods. For example, consider this expression using Rust iterators:

```
web.into_iter().chain(db).cycle()
```

Suppose `web` and `db` are two vectors of `Users`, representing two teams of engineers. This expression creates an iterator over the members of the web team and then calls `.chain(db)` to create a second interator that concatenates the web and db team members together. The call to `.cycle()` creates a final iterator that repeats all the `Users` in a cycle, endlessly.

What is the type of this iterator?

It does have a type that you can write out, but it's not pretty. If you want to put this code in a function, you'll have to write something like this:

```
use std::iter::{Chain, Cycle};
use std::vec::IntoIter;

fn rotation(
    web: Vec<User>,
    db: Vec<User>,
) -> Cycle<Chain<IntoIter<User>, IntoIter<User>>> {
    web.into_iter().chain(db).cycle()
}
```

The return type we had to write here is longer than the whole body of the function, and it seems to have captured the full history of all the iterators we built along the way.

A function's type signature isn't meant to reveal so much detail about the implementation. What we want to say here is simply, "This function returns an iterator over `Users`." We could say that using `dyn`:

```
fn rotation(
    web: Vec<User>,
    db: Vec<User>,
) -> Box<dyn Iterator<Item = User>> {
    Box::new(web.into_iter().chain(db).cycle())
}
```

But it would be nice to avoid the run-time overhead of `Box` and `dyn`. Rust has a feature called `impl Trait` that lets us do just that.

With `impl Trait`, we can "erase" the type of a return value, specifying only the trait or traits it implements:

```
fn rotation(web: Vec<User>, db: Vec<User>) -> impl Iterator<Item
= User> {
    web.into_iter().chain(db).cycle()
}
```

Now, rather than specifying a particular nested type of iterator combinator structs, `rotation`'s signature just states that it returns some kind of iterator over `User` values. We could change the actual type of the iterator being returned in the future, as long as it still implements `Iterator<Item = User>`, and any code calling the function will continue to compile without an issue. Only the relevant functionality is encoded in the type signature.

In fact, only that functionality is available to the caller. `impl Trait` hides everything else. For example, even though this function creates an iterator that supports the `Clone` and `Debug` traits, callers can't make use of those traits, because the return type doesn't include them. We could make the

return type `impl Iterator<Item = User> + Clone + Debug` to enable these extra features.

It might be tempting to use `impl Trait` to approximate a statically dispatched version of the factory pattern that's commonly used in object-oriented languages. For example, you might define a trait like this:

```
trait Shape {
    fn perimeter(&self) -> f64;
    fn area(&self) -> f64;
}
```

After implementing it for a few types, you might want to use different `Shapes` depending on a run-time value, like a string that a user enters. This doesn't work with `impl Shape` as the return type:

```
fn make_shape(shape: &str) -> impl Shape {
    match shape {
        "circle" => Circle::new(),
        "triangle" => Triangle::new(),  // error: incompatible
types
        "rectangle" => Rectangle::new(),
        ...
    }
}
```

This error highlights the difference between `impl Trait` and `dyn Trait`. We've seen that `dyn Shape` means "any type that supports the `Shape` trait." By contrast, `impl Shape` means "some particular type that supports the `Shape` trait (but we're not saying which one)." Type inference must be able to determine the type. It can be `Circle`, `Triangle`, or `Rectangle`, but it can't be all three for the same function.

`impl Trait` can also be used in function arguments. For example:

```
fn print(val: impl Display) {
    println!("{val}");
}
```

Each place this function is called, type inference will determine the type of `val` based on the argument passed. It's a generic function, essentially the same as this one:

```
fn print<T: Display>(val: T) {
    println!("{val}");
}
```

The only difference is that when a function has an explicit type parameter, the caller may specify it using turbofish syntax: `print::<i32>(42)`. That doesn't work with `impl Trait` arguments.

Each `impl Trait` argument is assigned its own anonymous type parameter, so `impl Trait` for arguments is limited to only the simplest generic functions, with no relationships between the types of arguments.

## Lifetime Bounds

So far, we have mostly ignored the fact that types can have lifetimes—expiration dates, past which you're not allowed to use the type at all. We first mentioned this in "Structs Containing References".

Occasionally it's necessary to restrict the lifetime of a type parameter, using a *lifetime bound*. The bound `T: 'lifetime` means "the type `T` lives at least as long as `'lifetime`." For example, consider this function signature:

```
/// Starts analyzing the given `data` in the background and
returns
/// a `ProcessingJob` that can monitor progress and get results.
fn start_processing<D>(data: D) -> ProcessingJob
where
    D: DataSource + 'static,
```

The last line says that the type `D` must implement the `DataSource` trait and must have the `'static` lifetime. The `data` argument can't be a reference to a local variable, for example.

The function might need this `'static` lifetime bound because it's going to use the data source in a background worker thread. Rust's `std::thread::spawn()` function won't let you pass short-lived data to potentially long-running spawned threads, as we'll see in Chapter 19.

Rust also supports adding lifetime bounds to `dyn Trait` and `impl Trait`:

```
/// Returns an iterator over just the even numbers in `nums`.
fn evens<'slice>(nums: &'slice [i32]) -> Box<dyn Iterator<Item =
i32> + 'slice> {
    ...
}

/// Returns an iterator over just the odd numbers in `nums`.
fn odds<'slice>(nums: &'slice [i32]) -> impl Iterator<Item = i32>
+ 'slice {
    ...
}
```

Here the type `dyn Iterator<Item = i32> + 'slice` means "an `Iterator` value with `i32` items that lives at least as long as `'slice`." The caller won't be allowed to use that iterator after the reference `nums` is expired.

The type `impl Iterator<Item = i32> + 'slice` means much the same thing, but avoiding `Box` and `dyn` overhead.

What would it mean if these functions used a `'static` bound on the return types instead of `'slice`? They would be promising to return iterators that can be kept around as long as the caller wants them, even after the borrowed reference `nums` expires. The caller might find that useful in some cases, like for sending the iterator to another thread, but it would be bad for performance: the only way to return such an iterator is by copying all the data.

It's common to omit the lifetime parameter `<'slice>` in function signatures like these:

```
fn evens(nums: &[i32]) -> Box<dyn Iterator<Item = i32> + '_>

fn odds(nums: &[i32]) -> impl Iterator<Item = i32> + '_
```

The placeholder lifetime `'_` in these functions' return types is inferred to mean the lifetime of the reference `nums`.

## use Bounds

You may see the syntax `impl Trait + use<>`. This is called a *use bound*, and it solves a specific problem with `impl Trait` return types.

Suppose we have this generic function:

```
fn process_query<'q, 'd, D: DataSource>(
    query: &'q str,
    data: &'d D,
) -> impl RecordSet
```

This function takes a reference to any type of `DataSource`. It always returns some value implementing the trait `RecordSet`. We can imagine using the function like this:

```
let query = query_constraints.to_string();
return process_query(&query, &self.data_source);
```

However, we might encounter lifetime errors doing this. The return type `impl RecordSet` tells us what trait the return type supports, but it doesn't say anything about its lifetime. In particular, it doesn't say that the return value can outlive the query string, as it does when this code returns and `query` goes out of scope.

If the function's declared return type were `Vec<Vec<String>>`, there wouldn't be a problem. Clearly that type does not contain a short-lived reference back to the original query string. It contains no lifetimes at all. Callers can keep it around for however long they need it.

If we were to change the return type to `impl RecordSet + 'static`, then, again, callers would be in good shape. The `'static` bound promises that whatever type the function returns, it has no expiration date attached.

If adding `'static` works, we're done. But it's fairly likely that the actual return value of this function would contain a reference to the data source. That means its lifetime cannot exceed `'d`. The strong promise of a `'static` bound would make callers happy, but the function body might not be able to keep that promise!

The fix is to add a `use` bound:

```
fn process_query<'q, 'd, D: DataSource>(
    query: &'q str,
    data: &'d D,
) -> impl RecordSet + use<'d, D>
```

The meaning of `use<'d, D>` is "this return type may use `'d` and `D`, but not `'q`." This rules out types that contain a field of type `&'q str`, while allowing types that contain a `&'d D` reference to the data source.

So, the actual return type could be something like `Vec<Vec<String>>`, or perhaps `SqlRecordSet<'d, D>`, but nothing that contains `'q`.

## Reverse-Engineering Bounds

Writing generic code can be a real slog when there's no single trait that does everything you need. Suppose we have written this nongeneric function to do some computation:

```
fn dot(v1: &[i64], v2: &[i64]) -> i64 {
    let mut total = 0;
    for i in 0..v1.len() {
        total = total + v1[i] * v2[i];
    }
    total
}
```

Now we want to use the same code with floating-point values. We might try something like this:

```
fn dot<N>(v1: &[N], v2: &[N]) -> N {
    let mut total: N = 0;
    for i in 0..v1.len() {
        total = total + v1[i] * v2[i];
    }
    total
}
```

No such luck: Rust complains about the use of `*` and the type of `0`. We can require `N` to be a type that supports `+` and `*` using the `Add` and `Mul` traits. Our use of `0` needs to change, though, because `0` is always an integer in Rust; the corresponding floating-point value is `0.0`. Fortunately, there is a standard `Default` trait for types that have default values. For numeric types, the default is always 0:

```
use std::ops::{Add, Mul};

fn dot<N: Add + Mul + Default>(v1: &[N], v2: &[N]) -> N {
    let mut total = N::default();
    for i in 0..v1.len() {
        total = total + v1[i] * v2[i];
    }
    total
}
```

This is closer, but still does not quite work:

```
error: mismatched types
  |
5 | fn dot<N: Add + Mul + Default>(v1: &[N], v2: &[N]) -> N {
  |        - expected this type parameter
...
8 |         total = total + v1[i] * v2[i];
  |                 -----   ^^^^^^^^^^^^^^ expected type parameter
`N`,
  |                 |                      found associated type
  |                 expected because this is `N`
  |
  = note: expected type parameter `N`
```

```
            found associated type `<N as Mul>::Output`
help: consider further restricting this bound
  |
5 | fn dot<N: Add + Mul<Output = N> + Default>(v1: &[N], v2: &
[N]) -> N {
  |                      ++++++++++++
```

Our new code assumes that multiplying two values of type `N` produces another value of type `N`. This isn't necessarily the case. You can overload the multiplication operator to return whatever type you want. We need to somehow tell Rust that this generic function works only with types that have the normal flavor of multiplication, where multiplying `N * N` returns an `N`. The suggestion in the error message is *almost* right: we can do this by replacing `Mul` with `Mul<Output = N>`, and the same for `Add`:

```
fn dot<N: Add<Output = N> + Mul<Output = N> + Default>(v1: &[N],
v2: &[N]) -> N {
    ...
}
```

At this point, the bounds are starting to pile up, making the code hard to read. Let's move the bounds into a `where` clause:

```
fn dot<N>(v1: &[N], v2: &[N]) -> N
where
    N: Add<Output = N> + Mul<Output = N> + Default,
{
    ...
}
```

Great. But Rust still complains about this line of code:

```
error: cannot move out of type `[N]`, a non-copy slice
  |
8 |         total = total + v1[i] * v2[i];
  |                         ^^^^^
  |                         |
  |                         cannot move out of here
  |                         move occurs because `v1[_]` has type
`N`,
```

```
  |                         which does not implement the `Copy`
trait
```

Since we haven't required `N` to be a copyable type, Rust interprets `v1[i]` as an attempt to move a value out of the slice, which is forbidden. But we don't want to modify the slice at all; we just want to copy the values out to operate on them. Fortunately, all of Rust's built-in numeric types implement `Copy`, so we can simply add that to our constraints on N:

```
where
    N: Add<Output = N> + Mul<Output = N> + Default + Copy,
```

With this, the code compiles and runs. The final code looks like this:

```
use std::ops::{Add, Mul};

fn dot<N>(v1: &[N], v2: &[N]) -> N
where
    N: Add<Output = N> + Mul<Output = N> + Default + Copy,
{
    let mut total = N::default();
    for i in 0..v1.len() {
        total = total + v1[i] * v2[i];
    }
    total
}

#[test]
fn test_dot() {
    assert_eq!(dot(&[1, 2, 3, 4], &[1, 1, 1, 1]), 10);
    assert_eq!(dot(&[53.0, 7.0], &[1.0, 5.0]), 88.0);
}
```

This occasionally happens in Rust: there is a period of intense arguing with the compiler, at the end of which the code looks rather nice, as if it had been a breeze to write, and runs beautifully.What we've been doing here is reverse-engineering the bounds on `N`, using the compiler to guide and check our work. The reason it was a bit of a pain is that there wasn't a single `Number` trait in the standard library that included all the operators and methods we wanted to use.

As it happens, there's a popular open source crate called `num` that defines such a trait!

Had we known, we could have added `num` to our *Cargo.toml* and written:

```
use num::Num;

fn dot<N: Num + Copy>(v1: &[N], v2: &[N]) -> N {
    let mut total = N::zero();
    for i in 0..v1.len() {
        total = total + v1[i] * v2[i];
    }
    total
}
```

Just as in object-oriented programming, the right interface makes everything nice; in generic programming, the right trait makes everything nice. Still, why go to all this trouble? Why didn't Rust's designers make the generics more like C++ templates, where the constraints are left implicit in the code, à la "duck typing"?

One advantage of Rust's approach is forward compatibility of generic code. You can change the implementation of a public generic function or method, and if you didn't change the signature, you haven't broken any of its users.

Another advantage of bounds is that when you do get a compiler error, at least the compiler can tell you where the trouble is. C++ compiler error messages involving templates can be much longer than Rust's, pointing at many different lines of code, because the compiler has no way to tell who's to blame for a problem: the template, or its caller, which might also be a template, or *that* template's caller....

Perhaps the most important advantage of writing out the bounds explicitly is simply that they are there, in the code and in the documentation. You can look at the signature of a generic function in Rust and see exactly what kind of arguments it accepts. The same can't be said for templates. The work that goes into fully documenting argument types in C++ libraries like Boost is even *more* arduous than what we went through here. The Boost developers don't have a compiler that checks their work.

## Traits as a Foundation

Traits are one of the main organizing features in Rust, and with good reason. There's nothing better to design a program or library around than a good interface.

This chapter was a blizzard of syntax, rules, and explanations. Now that we've laid a foundation, we can start talking about the many ways traits and generics are used in Rust code. The fact is, we've only begun to scratch the surface. The next two chapters cover common traits provided by the standard library. Upcoming chapters cover closures, iterators, input/output, and concurrency. Traits and generics play a central role in all of these topics.

# Chapter 12. Operator Overloading

In the Mandelbrot set plotter we showed in Chapter 2, we used the `num` crate's `Complex` type to represent a number on the complex plane:

```
#[derive(Clone, Copy, Debug)]
struct Complex<T> {
    /// Real portion of the complex number
    re: T,

    /// Imaginary portion of the complex number
    im: T,
}
```

We were able to add and multiply `Complex` numbers just like any built-in numeric type, using Rust's `+` and `*` operators:

```
z = z * z + c;
```

You can make your own types support arithmetic and other operators, too, just by implementing a few built-in traits. This is called *operator overloading*, and the effect is much like operator overloading in C++, C#, Python, and Ruby.

The traits for operator overloading fall into a few categories depending on what part of the language they support, as shown in Table 12-1. In this chapter, we'll cover each category. Our goal is not just to help you integrate your own types nicely into the language but also to give you a better sense of how to write generic functions like the dot product function described in "Reverse-Engineering Bounds" that operate on types most naturally used via these operators. The chapter should also give some insight into how some features of the language itself are implemented.

*Table 12-1. Summary of traits for operator overloading*

| Category | Trait | Operator |
|---|---|---|
| Unary operators | `std::ops::Neg` | `-x` |
| | `std::ops::Not` | `!x` |
| Arithmetic operators | `std::ops::Add` | `x + y` |
| | `std::ops::Sub` | `x - y` |
| | `std::ops::Mul` | `x * y` |
| | `std::ops::Div` | `x / y` |
| | `std::ops::Rem` | `x % y` |
| Bitwise operators | `std::ops::BitAnd` | `x & y` |
| | `std::ops::BitOr` | `x \| y` |
| | `std::ops::BitXor` | `x ^ y` |
| | `std::ops::Shl` | `x << y` |
| | `std::ops::Shr` | `x >> y` |
| Compound assignment operators | `std::ops::AddAssign` | `x += y` |
| | `std::ops::SubAssign` | `x -= y` |
| | `std::ops::MulAssign` | `x *= y` |
| | `std::ops::DivAssign` | `x /= y` |
| | `std::ops::RemAssign` | `x %= y` |
| | `std::ops::BitAndAssign` | `x &= y` |

| Category | Trait | Operator |
|---|---|---|
| | `std::ops::BitOrAssign` | `x \|= y` |
| | `std::ops::BitXorAssign` | `x ^= y` |
| | `std::ops::ShlAssign` | `x <<= y` |
| | `std::ops::ShrAssign` | `x >>= y` |
| Comparison operators | `std::cmp::PartialEq` | `x == y`, `x != y` |
| | `std::cmp::PartialOrd` | `x < y`, `x <= y`, `x > y`, `x >= y` |
| Indexing | `std::ops::Index` | `x[y]`, `&x[y]` |
| | `std::ops::IndexMut` | `x[y] = z`, `&mut x[y]` |

## Arithmetic and Bitwise Operators

In Rust, the expression `a + b` is actually shorthand for `std::ops::Add::add(a, b)`, a call to the `add` method of the standard library's `Add` trait. If you import the trait, you can write this as an ordinary method call, `a.add(b)`:

```
use std::ops::Add;

assert_eq!(4.125f32.add(5.75), 9.875);
assert_eq!(10.add(20), 10 + 20);
```

Rust's standard numeric types all implement `std::ops::Add`. To make the expression `a + b` work for `Complex` values, the `num` crate implements this trait for `Complex` as well.

Similar traits cover the other operators: `a * b` is shorthand for `std::ops::Mul::mul(a, b)`, `std::ops::Neg` covers the prefix `-` negation operator, and so on.

Here's the definition of `std::ops::Add`:

```
trait Add<Rhs = Self> {
    type Output;
    fn add(self, rhs: Rhs) -> Self::Output;
}
```

In other words, the trait `Add<T>` is the ability to add a `T` value to yourself. For example, if you want to be able to add `i32` and `u32` values to your type, your type must implement both `Add<i32>` and `Add<u32>`. The trait's type parameter `Rhs` defaults to `Self`, so if you're implementing addition between two values of the same type, you can simply write `Add` for that case. The associated type `Output` describes the result of the addition.

For example, to be able to add `Complex<i32>` values together, `Complex<i32>` must implement `Add<Complex<i32>>`. Since we're adding a type to itself, we just write `Add`:

```
use std::ops::Add;

impl Add for Complex<i32> {
    type Output = Complex<i32>;
    fn add(self, rhs: Self) -> Self {
        Complex {
            re: self.re + rhs.re,
            im: self.im + rhs.im,
        }
    }
}
```

Of course, we shouldn't have to implement `Add` separately for `Complex<i32>`, `Complex<f32>`, `Complex<f64>`, and so on. All the definitions would look exactly the same except for the types involved, so we should be able to write a single generic implementation that covers them

all, as long as the type of the complex components themselves supports addition:

```
use std::ops::Add;

impl<T> Add for Complex<T>
where
    T: Add<Output = T>,
{
    type Output = Self;
    fn add(self, rhs: Self) -> Self {
        Complex {
            re: self.re + rhs.re,
            im: self.im + rhs.im,
        }
    }
}
```

By writing `where T: Add<Output = T>`, we restrict `T` to types that can be added to themselves, yielding another `T` value. This is a reasonable restriction, but we could loosen things still further: the `Add` trait doesn't require both operands of + to have the same type, nor does it constrain the result type. So a maximally generic implementation would let the left- and righthand operands vary independently and produce a `Complex` value of whatever component type that addition produces:

```
use std::ops::Add;

impl<L, R> Add<Complex<R>> for Complex<L>
where
    L: Add<R>,
{
    type Output = Complex<L::Output>;
    fn add(self, rhs: Complex<R>) -> Self::Output {
        Complex {
            re: self.re + rhs.re,
            im: self.im + rhs.im,
        }
    }
}
```

In practice, however, Rust tends to avoid supporting mixed-type operations. Since our type parameter `L` must implement `Add<R>`, it usually follows that `L` and `R` are going to be the same type: there simply aren't that many types available for `L` that implement anything else. So in the end, this maximally generic version may not be much more useful than the prior, simpler generic definition.

Rust's built-in traits for arithmetic and bitwise operators come in three groups: unary operators, binary operators, and compound assignment operators. Within each group, the traits and their methods all have the same form, so we'll cover one example from each.

## Unary Operators

Aside from the dereferencing operator `*`, which we'll cover separately in "Deref and DerefMut", Rust has two unary operators that you can customize, shown in Table 12-2.

*Table 12-2. Built-in traits for unary operators*

| Trait name | Expression | Equivalent method call |
|---|---|---|
| `std::ops::Neg` | `-x` | `Neg::neg(x)` |
| `std::ops::Not` | `!x` | `Not::not(x)` |

These traits' definitions are simple:

```
trait Neg {
    type Output;
    fn neg(self) -> Self::Output;
}

trait Not {
    type Output;
    fn not(self) -> Self::Output;
}
```

Negating a complex number simply negates each of its components. Here's how we might write a generic implementation of negation for `Complex` values:

```
use std::ops::Neg;

impl<T> Neg for Complex<T>
where
    T: Neg<Output = T>,
{
    type Output = Complex<T>;
    fn neg(self) -> Complex<T> {
        Complex {
            re: -self.re,
            im: -self.im,
        }
    }
}
```

## Binary Operators

Rust's binary arithmetic and bitwise operators and their corresponding built-in traits appear in Table 12-3.

*Table 12-3. Built-in traits for binary operators*

| Category | Trait name | Expression | Equivalent method call |
|---|---|---|---|
| Arithmetic operators | `std::ops::Add` | `x + y` | `Add::add(x, y)` |
| | `std::ops::Sub` | `x - y` | `Sub::sub(x, y)` |
| | `std::ops::Mul` | `x * y` | `Mul::mul(x, y)` |
| | `std::ops::Div` | `x / y` | `Div::div(x, y)` |
| | `std::ops::Rem` | `x % y` | `Rem::rem(x, y)` |
| Bitwise operators | `std::ops::BitAnd` | `x & y` | `BitAnd::bitand(x, y)` |
| | `std::ops::BitOr` | `x \| y` | `BitOr::bitor(x, y)` |
| | `std::ops::BitXor` | `x ^ y` | `BitXor::bitxor(x, y)` |
| | `std::ops::Shl` | `x << y` | `Shl::shl(x, y)` |
| | `std::ops::Shr` | `x >> y` | `Shr::shr(x, y)` |

All of the traits here have the same general form. The definition of `std::ops::BitXor`, for the `^` operator, looks like this:

```
trait BitXor<Rhs = Self> {
    type Output;
    fn bitxor(self, rhs: Rhs) -> Self::Output;
}
```

At the beginning of this chapter, we also showed `std::ops::Add`, another trait in this category, along with several sample implementations.

## Compound Assignment Operators

A compound assignment expression is one like `x += y` or `x &= y`: it takes two operands, performs some operation on them like addition or a bitwise AND, and stores the result back in the left operand. In Rust, the value of a compound assignment expression is always `()`, never the value stored.

The syntax `x += y` is shorthand for the method call `std::ops::AddAssign::add_assign(&mut x, y)`, using this built-in trait:

```
trait AddAssign<Rhs = Self> {
    fn add_assign(&mut self, rhs: Rhs);
}
```

If `x` doesn't implement `AddAssign`, then `x += y` is an error; Rust does not fall back to `x = x + y`.

Table 12-4 shows all of Rust's compound assignment operators and the built-in traits that implement them.

*Table 12-4. Built-in traits for compound assignment operators*

| Category | Trait name | Expression | Equivalent method call |
|---|---|---|---|
| Arithmetic operators | `std::ops::AddAssign` | `x += y` | `AddAssign::add_assign(&mut x, y)` |
| | `std::ops::SubAssign` | `x -= y` | `SubAssign::sub_assign(&mut x, y)` |
| | `std::ops::MulAssign` | `x *= y` | `MulAssign::mul_assign(&mut x, y)` |
| | `std::ops::DivAssign` | `x /= y` | `DivAssign::div_assign(&mut x, y)` |
| | `std::ops::RemAssign` | `x %= y` | `RemAssign::rem_assign(&mut x, y)` |
| Bitwise operators | `std::ops::BitAndAssign` | `x &= y` | `BitAndAssign::bitand_assign(&mut x, y)` |
| | `std::ops::BitOrAssign` | `x \|= y` | `BitOrAssign::bitor_assign(&mut x, y)` |
| | `std::ops::BitXorAssign` | `x ^= y` | `BitXorAssign::bitxor_assign(&mut x, y)` |
| | `std::ops::ShlAssign` | `x <<= y` | `ShlAssign::shl_assign(&mut x, y)` |
| | `std::ops::ShrAssign` | `x >>= y` | `ShrAssign::shr_assign(&mut x, y)` |

A generic implementation of `AddAssign` for our `Complex` type is straightforward:

```
use std::ops::AddAssign;
```

```
impl<T> AddAssign for Complex<T>
where
    T: AddAssign<T>,
{
    fn add_assign(&mut self, rhs: Complex<T>) {
        self.re += rhs.re;
        self.im += rhs.im;
    }
}
```

The built-in trait for a compound assignment operator is completely independent of the built-in trait for the corresponding binary operator. Implementing `std::ops::Add` does not automatically implement `std::ops::AddAssign`; if you want Rust to permit your type as the lefthand operand of a += operator, you must implement `AddAssign` yourself.

## Equivalence Comparisons

Rust's equality operators, == and `!=`, are shorthand for calls to the `std::cmp::PartialEq` trait's `eq` and `ne` methods:

```
assert_eq!(x == y, x.eq(&y));
assert_eq!(x != y, x.ne(&y));
```

Here's the definition of `std::cmp::PartialEq`. The curious `where Rhs: ?Sized` bound can be ignored for now; we'll explain it fully in "Sized".

```
trait PartialEq<Rhs = Self>
where
    Rhs: ?Sized,
{
    fn eq(&self, other: &Rhs) -> bool;
    fn ne(&self, other: &Rhs) -> bool {
        !self.eq(other)
    }
}
```

Note that the `ne` method comes with a default definition. It's likely you will never encounter a good reason to implement `ne` yourself. Anyone using `!=` will assume that `x != y` means exactly that `x` is not == to `y`, and that's what the default definition does. So the following is a complete implementation for `Complex`:

```
impl<T: PartialEq> PartialEq for Complex<T> {
    fn eq(&self, other: &Complex<T>) -> bool {
        self.re == other.re && self.im == other.im
    }
}
```

In other words, for any component type `T` that itself can be compared for equality, this implements comparison for `Complex<T>`. Assuming we've also implemented `std::ops::Mul` for `Complex` somewhere along the line, we can now write:

```
let x = Complex { re: 3, im: 4 };
let y = Complex { re: 0, im: 1 };
assert_eq!(x * y, Complex { re: -4, im: 3 });
```

Implementations of `PartialEq` are almost always of the form shown here: they compare each field of the left operand to the corresponding field of the right. These get tedious to write, and equality is a common operation to support, so if you ask, Rust will generate an implementation of `PartialEq` for you automatically. Simply add `PartialEq` to the type definition's `derive` attribute like so:

```
#[derive(Clone, Copy, Debug, PartialEq)]
struct Complex<T> {
    ...
}
```

Rust's automatically generated implementation is essentially identical to our hand-written code, comparing each field of the type in turn. Rust can derive `PartialEq` implementations for `enum` types as well. Naturally, each field of the `struct` or `enum` must itself implement `PartialEq`.

Unlike the arithmetic and bitwise traits, which take their operands by value, `PartialEq` takes its operands by reference. Meaning that comparing non-`Copy` values like `Strings`, `Vecs`, or `HashMaps` doesn't cause them to be moved, which would be troublesome:

```
let s = "d\x6fv\x65t\x61i\x6c".to_string();
let t = "\x64o\x76e\x74a\x69l".to_string();
assert!(s == t);  // s and t are only borrowed...

// ... so they still have their values here.
assert_eq!(format!("{s} {t}"), "dovetail dovetail");
```

You may be wondering why this trait is called `PartialEq`. Explaining this requires a bit of a detour into the weird behavior of floating-point not-a-numbers.

## The Eq Trait (Or: Equality vs. NaN)

We have already mentioned one rule about the `PartialEq` trait that all implementations ought to follow:

- `x != y` should return exactly the same result as `!(x == y)`.

Rust doesn't enforce this rule. You can implement both `eq` and `ne` by hand to do whatever you want. Breaking the rule won't lead to undefined behavior, but it's bound to be confusing for your users, and programmer confusion leads to bugs.

So the `PartialEq` trait is more than just a collection of methods. It consists of two methods plus the above rule—a promise of good behavior that `PartialEq` implementations make to their users.

The traditional mathematical definition of an *equivalence relation*, of which equality is one instance, consists of three further rules. For any values `x` and `y`:

- If `x == y` is true, then `y == x` must be true as well. In other words, swapping the two sides of an equality comparison doesn't

affect the result.

- If `x == y` and `y == z`, then it must be the case that `x == z`. Given any chain of values, each equal to the next, each value in the chain is directly equal to every other. Equality is contagious.
- It must always be true that `x == x`.

That last requirement might seem too obvious to be worth stating, but this is exactly where things go awry. Rust's `f32` and `f64` are IEEE standard floating-point values. According to that standard, expressions like `0.0/0.0` and others with no appropriate value must produce special *not-a-number* values, usually referred to as NaN values. The standard further requires that a NaN value be treated as unequal to every other value—including itself. For example, the standard requires all the following behaviors:

```
let nan: f64 = 0.0 / 0.0;
assert!(nan.is_nan());
assert_eq!(nan == nan, false);
assert_eq!(nan != nan, true);
```

Furthermore, any ordered comparison with a NaN value must return false:

```
assert_eq!(nan < nan, false);
assert_eq!(nan > nan, false);
assert_eq!(nan <= nan, false);
assert_eq!(nan >= nan, false);
```

So while Rust's == operator meets the first two requirements for equivalence relations, it clearly doesn't meet the third when used on IEEE floating-point values. This is called a *partial equivalence relation*, so Rust uses the name `PartialEq` for the == operator's built-in trait. If you write generic code with type parameters known only to be `PartialEq`, you may assume the first two requirements hold, but you can't assume that values always equal themselves.

This can be more than a little inconvenient. Suppose you're writing a generic lookup table. You might write something like `table_entry.key == search_key` to check whether an entry matches. This is the only reasonable thing to do, and it works correctly, except when the keys are floating-point numbers and we go searching for a NaN value. That exact NaN key might be present in the table, but it won't match, because NaN isn't == itself. The consequences might get quite silly. If the user decides to add a new entry whenever a match isn't found, a single lookup table could accumulate many entries with the same NaN key.

The only way to avoid this kind of nonsense in your generic code is to rule out types with such misbehaving values. Rust provides the `std::cmp::Eq` trait for this purpose. `Eq` represents a full equivalence relation: if a type implements `Eq`, then `x == x` must be `true` for every value `x` of that type. In practice, almost every type that implements `PartialEq` should implement `Eq` as well; `f32` and `f64` are the only types in the standard library that are `PartialEq` but not `Eq`.

The standard library defines `Eq` as an extension of `PartialEq`, adding no new methods:

```
trait Eq: PartialEq<Self> {}
```

The trait has no features of its own, only those implied by the supertrait `PartialEq<Self>`. `Eq` is, indeed, nothing more than `PartialEq` plus one additional rule. Implementing it is therefore trivial:

```
impl<T: Eq> Eq for Complex<T> {}
```

Even this one line of code can be derived:

```
#[derive(Clone, Copy, Debug, Eq, PartialEq)]
struct Complex<T> {
    ...
}
```

Derived implementations on a generic type may depend on the type parameters. With the `derive` attribute, `Complex<i32>` would implement `Eq`, because `i32` does, but `Complex<f32>` would only implement `PartialEq`, since `f32` doesn't implement `Eq`.

If you insincerely implement `Eq` for a type where values aren't equal to themselves, it won't lead to undefined behavior, but other code that relies on the `Eq` promise, including standard library features like `HashMap`, may behave strangely and produce silly results.

## Ordered Comparisons

Rust specifies the behavior of the ordered comparison operators <, >, <=, and >= all in terms of a single trait, `std::cmp::PartialOrd`:

```
trait PartialOrd<Rhs = Self>: PartialEq<Rhs>
where
    Rhs: ?Sized,
{
    fn partial_cmp(&self, other: &Rhs) -> Option<Ordering>;

    fn lt(&self, other: &Rhs) -> bool { ... }
    fn le(&self, other: &Rhs) -> bool { ... }
    fn gt(&self, other: &Rhs) -> bool { ... }
    fn ge(&self, other: &Rhs) -> bool { ... }
}
```

Note that `PartialOrd<Rhs>` extends `PartialEq<Rhs>`: you can do ordered comparisons only on types that you can also compare for equality.

The only method of `PartialOrd` you must implement yourself is `partial_cmp`. When `partial_cmp` returns `Some(o)`, then `o` indicates `self`'s relationship to `other`:

```
enum Ordering {
    Less,       // self < other
    Equal,      // self == other
    Greater,    // self > other
}
```

But if `partial_cmp` returns `None`, that means `self` and `other` are unordered with respect to each other: neither is greater than the other, nor are they equal. Among all of Rust's primitive types, only comparisons between floating-point values ever return `None`: specifically, comparing a NaN (not-a-number) value with anything else returns `None`.

Like the other binary operators, to compare values of two types `Left` and `Right`, `Left` must implement `PartialOrd<Right>`. Expressions like `x < y` or `x >= y` are shorthand for calls to `PartialOrd` methods, as shown in Table 12-5.

*Table 12-5. Ordered comparison operators and `PartialOrd` methods*

| Expression | Equivalent method call | Default definition |
|---|---|---|
| `x < y` | `PartialOrd::lt(&x, &y)` | `x.partial_cmp(&y) == Some(Less)` |
| `x > y` | `PartialOrd::gt(&x, &y)` | `x.partial_cmp(&y) == Some(Greater)` |
| `x <= y` | `PartialOrd::le(&x, &y)` | `matches!(x.partial_cmp(&y), Some(Less \| Equal))` |
| `x >= y` | `PartialOrd::ge(&x, &y)` | `matches!(x.partial_cmp(&y), Some(Greater \| Equal))` |

As in prior examples, the code in the table assumes that `std::cmp::PartialOrd` and `std::cmp::Ordering::*` are in scope.

If a type is totally ordered so that `partial_cmp` never returns `None`, then the type can implement the stricter `std::cmp::Ord` trait:

```
trait Ord: Eq + PartialOrd<Self> {
    fn cmp(&self, other: &Self) -> Ordering;

    fn max(self, other: Self) -> Self ...
```

```
    fn min(self, other: Self) -> Self ...
    fn clamp(self, lo: Self, hi: Self) -> Self ...
}
```

The `cmp` method here simply returns an `Ordering`, instead of an `Option<Ordering>` like `partial_cmp`: `cmp` always declares its arguments equal or indicates their relative order. Almost all types that implement `PartialOrd` should also implement `Ord`. In the standard library, `f32` and `f64` are the only exceptions to this rule. Again, as with `Eq`, this is due to NaN values.

`Ord` provides three additional methods, with straightforward default implementations:

- `a.max(b)` returns the greater of the two values `a` and `b`.
- `a.min(b)` returns the lesser of the two values.
- `a.clamp(lo, hi)` applies upper and lower bounds to the value `a`. That is, it returns the value in the inclusive range from `lo` to `hi` that is closest to `a`. It panics if `hi < lo`.

Types that implement `Ord` are sortable. As we'll see in Chapter 16, the standard library has several sorting-related features: the `.sort()` method on slices, binary searching, B-trees, and binary heaps. All of these work only on types that implement `Ord`.

However, there are real-world cases, even setting aside NaNs, where it makes sense to implement `PartialOrd` for a type that does not qualify as `Ord`. Suppose you're working with the following type, representing the set of numbers falling within a given half-open interval:

```
#[derive(Debug, PartialEq)]
struct Interval<T> {
    lower: T,  // inclusive
    upper: T,  // exclusive
}
```

You'd like to make values of this type partially ordered: one interval is less than another if it falls entirely before the other, with no overlap. If two unequal intervals overlap, they're unordered: some element of each side is less than some element of the other. And two equal intervals are simply equal. The following implementation of `PartialOrd` implements those rules:

```
use std::cmp::{Ordering, PartialOrd};

impl<T: PartialOrd> PartialOrd<Interval<T>> for Interval<T> {
    fn partial_cmp(&self, other: &Interval<T>) ->
Option<Ordering> {
        if self == other {
            Some(Ordering::Equal)
        } else if self.lower >= other.upper {
            Some(Ordering::Greater)
        } else if self.upper <= other.lower {
            Some(Ordering::Less)
        } else {
            None
        }
    }
}
```

With that implementation in place, you can write the following:

```
assert!(Interval { lower: 10, upper: 20 } <  Interval { lower:
20, upper: 40 });
assert!(Interval { lower: 7,  upper: 8  } >= Interval { lower: 0,
upper: 1  });
assert!(Interval { lower: 7,  upper: 8  } <= Interval { lower: 7,
upper: 8  });

// Overlapping intervals aren't ordered with respect to each
other.
let left  = Interval { lower: 10, upper: 30 };
let right = Interval { lower: 20, upper: 40 };
assert!(!(left < right));
assert!(!(left >= right));
```

Since this is not a total order, we've implemented only `PartialOrd`, not `Ord`. Therefore, if we want to sort a vector of intervals, simply calling

`.sort()` won't work. We must explicitly specify a sort order. Sorting by upper bound, for instance, can be done with `sort_by_key`:

```
intervals.sort_by_key(|i| i.upper);
```

`Interval<i32>` doesn't implement `Ord`, but our sort key (`i.upper`, which is an `i32`) does. For more about sorting, see "Sorting and Searching".

## Index and IndexMut

Lastly, you can specify how an indexing expression like `a[i]` works on your type by implementing the `std::ops::Index` and `std::ops::IndexMut` traits. `a[i]` is normally shorthand for `*std::ops::Index::index(&a, i)`. When it's assigned to or borrowed mutably, `a[i]` is instead shorthand for `*std::ops::IndexMut::index_mut(&mut a, i)`.

Here are the traits' definitions:

```
trait Index<Idx> {
    type Output: ?Sized;
    fn index(&self, index: Idx) -> &Self::Output;
}

trait IndexMut<Idx>: Index<Idx> {
    fn index_mut(&mut self, index: Idx) -> &mut Self::Output;
}
```

Note that these traits take the type of the index expression as a parameter. You can index a slice with a single `usize`, referring to a single element, because slices implement `Index<usize>`. But you can refer to a subslice with an expression like `a[i..j]` because they also implement `Index<Range<usize>>`. That expression is shorthand for:

```
*std::ops::Index::index(&a, std::ops::Range { start: i, end: j })
```

Rust's `HashMap` and `BTreeMap` collections can be indexed by key. The last line of the following example works because `HashMap<&str, i32>` implements `Index<&str>`:

```
use std::collections::HashMap;
let mut m = HashMap::new();
m.insert("十", 10);
m.insert("百", 100);
m.insert("千", 1000);
m.insert("万", 1_0000);
m.insert("億", 1_0000_0000);

assert_eq!(m["十"], 10);
```

The assertion is equivalent to:

```
assert_eq!(*std::ops::Index::index(&m, "十"), 10);
```

The `Index` trait's associated type `Output` specifies what type an indexing expression produces: for our `HashMap`, the `Index` implementation's `Output` type is `i32`.

The `IndexMut` trait extends `Index` with an `index_mut` method that takes a mutable reference to `self` and returns a mutable reference to an `Output` value. Rust automatically selects `index_mut` when the indexing expression occurs in a context where it's necessary. For example, suppose we write the following:

```
let mut desserts =
    vec!["Howalon".to_string(), "Soan papdi".to_string()];
desserts[0].push_str(" (fictional)");
desserts[1].push_str(" (real)");
```

Because the `push_str` method operates on `&mut self`, those last two lines are equivalent to:

```
use std::ops::IndexMut;
(*IndexMut::index_mut(&mut desserts, 0)).push_str("
```

```
(fictional)");
(*IndexMut::index_mut(&mut desserts, 1)).push_str(" (real)");
```

One limitation of `IndexMut` is that, by design, it must return a mutable reference to some value. This is why you can't use an expression like `m["十"] = 10;` to insert a value into the `HashMap` `m`: the table would need to create an entry for `"十"` first, with some default value, and return a mutable reference to that. But not all types have cheap default values, and some may be expensive to drop; it would be a waste to create such a value only to be immediately dropped by the assignment.

The most common use of indexing is for collections. For example, suppose we are working with bitmapped images, like the ones we created in the Mandelbrot set plotter in Chapter 2. Recall that our program contained code like this:

```
pixels[row * bounds.0 + column] = ...;
```

It would be nicer to have an `Image<u8>` type that acts like a two-dimensional array, allowing us to access pixels without having to write out all the arithmetic:

```
image[row][column] = ...;
```

To do this, we'll need to declare a struct:

```
struct Image<P> {
    width: usize,
    pixels: Vec<P>,
}

impl<P: Default + Copy> Image<P> {
    /// Creates a new image of the given size.
    fn new(width: usize, height: usize) -> Image<P> {
        Image {
            width,
            pixels: vec![P::default(); width * height],
        }
    }
}
```

And here are implementations of `Index` and `IndexMut` that would fit the bill:

```
impl<P> std::ops::Index<usize> for Image<P> {
    type Output = [P];
    fn index(&self, row: usize) -> &[P] {
        let start = row * self.width;
        &self.pixels[start..start + self.width]
    }
}

impl<P> std::ops::IndexMut<usize> for Image<P> {
    fn index_mut(&mut self, row: usize) -> &mut [P] {
        let start = row * self.width;
        &mut self.pixels[start..start + self.width]
    }
}
```

When you index into an `Image`, you get back a slice of pixels; indexing the slice gives you an individual pixel.

Note that when we write `image[row][column]`, if `row` is out of bounds, our `index` method will try to index `self.pixels` out of range, triggering a panic. This is how `Index` and `IndexMut` implementations are supposed to behave: out-of-bounds access is detected and causes a panic, the same as when you index an array, slice, or vector out of bounds.

## Other Operators

Not all operators can be overloaded in Rust. So far, the error-checking `?` operator works only with `Result` and a few other standard library types, but work is in progress to expand this to user-defined types as well. Similarly, the logical operators `&&` and `||` are limited to Boolean values only. The `..` and `..=` operators always create a struct representing the range's bounds, the `&` operator always borrows references, and the `=` operator always moves or copies values. None of them can be overloaded.

The dereferencing operator, `*val`, and the dot operator for accessing fields and calling methods, as in `val.field` and `val.method()`, can be overloaded using the `Deref` and `DerefMut` traits, which are covered in the next chapter. (We did not include them here because these traits do more than just overload a few operators.)

Rust does not support overloading the function call operator, `f(x)`. Instead, when you need a callable value, you'll typically just write a closure. We'll explain how this works and cover the `Fn`, `FnMut`, and `FnOnce` special traits in Chapter 14.

# Chapter 13. Utility Traits

> *Science is nothing else than the search to discover unity in the wild variety of nature—or, more exactly, in the variety of our experience. Poetry, painting, the arts are the same search, in Coleridge's phrase, for unity in variety.*
>
> —Jacob Bronowski

This chapter describes what we call Rust's "utility" traits, a grab bag of traits from the standard library that have a significant impact on the way Rust is written. You'll need to be familiar with them to write idiomatic code and design public interfaces for your crates that users will judge to be properly "Rustic."

Some of these traits are built into the Rust language. For example, a type that implements the `Drop` trait has a special method that Rust calls automatically whenever a value is dropped. This is critical for types that own heap memory (`String`, `Vec`) or system resources (`File`, `TcpStream`). Similarly, the `Deref` trait allows smart pointer types to "look and feel" like references, reducing boilerplate every time you use a `Box` or `Rc`. The Rust compiler knows about these traits and uses them implicitly.

Others, like the `Default` trait and Rust's many conversion traits, have no magical compiler integration. You could define an equivalent trait in your own code. But they serve the important goal of setting down conventional solutions for common problems. These are especially valuable in public interfaces: by reducing needless variation, they make interfaces easier to understand, but they also increase the likelihood that features from different crates can simply be plugged together directly, without boilerplate or custom glue code.

Table 13-1 summarizes the traits covered in this chapter.

*Table 13-1. Summary of utility traits*

| Trait | Description |
|---|---|
| `Drop` | Types with destructors: cleanup code that Rust runs automatically whenever a value is dropped |
| `Sized` | Types whose values have a fixed size, known at compile time, as opposed to dynamically sized types like `[u8]`, `str`, and `dyn Write` |
| `Clone` | Types whose values can be cloned |
| `Copy` | Types whose values can be cloned simply by making a byte-for-byte copy of the memory containing the value |
| `Deref` and `DerefMut` | Traits for smart pointer types |
| `Default` | Types that have a sensible "default value" |
| `AsRef` and `AsMut` | Conversion traits for borrowing one type of reference from another |
| `Borrow` and `BorrowMut` | Conversion traits, like `AsRef`/`AsMut`, but additionally guaranteeing consistent hashing, ordering, and equality |
| `From` and `Into` | Conversion traits for transforming one type of value into another |
| `TryFrom` and `TryInto` | Conversion traits for transforming one type of value into another, for transformations that might fail |
| `ToOwned` | Conversion trait for converting a reference to an owned value |

There are other important standard library traits as well. We'll cover `Iterator` and `IntoIterator` in Chapter 15. The `Hash` trait, for computing hash codes, is covered in Chapter 16. And a pair of traits that mark thread-safe types, `Send` and `Sync`, are covered in Chapter 19.

## Drop

When a value's owner goes away, we say that Rust *drops* the value. Dropping a value entails freeing whatever other values, heap storage, and system resources the value owns. Drops occur under a variety of circumstances: when a variable goes out of scope; at the end of an expression statement; when you truncate a vector, removing elements from its end; and so on.

For the most part, Rust handles dropping values for you automatically. For example, suppose you define the following type:

```
struct Appellation {
    name: String,
    nicknames: Vec<String>,
}
```

An `Appellation` owns heap storage for the strings' contents and the vector's buffer of elements. Rust takes care of cleaning all that up whenever an `Appellation` is dropped, without any further coding necessary on your part.

However, if you want, you can customize how Rust drops values of your type by implementing the `std::ops::Drop` trait:

```
trait Drop {
    fn drop(&mut self);
}
```

An implementation of `Drop` is analogous to a destructor in C++, or a finalizer in other languages. When a value is dropped, if it implements `std::ops::Drop`, Rust calls its `drop` method, before proceeding to

drop whatever values its fields or elements own, as it normally would. This implicit invocation of `drop` is the only way to call that method; if you try to invoke it explicitly yourself, Rust flags that as an error.

Because Rust calls `Drop::drop` on a value before dropping its fields or elements, the value the method receives is always still fully initialized. An implementation of `Drop` for our `Appellation` type can make full use of its fields:

```
impl Drop for Appellation {
    fn drop(&mut self) {
        print!("Dropping {}", self.name);
        if !self.nicknames.is_empty() {
            print!(" (AKA {})", self.nicknames.join(", "));
        }
        println!();
    }
}
```

Given that implementation, we can write the following:

```
{
    let mut a = Appellation {
        name: "Zeus".to_string(),
        nicknames: vec![
            "cloud collector".to_string(),
            "king of the gods".to_string(),
        ],
    };

    println!("before assignment");
    a = Appellation {
        name: "Hera".to_string(),
        nicknames: vec![],
    };
    println!("at end of block");
}
```

When we assign the second `Appellation` to `a`, the first is dropped, and when we leave the scope of `a`, the second is dropped. This code prints the following:

```
before assignment
Dropping Zeus (AKA cloud collector, king of the gods)
at end of block
Dropping Hera
```

Since our `std::ops::Drop` implementation for `Appellation` does nothing but print a message, how, exactly, does its memory get cleaned up? The `Vec` type implements `Drop`, dropping each of its elements and then freeing the heap-allocated buffer they occupied. A `String` uses a `Vec<u8>` internally to hold its text, so `String` need not implement `Drop` itself; it lets its `Vec` take care of freeing the characters. The same principle extends to `Appellation` values: when one gets dropped, in the end it is `Vec`'s implementation of `Drop` that actually takes care of freeing each of the strings' contents and finally freeing the buffer holding the vector's elements. As for the memory that holds the `Appellation` value itself, it too has some owner, perhaps a local variable or some data structure that is responsible for freeing it.

If a variable's value gets moved elsewhere so that the variable is uninitialized when it goes out of scope, then Rust will not try to drop that variable: there is no value in it to drop.

This principle holds even when a variable may or may not have had its value moved away, depending on the flow of control. In cases like this, Rust keeps track of the variable's state with an invisible flag indicating whether the variable's value needs to be dropped or not:

```
let p;
{
    let q = Appellation {
        name: "Cardamine hirsuta".to_string(),
        nicknames: vec![
            "shotweed".to_string(),
            "bittercress".to_string(),
        ],
    };
    if complicated_condition() {
        p = q;
    }
```

```
}
println!("Sproing! What was that?");
```

Depending on whether `complicated_condition` returns `true` or `false`, either `p` or `q` will end up owning the `Appellation`, with the other uninitialized. Where it lands determines whether it is dropped before or after the `println!`, since `q` goes out of scope before the `println!`, and `p` after. Although a value may be moved from place to place, Rust drops it only once.

You usually won't need to implement `std::ops::Drop` unless you're defining a type that owns resources Rust doesn't already know about. For example, on Unix systems, Rust's standard library uses the following type internally to represent an operating system file descriptor:

```
struct FileDesc {
    fd: c_int,
}
```

The `fd` field of a `FileDesc` is simply the number of the file descriptor that should be closed when the program is done with it; `c_int` is an alias for `i32`. The standard library implements `Drop` for `FileDesc` as follows:

```
impl Drop for FileDesc {
    fn drop(&mut self) {
        let _ = unsafe { libc::close(self.fd) };
    }
}
```

Here, `libc::close` is the Rust name for the C library's `close` function. Rust code may call C functions only within `unsafe` blocks, so the library uses one here.

If a type implements `Drop`, it cannot implement the `Copy` trait. If a type is `Copy`, that means that simple byte-for-byte duplication is sufficient to produce an independent copy of the value. But it is typically a mistake to call the same `drop` method more than once on the same data. The standard

prelude includes a function to drop a value, `drop`, but its definition is anything but magical:

```
fn drop<T>(_x: T) {}
```

In other words, it receives its argument by value, taking ownership from the caller—and then does nothing with it. Rust drops the value of `_x` when it goes out of scope, as it would for any other variable.

## Sized

A *fixed-size type* is one whose values all have the same size in memory. Almost all types in Rust are fixed-size: every `u64` takes 8 bytes, every `(f32, f32, f32)` tuple 12. Even enums have a fixed size: no matter which variant is actually present, an enum always occupies enough space to hold its largest variant. And although a `Vec<T>` owns a heap-allocated buffer whose size can vary, the `Vec` value itself is a pointer to the buffer, its capacity, and its length, so `Vec<T>` has a fixed size.

All fixed-size types implement the `std::marker::Sized` trait, which has no methods or associated types. Rust implements it automatically for all types to which it applies; you can't implement it yourself. The only use for `Sized` is as a bound for type variables: a bound like `T: Sized` requires `T` to be a type whose size is known at compile time. Traits of this sort are called *marker traits*, because the Rust language itself uses them to mark certain types as having characteristics of interest.

However, Rust also has a few *dynamically sized types* whose values are not all the same size. For example, the string slice type `str` (note, without an `&`) is dynamically sized. The string literals `"diminutive"` and `"big"` are references to `str` slices that occupy 10 and 3 bytes. Both are shown in Figure 13-1. Array slice types like `[T]` (again, without an `&`) are dynamically sized, too: a shared reference like `&[u8]` can point to a `[u8]` slice of any size.

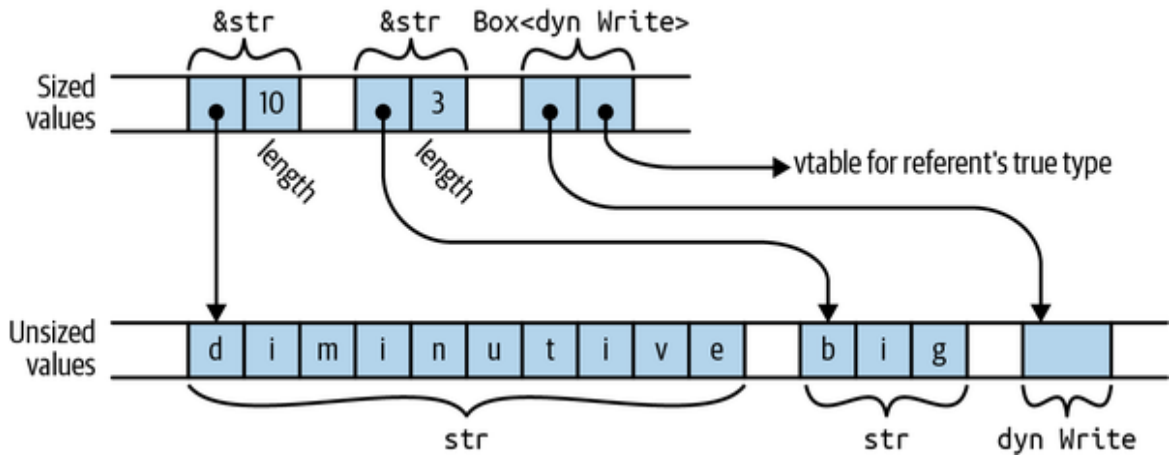


*Figure 13-1. References to values of dynamically sized types*

The other common kind of dynamically sized type in Rust is a `dyn` type, or trait object. As we explained in "Using dyn", a `dyn` reference can refer to a value of any type that implements a given trait. For example, the types `&dyn std::io::Write` and `Box<dyn std::io::Write>` are pointers to some value that implements the `Write` trait. The referent might be a file or a network socket or some type of your own for which you have implemented `Write`. Since the set of types that implement `Write` is open-ended, the type `dyn Write` is dynamically sized; its values have various sizes.

A variable or argument can't have a dynamically sized type. You can only deal with values of dynamically sized types through pointers like `&str` or `Box<dyn Write>`, which themselves are fixed-size. As shown in Figure 13-1, a pointer to a dynamically sized value is always a fat pointer, two words wide: a pointer to a slice also carries the slice's length, and a pointer to a trait object also carries a vtable pointer.

Pointers to slices and pointers to trait objects are nicely symmetrical. In both cases, the type lacks information necessary to use it: Rust can't index a `[u8]` without knowing its length, nor can it invoke a method on a `dyn Write` without knowing the actual type of the writer. And in both cases, the fat pointer fills in the information missing from the type, carrying a length or a vtable pointer. The omitted static information is replaced with dynamic information.

Since dynamically sized types are so limited, most generic type variables should be restricted to `Sized` types. In fact, this is necessary so often that it is the implicit default in Rust: if you write `struct S<T> { ... }`, Rust understands you to mean `struct S<T: Sized> { ... }`. If you do not want to constrain `T` this way, you must explicitly opt out, writing `struct S<T: ?Sized> { ... }`. The `?Sized` syntax is specific to this case and means "not necessarily `Sized`."

Marking a type parameter as `T: ?Sized` makes sense for generic code that always handles values of that type through references or other pointers. For example, if you write `struct S<T: ?Sized> { b: Box<T> }`, then Rust will allow you to write `S<str>` and `S<dyn Write>`, where the box becomes a fat pointer, as well as `S<i32>` and `S<String>`, where the box is an ordinary pointer.

The standard `PartialEq` trait is another example of generic code with a `?Sized` bound:

```
trait PartialEq<Rhs = Self>
where
    Rhs: ?Sized,
{
    fn eq(&self, other: &Rhs) -> bool;
    fn ne(&self, other: &Rhs) -> bool {
        !self.eq(other)
    }
}
```

It's possible for this trait to have `Rhs: ?Sized` because every use of `Rhs` is by reference. It's desirable because it means dynamically sized types like `str` can support the == operator.

Despite their restrictions, dynamically sized types make Rust's type system work more smoothly. Reading the standard library documentation, you will occasionally come across a `?Sized` bound on a type variable; this almost always means that the given type is only pointed to and allows the associated code to work with slices and trait objects as well as ordinary

values. When a type variable has the `?Sized` bound, people often say it is *questionably sized*: it might be `Sized`, or it might not.

Aside from slices and trait objects, there is one more kind of dynamically sized type. A struct type's last field (but only its last) may be dynamically sized, and such a struct is itself dynamically sized. For example, an `Rc<T>` reference-counted pointer is implemented internally as a pointer to the private type `RcBox<T>`, which stores the reference count alongside the `T`. Here's a simplified definition of `RcBox`:

```
struct RcBox<T: ?Sized> {
    ref_count: usize,
    value: T,
}
```

The `value` field is the `T` to which `Rc<T>` is counting references; `Rc<T>` dereferences to a pointer to this field. The `ref_count` field holds the reference count.

The real `RcBox` is just an implementation detail of the standard library and isn't available for public use. But suppose we are working with the preceding definition. You can use this `RcBox` with `Sized` types, like `RcBox<String>`; the result is a `Sized` struct type. Or you can use it with dynamically sized types, like `RcBox<dyn std::fmt::Display>` (where `Display` is the trait for types that can be formatted by `println!` and similar macros); `RcBox<dyn Display>` is a dynamically sized struct type.

You can't build an `RcBox<dyn Display>` value directly. Instead, you first need to create an ordinary, fixed-size `RcBox` whose `value` type implements `Display`, like `RcBox<String>`. Rust then lets you convert a reference `&RcBox<String>` to a fat reference `&RcBox<dyn Display>`:

```
let boxed_lunch: RcBox<String> = RcBox {
    ref_count: 1,
    value: "lunch".to_string(),
```

```
};

use std::fmt::Display;
let boxed_displayable: &RcBox<dyn Display> = &boxed_lunch;
```

This conversion happens implicitly when passing values to functions, so you can pass a `&RcBox<String>` to a function that expects a `&RcBox<dyn Display>`:

```
fn display(boxed: &RcBox<dyn Display>) {
    println!("For your enjoyment: {}", &boxed.value);
}

display(&boxed_lunch);
```

This would produce the following output:

```
For your enjoyment: lunch
```

## Clone

The `std::clone::Clone` trait is for types that can make copies of themselves. `Clone` is defined as follows:

```
trait Clone: Sized {
    fn clone(&self) -> Self;
    fn clone_from(&mut self, source: &Self) {
        *self = source.clone();
    }
}
```

The `clone` method should construct an independent copy of `self` and return it. Since this method's return type is `Self` and functions may not return dynamically sized types, the `Clone` trait itself extends the `Sized` trait: this has the effect of bounding implementations' `Self` types to be `Sized`.

Cloning a value usually entails allocating copies of anything it owns, as well, so a `clone` can be expensive, in both time and memory. For example, cloning a `Vec<String>` not only copies the vector but also copies each of its `String` elements. This is why Rust doesn't just clone values automatically but instead requires you to make an explicit method call. The reference-counted pointer types like `Rc<T>` and `Arc<T>` are exceptions: cloning one of these simply increments the reference count and hands you a new pointer.

The `clone_from` method modifies `self` into a copy of `source`. The default definition of `clone_from` simply clones `source` and then moves that into `*self`. This always works, but for some types, there is a faster way to get the same effect. For example, suppose `s` and `t` are `String`s. The statement `s = t.clone();` must clone `t`, drop the old value of `s`, and then move the cloned value into `s`; that's one heap allocation and one heap deallocation. But if the heap buffer belonging to the original `s` has enough capacity to hold `t`'s contents, no allocation or deallocation is necessary: you can simply copy `t`'s text into `s`'s buffer and adjust the length. In generic code, you should use `clone_from` whenever possible to take advantage of optimized implementations when present.

If your `Clone` implementation simply applies `clone` to each field of your type and then constructs a new value from those clones and the default definition of `clone_from` is good enough, then Rust will implement that for you: simply put `#[derive(Clone)]` above your type definition.

Pretty much every type in the standard library that makes sense to copy implements `Clone`. Primitive types like `bool` and `i32` do. Container types like `String`, `Vec<T>`, and `HashMap` do, too. Some types don't make sense to copy, like `std::sync::Mutex`; those don't implement `Clone`. Some types like `std::fs::File` can be copied, but the copy might fail if the operating system doesn't have the necessary resources; these types don't implement `Clone`, since `clone` must be infallible. Instead, `std::fs::File` provides a `try_clone` method, which returns a `std::io::Result<File>`, which can report a failure.

## Copy

In Chapter 4, we explained that, for most types, assignment moves values, rather than copying them. Moving values makes it much simpler to track the resources they own. But in "Copy Types: The Exception to Moves", we pointed out the exception: simple types that don't own any resources can be `Copy` types, where assignment makes a copy of the source, rather than moving the value and leaving the source uninitialized.

At that time, we left it vague exactly what `Copy` was, but now we can tell you: a type is `Copy` if it implements the `std::marker::Copy` marker trait, which is defined as follows:

```
trait Copy: Clone {}
```

This is certainly easy to implement for your own types:

```
impl Copy for MyType {}
```

But because `Copy` is a marker trait with special meaning to the language, Rust permits a type to implement `Copy` only if a shallow byte-for-byte copy is all it needs. Types that own any other resources, like heap buffers or operating system handles, cannot implement `Copy`.

Any type that implements the `Drop` trait cannot be `Copy`. Rust presumes that if a type needs special cleanup code, it must also require special copying code and thus can't be `Copy`.

As with `Clone`, you can ask Rust to derive `Copy` for you using `#[derive(Copy)]`. You will often see both derived at once with `#[derive(Copy, Clone)]`.

Think carefully before making a type `Copy`. Although doing so makes the type easier to use, it places heavy restrictions on its implementation. Implicit copies can also be expensive. We explain these factors in detail in "Copy Types: The Exception to Moves".

## Deref and DerefMut

You can specify how dereferencing operators like `*` and `.` behave on your types by implementing the `std::ops::Deref` and `std::ops::DerefMut` traits. Pointer types like `Box<T>` and `Rc<T>` implement these traits so that they can behave as Rust's built-in pointer types do. For example, if you have a `Box<Complex>` value `b`, then `*b` refers to the `Complex` value that `b` points to, and `b.re` refers to its real component. If the context assigns or borrows a mutable reference to the referent, Rust uses the `DerefMut` ("dereference mutably") trait; otherwise, read-only access is enough, and it uses `Deref`.

The traits are defined like this:

```
trait Deref {
    type Target: ?Sized;
    fn deref(&self) -> &Self::Target;
}

trait DerefMut: Deref {
    fn deref_mut(&mut self) -> &mut Self::Target;
}
```

The `deref` and `deref_mut` methods take `self` by reference and return a reference to a `Self::Target`. The type `Target` should be something that `Self` contains, owns, or refers to: for `Box<Complex>` the `Target` type is `Complex`. Note that `DerefMut` extends `Deref`: if you can dereference something and modify it, certainly you should be able to borrow a shared reference to it as well. Since the methods return a reference with the same lifetime as `&self`, `self` remains borrowed for as long as the returned reference lives.

The `Deref` and `DerefMut` traits play another role as well. Since `deref` takes a `&Self` reference and returns a `&Self::Target` reference, Rust uses this to automatically convert references of the former type into the latter. In other words, if inserting a `deref` call would prevent a type mismatch, Rust inserts one for you. Implementing `DerefMut` enables the

corresponding conversion for mutable references. These are called the *deref coercions*: one type is being "coerced" into behaving as another.

Although the deref coercions aren't anything you couldn't write out explicitly yourself, they're convenient:

- If you have some `Rc<String>` value `r` and want to apply `String::find` to it, you can simply write `r.find('?')`, instead of `(*r).find('?')`: the method call implicitly borrows `r`, and `&Rc<String>` coerces to `&String`, because `Rc<T>` implements `Deref<Target = T>`.
- You can use methods like `split_at` on `String` values, even though `split_at` is a method of the `str` slice type, because `String` implements `Deref<Target = str>`. There's no need for `String` to reimplement all of `str`'s methods, since you can coerce a `&str` from a `&String`.
- If you have a vector of bytes `v` and you want to pass it to a function that expects a byte slice `&[u8]`, you can simply pass `&v` as the argument, since `Vec<T>` implements `Deref<Target = [T]>`.

Rust will apply several deref coercions in succession if necessary. For example, using the coercions mentioned before, you can apply `split_at` directly to an `Rc<String>`, since `&Rc<String>` dereferences to `&String`, which dereferences to `&str`, which has the `split_at` method. For example, suppose you have the following type:

```
struct Selector<T> {
    /// Elements available in this `Selector`.
    elements: Vec<T>,

    /// The index of the "current" element in `elements`. A
`Selector`
    /// behaves like a pointer to the current element.
    current: usize,
}
```

To make the `Selector` behave as the doc comment claims, you must implement `Deref` and `DerefMut` for the type:

```
use std::ops::{Deref, DerefMut};

impl<T> Deref for Selector<T> {
    type Target = T;
    fn deref(&self) -> &T {
        &self.elements[self.current]
    }
}

impl<T> DerefMut for Selector<T> {
    fn deref_mut(&mut self) -> &mut T {
        &mut self.elements[self.current]
    }
}
```

Given those implementations, you can use a `Selector` like this:

```
let mut s = Selector {
    elements: vec!['x', 'y', 'z'],
    current: 2,
};

// Because `Selector` implements `Deref`, we can use the `*`
operator to
// refer to its current element.
assert_eq!(*s, 'z');

// Assert that 'z' is alphabetic, using a method of `char`
directly on a
// `Selector`, via deref coercion.
assert!(s.is_alphabetic());

// Change the 'z' to a 'w', by assigning to the `Selector`'s
referent.
*s = 'w';

assert_eq!(s.elements, ['x', 'y', 'w']);
```

The `Deref` and `DerefMut` traits are designed for implementing smart pointer types, like `Box`, `Rc`, and `Arc`, and types that serve as owning

versions of something you would also frequently use by reference, the way `Vec<T>` and `String` serve as owning versions of `[T]` and `str`. You should not implement `Deref` and `DerefMut` for a type just to make the `Target` type's methods appear on it automatically, the way a C++ base class's methods are visible on a subclass. This will not always work as you expect and can be confusing when it goes awry.

The deref coercions come with a caveat that can cause some confusion: Rust applies them to resolve type conflicts, but not to satisfy bounds on type variables. For example, the following code works fine:

```
let s = Selector {
    elements: vec!["good", "bad", "ugly"],
    current: 2,
};

fn show_it(thing: &str) {
    println!("{thing}");
}
show_it(&s);
```

In the call `show_it(&s)`, Rust sees an argument of type `&Selector<&str>` and a parameter of type `&str`, finds the `Deref<Target = str>` implementation, and rewrites the call as `show_it(s.deref())`, just as needed.

However, if you change `show_it` into a generic function, Rust is suddenly no longer cooperative:

```
use std::fmt::Display;

fn show_generic<T: Display>(thing: T) {
    println!("{thing}");
}

show_generic(&s);
```

Rust complains:

```
error: `Selector<&str>` doesn't implement `std::fmt::Display`
   |
41 |     show_generic(&s);
   |     ------------  ^ unsatisfied trait bound
   |     |
   |     required by a bound introduced by this call
   |
help: the trait `std::fmt::Display` is not implemented for
`Selector<&str>`
   |
 7 | struct Selector<T> {
   | ^^^^^^^^^^^^^^^^^^
   = note: required for `&Selector<&str>` to implement
`std::fmt::Display`
note: required by a bound in `show_generic`
   |
35 |  fn show_generic<T: Display>(thing: T) {
   |                     ^^^^^^^ required by this bound in
`show_generic`
help: consider dereferencing here
   |
41 |     show_generic(&*s);
   |                   +
```

This can be bewildering: How could making a function generic introduce an error? True, `Selector<&str>` does not implement `Display` itself, but it dereferences to `&str`, which certainly does.

Since you're passing an argument of type `&Selector<&str>` and the function's parameter type is `&T`, the type variable `T` must be `Selector<&str>`. Then, Rust checks whether the bound `T: Display` is satisfied: since it does not apply deref coercions to satisfy bounds on type variables, this check fails.

To work around this problem, you can spell out the coercion using the `as` operator:

```
show_it_generic(&s as &str);
```

Or, as the compiler suggests, you can force the coercion with `&*`:

```
show_it_generic(&*s);
```

# Default

Some types have a reasonably obvious default value: the default vector or string is empty, the default number is zero, the default `Option` is `None`, and so on. Types like this can implement the `std::default::Default` trait:

```
trait Default {
    fn default() -> Self;
}
```

The `default` method simply returns a fresh value of type `Self`. `String`'s implementation of `Default` is straightforward:

```
impl Default for String {
    fn default() -> String {
        String::new()
    }
}
```

All of Rust's collection types—`Vec`, `HashMap`, `BinaryHeap`, and so on—implement `Default`, with `default` methods that return an empty collection. This is helpful when you need to build a collection of values but want to let your caller decide exactly what sort of collection to build. For example, the `Iterator` trait's `partition` method splits the values the iterator produces into two collections, using a closure to decide where each value goes:

```
use std::collections::HashSet;
let squares = [4, 9, 16, 25, 36, 49, 64];
let (powers_of_two, impure): (HashSet<i32>, HashSet<i32>) =
    squares.iter().partition(|&n| n & (n - 1) == 0);

assert_eq!(powers_of_two.len(), 3);
assert_eq!(impure.len(), 4);
```

The closure `|&n| n & (n-1) == 0` uses some bit fiddling to recognize numbers that are powers of two, and `partition` uses that to

produce two `HashSets`. But of course, `partition` isn't specific to `HashSets`; you can use it to produce any sort of collection you like, as long as the collection type implements `Default`, to produce an empty collection to start with, and `Extend<T>`, to add a `T` to the collection. `String` implements `Default` and `Extend<char>`, so you can write:

```
let (upper, lower): (String, String) =
    "Great Teacher Onizuka".chars().partition(|&c|
c.is_uppercase());
assert_eq!(upper, "GTO");
assert_eq!(lower, "reat eacher nizuka");
```

Another common use of `Default` is to produce default values for structs that represent a large collection of parameters, most of which you won't usually need to change. For example, the `glium` crate provides Rust bindings for the powerful and complex OpenGL graphics library.

The `glium::DrawParameters` struct includes 24 fields, each controlling a different detail of how OpenGL should render some bit of graphics. The `glium` `draw` function expects a `DrawParameters` struct as an argument.

Since `DrawParameters` implements `Default`, you can create one to pass to `draw`, mentioning only those fields you want to change:

```
let params = glium::DrawParameters {
    line_width: Some(0.02),
    point_size: Some(0.02),
    ..Default::default()
};

target.draw(..., &params).unwrap();
```

This calls `Default::default()` to create a `DrawParameters` value initialized with the default values for all its fields and then uses the `..` syntax for structs to create a new one with the `line_width` and `point_size` fields changed, ready for you to pass it to `target.draw`.

If a type `T` implements `Default`, then the standard library implements `Default` automatically for `Rc<T>`, `Arc<T>`, `Box<T>`, `Cell<T>`, `RefCell<T>`, `Cow<T>`, `Mutex<T>`, and `RwLock<T>`. The default value for the type `Rc<T>`, for example, is an `Rc` pointing to the default value for type `T`.

If all the field types of a tuple type implement `Default`, then the tuple type does too, defaulting to a tuple holding each field's default value.

Rust does not implicitly implement `Default` for struct types, but if all of a struct's fields implement `Default`, you can implement `Default` for the struct automatically using `#[derive(Default)]`.

You can automatically implement `Default` for enum types with `#[derive(Default)]` too, by marking the default variant with `#[default]`:

```
#[derive(Default)]
enum Background {
    #[default]
    Empty,
    Color(Color),
    Image(PathBuf),
}
```

If the default variant has any fields, they must also implement `Default`.

## AsRef and AsMut

When a type implements `AsRef<T>`, that means you can borrow a `&T` from it efficiently. `AsMut` is the analogue for mutable references. Their definitions are as follows:

```
trait AsRef<T: ?Sized> {
    fn as_ref(&self) -> &T;
}

trait AsMut<T: ?Sized> {
```

```
    fn as_mut(&mut self) -> &mut T;
}
```

So, for example, `Vec<T>` implements `AsRef<[T]>`, and `String` implements `AsRef<str>`. You can also borrow a `String`'s contents as an array of bytes, so `String` implements `AsRef<[u8]>` as well.

`AsRef` is typically used to make functions more flexible in the argument types they accept. For example, the `std::fs::File::open` function is declared like this:

```
fn open<P: AsRef<Path>>(path: P) -> Result<File>
```

What `open` really wants is a `&Path`, the type representing a filesystem path. But with this signature, `open` accepts anything it can borrow a `&Path` from—that is, anything that implements `AsRef<Path>`. Such types include `String` and `str`, the operating system interface string types `OsString` and `OsStr`, and of course `PathBuf` and `Path`; see the library documentation for the full list. This is what allows you to pass string literals to `open`:

```
let dot_emacs = std::fs::File::open("/home/jimb/.emacs")?;
```

All of the standard library's filesystem access functions accept path arguments this way. For callers, the effect resembles that of an overloaded function in C++, although Rust takes a different approach toward establishing which argument types are acceptable.

But this can't be the whole story. A string literal is a `&str`, but the type that implements `AsRef<Path>` is `str`, without an `&`. And as we explained in "Deref and DerefMut", Rust doesn't try deref coercions to satisfy type variable bounds, so they won't help here either.

Fortunately, the standard library includes the blanket implementation:

```
impl<T, U> AsRef<U> for &T
where
```

```
    T: AsRef<U> + ?Sized,
    U: ?Sized,
{
    fn as_ref(&self) -> &U {
        (*self).as_ref()
    }
}
```

In other words, for any types `T` and `U`, if `T: AsRef<U>`, then `&T: AsRef<U>` as well: simply follow the reference and proceed as before. In particular, since `str: AsRef<Path>`, then `&str: AsRef<Path>` as well. In a sense, this is a way to get a limited form of deref coercion in checking `AsRef` bounds on type variables.

You might assume that if a type implements `AsRef<T>`, it should also implement `AsMut<T>`. However, there are cases where this isn't appropriate. For example, we've mentioned that `String` implements `AsRef<[u8]>`; this makes sense, as each `String` certainly has a buffer of bytes that can be useful to access as binary data. However, `String` further guarantees that those bytes are a well-formed UTF-8 encoding of Unicode text; if `String` implemented `AsMut<[u8]>`, that would let callers change the `String`'s bytes to anything they wanted, and you could no longer trust a `String` to be well-formed UTF-8. It only makes sense for a type to implement `AsMut<T>` if modifying the given `T` cannot violate the type's invariants.

Although `AsRef` and `AsMut` are pretty simple, providing standard, generic traits for reference conversion avoids the proliferation of more specific conversion traits. You should avoid defining your own `AsFoo` traits when you could just implement `AsRef<Foo>`.

## Borrow and BorrowMut

The `std::borrow::Borrow` trait is similar to `AsRef`: if a type implements `Borrow<T>`, then its `borrow` method efficiently borrows a `&T` from it. But `Borrow` imposes more restrictions: a type should

implement `Borrow<T>` only when a `&T` hashes and compares the same way as the value it's borrowed from. (Rust doesn't enforce this; it's just the documented intent of the trait.) This makes `Borrow` valuable in dealing with keys in hash tables and trees or when dealing with values that will be hashed or compared for some other reason.

This distinction matters when borrowing from `String`s, for example: `String` implements `AsRef<str>`, `AsRef<[u8]>`, and `AsRef<Path>`, but those three target types will generally have different hash values. Only the `&str` slice is guaranteed to hash like the equivalent `String`, so `String` implements only `Borrow<str>`.

`Borrow`'s definition is identical to that of `AsRef`; only the names have been changed:

```
trait Borrow<Borrowed: ?Sized> {
    fn borrow(&self) -> &Borrowed;
}
```

`Borrow` is designed to address a specific situation with generic hash tables and other associative collection types. For example, suppose you have a `std::collections::HashMap<String, i32>`, mapping strings to numbers. This table's keys are `String`s; each entry owns one.

What should the signature of the method that looks up an entry in this table be? Here's a first attempt:

```
impl<K, V> HashMap<K, V>
where
    K: Eq + Hash,
{
    fn get(&self, key: K) -> Option<&V> { ... }
}
```

This makes sense: to look up an entry, you must provide a key of the appropriate type for the table. But in this case, `K` is `String`; this signature would force you to pass a `String` by value to every call to `get`, which is clearly wasteful. You really just need a reference to the key:

```
impl<K, V> HashMap<K, V>
where
    K: Eq + Hash,
{
    fn get(&self, key: &K) -> Option<&V> { ... }
}
```

This is slightly better, but now you have to pass the key as a `&String`, so if you wanted to look up a constant string, you'd have to write:

```
hashtable.get(&"twenty-two".to_string())
```

This is ridiculous: it allocates a `String` buffer in the heap and copies the text into it, just so it can borrow it as a `&String`, pass it to `get`, and then drop it. It should be good enough to pass anything that can be hashed and compared with our key type; a `&str` should be perfectly adequate, for example. So here's the final iteration, which is what you'll find in the standard library:

```
impl<K, V> HashMap<K, V>
where
    K: Eq + Hash,
{
    fn get<Q>(&self, key: &Q) -> Option<&V>
    where
        K: Borrow<Q>,
        Q: Eq + Hash + ?Sized,
    { ... }
}
```

In other words, if you can borrow an entry's key as a `&Q` and the resulting reference hashes and compares just the way the key itself would, then clearly `&Q` ought to be an acceptable key type. Since `String` implements `Borrow<str>` and `Borrow<String>`, this final version of `get` allows you to pass either `&String` or `&str` as a key, as needed.

`Vec<T>` and `[T; N]` implement `Borrow<[T]>`. Every string-like type allows borrowing its corresponding slice type: `String` implements `Borrow<str>`, `PathBuf` implements `Borrow<Path>`, and so on. And

all the standard library's associative collection types use `Borrow` to decide which types can be passed to their lookup functions.

The standard library includes a blanket implementation so that every type `T` can be borrowed from itself: `T: Borrow<T>`. This ensures that `&K` is always an acceptable type for looking up entries in a `HashMap<K, V>`.

As a convenience, every `&mut T` type also implements `Borrow<T>`, returning a shared reference `&T` as usual. This allows you to pass mutable references to collection lookup functions without having to reborrow a shared reference, emulating Rust's usual implicit coercion from mutable references to shared references.

The `BorrowMut` trait is the analogue of `Borrow` for mutable references:

```
trait BorrowMut<Borrowed: ?Sized>: Borrow<Borrowed> {
    fn borrow_mut(&mut self) -> &mut Borrowed;
}
```

The same expectations described for `Borrow` apply to `BorrowMut` as well.

## From and Into

The `std::convert::From` and `std::convert::Into` traits represent conversions that consume a value of one type and return a value of another. Whereas the `AsRef` and `AsMut` traits borrow a reference of one type from another, `From` and `Into` take ownership of their argument, transform it, and then return ownership of the result back to the caller.

Their definitions are nicely symmetrical:

```
trait Into<T>: Sized {
    fn into(self) -> T;
}

trait From<T>: Sized {
    fn from(other: T) -> Self;
}
```

The standard library automatically implements the trivial conversion from each type to itself: every type `T` implements `From<T>` and `Into<T>`. Although the traits simply provide two ways to do the same thing, they lend themselves to different uses.

You generally use `Into` to make your functions more flexible in the arguments they accept. For example, if you write:

```
use std::net::Ipv4Addr;

fn ping<A>(address: A) -> std::io::Result<bool>
where
    A: Into<Ipv4Addr>,
{
    let ipv4_address = address.into();
    ...
}
```

Then `ping` can accept not just an `Ipv4Addr` as an argument but also a `u32` or a `[u8; 4]` array, since those types both conveniently happen to implement `Into<Ipv4Addr>`. (It's sometimes useful to treat an IPv4 address as a single 32-bit value, or an array of four bytes.) Because the only thing `ping` knows about `address` is that it implements `Into<Ipv4Addr>`, there's no need to specify which type you want when you call `into`; there's only one that could possibly work, so type inference fills it in for you.

As with `AsRef` in the previous section, the effect is like that of overloading a function in C++. With the definition of `ping` from before, we can make any of these calls:

```
println!("{:?}", ping(Ipv4Addr::new(23, 21, 68, 141)));  // pass
an Ipv4Addr
println!("{:?}", ping([66, 146, 219, 98]));              // pass
a [u8; 4]
println!("{:?}", ping(0xd076eb94_u32));                  // pass
a u32
```

The `From` trait, however, plays a different role. The `from` method serves as a generic constructor for producing an instance of a type from some other single value. For example, rather than `Ipv4Addr` having two methods named `from_array` and `from_u32`, it simply implements `From<[u8;4]>` and `From<u32>`, allowing us to write:

```
let addr1 = Ipv4Addr::from([66, 146, 219, 98]);
let addr2 = Ipv4Addr::from(0xd076eb94_u32);
```

We can let type inference sort out which implementation applies. Given an appropriate `From` implementation, the standard library automatically implements the corresponding `Into` trait. When you define your own type, if it has single-argument constructors, you should write them as implementations of `From<T>` for the appropriate types; Rust already knows how to adapt your conversion code from `From` into `Into`.

Because the `from` and `into` conversion methods take ownership of their arguments, a conversion can reuse the original value's resources to construct the converted value. For example, suppose you write:

```
let text = "Beautiful Soup".to_string();
let bytes: Vec<u8> = text.into();
```

The implementation of `Into<Vec<u8>>` for `String` simply takes the `String`'s heap buffer and repurposes it, unchanged, as the returned vector's element buffer. The conversion has no need to allocate or copy the text. This is another case where moves enable efficient implementations.

These conversions also provide a nice way to relax a value of a constrained type into something more flexible, without weakening the constrained type's guarantees. For example, a `String` guarantees that its contents are always valid UTF-8; its mutating methods are carefully restricted to ensure that nothing you can do will ever introduce bad UTF-8. But this example efficiently "demotes" a `String` to a block of plain bytes that you can do anything you like with: perhaps you're going to compress it or combine it with other binary data that isn't UTF-8.

Because `into` takes its argument by value, `text` is no longer initialized after the conversion, meaning that we can freely access the former `String`'s buffer without being able to corrupt any extant `String`.

However, cheap conversions are not part of `Into` and `From`'s contract. Whereas `AsRef` and `AsMut` conversions are expected to be cheap, `From` and `Into` conversions may allocate, copy, or otherwise process the value's contents. For example, `String` implements `From<&str>`, which copies the string slice into a new heap-allocated buffer for the `String`. And `std::collections::BinaryHeap<T>` implements `From<Vec<T>>`, which compares and reorders the elements according to its algorithm's requirements.

The `?` operator uses `From` and `Into` to clean up code in functions that could fail in multiple ways by automatically converting specific error types to general ones when needed. For instance, imagine a system that needs to read binary data and convert some portion of it from base-10 numbers written out as UTF-8 text. That means using `str::from_utf8` and the `FromStr` implementation for `i32`, which can each return errors of different types. Assuming we use the `anyhow::Error` type described in Chapter 7, the `?` operator will do the conversion for us:

```
fn parse_i32_bytes(b: &[u8]) -> anyhow::Result<i32> {
    Ok(str::from_utf8(b)?.parse::<i32>()?)
}
```

Like most error types, `Utf8Error` and `ParseIntError` implement the `std::error::Error` trait, and `anyhow` gives us a blanket `From` `impl` for converting from anything that implements `std::error::Error` to an `anyhow::Error`, which `?` automatically uses:

```
// (code from the `anyhow` crate)
impl<E> From<E> for Error
where
    E: std::error::Error + Send + Sync + 'static,
{
```

```
    fn from(error: E) -> Self {
        let backtrace = ...;
        Error::construct_from_std(error, backtrace)
    }
}
```

This turns what would have been a fairly large function with two `match` statements into a one-liner.

Before `From` and `Into` were added to the standard library, Rust code was full of ad hoc conversion traits and construction methods, each specific to a single type. `From` and `Into` codify conventions that you can follow to make your types easier to use, since your users are already familiar with them. Other libraries and the language itself can also rely on these traits as a canonical, standardized way to encode conversions.

`From` and `Into` are infallible traits—their API requires that conversions will not fail. Unfortunately, many conversions are more complex than that. For example, large integers like `i64` can store numbers far larger than `i32`, and converting a number like `2_000_000_000_000_000i64` into `i32` doesn't make much sense without some additional information. Doing a simple bitwise conversion, in which the first 32 bits are thrown out, doesn't often yield the result we would hope for:

```
let huge = 2_000_000_000_000_000i64;
let smaller = huge as i32;
println!("{smaller}");  // -1454759936
```

There are many options for handling this situation. Depending on the context, such a "wrapping" conversion might be appropriate. On the other hand, applications such as digital signal processing and control systems can often make do with a "saturating" conversion, in which numbers larger than the maximum possible value are limited to that maximum.

## TryFrom and TryInto

Since it's not clear how such a conversion should behave, Rust doesn't implement `From<i64>` for `i32`, or any other conversion between numerical types that would lose information. Instead, `i32` implements `TryFrom<i64>`. `TryFrom` and `TryInto` are the fallible cousins of `From` and `Into` and are similarly reciprocal; implementing `TryFrom` means that `TryInto` is implemented as well.

Their definitions are only a little more complex than `From` and `Into`:

```
pub trait TryFrom<T>: Sized {
    type Error;
    fn try_from(value: T) -> Result<Self, Self::Error>;
}

pub trait TryInto<T>: Sized {
    type Error;
    fn try_into(self) -> Result<T, Self::Error>;
}
```

The `try_into()` method gives us a `Result`, so we can choose what to do in the exceptional case, such as a number that's too large to fit in the resulting type:

```
// Saturate on overflow, rather than wrapping
let smaller: i32 = huge.try_into().unwrap_or(i32::MAX);
```

To also handle the negative case, we can use the `unwrap_or_else()` method of `Result`:

```
let smaller: i32 = huge.try_into().unwrap_or_else(|_|{
    if huge >= 0 {
        i32::MAX
    } else {
        i32::MIN
    }
});
```

Implementing fallible conversions for your own types is easy, too. The `Error` type can be as simple, or as complex, as a particular application

demands. Here, the standard library uses an empty struct, providing no information beyond the fact that an error occurred, since the only possible error is an overflow. On the other hand, conversions between more complex types might want to return more information:

```
impl TryInto<LinearShift> for Transform {
    type Error = TransformError;

    fn try_into(self) -> Result<LinearShift, Self::Error> {
        if !self.normalized() {
            return Err(TransformError::NotNormalized);
        }
        ...
    }
}
```

Where `From` and `Into` relate types with simple conversions, `TryFrom` and `TryInto` extend the simplicity of `From` and `Into` conversions with the expressive error handling afforded by `Result`. These four traits can be used together to relate many types in a single crate.

## ToOwned

Given a reference, the usual way to produce an owned copy of its referent is to call `clone`, assuming the type implements `std::clone::Clone`. But what if you want to clone a `&str` or a `&[i32]`? What you probably want is a `String` or a `Vec<i32>`, but `Clone`'s definition doesn't permit that: by definition, cloning a `&T` must always return a value of type `T`, and `str` and `[u8]` are dynamically sized; they aren't even types that a function could return.

The `std::borrow::ToOwned` trait provides a slightly looser way to convert a reference to an owned value:

```
trait ToOwned {
    type Owned: Borrow<Self>;
    fn to_owned(&self) -> Self::Owned;
}
```

Unlike `clone`, which must return exactly `Self`, `to_owned` can return anything you could borrow a `&Self` from: the `Owned` type must implement `Borrow<Self>`. You can borrow a `&[T]` from a `Vec<T>`, so `[T]` can implement `ToOwned<Owned = Vec<T>>`, as long as `T` implements `Clone`, so that we can copy the slice's elements into the vector. Similarly, `str` implements `ToOwned<Owned = String>`, `Path` implements `ToOwned<Owned = PathBuf>`, and so on.

## Borrow and ToOwned at Work: The Humble Cow

Making good use of Rust involves thinking through questions of ownership, like whether a function should receive a parameter by reference or by value. Usually you can settle on one approach or the other, and the parameter's type reflects your decision. But in some cases you cannot decide whether to borrow or own until the program is running; the `std::borrow::Cow` type (for "clone on write") provides one way to do this.

Its definition is shown here:

```
enum Cow<'a, B: ?Sized>
where
    B: ToOwned,
{
    Borrowed(&'a B),
    Owned(<B as ToOwned>::Owned),
}
```

A `Cow<B>` either borrows a shared reference to a `B` or owns a value from which we could borrow such a reference. Since `Cow` implements `Deref`, you can call methods on it as if it were a shared reference to a `B`: if it's `Owned`, it borrows a shared reference to the owned value; and if it's `Borrowed`, it just hands out the reference it's holding.

You can also get a mutable reference to a `Cow`'s value by calling its `to_mut` method, which returns a `&mut B`. If the `Cow` happens to be

`Cow::Borrowed`, `to_mut` simply calls the reference's `to_owned` method to get its own copy of the referent, changes the `Cow` into a `Cow::Owned`, and borrows a mutable reference to the newly owned value. This is the "clone on write" behavior the type's name refers to.

Similarly, `Cow` has an `into_owned` method that promotes the reference to an owned value, if necessary, and then returns it, moving ownership to the caller and consuming the `Cow` in the process.

One common use for `Cow` is to return either a statically allocated string constant or a computed string. For example, suppose you need to convert an error enum to a message. Most of the variants can be handled with fixed strings, but some of them have additional data that should be included in the message.

You can return a `Cow<'static, str>`:

```
use std::borrow::Cow;
use std::path::PathBuf;

fn describe(error: &Error) -> Cow<'static, str> {
    match *error {
        Error::OutOfMemory => "out of memory".into(),
        Error::StackOverflow => "stack overflow".into(),
        Error::MachineOnFire => "machine on fire".into(),
        Error::Unfathomable => "machine bewildered".into(),
        Error::FileNotFound(ref path) => {
            format!("file not found: {}", path.display()).into()
        }
    }
}
```

This code uses `Cow`'s implementation of `Into` to construct the values. Most arms of this `match` statement return a `Cow::Borrowed` referring to a statically allocated string. But when we get a `FileNotFound` variant, we use `format!` to construct a message incorporating the given filename. This arm of the `match` statement produces a `Cow::Owned` value.

Callers of `describe` that don't need to change the value can simply treat the `Cow` as a `&str`:

```
println!("Disaster has struck: {}", describe(&error));
```

Callers who do need an owned value can readily produce one:

```
let mut log: Vec<String> = Vec::new();
...
log.push(describe(&error).into_owned());
```

Using `Cow` helps `describe` and its callers put off allocation until the moment it becomes necessary.

# Chapter 14. Closures

*Save the environment! Create a closure today!*

—Cormac Flanagan

Sorting a vector of integers is easy:

```
integers.sort();
```

It is, therefore, a sad fact that when we want some data sorted, it's hardly ever a vector of integers. We typically have records of some kind, and the built-in `sort` method typically does not work:

```
struct City {
    name: String,
    population: i64,
    country: String,
    ...
}

fn sort_cities(cities: &mut Vec<City>) {
    cities.sort();  // error: how do you want them sorted?
}
```

Rust complains that `City` does not implement `std::cmp::Ord`. We need to specify the sort order, like this:

```
/// Helper function for sorting cities by latitude.
fn city_latitude(city: &City) -> i64 {
    city.latitude
}

fn sort_cities(cities: &mut Vec<City>) {
    cities.sort_by_key(city_latitude);  // ok
}
```

The helper function, `city_latitude`, takes a `City` record and extracts the *key*, the field by which we want to sort our data. The `sort_by_key` method takes this key function as a parameter.

This works fine, but it's more concise to write the helper function as a *closure*, an anonymous function expression:

```
fn sort_cities(cities: &mut Vec<City>) {
    cities.sort_by_key(|city| city.latitude);
}
```

The closure here is `|city| city.latitude`. It takes an argument `city` and returns `city.latitude`. Rust infers the argument type and return type from how the closure is used.

Other examples of standard library features that accept closures include:

- `Iterator` methods such as `map` and `filter`, for working with sequential data. We'll cover these methods in Chapter 15.
- Threading APIs like `thread::spawn`, which starts a new system thread. Concurrency is all about moving work to other threads, and closures conveniently represent units of work. We'll cover these features in Chapter 19.
- Some methods that conditionally need to compute a default value, like the `or_insert_with` method of `HashMap` entries. This method either gets or creates an entry in a `HashMap`, and it's used when the default value is expensive to compute. The default value is passed in as a closure that is called only if a new entry must be created.

Of course, anonymous functions are everywhere these days, even in languages like Java, C#, Python, and C++ that didn't originally have them. We'll assume you've seen anonymous functions before and focus on what makes Rust's closures a little different. In this chapter, you'll learn how to use closures with standard library methods, how a closure can "capture" variables in its scope, how to write your own functions and methods that

take closures as arguments, and how to store closures for later use as callbacks. We'll also explain how Rust closures are implemented and why they're faster than you might expect.

## Capturing Variables

A closure can use data that belongs to an enclosing function. For example:

```
/// Sorts cities by population according to a demographic
database.
fn sort_by_population(cities: &mut Vec<City>, db: Demographics) {
    cities.sort_by_key(|city| db.get_population(city));
}
```

The closure here uses `db`, owned by the enclosing function `sort_by_population`. We say that the closure "captures" `db`. This is one of the classic features of closures, so naturally, Rust supports it; but in Rust, this feature comes with a string attached.

In most languages with closures, garbage collection plays an important role. For example, consider this JavaScript code:

```
// Starts an animation that rearranges the rows in a table of
cities.
function startSortingAnimation(cities, db) {
    // Helper function that we'll use to sort the table.
    // Note that this function refers to db.
    function keyfn(city) {
        return db.get_population(city);
    }

    if (pendingSort)
        pendingSort.cancel();

    // Now kick off an animation, passing keyfn to it.
    // The sorting algorithm will call keyfn later.
    pendingSort = new SortingAnimation(cities, keyfn);
}
```

The closure `keyfn` is stored in the new `SortingAnimation` object. It's meant to be called after `startSortingAnimation` returns. Now, normally when a function returns, all its variables and arguments go out of scope and are discarded. But here, the JavaScript engine must keep `db` around somehow, since the closure uses it. Most JavaScript engines do this by allocating `db` in the heap and letting the garbage collector reclaim it later.

Rust doesn't have garbage collection. How will this work? To answer this question, we'll look at two examples.

## Closures That Borrow

First, let's repeat the opening example of this section:

```
/// Sorts cities by population according to a demographic
database.
fn sort_by_population(cities: &mut Vec<City>, db: Demographics) {
    cities.sort_by_key(|city| db.get_population(city));
}
```

In this case, when Rust creates the closure, it automatically borrows a reference to `db`. It stands to reason: the closure refers to `db`, so it must have a reference to it.

The rest is simple. The closure is subject to the rules about borrowing and lifetimes that we described in Chapter 5. In particular, since the closure contains a reference to `db`, Rust won't let it outlive `db`. Since the closure is only used during sorting, this example is fine.

In short, Rust ensures safety by using lifetimes instead of garbage collection. Rust's way is faster: even a fast heap allocation will be slower than storing `db` on the stack, as Rust does in this case.

## Closures That Steal

The second example is trickier:

```
use std::thread;

fn start_sorting_thread(
    mut cities: Vec<City>,
    db: Demographics,
) -> thread::JoinHandle<Vec<City>> {
    let key_fn = |city: &City| -> Option<i64> {
db.get_population(city) };

    thread::spawn(|| {
        cities.sort_by_key(key_fn);
        cities
    })
}
```

This is a bit more like what our JavaScript example was doing: `thread::spawn` takes a closure and calls it in a new system thread. Note that `||` is the closure's empty argument list.

The new thread runs in parallel with the caller. When the closure returns, the new thread exits. (The closure's return value is sent back to the calling thread as a `JoinHandle` value. We'll cover that in Chapter 19.)

Again, the closure `key_fn` contains a reference to `db`. But this time, Rust can't guarantee that the reference is used safely. Rust therefore rejects this program:

```
error: closure may outlive the current function, but it borrows
`db`,
       which is owned by the current function
   |
33 | let key_fn = |city: &City| -> Option<i64> {
db.get_population(city) };
   |              ^^^^^^^^^^^^^^^^^^^^^^^^^^^^   -- `db` is
borrowed here
   |              |
   |              may outlive borrowed value `db`
```

In fact, there are two problems here, because `cities` is shared unsafely as well. Quite simply, the new thread created by `thread::spawn` might not finish its work before `cities` and `db` are destroyed at the end of the function.

The solution to both problems is the same: tell Rust to *move* `cities` and `db` into the closures that use them instead of borrowing references to them:

```
fn start_sorting_thread(
    mut cities: Vec<City>,
    db: Demographics,
) -> thread::JoinHandle<Vec<City>> {
    let key_fn = move |city: &City| -> Option<i64> {
        db.get_population(city)
    };

    thread::spawn(move || {
        cities.sort_by_key(key_fn);
        cities
    })
}
```

The only thing we've changed is to add the `move` keyword before each of the two closures. The `move` keyword tells Rust that, even if it looks like a closure only uses references to the variables it uses, it doesn't just borrow those variables: it steals them.

The first closure, `key_fn`, takes ownership of `db`. Then the second closure takes ownership of both `cities` and `key_fn`.

Rust thus offers two ways for closures to get data from enclosing scopes: moves and borrowing. Rust will infer whether a closure needs to steal any captured values, but it only considers the body of the closure, not its context. The `move` keyword lets us override Rust's decision-making. Otherwise, closures follow the same rules about moves and borrowing that we covered in Chapters 4 and 5. A few cases in point:

- Just as everywhere else in the language, if a closure would move a value of a copyable type, like `i32`, it copies the value instead. So if `Demographics` happened to be a copyable type, we could keep using `db` even after creating a `move` closure that uses it.
- Values of noncopyable types, like `Vec<City>`, really are moved: the preceding code transfers `cities` to the new thread, by way of

the `move` closure. Rust would not let us access `cities` by name after creating the closure.

- As it happens, this code doesn't need to use `cities` after the point where the closure moves it. If we did, though, the workaround would be easy: we could tell Rust to clone `cities` and store the copy in a different variable. The closure would steal only one of the copies—whichever one it refers to.

We get something important by accepting Rust's strict rules: thread safety. It is precisely because the vector is moved, rather than being shared across threads, that we know the old thread won't free the vector while the new thread is modifying it.

## Function and Closure Types

Throughout this chapter, we've seen functions and closures used as values. Naturally, this means that they have types. For example:

```
fn city_latitude(city: &City) -> i64 {
    city.latitude
}
```

This function takes one argument (a `&City`) and returns an `i64`. It has the type `fn(&City) -> i64`.

You can do all the same things with functions that you do with other values. You can store them in variables. You can use all the Rust syntax to compute function values:

```
// Choose between two functions of type `fn (&City) -> f64`
let my_key_fn = if user.prefs.latitude_sort {
    city_latitude
} else {
    city_longitude
};

cities.sort_by_key(my_key_fn);
```

Structs may have function-typed fields. Generic types like `Vec` can store scads of functions, called *function pointers*, or `fn` types. These types, such as `fn(u32) -> u32`, act a lot like closures:

```
fn add_ten(x: u32) -> u32 {
    x + 10
}

let fn_ptr: fn(u32) -> u32 = add_ten;
let eleven = fn_ptr(1);  //11
```

In fact, closures that don't capture anything from their environment are effectively `fn`s, since they don't need to hold any extra information about captured variables. If you specify the appropriate `fn` type, either in a binding or in a function signature, the compiler is happy to let you use them that way:

```
let closure_ptr: fn(u32) -> u32 = |x| x + 1;
let two = closure_ptr(1);  // 2
```

Unlike capturing closures, these function pointers are tiny, consisting only of the memory address of the function's machine code, just like a function pointer in C++.

A function can also take another function as an argument. For example:

```
/// Given a list of cities and a test function,
/// this counts how many cities pass the test.
fn count_selected_cities(
    cities: &Vec<City>,
    test_fn: fn(&City) -> bool,
) -> usize {
    let mut count = 0;
    for city in cities {
        if test_fn(city) {
            count += 1;
        }
    }
    count
}
```

```
/// An example of a test function. Note that the type of
/// this function is `fn(&City) -> bool`, the same as
/// the `test_fn` argument to `count_selected_cities`.
fn is_irish(city: &City) -> bool {
    city.country == "Ireland"
}

// How many cities are in Ireland?
let n = count_selected_cities(&my_cities, is_irish);
```

If you're familiar with function pointers in C/C++, you'll see that Rust's function values are exactly the same thing. After all this, it may come as a surprise that closures do *not* have the same type as functions:

```
let country = preferences.country();
let n = count_selected_cities(
    &my_cities,
    |city| city.country == country,  // error: mismatched types
);
```

The second argument causes a type error. To support closures, we must change the type signature of this function. It needs to look like this:

```
fn count_selected_cities<F>(cities: &Vec<City>, test_fn: F) ->
usize
where
    F: Fn(&City) -> bool,
{
    let mut count = 0;
    for city in cities {
        if test_fn(city) {
            count += 1;
        }
    }
    count
}
```

We have changed only the type signature of `count_selected_cities`, not the body. The new version is generic. It takes a `test_fn` of any type `F` as long as `F` implements the special trait `Fn(&City) -> bool`. This trait is automatically implemented by all

functions and most closures that take a single `&City` as an argument and return a Boolean value:

```
fn(&City) -> bool     // fn type (function pointer: fn or non-
capturing closure)
Fn(&City) -> bool     // Fn trait (also covers capturing closure
types)
```

This special syntax is built into the language. The `->` and return type are optional; if omitted, the return type is `()`. The new version of `count_selected_cities` accepts either a function or a closure:

```
count_selected_cities(
    &my_cities,
    is_irish,  // ok
);

count_selected_cities(
    &my_cities,
    |city| city.country == "Ireland",  // also ok
);
```

Why didn't our first attempt work? Well, a closure is callable, but it's not necessarily as simple as a function pointer; a closure can be used as a function pointer, written `fn`, only if it doesn't capture any variables. The closure `|city| city.country == "Ireland"` has its own type that's not a `fn` type.

In fact, every closure you write has its own type, because a closure may contain data: values either borrowed or stolen from enclosing scopes. This could be any number of variables, in any combination of types. So every closure has an ad hoc type created by the compiler, large enough to hold that data. No two closures have exactly the same type. But every closure implements a `Fn` trait; the closure in our example implements `Fn(&City) -> i64`.

Since every closure has its own type, code that works with closures usually needs to be generic, like `count_selected_cities`. It's a little clunky

to spell out the generic types each time, but to see the advantages of this design, just read on.

## Closure Performance

Rust's closures are designed to be fast: faster than function pointers, fast enough that you can use them even in red-hot, performance-sensitive code. If you're familiar with C++ lambdas, you'll find that Rust closures are just as fast and compact, but safer.

In most languages, closures are allocated in the heap, dynamically dispatched, and garbage collected. So creating, calling, and collecting each of them costs a tiny bit of extra CPU time. Worse, closures tend to rule out *inlining*, a key technique compilers use to eliminate function call overhead and enable a raft of other optimizations. All told, closures are slow enough in these languages that it can be worth manually removing them from tight inner loops.

Rust closures have none of these performance drawbacks. They're not garbage collected. Like everything else in Rust, they aren't allocated in the heap unless you put them in a `Box`, `Vec`, or other container. And since each closure has a distinct type, whenever the Rust compiler knows the type of the closure you're calling, it can inline the code for that particular closure. This makes it OK to use closures in tight loops, and Rust programs often do so, enthusiastically, as you'll see in Chapter 15.

Figure 14-1 shows how Rust closures are laid out in memory. At the top of the figure, we show a couple of local variables that our closures will refer to: a string `food` and a simple enum `weather`, whose numeric value happens to be 27.

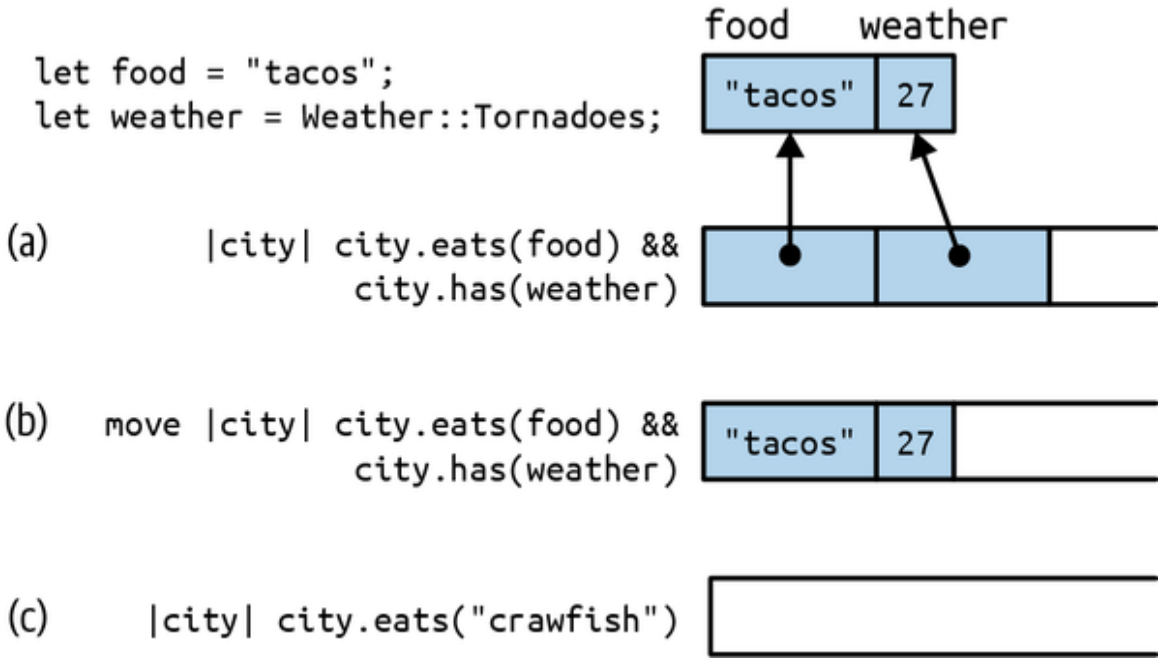


*Figure 14-1. Layout of closures in memory*

Closure (a) uses both variables. Apparently we're looking for cities that have both tacos and tornadoes. In memory, this closure looks like a small struct containing references to the variables it uses.

Note that it doesn't contain a pointer to its code! That's not necessary: as long as Rust knows the closure's type, it knows which code to run when you call it.

Closure (b) is exactly the same, except it's a `move` closure, so it contains values instead of references.

Closure (c) doesn't use any variables from its environment. The struct is empty, so this closure does not take up any memory at all.

As the figure shows, these closures don't take up much space. But even those few bytes are not always needed in practice. Often, the compiler can inline all calls to a closure, and then even the small structs shown in this figure are optimized away.

In "Callbacks", we'll show how to allocate closures in the heap and call them dynamically, using `dyn`. That is a bit slower, but it is still as fast as any other `dyn` method call.

# Closures and Safety

Throughout the chapter so far, we've talked about how Rust ensures that closures respect the language's safety rules when they borrow or move variables from the surrounding code. But there are some further consequences that are not exactly obvious. In this section, we'll explain a bit more about what happens when a closure drops or modifies a captured value.

## Closures That Kill

We have seen closures that borrow values and closures that steal them; it was only a matter of time before they went all the way bad. Of course, *kill* is not really the right terminology. In Rust, we *drop* values. The most straightforward way to do it is to call `drop()`:

```
let my_string = "hello".to_string();
let f = || drop(my_string);
```

When `f` is called, `my_string` is dropped. Note that we don't have to write `move` here. Rust is smart enough to see that we *must* mean for `my_string` to be stolen by `f`.

So what happens if we call it twice?

```
f();
f();
```

Let's think it through. The first time we call `f`, it drops `my_string`, which means the memory where the string is stored is freed, returned to the system. The second time we call `f`, the same thing happens. It's a *double free*, a classic mistake in C++ programming that triggers undefined behavior.

Dropping a `String` twice would be an equally bad idea in Rust. Fortunately, Rust can't be fooled so easily:

```
f();  // ok
f();  // error: use of moved value
```

Rust knows this closure can't be called twice.

A closure that can be called only once may seem like a rather extraordinary thing, but we've been talking throughout this book about ownership and lifetimes. The idea of values being used up (that is, moved) is one of the core concepts in Rust. It works the same with closures as with everything else.

## FnOnce

Let's try once more to trick Rust into dropping a `String` twice. This time, we'll use this generic function:

```
fn call_twice<F>(closure: F)
where
    F: Fn(),
{
    closure();
    closure();
}
```

This generic function may be passed any closure that implements the trait `Fn()`: that is, closures that take no arguments and return `()`. (As with functions, the return type can be omitted if it's `()`; `Fn()` is shorthand for `Fn() -> ()`.)

Now what happens if we pass our unsafe closure to this generic function?

```
let my_string = "hello".to_string();
let f = || drop(my_string);
call_twice(f);
```

Again, the closure will drop `my_string` when it's called. Calling it twice would be a double free. But again, Rust is not fooled:

```
error: expected a closure that implements the `Fn` trait, but
       this closure only implements `FnOnce`
    |
  8 | let f = || drop(my_string);
    |         ^^      ---------
    |         |       |
    |         |       closure is `FnOnce` because it moves the
variable
    |         |       `my_string` out of its environment
    |         this closure implements `FnOnce`, not `Fn`
  9 | call_twice(f);
    |            - the requirement to implement `Fn` derives from
here
```

This error message tells us more about how Rust handles “closures that kill.” They could have been banned from the language entirely, but cleanup closures are useful sometimes. So instead, Rust restricts their use. Closures that drop values, like `f`, are not allowed to have `Fn`. They are, quite literally, no `Fn` at all. They implement a less powerful trait, `FnOnce`, the trait of closures that can be called once. The first time you call a `FnOnce` closure, *the closure itself is used up.* It’s as though the two traits, `Fn` and `FnOnce`, were defined like this:

```
// Pseudocode for `Fn` and `FnOnce` traits with no arguments.
trait Fn() -> R {
    fn call(&self) -> R;
}

trait FnOnce() -> R {
    fn call_once(self) -> R;
}
```

Just as an arithmetic expression like `a + b` is shorthand for a method call, `Add::add(a, b)`, Rust treats `closure()` as shorthand for one of the two trait methods shown in the preceding example. For a `Fn` closure, `closure()` expands to `closure.call()`. This method takes `self` by reference, so the closure is not moved. But if the closure is only safe to call once, then `closure()` expands to `closure.call_once()`. That

method takes `self` by value, so the closure is used up.Of course we've been deliberately stirring up trouble here by using `drop()`.

In practice, you'll mostly get into this situation by accident. It doesn't happen often, but once in a while you'll write some closure code that unintentionally uses up a value:

```
let dict = produce_glossary();
let debug_dump_dict = || {
    for (key, value) in dict {  // oops!
        println!("{key:?} - {value:?}");
    }
};
```

Then, when you call `debug_dump_dict()` more than once, you'll get an error message like this:

```
error: use of moved value: `debug_dump_dict`
   |
19 |     debug_dump_dict();
   |     ----------------- `debug_dump_dict` moved due to this
call
20 |     debug_dump_dict();
   |     ^^^^^^^^^^^^^^^^ value used here after move
   |
note: closure cannot be invoked more than once because it moves
the variable
`dict` out of its environment
   |
13 |         for (key, value) in dict {
   |                             ^^^^
```

To debug this, we have to figure out why the closure is a `FnOnce`. Which value is being used up here? The compiler helpfully points out that it's `dict`, which in this case is the only one we're referring to at all. Ah, there's the bug: we're using up `dict` by iterating over it directly. We should be looping over `&dict`, rather than plain `dict`, to access the values by reference:

```
let debug_dump_dict = || {
    for (key, value) in &dict {  // does not use up dict
```

```
            println!("{key:?} - {value:?}");
        }
    };
```

This fixes the error; the function is now a `Fn` and can be called any number of times.

## FnMut

There is one more kind of closure, the kind that contains mutable data or `mut` references. Rust considers non-`mut` values safe to share across threads. But it wouldn't be safe to share non-`mut` closures that contain `mut` data: calling such a closure from multiple threads could lead to all sorts of race conditions as multiple threads try to read and write the same data at the same time.

Therefore, Rust has one more category of closure, `FnMut`, the category of closures that write. `FnMut` closures are called by `mut` reference, as if they were defined like this:

```
// Pseudocode for `Fn`, `FnMut`, and `FnOnce` traits.
trait Fn() -> R {
    fn call(&self) -> R;
}

trait FnMut() -> R {
    fn call_mut(&mut self) -> R;
}

trait FnOnce() -> R {
    fn call_once(self) -> R;
}
```

Any closure that requires `mut` access to a value, but doesn't drop any values, is a `FnMut` closure. For example:

```
let mut i = 0;
let incr = || {
    i += 1;  // incr borrows a mut reference to i
    println!("Ding! i is now: {i}");
```

```
};
call_twice(incr);
```

The way we wrote `call_twice`, it requires a `Fn`. Since `incr` is a `FnMut` and not a `Fn`, this code fails to compile. There's an easy fix, though. To understand the fix, let's take a step back and summarize what you've learned about the three categories of Rust closures:

- `Fn` is the family of closures and functions that you can call multiple times without restriction. This highest category also includes all `fn` functions.
- `FnMut` is the family of closures that can be called multiple times if the closure itself is declared `mut`.
- `FnOnce` is the family of closures that can be called once, if the caller owns the closure.

Every `Fn` meets the requirements for `FnMut`, and every `FnMut` meets the requirements for `FnOnce`. As shown in Figure 14-2, they're not three separate categories. Instead, `Fn()` is a subtrait of `FnMut()`, which is a subtrait of `FnOnce()`. This makes `Fn` the most exclusive and most powerful category. `FnMut` and `FnOnce` are broader categories that include closures with usage restrictions.

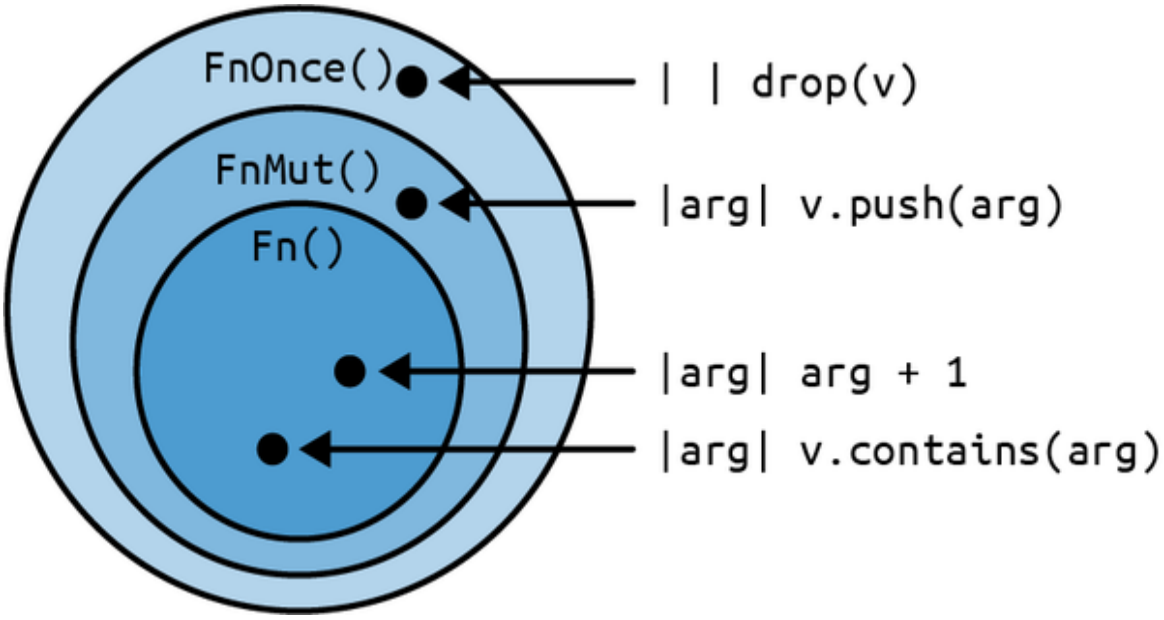


*Figure 14-2. Venn diagram of the three closure categories*

Now that we've organized what we know, it's clear that to accept the widest possible swath of closures, our `call_twice` function really ought to accept all `FnMut` closures, like this:

```
fn call_twice<F>(mut closure: F)
where
    F: FnMut(),
{
    closure();
    closure();
}
```

The bound on the first line was `F: Fn()`, and now it's `F: FnMut()`. With this change, we still accept all `Fn` closures, and we additionally can use `call_twice` on closures that mutate data:

```
let mut i = 0;
call_twice(|| i += 1);  // ok!
assert_eq!(i, 2);
```

## Copy and Clone for Closures

Just as Rust automatically figures out which closures can be called only once, it can figure out which closures can implement `Copy` and `Clone` and which cannot.

As we explained earlier, closures are represented as structs that contain either the values (for `move` closures) or references to the values (for non-`move` closures) of the variables they capture. The rules for `Copy` and `Clone` on closures are just like the `Copy` and `Clone` rules for regular structs. A non-`move` closure that doesn't mutate variables holds only shared references, which are both `Clone` and `Copy`, so that closure is both `Clone` and `Copy` as well:

```
let y = 10;
let add_y = |x| x + y;
let copy_of_add_y = add_y;                    // This closure is
`Copy`, so...
assert_eq!(add_y(copy_of_add_y(22)), 42);  // ... we can call
both.
```

On the other hand, a non-`move` closure that *does* mutate values has mutable references within its internal representation. Mutable references are neither `Clone` nor `Copy`, so neither is a closure that uses them:

```
let mut x = 0;
let mut add_to_x = |n| { x += n; x };

let copy_of_add_to_x = add_to_x;          // this moves, rather
than copies
assert_eq!(add_to_x(copy_of_add_to_x(1)), 2);  // error: use of
moved value
```

For a `move` closure, the rules are even simpler. If everything a `move` closure captures is `Copy`, it's `Copy`. If everything it captures is `Clone`, it's `Clone`. For instance:

```
let mut greeting = String::from("Hello, ");
let greet = move |name| {
    greeting.push_str(name);
    println!("{greeting}");
```

```
};
greet.clone()("Alfred");
greet.clone()("Bruce");
```

This `.clone()(...)` syntax is a little weird, but it just means that we clone the closure and then call the clone. This program outputs:

```
Hello, Alfred
Hello, Bruce
```

When `greeting` is used in `greet`, it's moved into the struct that represents `greet` internally, because it's a `move` closure. So, when we clone `greet`, everything inside it is cloned, too. There are two copies of `greeting`, which are each modified separately when the clones of `greet` are called. This isn't so useful on its own, but when you need to pass the same closure into more than one function, it can be very helpful.

## Callbacks

A lot of libraries use *callbacks* as part of their API: functions provided by the user, for the library to call later. In fact, you've seen some APIs like that already in this book. Back in Chapter 2, we used the `actix-web` framework to write a simple web server. One important part of that program was the router, which looked like this:

```
App::new()
    .route("/", web::get().to(get_index))
    .route("/gcd", web::post().to(post_gcd))
```

The purpose of the router is to route incoming requests from the internet to the bit of Rust code that handles that particular kind of request. In this example, `get_index` and `post_gcd` were the names of functions that we declared elsewhere in the program, using the `fn` keyword. But we could have passed closures instead, like this:

```
App::new()
    .route(
        "/",
        web::get().to(|| {
            HttpResponse::Ok()
                .content_type("text/html")
                .body("<title>GCD Calculator</title>...")
        }),
    )
    .route(
        "/gcd",
        web::post().to(|form: web::Form<GcdParameters>| {
            HttpResponse::Ok()
                .content_type("text/html")
                .body(format!(
                    "The GCD of {} and {} is {}.",
                    form.n, form.m, gcd(form.n, form.m),
                ))
        }),
    )
```

This is because `actix-web` was written to accept any thread-safe `Fn` as an argument. How can we do that in our own programs? Let's try writing our own simple router from scratch, without using any code from `actix-web`. We can begin by declaring a few types to represent HTTP requests and responses:

```
struct Request {
    method: String,
    url: String,
    headers: HashMap<String, String>,
    body: Vec<u8>,
}

struct Response {
    code: u32,
    headers: HashMap<String, String>,
    body: Vec<u8>,
}
```

Now the job of a router is simply to store a table that maps URLs to callbacks so that the right callback can be called on demand. (For

simplicity's sake, we'll only allow users to create routes that match a single exact URL.)

```
struct BasicRouter<C>
where
    C: Fn(&Request) -> Response,
{
    routes: HashMap<String, C>,
}

impl<C> BasicRouter<C>
where
    C: Fn(&Request) -> Response,
{
    /// Creates an empty router.
    fn new() -> BasicRouter<C> {
        BasicRouter {
            routes: HashMap::new(),
        }
    }

    /// Adds a route to the router.
    fn add_route(&mut self, url: &str, callback: C) {
        self.routes.insert(url.to_string(), callback);
    }
}
```

Unfortunately, we've made a mistake. Did you notice it? This router works fine as long as we add only one route to it:

```
let mut router = BasicRouter::new();
router.add_route("/", |_| get_form_response());
```

This much compiles and runs. Unfortunately, if we add another route:

```
router.add_route("/gcd", |req| get_gcd_response(req));
```

Then we get errors:

```
error: mismatched types
   |
71 |     router.add_route("/gcd", |req| get_gcd_response(req));
```

```
   |             ---------          ^^^^^^^^^^^^^^^^^^^^^^^^^^^
   |             |                  expected closure, found a
different closure
   |             arguments to this method are incorrect
   |
   = note: expected closure `{closure@bad_router.rs:70:27:
70:30}`
              found closure `{closure@bad_router.rs:71:30:
71:35}`
   = note: no two closures, even if identical, have the same type
   = help: consider boxing your closure and/or using it as a
trait object
```

Our mistake was in how we defined the `BasicRouter` type:

```
struct BasicRouter<C>
where
    C: Fn(&Request) -> Response,
{
    routes: HashMap<String, C>,
}
```

We unwittingly declared that each `BasicRouter` has a single callback type `C`, and all the callbacks in the `HashMap` are of that type. Back in "Which to Use", we showed a `Salad` type that had the same problem:

```
struct Salad<V: Vegetable> {
    veggies: Vec<V>,
}
```

The solution is the same as the salad: we want to support a variety of types, so we need to use boxes and `dyn`:

```
type BoxedCallback = Box<dyn Fn(&Request) -> Response>;

struct BasicRouter {
    routes: HashMap<String, BoxedCallback>,
}
```

Each box can contain a different type of closure, so a `HashMap` can contain all sorts of callbacks. Note the type parameter `C` is gone, requiring

adjustments to the methods:

```
impl BasicRouter {
    // Create an empty router.
    fn new() -> BasicRouter {
        BasicRouter {
            routes: HashMap::new(),
        }
    }

    // Add a route to the router.
    fn add_route<C>(&mut self, url: &str, callback: C)
    where
        C: Fn(&Request) -> Response + 'static,
    {
        self.routes.insert(url.to_string(), Box::new(callback));
    }
}
```

> **NOTE**
>
> Note the two bounds on `C` in the type signature for `add_route`: a particular `Fn` trait and the `'static` lifetime. Rust makes us add this `'static` bound. Without it, the call to `Box::new(callback)` would be an error, because it's not safe to store a closure if it contains borrowed references to variables that are about to go out of scope.

Finally, our simple router is ready to handle incoming requests:

```
impl BasicRouter {
    fn handle_request(&self, request: &Request) -> Response {
        match self.routes.get(&request.url) {
            None => not_found_response(),
            Some(callback) => callback(request),
        }
    }
}
```

At the cost of some flexibility, we could also write a more space-efficient version of this router that, rather than storing trait objects, uses function pointers. The routing table would look like this:

```
struct FnPointerRouter {
    routes: HashMap<String, fn(&Request) -> Response>,
}
```

Here, the `HashMap` is storing just a single `usize` per `String`, and critically, there's no `Box`. In exchange for not supporting capturing closures, we've removed all dynamic allocation aside from the `HashMap` itself. Of course, the methods need to be adjusted as well:

```
impl FnPointerRouter {
    // Create an empty router.
    fn new() -> FnPointerRouter {
        FnPointerRouter {
            routes: HashMap::new(),
        }
    }

    // Add a route to the router.
    fn add_route(&mut self, url: &str, callback: fn(&Request) ->
Response) {
        self.routes.insert(url.to_string(), callback);
    }
}
```

As laid out in Figure 14-1, closures have unique types because each one captures different variables, so among other things, they're each a different size. If they don't capture anything, though, there's nothing to store. By using `fn` pointers in functions that take callbacks, you can restrict a caller to use only these noncapturing closures, gaining some performance and flexibility within the code using callbacks at the cost of flexibility for the users of your API.

## Using Closures Effectively

As we've seen, Rust's closures are different from closures in most other languages. The biggest difference is that in languages with garbage collection, you can use local variables in a closure without having to think about lifetimes or ownership. Without garbage collection, things are

different. Some design patterns that are commonplace in Java, C#, and JavaScript won't work in Rust without changes.

For example, take the Model-View-Controller design pattern (MVC for short), illustrated in Figure 14-3. For every element of a user interface, an MVC framework creates three objects: a *model* representing that UI element's state, a *view* that's responsible for its appearance, and a *controller* that handles user interaction. Countless variations on MVC have been implemented over the years, but the general idea is that three objects divvy up the UI responsibilities somehow.

Here's the problem. Typically, each object has a reference to one or both of the others, directly or through a callback, as shown in Figure 14-3. Whenever anything happens to one of the objects, it notifies the others, so everything updates promptly. The question of which object "owns" the others never comes up.

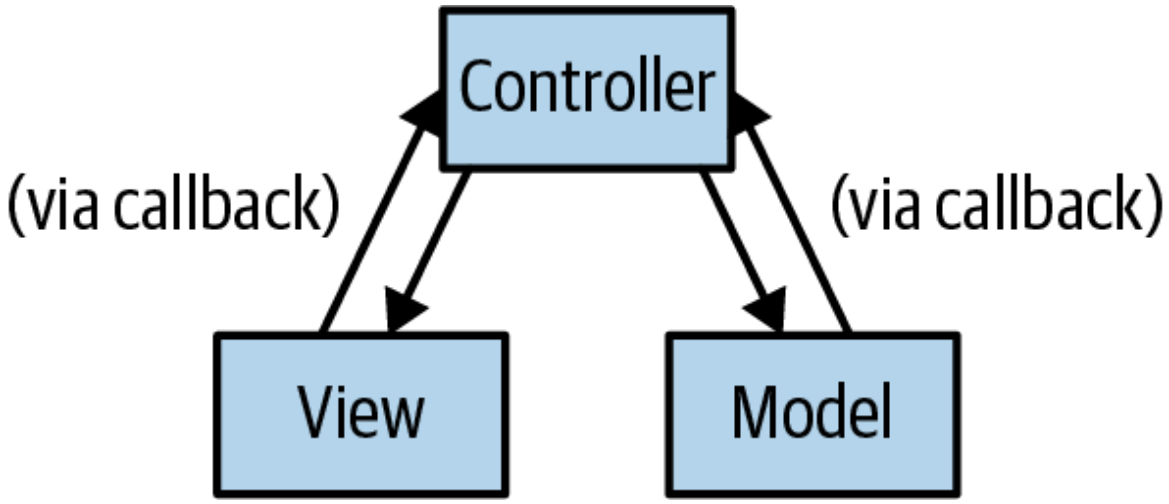


*Figure 14-3. The Model-View-Controller design pattern*

You can't implement this pattern in Rust without making some changes. Ownership must be made explicit, and reference cycles must be eliminated. The model and the controller can't have direct references to each other.

Rust's radical wager is that good alternative designs exist. Sometimes you can fix a problem with closure ownership and lifetimes by having each closure receive the references it needs as arguments. Sometimes you can assign each thing in the system a number and pass around the numbers

instead of references. You can implement one of the many variations on MVC where the objects don't all have references to each other. Or you can model your toolkit after a non-MVC system with unidirectional data flow, like the Elm architecture, shown in Figure 14-4, which was pioneered by the Elm language and is used in the Rust library `relm` and popular web development libraries like React and Redux.

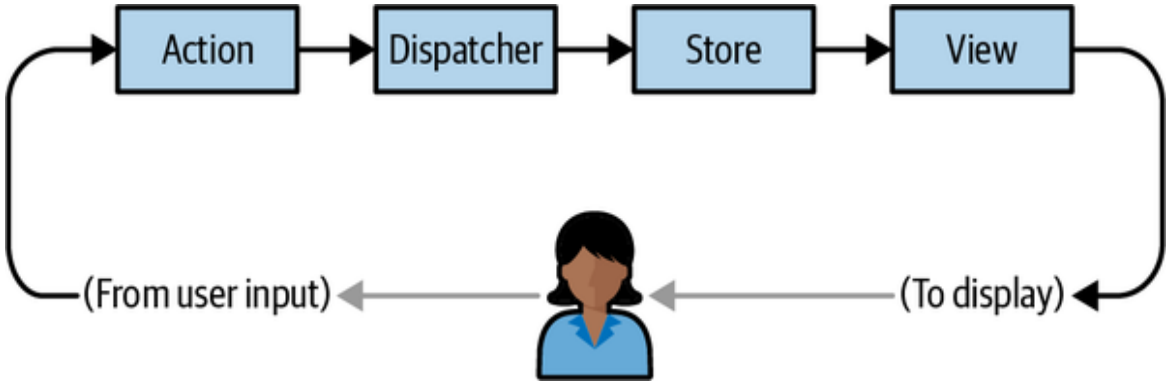


*Figure 14-4. The Elm architecture, an alternative to MVC*

In short, if you try to use Rust closures to make a "sea of objects," you're going to have a hard time. But there are alternatives. In this case, it seems software engineering as a discipline is already gravitating to the alternatives anyway, because they're simpler.

In the next chapter, we turn to a topic where closures really shine. We'll be writing a kind of code that takes full advantage of the concision, speed, and efficiency of Rust closures, and that's fun to write, easy to read, and eminently practical. Up next: Rust iterators.

# Chapter 15. Iterators

*It was the end of a very long day.*

—Phil Connors

An *iterator* is a value that produces a sequence of values, typically for a loop to operate on. Rust's standard library provides iterators that traverse vectors, strings, hash tables, and other collections, but also iterators to produce lines of text from an input stream, connections arriving at a network server, values received from other threads over a communications channel, and so on. And of course, you can implement iterators for your own purposes. Rust's `for` loop provides a natural syntax for using iterators, but iterators themselves also provide a rich set of methods for mapping, filtering, joining, collecting, and so on.

Rust's iterators are flexible, expressive, and efficient. Consider the following function, which returns the sum of the first `n` positive integers (often called the *nth triangle number*):

```
fn triangle(n: i32) -> i32 {
    let mut sum = 0;
    for i in 1..=n {
        sum += i;
    }
    sum
}
```

The expression `1..=n` is a `RangeInclusive<i32>` value. A `RangeInclusive<i32>` is an iterator that produces the integers from its start value to its end value (both inclusive), so you can use it as the operand of the `for` loop to sum the values from `1` to `n`.

Iterators also have a `fold` method, which you can use in the equivalent definition:

```
fn triangle(n: i32) -> i32 {
    (1..=n).fold(0, |sum, item| sum + item)
}
```

Starting with `0` as the running total, `fold` takes each value that `1..=n` produces and applies the closure `|sum, item| sum + item` to the running total and the value. The closure's return value is taken as the new running total. The last value it returns is what `fold` itself returns—in this case, the total of the entire sequence. This may look strange if you're used to `for` and `while` loops, but once you've gotten used to it, `fold` is a legible and concise alternative.

This is pretty standard fare for functional programming languages, which put a premium on expressiveness. But Rust's iterators were carefully designed to ensure that the compiler can translate them into excellent machine code as well. In a release build of the second definition shown before, Rust knows the definition of `fold` and inlines it into `triangle`. Next, the closure `|sum, item| sum + item` is inlined into that. Finally, Rust examines the combined code and recognizes that there's a simpler way to sum the numbers from one to `n`: the sum is always equal to `n * (n + 1) / 2`. Rust translates the entire body of `triangle`, loop, closure, and all, into a single multiplication instruction and a few other bits of arithmetic.

This example happens to involve simple arithmetic, but iterators also perform well when put to heavier use. They're another example of Rust providing flexible abstractions that impose little or no overhead in typical use.

In this chapter, we'll explain:

- The `Iterator` and `IntoIterator` traits, which are the foundation of Rust's iterators
- The three stages of a typical iterator pipeline: creating an iterator from some sort of value source, adapting one sort of iterator into

another by selecting or processing values as they go by, and then consuming the values the iterator produces

- How to implement iterators for your own types

There are a lot of methods, so it's fine to skim a section once you've got the general idea. But iterators are common in idiomatic Rust, and being familiar with the tools that come with them is essential to mastering the language.

## The Iterator and IntoIterator Traits

An iterator is any value that implements the `std::iter::Iterator` trait:

```
trait Iterator {
    type Item;
    fn next(&mut self) -> Option<Self::Item>;
    ...  // many default methods
}
```

`Item` is the type of value the iterator produces. The `next` method either returns `Some(v)`, where `v` is the iterator's next value, or returns `None` to indicate the end of the sequence. Here we've omitted `Iterator`'s many default methods; we'll cover them individually throughout the rest of this chapter.

If there's a natural way to iterate over some type, that type can implement `std::iter::IntoIterator`, whose `into_iter` method takes a value and returns an iterator over it:

```
trait IntoIterator
where
    Self::IntoIter: Iterator<Item = Self::Item>,
{
    type Item;
    type IntoIter: Iterator;
    fn into_iter(self) -> Self::IntoIter;
}
```

`IntoIter` is the type of the iterator value itself, and `Item` is the type of value it produces. We call any type that implements `IntoIterator` an *iterable*, because it's something you could iterate over if you asked.

Rust's `for` loop brings all these parts together nicely. To iterate over a vector's elements, you can write:

```
println!("There's:");
let v = vec!["antimony", "arsenic", "aluminum", "selenium"];

for element in &v {
    println!("{element}");
}
```

Under the hood, every `for` loop is just shorthand for calls to `IntoIterator` and `Iterator` methods:

```
let mut iterator = (&v).into_iter();
while let Some(element) = iterator.next() {
    println!("{element}");
}
```

The `for` loop uses `IntoIterator::into_iter` to convert its operand `&v` into an iterator and then calls `Iterator::next` repeatedly. Each time that returns `Some(element)`, the `for` loop executes its body; and if it returns `None`, the loop finishes.

With this example in mind, here's some terminology for iterators:

- As we've said, an *iterator* is any type that implements `Iterator`.
- An *iterable* is any type that implements `IntoIterator`: you can get an iterator over it by calling its `into_iter` method. The vector reference `&v` is the iterable here.
- An iterator *produces* values.
- The values an iterator produces are *items*. Here, the items are `"antimony"`, `"arsenic"`, and so on.

- The code that receives the items an iterator produces is the *consumer*. In this example, the `for` loop is the consumer.

Although a `for` loop always calls `into_iter` on its operand, you can also pass iterators to `for` loops directly; this occurs when you loop over a `Range`, for example. All iterators automatically implement `IntoIterator`, with an `into_iter` method that simply returns the iterator.

If you call an iterator's `next` method again after it has returned `None`, the `Iterator` trait doesn't specify what it should do. Most iterators will just return `None` again, but not all. (If this causes problems, `fuse` adapter covered in "fuse" can help.)

# Creating Iterators

The Rust standard library documentation explains in detail what sort of iterators each type provides, but the library follows some general conventions to help you get oriented and find what you need.

## iter and iter_mut Methods

Most collection types have an obvious algorithm for iteration over their elements. For a `Vec`, that's progressively incrementing an index; for a `LinkedList`, that's visiting each node one after the other. Collections like this provide `iter` and `iter_mut` methods that return the natural iterators over the type, producing a shared or mutable reference to each item. Array slices like `&[T]` and `&mut [T]` have `iter` and `iter_mut` methods too. These methods are the most common way to get an iterator, if you're not going to let a `for` loop take care of it for you:

```
let v = vec![4, 20, 12, 8, 6];
let mut iterator = v.iter();
assert_eq!(iterator.next(), Some(&4));
assert_eq!(iterator.next(), Some(&20));
assert_eq!(iterator.next(), Some(&12));
```

```
assert_eq!(iterator.next(), Some(&8));
assert_eq!(iterator.next(), Some(&6));
assert_eq!(iterator.next(), None);
```

This iterator's item type is `&i32`: each call to `next` produces a reference to the next element, until we reach the end of the vector. Each type is free to implement `iter` and `iter_mut` in whatever way makes the most sense for its purpose.

The `iter` method on `std::path::Path` returns an iterator that produces one path component at a time:

```
use std::ffi::OsStr;
use std::path::Path;

let path = Path::new("C:/Users/JimB/Downloads/Fedora.iso");
let mut iterator = path.iter();
assert_eq!(iterator.next(), Some(OsStr::new("C:")));
assert_eq!(iterator.next(), Some(OsStr::new("Users")));
assert_eq!(iterator.next(), Some(OsStr::new("JimB")));
...
```

This iterator's item type is `&std::ffi::OsStr`, a borrowed slice of a string of the sort accepted by operating system calls.

If there's more than one common way to iterate over a type, the type usually provides specific methods for each sort of traversal, since a `iter` method would be ambiguous. For example, there is no `iter` method on the `&str` string slice type. Instead, if `s` is a `&str`, then `s.bytes()` returns an iterator that produces each byte of `s`, whereas `s.chars()` interprets the contents as UTF-8 and produces each Unicode character.

## IntoIterator Implementations

When a type implements `IntoIterator`, you can call its `into_iter` method yourself, just as a `for` loop would:

```
// You should usually use HashSet, but its iteration order is
// nondeterministic, so BTreeSet works better in examples.
```

```
use std::collections::BTreeSet;
let mut favorites = BTreeSet::new();
favorites.insert("Lucy in the Sky With Diamonds".to_string());
favorites.insert("Liebesträume No. 3".to_string());

let mut it = favorites.into_iter();
assert_eq!(it.next(), Some("Liebesträume No. 3".to_string()));
assert_eq!(it.next(), Some("Lucy in the Sky With
Diamonds".to_string()));
assert_eq!(it.next(), None);
```

Most collections actually provide several implementations of `IntoIterator`, for shared references (`&T`), mutable references (`&mut T`), and moves (`T`):

- Given a *shared reference* to the collection, `into_iter` returns an iterator that produces shared references to its items. For example, in the preceding code, `(&favorites).into_iter()` would return an iterator whose `Item` type is `&String`.
- Given a *mutable reference* to the collection, `into_iter` returns an iterator that produces mutable references to the items. For example, if `vector` is some `Vec<String>`, the call `(&mut vector).into_iter()` returns an iterator whose `Item` type is `&mut String`.
- When passed the collection *by value*, `into_iter` returns an iterator that takes ownership of the collection and returns items by value; the items' ownership moves from the collection to the consumer, and the original collection is consumed in the process. For example, the call `favorites.into_iter()` in the preceding code returns an iterator that produces each string by value; the consumer receives ownership of each string. When the iterator is dropped, any elements remaining in the `BTreeSet` are dropped too, and the set's now-empty husk is disposed of.

Since a `for` loop applies `IntoIterator::into_iter` to its operand, these three implementations are what create the following idioms for

iterating over shared or mutable references to a collection, or consuming the collection and taking ownership of its elements:

```
for element in &collection { ... }
for element in &mut collection { ... }
for element in collection { ... }
```

Each of these simply results in a call to one of the `IntoIterator` implementations listed here.

Not every type provides all three implementations. For example, `HashSet`, `BTreeSet`, and `BinaryHeap` don't implement `IntoIterator` on mutable references, since modifying their elements would probably violate the type's invariants: the modified value might have a different hash value or be ordered differently with respect to its neighbors, so modifying it would leave it incorrectly placed. Other types do support mutation, but only partially. For example, `HashMap` and `BTreeMap` produce mutable reference to their entries' values, but only shared references to their keys, for similar reasons to those given earlier.

The general principle is that iteration should be efficient and predictable, so rather than providing implementations that are expensive or could exhibit surprising behavior (for example, rehashing modified `HashSet` entries and potentially encountering them again later in the iteration), Rust omits them entirely.

Slices implement two of the three `IntoIterator` variants; since they don't own their elements, there is no "by value" case. Instead, `into_iter` for `&[T]` and `&mut [T]` returns an iterator that produces shared and mutable references to the elements. If you imagine the underlying slice type `[T]` as a collection of some sort, this fits neatly into the overall pattern.

You may have noticed that the first two `IntoIterator` variants, for shared and mutable references, are equivalent to calling `iter` or `iter_mut` on the referent. Why does Rust provide both?

`IntoIterator` is what makes `for` loops work, so that's obviously necessary. But when you're not using a `for` loop, it's clearer to write `favorites.iter()` than `(&favorites).into_iter()`. Iteration by shared reference is something you'll need frequently, so `iter` and `iter_mut` are still valuable for their ergonomics.

`IntoIterator` can also be useful in generic code: you can use a bound like `T: IntoIterator` to restrict the type variable `T` to types that can be iterated over. Or, you can write `T: IntoIterator<Item = U>` to further require the iteration to produce a particular type `U`. For example, this function dumps values from any iterable whose items are printable with the `"{:?}"` format:

```
use std::fmt::Debug;

fn dump<T, U>(t: T)
where
    T: IntoIterator<Item = U>,
    U: Debug,
{
    for u in t {
        println!("{u:?}");
    }
}
```

You can't write this generic function using `iter` and `iter_mut`, since they're not methods of any trait: most iterable types just happen to have methods by those names.

## from_fn and successors

One simple and general way to produce a sequence of values is to provide a closure that returns them. Given a function returning `Option<T>`, `std::iter::from_fn` returns an iterator that simply calls the function to produce its items. For example:

```
// Cargo.toml: rand = "0.10.1"
use std::iter;
```

```
// Generate the lengths of 1000 random line segments whose
endpoints
// are uniformly distributed across the interval [0, 1]. (This
isn't a
// distribution you're going to find in the `rand_distr` crate,
but
// it's easy to make yourself.)
let lengths: Vec<f64> =
    iter::from_fn(|| {
        Some((rand::random::<f64>() - rand::random::<f64>
()).abs())
    })
    .take(1000)
    .collect();
```

This calls `from_fn` to make an iterator producing random numbers. Since the iterator always returns `Some`, the sequence never ends, but we call `take(1000)` to limit it to the first 1,000 elements. Then `collect` builds the vector from the resulting iteration. This is an efficient way of constructing initialized vectors; we explain why in "Building Collections: collect and FromIterator", later in this chapter.

If each item depends on the one before, the `std::iter::successors` function works nicely. Consider this implementation of the famous Collatz process:

```
fn collatz_iterations(n: u64) -> u64 {
    let next = |n| match n {
        1 => None,
        n if n % 2 == 0 => Some(n / 2),
        n => Some(3 * n + 1),
    };

    iter::successors(next(n), |&n| next(n))
        .count() as u64
}
```

The Collatz process is simple: take a number, and if it's even, divide it by two; otherwise, multiply by three and add one. Then repeat. Nobody has ever been able to find a number that doesn't eventually reach 1 after a finite number of iterations, but nobody has been able to prove that it's impossible

either. The closure `next` returns `None` if the provided value is 1, stopping the iteration; otherwise, it applies the Collatz procedure and returns `Some`, allowing the iteration to continue with the new value as the input. That closure is used both for the first value of the iterator and for all subsequent iterations. The `collatz_iterations` function just counts the number of iterations before the inevitable happens and returns that value.

Both `from_fn` and `successors` accept `FnMut` closures, so your closures can capture and modify variables from the surrounding scopes. For example, this `fibonacci` function uses a `move` closure to capture a variable and use it as its running state:

```
fn fibonacci() -> impl Iterator<Item = usize> {
    let mut state = (0, 1);
    std::iter::from_fn(move || {
        state = (state.1, state.0 + state.1);
        Some(state.0)
    })
}

assert_eq!(
    fibonacci().take(8).collect::<Vec<_>>(),
    vec![1, 1, 2, 3, 5, 8, 13, 21],
);
```

A note of caution: the `from_fn` and `successors` methods are flexible enough that you could turn pretty much any use of iterators into a single call to one or the other, passing complex closures to get the behavior you need. But doing so neglects the opportunity that iterators provide to clarify how data flows through the computation and use standard names for common patterns. Make sure you've familiarized yourself with the other iterator methods in this chapter before you lean on these two; there are often nicer ways to get the job done.

## drain Methods

Many collection types provide a `drain` method that takes a mutable reference to the collection and returns an iterator that passes ownership of

each element to the consumer. However, unlike the `into_iter()` method, which takes the collection by value and consumes it, `drain` merely borrows a mutable reference to the collection, and when the iterator is dropped, it removes any remaining elements from the collection and leaves it empty. On types that can be indexed by a range, like `Strings`, vectors, and `VecDeques`, the `drain` method takes a range of elements to remove rather than draining the entire sequence:

```
let mut outer = "Earth".to_string();
let inner = String::from_iter(outer.drain(1..4));

assert_eq!(outer, "Eh");
assert_eq!(inner, "art");
```

If you do need to drain the entire sequence, use the full range, `..`, as the argument.

## Other Iterator Sources

The previous sections are mostly concerned with collection types like vectors and `HashMap`, but there are many other types in the standard library that support iteration. Table 15-1 summarizes the more interesting ones, but there are many more. We cover some of these methods in more detail in the chapters dedicated to the specific types (namely, Chapters 16, 17, and 18).

*Table 15-1. Other iterators in the standard library*

| Type or trait | Expression | Notes |
|---|---|---|
| `std::ops::Range` | `1..10` | Start value is included; end value is not, only ranges of integers are iterable |
| | `(1..10).step_by(2)` | Produces `1`, `3`, `5`, `7`, `9` |
| `std::ops::RangeFrom` | `1..` | Unbounded iteration of integers; may panic or overflow |
| `std::ops::RangeInclusive` | `1..=10` | Like `Range`, but includes end value |
| `Option<T>` | `Some(10).iter()` | Yields either no values (`None`) or one value (`Some(v)`) |
| `Result<T, E>` | `Ok("blah").iter()` | Similar to `Option`, producing `Ok` values |
| `Vec<T>`, `&[T]` | `v.windows(16)` | Produces every contiguous slice of the given length, from left to right, with overlap |
| | `v.chunks(16)` | Produces nonoverlapping, contiguous slices of the given length, from left to right |
| | `v.chunks_mut(1024)` | Like `chunks`, but slices are mutable |
| | `v.split(\|byte\| byte & 1 != 0)` | Produces slices separated by elements that match the given predicate |

| Type or trait | Expression | Notes |
| --- | --- | --- |
| | `v.split_mut(...)` | As above, but produces mutable slices |
| | `v.rsplit(...)` | Like `split`, but produces slices from right to left |
| | `v.splitn(n, ...)` | Like `split`, but produces at most `n` slices |
| `String`, `&str` | `s.bytes()` | Produces the bytes of the UTF-8 form |
| | `s.chars()` | Produces the `char`s the UTF-8 represents |
| | `s.split_whitespace()` | Splits string by whitespace, and produces slices of nonspace characters |
| | `s.lines()` | Produces slices of the lines of the string |
| | `s.split('/')` | Splits string by a character, string, or closure, producing the slices between matches |
| | `s.matches(char::is_numeric)` | Produces slices matching the given pattern |
| `std::collections::HashMap`, `std::collections::BTreeMap` | `map.keys()`, `map.values()` | Produces shared references to keys or values of the map |
| | `map.values_mut()` | Produces mutable references to entries' values |

| Type or trait | Expression | Notes |
| --- | --- | --- |
| `std::collections::HashSet`, `std::collections::BTreeSet` | `set1.union(set2)` | Produces shared references to elements of union of `set1` and `set2` |
| | `set1.intersection(set2)` | Produces shared references to elements of intersection of `set1` and `set2` |
| `std::sync::mpsc::Receiver` | `recv.iter()` | Produces values sent from another thread on the corresponding `Sender` |
| `std::io::Read` | `stream.bytes()` | Produces bytes from an I/O stream |
| | `stream.chars()` | Parses stream as UTF-8 and produces `char`s |
| `std::io::BufRead` | `bufstream.lines()` | Parses stream as UTF-8, produces lines as `String`s |
| | `bufstream.split(0)` | Splits stream on given byte, produces inter-byte `Vec<u8>` buffers |
| `std::fs::ReadDir` | `std::fs::read_dir(path)` | Produces directory entries |
| `std::net::TcpListener` | `listener.incoming()` | Produces incoming network connections |
| Free functions | `std::iter::empty()` | Produces no values, like `[].into_iter()` |
| | `std::iter::once(5)` | Produces the given value once, like `[5].into_iter()` |

| Type or trait | Expression | Notes |
| --- | --- | --- |
| | `std::iter::repeat_n("nan", 16)` | Repeats the given value several times, like `["nan"; 16].into_iter()` but more memory-efficient |
| | `std::iter::repeat("#9")` | Repeats the given value forever |

# Iterator Adapters

Once you have an iterator in hand, the `Iterator` trait provides a broad selection of *adapter methods*, or simply *adapters*, that consume one iterator and build a new one with useful behaviors. To see how adapters work, we'll start with two popular adapters: `map` and `filter`. Then we'll cover the rest of the adapter toolbox, covering almost any way you can imagine to make sequences of values from other sequences: truncation, skipping, combination, reversal, concatenation, repetition, and more.

## map and filter

The `Iterator` trait's `map` adapter lets you transform an iterator by applying a closure to its items. The `filter` adapter lets you filter out items from an iterator, using a closure to decide which to keep and which to drop.

For example, suppose you're iterating over lines of text and want to omit leading and trailing whitespace from each line. The standard library's `str::trim` method drops leading and trailing whitespace from a single `&str`, returning a new, trimmed `&str` that borrows from the original. You can use the `map` adapter to apply `str::trim` to each line from the iterator:

```
let text = "  ponies  \n   giraffes\niguanas
\nsquid".to_string();
```

```
let v: Vec<&str> = text
    .lines()
    .map(str::trim)
    .collect();
assert_eq!(v, ["ponies", "giraffes", "iguanas", "squid"]);
```

The `text.lines()` call returns an iterator that produces the string's lines. Calling `map` on that iterator returns a second iterator that applies `str::trim` to each line and produces the results as its items. Finally, `collect` gathers those items into a vector.

The iterator that `map` returns is, of course, itself a candidate for further adaptation. If you want to exclude iguanas from the result, you can write the following:

```
let text = "  ponies  \n   giraffes\niguanas
\nsquid".to_string();
let v: Vec<&str> = text
    .lines()
    .map(str::trim)
    .filter(|s| *s != "iguanas")
    .collect();
assert_eq!(v, ["ponies", "giraffes", "squid"]);
```

Here, `filter` returns a third iterator that produces only those items from the `map` iterator for which the closure `|s| *s != "iguanas"` returns `true`. A chain of iterator adapters is like a pipeline in the Unix shell: each adapter has a single purpose, and it's clear how the sequence is being transformed as one reads from left to right.

These adapters' signatures are as follows:

```
fn map<B, F>(self, f: F) -> impl Iterator<Item = B>
where
    Self: Sized,
    F: FnMut(Self::Item) -> B;

fn filter<P>(self, predicate: P) -> impl Iterator<Item =
Self::Item>
where
```

```
        Self: Sized,
        P: FnMut(&Self::Item) -> bool;
```

In the standard library, `map` and `filter` actually return specific opaque `struct` types named `std::iter::Map` and `std::iter::Filter`. However, just seeing their names is not very informative, so in this book, we're just going to write `-> impl Iterator<Item = ...>` instead, since that tells us what we really want to know: the method returns an `Iterator` that produces items of the given type.

Since most adapters take `self` by value, they require `Self` to be `Sized` (which all common iterators are).

A `map` iterator passes each item to its closure by value and, in turn, passes along ownership of the closure's result to its consumer. A `filter` iterator passes each item to its closure by shared reference, retaining ownership in case the item is selected to be passed on to its consumer. This is why the example must dereference `s` to compare it with `"iguanas"`: the `filter` iterator's item type is `&str`, so the type of the closure's argument `s` is `&&str`. There are two important points to notice about iterator adapters.

First, simply calling an adapter on an iterator doesn't consume any items; it just returns a new iterator, ready to produce its own items by drawing from the first iterator as needed. In a chain of adapters, the only way to make any work actually get done is to call `next` on the final iterator.

So in our earlier example, the method call `text.lines()` itself doesn't actually parse any lines from the string; it just returns an iterator that *would* parse lines if asked. Similarly, `map` and `filter` just return new iterators that *would* map or filter if asked. No work takes place until `collect` starts calling `next` on the `filter` iterator.

This point is especially important if you use adapters that have side effects. For example, this code prints nothing at all:

```
["earth", "water", "air", "fire"]
    .iter()
    .map(|elt| println!("{elt}"));
```

The `iter` call returns an iterator over the array's elements, and the `map` call returns a second iterator that applies the closure to each value the first produces. But there is nothing here that ever actually demands a value from the whole chain, so no `next` method ever runs.

In fact, Rust will warn you about this:

```
warning: unused `std::iter::Map` that must be used
  |
7 | /     ["earth", "water", "air", "fire"]
8 | |         .iter()
9 | |         .map(|elt| println!("{elt}"));
  | |_____________________________________^
  |
  = note: iterators are lazy and do nothing unless consumed
```

The term "lazy" in the error message is not a disparaging term; it's just jargon for any mechanism that puts off a computation until its value is needed. It is Rust's convention that iterators should do the minimum work necessary to satisfy each call to `next`; in the example, there are no such calls at all, so no work takes place.

The second important point is that iterator adapters are a zero-overhead abstraction. Since `map`, `filter`, and their companions are generic, applying them to an iterator specializes their code for the specific iterator type involved. This means that Rust has enough information to inline each iterator's `next` method into its consumer and then translate the entire arrangement into machine code as a unit. So the `lines`/`map`/`filter` chain of iterators we showed before is as efficient as the code you would probably write by hand:

```
for line in text.lines() {
    let line = line.trim();
    if line != "iguanas" {
        v.push(line);
    }
}
```

The rest of this section covers the various adapters available on the `Iterator` trait.

## filter_map and flat_map

The `map` adapter is fine in situations where each incoming item produces one outgoing item. But what if you want to delete certain items from the iteration instead of processing them or replace single items with zero or more items? The `filter_map` and `flat_map` adapters grant you this flexibility.

The `filter_map` adapter is similar to `map` except that it lets its closure either transform the item into a new item (as `map` does) or drop the item from the iteration. Thus, it's a bit like a combination of `filter` and `map`. Its signature is as follows:

```
fn filter_map<B, F>(self, f: F) -> impl Iterator<Item = B>
where
    Self: Sized,
    F: FnMut(Self::Item) -> Option<B>;
```

This is the same as `map`'s signature, except that here the closure returns `Option<B>`, not simply `B`. When the closure returns `None`, the item is dropped from the iteration; when it returns `Some(b)`, then `b` is the next item the `filter_map` iterator produces.

For example, suppose you want to scan a string for whitespace-separated words that can be parsed as numbers, and process the numbers, dropping the other words. You can write:

```
use std::str::FromStr;

let text = "1\nfrond .25  289\n3.1415 estuary\n";
for number in text
    .split_whitespace()
    .filter_map(|w| f64::from_str(w).ok())
{
    println!("{number:4.2}");
}
```

This prints the following:

```
1.00
0.25
289.00
3.14
```

The closure given to `filter_map` tries to parse each whitespace-separated slice using `f64::from_str`. That returns a `Result<f64, ParseFloatError>`, which `.ok()` turns into an `Option<f64>`: a parse error becomes `None`, whereas a successful parse result becomes `Some(v)`. The `filter_map` iterator drops all the `None` values and produces the value `v` for each `Some(v)`.

But what's the point in fusing `map` and `filter` into a single operation like this, instead of just using those adapters directly? The `filter_map` adapter shows its value in situations like the one just shown, when the best way to decide whether to include the item in the iteration is to actually try to process it. You can do the same thing with only `filter` and `map`, but it's a bit ungainly:

```
text.split_whitespace()
    .map(|w| f64::from_str(w))
    .filter(|r| r.is_ok())
    .map(|r| r.unwrap())
```

You can think of the `flat_map` adapter as continuing in the same vein as `map` and `filter_map`, except that now the closure can return not just one item (as with `map`) or zero or one items (as with `filter_map`), but a sequence of any number of items. The `flat_map` iterator produces the concatenation of the sequences that the closure returns.

The signature of `flat_map` is shown here:

```
fn flat_map<U, F>(self, f: F) -> impl Iterator<Item = U::Item>
where
    F: FnMut(Self::Item) -> U,
    U: IntoIterator;
```

The closure passed to `flat_map` must return an iterable, but any sort of iterable will do.[1] For example, suppose we have a table mapping countries to their major cities. Given a list of countries, how can we iterate over their major cities?

```
use std::collections::HashMap;

let mut major_cities = HashMap::new();
major_cities.insert("Japan", vec!["Tokyo", "Kyoto"]);
major_cities.insert("The United States", vec!["Portland",
"Nashville"]);
major_cities.insert("Brazil", vec!["São Paulo", "Brasília"]);
major_cities.insert("Kenya", vec!["Nairobi", "Mombasa"]);
major_cities.insert("The Netherlands", vec!["Amsterdam",
"Utrecht"]);

let countries = ["Japan", "Brazil", "Kenya"];

for &city in countries.iter().flat_map(|country|
&major_cities[country]) {
    println!("{city}");
}
```

This prints the following:

```
Tokyo
Kyoto
São Paulo
Brasília
Nairobi
Mombasa
```

One way to look at this would be to say that, for each country, we retrieve the vector of its cities, concatenate all the vectors together into a single sequence, and print that.

But remember that iterators are lazy: it's only the `for` loop's calls to the `flat_map` iterator's `next` method that cause work to be done. The full concatenated sequence is never constructed in memory. Instead, what we have here is a little state machine that draws from the city iterator, one item at a time, until it's exhausted, and only then produces a new city iterator for

the next country. The effect is that of a nested loop but packaged up for use as an iterator.

## flatten

The `flatten` adapter concatenates an iterator's items, assuming each item is an iterable:

```
use std::collections::BTreeMap;

// A table mapping cities to their parks: each value is a vector.
let mut parks = BTreeMap::new();
parks.insert("Portland",  vec!["Mt. Tabor Park", "Forest Park"]);
parks.insert("Kyoto",     vec!["Tadasu-no-Mori Forest", "Maruyama
Koen"]);
parks.insert("Nashville", vec!["Percy Warner Park", "Dragon
Park"]);

// Build a vector of all parks. `values` gives us an iterator
producing
// vectors, and then `flatten` produces each vector's elements in
turn.
let all_parks: Vec<_> =
parks.values().flatten().cloned().collect();

assert_eq!(
    all_parks,
    vec![
        "Tadasu-no-Mori Forest", "Maruyama Koen", "Percy Warner
Park",
        "Dragon Park", "Mt. Tabor Park", "Forest Park",
    ],
);
```

The name "flatten" comes from the image of flattening a two-level structure into a one-level structure: the `BTreeMap` and its `Vec`s of names are flattened into an iterator producing all the names.

The signature of `flatten` is as follows:

```
fn flatten(self) -> impl Iterator<Item = <Self::Item as
IntoIterator>::Item>
```

```
    where
        Self::Item: IntoIterator;
```

In other words, the underlying iterator's items must themselves implement `IntoIterator` so that it is effectively a sequence of sequences. The `flatten` method then returns an iterator over the concatenation of those sequences. Of course, this is done lazily, drawing a new item from `self` only when we're done iterating over the last one.

The `flatten` method gets used in a few surprising ways. If you have a `Vec<Option<...>>` and you want to iterate over only the `Some` values, `flatten` works beautifully:

```
assert_eq!(
    vec![None, Some("day"), None, Some("one")]
        .into_iter()
        .flatten()
        .collect::<Vec<_>>(),
    vec!["day", "one"],
);
```

This works because `Option` itself implements `IntoIterator`, representing a sequence of either zero or one elements. The `None` elements contribute nothing to the iteration, whereas each `Some` element contributes a single value. Similarly, you can use `flatten` to iterate over `Option<Vec<...>>` values: `None` behaves the same as an empty vector.

`Result` also implements `IntoIterator`, with `Err` representing an empty sequence, so applying `flatten` to an iterator of `Result` values effectively squeezes out all the `Err`s and throws them away, resulting in a stream of the unwrapped success values. We do not recommend ignoring errors in your code, but this is a neat trick people use when they think they know what's going on.

You may find yourself reaching for `flatten` when what you actually need is `flat_map`. For example, the standard library's

`str::to_uppercase` method, which converts a string to uppercase, works something like this:

```
fn to_uppercase(&self) -> String {
    self.chars()
        .map(char::to_uppercase)
        .flatten()  // there's a better way
        .collect()
}
```

The reason the `flatten` is necessary is that `ch.to_uppercase()` returns not a single character but an iterator producing one or more characters. Mapping each character to its uppercase equivalent results in an iterator of iterators of characters, and the `flatten` takes care of splicing them all together into something we can finally `collect` into a `String`.

But this combination of `map` and `flatten` is so common that `Iterator` provides the `flat_map` adapter for just that case. (In fact, `flat_map` was added to the standard library before `flatten`.) So the preceding code could instead be written:

```
fn to_uppercase(&self) -> String {
    self.chars().flat_map(char::to_uppercase).collect()
}
```

## take and take_while

The `Iterator` trait's `take` and `take_while` adapters let you end an iteration after a certain number of items or when a closure decides to cut things off. Their signatures are as follows:

```
fn take(self, n: usize) -> impl Iterator<Item = Self::Item>
where
    Self: Sized;

fn take_while<P>(self, predicate: P) -> impl Iterator<Item =
Self::Item>
where
    Self: Sized,
    P: FnMut(&Self::Item) -> bool;
```

Both take ownership of an iterator and return a new iterator that passes along items from the first one, possibly ending the sequence earlier. The `take` iterator returns `None` after producing at most `n` items. The `take_while` iterator applies `predicate` to each item and returns `None` in place of the first item for which `predicate` returns `false` and on every subsequent call to `next`.

For example, given an email message with a blank line separating the headers from the message body, you can use `take_while` to iterate over only the headers:

```
let message = "\
    To: jimb\r\n\
    From: superego <editor@oreilly.com>\r\n\
    \r\n\
    Did you get any writing done today?\r\n\
    When will you stop wasting time plotting fractals?\r\n";
for header in message.lines().take_while(|l| !l.is_empty()) {
    println!("{header}");
}
```

Recall from "String and Character Literals" that when a line in a string ends with a backslash, Rust doesn't include the indentation of the next line in the string, so none of the lines in the string has any leading whitespace. This means that the third line of `message` is blank. The `take_while` adapter terminates the iteration as soon as it sees that blank line, so this code prints only the two lines:

```
To: jimb
From: superego <editor@oreilly.com>
```

## skip and skip_while

The `Iterator` trait's `skip` and `skip_while` methods are the complement of `take` and `take_while`: they drop a certain number of items from the beginning of an iteration, or drop items until a closure finds one acceptable, and then pass the remaining items through unchanged. Their signatures are as follows:

```
fn skip(self, n: usize) -> impl Iterator<Item = Self::Item>
where
    Self: Sized;

fn skip_while<P>(self, predicate: P) -> impl Iterator<Item =
Self::Item>
where
    Self: Sized,
    P: FnMut(&Self::Item) -> bool;
```

One common use for the `skip` adapter is to skip the command name when iterating over a program's command-line arguments. In Chapter 2, our greatest common denominator calculator used the following code to loop over its command-line arguments:

```
for arg in std::env::args().skip(1) {
    ...
}
```

The `std::env::args` function returns an iterator that produces the program's arguments as `String`s, the first item being the name of the program itself. That's not a string we want to process in this loop. Calling `skip(1)` on that iterator returns a new iterator that drops the program name the first time it's called and then produces all the subsequent arguments. The `skip_while` adapter uses a closure to decide how many items to drop from the beginning of the sequence.

You can iterate over the body lines of the message from the previous section like this:

```
for body in message
    .lines()
    .skip_while(|l| !l.is_empty())
    .skip(1)
{
    println!("{body}");
}
```

This uses `skip_while` to skip nonblank lines, but that iterator does produce the blank line itself—after all, the closure returned `false` for that

line. So we use the `skip` method as well to drop that, giving us an iterator whose first item will be the message body's first line. Taken together with the declaration of `message` from the previous section, this code prints:

```
Did you get any writing done today?
When will you stop wasting time plotting fractals?
```

## peekable

A peekable iterator lets you peek at the next item that will be produced without actually consuming it. You can turn any iterator into a peekable iterator by calling the `Iterator` trait's `peekable` method:

```
fn peekable(self) -> std::iter::Peekable<Self>
where
    Self: Sized;
```

Here, `Peekable<Self>` is a `struct` that implements `Iterator<Item = Self::Item>`, and `Self` is the type of the underlying iterator. A `Peekable` iterator has an additional method `peek` that returns an `Option<&Item>`: `None` if the underlying iterator is done, and otherwise `Some(r)`, where `r` is a shared reference to the next item. (Note that if the iterator's item type is already a reference to something, this ends up being a reference to a reference.)

Calling `peek` tries to draw the next item from the underlying iterator and, if there is one, caches it until the next call to `next`. All the other `Iterator` methods on `Peekable` know about this cache: for example, `iter.last()` on a peekable iterator `iter` knows to check the cache after exhausting the underlying iterator.

Peekable iterators are essential when you can't decide how many items to consume from an iterator until you've gone too far. For example, if you're parsing numbers from a stream of characters, you can't decide where the number ends until you've seen the first nonnumber character following it:

```
use std::iter::Peekable;

fn parse_number<I>(tokens: &mut Peekable<I>) -> u32
where
    I: Iterator<Item = char>,
{
    let mut n = 0;
    loop {
        match tokens.peek() {
            Some(r) if r.is_digit(10) => {
                n = n * 10 + r.to_digit(10).unwrap();
            }
            _ => return n,
        }
        tokens.next();
    }
}

let mut chars = "226153980,1766319049".chars().peekable();
assert_eq!(parse_number(&mut chars), 226153980);
// Look, `parse_number` didn't consume the comma! So we will.
assert_eq!(chars.next(), Some(','));
assert_eq!(parse_number(&mut chars), 1766319049);
assert_eq!(chars.next(), None);
```

The `parse_number` function uses `peek` to check the next character and consumes it only if it is a digit. If it isn't a digit or the iterator is exhausted (that is, if `peek` returns `None`), we return the number we've parsed and leave the next character in the iterator, ready to be consumed.

## fuse

Once an `Iterator` has returned `None`, the trait doesn't specify how it ought to behave if you call its `next` method again. Most iterators just return `None` again, but not all. If your code counts on that behavior, you may be in for a surprise. The `fuse` adapter takes any iterator and produces one that will definitely continue to return `None` once it has done so the first time:

```
struct Flaky(bool);

impl Iterator for Flaky {
```

```
    type Item = &'static str;
    fn next(&mut self) -> Option<Self::Item> {
        if self.0 {
            self.0 = false;
            Some("totally the last item")
        } else {
            self.0 = true;  // D'oh!
            None
        }
    }
}

let mut flaky = Flaky(true);
assert_eq!(flaky.next(), Some("totally the last item"));
assert_eq!(flaky.next(), None);
assert_eq!(flaky.next(), Some("totally the last item"));

let mut not_flaky = Flaky(true).fuse();
assert_eq!(not_flaky.next(), Some("totally the last item"));
assert_eq!(not_flaky.next(), None);
assert_eq!(not_flaky.next(), None);
```

The `fuse` adapter is probably most useful in generic code that needs to work with iterators of uncertain origin. Rather than hoping that every iterator you'll have to deal with will be well-behaved, you can use `fuse` to make sure.

## Reversible Iterators and rev

Some iterators are able to draw items from both ends of the sequence. You can reverse such iterators by using the `rev` adapter. For example, an iterator over a vector could just as easily draw items from the end of the vector as from the start. Such iterators can implement the `std::iter::DoubleEndedIterator` trait, which extends `Iterator`:

```
trait DoubleEndedIterator: Iterator {
    fn next_back(&mut self) -> Option<Self::Item>;
}
```

You can think of a double-ended iterator as having two fingers marking the current front and back of the sequence. Drawing items from either end advances that finger toward the other; when the two meet, the iteration is done:

```
let bee_parts = ["head", "thorax", "abdomen"];

let mut iter = bee_parts.iter();
assert_eq!(iter.next(),      Some(&"head"));
assert_eq!(iter.next_back(), Some(&"abdomen"));
assert_eq!(iter.next(),      Some(&"thorax"));

assert_eq!(iter.next_back(), None);
assert_eq!(iter.next(),      None);
```

The structure of an iterator over a slice makes this behavior easy to implement: it is literally a pair of pointers to the start and end of the range of elements we haven't yet produced; `next` and `next_back` simply draw an item from one or the other. Iterators for ordered collections like `BTreeSet` and `BTreeMap` are double-ended too: their `next_back` method draws the greatest elements or entries first. In general, the standard library provides double-ended iteration whenever it's practical.

But not all iterators can do this so easily: an iterator producing values from other threads arriving at a channel's `Receiver` has no way to anticipate what the last value received might be. In general, you'll need to check the standard library's documentation to see which iterators implement `DoubleEndedIterator` and which don't.

If an iterator is double-ended, you can reverse it with the `rev` adapter:

```
fn rev(self) -> impl Iterator<Item = Self>
where
    Self: Sized + DoubleEndedIterator;
```

The returned iterator is also double-ended: its `next` and `next_back` methods are simply exchanged:

```
let meals = ["breakfast", "lunch", "dinner"];

let mut iter = meals.iter().rev();
assert_eq!(iter.next(), Some(&"dinner"));
assert_eq!(iter.next_back(), Some(&"breakfast"));
assert_eq!(iter.next(), Some(&"lunch"));
assert_eq!(iter.next_back(), None);
```

Most iterator adapters, if applied to a reversible iterator, return another reversible iterator. For example, `map` and `filter` preserve reversibility.

## inspect

The `inspect` adapter is handy for debugging pipelines of iterator adapters, but it isn't used much in production code. It simply applies a closure to a shared reference to each item and then passes the item through. The closure can't affect the items, but it can do things like print them or make assertions about them.

This example shows a case in which converting a string to uppercase changes its length:

```
let upper_case: String = "große"
    .chars()
    .inspect(|c| println!("before: {c:?}"))
    .flat_map(|c| c.to_uppercase())
    .inspect(|c| println!(" after:     {c:?}"))
    .collect();
assert_eq!(upper_case, "GROSSE");
```

The uppercase equivalent of the lowercase German letter "ß" is "SS," which is why `char::to_uppercase` returns an iterator over characters, not a single replacement character. The preceding code uses `flat_map` to concatenate all the sequences that `to_uppercase` returns into a single `String`, printing the following as it does so:

```
before: 'g'
 after:     'G'
before: 'r'
 after:     'R'
```

```
before: 'o'
 after:     'O'
before: 'ß'
 after:     'S'
 after:     'S'
before: 'e'
 after:     'E'
```

## chain

The `chain` adapter appends one iterator to another. More precisely, `i1.chain(i2)` returns an iterator that draws items from `i1` until it's exhausted and then draws items from `i2`.

The `chain` adapter's signature is as follows:

```
fn chain<U>(self, other: U) -> impl Iterator<Item = Self::Item>
where
    Self: Sized,
    U: IntoIterator<Item = Self::Item>;
```

In other words, you can chain an iterator together with any iterable that produces the same item type.

For example:

```
let v: Vec<i32> = (1..4).chain([20, 30, 40]).collect();
assert_eq!(v, [1, 2, 3, 20, 30, 40]);
```

A `chain` iterator is reversible if both of its underlying iterators are:

```
let v: Vec<i32> = (1..4).chain([20, 30, 40]).rev().collect();
assert_eq!(v, [40, 30, 20, 3, 2, 1]);
```

A `chain` iterator keeps track of whether each of the two underlying iterators has returned `None` and directs `next` and `next_back` calls to one or the other, as appropriate.

## enumerate

The `Iterator` trait's `enumerate` adapter attaches a running index to the sequence, taking an iterator that produces items `A, B, C, ...` and returning an iterator that produces pairs `(0, A), (1, B), (2, C), ...`. It looks trivial at first glance, but it's used surprisingly often.

Consumers can use that index to distinguish one item from another and establish the context in which to process each one. For example, the Mandelbrot set plotter in Chapter 2 splits the image into eight horizontal bands and assigns each one to a different thread. That code uses `enumerate` to tell each thread which portion of the image its band corresponds to.

It starts with a rectangular buffer of pixels:

```
let mut pixels = vec![0; columns * rows];
```

Next, it uses `chunks_mut` to split the image into horizontal bands, one per thread:

```
let rows_per_band = rows.div_ceil(threads);
...
let bands = pixels.chunks_mut(rows_per_band * columns);
```

And then it iterates over the bands, starting a thread for each one:

```
for (i, band) in bands.enumerate() {
    let top = rows_per_band * i;
    // start a thread to render rows `top..top + band_rows`
    ...
}
```

Each iteration gets a pair `(i, band)`, where `band` is the `&mut [u8]` slice of the pixel buffer the thread should draw into, and `i` is the index of that band in the overall image, courtesy of the `enumerate` adapter. Given the boundaries of the plot and the size of the bands, this is enough information for the thread to determine which portion of the image it has been assigned and thus what to draw into `band`.

You can think of the `(index, item)` pairs that `enumerate` produces as analogous to the `(key, value)` pairs that you get when iterating over a `HashMap` or other associative collection. If you're iterating over a slice or vector, the `index` is the "key" under which the `item` appears.

## zip

The `zip` adapter combines two iterators into a single iterator that produces pairs holding one value from each iterator, like a zipper joining its two sides into a single seam. The zipped iterator ends when either of the two underlying iterators ends.

For example, you can get the same effect as the `enumerate` adapter by zipping the unbounded-end range `0..` with the other iterator:

```
let v: Vec<_> = (0..).zip("ABCD".chars()).collect();
assert_eq!(v, vec![(0, 'A'), (1, 'B'), (2, 'C'), (3, 'D')]);
```

In this sense, you can think of `zip` as a generalization of `enumerate`: whereas `enumerate` attaches indices to the sequence, `zip` attaches any arbitrary iterator's items. We suggested before that `enumerate` can help provide context for processing items; `zip` is a more flexible way to do the same.

The argument to `zip` doesn't need to be an iterator itself; it can be any iterable:

```
use std::iter;

let endings = ["once", "twice", "chicken soup with rice"];
let rhyme: Vec<_> = iter::repeat("going")
    .zip(endings)
    .collect();
assert_eq!(
    rhyme,
    vec![
        ("going", "once"),
        ("going", "twice"),
        ("going", "chicken soup with rice"),
```

```
    ],
);
```

## by_ref

Throughout this section, we've been attaching adapters to iterators. Once you've done so, can you ever take the adapter off again? Usually, no: adapters take ownership of the underlying iterator and provide no method to give it back.

An iterator's `by_ref` method borrows a mutable reference to the iterator so that you can apply adapters to the reference. When you're done consuming items from these adapters, you drop them, the borrow ends, and regain access to your original iterator.

For example, earlier in the chapter we showed how to use `take_while` and `skip_while` to process the header lines and body of a mail message. But what if you want to do both, using the same underlying iterator?

Using `by_ref`, we can use `take_while` to handle the headers and, when that's done, get the underlying iterator back, which `take_while` has left exactly in position to handle the message body:

```
let message = "\
    To: jimb\r\n\
    From: id\r\n\
    \r\n\
    Oooooh, donuts!!\r\n";

let mut lines = message.lines();

println!("Headers:");
for header in lines.by_ref().take_while(|l| !l.is_empty()) {
    println!("{header}");
}

println!("\nBody:");
for body in lines {
    println!("{body}");
}
```

The call `lines.by_ref()` borrows a mutable reference to the iterator, and it is this reference that the `take_while` iterator takes ownership of. That iterator goes out of scope at the end of the first `for` loop, meaning that the borrow has ended, so you can use `lines` again in the second `for` loop. This prints the following:

```
Headers:
To: jimb
From: id

Body:
Oooooh, donuts!!
```

The `by_ref` adapter's definition is trivial: it returns a mutable reference to the iterator. Then, the standard library includes this strange little implementation:

```
impl<I: Iterator + ?Sized> Iterator for &mut I {
    type Item = I::Item;
    fn next(&mut self) -> Option<I::Item> {
        (**self).next()
    }
    ...
}
```

In other words, if `I` is some iterator type, then `&mut I` is an iterator too, whose `next` method defers to its referent. When you call an adapter on a mutable reference to an iterator, the adapter takes ownership of the *reference*, not the iterator itself. That's just a borrow that ends when the adapter goes out of scope.

## cloned, copied

The `cloned` adapter takes an iterator that produces references and returns an iterator that produces values cloned from those references, much like `iter.map(|item| item.clone())`. Naturally, the referent type must implement `Clone`. For example:

```
let a = ['1', '2', '3', '∞'];

assert_eq!(a.iter().next(),          Some(&'1'));
assert_eq!(a.iter().cloned().next(), Some('1'));
```

The `copied` adapter is the same idea, but more restrictive: the referent type must implement `Copy`. A call like `iter.copied()` is roughly the same as `iter.map(|r| *r)`. Since every type that implements `Copy` also implements `Clone`, `cloned` is strictly more general, but depending on the item type, a `clone` call can do arbitrary amounts of allocation and copying.

If you're assuming that would never happen because your item type is something simple, it's best to use `copied` to make the type checker check your assumptions.

## cycle

The `cycle` adapter returns an iterator that endlessly repeats the sequence produced by the underlying iterator. The underlying iterator must implement `std::clone::Clone` so that `cycle` can save its initial state and reuse it each time the cycle starts again.

For example:

```
let dirs = ["North", "East", "South", "West"];
let mut spin = dirs.iter().cycle();
assert_eq!(spin.next(), Some(&"North"));
assert_eq!(spin.next(), Some(&"East"));
assert_eq!(spin.next(), Some(&"South"));
assert_eq!(spin.next(), Some(&"West"));
assert_eq!(spin.next(), Some(&"North"));
assert_eq!(spin.next(), Some(&"East"));
```

Or, for a really gratuitous use of iterators:

```
use std::iter;

let fizzes = iter::repeat_n("",
2).chain(iter::once("fizz")).cycle();
```

```
let buzzes = iter::repeat_n("",
4).chain(iter::once("buzz")).cycle();
let fizzes_buzzes = fizzes.zip(buzzes);

let fizz_buzz = (1..100)
    .zip(fizzes_buzzes)
    .map(|tuple| match tuple {
        (i, ("", "")) => i.to_string(),
        (_, (fizz, buzz)) => format!("{fizz}{buzz}"),
    });

for line in fizz_buzz {
    println!("{line}");
}
```

This plays a children's word game, now sometimes used as a job interview question for coders, in which the players take turns counting, replacing any number divisible by three with the word `fizz`, and any number divisible by five with `buzz`. Numbers divisible by both become `fizzbuzz`.

# Consuming Iterators

So far we've covered creating iterators and adapting them into new iterators; here we finish off the process by showing ways to consume them.

Of course, you can consume an iterator with a `for` loop, or call `next` explicitly, but there are many common tasks that you shouldn't have to write out again and again. The `Iterator` trait provides a broad selection of methods to cover many of these.

## Simple Accumulation: count, sum, product

The `count` method draws items from an iterator until it returns `None` and tells you how many it got. Here's a short program that counts the number of English vowels in a string:

```
const VOWELS: [char; 5] = ['A', 'E', 'I', 'O', 'U'];

fn count_vowels(s: &str) -> usize {
    s.to_uppercase()
```

```
        .chars()
        .filter(|c| VOWELS.contains(c))
        .count()
}
```

The `sum` and `product` methods compute the sum or product of the iterator's items, which must be integers or floating-point numbers:

```
fn triangle(n: u64) -> u64 {
    (1..=n).sum()
}
assert_eq!(triangle(20), 210);

fn factorial(n: u64) -> u64 {
    (1..=n).product()
}
assert_eq!(factorial(20), 2432902008176640000);
```

(You can extend `sum` and `product` to work with other types by implementing the `std::iter::Sum` and `std::iter::Product` traits, which we won't describe in this book.)

## max, min

The `min` and `max` methods on `Iterator` return the least or greatest item the iterator produces. The iterator's item type must implement `std::cmp::Ord` so that items can be compared with one another. For example:

```
assert_eq!([-2, 0, 1, 0, -2, -5].iter().max(), Some(&1));
assert_eq!([-2, 0, 1, 0, -2, -5].iter().min(), Some(&-5));
```

These methods return an `Option<Self::Item>` so that they can return `None` if the iterator produces no items.

As explained in "Ordered Comparisons", Rust's floating-point types `f32` and `f64` implement only `std::cmp::PartialOrd`, not `std::cmp::Ord`, so you can't use the `min` and `max` methods to compute the least or greatest of a sequence of floating-point numbers. This is not a

popular aspect of Rust's design, but it is deliberate: it's not clear what such functions should do with IEEE NaN values. Simply ignoring them would risk masking more serious problems in the code.

If you know how you would like to handle NaN values, you can use the `max_by` and `min_by` iterator methods instead, which let you supply your own comparison function.

## max_by, min_by

The `max_by` and `min_by` methods return the maximum or minimum item the iterator produces, as determined by a comparison function you provide:

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

// Compare two f64 values. Panic if given a NaN.
fn cmp(lhs: &f64, rhs: &f64) -> Ordering {
    lhs.partial_cmp(rhs).unwrap()
}

let numbers = [1.0, 4.0, 2.0];
assert_eq!(numbers.iter().copied().max_by(cmp), Some(4.0));
assert_eq!(numbers.iter().copied().min_by(cmp), Some(1.0));

let numbers = [1.0, 4.0, f64::NAN, 2.0];
assert_eq!(numbers.iter().copied().max_by(cmp), Some(4.0));  //
panics
```

The `max_by` and `min_by` methods pass items to the comparison function by reference so that they can work efficiently with any sort of iterator, so `cmp` expects to take its arguments by reference, even though we've used `copied` to get an iterator that produces `f64` items.

## max_by_key, min_by_key

The `max_by_key` and `min_by_key` methods on `Iterator` let you select the maximum or minimum item as determined by a closure applied to each item. The closure can select some field of the item or perform a computation on the items. Since you're often interested in data associated

with some minimum or maximum, not just the extremum itself, these functions are often more useful than `min` and `max`. Their signatures are as follows:

```
fn min_by_key<B: Ord, F>(self, f: F) -> Option<Self::Item>
where
    Self: Sized,
    F: FnMut(&Self::Item) -> B;

fn max_by_key<B: Ord, F>(self, f: F) -> Option<Self::Item>
where
    Self: Sized,
    F: FnMut(&Self::Item) -> B;
```

That is, given a closure that takes an item and returns any ordered type `B`, return the item for which the closure returned the maximum or minimum `B`, or `None` if no items were produced.

For example, if you need to scan a hash table of cities to find the cities with the largest and smallest populations, you could write:

```
use std::collections::HashMap;

let mut populations = HashMap::new();
populations.insert("Portland",  583_776);
populations.insert("Fossil",        449);
populations.insert("Greenhorn",       2);
populations.insert("Boring",      7_762);
populations.insert("The Dalles", 15_340);

assert_eq!(
    populations.iter().max_by_key(|&(_name, pop)| pop),
    Some((&"Portland", &583_776)),
);
assert_eq!(
    populations.iter().min_by_key(|&(_name, pop)| pop),
    Some((&"Greenhorn", &2)),
);
```

The closure `|&(_name, pop)| pop` gets applied to each item the iterator produces and returns the value to use for comparison—in this case, the city's population. The value returned is the entire item, not just the value

the closure returns. (Naturally, if you were making queries like this often, you'd probably want to arrange for a more efficient way to find the entries than making a linear search through the table.)

## Comparing Item Sequences

You can use the < and == operators to compare strings, vectors, and slices, assuming their individual elements can be compared. Although iterators do not support Rust's comparison operators, they do provide methods like `eq` and `lt` that do the same job, drawing pairs of items from the iterators and comparing them until a decision can be reached. For example:

```
let packed =  "Helen of Troy";
let spaced =  "Helen   of    Troy";
let obscure = "Helen of Sandusky";  // nice person, just not
famous

assert!(packed != spaced);
assert!(packed.split_whitespace().eq(spaced.split_whitespace()));

// This is true because ' ' < 'o'.
assert!(spaced < obscure);

// This is true because "Troy" > "Sandusky".
assert!
(spaced.split_whitespace().gt(obscure.split_whitespace()));
```

The calls to `split_whitespace` return iterators over the whitespace-separated words of the string. Using the `eq` and `gt` methods on these iterators performs a word-by-word comparison instead of a character-by-character comparison. These are all possible because `&str` implements `PartialOrd` and `PartialEq`.

Iterators provide the `eq` and `ne` methods for equality comparisons and the `lt`, `le`, `gt`, and `ge` methods for ordered comparisons. The `cmp` and `partial_cmp` methods behave like the corresponding methods of the `Ord` and `PartialOrd` traits.

## any and all

The `any` and `all` methods apply a closure to each item the iterator produces and return `true` if the closure returns `true` for any item, or for all the items:

```
let id = "Iterator";

assert!( id.chars().any(char::is_uppercase));
assert!(!id.chars().all(char::is_uppercase));
```

These methods consume only as many items as they need to determine the answer. For example, if the closure ever returns `true` for a given item, then `any` returns `true` immediately, without drawing any more items from the iterator.

## position, rposition, and ExactSizeIterator

The `position` method applies a closure to each item from the iterator and returns the index of the first item for which the closure returns `true`. More precisely, it returns an `Option` of the index: if the closure returns `true` for no item, `position` returns `None`. It stops drawing items as soon as the closure returns `true`. For example:

```
let text = "Xerxes";
assert_eq!(text.chars().position(|c| c == 'e'), Some(1));
assert_eq!(text.chars().position(|c| c == 'z'), None);
```

The `rposition` method is the same, except that it searches from the right. For example:

```
let bytes = b"Xerxes";
assert_eq!(bytes.iter().rposition(|&c| c == b'e'), Some(4));
assert_eq!(bytes.iter().rposition(|&c| c == b'X'), Some(0));
```

The `rposition` method requires a reversible iterator so that it can draw items from the right end of the sequence. It also requires an exact-size

iterator so that it can assign indices the same way `position` would, starting with `0` at the left. An exact-size iterator is one that implements the `std::iter::ExactSizeIterator` trait:

```
trait ExactSizeIterator: Iterator {
    fn len(&self) -> usize { ... }
    fn is_empty(&self) -> bool { ... }
}
```

The `len` method returns the number of items remaining, and the `is_empty` method returns `true` if iteration is complete.

Naturally, not every iterator knows how many items it will produce in advance. For example, the `str::chars` iterator used earlier does not (since UTF-8 is a variable-width encoding), so you can't use `rposition` on strings. But an iterator over an array of bytes certainly knows the array's length, so it can implement `ExactSizeIterator`.

## fold and rfold

The `fold` method is a very general tool for accumulating some sort of result over the entire sequence of items an iterator produces. Given an initial value, which we'll call the *accumulator*, and a closure, `fold` repeatedly applies the closure to the current accumulator and the next item from the iterator. The value the closure returns is taken as the new accumulator, to be passed to the closure with the next item. The final accumulator value is what `fold` itself returns. If the sequence is empty, `fold` simply returns the initial accumulator.

Many other methods for consuming an iterator's values can be written as uses of `fold`:

```
let a = [5, 6, 7, 8, 9, 10];

assert_eq!(a.iter().fold(0, |n, _| n + 1), 6);        // count
assert_eq!(a.iter().fold(0, |n, i| n + i), 45);       // sum
assert_eq!(a.iter().fold(1, |n, i| n * i), 151200);   // product
```

```
// max
assert_eq!(
    a.iter().cloned().fold(i32::min_value(), std::cmp::max),
    10,
);
```

The `fold` method's signature is as follows:

```
fn fold<A, F>(self, init: A, f: F) -> A
where
    Self: Sized,
    F: FnMut(A, Self::Item) -> A;
```

Here, `A` is the accumulator type. The `init` argument is an `A`, as is the closure's first argument and return value, and the return value of `fold` itself. Note that the accumulator values are moved into and out of the closure, so you can use `fold` with non-`Copy` accumulator types:

```
let a = ["Pack", "my", "box", "with", "five", "dozen", "liquor",
"jugs"];

// See also: the `join` method on slices, which won't
// give you that extra space at the end.
let pangram = a.iter().fold(String::new(), |s, w| s + w + " ");
assert_eq!(pangram, "Pack my box with five dozen liquor jugs ");
```

The `rfold` method is the same as `fold`, except that it requires a double-ended iterator and processes its items from last to first:

```
let weird_pangram = a.iter().rfold(String::new(), |s, w| s + w +
" ");
assert_eq!(weird_pangram, "jugs liquor dozen five with box my
Pack ");
```

## try_fold and try_rfold

The `try_fold` method is the same as `fold`, except that iteration can exit early, without consuming all the values from the iterator. The value returned by the closure you pass to `try_fold` indicates whether it should return

immediately, or continue folding the iterator's items. Your closure can return any one of several types, indicating how folding should proceed:

- If your closure returns `Result<T, E>`, perhaps because it does I/O or carries out some other fallible operation, then returning `Ok(v)` tells `try_fold` to continue folding, with `v` as the new accumulator value. Returning `Err(e)` causes folding to stop immediately. The fold's final value is a `Result` carrying the final accumulator value, or the error returned by the closure.
- If your closure returns `Option<T>`, then `Some(v)` indicates that folding should continue with `v` as the new accumulator value, and `None` indicates that iteration should stop immediately. The fold's final value is also an `Option`.
- Finally, the closure can return a `std::ops::ControlFlow` value. This type is an enum with two variants, `Continue(c)` and `Break(b)`, meaning to continue with new accumulator value `c`, or stop early. The result of the fold is a `ControlFlow` value: `Continue(v)` if the fold consumed the entire iterator, yielding the final accumulator value `v`; or `Break(b)`, if the closure returned that value.

  `Continue(c)` and `Break(b)` behave exactly like `Ok(c)` and `Err(b)`. The advantage of using `ControlFlow` instead of `Result` is that it makes your code a little more legible when an early exit doesn't indicate an error, but merely that the answer is ready early. We show an example of this next.

Here's a program that sums numbers read from its standard input:

```
use std::error::Error;
use std::str::FromStr;

fn main() -> Result<(), Box<dyn Error>> {
    let sum = std::io::stdin()
        .lines()
        .try_fold(0, |sum, line| -> Result<u64, Box<dyn Error>> {
```

```
            Ok(sum + u64::from_str(line?.trim())?)
        })?;
    println!("{sum}");
    Ok(())
}
```

The `lines` iterator on buffered input streams produces items of type `Result<String, std::io::Error>`, and parsing the `String` as an integer may fail as well. Using `try_fold` here lets the closure return `Result<u64, ...>`, so we can use the `?` operator to propagate failures from the closure out to the `main` function.

Because `try_fold` is so flexible, it is used to implement many of `Iterator`'s other consumer methods. For example, here's an implementation of `all`:

```
fn all<P>(&mut self, mut predicate: P) -> bool
where
    Self: Sized,
    P: FnMut(Self::Item) -> bool,
{
    use std::ops::ControlFlow::*;
    self.try_fold((), |_, item| {
        if predicate(item) { Continue(()) } else { Break(()) }
    }) == Continue(())
}
```

Note that this cannot be written with ordinary `fold`: `all` promises to stop consuming items from the underlying iterator as soon as `predicate` returns false, but `fold` always consumes the entire iterator.

If you are implementing your own iterator type, it's worth investigating whether your iterator could implement `try_fold` more efficiently than the default definition from the `Iterator` trait. If you can speed up `try_fold`, all the other methods built on it will benefit as well.

The `try_rfold` method, as its name suggests, is the same as `try_fold`, except that it draws values from the back, instead of the front, and requires a double-ended iterator.

## nth, nth_back

The `nth` method takes an index `n`, skips that many items from the iterator, and returns the next item, or `None` if the sequence ends before that point. Calling `.nth(0)` is equivalent to `.next()`. It doesn't take ownership of the iterator the way an adapter would, so you can call it many times:

```
let mut squares = (0..10).map(|i| i * i);

assert_eq!(squares.nth(4), Some(16));
assert_eq!(squares.nth(0), Some(25));
assert_eq!(squares.nth(6), None);
```

Its signature is shown here:

```
fn nth(&mut self, n: usize) -> Option<Self::Item>
where
    Self: Sized;
```

The `nth_back` method is much the same, except that it draws from the back of a double-ended iterator. Calling `.nth_back(0)` is equivalent to `.next_back()`: it returns the last item, or `None` if the iterator is empty.

## last

The `last` method returns the last item the iterator produces, or `None` if it's empty. Its signature is as follows:

```
fn last(self) -> Option<Self::Item>;
```

For example:

```
let squares = (0..10).map(|i| i * i);
assert_eq!(squares.last(), Some(81));
```

This consumes all the iterator's items starting from the front, even if the iterator is reversible. If you have a reversible iterator and don't need to consume all its items, you should instead just write `iter.next_back()`.

## find, rfind, and find_map

The `find` method draws items from an iterator, returning the first item for which the given closure returns `true`, or `None` if the sequence ends before a suitable item is found. Its signature is:

```
fn find<P>(&mut self, predicate: P) -> Option<Self::Item>
where
    Self: Sized,
    P: FnMut(&Self::Item) -> bool;
```

The `rfind` method is similar, but it requires a double-ended iterator and searches values from back to front, returning the *last* item for which the closure returns `true`. For example, using the table of cities and populations from "max_by_key, min_by_key", you could write:

```
assert_eq!(
    populations.iter().find(|&(_name, &pop)| pop > 1_000_000),
    None,
);
assert_eq!(
    populations.iter().find(|&(_name, &pop)| pop > 500_000),
    Some((&"Portland", &583_776)),
);
```

None of the cities in the table have a population greater than a million, but there is one city with half a million people. Sometimes your closure isn't just a simple predicate casting a Boolean judgment on each item and moving on: it might be something more complex that produces an interesting value in its own right. In this case, `find_map` is just what you want. Its signature is:

```
fn find_map<B, F>(&mut self, f: F) -> Option<B>
where
    F: FnMut(Self::Item) -> Option<B>;
```

This is just like `find`, except that instead of returning `bool`, the closure should return an `Option` of some value. `find_map` returns the first

`Option` that is `Some`. For example, if we have a database of each city's parks, we might want to see if any of them are volcanoes and provide the name of the park if so:

```
let big_city_with_volcano_park = populations
    .iter()
    .find_map(|(&city, _)| {
        if let Some(park) = find_volcano_park(city, &parks) {
            // find_map returns this value, so our caller knows
            // *which* park we found.
            return Some((city, park.name));
        }

        // Reject this item, and continue the search.
        None
    });

assert_eq!(big_city_with_volcano_park, Some(("Portland", "Mt.
Tabor Park")));
```

## Building Collections: collect and FromIterator

Throughout the book, we've been using the `collect` method to build vectors holding an iterator's items. For example, in Chapter 2, we called `std::env::args()` to get an iterator over the program's command-line arguments and then called that iterator's `collect` method to gather them into a vector:

```
let args: Vec<String> = std::env::args().collect();
```

But `collect` isn't specific to vectors: in fact, it can build any kind of collection from Rust's standard library, as long as the iterator produces a suitable item type:

```
use std::collections::{HashSet, BTreeSet, LinkedList, HashMap,
BTreeMap};

let args: HashSet<String> = std::env::args().collect();
let args: BTreeSet<String> = std::env::args().collect();
let args: LinkedList<String> = std::env::args().collect();
```

```
// Collecting a map requires (key, value) pairs, so for this
example,
// zip the sequence of strings with a sequence of integers.
let args: HashMap<String, usize> =
std::env::args().zip(0..).collect();
let args: BTreeMap<String, usize> =
std::env::args().zip(0..).collect();

// and so on
```

Naturally, `collect` itself doesn't know how to construct all these types. Rather, when some collection type like `Vec` or `HashMap` knows how to construct itself from an iterator, it implements the `std::iter::FromIterator` trait, for which `collect` is just a convenient veneer:

```
trait FromIterator<A>: Sized {
    fn from_iter<T: IntoIterator<Item = A>>(iter: T) -> Self;
}
```

If a collection type implements `FromIterator<A>`, then its associated function `from_iter` builds a value of that type from an iterable producing items of type `A`.

In the simplest case, the implementation could simply construct an empty collection and then add the items from the iterator one by one. For example, `std::collections::LinkedList`'s implementation of `FromIterator` works this way. However, some types can do better than that. For example, constructing a vector from some iterator `iter` could be as simple as:

```
let mut vec = Vec::new();
for item in iter {
    vec.push(item);
}
vec
```

But this isn't ideal: as the vector grows, it may need to expand its buffer, requiring a call to the heap allocator and a copy of the extant elements.

Vectors do take algorithmic measures to keep this overhead low, but if there were some way to simply allocate a buffer of the right size to begin with, there would be no need to resize at all.

This is where the `Iterator` trait's `size_hint` method comes in:

```
trait Iterator {
    ...
    fn size_hint(&self) -> (usize, Option<usize>) {
        (0, None)
    }
}
```

This method returns a lower bound and optional upper bound on the number of items the iterator will produce. The default definition returns zero as the lower bound and declines to name an upper bound, saying, in effect, "I have no idea," but many iterators can do better than this. An iterator over a `Range`, for example, knows exactly how many items it will produce, as does an iterator over a `Vec` or `HashMap`. Such iterators provide their own specialized definitions for `size_hint`.

These bounds are exactly the information that `Vec`'s implementation of `FromIterator` needs to size the new vector's buffer correctly from the start. Insertions check that the buffer is large enough, so even if the hint is incorrect, only performance is affected, not safety. Other types can take similar steps: for example, `HashSet` and `HashMap` also use `Iterator::size_hint` to choose an appropriate initial size for their hash table.

One note about type inference: at the top of this section, it's a bit strange to see the same call, `std::env::args().collect()`, produce four different kinds of collections depending on its context. The return type of `collect` is its type parameter, so the first two calls are equivalent to the following:

```
let args = std::env::args().collect::<Vec<String>>();
let args = std::env::args().collect::<HashSet<String>>();
```

But as long as there's only one type that could possibly work as `collect`'s argument, Rust's type inference will supply it for you. When you spell out the type of `args`, you ensure this is the case.

## The Extend Trait

If a type implements the `std::iter::Extend` trait, then its `extend` method adds an iterable's items to the collection:

```
let mut v: Vec<i32> = (0..5).map(|i| 1 << i).collect();
v.extend([31, 57, 99, 163]);
assert_eq!(v, [1, 2, 4, 8, 16, 31, 57, 99, 163]);
```

All of the standard collections implement `Extend`, so they all have this method; so does `String`. Arrays and slices, which have a fixed length, do not. The trait's definition is as follows:

```
trait Extend<A> {
    fn extend<T>(&mut self, iter: T)
    where
        T: IntoIterator<Item = A>;
}
```

Obviously, this is similar to `std::iter::FromIterator`: that creates a new collection, whereas `Extend` extends an existing collection. In fact, several implementations of `FromIterator` in the standard library simply create a new empty collection and then call `extend` to populate it. For example, the implementation of `FromIterator` for `std::collections::LinkedList` works this way:

```
impl<T> FromIterator<T> for LinkedList<T> {
    fn from_iter<I: IntoIterator<Item = T>>(iter: I) -> Self {
        let mut list = Self::new();
        list.extend(iter);
        list
    }
}
```

## partition

The `partition` method divides an iterator's items among two collections, using a closure to decide where each item belongs:

```
let things = ["doorknob", "mushroom", "noodle", "giraffe",
"grapefruit"];

// Amazing fact: the name of a living thing always starts with an
// odd-numbered letter.
let (living, nonliving): (Vec<&str>, Vec<&str>) =
    things.iter().partition(|name| name.as_bytes()[0] & 1 != 0);

assert_eq!(living,    vec!["mushroom", "giraffe", "grapefruit"]);
assert_eq!(nonliving, vec!["doorknob", "noodle"]);
```

Like `collect`, `partition` can make any sort of collections you like, although both must be of the same type. And like `collect`, you'll need to specify the return type: the preceding example writes out the type of `living` and `nonliving` and lets type inference choose the right type parameters for the call to `partition`.

The signature of `partition` is as follows:

```
fn partition<B, F>(self, f: F) -> (B, B)
where
    Self: Sized,
    B: Default + Extend<Self::Item>,
    F: FnMut(&Self::Item) -> bool;
```

Whereas `collect` requires its result type to implement `FromIterator`, `partition` instead requires `std::default::Default`, which all Rust collections implement by returning an empty collection, and `std::iter::Extend`.

Other languages offer `partition` operations that just split the iterator into two iterators, instead of building two collections. But this isn't a good fit for Rust: items drawn from the underlying iterator but not yet drawn from the appropriate partitioned iterator would need to be buffered

somewhere; you would end up building a collection of some sort internally, anyway.

## for_each and try_for_each

The `for_each` method simply applies a closure to each item:

```
["doves", "hens", "birds"]
    .iter()
    .zip(["turtle", "french", "calling"])
    .zip(2..5)
    .rev()
    .map(|((item, kind), quantity)| {
        format!("{quantity} {kind} {item}")
    })
    .for_each(|gift| {
        println!("You have received: {gift}");
    });
```

This prints:

```
You have received: 4 calling birds
You have received: 3 french hens
You have received: 2 turtle doves
```

This is similar to a simple `for` loop, which could also use control structures like `break` and `continue`. Long chains of adapter calls like this are a little awkward in `for` loops:

```
for gift in ["doves", "hens", "birds"]
    .iter()
    .zip(["turtle", "french", "calling"])
    .zip(2..5)
    .rev()
    .map(|((item, kind), quantity)| {
        format!("{quantity} {kind} {item}")
    })
{
    println!("You have received: {gift}");
}
```

The pattern being bound, `gift`, can end up quite far away from the loop body in which it is used. If your closure needs to be fallible or exit early, you can use `try_for_each`:

```
...
    .try_for_each(|gift| {
        writeln!(&mut output_file, "You have received: {gift}")
    })?;
```

## Implementing Your Own Iterators

You can implement the `IntoIterator` and `Iterator` traits for your own types, making all the adapters and consumers shown in this chapter available for use, along with lots of other library and crate code written to work with the standard iterator interface. In this section, we'll show a simple iterator over a range type and then a more complex iterator over a binary tree type. Suppose we have the following range type (simplified from the standard library's `std::ops::Range<T>` type):

```
struct I32Range {
    start: i32,
    end: i32,
}
```

Iterating over an `I32Range` requires two pieces of state: the current value and the limit at which the iteration should end. This happens to be a nice fit for the `I32Range` type itself, using `start` as the next value, and `end` as the limit. So you can implement `Iterator` like so:

```
impl Iterator for I32Range {
    type Item = i32;
    fn next(&mut self) -> Option<i32> {
        if self.start >= self.end {
            return None;
        }
        let result = Some(self.start);
        self.start += 1;
        result
```

```
        }
    }
```

This iterator produces `i32` items, so that's the `Item` type. If the iteration is complete, `next` returns `None`; otherwise, it produces the next value and updates its state to prepare for the next call.

Of course, a `for` loop uses `IntoIterator::into_iter` to convert its operand into an iterator. But the standard library provides a blanket implementation of `IntoIterator` for every type that implements `Iterator`, so `I32Range` is ready for use:

```
let mut pi = 0.0;
let mut numerator = 1.0;

for k in (I32Range { start: 0, end: 14 }) {
    pi += numerator / (2 * k + 1) as f64;
    numerator /= -3.0;
}
pi *= 12.0_f64.sqrt();

// IEEE 754 specifies this result exactly.
assert_eq!(pi as f32, std::f32::consts::PI);
```

But `I32Range` is a special case, in that the iterable and iterator are the same type. Many cases aren't so simple. For example, here's the binary tree type from Chapter 10:

```
enum BinaryTree<T> {
    Empty,
    NonEmpty(Box<TreeNode<T>>),
}

struct TreeNode<T> {
    element: T,
    left: BinaryTree<T>,
    right: BinaryTree<T>,
}
```

The classic way to walk a binary tree is to recurse, using the stack of function calls to keep track of your place in the tree and the nodes yet to be

visited. But when implementing `Iterator` for `BinaryTree<T>`, each call to `next` must produce exactly one value and return. To keep track of the tree nodes it has yet to produce, the iterator must maintain its own stack. Here's one possible iterator type for `BinaryTree`:

```
use self::BinaryTree::*;

// The state of an in-order traversal of a `BinaryTree`.
struct TreeIter<'a, T> {
    // A stack of references to tree nodes. Since we use `Vec`'s
    // `push` and `pop` methods, the top of the stack is the end
of the
    // vector.
    //
    // The node the iterator will visit next is at the top of the
stack,
    // with those ancestors still unvisited below it. If the
stack is empty,
    // the iteration is over.
    unvisited: Vec<&'a TreeNode<T>>,
}
```

When we create a new `TreeIter`, its initial state should be about to produce the leftmost leaf node in the tree. According to the rules for the `unvisited` stack, it should thus have that leaf on the top, followed by its unvisited ancestors: the nodes along the left edge of the tree. We can initialize `unvisited` by walking the left edge of the tree from root to leaf and pushing each node we encounter, so we'll define a method on `TreeIter` to do that:

```
impl<'a, T: 'a> TreeIter<'a, T> {
    fn push_left_edge(&mut self, mut tree: &'a BinaryTree<T>) {
        while let NonEmpty(ref node) = *tree {
            self.unvisited.push(node);
            tree = &node.left;
        }
    }
}
```

Writing `mut tree` lets the loop change which node `tree` points to as it walks down the left edge, but since `tree` is a shared reference, it can't mutate the nodes themselves. With this helper method in place, we can give `BinaryTree` an `iter` method that returns an iterator over the tree:

```
impl<T> BinaryTree<T> {
    fn iter(&self) -> TreeIter<'_, T> {
        let mut iter = TreeIter {
            unvisited: Vec::new(),
        };
        iter.push_left_edge(self);
        iter
    }
}
```

The `iter` method constructs a `TreeIter` with an empty `unvisited` stack and then calls `push_left_edge` to initialize it. The leftmost node ends up on the top, as required by the `unvisited` stack's rules.

Following the standard library's practices, we can then implement `IntoIterator` on a shared reference to a tree with a call to `BinaryTree::iter`:

```
impl<'a, T: 'a> IntoIterator for &'a BinaryTree<T> {
    type Item = &'a T;
    type IntoIter = TreeIter<'a, T>;
    fn into_iter(self) -> Self::IntoIter {
        self.iter()
    }
}
```

The `IntoIter` definition establishes `TreeIter` as the iterator type for a `&BinaryTree`.

Finally, in the `Iterator` implementation, we get to actually walk the tree. Like `BinaryTree`'s `iter` method, the iterator's `next` method is guided by the stack's rules:

```
impl<'a, T> Iterator for TreeIter<'a, T> {
    type Item = &'a T;
```

```
    fn next(&mut self) -> Option<&'a T> {
        // Find the node this iteration must produce,
        // or finish the iteration. (Use the `?` operator
        // to return immediately if it's `None`.)
        let node = self.unvisited.pop()?;

        // After `node`, the next thing we produce must be the
leftmost
        // child in `node`'s right subtree, so push the path from
here
        // down. Our helper method turns out to be just what we
need.
        self.push_left_edge(&node.right);

        // Produce a reference to this node's value.
        Some(&node.element)
    }
}
```

If the stack is empty, the iteration is complete. Otherwise, `node` is a reference to the node to visit now; this call will return a reference to its `element` field. But first, we must advance the iterator's state to the next node. If this node has a right subtree, the next node to visit is the subtree's leftmost node, and we can use `push_left_edge` to push it, and its unvisited ancestors, onto the stack. But if this node has no right subtree, `push_left_edge` has no effect, which is just what we want: we can count on the new top of the stack to be `node`'s first unvisited ancestor, if any. With `IntoIterator` and `Iterator` implementations in place, we can finally use a `for` loop to iterate over a `BinaryTree` by reference.

Here we are using the `add` method on `BinaryTree` from "Populating a Binary Tree":

```
// Build a small tree.
let mut tree = BinaryTree::Empty;
tree.add("jaeger");
tree.add("robot");
tree.add("droid");
tree.add("mecha");

// Iterate over it.
let mut v = Vec::new();
```

```
for kind in &tree {
    v.push(*kind);
}
assert_eq!(v, ["droid", "jaeger", "mecha", "robot"]);
```

Figure 15-1 shows how the `unvisited` stack behaves as we iterate through a sample tree. At every step, the next node to be visited is at the top of the stack, with all its unvisited ancestors below it.

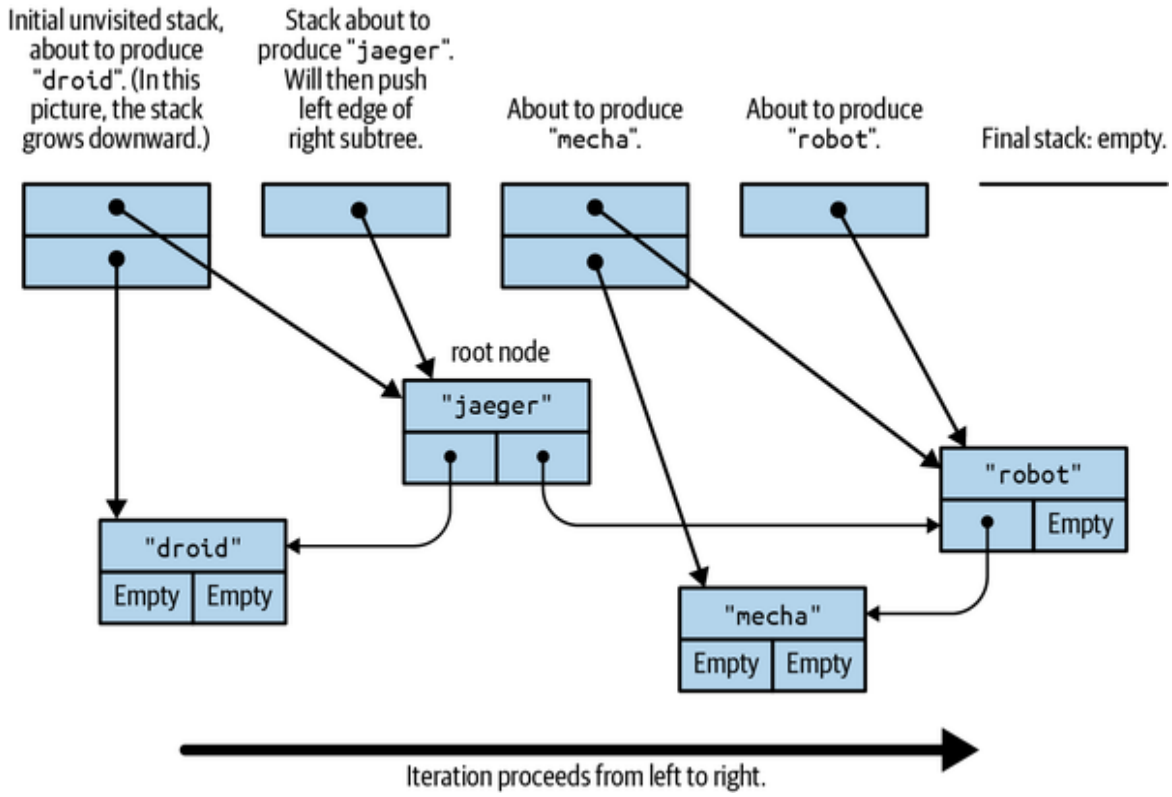


*Figure 15-1. Iterating over a binary tree*

All the usual iterator adapters and consumers are ready for use on our trees:

```
assert_eq!(
    tree.iter()
        .map(|name| format!("mega-{name}"))
        .collect::<Vec<_>>(),
    vec!["mega-droid", "mega-jaeger", "mega-mecha", "mega-
robot"],
);
```

Iterators are the embodiment of Rust's philosophy of providing powerful, zero-cost abstractions that improve the expressiveness and readability of code. Iterators don't replace loops entirely, but they do provide a capable primitive with built-in lazy evaluation and excellent performance.

---

[1] In fact, since `Option` is an iterable behaving like a sequence of zero or one items, `iterator.filter_map(closure)` is equivalent to `iterator.flat_map(closure)`, assuming `closure` returns an `Option<T>`.

# Chapter 16. Collections

> *We all behave like Maxwell's demon. Organisms organize. In everyday experience lies the reason sober physicists across two centuries kept this cartoon fantasy alive. We sort the mail, build sand castles, solve jigsaw puzzles, separate wheat from chaff, rearrange chess pieces, collect stamps, alphabetize books, create symmetry, compose sonnets and sonatas, and put our rooms in order, and all this we do requires no great energy, as long as we can apply intelligence.*
>
> —James Gleick, *The Information: A History, a Theory, a Flood*

The Rust standard library contains several *collections*, generic types for storing data in memory. We've already been using collections, such as `Vec` and `HashMap`, throughout this book. In this chapter, we'll cover the methods of these two types in detail, along with the other half-dozen standard collections. Before we begin, let's address a few systematic differences between Rust's collections and those in other languages.

First, moves and borrowing are everywhere. Rust uses moves to avoid deep-copying values. That's why the method `Vec<T>::push(item)` takes its argument by value, not by reference. The value is moved into the vector. The diagrams in Chapter 4 show how this works out in practice: pushing a Rust `String` to a `Vec<String>` is quick, because Rust doesn't have to copy the string's character data, and ownership of the string is always clear.

Second, Rust doesn't have invalidation errors—the kind of dangling-pointer bug where a collection is resized, or otherwise changed, while the program is holding a pointer to data inside it. Invalidation errors are another source of undefined behavior in C++, and they cause the occasional `ConcurrentModificationException` even in memory-safe languages. Rust's borrow checker rules them out at compile time.

Finally, Rust does not have `null`, so we'll see `Option`s in places where other languages would use `null`.

Apart from these differences, Rust's collections are about what you'd expect. If you're an experienced programmer in a hurry, you can skim here, but don't miss "Entries".

## Overview

Table 16-1 shows Rust's eight standard collections. All of them are generic types.

*Table 16-1. Summary of the standard Rust collections*

| | | Similar collection type in... | | |
|---|---|---|---|---|
| **Collection** | **Description** | **C++** | **Java** | **Pyth** |
| `Vec<T>` | Growable array | `vector` | `ArrayList` | `list` |
| `VecDeque<T>` | Double-ended queue (growable ring buffer) | `deque` | `ArrayDeque` | `colle eque` |
| `LinkedList<T>` | Doubly linked list | `list` | `LinkedList` | `___` |
| `BinaryHeap<T> where T: Ord` | Max heap | `priority_queue` | `PriorityQueue` | `heapq` |
| `HashMap<K, V> where K: Eq + Hash` | Key-value hash table | `unordered_map` | `HashMap` | `dict` |
| `BTreeMap<K, V> where K: Ord` | Sorted key-value table | `map` | `TreeMap` | `___` |
| `HashSet<T> where T: Eq + Hash` | Unordered, hash-based set | `unordered_set` | `HashSet` | `set` |
| `BTreeSet<T> where T: Ord` | Sorted set | `set` | `TreeSet` | `___` |

`Vec<T>`, `HashMap<K, V>`, and `HashSet<T>` are the most generally useful collection types. The rest have niche uses. This chapter discusses each collection type in turn:

`Vec<T>`

: A growable, heap-allocated array of values of type `T`. About half of this chapter is dedicated to `Vec` and its many useful methods.

`VecDeque<T>`

: Like `Vec<T>`, but better for use as a first in, first out queue. It supports efficiently adding and removing values at the front of the list as well as the back. This comes at the cost of making all other operations slightly slower.

`BinaryHeap<T>`

: A priority queue. The values in a `BinaryHeap` are organized so that it's always efficient to find and remove the maximum value.

`HashMap<K, V>`

: A table of key-value pairs. Looking up a value by its key is fast. The entries are stored in an arbitrary order.

`BTreeMap<K, V>`

: Like `HashMap<K, V>`, but it keeps the entries sorted by key. A `BTreeMap<String, i32>` stores its entries in `String` comparison order. Unless you need the entries to stay sorted, a `HashMap` is faster.

`HashSet<T>`

: A set of values of type `T`. Adding and removing values is fast, and it's fast to ask whether a given value is in the set or not.

`BTreeSet<T>`

: Like `HashSet<T>`, but it keeps the elements sorted by value. Again, unless you need the data sorted, a `HashSet` is faster.

Because `LinkedList` is rarely used (and there are better alternatives, both in performance and interface, for most use cases), we do not describe it here.

## Vec<T>

We'll assume some familiarity with `Vec`, since we've been using it throughout the book. For an introduction, see "Vectors". Here we'll finally describe its methods and inner workings in depth.

The easiest way to create a vector is to use the `vec!` macro:

```
// Create an empty vector
let mut numbers: Vec<i32> = vec![];

// Create a vector with given contents
let words = vec!["step", "on", "no", "pets"];
let mut buffer = vec![0u8; 1024];  // 1024 zeroed-out bytes
```

As described in Chapter 4, a vector has three fields: the length, the capacity, and a pointer to a heap allocation where the elements are stored. Figure 16-1 shows how the preceding vectors would appear in memory. The empty vector, `numbers`, initially has a capacity of 0. No heap memory is allocated for it until the first element is added.

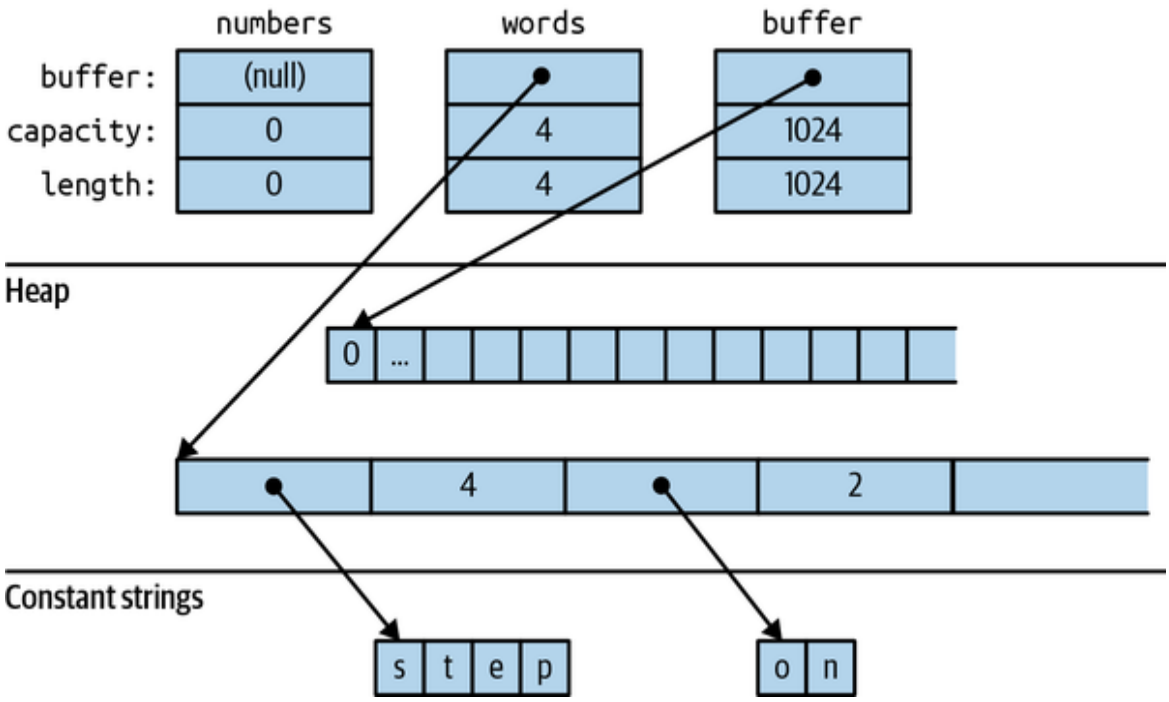


*Figure 16-1. Vector layout in memory: each element of `words` is a `&str` value consisting of a pointer and a length*

Like all collections, `Vec` implements `std::iter::FromIterator`, so you can create a vector from any iterator using the iterator's `.collect()` method, as described in "Building Collections: collect and FromIterator":

```
// Convert another collection to a vector.
let my_vec = my_set.into_iter().collect::<Vec<String>>();
```

## Accessing Elements

Getting elements of an array, slice, or vector by index is straightforward:

```
// Get a reference to an element
let first_line = &lines[0];

// Get a copy of an element
let fifth_number = numbers[4];        // requires Copy
let second_line = lines[1].clone();   // requires Clone

// Get a reference to a slice
let my_ref = &buffer[4..12];
```

```
// Get a copy of a slice
let my_copy = buffer[4..12].to_vec();  // requires Clone
```

All of these forms panic if an index is out of bounds.

Rust is picky about numeric types, and it makes no exceptions for vectors. Vector lengths and indices are of type `usize`. Trying to use a `u32`, `u64`, or `isize` as a vector index is an error. You can use an `n as usize` cast to convert as needed; see "Type Casts".

Several methods provide easy access to particular elements of a vector or slice (note that all slice methods are available on arrays and vectors too):

`slice.first()`

Returns a reference to the first element of `slice`, if any.

The return type is `Option<&T>`, so the return value is `None` if `slice` is empty and `Some(&slice[0])` if it's not empty:

```
if let Some(item) = v.first() {
    println!("We got one! {item}");
}
```

`slice.last()`

Similar but returns a reference to the last element.

`slice.get(index)`

Returns `Some` reference to `slice[index]`, if it exists. If `slice` has fewer than `index+1` elements, this returns `None`:

```
let slice = [0, 1, 2, 3];
assert_eq!(slice.get(2), Some(&2));
assert_eq!(slice.get(4), None);
```

`slice.first_mut()`, `slice.last_mut()`, `slice.get_mut(index)`

Variations of the preceding that borrow `mut` references:

```
let mut slice = [0, 1, 2, 3];
{
    let last = slice.last_mut().unwrap();    // type of last:
&mut i32
    assert_eq!(*last, 3);
    *last = 100;
}
assert_eq!(slice, [0, 1, 2, 100]);
```

Because returning a `T` by value would mean moving it, methods that access elements in place typically return those elements by reference.

An exception is the `.to_vec()` method, which makes copies:

`slice.to_vec()`

Clones a whole slice, returning a new vector:

```
let v = [1, 2, 3, 4, 5, 6, 7, 8, 9];
assert_eq!(v.to_vec(), vec![1, 2, 3, 4, 5, 6, 7, 8, 9]);
assert_eq!(v[0..6].to_vec(), vec![1, 2, 3, 4, 5, 6]);
```

This method is available only if the elements are cloneable, that is, `where T: Clone`.

## Iteration

Vectors, arrays, and slices are iterable, either by value or by reference, following the pattern described in "IntoIterator Implementations":

- Iterating over a `Vec<T>` or array `[T; N]` produces items of type `T`. The elements are moved out of the vector or array one by one, consuming it.
- Iterating over a value of type `&[T; N]`, `&[T]`, or `&Vec<T>`—that is, a reference to an array, slice, or vector—produces items of type `&T`, references to the individual elements, which are not moved.
- Iterating over a value of type `&mut [T; N]`, `&mut [T]`, or `&mut Vec<T>` produces items of type `&mut T`.

Arrays, slices, and vectors also have `.iter()` and `.iter_mut()` methods (described in "iter and iter_mut Methods") for creating iterators that produce references to their elements.

We'll cover some fancier ways to iterate over a slice in "Splitting".

## Length and Capacity

The *length* of an array, slice, or vector is the number of elements it contains:

`slice.len()`

Returns a `slice`'s length, as a `usize`.

`slice.is_empty()`

Is true if `slice` contains no elements (that is, `slice.len() == 0`).

All of a vector's elements are stored in a contiguous, heap-allocated chunk of memory. The *capacity* of a vector is the maximum number of elements that would fit in this chunk. `Vec` normally manages the capacity for you, automatically allocating a larger buffer and moving the elements into it

when more space is needed. There are also a few methods for managing capacity explicitly:

`Vec::with_capacity(n)`

Creates a new, empty vector with capacity `n`.

`vec.capacity()`

Returns `vec`'s capacity, as a `usize`. It's always true that `vec.capacity() >= vec.len()`.

`vec.shrink_to_fit()`

Tries to free up the extra memory if `vec.capacity()` is greater than `vec.len()`.

`vec.reserve(n)`

Makes sure the vector has at least enough spare capacity for `n` more elements: that is, `vec.capacity()` is at least `vec.len() + n`. If there's already enough room, this does nothing. If not, this allocates a larger buffer and moves the vector's contents into it.

`vec.reserve_exact(n)`

Like `vec.reserve(n)`, but tells `vec` not to allocate any extra capacity for future growth beyond `n`. Afterward, `vec.capacity()` is exactly `vec.len() + n`.

`vec.try_reserve(n)`, `vec.try_reserve_exact(n)`

Like `vec.reserve(n)` and `vec.reserve_exact(n)`, but returning a `Result<(), TryReserveError>`. As discussed in "Aborting", memory allocation failures are rare, and Rust normally handles them by aborting the process. These methods return an error instead. They can be useful in code that allocates a potentially huge chunk of memory, such as a bitmap for a large image.

## Growing and Shrinking Vectors

`Vec<T>` has many methods that add or remove elements, changing the vector's length. Each of these takes its `self` argument by `mut` reference.

These two methods add or remove a single value at the end of a vector:

`vec.push(value)`

Adds the given `value` to the end of `vec`.

`vec.pop()`

Removes and returns the last element. The return type is `Option<T>`. This returns `Some(x)` if the popped element is `x`, and `None` if the vector was already empty.

Note that `.push()` takes its argument by value, not by reference. Likewise, `.pop()` returns the popped value, not a reference. The same is true of most of the remaining methods in this section. They move values in and out of vectors.

These two methods add or remove a value anywhere in a vector:

`vec.insert(index, value)`

Inserts the given `value` at `vec[index]`, sliding any existing values in `vec[index..]` one spot to the right to make room.

Panics if `index > vec.len()`.

`vec.remove(index)`

Removes and returns `vec[index]`, sliding any existing values in `vec[index+1..]` one spot to the left to close the gap.

Panics if `index >= vec.len()`, since in that case there is no element `vec[index]` to remove.

The longer the vector, the slower this operation gets. If you find yourself doing `vec.remove(0)` a lot, consider using a `VecDeque`

(explained in "VecDeque<T>") instead of a `Vec`.

Both `.insert()` and `.remove()` are slower the more elements have to be shifted.

Four methods change the length of a vector to a specific value:

`vec.resize(new_len, value)`

Sets `vec`'s length to `new_len`. If this increases `vec`'s length, copies of `value` are added to fill the new space. The element type must implement the `Clone` trait.

`vec.resize_with(new_len, closure)`

Just like `vec.resize`, but calls the closure to construct each new element. It can be used with vectors of elements that are not `Clone`.

`vec.truncate(new_len)`

Reduces the length of `vec` to `new_len`, dropping any elements that were in the range `vec[new_len..]`.

If `vec.len()` is already less than or equal to `new_len`, nothing happens.

`vec.clear()`

Removes all elements from `vec`. It's the same as `vec.truncate(0)`.

Four methods add or remove many values at once:

`vec.extend(iterable)`

Adds all items from the given `iterable` value at the end of `vec`, in order. It's like a multivalue version of `.push()`. The `iterable` argument can be anything that implements `IntoIterator<Item = T>`.

This method is so useful that there's a standard trait for it, the `Extend` trait, which all standard collections implement. Unfortunately, this causes `rustdoc` to lump `.extend()` with other trait methods in a big pile at the bottom of the generated HTML, so it's hard to find when you need it. You just have to remember it's there! See "The Extend Trait" for more.

`vec.split_off(index)`

Like `vec.truncate(index)`, except that it returns a `Vec<T>` containing the values removed from the end of `vec`. It's like a multivalue version of `.pop()`.

`vec.append(&mut vec2)`

This moves all elements from `vec2` into `vec`, where `vec2` is another vector of type `Vec<T>`. Afterward, `vec2` is empty.

This is like `vec.extend(vec2)` except that `vec2` still exists afterward, with its capacity unaffected.

`vec.drain(range)`

This removes the `range` `vec[range]` from `vec` and returns an iterator over the removed elements, where `range` is a range value, like `..` or `0..4`.

There are a few oddball methods for selectively removing some of a vector's elements:

`vec.retain(test)`

Removes all elements that don't pass the given test. The `test` argument is a function or closure that implements `FnMut(&T) -> bool`. For each element of `vec`, this calls `test(&element)`, and if it returns `false`, the element is removed from the vector and dropped.

Apart from performance, this is like writing:

```
vec = vec.into_iter().filter(test).collect();
```

`vec.dedup()`

Drops repeated elements. It's like the Unix `uniq` shell utility. It scans `vec` for places where adjacent elements are equal and drops the extra equal values so that only one is left:

```
let mut byte_vec = b"Mississsssissippi".to_vec();
byte_vec.dedup();
assert_eq!(&byte_vec, b"Misisipi");
```

Note that there are still two `'s'` characters in the output. This method only removes *adjacent* duplicates. To eliminate all duplicates, you have three options: sort the vector before calling `.dedup()`, move the data into a set, or (to keep the elements in their original order) use this `.retain()` trick:

```
let mut byte_vec = b"Mississsssissippi".to_vec();

let mut seen = HashSet::new();
byte_vec.retain(|r| seen.insert(*r));

assert_eq!(&byte_vec, b"Misp");
```

This works because `.insert()` returns `false` when the set already contains the item we're inserting.

`vec.dedup_by(same)`

The same as `vec.dedup()`, but it uses the function or closure `same(&mut elem1, &mut elem2)`, instead of the == operator, to

check whether two elements should be considered equal.

`vec.dedup_by_key(key)`

The same as `vec.dedup()`, but it treats two elements as equal if `key(&mut elem1) == key(&mut elem2)`.

For example, if `errors` is a `Vec<Box<dyn Error>>`, you can write:

```
// Remove errors with redundant messages.
errors.dedup_by_key(|err| err.to_string());
```

Of all the methods covered in this section, only `.resize()` ever clones values. The others work by moving values from one place to another.

## Splitting

It's easy to get many non-`mut` references into an array, slice, or vector at once:

```
let v = vec![0, 1, 2, 3];
let a = &v[i];
let b = &v[j];

let mid = v.len() / 2;
let front_half = &v[..mid];
let back_half = &v[mid..];
```

Getting multiple `mut` references is not so easy:

```
let mut v = vec![0, 1, 2, 3];
let a = &mut v[i];
let b = &mut v[j];  // error: cannot borrow `v` as mutable
                    //        more than once at a time

*a = 6;             // references `a` and `b` get used here,
*b = 7;             // so their lifetimes must overlap
```

Rust forbids this because if `i == j`, then `a` and `b` would be two `mut` references to the same integer, in violation of Rust's safety rules. (See "Sharing Versus Mutation".)

Rust has several methods that can borrow `mut` references to two or more parts of an array, slice, or vector at once. Unlike the preceding code, these methods are safe, because by design, they always split the data into *nonoverlapping* regions. Many of these methods are also handy for working with non-`mut` slices, so there are `mut` and non-`mut` versions of each. Figure 16-2 illustrates these methods.

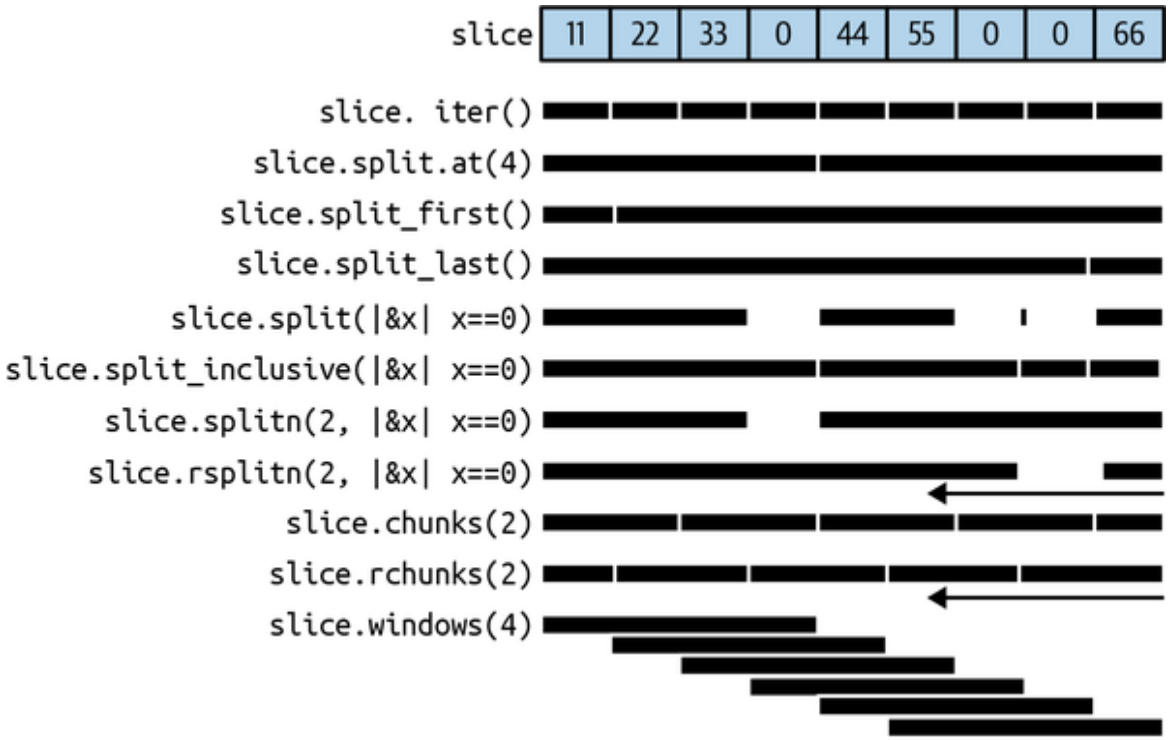


*Figure 16-2. Splitting methods illustrated. The little rectangle in the output of `slice.split()` is an empty slice caused by the two adjacent separators. Note that `rsplitn` and `rchunks` produce their output in reverse order.*

None of these methods directly modifies an array, slice, or vector; they merely return new references to parts of the data inside:

`slice.iter()`, `slice.iter_mut()`

Produce a reference to each element of `slice`. We covered them in "Iteration".

`slice.split_at(index)`, `slice.split_at_mut(index)`

Break a slice in two, returning a pair. `slice.split_at(index)` is equivalent to `(&slice[..index], &slice[index..])`. These methods panic if `index` is out of bounds.

`slice.split_first()`, `slice.split_first_mut()`

Also return a pair: a reference to the first element (`slice[0]`) and a slice reference to all the rest (`slice[1..]`).

The return type of `.split_first()` is `Option<(&T, &[T])>`; the result is `None` if `slice` is empty.

`slice.split_last()`, `slice.split_last_mut()`

These are analogous but split off the last element rather than the first.

The return type of `.split_last()` is `Option<(&T, &[T])>`.

`slice.split(is_sep)`, `slice.split_mut(is_sep)`

Split `slice` into one or more subslices, using the function or closure `is_sep` to figure out where to split. They return an iterator over the subslices.

As you consume the iterator, it calls `is_sep(&element)` for each element in the slice. If `is_sep(&element)` is `true`, the element is a separator. Separators are not included in any output subslice.

The output always contains at least one subslice, plus one per separator. Empty subslices are included whenever separators appear adjacent to each other or to the ends of `slice`.

`slice.split_inclusive(is_sep)`,
`slice.split_inclusive_mut(is_sep)`

These work just like `split` and `split_mut`, but include the separator at the end of the previous subslice rather than excluding it.

`slice.rsplit(is_sep)`, `slice.rsplit_mut(is_sep)`

Just like `split` and `split_mut`, but start at the end of the slice.

`slice.splitn(n, is_sep)`, `slice.splitn_mut(n, is_sep)`

The same but they produce at most `n` subslices. After the first `n-1` slices are found, `is_sep` is not called again. The last subslice contains all the remaining elements.

`slice.rsplitn(n, is_sep)`, `slice.rsplitn_mut(n, is_sep)`

Just like `.splitn()` and `.splitn_mut()` except that the slice is scanned in reverse order. That is, these methods split on the *last* `n-1` separators in the slice, rather than the first, and the subslices are produced starting from the end.

`slice.chunks(n)`, `slice.chunks_mut(n)`

Return an iterator over nonoverlapping subslices of length `n`. If `n` doesn't divide `slice.len()` exactly, the last chunk will contain fewer than `n` elements.

`slice.rchunks(n)`, `slice.rchunks_mut(n)`

Just like `slice.chunks` and `slice.chunks_mut`, but start at the end of the slice.

`slice.chunks_exact(n)`, `slice.chunks_exact_mut(n)`

Return an iterator over nonoverlapping subslices of length `n`. If `n` doesn't divide `slice.len()`, the last chunk (with less than `n` elements) is available in the result's `remainder()` method.

`slice.rchunks_exact(n)`, `slice.rchunks_exact_mut(n)`

Just like `slice.chunks_exact` and `slice.chunks_exact_mut`, but start at the end of the slice.

There's one more method for iterating over subslices:

`slice.windows(n)`

Returns an iterator that behaves like a "sliding window" over the data in `slice`. It produces subslices that span `n` consecutive elements of `slice`. The first value produced is `&slice[0..n]`, the second is `&slice[1..n+1]`, and so on.

If `n` is greater than the length of `slice`, then no slices are produced. If `n` is 0, the method panics.

For example, if `days.len() == 31`, then we can produce all seven-day spans in `days` by calling `days.windows(7)`.

A sliding window of size 2 is handy for exploring how a data series changes from one data point to the next:

```
let changes = daily_high_temperatures
    .windows(2)              // get adjacent days' temps
    .map(|w| w[1] - w[0])    // how much did it change?
    .collect::<Vec<_>>();
```

Because the subslices overlap, there is no variation of this method that returns `mut` references.

If none of the above slice methods elegantly produces the nonoverlapping `mut` references you're after, there is one last tool in the box:

`slice.get_disjoint_mut([i, j, ...])`

Gets `mut` references to the specified elements of `slice`. This returns a `Result`; it's an error if any indices are out of bounds, or if any two are

equal.

For example, in the dark academia adventure Poet and Villain, we have this code simulating literary combat:

```
let [attacker, defender] = poets.get_disjoint_mut([att_id,
def_id])?;
defender.confidence -= attacker.prestige;
defender.check_for_death();
```

Here, `poets` is a `&mut Vec<Poet>`, so `get_disjoint_mut` returns a `Result<[&mut Poet; 2], GetDisjointMutError>`. This code would return an error if the player were to attack their own poetry.

You can pass an array of any number of `usize` values to `get_disjoint_mut`; it returns an array of the same number of references. It can also take an array of ranges, returning an error if any overlap and an array of `&mut [T]` slices on success.

## Swapping

There are convenience methods for swapping the contents of slices:

`slice.swap(i, j)`

Swaps the two elements `slice[i]` and `slice[j]`.

`slice_a.swap_with_slice(&mut slice_b)`

Swaps the entire contents of `slice_a` and `slice_b`. Panics if the slices are not the same length.

Vectors have a related method for efficiently removing any element:

`vec.swap_remove(i)`

Removes and returns `vec[i]`. This is like `vec.remove(i)` except that instead of sliding the rest of the vector's elements over to close the gap, it simply moves `vec`'s last element into the gap. It's useful when you don't care about the order of the items left in the vector.

## Filling

There are two convenience methods for replacing the contents of mutable slices:

`slice.fill(value)`

Fills the slice with clones of `value`. The most common use is to zero out part of a buffer.

`slice.fill_with(function)`

Fills the slice with values made by calling the given function with no arguments. This can be useful when the element type is not `Clone`. It's also handy for generating values: `buf.fill_with(rand::random)`.

## Sorting and Searching

Slices offer three methods for sorting:

`slice.sort()`

Sorts the elements into increasing order. This method is present only when the element type implements `Ord`.

`slice.sort_by(cmp)`

Sorts the elements of `slice` using a function or closure `cmp` to specify the sort order. `cmp` must implement `Fn(&T, &T) -> std::cmp::Ordering`.

Hand-implementing `cmp` is a pain, unless you delegate to a `.cmp()` method:

```
students.sort_by(|a, b| a.last_name.cmp(&b.last_name));
```

To sort by one field, using a second field as a tiebreaker, compare tuples:

```
students.sort_by(|a, b| {
    let a_key = (&a.last_name, &a.first_name);
    let b_key = (&b.last_name, &b.first_name);
    a_key.cmp(&b_key)
});
```

Floating-point types don't implement `Ord`, so they do not have a `.cmp()` method. Use `.total_cmp()` instead:

```
students.sort_by(|a, b|
a.average_grade().total_cmp(&b.average_grade()));
```

This method puts all floating-point values in a deterministic order, even NaN values—although in this example it seems best to make sure `average_grade` always returns a real number.

`slice.sort_by_key(key)`

Sorts the elements of `slice` into increasing order by a sort key, given by the function or closure `key`:

```
racers.sort_by_key(|r| r.finish_time);  // fastest first

racers.sort_by_key(|r| r.team_id);  // or, sort teammates
together
```

The key function must implement `Fn(&T) -> K` where `K: Ord`. Note that these sort-key values are not cached during sorting, so the key function will typically be called several times per element. For technical reasons, `key(element)` can't return any references borrowed from the element. This won't work:

```
racers.sort_by_key(|r| &r.last_name);  // error: can't infer
lifetime
```

But in these cases, it's easy enough to fall back on `.sort_by()`.

The wrapper type `std::cmp::Reverse<T>` can be used as a sort key to reverse the usual sort order. For any type `T` that implements `Ord`, `Reverse<T>` implements `Ord` too, but with reversed ordering. For example, to list the highest-scoring players first:

```
use std::cmp::Reverse;
players.sort_by_key(|p| Reverse(p.points));
```

To add a tiebreaker, in case two players scored the same number of points, use a tuple as the sort key:

```
players.sort_by_key(|p| (Reverse(p.points),
Reverse(p.rebounds)));
```

Since floating-point types don't implement `Ord`, they can't be used directly as sort keys. Use the `OrderedFloat` wrapper type from the `ordered-float` crate instead:

```
use ordered_float::OrderedFloat;
```

```
    players.sort_by_key(|p| Reverse(OrderedFloat(p.fg_percent)));
```

All three methods perform a stable sort: they do not reorder elements that are considered equal in your chosen sort order. The corresponding methods `sort_unstable`, `sort_unstable_by`, and `sort_unstable_by_key` are typically a bit faster, but reorder equal elements arbitrarily.

To sort in reverse order, you can use `sort_by` with a `cmp` closure that swaps the two arguments. Taking arguments `|b, a|` rather than `|a, b|` effectively produces the opposite order. Or, you can just call the `.reverse()` method after sorting:

`slice.reverse()`

Reverses a slice in place.

The following boolean methods `slice.is_sorted()`, `.is_sorted_by(cmp)`, and `.is_sorted_by_key(key)` return true if the elements of a slice are in the specified order.

Once a slice is sorted, it can be efficiently searched:

`slice.binary_search(&value)`,
`slice.binary_search_by(&value, cmp)`,
`slice.binary_search_by_key(&value, key)`

All search for `value` in the given sorted `slice`. Note that `value` is passed by reference.

The return type of these methods is `Result<usize, usize>`. They return `Ok(index)` if `slice[index]` equals `value` under the specified sort order. If there is no such index, then they return `Err(insertion_point)` such that inserting `value` at `insertion_point` would preserve the order.

`slice.partition_point(p)`

This method can perform a binary search in `slice` even when you don't have a value of the right type for `binary_search`. The predicate `p` takes a reference to an element and returns a boolean. The `slice` must be arranged so that `p(slice[x])` returns `true` for all elements at the front of the slice, up to some cutoff point, and `false` for all elements after that. Then `partition_point` uses a binary search to find and return the cutoff point—that is, the number of elements in the front part that satisfy the predicate.

For example, `computers.partition_point(|c| c.price <= 2000)` finds the index of the first computer with a price over `2000` if the computers are sorted by price.

Of course, a binary search works only if the slice is in fact sorted in the specified order. Otherwise, the results are arbitrary—garbage in, garbage out.

Since `f32` and `f64` have NaN values, they do not implement `Ord` and can't be used directly as keys with the sorting and binary search methods. To get similar methods that work on floating-point data, use the `ord_subset` crate.

There's one method for searching a vector that is not sorted:

`slice.contains(&value)`

Returns `true` if any element of `slice` is equal to `value`. This simply checks each element of the slice until a match is found. Again, `value` is passed by reference.

To find the location of a value in a slice, like `array.indexOf(value)` in JavaScript, use an iterator:

```
slice.iter().position(|x| *x == value)
```

This returns an `Option<usize>`.

## Comparing Slices

If a type `T` supports the == and `!=` operators (the `PartialEq` trait, described in "Equivalence Comparisons"), then arrays `[T; N]`, slices `[T]`, and vectors `Vec<T>` support them too. Two slices are equal if they're the same length and their corresponding elements are equal. The same goes for arrays and vectors.

If `T` supports the operators <, <=, >, and >= (the `PartialOrd` trait, described in "Ordered Comparisons"), then arrays, slices, and vectors of `T` do too. Slice comparisons are lexicographical. Two convenience methods perform common slice comparisons:

`slice.starts_with(other)`

Returns `true` if `slice` starts with a sequence of values that are equal to the elements of the slice `other`:

```
assert_eq!([1, 2, 3, 4].starts_with(&[1, 2]), true);
assert_eq!([1, 2, 3, 4].starts_with(&[2, 3]), false);
```

`slice.ends_with(other)`

Similar but checks the end of `slice`:

```
assert_eq!([1, 2, 3, 4].ends_with(&[3, 4]), true);
```

## Random Elements

Random numbers are not built into the Rust standard library. The `rand` crate provides them, offering these methods for getting random output from an array, slice, or vector:

`slice.choose(&mut rng)`

Returns a reference to a random element of a slice. Like `slice.first()` and `slice.last()`, this returns an

`Option<&T>` that is `None` only if the slice is empty.

`slice.shuffle(&mut rng)`

Randomly reorders the elements of a slice in place. The slice must be passed by `mut` reference.

These are methods of the `rand::seq::SliceRandom` trait, which is implemented for all slices. To call these methods, you need a `Rng`, a random number generator. Fortunately, it's easy to get one by calling `rand::rng()`. To shuffle the vector `my_vec`, we can write:

```
use rand::seq::SliceRandom;

my_vec.shuffle(&mut rand::rng());
```

## Rust Rules Out Invalidation Errors

Most mainstream programming languages have collections and iterators, and they all have some variation on this rule: don't modify a collection while you're iterating over it. For example, the Python equivalent of a vector is a list:

```
my_list = [1, 3, 5, 7, 9]
```

Suppose we try to remove all values greater than `4` from `my_list`:

```
for index, val in enumerate(my_list):
    if val > 4:
        del my_list[index]  # bug: modifying list while iterating

print(my_list)
```

(The `enumerate` function is Python's equivalent of Rust's `.enumerate()` method, described in "enumerate".)

This program, surprisingly, prints `[1, 3, 7]`. But `7` is greater than `4`. How did that slip through? This is an invalidation error: the program

modifies data while iterating over it, *invalidating* the iterator. In Java, the result would be an exception; in C++ it is undefined behavior. In Python, while the behavior is well-defined, it's unintuitive: the iterator skips an element. `val` is never `7`.

Let's try to reproduce this bug in Rust:

```
fn main() {
    let mut my_vec = vec![1, 3, 5, 7, 9];

    for (index, &val) in my_vec.iter().enumerate() {
        if val > 4 {
            my_vec.remove(index);  // error: can't borrow
`my_vec` as mutable
        }
    }
    println!("{my_vec:?}");
}
```

Naturally, Rust rejects this program at compile time. When we call `my_vec.iter()`, it borrows a shared (non-`mut`) reference to the vector. The reference lives as long as the iterator, to the end of the `for` loop. We can't modify the vector by calling `my_vec.remove(index)` while a non-`mut` reference exists.

Having an error pointed out to you is nice, but of course, you still need to find a way to get the desired behavior! The easiest fix here is to write:

```
my_vec.retain(|&val| val <= 4);
```

Or, you can do what you'd do in Python or any other language: create a new vector using a `filter`.

## VecDeque<T>

`Vec` supports efficiently adding and removing elements only at the end. When a program needs a place to store values that are "waiting in line," `Vec` can be slow.

Rust's `std::collections::VecDeque<T>` is a *deque* (pronounced "deck"), a double-ended queue. It supports efficient add and remove operations at both the front and the back:

`deque.push_front(value)`

Adds a value at the front of the queue.

`deque.push_back(value)`

Adds a value at the end. (This method is used much more than `.push_front()`, because the usual convention for queues is that values are added at the back and removed at the front, like people waiting in a line.)

`deque.pop_front()`

Removes and returns the front value of the queue, returning an `Option<T>` that is `None` if the queue is empty, like `vec.pop()`.

`deque.pop_back()`

Removes and returns the value at the back, again returning an `Option<T>`.

`deque.front()`, `deque.back()`

Work like `vec.first()` and `vec.last()`. They return a reference to the front or back element of the queue. The return value is an `Option<&T>` that is `None` if the queue is empty.

`deque.front_mut()`, `deque.back_mut()`

Work like `vec.first_mut()` and `vec.last_mut()`, returning `Option<&mut T>`.

The implementation of `VecDeque` is a ring buffer, as shown in Figure 16-3.

Like a `Vec`, it has a single heap allocation where elements are stored. Unlike `Vec`, the data does not always start at the beginning of this region, and it can "wrap around" the end, as shown. The elements of this deque, in order, are `['A', 'B', 'C', 'D', 'E']`. `VecDeque` has private fields, labeled `start` and `stop` in the figure, that it uses to remember where in the buffer the data begins and ends.

Adding a value to the queue, on either end, means claiming one of the unused slots, illustrated as the darker blocks, wrapping around or allocating a bigger chunk of memory if needed.

`VecDeque` manages wrapping, so you don't have to think about it. Figure 16-3 is a behind-the-scenes view of how Rust makes `.pop_front()` fast.

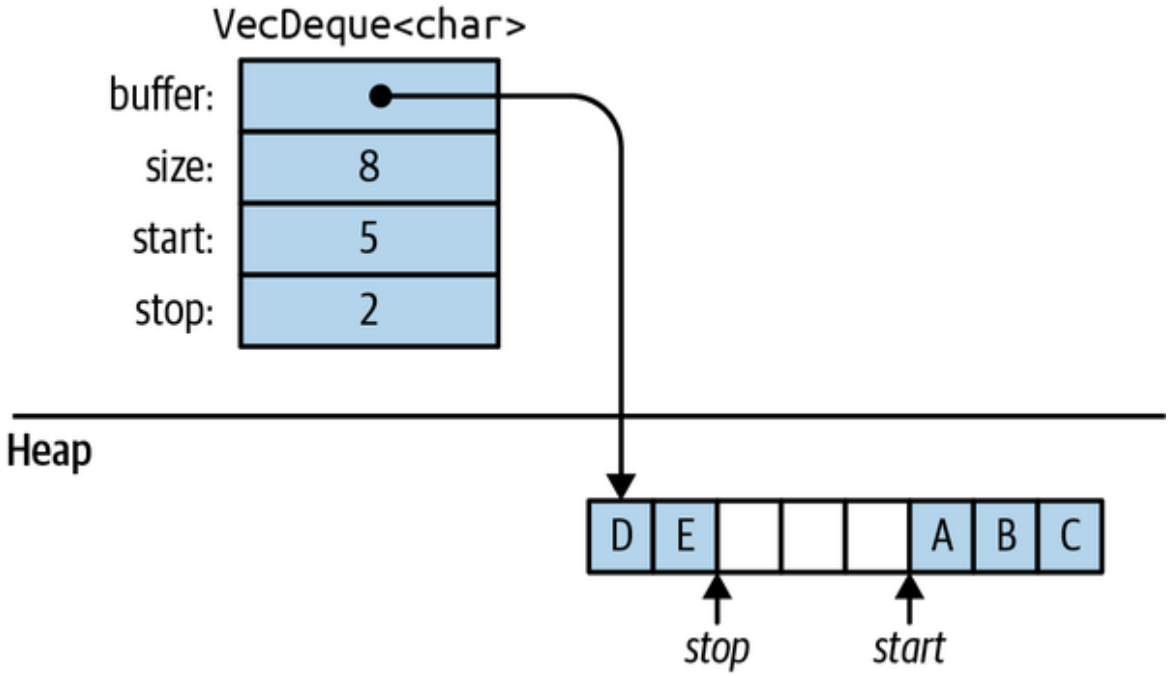


*Figure 16-3. How a `VecDeque` is stored in memory*

Oftentimes, when you need a deque, `.push_back()` and `.pop_front()` are the only two methods that you'll need. The associated functions `VecDeque::new()` and `VecDeque::with_capacity(n)`, for creating queues, are just like their counterparts in `Vec`. Many `Vec` methods are also implemented for

`VecDeque`: `.len()` and `.is_empty()`, `.insert(index, value)`, `.remove(index)`, `.extend(iterable)`, and so on.

Deques, like vectors, can be iterated by value, by shared reference, or by `mut` reference. They have the three iterator methods `.into_iter()`, `.iter()`, and `.iter_mut()`. They can be indexed in the usual way: `deque[index]`.

Because deques don't store their elements contiguously in memory, they can't inherit all the methods of slices. But if you're willing to pay the cost of shifting the contents around, `VecDeque` provides a method that will fix that:

`deque.make_contiguous()`

> Takes `&mut self` and rearranges the `VecDeque` into contiguous memory, returning `&mut [T]`.

`Vec`s and `VecDeque`s are closely related, and the standard library provides two trait implementations for easily converting between the two:

`Vec::from(deque)`

> `Vec<T>` implements `From<VecDeque<T>>`, so this turns a deque into a vector. This costs O(*n*) time, since it may require rearranging the elements.

`VecDeque::from(vec)`

> `VecDeque<T>` implements `From<Vec<T>>`, so this turns a vector into a deque. This is also O(*n*), but it's usually fast, even if the vector is large, because the vector's heap allocation can simply be moved to the new deque.
>
> This method makes it easy to create a deque with specified elements, even though there is no standard `vec_deque![]` macro:

```
use std::collections::VecDeque;


let v = VecDeque::from(vec![1, 2, 3, 4]);
```

## BinaryHeap<T>

A `BinaryHeap` is a collection whose elements are kept loosely organized so that the greatest value always bubbles up to the front of the queue. Here are the three most commonly used `BinaryHeap` methods:

`heap.push(value)`

Adds a value to the heap.

`heap.pop()`

Removes and returns the greatest value from the heap. It returns an `Option<T>` that is `None` if the heap was empty.

`heap.peek()`

Returns a reference to the greatest value in the heap. The return type is `Option<&T>`.

`heap.peek_mut()`

Returns a `PeekMut<T>`, which acts as a mutable reference to the greatest value in the heap and provides the associated function `pop()` to pop this value from the heap. Using this method, we can choose to pop or not pop from the heap based on the maximum value:

```
use std::collections::binary_heap::PeekMut;


if let Some(top) = heap.peek_mut() {
    if *top > 10 {
```

```
                PeekMut::pop(top);
            }
        }
```

`BinaryHeap` also supports a subset of the methods on `Vec`, including `BinaryHeap::new()`, `.len()`, `.is_empty()`, `.capacity()`, `.clear()`, and `.append(&mut heap2)`.

For example, suppose we populate a `BinaryHeap` with a bunch of numbers:

```
use std::collections::BinaryHeap;

let mut heap = BinaryHeap::from(vec![2, 3, 8, 6, 9, 5, 4]);
```

The value `9` is at the top of the heap:

```
assert_eq!(heap.peek(), Some(&9));
assert_eq!(heap.pop(), Some(9));
```

Removing the value `9` also rearranges the other elements slightly so that `8` is now at the front, and so on:

```
assert_eq!(heap.pop(), Some(8));
assert_eq!(heap.pop(), Some(6));
assert_eq!(heap.pop(), Some(5));
...
```

Of course, `BinaryHeap` is not limited to numbers. It can hold any type of value that implements the `Ord` built-in trait.

This makes `BinaryHeap` useful as a work queue. You can define a task struct that implements `Ord` on the basis of priority so that higher-priority tasks are `Greater` than lower-priority tasks. Then, create a `BinaryHeap` to hold all pending tasks. Its `.pop()` method will always return the most important item, the task your program should work on next.

Note that `BinaryHeap` is iterable, and it has an `.iter()` method, but the iterators produce the heap's elements in an arbitrary order, not from greatest to least. To consume values from a `BinaryHeap` in order of priority, use a `while` loop:

```
while let Some(task) = heap.pop() {
    handle(task);
}
```

## HashMap<K, V> and BTreeMap<K, V>

A *map* is a collection of key-value pairs (called *entries*). No two entries have the same key, and the entries are kept organized so that if you have a key, you can efficiently look up the corresponding value in a map. In short, a map is a lookup table.

Rust offers two map types: `HashMap<K, V>` and `BTreeMap<K, V>`. The two share many of the same methods; the difference is in how the two keep entries arranged for fast lookup.

A `HashMap` stores the keys and values in a hash table, so it requires a key type `K` that implements `Hash` and `Eq`, the standard traits for hashing and equality.

Figure 16-4 shows how a `HashMap` is arranged in memory. All keys, values, and cached hash code bits are stored in a single heap-allocated table. Adding entries eventually forces the `HashMap` to allocate a larger table and move all the data into it. The implementation is based on Google's brilliant SwissTable. If the picture does not look like hash table diagrams you've seen before, using fewer allocations or a density of entries that seems unlikely, this is why. We regret not having room to describe SwissTable in detail here; see Matt Kulukundis's talk at CppCon 2017 for a full explanation.

The `build_hasher` field is explained in further detail in "Using a Custom Hashing Algorithm".

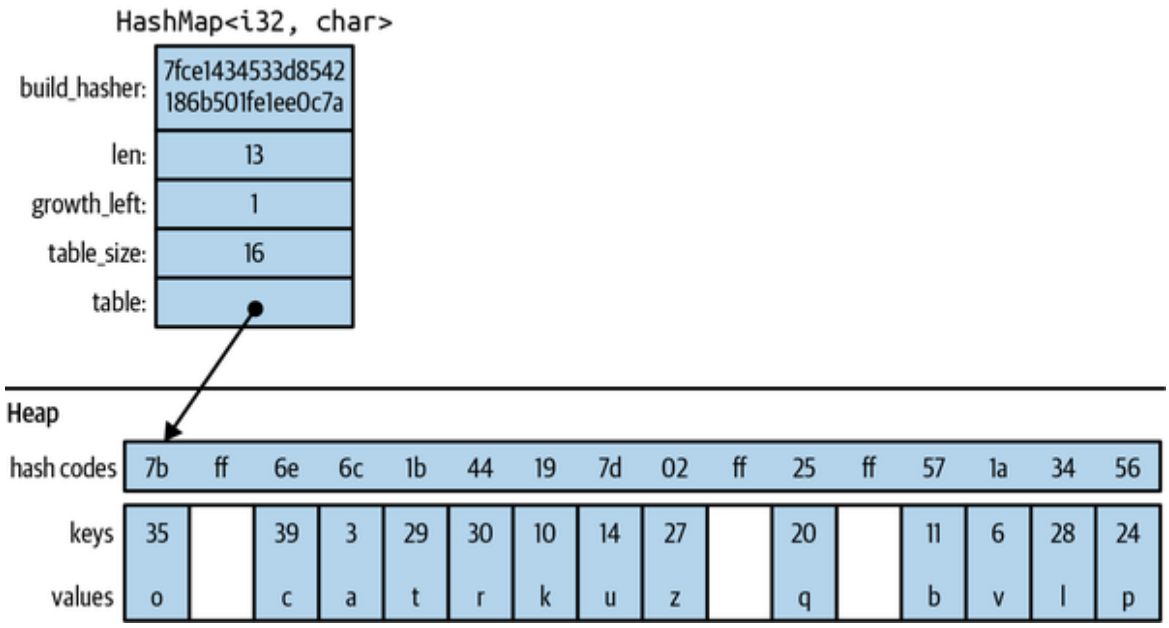


*Figure 16-4. A `HashMap` in memory*

A `BTreeMap` stores the entries in order by key, in a tree structure, so it requires a key type `K` that implements `Ord`. Figure 16-5 shows a `BTreeMap`. Again, the darker regions are unused spare capacity.

A `BTreeMap` stores its entries in *nodes*. Most nodes in a `BTreeMap` contain only key-value pairs. Nonleaf nodes, like the root node shown in this figure, also have room for pointers to child nodes. The pointer between `(20, 'q')` and `(30, 'r')` points to a child node containing keys between `20` and `30`. Adding entries often requires sliding some of a node's existing entries to the right, to keep them sorted, and occasionally involves allocating new nodes.

This picture is a bit simplified to fit on the page. For example, real `BTreeMap` nodes have room for 11 entries, not 4.

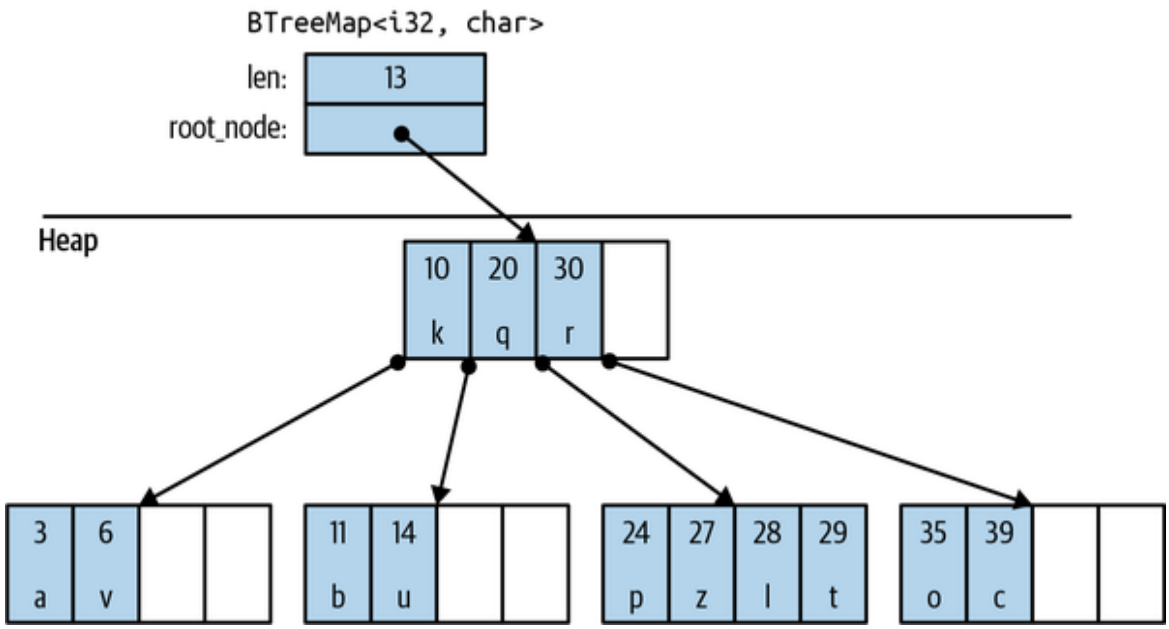


*Figure 16-5. A `BTreeMap` in memory*

The Rust standard library uses B-trees rather than balanced binary trees because B-trees are faster on modern hardware. A binary tree may use fewer comparisons per search than a B-tree, but searching a B-tree has better *locality*—that is, the memory accesses are grouped together rather than scattered across the whole heap. This makes CPU cache misses rarer. It's a significant speed boost.

There are several ways to create a map:

`HashMap::new()`, `BTreeMap::new()`

: Creates new, empty maps.

`iter.collect()`

: Can be used to create and populate a new `HashMap` or `BTreeMap` from key-value pairs. `iter` must be an `Iterator<Item = (K, V)>`.

`HashMap::with_capacity(n)`

: Creates a new, empty hash map with room for at least *n* entries. `HashMap`s, like vectors, store their data in a single heap allocation, so

they have a capacity and the related methods. `BTreeMap`s do not.

`HashMap`s and `BTreeMap`s have the same core methods for working with keys and values:

`map.len()`

Returns the number of entries.

`map.is_empty()`

Returns `true` if `map` has no entries.

`map.contains_key(&key)`

Returns `true` if the map has an entry for the given `key`.

`map.get(&key)`

Searches `map` for an entry with the given `key`. If a matching entry is found, this returns `Some(r)`, where `r` is a reference to the corresponding value. Otherwise, this returns `None`.

`map.get_mut(&key)`

Similar, but it returns a `mut` reference to the value.

In general, maps let you have `mut` access to the values stored inside them, but not the keys. The values are yours to modify however you like. The keys belong to the map itself; it needs to ensure that they don't change, because the entries are organized by their keys. Modifying a key in-place would be a bug.

`map.insert(key, value)`

Inserts the entry `(key, value)` into `map` and returns the old value, if any. The return type is `Option<V>`. If there's already an entry for `key` in the map, the newly inserted `value` overwrites the old one.

`map.extend(iterable)`

Iterates over the `(K, V)` items of `iterable` and inserts each of those key-value pairs into `map`.

`map.append(&mut map2)`

Moves all entries from `map2` into `map`. Afterward, `map2` is empty.

`map.remove(&key)`

Finds and removes any entry with the given `key` from `map`, returning the removed value, if any. The return type is `Option<V>`.

`map.remove_entry(&key)`

Finds and removes any entry with the given `key` from `map`, returning the removed key and value, if any. The return type is `Option<(K, V)>`.

`map.retain(test)`

Removes all elements that don't pass the given test. The `test` argument is a function or closure that implements `FnMut(&K, &mut V) -> bool`. For each element of `map`, this calls `test(&key, &mut value)`, and if it returns `false`, the element is removed from the map and dropped.

Apart from performance, this is like writing:

```
map = map.into_iter().filter(test).collect();
```

`map.clear()`

Removes all entries.

A map can also be queried using square brackets: `map[&key]`. That is, maps implement the `Index` built-in trait. However, this panics if there is not already an entry for the given `key`, like an out-of-bounds array access, so use this syntax only if the entry you're looking up is sure to be populated.

The `key` argument to `.contains_key()`, `.get()`, `.get_mut()`, and `.remove()` does not have to have the exact type `&K`. These methods are generic over types that can be borrowed from `K`. It's OK to call `fish_map.contains_key("conger")` on a `HashMap<String, Fish>`, even though `"conger"` isn't exactly a `String`, because `String` implements `Borrow<str>`. For details, see "Borrow and BorrowMut".

Because a `BTreeMap<K, V>` keeps its entries sorted by key, it supports an additional operation:

`btree_map.split_off(&key)`

> Splits `btree_map` in two. Entries with keys less than `key` are left in `btree_map`. Returns a new `BTreeMap<K, V>` containing the other entries.

## Entries

Both `HashMap` and `BTreeMap` have a corresponding `Entry` type. The point of entries is to eliminate redundant map lookups. For example, here's some code to get or create a student record:

```
// Do we already have a record for this student?
if !student_map.contains_key(name) {
    // No: create one.
    student_map.insert(name.to_string(), Student::new());
}
// Now a record definitely exists.
let record = student_map.get_mut(name).unwrap();
...
```

This works fine, but it accesses `student_map` two or three times, doing the same lookup each time.

The idea with entries is that we do the lookup just once, producing an `Entry` value that is then used for all subsequent operations. This one-liner is equivalent to all the preceding code, except that it does the lookup only once:

```
let record =
student_map.entry(name.to_string()).or_insert_with(Student::new);
```

The `Entry` value returned by `student_map.entry(name.to_string())` acts like a mutable reference to a place within the map that's either *occupied* by a key-value pair, or *vacant*, meaning there's no entry there yet. If vacant, the entry's `.or_insert_with()` method inserts a new `Student`. Most uses of entries are like this: short and sweet. All `Entry` values are created by the same method:

`map.entry(key)`

> Returns an `Entry` for the given `key`. If there's no such key in the map, this returns a vacant `Entry`.
>
> This method takes its `self` argument by `mut` reference and returns an `Entry` with a matching lifetime:
>
> ```
> pub fn entry<'a>(&'a mut self, key: K) -> Entry<'a, K, V>
> ```
>
> The `Entry` type has a lifetime parameter `'a` because it's effectively a fancy kind of borrowed `mut` reference to the map. As long as the `Entry` exists, it has exclusive access to the map.
>
> Back in "Structs Containing References", we saw how to store references in a type and how that affects lifetimes. Now we're seeing what that looks like from a user's perspective. That's what's going on with `Entry`.

Unfortunately, it isn't possible to pass a reference of type `&str` to this method if the map has `String` keys. The `.entry()` method, in that case, requires a real `String`.

`Entry` values provide three methods to deal with vacant entries:

`map.entry(key).or_insert(value)`

Ensures that `map` contains an entry with the given `key`, inserting a new entry with the given `value` if needed. It returns a `mut` reference to the new or existing value.

Suppose we need to count votes. We can write:

```
let mut vote_counts: HashMap<String, usize> = HashMap::new();
for name in ballots {
    let count = vote_counts.entry(name).or_insert(0);
    *count += 1;
}
```

`.or_insert()` returns a `mut` reference, so the type of `count` is `&mut usize`.

`map.entry(key).or_default()`

Ensures that `map` contains an entry with the given key, inserting a new entry with the value returned by `Default::default()` if needed. This only works for types that implement `Default`. Like `or_insert`, this method returns a `mut` reference to the new or existing value.

`map.entry(key).or_insert_with(default_fn)`

This is the same, except that if it needs to create a new entry, it calls `default_fn()` to produce the default value. If there's already an

entry for `key` in the `map`, then `default_fn` is not used.

Suppose we want to know which words appear in which files. We can write:

```
// This map contains, for each word, the set of files it
appears in.
let mut word_occurrence: HashMap<String, HashSet<String>> =
    HashMap::new();
for file in files {
    for word in read_words(file)? {
        let set = word_occurrence
            .entry(word)
            .or_insert_with(HashSet::new);
        set.insert(file.clone());
    }
}
```

`Entry` also provides a convenient way to modify only extant fields:

`map.entry(key).and_modify(closure)`

Calls `closure` if an entry with the key `key` exists, passing in a mutable reference to the value. It returns the `Entry`, so it can be chained with other methods.

For instance, we could use this to count the number of occurrences of words in a string:

```
// This map contains all the words in a given string,
// along with the number of times they occur.
```

```
let mut word_frequency: HashMap<&str, u32> = HashMap::new();

for c in text.split_whitespace() {

    word_frequency

        .entry(c)

        .and_modify(|count| *count += 1)

        .or_insert(1);

}
```

The `Entry` type is an enum, defined like this for `HashMap` (and similarly for the `BTreeMap`):

```
// (in std::collections::hash_map)
pub enum Entry<'a, K, V> {
    Occupied(OccupiedEntry<'a, K, V>),
    Vacant(VacantEntry<'a, K, V>),
}
```

The `OccupiedEntry` and `VacantEntry` types have methods for inserting, removing, and accessing entries without repeating the initial lookup. You can find them in the online documentation. The extra methods can occasionally be used to eliminate a redundant lookup or two, but `.or_insert()` and `.or_insert_with()` cover the common cases.

## Map Iteration

There are several ways to iterate over a map:

- Iterating by value (`for (k, v) in map`) produces `(K, V)` pairs. This consumes the map.
- Iterating over a shared reference (`for (k, v) in &map`) produces `(&K, &V)` pairs.

- Iterating over a `mut` reference (`for (k, v) in &mut map`) produces `(&K, &mut V)` pairs. (Again, there's no way to get `mut` access to keys stored in a map, because the entries are organized by their keys.)

Like vectors, maps have `.iter()` and `.iter_mut()` methods that return by-reference iterators, just like iterating over `&map` or `&mut map`. In addition:

`map.keys()`

Returns an iterator over just the keys, by reference.

`map.values()`

Returns an iterator over the values, by reference.

`map.values_mut()`

Returns an iterator over the values, by `mut` reference.

`map.into_iter()`, `map.into_keys()`, `map.into_values()`

Consume the map, returning an iterator over tuples `(K, V)` of keys and values, keys, or values, respectively.

All `HashMap` iterators visit the map's entries in an arbitrary order. `BTreeMap` iterators visit them in order by key.

## HashSet<T> and BTreeSet<T>

*Sets* are collections of values arranged for fast membership testing:

```
let b1 = large_vector.contains(&"needle");     // slow, checks
every element
let b2 = large_hash_set.contains(&"needle");   // fast, hash
lookup
```

A set never contains multiple copies of the same value.

Maps and sets have different methods, but behind the scenes, a set is like a map with only keys, rather than key-value pairs. In fact, Rust's two set types, `HashSet<T>` and `BTreeSet<T>`, are implemented as thin wrappers around `HashMap<T, ()>` and `BTreeMap<T, ()>`.

The common ways to create a set are:

`HashSet::new()`, `BTreeSet::new()`

: Create new sets.

`iter.collect()`

: Can be used to create a new set from any iterator. If `iter` produces any values more than once, the duplicates are dropped.

`HashSet::with_capacity(n)`

: Creates an empty `HashSet` with room for at least `n` values.

`HashSet<T>` and `BTreeSet<T>` have all the basic methods in common:

`set.len()`

: Returns the number of values in `set`.

`set.is_empty()`

: Returns `true` if the set contains no elements.

`set.contains(&value)`

: Returns `true` if the set contains the given `value`.

`set.insert(value)`

: Adds a `value` to the set. Returns `true` if a value was added, `false` if it was already a member of the set.

`set.remove(&value)`

Removes a `value` from the set. Returns `true` if a value was removed, `false` if it already wasn't a member of the set.

`set.retain(test)`

Removes all elements that don't pass the given test. The `test` argument is a function or closure that implements `FnMut(&T) -> bool`. For each element of `set`, this calls `test(&value)`, and if it returns `false`, the element is removed from the set and dropped.

Apart from performance, this is like writing:

```
set = set.into_iter().filter(test).collect();
```

As with maps, the methods that look up a value by reference are generic over types that can be borrowed from `T`. For details, see "Borrow and BorrowMut".

## Set Iteration

There are two ways to iterate over sets:

- Iterating by value ("`for v in set`") produces the members of the set (and consumes the set).
- Iterating by shared reference ("`for v in &set`") produces shared references to the members of the set.

Iterating over a set by `mut` reference is not supported. There's no way to get a `mut` reference to a value stored in a set.

`set.iter()`

Returns an iterator over the members of `set` by reference.

`HashSet` iterators, like `HashMap` iterators, produce their values in an arbitrary order. `BTreeSet` iterators produce values in order, like a sorted vector.

## When Equal Values Are Different

Sets have a few odd methods that you need to use only if you care about differences between "equal" values. Such differences do often exist. Two identical `String` values, for example, store their characters in different locations in memory:

```
let s1 = "hello".to_string();
let s2 = "hello".to_string();
println!("{:p}", &s1 as &str);  // 0x7f8b32060008
println!("{:p}", &s2 as &str);  // 0x7f8b32060010
```

Usually, we don't care.

But in case you ever do, you can get access to the actual values stored inside a set by using the following methods. Each one returns an `Option` that's `None` if `set` did not contain a matching value:

`set.get(&value)`

> Returns a shared reference to the member of `set` that's equal to `value`, if any. Returns an `Option<&T>`.

`set.take(&value)`

> Like `set.remove(&value)`, but it returns the removed value, if any. Returns an `Option<T>`.

`set.replace(value)`

> Like `set.insert(value)`, but if `set` already contains a value that's equal to `value`, this replaces and returns the old value. Returns an `Option<T>`.

## Whole-Set Operations

So far, most of the set methods we've seen are focused on a single value in a single set. Sets also have methods that operate on whole sets:

`set1.intersection(&set2)`

Returns an iterator over all values that are in both `set1` and `set2`.

For example, if we want to print the names of all students who are taking both brain surgery and rocket science classes, we could write:

```
for student in &brain_class {
    if rocket_class.contains(student) {
        println!("{student}");
    }
}
```

Or, shorter:

```
for student in brain_class.intersection(&rocket_class) {
    println!("{student}");
}
```

Amazingly, there's an operator for this.

`&set1 & &set2` returns a new set that's the intersection of `set1` and `set2`. This is the binary bitwise AND operator, applied to two references. This finds values that are in both `set1` *and* `set2`:

```
let overachievers = &brain_class & &rocket_class;
```

`set1.union(&set2)`

Returns an iterator over values that are in either `set1` or `set2`, or both.

`&set1 | &set2` returns a new set containing all those values. It finds values that are in either `set1` *or* `set2`.

`set1.difference(&set2)`

Returns an iterator over values that are in `set1` but not in `set2`.

`&set1 - &set2` returns a new set containing all those values.

`set1.symmetric_difference(&set2)`

Returns an iterator over values that are in either `set1` or `set2`, but not both.

`&set1 ^ &set2` returns a new set containing all those values.

And there are three methods for testing relationships between sets:

`set1.is_disjoint(set2)`

True if `set1` and `set2` have no values in common—the intersection between them is empty.

`set1.is_subset(set2)`

True if `set1` is a subset of `set2`—that is, all values in `set1` are also in `set2`.

`set1.is_superset(set2)`

This is the reverse: it's true if `set1` is a superset of `set2`.

Sets also support equality testing with == and `!=`; two sets are equal if they contain the same values.

# Hashing

`std::hash::Hash` is the standard library trait for hashable types. `HashMap` keys and `HashSet` elements must implement both `Hash` and `Eq`. Most built-in types that implement `Eq` also implement `Hash`. The integer types, `char`, and `String` are all hashable; so are tuples, arrays, slices, and vectors, as long as their elements are hashable.

One principle of the standard library is that a value should have the same hash code regardless of where you store it or how you point to it. Therefore, a reference has the same hash code as the value it refers to, and a `Box` has the same hash code as the boxed value. A vector `vec` has the same hash code as the slice containing all its data, `&vec[..]`. A `String` has the same hash code as a `&str` with the same characters.

Structs and enums don't implement `Hash` by default, but an implementation can be derived:

```
/// The ID number for an object in the British Museum's
collection.
#[derive(Clone, PartialEq, Eq, Hash)]
enum MuseumNumber {
    ...
}
```

This works as long as the type's fields are all hashable.

If you implement `PartialEq` by hand for a type, you should implement `Hash` by hand. Suppose we have a type that represents priceless historical treasures:

```
struct Artifact {
    id: MuseumNumber,
    name: String,
    cultures: Vec<Culture>,
    date: RoughTime,
    ...
}
```

Two `Artifacts` are considered equal if they have the same ID:

```
impl PartialEq for Artifact {
    fn eq(&self, other: &Artifact) -> bool {
        self.id == other.id
    }
}

impl Eq for Artifact {}
```

Since we compare artifacts purely on the basis of their ID, we must hash them the same way:

```
use std::hash::{Hash, Hasher};

impl Hash for Artifact {
    fn hash<H: Hasher>(&self, hasher: &mut H) {
        // Delegate hashing to the MuseumNumber.
        self.id.hash(hasher);
    }
}
```

(Otherwise, `HashSet<Artifact>` would not work properly; like all hash tables, it requires that `hash(a) == hash(b)` if `a == b`.)

This allows us to create a `HashSet` of `Artifacts`:

```
let mut collection = HashSet::<Artifact>::new();
```

As this code shows, when you implement `Hash` by hand, you don't need to know anything about hashing algorithms. `.hash()` receives a reference to a `Hasher`, which represents the hashing algorithm. You feed this `Hasher` all the data that's relevant to the == operator. The `Hasher` computes a hash code from whatever you give it.

## Using a Custom Hashing Algorithm

Rust supports pluggable hashing algorithms with two more standard traits, `Hasher` and `BuildHasher`. A `Hasher` is a single-use gadget for computing one hash code. A `BuildHasher` is reusable; it builds a `Hasher` each time a hash code is needed.

Programs rarely use these traits directly. Instead, every `HashMap` contains a `BuildHasher` that it uses internally to compute hash codes. If you need hash codes for your own purposes, you too can use the standard library's default `BuildHasher`, the awkwardly named `RandomState`:

```
use std::hash::{BuildHasher, RandomState};

let build_hasher = RandomState::new();
// hash_one() builds a hasher, feeds one value to it, and returns
a u64.
let h = build_hasher.hash_one("my hashable value");
```

Each `RandomState` you create is, as the name suggests, random. No two `HashMaps` use the same hash codes, so each map stores data a little differently. This is why iterating over two `HashMaps` with identical data produces the entries in a different order.

The default hashing algorithm implemented by `RandomState` is a well-known algorithm called SipHash-1-3. SipHash is fast, and it's good at minimizing hash collisions. In fact, SipHash was designed to be a secure pseudorandom function: there's no known efficient way to generate SipHash-1-3 collisions. Since Rust uses a fresh random key for each hash table (the random bytes shown in the `build_hasher` field of Figure 16-4), `HashMap` is secure against a kind of denial-of-service attack called HashDoS, where attackers deliberately use hash collisions to trigger worst-case performance in a server.

If your application does not need HashDoS resistance, you may be interested in using a different hashing algorithm, one that trades statistical quality and HashDoS resistance for sheer speed. The `ahash` crate provides one such algorithm. To try it out, add `ahash` to your project and then import its map and set types:

```
use ahash::{HashMap, HashSet};
```

You can use these two types as drop-in replacements for the corresponding `std::collections` types. A peek inside the `ahash` source code reveals how they're defined:

```
pub type HashMap<K, V> = std::collections::HashMap<K, V,
crate::RandomState>;

pub type HashSet<K> = std::collections::HashSet<K,
crate::RandomState>;
```

The standard `HashMap` and `HashSet` collections accept an optional extra type parameter specifying the hashing algorithm; the collections in `ahash` are generic type aliases for those types, specifying `ahash`'s own `RandomState` type for that parameter.

The `std::hash` framework is designed for keyed hash functions, which are well suited for in-memory data structures like `HashMap`. Cryptographic hash functions, like SHA-256, are a different category of algorithm, slower to compute but consistent from one program run to the next, and secure against collisions even without a secret key. For open source implementations of these, see the `sha2` and `blake3` crates, among others.

## Beyond the Standard Collections

Creating a new, custom collection type in Rust is much the same as in any other language. You arrange data by combining the parts the language provides: structs and enums, standard collections, `Options`, `Boxes`, and so on. For an example, see the `BinaryTree<T>` type defined in "Generic Enums".

If you're used to implementing data structures in C++, using raw pointers, manual memory management, placement `new`, and explicit destructor calls to get the best possible performance, you'll undoubtedly find safe Rust rather limiting. All of those tools are inherently unsafe. They are available

in Rust, but only if you opt in to unsafe code. Chapter 23 shows how; it includes an example that uses some unsafe code to implement a safe custom collection.

For now, we'll just bask in the warm glow of the standard collections and their safe, efficient APIs. Like much of the Rust standard library, they're designed to ensure that the need to write `unsafe` is as rare as possible.

# Chapter 17. Strings and Text

> *The string is a stark data structure and everywhere it is passed there is much duplication of process. It is a perfect vehicle for hiding information.*
>
> —Alan Perlis, epigram #34

We've been using Rust's main textual types, `String`, `str`, and `char`, throughout the book. In "String and Character Types", we described the syntax for character and string literals and showed how strings are represented in memory. In this chapter, we cover text handling in more detail.

In this chapter:

- We give you some background on Unicode that should help you make sense of the standard library's design.
- We describe the `char` type, representing a single Unicode code point.
- We describe the `String` and `str` types, representing owned and borrowed sequences of Unicode characters. These have a broad variety of methods for building, searching, modifying, and iterating over their contents.
- We cover Rust's string formatting facilities, like the `println!` and `format!` macros. You can write your own macros that work with formatting strings and extend them to support your own types.
- Finally, we give an overview of Rust's regular expression support.

## Some Unicode Background

This book is about Rust, not Unicode, which has entire books devoted to it already. But Rust's character and string types are designed around Unicode. Here are a few bits of Unicode that help explain Rust.

## ASCII, Latin-1, and Unicode

Unicode and ASCII match for all of ASCII's code points, from `0` to `0x7f`. For example, both assign the character `*` the code point `42`. Similarly, Unicode assigns `0` through `0xff` to the same characters as the ISO/IEC 8859-1 character set, an eight-bit superset of ASCII for use with Western European languages. Unicode calls this range of code points the *Latin-1 code block*, so we'll refer to ISO/IEC 8859-1 by the more evocative name *Latin-1*.

Since Unicode is a superset of Latin-1, converting Latin-1 to Unicode doesn't even require a table:

```
fn latin1_to_char(latin1: u8) -> char {
    latin1 as char
}
```

The reverse conversion is trivial as well, assuming the code points fall in the Latin-1 range:

```
fn char_to_latin1(c: char) -> Option<u8> {
    if c as u32 <= 0xff {
        Some(c as u8)
    } else {
        None
    }
}
```

## UTF-8

The Rust `String` and `str` types represent text using the UTF-8 encoding form. UTF-8 encodes a character as a sequence of 1 to 4 bytes (Figure 17-1).

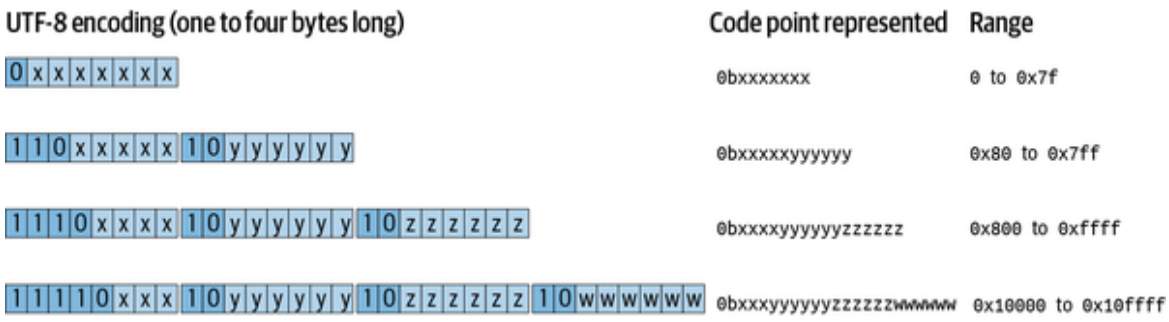


*Figure 17-1. The UTF-8 encoding*

There are two restrictions on well-formed UTF-8 sequences. First, only the shortest encoding for any given code point is considered well-formed; you can't spend four bytes encoding a code point that would fit in three. This rule ensures that there is exactly one UTF-8 encoding for a given code point. Second, well-formed UTF-8 must not encode numbers from `0xd800` through `0xdfff` or beyond `0x10ffff`: those are either reserved for noncharacter purposes or outside Unicode's range entirely.

Figure 17-2 shows some examples.

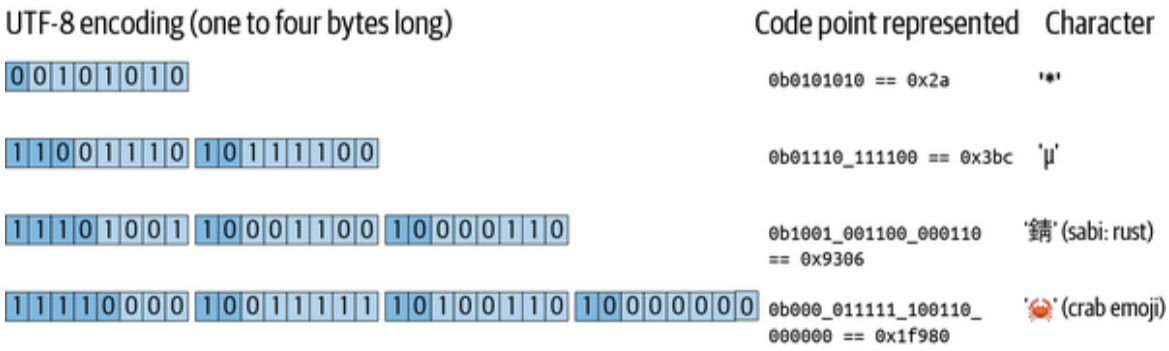


*Figure 17-2. UTF-8 examples*

Note that, even though the crab emoji has an encoding whose leading byte contributes only zeros to the code point, it still needs a 4-byte encoding: 4-byte UTF-8 encodings can only convey 16-bit code points, and `0x1f980` is 17 bits long.

Here's a quick example of a string containing characters with encodings of varying lengths:

```
assert_eq!(
    "うどん: udon".as_bytes(),
```

```
    &[
        0xe3, 0x81, 0x86,  // う
        0xe3, 0x81, 0xa9,  // ど
        0xe3, 0x82, 0x93,  // ん
        0x3a, 0x20, 0x75, 0x64, 0x6f, 0x6e,  // : udon
    ],
);
```

Figure 17-2 also shows some very helpful properties of UTF-8:

- Since UTF-8 encodes code points `0` through `0x7f` as nothing more than the bytes `0` through `0x7f`, a range of bytes holding ASCII text is valid UTF-8. And if a string of UTF-8 includes only characters from ASCII, the reverse is also true: the UTF-8 encoding is valid ASCII.

  The same is not true for Latin-1: for example, Latin-1 encodes `é` as the byte `0xe9`, which UTF-8 would interpret as the first byte of a three-byte encoding.

- From looking at any byte's upper bits, you can immediately tell whether it is the start of some character's UTF-8 encoding or a byte from the midst of one.

- An encoding's first byte alone tells you the encoding's full length, via its leading bits.

- Since no encoding is longer than four bytes, UTF-8 processing never requires unbounded loops, which is nice when working with untrusted data.

- In well-formed UTF-8, you can always tell unambiguously where characters' encodings begin and end, even if you start from an arbitrary point in the midst of the bytes. UTF-8 first bytes and following bytes are always distinct, so one encoding cannot start in the midst of another. The first byte determines the encoding's total length, so no encoding can be a prefix of another. This has a lot of nice consequences. For example, searching a UTF-8 string for an ASCII delimiter character requires only a simple scan for the

delimiter's byte. It can never appear as any part of a multibyte encoding, so there's no need to keep track of the UTF-8 structure at all. Similarly, algorithms that search for one byte string in another will work without modification on UTF-8 strings, even though some don't even examine every byte of the text being searched.

Although variable-width encodings are more complicated than fixed-width encodings, these characteristics make UTF-8 more comfortable to work with than you might expect. The standard library handles most aspects for you.

### Text Directionality

Whereas scripts like Latin, Cyrillic, and Thai are written from left to right, other scripts like Hebrew and Arabic are written from right to left. Unicode stores characters in the order in which they would normally be written or read, so the initial bytes of a string holding, say, Hebrew text encode the character that would be written at the right:

```
assert_eq!("ערב טוב".chars().next(), Some('ע'));
```

## Characters (char)

A Rust `char` is a 32-bit value holding a Unicode code point. A `char` is guaranteed to fall in the range from `0` to `0xd7ff` or in the range `0xe000` to `0x10ffff`; all the methods for creating and manipulating `char` values ensure that this is true. The `char` type implements `Copy` and `Clone`, along with all the usual traits for comparison, hashing, and formatting.

A string slice can produce an iterator over its characters with `slice.chars()`:

```
assert_eq!("カニ".chars().next(), Some('カ'));
```

In the descriptions that follow, the variable `ch` is always of type `char`.

## Classifying Characters

The `char` type has methods for classifying characters into a few common categories, as listed in Table 17-1. These all draw their definitions from Unicode.

*Table 17-1. Classification methods for `char` type*

| Method | Description | Examples |
|---|---|---|
| `ch.is_numeric()` | A numeric character. This includes the Unicode general categories “Number; digit” and “Number; letter” but not “Number; other”. | `'4'.is_numeric()`<br>`'〩'.is_numeric()`<br>`'⑧'.is_numeric()` |
| `ch.is_alphabetic()` | An alphabetic character: Unicode’s “Alphabetic” derived property. | `'q'.is_alphabetic()`<br>`'七'.is_alphabetic()` |
| `ch.is_alphanumeric()` | Either numeric or alphabetic, as defined earlier. | `'9'.is_alphanumeric()`<br>`'饂'.is_alphanumeric()`<br>`!'*'.is_alphanumeric()` |
| `ch.is_whitespace()` | A whitespace character: Unicode character property “WSpace=Y”. | `' '.is_whitespace()`<br>`'\n'.is_whitespace()`<br>`'\u{A0}'.is_whitespace()` |
| `ch.is_control()` | A control character: Unicode’s “Other, control” general category. | `'\n'.is_control()`<br>`'\u{85}'.is_control()` |

A parallel set of methods restricts itself to ASCII only, returning `false` for any non-ASCII `char` (Table 17-2).

*Table 17-2. ASCII classification methods for* `char`

| Method | Description | Examples |
|---|---|---|
| `ch.is_ascii()` | An ASCII character: one whose code point falls between `0` and `127`, inclusive | `'n'.is_ascii()`<br>`!'ñ'.is_ascii()` |
| `ch.is_ascii_alphabetic()` | An upper- or lowercase ASCII letter, in the range `'A'..='Z'` or `'a'..='z'` | `'n'.is_ascii_alphabetic()`<br>`!'1'.is_ascii_alphabetic()`<br>`!'ñ'.is_ascii_alphabetic()` |
| `ch.is_ascii_digit()` | An ASCII digit, in the range `'0'..='9'` | `'8'.is_ascii_digit()`<br>`!'-'.is_ascii_digit()`<br>`!'⑧'.is_ascii_digit()` |
| `ch.is_ascii_hexdigit()` | Any character in the ranges `'0'..='9'`, `'A'..='F'`, or `'a'..='f'` | |
| `ch.is_ascii_alphanumeric()` | An ASCII digit or upper- or lowercase letter | `'q'.is_ascii_alphanumeric()`<br>`'0'.is_ascii_alphanumeric()` |
| `ch.is_ascii_control()` | An ASCII control character, including ‘DEL’ | `'\n'.is_ascii_control()`<br>`'\x7f'.is_ascii_control()` |

| Method | Description | Examples |
| --- | --- | --- |
| `ch.is_ascii_graphic()` | Any ASCII character that leaves ink on the page: neither a space nor a control character | `'Q'.is_ascii_graphic()`<br>`'~'.is_ascii_graphic()`<br>`!' '.is_ascii_graphic()` |
| `ch.is_ascii_uppercase()`, `ch.is_ascii_lowercase()` | ASCII uppercase and lowercase letters | `'z'.is_ascii_lowercase()`<br>`'Z'.is_ascii_uppercase()` |
| `ch.is_ascii_punctuation()` | Any ASCII graphic character that is neither alphabetic nor a digit | |
| `ch.is_ascii_whitespace()` | An ASCII whitespace character: a space, horizontal tab, line feed, form feed, or carriage return | `' '.is_ascii_whitespace()`<br>`'\n'.is_ascii_whitespace()`<br>`!'\u{A0}'.is_ascii_whitespace()` |

All the `is_ascii_...` methods are also available on the `u8` byte type:

```
assert!(32u8.is_ascii_whitespace());
assert!(b'9'.is_ascii_digit());
```

Take care when using these functions to implement an existing specification like a programming language standard or file format. Classifications can differ in surprising ways, for example, `is_whitespace` and `is_ascii_whitespace` differ in their treatment of certain characters:

```
let line_tab = '\u{000b}';  // 'line tab', AKA 'vertical tab'
assert_eq!(line_tab.is_whitespace(), true);
assert_eq!(line_tab.is_ascii_whitespace(), false);
```

Function `char::is_ascii_whitespace` implements a definition of whitespace common to many web standards, whereas `char::is_whitespace` follows the Unicode standard.

## Handling Digits

For handling digits, you can use the following methods:

`ch.to_digit(radix)`

> Decides whether `ch` is a digit in base `radix`. If it is, it returns `Some(num)`, where `num` is a `u32`. Otherwise, it returns `None`. This recognizes only ASCII digits, not the broader class of characters covered by `char::is_numeric`. The `radix` parameter can range from 2 to 36. For radixes larger than 10, ASCII letters of either case are considered digits with values from 10 through 35.

`char::from_digit(num, radix)`

> A free function that converts the `u32` digit value `num` to a `char`, if possible. If `num` can be represented as a single digit in `radix`, `from_digit` returns `Some(ch)`, where `ch` is the digit. When `radix` is greater than 10, `ch` may be a lowercase letter. Otherwise, it returns `None`.
>
> This is the reverse of `to_digit`. If `char::from_digit(num, radix)` is `Some(ch)`, then `ch.to_digit(radix)` is `Some(num)`. If `ch` is an ASCII digit or lowercase letter, the converse holds as well.

`ch.is_digit(radix)`

> Returns `true` if `ch` is an ASCII digit in base `radix`. This is equivalent to `ch.to_digit(radix) != None`.

So, for example:

```
assert_eq!('F'.to_digit(16), Some(15));
assert_eq!(char::from_digit(15, 16), Some('f'));
assert!(char::is_digit('f', 16));
```

## Case Conversion for Characters

For handling character case:

`ch.is_lowercase()`, `ch.is_uppercase()`

Indicate whether `ch` is a lower- or uppercase alphabetic character. These follow Unicode's Lowercase and Uppercase derived properties, so they cover non-Latin alphabets like Greek and Cyrillic and give the expected results for ASCII as well.

`ch.to_lowercase()`, `ch.to_uppercase()`

Return iterators that produce the characters of the lower- and uppercase equivalents of `ch`, according to the Unicode Default Case Conversion algorithms:

```
let mut upper = 's'.to_uppercase();

assert_eq!(upper.next(), Some('S'));

assert_eq!(upper.next(), None);
```

These methods return an iterator instead of a single character because case conversion in Unicode isn't always a one-to-one process:

```
// The uppercase form of the German letter "sharp S" is "SS":

let mut upper = 'ß'.to_uppercase();

assert_eq!(upper.next(), Some('S'));

assert_eq!(upper.next(), Some('S'));

assert_eq!(upper.next(), None);
```

```
// Unicode says the lowercase of Turkish dotted capital 'İ' is
// 'i' followed by `'\u{307}'`, COMBINING DOT ABOVE, so that a
// subsequent conversion back to uppercase preserves the dot.
let ch = 'İ';  // `'\u{130}'`
let mut lower = ch.to_lowercase();
assert_eq!(lower.next(), Some('i'));
assert_eq!(lower.next(), Some('\u{307}'));
assert_eq!(lower.next(), None);
```

As a convenience, these iterators implement the `std::fmt::Display` trait, so you can pass them directly to a `println!` or `write!` macro.

## Conversions to and from Integers

Rust's `as` operator will convert a `char` to any integer type, silently masking off any upper bits:

```
assert_eq!('B' as u32, 66);
assert_eq!('饂' as u8, 66);     // upper bits truncated
assert_eq!('二' as i8, -116);  // same
```

The `as` operator will convert any `u8` value to a `char`, and `char` implements `From<u8>` as well, but wider integer types can represent invalid code points, so for those you must use `char::from_u32`, which returns `Option<char>`:

```
assert_eq!(char::from(66), 'B');
assert_eq!(char::from_u32(0x9942), Some('饂'));
assert_eq!(char::from_u32(0xd800), None);  // reserved for UTF-16
```

## String and str

Rust's `String` and `str` types are guaranteed to hold only well-formed UTF-8. The library ensures this by restricting the ways you can create `String` and `str` values and the operations you can perform on them, such that the values are well-formed when introduced and remain so as you work with them. All their methods protect this guarantee: no safe operation on them can introduce ill-formed UTF-8. This simplifies code that works with the text.

Rust places text-handling methods on either `str` or `String` depending on whether the method needs a resizable buffer or is content just to use the text in place. Since `String` dereferences to `&str`, every method defined on `str` is directly available on `String` as well. This section presents methods from both types, grouped roughly by area of utility.

These methods index text by byte offsets and measure its length in bytes, rather than characters. In practice, given the nature of Unicode, indexing by character is not as useful as it may seem, and byte offsets are faster and simpler. If you try to use a byte offset that lands in the midst of some character's UTF-8 encoding, the method panics, so you can't introduce ill-formed UTF-8 this way.

A `String` is implemented as a wrapper around a `Vec<u8>` that ensures the vector's contents are always well-formed UTF-8. Rust will never change `String` to use a more complicated representation, so you can assume that `String` shares `Vec`'s performance characteristics.

In these explanations, the variables have the types given in Table 17-3.

*Table 17-3. Types of variables used in explanations*

| Variable | Presumed type |
|---|---|
| `string` | `String` |
| `slice` | `&str` or something that dereferences to one, like `String` or `Rc<String>` |
| `ch` | `char` |
| `n` | `usize`, a length |
| `i`, `j` | `usize`, a byte offset |
| `range` | A range of `usize` byte offsets, either fully bounded like `i..j` or partly bounded like `i..`, `..j`, or `..` |
| `pattern` | Any of several types used as patterns for searching strings; see "Patterns for Searching Text" |

## Creating String Values

There are a few common ways to create `String` values:

`String::new()`

: Returns a fresh, empty string, has no heap-allocated buffer, but allocates one as needed.

`String::with_capacity(n)`

: Returns a fresh, empty string with a buffer pre-allocated to hold at least `n` bytes. If you know the length of the string you're building in advance, this constructor lets you get the buffer sized correctly from the start, instead of resizing the buffer as you build the string. The string will still grow its buffer as needed if its length exceeds `n` bytes. Like vectors,

strings have `capacity`, `reserve`, and `shrink_to_fit` methods, but usually the default allocation logic is fine.

`str_slice.to_string()` *and* `String::from(str_slice)`

Allocates a fresh `String` whose contents are a copy of `str_slice`. We've been using expressions like `"literal text".to_string()` to make `String`s from string literals, and `String::from("literal text")` does the same.

*The* `format!()` *macro*

Returns a fresh `String` whose contents are built from the provided format string and arguments, similarly to `println!`. This small language is described in more detail in "Formatting Values".

`iter.collect()`

Constructs a string by concatenating an iterator's items, which can be `char`, `&str`, or `String` values. For example, to remove all spaces from a string, you can write:

```
let spacey = "man hat tan";
let spaceless: String =
    spacey.chars().filter(|c| !c.is_whitespace()).collect();
assert_eq!(spaceless, "manhattan");
```

Using `collect` this way takes advantage of `String`'s implementations of the `std::iter::FromIterator` trait.

## Simple Inspection

These methods get basic information from string slices:

`slice.len()`

The length of `slice`, in bytes.

`slice.is_empty()`

True if `slice.len() == 0`.

`slice[range]`

Returns a slice borrowing the given portion of `slice`. Partially bounded and unbounded ranges are OK. For example:

```
let full = "bookkeeping";
assert_eq!(&full[..4], "book");
assert_eq!(&full[5..], "eeping");
assert_eq!(&full[2..4], "ok");
assert_eq!(full[..].len(), 11);
assert_eq!(full[5..].contains("boo"), false);
```

Note that you cannot index a string slice with a single position, like `slice[i]`. Fetching a single character at a given byte offset is a bit clumsy: you must produce a `chars` iterator over the slice, and ask it to parse one character's UTF-8:

```
let parenthesized = "Rust (錆)";
assert_eq!(parenthesized[6..].chars().next(), Some('錆'));
```

However, you should rarely need to do this. Rust has much nicer ways to iterate over slices, which we describe in "Iterating over Text".

`slice.split_at(i)`

Returns a tuple of two shared slices borrowed from `slice`: the portion up to byte offset `i`, and the portion after it. In other words, this returns `(slice[..i], slice[i..])`.

`slice.is_char_boundary(i)`

True if the byte offset `i` falls between character boundaries and is thus suitable as an offset into `slice`. Zero and `slice.len()` always count as character boundaries.

Naturally, slices can be compared for equality, ordered, and hashed. Ordered comparison simply treats the string as a sequence of Unicode code points and compares them in lexicographic order.

## Appending and Inserting Text

The following methods add text to a `String`:

`string.push(ch)`

Appends the character `ch` to the end `string`.

`string.push_str(slice)`

Appends the full contents of `slice`.

`string.extend(iter)`

Appends the items produced by the iterator `iter` to the string. The iterator can produce `char`, `str`, or `String` values. These are `String`'s implementations of `std::iter::Extend`:

```
let mut also_spaceless = "con".to_string();
also_spaceless.extend("tri but ion".split_whitespace());
assert_eq!(also_spaceless, "contribution");
```

`string.insert(i, ch)`

Inserts the single character `ch` at byte offset `i` in `string`. This entails shifting over any characters after `i` to make room for `ch`, so building up

a string this way can require time quadratic in the length of the string.

`string.insert_str(i, slice)`

This does the same for `slice`, with the same performance caveat.

`String` implements `std::fmt::Write`, meaning that the `write!` and `writeln!` macros can append formatted text to `String`s:

```
use std::fmt::Write;

let mut letter = String::new();
writeln!(letter, "Whose {} these are I think I know",
"rutabagas")?;
writeln!(letter, "His house is in the village though;")?;
assert_eq!(
    letter,
    "Whose rutabagas these are I think I know\n\
        His house is in the village though;\n",
);
```

Since `write!` and `writeln!` are designed for writing to output streams, they return a `Result`, which Rust complains if you ignore. This code uses the `?` operator to handle it, but writing to a `String` is actually infallible, so in this case calling `.unwrap()` would be OK too.

Since `String` implements `Add<&str>` and `AddAssign<&str>`, you can write code like:

```
let left = "partners".to_string();
let mut right = "crime".to_string();
assert_eq!(left + " in " + &right, "partners in crime");

right += " doesn't pay";
assert_eq!(right, "crime doesn't pay");
```

When applied to strings, the + operator takes its left operand by value, so it can actually reuse that `String` as the result of the addition. As a consequence, if the left operand's buffer is large enough to hold the result,

no allocation is needed. In an unfortunate lack of symmetry, `String + &str` works, but `&str + String` doesn't:

```
let note = "NOTE: " + string;  // error: cannot add `String` to
`&str`
```

The easiest workaround is to use `format!`:

```
let note = format!("NOTE: {string}");
```

Rust could easily make `&str` implement `Add<String>`, but this operation requires shifting existing text in the `String` toward the end of the buffer, to make room at the front. It's slow, like inserting items at the front of a `Vec`. Doing this repeatedly to build up a `String`, adding a few characters at a time to the front, is a performance pitfall.

Building strings from beginning to end by appending small pieces, however, is efficient. A `String` behaves like a vector, keeping extra capacity at the end and doubling the buffer size when it needs more room.

## Removing and Replacing Text

`String` has a few methods for removing text (these do not affect the string's capacity; use `shrink_to_fit` if you need to free memory):

`string.clear()`

: Resets `string` to the empty string.

`string.truncate(n)`

: Discards all characters after the byte offset `n`, leaving `string` with a length of at most `n`. If `string` is shorter than `n` bytes, this has no effect.

`string.pop()`

Removes the last character from `string`, if any, and returns it as an `Option<char>`.

`string.remove(i)`

Removes the character at byte offset `i` from `string` and returns it, shifting any following characters toward the front. This takes time linear in the number of following characters.

`string.drain(range)`

Returns an iterator over the given range of byte indices and removes the characters once the iterator is dropped. Characters after the range are shifted toward the front:

```
let mut choco = "chocolate".to_string();
assert_eq!(choco.drain(3..6).collect::<String>(), "col");
assert_eq!(choco, "choate");
```

If you just want to remove the range, you can just drop the iterator immediately, without drawing any items from it:

```
let mut winston = "Churchill".to_string();
winston.drain(2..6);
assert_eq!(winston, "Chill");
```

`string.replace_range(range, replacement)`

Replaces the given range in `string` with the given replacement string slice. The slice doesn't have to be the same length as the range being replaced, but unless the range being replaced goes to the end of `string`, that will require moving all the bytes after the end of the range:

```
let mut beverage = "a piña colada".to_string();
beverage.replace_range(2..7, "kahlua");  // 'ñ' is two bytes!
assert_eq!(beverage, "a kahlua colada");
```

## Conventions for Searching and Iterating

Rust's standard library functions for searching text and iterating over text follow some naming conventions to make them easier to remember:

`r`

: Most operations process text from start to end, but operations with names starting with `r` work from end to start. For example, `rsplit` is the end-to-start version of `split`. In some cases changing direction can affect not only the order in which values are produced but also the values themselves. See the diagram in Figure 17-3 for an example of this.

`n`

: Iterators with names ending in `n` limit themselves to a given number of matches.

`_indices`

: Iterators with names ending in `_indices` produce, together with their usual iteration values, the byte offsets in the slice at which they appear.

The standard library doesn't provide all combinations for every operation. For example, many operations don't need an `n` variant, as it's easy enough to simply end the iteration early.

## Patterns for Searching Text

When a standard library function needs to search, match, split, or trim text, it accepts several different types to represent what to look for:

```
let haystack = "One fine day, in the middle of the night";

assert_eq!(haystack.find(','), Some(12));
assert_eq!(haystack.find("night"), Some(35));
assert_eq!(haystack.find(char::is_whitespace), Some(3));
```

These types are called *patterns*, and most operations support them:

```
assert_eq!(
    "## Elephants"
        .trim_start_matches(|ch: char| ch == '#' ||
ch.is_whitespace()),
    "Elephants",
);
```

The standard library supports four main kinds of patterns:

- A `char` as a pattern matches that character.
- A `String` or `&str` or `&&str` as a pattern matches a substring equal to the pattern.
- A `FnMut(char) -> bool` closure as a pattern matches a single character for which the closure returns true.
- A `[char; N]` or `&[char]` as a pattern matches any single character that appears in the list:

  ```
  let code = "\t    function noodle() { ";
  assert_eq!(
      code.trim_start_matches([' ', '\t']),
      "function noodle() { ",
  );
  ```

In the library's own code, a pattern is any type that implements the `std::str::Pattern` trait. The details of `Pattern` are not yet stable, so you can't implement it for your own types in stable Rust, but the door is open to permit regular expressions and other sophisticated patterns in the future. Rust does guarantee that the pattern types supported now will continue to work in the future.

## Searching and Replacing

Rust has a few methods for searching for patterns in slices and possibly replacing them with new text:

`slice.contains(pattern)`

Returns true if `slice` contains a match for `pattern`.

`slice.starts_with(pattern)`, `slice.ends_with(pattern)`

Return true if `slice`'s initial or final text matches `pattern`:

```
assert!("2017".starts_with(char::is_numeric));
```

`slice.find(pattern)`, `slice.rfind(pattern)`

Return `Some(i)` if `slice` contains a match for `pattern`, where `i` is the byte offset at which the pattern appears. The `find` method returns the first match, `rfind` the last:

```
let quip = "We also know there are known unknowns";
assert_eq!(quip.find("know"), Some(8));
assert_eq!(quip.rfind("know"), Some(31));
assert_eq!(quip.find("ya know"), None);
assert_eq!(quip.rfind(char::is_uppercase), Some(0));
```

`slice.replace(pattern, replacement)`

Returns a new `String` formed by eagerly replacing all matches for `pattern` with `replacement`:

```
assert_eq!(
    "The only thing we have to fear is fear itself"
```

```
            .replace("fear", "spin"),
        "The only thing we have to spin is spin itself",
    );

    assert_eq!(
        "`Borrow` and `BorrowMut`"
            .replace(|ch: char| !ch.is_alphanumeric(), ""),
        "BorrowandBorrowMut",
    );
```

Because the replacement is done eagerly, `.replace()`'s behavior on overlapping matches can be surprising. Here, there are four instances of the pattern, `"aba"`, but the second and fourth no longer match after the first and third are replaced:

```
    assert_eq!(
        "cabababababbage".replace("aba", "***"),
        "c***b***babbage",
    );
```

`slice.replacen(pattern, replacement, n)`

This does the same, but replaces at most the first `n` matches.

## Iterating over Text

The standard library provides several ways to iterate over a slice's text. Figure 17-3 shows examples of some. You can think of the `split` and `match` families as being complements of each other: splits are the ranges between matches.

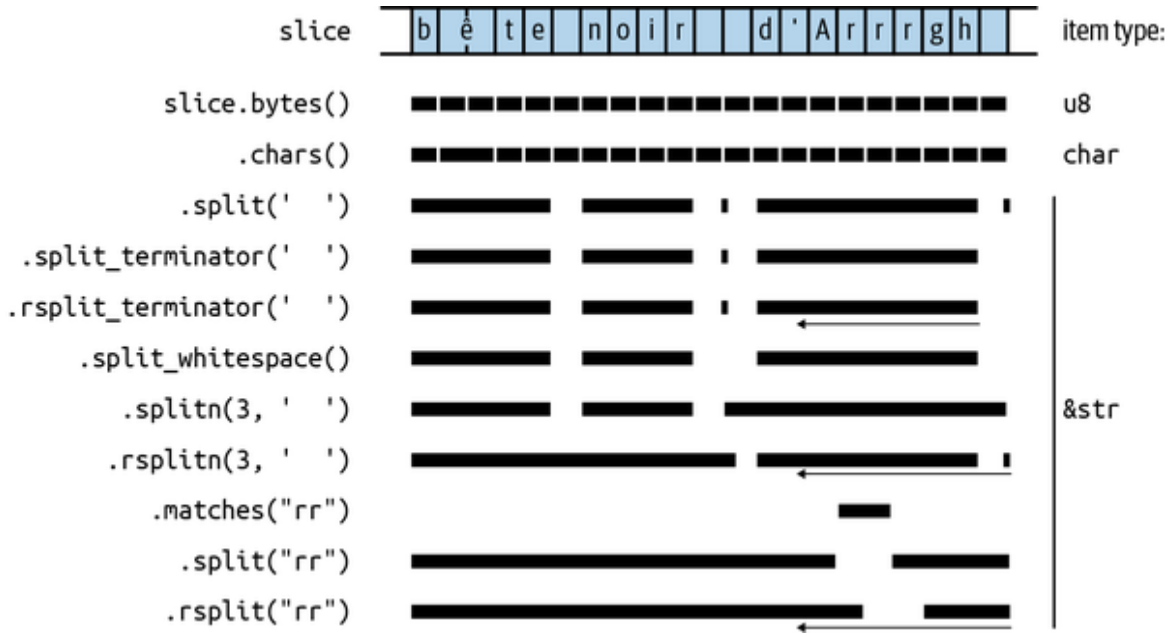


*Figure 17-3. Some ways to iterate over a slice*

The iteration methods include:

`slice.chars()`

Returns an iterator over `slice`'s characters.

`slice.char_indices()`

Returns an iterator over `slice`'s characters and their byte offsets:

```
assert_eq!(
    "élan".char_indices().collect::<Vec<_>>(),
    vec![
        (0, 'é'),  // has a two-byte UTF-8 encoding
        (2, 'l'),
        (3, 'a'),
        (4, 'n'),
    ],
);
```

Note that this is not equivalent to `.chars().enumerate()`, since it supplies each character's byte offset within the slice, instead of just numbering the characters.

`slice.bytes()`

Returns an iterator over the individual bytes of `slice`, exposing the UTF-8 encoding:

```
assert_eq!(
    "élan".bytes().collect::<Vec<_>>(),
    vec![195, 169, b'l', b'a', b'n'],
);
```

`slice.lines()`

Returns an iterator over the lines of `slice`. Lines are terminated by `"\n"` or `"\r\n"`. Each item produced is a `&str` borrowing from `slice`. The items do not include the lines' terminating characters.

`slice.split(pattern)`

Returns an iterator over the portions of `slice` separated by matches of `pattern`. This produces empty strings between immediately adjacent matches, as well as for matches at the beginning and end of `slice`.

The returned iterator is not reversible if `pattern` is a `&str`. Such patterns can produce different sequences of matches depending on which direction you scan from, which reversible iterators are forbidden to do. Instead, you may be able to use the `rsplit` method, described next.

`slice.rsplit(pattern)`

This method is the same, but scans `slice` from end to start, producing matches in that order.

`slice.split_terminator(pattern)`,
`slice.rsplit_terminator(pattern)`

These are similar, except that the pattern is treated as a terminator, not a separator: if `pattern` matches at the very end of `slice`, the iterators do not produce an empty slice representing the empty string between that match and the end of the slice, as `split` and `rsplit` do. For example:

```
// The ':' characters are separators here. Note the final "".
assert_eq!(
    "jimb:1000:Jim Blandy:".split(':').collect::<Vec<_>>(),
    vec!["jimb", "1000", "Jim Blandy", ""],
);

// The '\n' characters are terminators here.
assert_eq!(
    "127.0.0.1  localhost\n\
     127.0.0.1  www.reddit.com\n"
        .split_terminator('\n')
        .collect::<Vec<_>>(),
    vec![
        "127.0.0.1  localhost",
        "127.0.0.1  www.reddit.com",
        // Note, no final ""!
    ],
);
```

`slice.splitn(n, pattern)`, `slice.rsplitn(n, pattern)`

These are like `split` and `rsplit`, except that they split the string into at most `n` slices, at the first or last `n-1` matches for `pattern`.

`slice.split_whitespace()`,
`slice.split_ascii_whitespace()`

Return an iterator over the whitespace-separated portions of `slice`. A run of multiple whitespace characters is considered a single separator. Trailing whitespace is ignored.

The `split_ascii_whitespace` method uses `char::is_ascii_whitespace` instead, which recognizes only ASCII whitespace characters. The `split_whitespace` method uses the Unicode definition of whitespace, as implemented by the `is_whitespace` method on `char`:

```
let poem = "\
    This  is  just  to say\n\
    I have eaten\n\
    the plums\n\
    again\n";


assert_eq!(
    poem.split_whitespace().collect::<Vec<_>>(),
    vec![
        "This", "is", "just", "to", "say", "I", "have",
"eaten",
        "the", "plums", "again",
```

```
        ],
    );
```

`slice.matches(pattern)`

Returns an iterator over the matches for `pattern` in slice. `slice.rmatches(pattern)` is the same, but iterates from end to start.

`slice.match_indices(pattern)`,
`slice.rmatch_indices(pattern)`

These are similar, except that the items produced are `(offset, match)` pairs, where `offset` is the byte offset at which the match begins, and `match` is the matching slice.

Most of these methods return iterators that are reversible (that is, they implement `DoubleEndedIterator`): calling their `.rev()` adapter method gives you an iterator that produces the same items, but in reverse order.

## Trimming

To *trim* a string is to remove text, usually whitespace, from the beginning or end of the string. It's often useful in cleaning up input read from a file where the user might have indented text for legibility or accidentally left trailing whitespace on a line.

`slice.trim()`

Returns a subslice of `slice` that omits any leading and trailing whitespace. `slice.trim_start()` omits only leading whitespace.

While `slice.trim_end()` omits only trailing whitespace:

```
assert_eq!("\t*.rs  ".trim(), "*.rs");
assert_eq!("\t*.rs  ".trim_start(), "*.rs  ");
assert_eq!("\t*.rs  ".trim_end(), "\t*.rs");
```

`slice.trim_matches(pattern)`

Returns a subslice of `slice` that omits all matches of `pattern` from the beginning and end. The `trim_start_matches` and `trim_end_matches` methods do the same for only leading or trailing matches:

```
assert_eq!("001990".trim_start_matches('0'), "1990");
```

`slice.strip_prefix(pattern)`,
`slice.strip_suffix(pattern)`

If `slice` begins with `pattern`, `strip_prefix` returns `Some` holding the slice with the matching text removed. Otherwise, it returns `None`. The `strip_suffix` method is similar, but checks for a match at the end of the string.

These are like `trim_start_matches` and `trim_end_matches`, except that they return an `Option`, and only one copy of `pattern` is removed:

```
let slice = "banana";
assert_eq!(slice.strip_suffix("na"), Some("bana"));
```

## Case Conversion for Strings

The methods `slice.to_uppercase()` and `slice.to_lowercase()` return a freshly allocated `String` holding the text of `slice` converted to uppercase or lowercase. The result might

not be the same length as `slice`; see "Case Conversion for Characters" for details.

## Parsing Other Types from Strings

Rust provides standard traits for both parsing values from strings and producing textual representations of values. If a type implements the `std::str::FromStr` trait, then it provides a standard way to parse a value from a string slice:

```
pub trait FromStr: Sized {
    type Err;
    fn from_str(s: &str) -> Result<Self, Self::Err>;
}
```

All the usual machine types implement `FromStr`:

```
use std::str::FromStr;

assert_eq!(usize::from_str("3628800"), Ok(3628800));
assert_eq!(f64::from_str("128.5625"), Ok(128.5625));
assert_eq!(bool::from_str("true"), Ok(true));

assert!(f64::from_str("not a float at all").is_err());
assert!(bool::from_str("TRUE").is_err());
```

The `char` type also implements `FromStr`, for strings with just one character:

```
assert_eq!(char::from_str("é"), Ok('é'));
assert!(char::from_str("abcdefg").is_err());
```

The `std::net::IpAddr` type, an `enum` holding either an IPv4 or an IPv6 internet address, implements `FromStr` too:

```
use std::net::IpAddr;

let address =
IpAddr::from_str("fe80::0000:3ea9:f4ff:fe34:7a50")?;
```

```
assert_eq!(
    address,
    IpAddr::from([0xfe80, 0, 0, 0, 0x3ea9, 0xf4ff, 0xfe34,
0x7a50]),
);
```

String slices have a `parse` method that parses the slice into whatever type you like, assuming it implements `FromStr`. As with `Iterator::collect`, you will sometimes need to spell out which type you want, so `parse` is not always much more legible than calling `from_str` directly:

```
let address = "fe80::0000:3ea9:f4ff:fe34:7a50".parse::<IpAddr>
()?;
```

## Converting Other Types to Strings

There are three main ways to convert nontextual values to strings:

- Types that have a natural human-readable printed form can implement the `std::fmt::Display` trait, which lets you use the `{}` format specifier in the `format!` macro:

  ```
  assert_eq!(format!("{}", 1 + 1 == 2), "true");
  assert_eq!(
      format!("({:.3}, {:.3})", 0.5, 3f64.sqrt() / 2.0),
      "(0.500, 0.866)",
  );

  // Using `address` from above.
  let formatted_addr: String = format!("{address}");
  assert_eq!(formatted_addr, "fe80::3ea9:f4ff:fe34:7a50");
  ```

  All Rust's machine numeric types implement `Display`, as do characters, strings, and slices. The smart pointer types `Box<T>`, `Rc<T>`, and `Arc<T>` implement `Display` if `T` itself does: their displayed form is simply that of their referent. Containers like `Vec` and `HashMap` do not implement `Display`, as there's no single natural human-readable form for those types.

- If a type implements `Display`, the standard library automatically implements the `std::str::ToString` trait for it, whose sole method `to_string` can be more convenient when you don't need the flexibility of `format!`:

  ```
  // Continued from above.
  assert_eq!(address.to_string(),
  "fe80::3ea9:f4ff:fe34:7a50");
  ```

  The `ToString` trait predates the introduction of `Display` and is less flexible. For your own types, you should generally implement `Display` instead of `ToString`.

- Every public type in the standard library implements `std::fmt::Debug`, which takes a value and formats it as a string in a way helpful to programmers. The easiest way to use `Debug` to produce a string is via the `format!` macro's `{:?}` format specifier:

  ```
  // Continued from above.
  let addresses = vec![address,
  IpAddr::from_str("192.168.0.1")?];
  assert_eq!(
      format!("{addresses:?}"),
      "[fe80::3ea9:f4ff:fe34:7a50, 192.168.0.1]",
  );
  ```

  This takes advantage of a blanket implementation of `Debug` for `Vec<T>`, for any `T` that itself implements `Debug`. All of Rust's collection types have such implementations.

  You should implement `Debug` for your own types, too. Usually it's best to let Rust derive an implementation, as we did for the `Complex` type in Chapter 12:

  ```
  #[derive(Copy, Clone, Debug)]
  struct Complex {
      re: f64,
      im: f64,
  }
  ```

The `Display` and `Debug` formatting traits are just two among several that the `format!` macro and its relatives use to format values as text. We'll cover the others and explain how to implement them all in "Formatting Values".

## Borrowing as Other Text-Like Types

You can borrow a slice's contents in several different ways:

- Slices and `String`s implement `AsRef<str>`, `AsRef<[u8]>`, `AsRef<Path>`, and `AsRef<OsStr>`. Many standard library functions use these traits as bounds on their parameter types, so you can pass slices and strings to them directly, even when what they really want is some other type. See "AsRef and AsMut" for a more detailed explanation.
- Slices and strings also implement the `std::borrow::Borrow<str>` trait. `HashMap` and `BTreeMap` use `Borrow` to make `String`s work nicely as keys in a table. See "Borrow and BorrowMut" for details.

## Accessing Text as UTF-8

There are two main ways to get at the bytes representing text, depending on whether you want to take ownership of the bytes or just borrow them:

`slice.as_bytes()`

Borrows `slice`'s bytes as a `&[u8]`. Since this is not a mutable reference, `slice` can assume its bytes will remain well-formed UTF-8.

`string.into_bytes()`

Takes ownership of `string` and returns a `Vec<u8>` of the string's bytes by value. This is a cheap conversion, as it simply hands over the `Vec<u8>` that the string had been using as its buffer. Since `string` no

longer exists, there's no need for the bytes to continue to be well-formed UTF-8, and the caller is free to modify the `Vec<u8>` as it pleases.

## Producing Text from UTF-8 Data

If you have a block of bytes that you believe contains UTF-8 data, you have a few options for converting them into `String`s or slices, depending on how you want to handle errors:

`str::from_utf8(byte_slice)`

Takes a `&[u8]` slice of bytes and returns a `Result`: either `Ok(&str)` if `byte_slice` contains well-formed UTF-8 or an error otherwise.

`String::from_utf8(vec)`

Tries to construct a string from a `Vec<u8>` passed by value. If `vec` holds well-formed UTF-8, `from_utf8` returns `Ok(string)`, where `string` has taken ownership of `vec` for use as its buffer. No heap allocation or copying of the text takes place.

If the bytes are not valid UTF-8, this returns `Err(e)`, where `e` is a `FromUtf8Error` error value. The call `e.into_bytes()` gives you back the original vector `vec`, so it is not lost when the conversion fails:

```
let good_utf8: Vec<u8> = vec![0xe9, 0x8c, 0x86];
assert_eq!(String::from_utf8(good_utf8).ok(), Some("錆
".to_string()));

let bad_utf8: Vec<u8> = vec![0x9f, 0xf0, 0xa6, 0x80];
let result = String::from_utf8(bad_utf8);
assert!(result.is_err());
// Since String::from_utf8 failed, it didn't consume the
original
```

```
    // vector, and the error value hands it back to us unharmed.
    assert_eq!(
        result.unwrap_err().into_bytes(),
        vec![0x9f, 0xf0, 0xa6, 0x80],
    );
```

`String::from_utf8_lossy(byte_slice)`

Tries to construct a `String` or `&str` from a `&[u8]` shared slice of bytes. This conversion always succeeds, replacing any ill-formed UTF-8 with Unicode replacement characters. The return value is a `Cow<str>` that either borrows a `&str` directly from `byte_slice` if it contains well-formed UTF-8 or owns a freshly allocated `String` with replacement characters substituted for the ill-formed bytes. Hence, when `byte_slice` is well-formed, no heap allocation or copying takes place. We discuss `Cow<str>` in detail in "Putting Off Allocation".

`String::from_utf8_unchecked(vec)`

If you know for a fact that your `Vec<u8>` contains well-formed UTF-8, then you can call this unsafe function. This simply wraps `vec` up as a `String` and returns it, without examining the bytes at all.

All of Rust's string methods assume that they always operate on valid UTF-8. If you pass ill-formed UTF-8 to this function, producing an invalid `String`, those methods might return nonsense, crash, or worse. Rust makes no promises. Accordingly, the standard library declares this as an `unsafe fn`. It can only be called inside an `unsafe` block. If you use it, the responsibility for passing it well-formed UTF-8 is yours.

`str::from_utf8_unchecked(byte_slice)`

Similarly, this takes a `&[u8]` and returns it as a `&str`, without checking to see if it holds well-formed UTF-8. As with `String::from_utf8_unchecked`, you are responsible for making sure this is safe.

## Putting Off Allocation

Suppose you want your program to greet the user. On Unix, you could write:

```
fn get_name() -> String {
    std::env::var("USER")  // Windows uses "USERNAME"
        .unwrap_or("whoever you are".to_string())
}

println!("Greetings, {}!", get_name());
```

For Unix users, this greets them by username. For Windows users and the tragically unnamed, it provides alternative stock text.

The `std::env::var` function returns a `String`—and has good reasons to do so that we won't go into here. But that means the alternative stock text must also be returned as a `String`. This is disappointing: when `get_name` returns a static string, no allocation should be necessary at all.

The problem is that sometimes the return value of `get_name` should be an owned `String`, sometimes it should be a `&'static str`, and we can't know which one it'll be until we run the program. This dynamic character is the hint to consider using `std::borrow::Cow`, the clone-on-write type that can hold either owned or borrowed data.

As explained in "Borrow and ToOwned at Work: The Humble Cow", `Cow<'a, T>` is an enum with two variants: `Owned` and `Borrowed`. `Borrowed` holds a reference `&'a T`, and `Owned` holds the owning version of `&T`: `String` for `&str`, `Vec<i32>` for `&[i32]`, and so on. Whether `Owned` or `Borrowed`, a `Cow<'a, T>` can always produce a `&T`

for you. In fact, `Cow<'a, T>` dereferences to `&T`, behaving as a kind of smart pointer.

Changing `get_name` to return a `Cow` results in the following:

```
use std::borrow::Cow;

fn get_name() -> Cow<'static, str> {
    match std::env::var("USER").ok() {
        Some(v) => Cow::Owned(v),
        None => Cow::Borrowed("whoever you are"),
    }
}
```

If this succeeds in reading the `"USER"` environment variable, the `Some(v)` arm of the `match` returns the resulting `String` as a `Cow::Owned`. If it fails, the `None` arm returns its static `&str` as a `Cow::Borrowed`. The caller can remain unchanged:

```
println!("Greetings, {}!", get_name());
```

As long as `T` implements the `std::fmt::Display` trait, displaying a `Cow<'a, T>` produces the same results as displaying a `T`.

`Cow` is also useful when you may or may not need to modify some text you've borrowed. When no changes are necessary, you can continue to borrow it. But the namesake clone-on-write behavior of `Cow` can give you an owned, mutable copy of the value on demand. `Cow`'s `to_mut` method makes sure the `Cow` is `Cow::Owned`, applying the value's `ToOwned` implementation if necessary, and then returns a mutable reference to the value.

So if you find that some of your users, but not all, have titles by which they would prefer to be addressed, you can say:

```
fn get_title() -> Option<&'static str> { ... }

let mut name = get_name();
if let Some(title) = get_title() {
```

```
        name.to_mut().push_str(", ");
        name.to_mut().push_str(title);
    }

    println!("Greetings, {name}!");
```

This might produce output like the following:

```
$ cargo run
Greetings, jimb, Esq.!
$
```

What's nice here is that if `get_name()` returns a static string and `get_title` returns `None`, the `Cow` simply carries the static string all the way through to the `println!`. You've managed to put off allocation unless it's really necessary, while still writing straightforward code.

Since `Cow` is frequently used for strings, the standard library has some special support for `Cow<'a, str>`. It provides `From` and `Into` conversions from both `String` and `&str`, so you can write `get_name` more tersely:

```
fn get_name() -> Cow<'static, str> {
    std::env::var("USER")
        .map(|v| v.into())
        .unwrap_or("whoever you are".into())
}
```

`Cow<'a, str>` also implements `std::ops::Add` and `std::ops::AddAssign`, so to add the title to the name, you could write:

```
if let Some(title) = get_title() {
    name += ", ";
    name += title;
}
```

Or, since a `String` can be a `write!` macro's destination:

```
use std::fmt::Write;

if let Some(title) = get_title() {
    write!(name.to_mut(), ", {title}").unwrap();
}
```

As before, no allocation occurs until you try to modify the `Cow`. Keep in mind that not every `Cow<..., str>` must be `'static`: you can use `Cow` to borrow previously computed text until the moment a copy becomes necessary.

### Strings as Generic Collections

`String` implements both `std::default::Default` and `std::iter::Extend`: `default` returns an empty string, and `extend` can append characters, string slices, `Cow<..., str>`s, or strings to the end of a string. This is the same combination of traits implemented by Rust's other collection types like `Vec` and `HashMap` for generic construction patterns such as `collect` and `partition`.

The `&str` type also implements `Default`, returning an empty slice. This is handy in some corner cases; for example, it lets you derive `Default` for structures containing string slices.

## Formatting Values

Throughout the book, we've been using text formatting macros like `println!`:

```
println!(
    "{:.3}µs: relocated {} at {:#x} to {:#x}, {} bytes",
    0.84391, "object", 140737488346304_usize, 6299664_usize, 64,
);
```

That call produces the following output:

```
0.844µs: relocated object at 0x7fffffffdcc0 to 0x602010, 64 bytes
```

The format string serves as a template for the output: each `{...}` in the template gets replaced by the formatted form of one of the following arguments. The format string must be a constant so that Rust can check it against the types of the arguments at compile time. Each argument must be used; Rust reports a compile-time error otherwise.

Several standard library features share this little language for formatting strings:

- The `format!` macro uses it to build `String`s.
- The `println!` and `print!` macros write formatted text to the standard output stream.
- The `writeln!` and `write!` macros write it to a designated output stream.
- The `panic!` macro uses it to build an (ideally informative) expression of terminal dismay.

Rust's formatting facilities are designed to be open-ended. You can extend these macros to support your own types by implementing the `std::fmt` module's formatting traits. And you can use the `format_args!` macro and the `std::fmt::Arguments` type to make your own functions and macros support the formatting language.

Formatting macros always borrow shared references to their arguments; they never take ownership of them or mutate them.

The template's `{...}` forms are called *format parameters* and have the form `{which:how}`. Both parts are optional; `{}` is frequently used.

The *`which`* value selects what should take the parameter's place. You can select individual identifiers from the environment, or arguments following the template by index or by name. Parameters with no *`which`* value are simply paired with arguments from left to right.

The *`how`* value says how the argument should be formatted: how much padding, to which precision, in which numeric radix, and so on. If *`how`* is

present, the colon before it is required. Table 17-4 presents some examples.

*Table 17-4. Formatted string examples*

| Format string | Argument list | Result |
|---|---|---|
| `"number of {}: {}"` | `"elephants", 19` | `"number of elephant s: 19"` |
| `"from {1} to {0}"` | `"the grave", "the cr adle"` | `"from the cradle to the grave"` |
| `"v = {:?}"` | `vec![0,1,2,5,12,29]` | `"v = [0, 1, 2, 5, 1 2, 29]"` |
| `"name = {:?}"` | `"Nemo"` | `"name = \"Nemo\""` |
| `"{:8.2} km/s"` | `11.186` | `"   11.19 km/s"` |
| `"{:11} {:02x} {:02 x}"` | `"adc #42", 105, 42` | `"adc #42     69 2a"` |
| `"{1:02x} {2:02x} {0}"` | `"adc #42", 105, 42` | `"69 2a  adc #42"` |
| `"{lsb:02x} {msb:02 x}  {insn}"` | `insn="adc #42", lsb= 105, msb=42` | `"69 2a  adc #42"` |
| `"{:02?}"` | `[110, 11, 9]` | `"[110, 11, 09]"` |
| `"{:02x?}"` | `[110, 11, 9]` | `"[6e, 0b, 09]"` |

If you want to include `{` or `}` characters in your output, double the characters in the template:

```
assert_eq!(
    format!("{{a, c}} ⊂ {{a, b, c}}"),
    "{a, c} ⊂ {a, b, c}",
);
```

## Formatting Text Values

When formatting a textual type like `&str` or `String` (`char` is treated like a single-character string), the *`how`* value of a parameter has several parts, all optional:

*Text length limit*

Rust truncates your argument if it is longer than this. If you specify no limit, Rust uses the full text.

*Minimum field width*

After any truncation, if your argument is shorter than this, Rust pads it on the right (by default) with spaces (by default) to make a field of this width. If omitted, Rust doesn't pad your argument.

*Alignment*

If your argument needs to be padded to meet the minimum field width, this says where your text should be placed within the field. <, ^, and > put your text at the start, middle, and end, respectively.

*Padding character to use in this padding process*

If omitted, Rust uses spaces. If you specify the padding character, you must also specify the alignment.

Table 17-5 contains some examples showing how to write things out and their effects. All are using the same eight-character argument, `"bookends"`.

*Table 17-5. Format specifiers for text*

| Features in use | Format string | Result |
|---|---|---|
| Default | `"{}"` | `"bookends"` |
| Minimum field width | `"{:4}"` | `"bookends"` |
| | `"{:12}"` | `"bookends    "` |
| Text length limit | `"{:.4}"` | `"book"` |
| | `"{:.12}"` | `"bookends"` |
| Field width, length limit | `"{:12.20}"` | `"bookends    "` |
| | `"{:4.20}"` | `"bookends"` |
| | `"{:4.6}"` | `"booken"` |
| | `"{:6.4}"` | `"book  "` |
| Aligned left, width | `"{:<12}"` | `"bookends    "` |
| Centered, width | `"{:^12}"` | `"  bookends  "` |
| Aligned right, width | `"{:>12}"` | `"    bookends"` |
| Pad with `'='`, centered, width | `"{:=^12}"` | `"==bookends=="` |
| Pad `'*'`, aligned right, width, limit | `"{:*>12.4}"` | `"********book"` |

Rust's formatter has a naïve understanding of width: it assumes each character occupies one column, with no regard for combining characters, half-width katakana, zero-width spaces, or the other messy realities of Unicode. For example:

```
assert_eq!(format!("{:4}", "th\u{e9}"),   "th\u{e9} ");
assert_eq!(format!("{:4}", "the\u{301}"), "the\u{301}");
```

Although Unicode says these strings are both equivalent to `"thé"`, Rust's formatter doesn't know that characters like `'\u{301}'`, COMBINING ACUTE ACCENT, need special treatment. It pads the first string correctly but assumes the second is four columns wide and adds no padding. Although it's easy to see how Rust could improve in this specific case, true multilingual text formatting for all of Unicode's scripts is a monumental task, best handled by relying on your platform's user interface toolkits, or perhaps by generating HTML and CSS and making a web browser sort it all out. There is a popular crate, `unicode-width`, that handles some aspects of this.

Along with `&str` and `String`, you can also pass formatting macros smart pointer types with textual referents, like `Rc<String>` or `Cow<'a, str>`, without ceremony.

Since filename paths are not necessarily well-formed UTF-8, `std::path::Path` isn't quite a textual type; you can't pass a `std::path::Path` directly to a formatting macro. However, a `Path`'s `display` method returns a value you can format that sorts things out in a platform-appropriate way:

```
println!("processing file: {}", path.display());
```

## Formatting Numbers

When the formatting argument has a numeric type like `usize` or `f64`, the parameter's *`how`* value has the following parts, all optional:

- A *padding* and *alignment*, which work as they do with textual types.
- A + character, requesting that the number's sign always be shown, even when the argument is positive.

- A `#` character, requesting an explicit radix prefix like `0x` or `0b`. See the "notation" bullet point that concludes this list.
- A `0` character, requesting that the minimum field width be satisfied by including leading zeros in the number, instead of the usual padding approach.
- A *minimum field width*. If the formatted number is not at least this wide, Rust pads it on the left (by default) with spaces (by default) to make a field of the given width.
- A *precision* for floating-point arguments, indicating how many digits Rust should include after the decimal point. Rust rounds or zero-extends as necessary to produce exactly this many fractional digits. If the precision is omitted, Rust tries to accurately represent the value using as few digits as possible. For arguments of integer type, the precision is ignored.
- A *notation*. For integer types, this can be `b` for binary, `o` for octal, or `x` or `X` for hexadecimal with lower- or uppercase letters. If you included the `#` character, these include an explicit Rust-style radix prefix, `0b`, `0o`, `0x`, or `0X`. For floating-point types, a radix of `e` or `E` requests scientific notation, with a normalized coefficient, using `e` or `E` for the exponent. If you don't specify any notation, Rust formats numbers in decimal.

Table 17-6 shows some examples of formatting the `i32` value `1234`.

*Table 17-6. Format specifiers for integers*

| Features in use | Format string | Result |
|---|---|---|
| Default | `"{}"` | `"1234"` |
| Forced sign | `"{:+}"` | `"+1234"` |
| Minimum field width | `"{:12}"` | `"        1234"` |
| | `"{:2}"` | `"1234"` |
| Sign, width | `"{:+12}"` | `"       +1234"` |
| Leading zeros, width | `"{:012}"` | `"000000001234"` |
| Sign, zeros, width | `"{:+012}"` | `"+00000001234"` |
| Aligned left, width | `"{:<12}"` | `"1234        "` |
| Centered, width | `"{:^12}"` | `"    1234    "` |
| Aligned right, width | `"{:>12}"` | `"        1234"` |
| Aligned left, sign, width | `"{:<+12}"` | `"+1234       "` |
| Centered, sign, width | `"{:^+12}"` | `"   +1234    "` |
| Aligned right, sign, width | `"{:>+12}"` | `"       +1234"` |
| Padded with `'='`, centered, width | `"{:=^12}"` | `"====1234====="` |
| Binary notation | `"{:b}"` | `"10011010010"` |
| Width, octal notation | `"{:12o}"` | `"        2322"` |

| Features in use | Format string | Result |
|---|---|---|
| Sign, width, hexadecimal notation | `"{:+12x}"` | `"          +4d2"` |
| Sign, width, hex with capital digits | `"{:+12X}"` | `"          +4D2"` |
| Sign, explicit radix prefix, width, hex | `"{:+#12x}"` | `"        +0x4d2"` |
| Sign, radix, zeros, width, hex | `"{:+#012x}"` | `"+0x0000004d2"` |
|  | `"{:+#06x}"` | `"+0x4d2"` |

As the previous two examples show, the minimum field width applies to the entire number, sign, radix prefix, and all. Negative numbers always include their sign. The results are like those shown in the “forced sign” examples. When you request leading zeros, alignment and padding characters are simply ignored, since the zeros expand the number to fill the entire field.

Using the argument `1234.5678`, we can show effects specific to floating-point types (Table 17-7).

*Table 17-7. Format specifiers for floating-point numbers*

| Features in use | Format string | Result |
|---|---|---|
| Default | `"{}"` | `"1234.5678"` |
| Precision | `"{:.2}"` | `"1234.57"` |
| | `"{:.6}"` | `"1234.567800"` |
| Minimum field width | `"{:12}"` | `"   1234.5678"` |
| Minimum, precision | `"{:12.2}"` | `"     1234.57"` |
| | `"{:12.6}"` | `" 1234.567800"` |
| Leading zeros, minimum, precision | `"{:012.6}"` | `"01234.567800"` |
| Scientific | `"{:e}"` | `"1.2345678e3"` |
| Scientific, precision | `"{:.3e}"` | `"1.235e3"` |
| Scientific, minimum, precision | `"{:12.3e}"` | `"     1.235e3"` |
| | `"{:12.3E}"` | `"     1.235E3"` |

## Formatting Other Types

Beyond strings and numbers, you can format several other standard library types:

- Error types can all be formatted directly, making it easy to include them in error messages. Every error type should implement the `std::error::Error` trait, which extends the default formatting trait `std::fmt::Display`. As a consequence, any type that implements `Error` is ready to format.

- You can format network address types like `std::net::IpAddr` and `std::net::SocketAddr`.
- The Boolean `true` and `false` values can be formatted, although these are usually not the best strings to present directly to end users.

You should use the same sorts of format parameters that you would for strings. Length limit, field width, and alignment controls work as expected.

## Formatting Values for Debugging

To help with debugging and logging, the `{:?}` parameter formats any public type in the Rust standard library in a helpful way for programmers. You can use this to inspect vectors, slices, tuples, hash tables, threads, and hundreds of other types.

For example, you can write the following:

```
use std::collections::HashMap;
let mut map = HashMap::new();
map.insert("Portland", (45.5237606,-122.6819273));
map.insert("Taipei",   (25.0375167, 121.5637));
println!("{map:?}");
```

This prints:

```
{"Taipei": (25.0375167, 121.5637), "Portland": (45.5237606,
-122.6819273)}
```

The `HashMap` and `(f64, f64)` types already know how to format themselves, with no effort required on your part.

If you include the `#` character in the format parameter, Rust will pretty-print the value. Changing this code to say `println!("{map:#?}")` leads to this output:

```
{
    "Taipei": (
```

```
        25.0375167,
        121.5637,
    ),
    "Portland": (
        45.5237606,
        -122.6819273,
    ),
}
```

These exact forms aren't guaranteed and do sometimes change from one Rust release to the next. Debugging formatting usually prints numbers in decimal, but you can put an `x` or `X` before the question mark to request hexadecimal instead. Leading zero and field width syntax is also respected. For example, you can write:

```
println!("ordinary: {:02?}",  [9, 15, 240]);
println!("hex:      {:02x?}", [9, 15, 240]);
```

This prints:

```
ordinary: [09, 15, 240]
hex:      [09, 0f, f0]
```

You can use the `#[derive(Debug)]` syntax to make your own types work with `{:?}`:

```
#[derive(Copy, Clone, Debug)]
struct Complex {
    re: f64,
    im: f64,
}
```

With this definition in place, we can use a `{:?}` format to print `Complex` values:

```
let third = Complex { re: -0.5, im: 3f64.sqrt() / 2.0 };
println!("{third:?}");
```

This prints:

```
Complex { re: -0.5, im: 0.8660254037844386 }
```

This is fine for debugging, but it might be nice if `{}` could print them in a more traditional form, like `-0.5 + 0.8660254037844386i`. In "Formatting Your Own Types", we'll show how to do exactly that.

## Formatting Pointers for Debugging

Normally, if you pass any sort of pointer to a formatting macro—a reference, a `Box`, an `Rc`—the macro simply follows the pointer and formats its referent; the pointer itself is not of interest. But when you're debugging, it's sometimes helpful to see the pointer: an address can serve as a rough "name" for an individual value, which can be illuminating when examining structures with cycles or sharing.

The `{:p}` notation formats references, boxes, and other pointer-like types as addresses:

```
use std::rc::Rc;
let original = Rc::new("mazurka".to_string());
let cloned = original.clone();
let impostor = Rc::new("mazurka".to_string());
println!("text:     {original}, {cloned}, {impostor}");
println!("pointers: {original:p}, {cloned:p}, {impostor:p}");
```

This code prints:

```
text:     mazurka, mazurka, mazurka
pointers: 0x7f99af80e000, 0x7f99af80e000, 0x7f99af80e030
```

Of course, the specific pointer values will vary from run to run, but even so, comparing the addresses makes it clear that the first two are references to the same `String`, whereas the third points to a distinct value. Addresses do tend to look like hexadecimal soup, so more refined visualizations can be worthwhile, but the `{:p}` style can still be an effective quick-and-dirty solution.

## Referring to Arguments by Index or Name

A format parameter can explicitly select which argument it uses. For example:

```
assert_eq!(
    format!("{1},{0},{2}", "zeroth", "first", "second"),
    "first,zeroth,second",
);
```

You can include format parameters after a colon:

```
assert_eq!(
    format!("{2:#06x},{1:b},{0:=>10}", "first", 10, 100),
    "0x0064,1010,=====first",
);
```

You can also select arguments by name:

```
assert_eq!(
    format!(
        "{description:.<25}{quantity:2} @ {price:5.2}",
        price = 4.25,
        quantity = 3,
        description = "Maple Turmeric Latte",
    ),
    "Maple Turmeric Latte..... 3 @  4.25",
);
```

But that named-argument syntax is not often used, since format strings can just as easily refer to variables in the enclosing scope:

```
let (quantity, description, price) = (2, "Amaretto Chai Breve",
4.75);
assert_eq!(
    format!("{description:.<25}{quantity:2} @ {price:5.2}"),
    "Amaretto Chai Breve...... 2 @  4.75",
);
```

You can mix indexed, named, and positional (that is, no index or name) parameters together in a single formatting macro use. The positional

parameters are paired with arguments from left to right as if the indexed and named parameters weren't there:

```
assert_eq!(
    format!(
        "{mode} {2} {} {}",
        "people", "eater", "purple", mode = "flying",
    ),
    "flying purple people eater",
);
```

Named arguments must appear at the end of the list.

## Dynamic Widths and Precisions

A parameter's minimum field width, text length limit, and numeric precision need not always be fixed values; you can choose them at run time.

We've been looking at cases like this expression, which gives you the string `content` right-justified in a field 20 characters wide:

```
format!("{content:>20}")
```

But if you'd like to choose the field width at run time, you can write:

```
format!("{content:>0$}", get_width())
```

Writing `0$` for the minimum field width tells `format!` to use the value of the first argument as the width. The cited argument must be a `usize`. You can also refer to the argument by name:

```
format!("{content:>width$}", width = get_width())
```

The same approach works for the text length limit as well:

```
format!("{content:>width$.limit$}", width = get_width(), limit =
get_limit())
```

In place of the text length limit or floating-point precision, you can also write `*`, which says to take the next positional argument as the precision. The following clips `content` to at most `get_limit()` characters:

```
format!("{content:.*}", get_limit())
```

The argument taken as the precision must be a `usize`. There is no corresponding syntax for the field width.

## Formatting Your Own Types

The formatting macros use a set of traits defined in the `std::fmt` module to convert values to text. You can make Rust's formatting macros format your own types by implementing one or more of these traits yourself. The notation of a format specifier indicates which trait its argument's type must implement, as illustrated in Table 17-8.

*Table 17-8. Format specifier notation*

| Notation | Example | Trait | Purpose |
|---|---|---|---|
| none | `{}` | `std::fmt::Display` | Text, numbers, errors: the catchall trait |
| `b` | `{bits:#b}` | `std::fmt::Binary` | Numbers in binary |
| `o` | `{:#5o}` | `std::fmt::Octal` | Numbers in octal |
| `x` | `{:4x}` | `std::fmt::LowerHex` | Numbers in hexadecimal, lowercase digits |
| `X` | `{:016X}` | `std::fmt::UpperHex` | Numbers in hexadecimal, uppercase digits |
| `e` | `{:.3e}` | `std::fmt::LowerExp` | Floating-point numbers in scientific notation |
| `E` | `{:.3E}` | `std::fmt::UpperExp` | Same, uppercase `E` |
| `?` | `{:#?}` | `std::fmt::Debug` | Debugging view, for developers |
| `p` | `{:p}` | `std::fmt::Pointer` | Pointer as address, for developers |

When you put the `#[derive(Debug)]` attribute on a type definition so that you can use the `{:?}` format parameter, you are simply asking Rust to

implement the `std::fmt::Debug` trait for you.

The formatting traits all have the same structure, differing only in their names. We'll use `std::fmt::Display` as a representative:

```
trait Display {
    fn fmt(&self, dest: &mut std::fmt::Formatter) ->
std::fmt::Result;
}
```

The `fmt` method's job is to produce a properly formatted representation of `self` and write its characters to `dest`. In addition to serving as an output stream, the `dest` argument also carries details parsed from the format parameter, like the alignment and minimum field width. For example, earlier in this chapter we suggested that it would be nice if `Complex` values printed themselves in the usual `a + bi` form. Here's a `Display` implementation that does that:

```
use std::fmt;

impl fmt::Display for Complex {
    fn fmt(&self, dest: &mut fmt::Formatter) -> fmt::Result {
        let im_sign = if self.im < 0.0 { '-' } else { '+' };
        write!(dest, "{} {im_sign} {}i", self.re, self.im.abs())
    }
}
```

This takes advantage of the fact that `Formatter` is itself an output stream, so the `write!` macro can do most of the work for us. With this implementation in place, we can write the following:

```
let one_twenty = Complex { re: -0.5, im: 0.866 };
assert_eq!(format!("{one_twenty}"), "-0.5 + 0.866i");

let two_forty = Complex { re: -0.5, im: -0.866 };
assert_eq!(format!("{two_forty}"), "-0.5 - 0.866i");
```

It's sometimes helpful to display complex numbers in polar form: if you imagine a line drawn on the complex plane from the origin to the number,

the polar form gives the line's length, and its clockwise angle to the positive x-axis.

The # character in a format parameter typically selects some alternate display form; the `Display` implementation could treat it as a request to use polar form:

```
impl fmt::Display for Complex {
    fn fmt(&self, dest: &mut fmt::Formatter) -> fmt::Result {
        let (re, im) = (self.re, self.im);
        if dest.alternate() {
            let abs = re.hypot(im);
            let angle = im.atan2(re) / std::f64::consts::PI *
180.0;
            write!(dest, "{abs} ∠ {angle}°")
        } else {
            let im_sign = if im < 0.0 { '-' } else { '+' };
            write!(dest, "{re} {im_sign} {}i", im.abs())
        }
    }
}
```

Using this implementation:

```
let ninety = Complex { re: 0.0, im: 2.0 };
assert_eq!(format!("{ninety}"), "0 + 2i");
assert_eq!(format!("{ninety:#}"), "2 ∠ 90°");
```

Although the formatting traits' `fmt` methods return an `fmt::Result` value (a typical module-specific `Result` type), you should propagate failures only from operations on the `Formatter`, as the `fmt::Display` implementation does with its calls to `write!`; your formatting functions must never originate errors themselves. This allows macros like `format!` to simply return a `String` instead of a `Result<String, ...>`, since appending the formatted text to a `String` never fails. It also ensures that any errors you do get from `write!` or `writeln!` reflect real problems from the underlying I/O stream, not formatting issues.

`Formatter` has plenty of other helpful methods, including some for handling structured data like maps, lists, and so on, which we won't cover

here; consult the online documentation for the full details.

## Using the Formatting Language in Your Own Code

You can write your own functions and macros that accept format templates and arguments by using Rust's `format_args!` macro and the `std::fmt::Arguments` type. For example, suppose your program needs to log status messages as it runs, and you'd like to use Rust's text formatting language to produce them.

The following is a start:

```
fn logging_enabled() -> bool { ... }

use std::fs::OpenOptions;
use std::io::Write;

fn write_log_entry(entry: std::fmt::Arguments) {
    if logging_enabled() {
        // Keep things simple for now, and just
        // open the file every time.
        let mut log_file = OpenOptions::new()
            .append(true)
            .create(true)
            .open("log-file-name")
            .expect("failed to open log file");

        log_file
            .write_fmt(entry)
            .expect("failed to write to log");
    }
}
```

You can call `write_log_entry` like so:

```
write_log_entry(format_args!("Hark! {mysterious_value:?}\n"));
```

At compile time, the `format_args!` macro parses the format string and checks it against the arguments' types. At run time, it evaluates the arguments and builds an `Arguments` value carrying all the information

necessary to format the text: a pre-parsed form of the template, along with shared references to the argument values.

Constructing an `Arguments` value is cheap: it's just gathering up some pointers. No formatting work takes place yet, only the collection of the information needed to do so later. This can be important: if logging is not enabled, any time spent converting numbers to decimal, padding values, and so on would be wasted.

The `File` type implements the `std::io::Write` trait, whose `write_fmt` method takes an `Arguments` and does the formatting. It writes the results to the underlying stream. That call to `write_log_entry` isn't pretty. This is where a macro can help:

```
macro_rules! log {  // no ! needed after name in macro
definitions
    ($format:tt $($arg:tt)*) => (
        write_log_entry(format_args!($format $($arg)*))
    )
}
```

We cover macros in detail in Chapter 22. For now, take it on faith that this defines a new `log!` macro that passes its arguments along to `format_args!` and then calls your `write_log_entry` function on the resulting `Arguments` value. The formatting macros like `println!`, `writeln!`, and `format!` are all roughly the same idea.

You can use `log!` like so:

```
log!("O day and night, but this is wondrous strange!
{mysterious_value:?}\n");
```

Ideally, this looks a little better.

## Regular Expressions

The external `regex` crate is Rust's official regular expression library. It provides the usual searching and matching functions, having good support for Unicode. It can also search byte strings. Although it doesn't support some features you'll find in other regular expression packages, like backreferences and look-around patterns, those simplifications allow `regex` to ensure that searches take time linear in the size of the expression and in the length of the text being searched. These guarantees, among others, make `regex` safe to use even with untrusted expressions searching untrusted text.

In this book, we'll provide only an overview of `regex`; you should consult its online documentation for details. Although the `regex` crate is not in `std`, it is maintained by the Rust library team, the same group responsible for `std`.

## Basic Regex Use

A `Regex` value represents a parsed regular expression ready to use. The `Regex::new` constructor tries to parse a `&str` as a regular expression and returns a `Result`:

```
use regex::Regex;  // Cargo.toml: regex = "1.12.3"

// A semver version number, like 0.2.1.
// May contain a pre-release version suffix, like 0.2.1-alpha.
// (No build metadata suffix, for brevity.)
//
// Note use of r"..." raw string syntax, to avoid backslash
blizzard.
let semver = Regex::new(r"(\d+)\.(\d+)\.(\d+)(-[-.
[:alnum:]]*)?")?;

// Simple search, with a Boolean result.
let haystack = r#"regex = "0.2.5""#;
assert!(semver.is_match(haystack));
```

The `Regex::captures` method searches a string for the first match and returns a `regex::Captures` value holding match information for each

group in the expression:

```
// You can retrieve capture groups:
let captures = semver
    .captures(haystack)
    .ok_or("semver regex should have matched")?;
assert_eq!(&captures[0], "0.2.5");
assert_eq!(&captures[1], "0");
assert_eq!(&captures[2], "2");
assert_eq!(&captures[3], "5");
```

Indexing a `Captures` value panics if the requested group didn't match. To test whether a particular group matched, you can call `Captures::get`, which returns an `Option<regex::Match>`. A `Match` value records a single group's match:

```
assert_eq!(captures.get(4), None);
assert_eq!(captures.get(3).unwrap().start(), 13);
assert_eq!(captures.get(3).unwrap().end(), 14);
assert_eq!(captures.get(3).unwrap().as_str(), "5");
```

You can iterate over all the matches in a string:

```
let haystack = "\
    In the beginning, there was 1.0.0. \
    For a while, we used 1.0.1-beta, \
    but in the end, we settled on 1.2.4.";

let matches: Vec<&str> = semver
    .find_iter(haystack)
    .map(|match_| match_.as_str())
    .collect();
assert_eq!(matches, vec!["1.0.0", "1.0.1-beta", "1.2.4"]);
```

The `find_iter` iterator produces a `Match` value for each nonoverlapping match of the expression, working from the start of the string to the end. The `captures_iter` method is similar, but produces `Captures` values recording all capture groups. Searching is slower when capture groups must be reported, so if you don't need them, it's best to use one of the methods that doesn't return them.

## Building Regex Values Lazily

The `Regex::new` constructor can be expensive: constructing a `Regex` for a 1,200-character regular expression can take almost a millisecond on a fast developer machine, and even a trivial expression takes microseconds. It's best to keep `Regex` construction out of heavy computational loops; instead, you should construct your `Regex` once and then reuse the same one.

The `LazyLock` type provides a nice way to construct static values. The code constructing the value is provided as a closure (run at most once) the first time the value is used:

```
use std::sync::LazyLock;

static SEMVER: LazyLock<Regex> = LazyLock::new(|| {
    Regex::new(r"(\d+)\.(\d+)\.(\d+)(-[-.[:alnum:]]*)?")
        .expect("error parsing regex")
});
```

With this declaration in place, using `SEMVER` is straightforward:

```
for line_result in std::io::stdin().lines() {
    let line = line_result?;
    if let Some(match_) = SEMVER.find(&line) {
        println!("{}", match_.as_str());
    }
}
```

You can put the `static` declaration in a module, or even inside the function that uses the `Regex`, if that's the most appropriate scope. Even if multiple threads of execution try to access the value at nearly the same time, the regular expression is still always compiled only once per program execution.

# Chapter 18. Input and Output

*Doolittle: What concrete evidence do you have that you exist?*

*Bomb #20: Hmmmm... well... I think, therefore I am.*

*Doolittle: That's good. That's very good. But how do you know that anything else exists?*

*Bomb #20: My sensory apparatus reveals it to me.*

*—Dark Star*

Input and output are the limbs that turn the disembodied logic of a program into something that can reach out and interact with the world. Most of the time, that means working with filesystems and network interfaces, but there are more exotic types of I/O, too.

As it often strives to do, Rust's standard library makes the easy cases easy. Reading a UTF-8 formatted text file (or HTML document or CSV or what have you) is as easy as calling `std::fs::read_to_string`:

```
let contents = std::fs::read_to_string("file.txt")
    .expect("Unable to read file");
```

Convenience functions like this make it easy to write lots of programs, but they're all built on top of a relatively simple foundation of two I/O traits: `Read` and `Write`. In this chapter, we'll demonstrate how to use these traits to read and write files and how to work with the filesystem, the terminal, and the network.

## Readers and Writers

*Readers* are values that your program can read bytes from. They implement the `std::io::Read` trait. Examples include:

- Files opened using `std::fs::File::open(filename)`
- `std::net::TcpStream`s, for receiving data over the network
- `std::io::stdin()`, for reading from the process's standard input stream
- `std::io::Cursor<&[u8]>` and `std::io::Cursor<Vec<u8>>` values, which are readers that "read" from a byte array or vector that's already in memory

*Writers* are values that your program can write bytes to. They implement the `std::io::Write` trait. Examples include:

- Files opened using `std::fs::File::create(filename)`
- `std::net::TcpStream`s, for sending data over the network
- `std::io::stdout()` and `std::io:stderr()`, for writing to the terminal
- `Vec<u8>`, a writer whose `write` methods append to the vector
- `std::io::Cursor<Vec<u8>>`, which is similar but lets you both read and write data and seek to different positions within the vector
- `std::io::Cursor<&mut [u8]>`, which is much like `std::io::Cursor<Vec<u8>>`, except that it can't grow the buffer, since it's just a slice of some existing byte array

Since the `Read` and `Write` traits are part of the standard library, they are used throughout the Rust ecosystem, and it's quite common to write generic code that works across a variety of input or output channels. For example, here's a function that copies all bytes from any reader to any writer:

```
use std::io::{self, ErrorKind, Read, Write};

const DEFAULT_BUF_SIZE: usize = 8 * 1024;
```

```
pub fn copy<R, W>(reader: &mut R, writer: &mut W) ->
io::Result<u64>
where
    R: Read + ?Sized,
    W: Write + ?Sized,
{
    let mut buf = [0; DEFAULT_BUF_SIZE];
    let mut written = 0;
    loop {
        let len = match reader.read(&mut buf) {
            Ok(0) => return Ok(written),
            Ok(len) => len,
            Err(ref e) if e.kind() == ErrorKind::Interrupted =>
continue,
            Err(e) => return Err(e),
        };
        writer.write_all(&buf[..len])?;
        written += len as u64;
    }
}
```

This is a simplified implementation of `std::io::copy()` from Rust's standard library. Since it's generic, you can use it to copy data from a `File` to a `TcpStream`, from `Stdin` to an in-memory `Vec<u8>`, etc.

If the error-handling code here is unclear, revisit Chapter 7. We'll be using the `Result` type constantly in the pages ahead; it's important to have a good grasp of how it works.

The `std::io` traits `Read` and `Write`, along with `BufRead` and `Seek`, are so commonly used that there's a `prelude` module containing only those traits:

```
use std::io::prelude::*;
```

You'll see this once or twice in this chapter. We also make a habit of importing the `std::io` module itself:

```
use std::io::{self, ErrorKind, Read, Write};
```

The `self` keyword here declares `io` as an alias to the `std::io` module. That way, `std::io::Result` and `std::io::Error` can be written more concisely as `io::Result` and `io::Error`, and so on.

## Readers

`std::io::Read` has several methods for reading data. All of them take the reader itself by `mut` reference:

`reader.read(&mut buffer)`

Reads some bytes from the data source and stores them in the given `buffer`. The type of the `buffer` argument is `&mut [u8]`. This reads up to `buffer.len()` bytes.

The return type is `io::Result<u64>`, which is a type alias for `Result<u64, io::Error>`. On success, the `u64` value is the number of bytes read—which may be equal to or less than `buffer.len()`, *even if there's more data to come,* at the whim of the data source. `Ok(0)` means there is no more input to read.

On error, `.read()` returns an `io::Error`. This error type has a `.kind()` method that returns an error code of type `io::ErrorKind`, an enum with members like `PermissionDenied` and `ConnectionReset`. Most indicate serious errors that can't be ignored, but one kind of error should be handled specially. `io::ErrorKind::Interrupted` corresponds to the Unix error code `EINTR`, which means the read happened to be interrupted by a signal. Unless the program is designed to do something clever with signals, it should just retry the read. The code for `copy()`, in the preceding section, shows an example of this.

As you can see, the `.read()` method is very low level, even inheriting quirks of the underlying operating system. If you're implementing the `Read` trait for a new type of data source, this gives you a lot of leeway. If you're trying to read some data, it's a pain. Therefore, Rust provides several higher-level convenience methods. All of them have default

implementations in terms of `.read()`. They all handle `ErrorKind::Interrupted`, so you don't have to.

`reader.read_to_end(&mut byte_vec)`

Reads all remaining input from this reader, appending it to `byte_vec`, which is a `Vec<u8>`. Returns an `io::Result<usize>`, the number of bytes read.

There is no limit on the amount of data this method will pile into the vector, so don't use it on an untrusted source. (You can impose a limit using the `.take()` method, described in the next list.)

`reader.read_to_string(&mut string)`

This is the same but appends the data to the given `String`. If the stream isn't valid UTF-8, this returns an `ErrorKind::InvalidData` error.

In some programming languages, byte input and character input are handled by different types. These days, UTF-8 is so dominant that Rust acknowledges this de facto standard and supports UTF-8 everywhere. Other character sets are supported with the open source `encoding` crate.

`reader.read_exact(&mut buf)`

Reads exactly enough data to fill the given buffer. The argument type is `&[u8]`. If the reader runs out of data before reading `buf.len()` bytes, this returns an `ErrorKind::UnexpectedEof` error.

Those are the main methods of the `Read` trait. In addition, there are three adapter methods that take the `reader` by value, transforming it into an iterator or a different reader:

`reader.bytes()`

Returns an iterator over the bytes of the input stream. The item type is `io::Result<u8>`, so an error check is required for every byte. Furthermore, this calls `reader.read()` once per byte, which will be very inefficient if the reader is not buffered.

`reader.chain(reader2)`

Returns a new reader that produces all the input from `reader`, followed by all the input from `reader2`.

`reader.take(n)`

Returns a new reader that reads from the same source as `reader`, but is limited to `n` bytes of input.

There is no method for closing a reader. Readers and writers typically implement `Drop` so that they are closed automatically.

## Buffered Readers

For efficiency, readers and writers can be *buffered*, which simply means they have a chunk of memory (a buffer) that holds some input or output data in memory. This saves on system calls, as shown in Figure 18-1. The application reads data from the `BufReader`, in this example by calling its `.read_line()` method. The `BufReader` in turn gets its input in larger chunks from the operating system.

This picture is not to scale. The actual default size of a `BufReader`'s buffer is several kilobytes, so a single system `read` can serve hundreds of `.read_line()` calls. This matters because system calls are slow.

As Figure 18-1 shows, the operating system has a buffer too, for the same reason: system calls are slow, but reading data from a disk is slower.

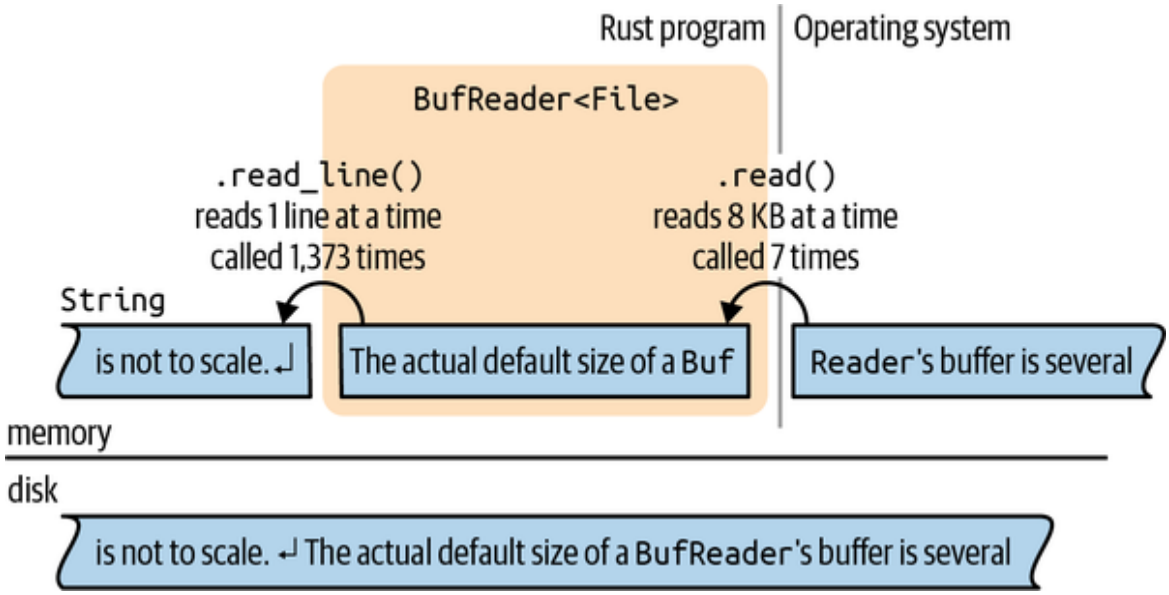


*Figure 18-1. A buffered file reader*

Buffered readers implement both `Read` and a second trait, `BufRead`, which adds the following methods:

`reader.read_line(&mut line)`

Reads a line of text and appends it to `line`, which is a `String`. The newline character `'\n'` at the end of the line is included in `line`. If the input has Windows-style line endings, `"\r\n"`, both characters are included in `line`.

The return value is an `io::Result<usize>`, the number of bytes read, including the line ending, if any.

If the reader is at the end of the input, this leaves `line` unchanged and returns `Ok(0)`.

`reader.lines()`

Returns an iterator over the lines of the input. The item type is `io::Result<String>`. Newline characters are *not* included in the strings. If the input has Windows-style line endings, `"\r\n"`, both characters are stripped.

This method is almost always what you want for text input. The next two sections show some examples of its use.

`reader.read_until(stop_byte, &mut byte_vec)`,
`reader.split(stop_byte)`

These are just like `.read_line()` and `.lines()`, but byte-oriented, producing `Vec<u8>`s instead of `String`s. You choose the delimiter `stop_byte`.

`BufRead` also provides a pair of low-level methods, `.fill_buf()` and `.consume(n)`, for direct access to the reader's internal buffer. For more about these methods, see the online documentation. The next two sections cover buffered readers in more detail.

## Reading Lines

Here is a function that implements the Unix `grep` utility. It searches many lines of text, typically piped in from another command, for a given string:

```
use std::io;
use std::io::prelude::*;

fn grep(target: &str) -> io::Result<()> {
    for line_result in io::stdin().lines() {
        let line = line_result?;
        if line.contains(target) {
            println!("{line}");
        }
    }
    Ok(())
}
```

The function is straightforward: it loops over the lines coming from standard input. Because this iterator produces `Result` values, we use the `?` operator to check for errors.

Suppose we want to take our `grep` program a step further and add support for searching files on disk. We can make this function generic:

```
fn grep<R>(target: &str, reader: R) -> io::Result<()>
where
    R: BufRead,
{
    for line_result in reader.lines() {
        let line = line_result?;
        if line.contains(target) {
            println!("{line}");
        }
    }
    Ok(())
}
```

Now we can pass it either an `StdinLock` or a buffered `File`:

```
grep(&target, io::stdin().lock())?;  // ok

let f = File::open(file)?;
grep(&target, BufReader::new(f))?;  // also ok
```

Note that a `File` is not automatically buffered. `File` implements `Read` but not `BufRead`. However, it's easy to create a buffered reader for a `File`, or any other unbuffered reader. `BufReader::new(reader)` does this. (To set the size of the buffer, use `BufReader::with_capacity(size, reader)`.)

In most languages, files are buffered by default. If you want unbuffered input or output, you have to figure out how to turn buffering off. In Rust, `File` and `BufReader` are two separate library features, because sometimes you want files without buffering, and sometimes you want buffering without files (for example, you may want to buffer input from the network).

The full program, including error handling and some crude argument parsing, is shown here:

```
// grep - Search stdin or some files for lines matching a given
string.

use std::error::Error;
use std::fs::File;
```

```rust
use std::io::prelude::*;
use std::io::{self, BufReader};
use std::path::PathBuf;

fn grep<R>(target: &str, reader: R) -> io::Result<()>
where
    R: BufRead,
{
    for line_result in reader.lines() {
        let line = line_result?;
        if line.contains(target) {
            println!("{line}");
        }
    }
    Ok(())
}

fn grep_main() -> Result<(), Box<dyn Error>> {
    // Get the command-line arguments. The first argument is the
    // string to search for; the rest are filenames.
    let mut args = std::env::args().skip(1);
    let target = match args.next() {
        Some(s) => s,
        None => Err("usage: grep PATTERN FILE...")?,
    };
    let files: Vec<PathBuf> = args.map(PathBuf::from).collect();

    if files.is_empty() {
        grep(&target, io::stdin().lock())?;
    } else {
        for file in files {
            let f = File::open(file)?;
            grep(&target, BufReader::new(f))?;
        }
    }

    Ok(())
}

fn main() {
    let result = grep_main();
    if let Err(err) = result {
        eprintln!("{err}");
        std::process::exit(1);
    }
}
```

## Collecting Lines

Several reader methods, including `.lines()`, return iterators that produce `Result` values. The first time you want to collect all the lines of a file into one big vector, you'll run into a problem getting rid of the `Results`:

```
// ok, but not what you want
let results: Vec<io::Result<String>> = reader.lines().collect();

// error: can't convert collection of Results to Vec<String>
let lines: Vec<String> = reader.lines().collect();
```

The second try doesn't compile: what would happen to the errors? The straightforward solution is to write a `for` loop and check each item for errors:

```
let mut lines = vec![];
for line_result in reader.lines() {
    lines.push(line_result?);
}
```

Not bad; but it would be nice to use `.collect()` here, and it turns out that we can. We just have to know which type to ask for:

```
let lines = reader.lines().collect::<io::Result<Vec<String>>>()?;
```

How does this work? The standard library contains an implementation of `FromIterator` for `Result`—easy to overlook in the documentation—that makes this possible:

```
impl<T, E, C> FromIterator<Result<T, E>> for Result<C, E>
where
    C: FromIterator<T>,
{
    ...
}
```

This requires some careful reading, but it's a nice trick. Assume `C` is any collection type, like `Vec` or `HashSet`.

If we already know how to build a `C` from an iterator of `T` values, we can build a `Result<C, E>` from an iterator producing `Result<T, E>` values. We just need to draw values from the iterator and build the collection from the `Ok` results, but if we ever see an `Err`, stop and pass that along.

In other words, `io::Result<Vec<String>>` is a collection type, so the `.collect()` method can create and populate values of that type.

## Writers

As we've seen, input is mostly done using methods. Output is a bit different. Throughout the book, we've used `println!()` to produce plain-text output:

```
println!("Hello, world!");
println!("The greatest common divisor of {numbers:?} is {d}");
println!();  // print a blank line
```

There's also a `print!()` macro, which does not add a newline character at the end, and `eprintln!` and `eprint!` macros that write to the standard error stream. The formatting codes for all of these are the same as those for the `format!` macro, described in "Formatting Values".

To send output to a writer, use the `write!()` and `writeln!()` macros. They are the same as `print!()` and `println!()`, except for two differences:

```
writeln!(io::stderr(), "error: world not helloable")?;
writeln!(&mut byte_vec, "The greatest common divisor of
{numbers:?} is {d}")?;
```

One difference is that the `write` macros each take an extra first argument, a writer. The other is that they return a `Result`, so errors must be handled. That's why we used the `?` operator at the end of each line.

The `print` macros don't return a `Result`; they simply panic if the write fails. Since they write to the terminal, this is rare. The `Write` trait has these methods:

`writer.write(&buf)`

> Writes some of the bytes in the slice `buf` to the underlying stream. It returns an `io::Result<usize>`. On success, this gives the number of bytes written, which may be less than `buf.len()`, at the whim of the stream.
>
> Like `Reader::read()`, this is a low-level method that you should avoid using directly.

`writer.write_all(&buf)`

> Writes all the bytes in the slice `buf`. Returns `Result<()>`.

`writer.flush()`

> Flushes any buffered data to the underlying stream. Returns `Result<()>`.
>
> Note that while the `println!` and `eprintln!` macros automatically flush the `stdout` and `stderr` stream, the `print!` and `eprint!` macros do not. You may have to call `flush()` manually when using them.

Like readers, writers are closed automatically when they are dropped.

Just as `BufReader::new(reader)` adds a buffer to any reader, `BufWriter::new(writer)` adds a buffer to any writer:

```
let file = File::create("tmp.txt")?;
let writer = BufWriter::new(file);
```

To set the size of the buffer, use `BufWriter::with_capacity(size, writer)`.

When a `BufWriter` is dropped, all remaining buffered data is written to the underlying writer. However, if an error occurs during this write, the error is *ignored*. (Since this happens inside `BufWriter`'s `.drop()` method, there is no useful place to report the error.) To make sure your application notices all output errors, manually `.flush()` buffered writers before dropping them.

## Files

We've already seen two ways to open a file:

`File::open(filename)`

> Opens an existing file for reading. It returns an `io::Result<File>`, and it's an error if the file doesn't exist.

`File::create(filename)`

> Creates a new file for writing. If a file exists with the given filename, it is truncated.

Note that the `File` type is in the filesystem module, `std::fs`, not `std::io`.

When neither of these fits the bill, you can use `OpenOptions` to specify the exact desired behavior:

```
use std::fs::OpenOptions;

let log = OpenOptions::new()
    .append(true)  // if file exists, add to the end
    .open("server.log")?;

let file = OpenOptions::new()
    .write(true)
    .create_new(true)  // fail if file exists
    .open("new_file.txt")?;
```

The methods `.append()`, `.write()`, `.create_new()`, and so on are designed to be chained like this: each one returns `self`. This method-chaining design pattern is common enough to have a name in Rust: it's called a *builder*. `std::process::Command` is another example. For more details on `OpenOptions`, see the online documentation.

Once a `File` has been opened, it behaves like any other reader or writer. You can add a buffer if needed. The `File` will be closed automatically when you drop it.

In real-world code, you might want to consider using the `fs-err` crate. It works just like `std::fs`, except that it produces more detailed error messages. Its API is intentionally identical, so simply listing it as a dependency in your *Cargo.toml* file and changing your code's imports is enough:

```
use fs_err::OpenOptions;

let mut file = OpenOptions::new()
    .write(true)
    .create_new(true)
    .open("new_file.txt")?;
...
```

With `std::fs::OpenOptions`, this might fail with the error `File exists (os error 17)`, which is not very informative. `fs_err::OpenOptions` uses a little extra memory during each operation to produce messages that include more information:

```
failed to open file `new_file.txt`: File exists (os error 17)
```

## Seeking

`File` also implements the `Seek` trait, which means you can hop around within a `File` rather than reading or writing in a single pass from the beginning to the end. `Seek` is defined like this:

```
pub trait Seek {
    fn seek(&mut self, pos: SeekFrom) -> io::Result<u64>;
}

pub enum SeekFrom {
    Start(u64),
    End(i64),
    Current(i64),
}
```

Thanks to the enum, the `seek` method is nicely expressive: use `file.seek(SeekFrom::Start(0))` to rewind to the beginning, use `file.seek(SeekFrom::Current(-8))` to go back a few bytes, and so on. Seeking within a file is slow. Unless the file is stored entirely in memory, you should expect it to take as long as reading several megabytes of data.

## Other Reader and Writer Types

So far, this chapter has used `File` as its example workhorse, but there are many other useful reader and writer types:

`io::stdin()`

: Returns a reader for the standard input stream. Its type is `io::Stdin`. Since this is shared by all threads, each read acquires and releases a mutex.

  `Stdin` has a `.lock()` method that acquires the mutex and returns an `io::StdinLock`, a buffered reader that holds the mutex until it's dropped. Individual operations on the `StdinLock` therefore avoid the mutex overhead.

`io::stdout()`, `io::stderr()`

: Return `Stdout` and `Stderr` writer types for the standard output and standard error streams. These too have mutexes and `.lock()` methods.

`Vec<u8>`

Implements `Write`. Writing to a `Vec<u8>` extends the vector with the new data.

(`String`, however, does *not* implement `Write`. To build a string using `Write`, first write to a `Vec<u8>`, and then use `String::from_utf8(vec)` to convert the vector to a string.)

`Cursor::new(buf)`

Creates a `Cursor`, a buffered reader that reads from `buf`. This is how you create a reader that reads from a `String`. The argument `buf` can be any type that implements `AsRef<[u8]>`, so you can also pass a `&[u8]`, `&str`, or `Vec<u8>`.

`Cursor`s are trivial internally. They have just two fields: `buf` itself and an integer, the offset in `buf` where the next read will start. The position is initially 0.

Cursors implement `Read`, `BufRead`, and `Seek`. If the type of `buf` is `&mut [u8]` or `Vec<u8>`, then the `Cursor` also implements `Write`. Writing to a cursor overwrites bytes in `buf` starting at the current position. If you try to write past the end of a `&mut [u8]`, you'll get a partial write or an `io::Error`. Using a cursor to write past the end of a `Vec<u8>` is fine, though: it grows the vector. `Cursor<&mut [u8]>` and `Cursor<Vec<u8>>` thus implement all four of the `std::io::prelude` traits.

`std::net::TcpStream`

Represents a TCP network connection. Since TCP enables two-way communication, it's both a reader and a writer.

The constructor `TcpStream::connect(("hostname", PORT))` tries to connect to a server and returns an `io::Result<TcpStream>`.

## `std::process::Command`

Supports spawning a child process and piping data to its standard input, like so:

```
use std::process::{Command, Stdio};


let mut child = Command::new("grep")
    .arg("-e")
    .arg("a.*e.*i.*o.*u")
    .stdin(Stdio::piped())
    .spawn()?;


let mut to_child = child.stdin.take().unwrap();
for word in my_words {
    writeln!(to_child, "{word}")?;
}
drop(to_child);  // close grep's stdin, so it will exit
child.wait()?;
```

The type of `child.stdin` is `Option<std::process::ChildStdin>`; here we've used `.stdin(Stdio::piped())` when setting up the child process, so `child.stdin` is definitely populated when `.spawn()` succeeds. If we hadn't, `child.stdin` would be `None`.

`Command` also has similar methods, `.stdout()` and `.stderr()`, which can be used to request readers in `child.stdout` and `child.stderr`.

`std::io::pipe()`

Creates a pipe, a one-way channel for bytes, implemented by the operating system. On Unix, it's a thin wrapper around the `pipe` system call; on Windows, it wraps `CreatePipe`. It returns a `Result<(PipeReader, PipeWriter)>`: on success, a paired reader and writer. Any bytes written to the writer are stored in the pipe until they are consumed by reading from the reader.

`std::process::Command` has enough convenience methods for creating command pipelines that you usually won't need to call `std::io::pipe` yourself. However, we'll show one use for a pipe in Chapter 21.

The `std::io` module offers a few functions that return trivial readers and writers:

`io::sink()`

This is the no-op writer. All the write methods return `Ok`, but the data is discarded.

`io::empty()`

This is the no-op reader. Reading always succeeds, but returns end-of-input.

## Binary Data, Compression, and Serialization

Many open source crates build on the `std::io` framework to offer extra features.

The `byteorder` crate offers `ReadBytesExt` and `WriteBytesExt` traits that add methods to all readers and writers for binary input and output:

```
use byteorder::{LittleEndian, ReadBytesExt, WriteBytesExt};
```

```
let n = reader.read_u32::<LittleEndian>()?;
writer.write_i64::<LittleEndian>(n as i64)?;
```

The `flate2` crate provides adapter methods for reading and writing `gzip`ped data:

```
use flate2::read::GzDecoder;
let file = File::open("access.log.gz")?;
let mut gzip_reader = GzDecoder::new(file);
```

The `serde` crate, and its associated format crates such as `serde_json`, implement serialization and deserialization: they convert back and forth between Rust structs and bytes. We mentioned this once before, in "Traits and Other People's Types". Now we can take a closer look.

Suppose we have some data—the map for a text adventure game—stored in a `HashMap`:

```
type RoomId = String;                          // each room has a
unique name
type RoomExits = Vec<(char, RoomId)>;          // ...and a list of
exits
type RoomMap = HashMap<RoomId, RoomExits>;     // room names and
exits, simple

// Create a simple map.
let mut map = RoomMap::new();
map.insert(
    "Cobble Crawl".to_string(),
    vec![('W', "Debris Room".to_string())],
);
map.insert(
    "Debris Room".to_string(),
    vec![
        ('E', "Cobble Crawl".to_string()),
        ('W', "Sloping Canyon".to_string()),
    ],
);
...
```

Turning this data into JSON for output is a single line of code:

```
serde_json::to_writer(&mut std::io::stdout(), &map)?;
```

Internally, `serde_json::to_writer` uses the `serialize` method of the `serde::Serialize` trait. The library attaches this trait to all types that it knows how to serialize, and that includes all of the types that appear in our data: strings, characters, tuples, vectors, and `HashMap`s.

`serde` is flexible. In this program, the output is JSON data, because we chose the `serde_json` serializer. Other formats, like MessagePack, are also available. Likewise, you could send this output to a file, a `Vec<u8>`, or any other writer. The preceding code prints the data on `stdout`. Here it is:

```
{"Debris Room":[["E","Cobble Crawl"],["W","Sloping
Canyon"]],"Cobble Crawl":
[["W","Debris Room"]]}
```

`serde` also includes support for deriving the two key `serde` traits:

```
#[derive(Serialize, Deserialize)]
struct Player {
    location: String,
    items: Vec<String>,
    health: u32,
}
```

This `#[derive]` attribute can make your compiles take a bit longer, so you need to explicitly ask `serde` to support it when you list it as a dependency in your *Cargo.toml* file. Here's what we used for the preceding code:

```
[dependencies]
serde = { version = "1.0.228", features = ["derive"] }
serde_json = "1.0.150"
```

See the `serde` documentation for more details. In short, the build system autogenerates implementations of `serde::Serialize` and

`serde::Deserialize` for `Player` so that serializing a `Player` value is simple:

```
serde_json::to_writer(&mut std::io::stdout(), &player)?;
```

The output looks like this:

```
{"location":"Cobble Crawl","items":["a wand"],"health":3}
```

# Files and Directories

Now that we've shown how to work with readers and writers, the next few sections cover Rust's features for working with files and directories, which live in the `std::path` and `std::fs` modules. All of these features involve working with filenames, so we'll start with the filename types.

## OsStr and Path

Inconveniently, your operating system does not force filenames to be valid Unicode. Here are two Linux shell commands that create text files. Only the first uses a valid UTF-8 filename:

```
$ echo "hello world" > ô.txt
$ echo "O brave new world, that has such filenames in't" >
$'\xf4'.txt
```

Both commands pass without comment, because the Linux kernel doesn't know UTF-8 from Ogg Vorbis. To the kernel, any string of bytes (excluding null bytes and slashes) is an acceptable filename. It's a similar story on Windows: almost any string of 16-bit "wide characters" is an acceptable filename, even strings that are not valid UTF-16. The same is true of other strings the operating system handles, like command-line arguments and environment variables.

Rust strings are always valid Unicode. Filenames are *almost* always Unicode in practice, but Rust has to cope somehow with the rare case where

they aren't. This is why Rust has `std::ffi::OsStr` and `OsString`.

`OsStr` is a string type that's a superset of UTF-8. Its job is to be able to represent all filenames, command-line arguments, and environment variables on the current system, *whether they're valid Unicode or not.* On Unix, an `OsStr` can hold any sequence of bytes. On Windows, an `OsStr` is stored using an extension of UTF-8 that can encode any sequence of 16-bit values, including unmatched surrogates.

So we have two string types: `str` for actual Unicode strings, and `OsStr` for whatever nonsense your operating system can dish out. We'll introduce one more: `std::path::Path`, for filenames. This one is purely a convenience. `Path` is exactly like `OsStr`, but it adds many handy filename-related methods, which we'll cover in the next section. Use `Path` for both absolute and relative paths. For an individual component of a path, use `OsStr`.

Lastly, for each string type, there's a corresponding *owning* type: a `String` owns a heap-allocated `str`, a `std::ffi::OsString` owns a heap-allocated `OsStr`, and a `std::path::PathBuf` owns a heap-allocated `Path`. Table 18-1 outlines some of the features of each type.

All three of these types implement a common trait, `AsRef<Path>`, so we can easily declare a generic function that accepts "any filename type" as an argument. This uses a technique we showed in "AsRef and AsMut":

```
use std::io;
use std::path::Path;

fn swizzle_file<P>(path_arg: P) -> io::Result<()>
where
    P: AsRef<Path>,
{
    let path = path_arg.as_ref();
    ...
}
```

All the standard functions and methods that take `path` arguments use this technique, so you can freely pass string literals to any of them.

*Table 18-1. Filename types*

| | str | OsStr | Path |
|---|---|---|---|
| Dynamically sized type, always passed by reference | Yes | Yes | Yes |
| Can contain any Unicode text | Yes | Yes | Yes |
| Looks just like UTF-8, normally | Yes | Yes | Yes |
| Can contain non-Unicode data | No | Yes | Yes |
| Text processing methods | Yes | No | No |
| Filename-related methods | No | No | Yes |
| Owned, growable, heap-allocated equivalent | `String` | `OsString` | `PathBuf` |
| Convert to owned type | `.to_string()` | `.to_os_string()` | `.to_path_buf()` |

## Path and PathBuf Methods

`Path` offers the following methods, among others:

`Path::new(str)`

Converts a `&str` or `&OsStr` to a `&Path`. This doesn't copy the string. The new `&Path` points to the same bytes as the original `&str` or `&OsStr`:

```
use std::path::Path;

let home_dir = Path::new("/home/fwolfe");
```

(The similar method `OsStr::new(str)` converts a `&str` to a `&OsStr`.)

`path.parent()`

Returns the path's parent directory, if any. The return type is `Option<&Path>`.

This doesn't copy the path. The parent directory of `path` is always a substring of `path`:

```
assert_eq!(
    Path::new("/home/fwolfe/program.txt").parent(),
    Some(Path::new("/home/fwolfe")),
);
```

`path.file_name()`

Returns the last component of `path`, if any. The return type is `Option<&OsStr>`.

In the typical case, where `path` consists of a directory, then a slash, and then a filename, this returns the filename:

```
use std::ffi::OsStr;

assert_eq!(
```

```
        Path::new("/home/fwolfe/program.txt").file_name(),
        Some(OsStr::new("program.txt")),
    );
```

`path.is_absolute()`, `path.is_relative()`

These tell whether the file is absolute, like the Unix path */usr/bin/advent* or the Windows path *C:\Program Files*, or relative, like *src/main.rs*.

`path1.join(path2)`

Joins two paths, returning a new `PathBuf`:

```
let path1 = Path::new("/usr/share/dict");
assert_eq!(
    path1.join("words"),
    Path::new("/usr/share/dict/words"),
);
```

If `path2` is an absolute path, this just returns a copy of `path2`, so this method can be used to convert any path to an absolute path:

```
let abs_path = std::env::current_dir()?.join(any_path);
```

`path.components()`

Returns an iterator over the components of the given path, from left to right. The item type of this iterator is `std::path::Component`, an enum that can represent all the different pieces that can appear in filenames:

```
pub enum Component<'a> {
    Prefix(PrefixComponent<'a>),  // a drive letter or share
(on Windows)
    RootDir,                      // the root directory, `/`
or `\`
    CurDir,                       // the `.` special directory
    ParentDir,                    // the `..` special
directory
    Normal(&'a OsStr),            // plain file and directory
names
}
```

For example, the Windows path *\\venice\Music\A Love Supreme\04-Psalm.mp3* consists of a `Prefix` representing *\\venice\Music*, followed by a `RootDir`, and then two `Normal` components representing *A Love Supreme* and *04-Psalm.mp3*. For details, see the online documentation.

`path.ancestors()`

Returns an iterator that walks from `path` up to the root. Each item produced is a `Path`: first `path` itself, then its parent, then its grandparent, and so on:

```
let file = Path::new("/home/jimb/calendars/calendar-
18x18.pdf");
assert_eq!(
    file.ancestors().collect::<Vec<_>>(),
    vec![
        Path::new("/home/jimb/calendars/calendar-18x18.pdf"),
```

```
            Path::new("/home/jimb/calendars"),
            Path::new("/home/jimb"),
            Path::new("/home"),
            Path::new("/"),
        ],
    );
```

This is much like calling `parent` repeatedly until it returns `None`. The final item is always a root or prefix path.

These methods work on strings in memory. `Path`s also have some methods that query the filesystem: `.exists()`, `.is_file()`, `.is_dir()`, `.read_dir()`, `.canonicalize()`, and so on. See the online documentation to learn more.

There are three methods for converting `Path`s to strings. Each one allows for the possibility of invalid UTF-8 in the `Path`:

`path.to_str()`

Converts a `Path` to a string, as an `Option<&str>`. If `path` isn't valid UTF-8, this returns `None`:

```
if let Some(file_str) = path.to_str() {
    println!("{file_str}");
}  // ...otherwise skip this weirdly named file
```

`path.to_string_lossy()`

This is basically the same thing, but it manages to return some sort of string in all cases. If `path` isn't valid UTF-8, these methods make a copy, replacing each invalid byte sequence with the Unicode replacement character, U+FFFD (' ').

The return type is `std::borrow::Cow<str>`: an either borrowed or owned string. To get a `String` from this value, use its `.to_owned()` method. (For more about `Cow`, see "Borrow and ToOwned at Work: The Humble Cow".)

`path.display()`

This is for printing paths:

```
println!("Download found. You put it in: {}",
dir_path.display());
```

The value this returns isn't a string, but it implements `std::fmt::Display`, so it can be used with `format!()`, `println!()`, and friends. If the path isn't valid UTF-8, the output may contain the `?` character.

## Filesystem Access Functions

Table 18-2 shows some of the functions in `std::fs` and their approximate equivalents on Unix and Windows. All of these functions return `io::Result` values. They are `Result<()>` unless otherwise noted.

(The number returned by `copy()` is the size of the copied file, in bytes. For creating symbolic links, see "Platform-Specific Features".)

As you can see, Rust strives to provide portable functions that work predictably on Windows as well as macOS, Linux, and other Unix systems.

*Table 18-2. Summary of filesystem access functions*

| | Rust function | Unix | Windows |
|---|---|---|---|
| Creating and deleting | `create_dir(path)` | `mkdir()` | `CreateDirectory()` |
| | `create_dir_all(path)` | like `mkdir -p` | like `mkdir` |
| | `remove_dir(path)` | `rmdir()` | `RemoveDirectory()` |
| | `remove_dir_all(path)` | like `rm -r` | like `rmdir /s` |
| | `remove_file(path)` | `unlink()` | `DeleteFile()` |
| Copying, moving, and linking | `copy(src_path, dest_path)`<br>`  -> Result<u64>` | like `cp -p` | `CopyFileEx()` |
| | `rename(src_path, dest_path)` | `rename()` | `MoveFileEx()` |
| | `hard_link(src_path, dest_path)` | `link()` | `CreateHardLink()` |
| Inspecting | `canonicalize(path)`<br>`  -> Result<PathBuf>` | `realpath()` | `GetFinalPathNameByHandle()` |
| | `metadata(path)`<br>`  -> Result<Metadata>` | `stat()` | `GetFileInformationByHandle()` |
| | `symlink_metadata(path)`<br>`  -> Result<Metadata>` | `lstat()` | `GetFileInformationByHandle()` |
| | `read_dir(path)`<br>`  -> Result<ReadDir>` | `opendir()` | `FindFirstFile()` |

| | Rust function | Unix | Windows |
|---|---|---|---|
| | `read_link(path) -> Result<PathBuf>` | `readlink()` | `FSCTL_GET_REPARSE_POINT` |
| Permissions | `set_permissions(path, perm)` | `chmod()` | `SetFileAttributes()` |

A full tutorial on filesystems is beyond the scope of this book, but if you're curious about any of these functions, you can easily find more about them online. We'll show some examples in the next section.

All of these functions are implemented by calling out to the operating system. For example, `std::fs::canonicalize(path)` does not merely use string processing to eliminate `.` and `..` from the given `path`. It resolves relative paths using the current working directory, and it chases symbolic links. It's an error if the path doesn't exist.

The `Metadata` type that's produced by `std::fs::metadata(path)` and `std::fs::symlink_metadata(path)` contains such information as the file type and size, permissions, and timestamps. As always, consult the documentation for details. As a convenience, the `Path` type has a few of these built in as methods: `path.metadata()`, for example, is the same thing as `std::fs::metadata(path)`.

## Reading Directories

To list the contents of a directory, use `std::fs::read_dir` or, equivalently, the `.read_dir()` method of a `Path`:

```
for entry_result in path.read_dir()? {
    let entry = entry_result?;
    println!("{}", entry.file_name().to_string_lossy());
}
```

Note the two uses of `?` in this code. The first line checks for errors opening the directory. The second line checks for errors reading the next entry. The type of `entry` is `std::fs::DirEntry`, and it's a struct with just a few methods:

`entry.file_name()`

The name of the file or directory, as an `OsString`.

`entry.path()`

This is the same, but with the original path joined to it, producing a new `PathBuf`. If the directory we're listing is `"/home/jimb"`, and `entry.file_name()` is `".emacs"`, then `entry.path()` would return `PathBuf::from("/home/jimb/.emacs")`.

`entry.file_type()`

Returns an `io::Result<FileType>`. `FileType` has `.is_file()`, `.is_dir()`, and `.is_symlink()` methods.

`entry.metadata()`

Gets the rest of the metadata about this entry.

The special directories `.` and `..` are *not* listed when reading a directory. Here's a more substantial example. The following code recursively copies a directory tree from one place to another on disk:

```
use std::fs;
use std::io;
use std::path::Path;

/// Copies the existing directory `src` to the target path `dst`.
fn copy_dir_to(src: &Path, dst: &Path) -> io::Result<()> {
    if !dst.is_dir() {
        fs::create_dir(dst)?;
    }

    for entry_result in src.read_dir()? {
```

```
            let entry = entry_result?;
            let file_type = entry.file_type()?;
            copy_to(&entry.path(), &file_type,
&dst.join(entry.file_name()))?;
        }

        Ok(())
    }
```

A separate function, `copy_to`, copies individual directory entries:

```
/// Copies whatever is at `src` to the target path `dst`.
fn copy_to(src: &Path, src_type: &fs::FileType, dst: &Path) ->
io::Result<()> {
    if src_type.is_file() {
        fs::copy(src, dst)?;
    } else if src_type.is_dir() {
        copy_dir_to(src, dst)?;
    } else {
        return Err(io::Error::other(
            format!("don't know how to copy: {}", src.display()),
        ));
    }
    Ok(())
}
```

## Platform-Specific Features

So far, our `copy_to` function can copy files and directories. Suppose we also want to support symbolic links on Unix.

There is no portable way to create symbolic links that work on both Unix and Windows, but the standard library offers a Unix-specific `symlink` function:

```
use std::os::unix::fs::symlink;
```

With this, our job is easy. We need only add a branch to the `if` expression in `copy_to`:

```
...
} else if src_type.is_symlink() {
```

```
        let target = src.read_link()?;
        symlink(target, dst)?;
    ...
```

This will work as long as we compile our program only for Unix systems, such as Linux and macOS.

The `std::os` module contains various platform-specific features, like `symlink`. The actual body of `std::os` in the standard library looks like this (taking some poetic license):

```
//! OS-specific functionality.

#[cfg(unix)]                    pub mod unix;
#[cfg(windows)]                 pub mod windows;
#[cfg(target_os = "ios")]       pub mod ios;
#[cfg(target_os = "linux")]     pub mod linux;
#[cfg(target_os = "macos")]     pub mod macos;
...
```

The `#[cfg]` attribute indicates conditional compilation: each of these modules exists only on some platforms. This is why our modified program, using `std::os::unix`, will successfully compile only for Unix; on other platforms, `std::os::unix` doesn't exist.

If we want our code to compile on all platforms, with support for symbolic links on Unix, we must use `#[cfg]` in our program as well. In this case, it's easiest to import `symlink` on Unix, while defining our own `symlink` stub on other systems:

```
#[cfg(unix)]
use std::os::unix::fs::symlink;

/// Stub implementation of `symlink` for platforms that don't
provide it.
#[cfg(not(unix))]
fn symlink<P: AsRef<Path>, Q: AsRef<Path>>(
    src: P,
    _dst: Q,
) -> std::io::Result<()> {
    Err(io::Error::other(
```

```
            format!("can't copy symbolic link: {}",
    src.as_ref().display()),
        ))
    }
```

It turns out that `symlink` is something of a special case. Most Unix-specific features are not standalone functions but rather extension traits that add new methods to standard library types. (We covered extension traits in "Traits and Other People's Types".) There's a `prelude` module that can be used to enable all of these extensions at once:

```
use std::os::unix::prelude::*;
```

For example, on Unix, this adds a `.mode()` method to `std::fs::Permissions`, providing access to the underlying `u32` value that represents permissions on Unix. Similarly, it extends `std::fs::Metadata` with accessors for the fields of the underlying `struct stat` value—such as `.uid()`, the user ID of the file's owner.

All told, what's in `std::os` is pretty basic. Much more platform-specific functionality is available via third-party crates, like `winreg` for accessing the Windows registry.

## Networking

A tutorial on networking is well beyond the scope of this book. However, if you already know a bit about network programming, this section will help you get started with networking in Rust.

For low-level networking code, start with the `std::net` module, which provides cross-platform support for TCP and UDP networking. Use the `native_tls` crate for SSL/TLS support.

These modules provide the building blocks for straightforward, blocking input and output over the network. You can write a simple server in a few lines of code, using `std::net` and spawning a thread for each connection.

For example, an “echo” server:

```
use std::net::TcpListener;
use std::{io, thread};

/// Accepts connections forever, spawning a thread for each one.
fn echo_main(addr: &str) -> io::Result<()> {
    let listener = TcpListener::bind(addr)?;
    println!("listening on {addr}");
    loop {
        // Wait for a client to connect.
        let (mut stream, addr) = listener.accept()?;
        println!("connection received from {addr}");

        // Spawn a thread to handle this client.
        let mut write_stream = stream.try_clone()?;
        thread::spawn(move || {
            // Echo everything we receive from `stream` back to
it.
            io::copy(&mut stream, &mut write_stream)
                .expect("error in client thread: ");
            println!("connection closed");
        });
    }
}

fn main() {
    echo_main("127.0.0.1:17007").expect("error: ");
}
```

An echo server simply repeats back everything you send to it. This kind of code is not so different from what you’d write in Java or Python. (We’ll cover `std::thread::spawn()` in the next chapter.)

However, for high-performance servers, you’ll need to use asynchronous input and output. Chapter 20 covers Rust’s support for asynchronous programming.

Higher-level protocols are supported by third-party crates. For example, the `reqwest` crate offers a beautiful API for HTTP clients. Here is a complete command-line program that fetches any document with an `http:` or `https:` URL and dumps it to your terminal.

This code was written using `reqwest = "0.13.4"`, with its `"blocking"` feature enabled. `reqwest` also provides an asynchronous interface:

```
use std::error::Error;
use std::io;

fn http_get_main(url: &str) -> Result<(), Box<dyn Error>> {
    // Send the HTTP request and get a response.
    let mut response = reqwest::blocking::get(url)?;
    if !response.status().is_success() {
        Err(format!("{}", response.status()))?;
    }

    // Read the response body and write it to stdout.
    let stdout = io::stdout();
    io::copy(&mut response, &mut stdout.lock())?;

    Ok(())
}

fn main() {
    let args: Vec<String> = std::env::args().collect();
    if args.len() != 2 {
        eprintln!("usage: http-get URL");
        return;
    }

    if let Err(err) = http_get_main(&args[1]) {
        eprintln!("error: {err}");
    }
}
```

The `actix-web` framework for HTTP servers offers high-level touches such as the `Service` and `Transform` traits, which help you compose an app from pluggable parts. The `websocket` crate implements the WebSocket protocol. And so on. Rust is a young language with a busy open source ecosystem. Support for networking is rapidly expanding.

# Chapter 19. Threads

*In the long run it is not advisable to write large concurrent programs in machine-oriented languages that permit unrestricted use of store locations and their addresses. There is just no way we will be able to make such programs reliable (even with the help of complicated hardware mechanisms).*

—Per Brinch Hansen (1977)

*Patterns for communication are patterns for parallelism.*

—Whit Morriss

If your attitude toward threads has changed over the course of your career, you're not alone. It's a common story.

At first, writing multithreaded code is easy and fun. The tools—locks, queues, and so on—are a snap to pick up and use. There are a lot of pitfalls, it's true, but fortunately you know what they all are, and you are careful not to make mistakes.

At some point, you have to debug someone else's multithreaded code, and you're forced to conclude that *some* people really should not be using these tools.

Then at some point you have to debug your own multithreaded code.

Experience inculcates a healthy skepticism, if not outright cynicism, toward threads generally. This is helped along by the occasional article explaining in mind-numbing detail why some obviously correct locking idiom does not work at all. (It has to do with "the memory model.") But you eventually find one approach to concurrency that you think you can realistically use without constantly making mistakes. You can shoehorn pretty much everything into that idiom, and (if you're *really* good) you learn to say "no" to added complexity.

Of course, there are rather lots of idioms. Approaches that systems programmers commonly use include the following:

- A *background thread* that has a single job and periodically wakes up to do it.
- General-purpose *worker pools* that communicate with clients via *task queues*.
- *Pipelines* where data flows from one thread to the next, with each thread doing a little of the work.
- *Data parallelism*, where it is assumed (rightly or wrongly) that the whole computer will mainly just be doing one large computation, which is therefore split into *n* pieces and run on *n* threads in the hopes of putting all *n* of the machine's cores to work at once.
- *A sea of synchronized objects*, where multiple threads have access to the same data, and races are avoided using ad hoc *locking* schemes based on low-level primitives like mutexes. (Java includes built-in support for this model, which was quite popular during the 1990s and 2000s.)
- *Atomic integer operations* allow multiple cores to communicate by passing information through fields the size of one machine word. (This is even harder to get right than all the others, unless the data being exchanged is literally just integer values. In practice, it's usually pointers.)

In time, you may come to be able to use several of these approaches and combine them safely. You are a master of the art. And things would be great, if only nobody else were ever allowed to modify the system in any way. Programs that use threads well are full of unwritten rules.

Rust offers a better way to use concurrency: not by forcing all programs to adopt a single style (which for systems programmers would be no solution at all), but by supporting multiple styles safely. The unwritten rules are written down—in code—and enforced by the compiler.

You've heard that Rust lets you write safe, fast, concurrent programs. This is the chapter where we show you how it's done. We'll cover three ways to use Rust threads:

- Fork-join parallelism
- Channels
- Shared mutable state

And in the next chapter, we'll expand this view to include *asynchronous code*, a form of lightweight cooperative concurrency that is well-suited for network services. Asynchronous code and threads are distinct approaches to concurrency, but they build on the same foundational Rust concepts. Since threads are more fundamental and a bit simpler, we cover them first.

As you learn about threads in Rust, you're going to use everything you've learned so far about the language. The care Rust takes with references, mutability, and lifetimes is valuable enough in single-threaded programs, but it is in concurrent programming that the true significance of those rules becomes apparent. They make it possible to expand your toolbox, to hack multiple styles of multithreaded code quickly and correctly—without skepticism, without cynicism, without fear.

## Fork-Join Parallelism

The simplest use cases for threads arise when we have several completely independent tasks that we'd like to do at once.

For example, suppose we're doing natural language processing on a large corpus of documents. We could write a loop:

```
fn process_files(filenames: Vec<String>) -> io::Result<()> {
    for document in filenames {
        let text = load(&document)?;  // read source file
        let results = process(text);  // compute statistics
        save(&document, results)?;    // write output file
    }
```

```
        Ok(())
    }
```

The program would run as shown in Figure 19-1.

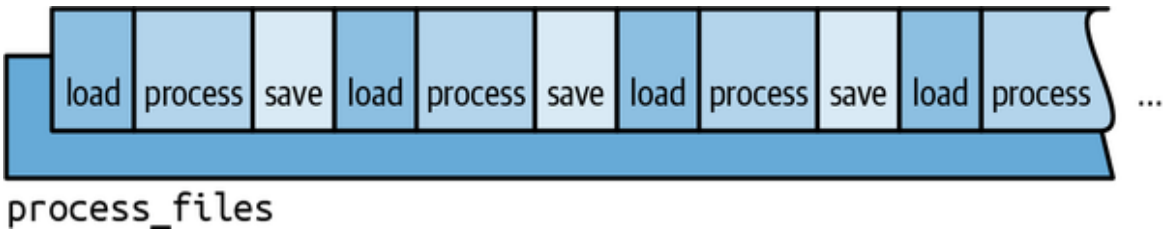


*Figure 19-1. Single-threaded execution of `process_files()`*

Since each document is processed separately, it's relatively easy to speed this task up by splitting the corpus into chunks and processing each chunk on a separate thread, as shown in Figure 19-2.

This pattern is called *fork-join parallelism*. To *fork* is to start a new thread, and to *join* a thread is to wait for it to finish. We've already seen this technique: we used it to speed up the Mandelbrot program in Chapter 2.

Fork-join parallelism is attractive for a few reasons:

- It's dead simple. Fork-join is easy to implement, and Rust makes it easy to get right.
- It avoids bottlenecks. There's no locking of shared resources in fork-join. The only time any thread has to wait for another is at the end. In the meantime, each thread can run freely. This helps keep task-switching overhead low.
- The performance math is straightforward. In the best case, by starting four threads, we can finish our work in a quarter of the time. Figure 19-2 shows one reason we shouldn't expect this ideal speedup: we might not be able to distribute the work evenly across all threads. Another reason for caution is that sometimes fork-join programs must spend some time after the threads join, *combining* the results computed by the threads. That is, isolating the tasks completely may make some extra work. Still, apart from those two

things, any CPU-bound program with isolated units of work can expect a significant boost.

- It's easy to reason about program correctness. A fork-join program is *deterministic* as long as the threads are really isolated, like the compute threads in the Mandelbrot program. The program always produces the same result, regardless of variations in thread speed. It's a concurrency model without race conditions.

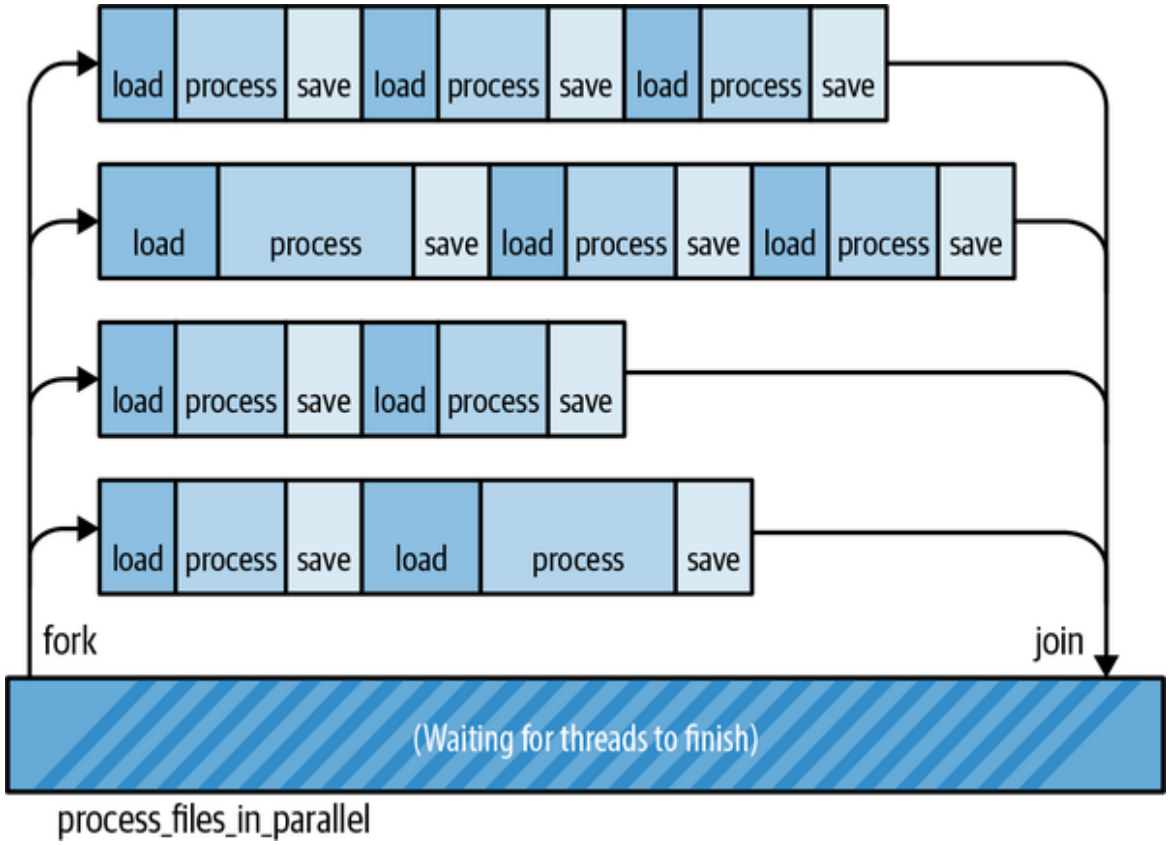


*Figure 19-2. Multithreaded file processing using a fork-join approach*

The main disadvantage of fork-join is that it requires isolated units of work. Later in this chapter, we'll consider some problems that don't split up so cleanly. For now, let's stick with the natural language processing example. We'll show a few ways of applying the fork-join pattern to the `process_files` function.

## spawn and join

The function `std::thread::spawn` starts a new thread:

```
use std::thread;

thread::spawn(|| {
    println!("hello from a child thread");
});
```

It takes one argument, a `FnOnce` closure or function. Rust starts a new thread to run the code of that closure or function. The new thread is a real operating system thread with its own stack, just like threads in C++, C#, and Java. Here's a more substantial example, using `spawn` to implement a parallel version of the `process_files` function from before:

```
use std::{io, thread};

fn process_files_in_parallel(filenames: Vec<String>) ->
io::Result<()> {
    // Divide the work into several chunks.
    const NTHREADS: usize = 8;
    let worklists = split_vec_into_chunks(filenames, NTHREADS);

    // Fork: Spawn a thread to handle each chunk.
    let mut thread_handles = vec![];
    for worklist in worklists {
        thread_handles.push(
            thread::spawn(move || process_files(worklist))
        );
    }

    // Join: Wait for all threads to finish.
    for handle in thread_handles {
        handle.join().unwrap()?;
    }

    Ok(())
}
```

Let's take this function line by line. Our new function has the same type signature as the original `process_files`, making it a handy drop-in replacement:

```
fn process_files_in_parallel(filenames: Vec<String>) ->
io::Result<()> {
```

We use a utility function `split_vec_into_chunks`, not shown here, to divide up the work. The result, `worklists`, is a vector of vectors. It contains eight evenly sized portions of the original vector `filenames`:

```
    // Divide the work into several chunks.
    const NTHREADS: usize = 8;
    let worklists = split_vec_into_chunks(filenames, NTHREADS);
```

We spawn a thread for each `worklist`. Each call to `thread::spawn` returns a value called a `JoinHandle`, which we'll use later. For now, we put all the `JoinHandles` into a vector:

```
    // Fork: Spawn a thread to handle each chunk.
    let mut thread_handles = vec![];
    for worklist in worklists {
        thread_handles.push(
            thread::spawn(move || process_files(worklist))
        );
    }
```

Note how we get the list of filenames into the worker thread:

- `worklist` is defined and populated by the `for` loop, in the parent thread.
- As soon as the `move` closure is created, `worklist` is moved into the closure.
- `spawn` then moves the closure (including the `worklist` vector) over to the new child thread.

These moves are cheap. Like the `Vec<String>` moves we discussed in Chapter 4, the `Strings` are not cloned. In fact, nothing is allocated or freed. The only data moved is the `Vec` itself: three machine words.

Most every thread you create needs both code and data to get started. Rust closures, conveniently, contain whatever code and data you want. Moving on:

```
    // Join: Wait for all threads to finish.
    for handle in thread_handles {
        handle.join().unwrap()?;
    }
```

We use the `.join()` method of the `JoinHandles` we collected earlier to wait for all eight threads to finish. Joining threads is often necessary for correctness, because a Rust program exits as soon as `main` returns, even if other threads are still running. Destructors are not called; the extra threads are just killed. If this isn't what you want, be sure to join any threads you care about before returning from `main`.

If we manage to get through this loop, it means all eight child threads finished successfully. Our function therefore ends by returning `Ok(())`:

```
    Ok(())
}
```

## Error Handling Across Threads

The code we used to join the child threads in our example is trickier than it looks because of error handling. Let's revisit that line of code:

```
handle.join().unwrap()?;
```

The `.join()` method does two neat things for us.

First, `handle.join()` returns a `std::thread::Result` that's an error *if the child thread panicked.* This makes threading in Rust dramatically more robust than in C++. In C++, an out-of-bounds array access is undefined behavior, and there's no protecting the rest of the system from the consequences.

In Rust, panic is safe and per thread. The boundaries between threads serve as a firewall for panic; panic doesn't automatically spread from one thread to the threads that depend on it. Instead, a panic in one thread is reported as an error `Result` in other threads. The program as a whole can easily recover.

In our program, though, we don't attempt any fancy panic handling. Instead, we immediately use `.unwrap()` on this `Result`, asserting that it is an `Ok` result and not an `Err` result. If a child thread *did* panic, then this assertion would fail, so the parent thread would panic too. We're explicitly propagating panic from the child threads to the parent thread.

Second, `handle.join()` passes the return value from the child thread back to the parent thread. The closure we passed to `spawn` has a return type of `io::Result<()>`, because that's what `process_files` returns. This return value isn't discarded. When the child thread is finished, its return value is saved, and `JoinHandle::join()` transfers that value back to the parent thread.

The full type that's returned by `handle.join()` in this program is `std::thread::Result<std::io::Result<()>>`. The `thread::Result` is part of the `spawn`/`join` API; the `io::Result` is part of our app.

In our case, after unwrapping the `thread::Result`, we use the `?` operator on the `io::Result`, explicitly propagating I/O errors from the child threads to the parent thread.

All of this may seem rather intricate. But consider that it's just one line of code and then compare this with other languages. The default behavior in Java and C# is for exceptions in child threads to be dumped to the terminal and then forgotten.

In C++, the default is to abort the process. In Rust, errors are `Result` values (data) instead of exceptions (control flow). They're delivered across threads just like any other value. Any time you use low-level threading

APIs, you end up having to write careful error-handling code, but *given that you have to write it,* `Result` is nice to have around.

## Sharing Immutable Data Across Threads

Suppose the analysis we're doing requires a large database of English words and phrases:

```
// before
fn process_files(filenames: Vec<String>)

// after
fn process_files(filenames: Vec<String>, glossary: &GigabyteMap)
```

This `glossary` is going to be big, so we're passing it in by reference. How can we update `process_files_in_parallel` to pass the glossary through to the worker threads?

The obvious change does not work:

```
fn process_files_in_parallel(
    filenames: Vec<String>,
    glossary: &GigabyteMap,
) -> io::Result<()> {
    ...
    for worklist in worklists {
        thread_handles.push(
            spawn(move || process_files(worklist, glossary)),  //
error
        );
    }
    ...
}
```

We've simply added a `glossary` argument to our function and passed it along to `process_files`. Rust complains:

```
error: borrowed data escapes outside of function
   |
24 |     glossary: &GigabyteMap,
   |     --------  - let's call the lifetime of this reference
```

```
`'1`
   |     |
   |     `glossary` is a reference that is only valid in the
function body
...
36 |             spawn(move || process_files(worklist,
glossary)),  // error
   |             ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
   |             |
   |             `glossary` escapes the function body here
   |             argument requires that `'1` must outlive
`'static`
```

The error is about the lifetime of the reference we're trying to share. `spawn` launches independent threads. Rust can't know how long the child thread will run, so it assumes the worst: it assumes the child may keep running even after the parent has finished and all values in the parent thread are gone. Obviously, if the child thread is going to last that long, the closure it's running needs to last that long too. But this closure has a bounded lifetime: it depends on the reference `glossary`, and references don't last forever.

Note that Rust is right to reject this code! The way we've written this function, it *is* possible for one thread to hit an I/O error, causing `process_files_in_parallel` to bail out before the other threads are finished. Child threads could end up trying to use the glossary after the main thread has freed it. It would be a race—with undefined behavior as the prize if the main thread should win. Rust can't allow this.

It seems `spawn` is too open-ended to support sharing references across threads. Indeed, we already saw a case like this in "Closures That Steal". There, our solution was to transfer ownership of the data to the new thread, using a `move` closure.

That won't work here, since we have many threads that all need to use the same data. One safe alternative is to `clone` the whole glossary for each thread, but since it's large, we want to avoid that. Fortunately, the standard library provides two tidy solutions to this problem: atomic reference counting and scoped threads.

We introduced Rust's reference counting types in "Rc and Arc: Shared Ownership". It's time to put `Arc` to use:

```
use std::sync::Arc;

fn process_files_in_parallel(
    filenames: Vec<String>,
    glossary: Arc<GigabyteMap>,
) -> io::Result<()> {
    ...
    for worklist in worklists {
        // This call to .clone() only clones the Arc and bumps
the
        // reference count. It does not clone the GigabyteMap.
        let glossary_for_child = glossary.clone();
        thread_handles.push(
            spawn(move || process_files(worklist,
&glossary_for_child))
        );
    }
    ...
}
```

We have changed the type of `glossary`. Now, to run the analysis in parallel, the caller must pass in an `Arc<GigabyteMap>`, a smart pointer to a `GigabyteMap` that's been moved into the heap, by using `Arc::new(giga_map)`.

When we call `glossary.clone()`, we are making a copy of the `Arc` smart pointer, not the whole `GigabyteMap`. This amounts to incrementing a reference count. With this change, the program compiles and runs, because it no longer depends on reference lifetimes. As long as *any* thread owns an `Arc<GigabyteMap>`, it will keep the map alive, even if the parent thread bails out early. There won't be any data races, because data in an `Arc` is immutable.

`Arc` is designed for shared ownership, and it's the most common way to share values across threads. In this particular case, *scoped threads* are another option. We used `std::thread::scope` in Chapter 2 to split the

computation of our Mandelbrot set image across eight threads. Similar code will work here:

```
fn process_files_in_parallel(
    filenames: Vec<String>,
    glossary: &GigabyteMap,
) -> io::Result<()> {
    ...
    std::thread::scope(|scope| {
        // Fork: Spawn a thread to handle each chunk.
        let mut thread_handles = vec![];
        for worklist in worklists {
            thread_handles.push(
                scope.spawn(move || process_files(worklist,
glossary))
            );
        }

        // Join: Wait for all threads to finish.
        for handle in thread_handles {
            handle.join().unwrap()?;
        }

        Ok(())
    }) // <-- Join backstop: thread::scope() waits for all
remaining threads
}
```

Note that we've switched from `Arc<GigabyteMap>` back to a regular reference. We can share it across our worker threads now, because they are scoped threads, guaranteed to finish before `std::thread::scope` returns.

The basic `std::thread::spawn` function requires its closure argument to last for the `'static` lifetime. This is how Rust prevents us from using it to share references unsafely. The `Scope::spawn` method is not so strict. Its closure argument only needs to live as long as the corresponding `std::thread::scope()` call, because `std::thread::scope` always waits for all its spawned threads to finish before returning. Thanks to the relaxed lifetime requirement, our scoped threads can use the reference `glossary` directly, without reference counting.

Code using scoped threads can often skip the `join()` phase, since all spawned threads are joined automatically. In our example, we're still calling `handle.join()` explicitly, because we want to check our threads' return values for errors. But if we do find an error and return early, `std::thread::scope` will nonetheless wait for the remaining threads, as required for safety.

## Rayon

The Rayon library, by Niko Matsakis and Josh Stone, is an even more powerful tool for fork-join parallelism. It provides two ways of running tasks concurrently:

```
use rayon::prelude::*;

// "do 2 things in parallel"
let (v1, v2) = rayon::join(fn1, fn2);

// "do N things in parallel"
giant_vector.par_iter().for_each(|value| {
    do_thing_with_value(value);
});
```

`rayon::join(fn1, fn2)` simply calls both functions and returns both results. The `.par_iter()` method creates a `ParallelIterator`, a value with `map`, `filter`, and other methods, much like a Rust `Iterator`.

In both cases, Rayon uses its own pool of worker threads to spread out the work when possible. You simply tell Rayon what tasks *can* be done in parallel; Rayon manages threads and distributes the work as best it can.

The diagrams in Figure 19-3 illustrate two ways of thinking about the call `giant_vector.par_iter().for_each(...)`. Rayon acts as though it spawns one thread per element in the vector, as shown in (a). Behind the scenes, Rayon has one worker thread per CPU core, as shown in (b). This pool of worker threads is shared by all your program's threads. When thousands of tasks come in at once, Rayon divides the work.

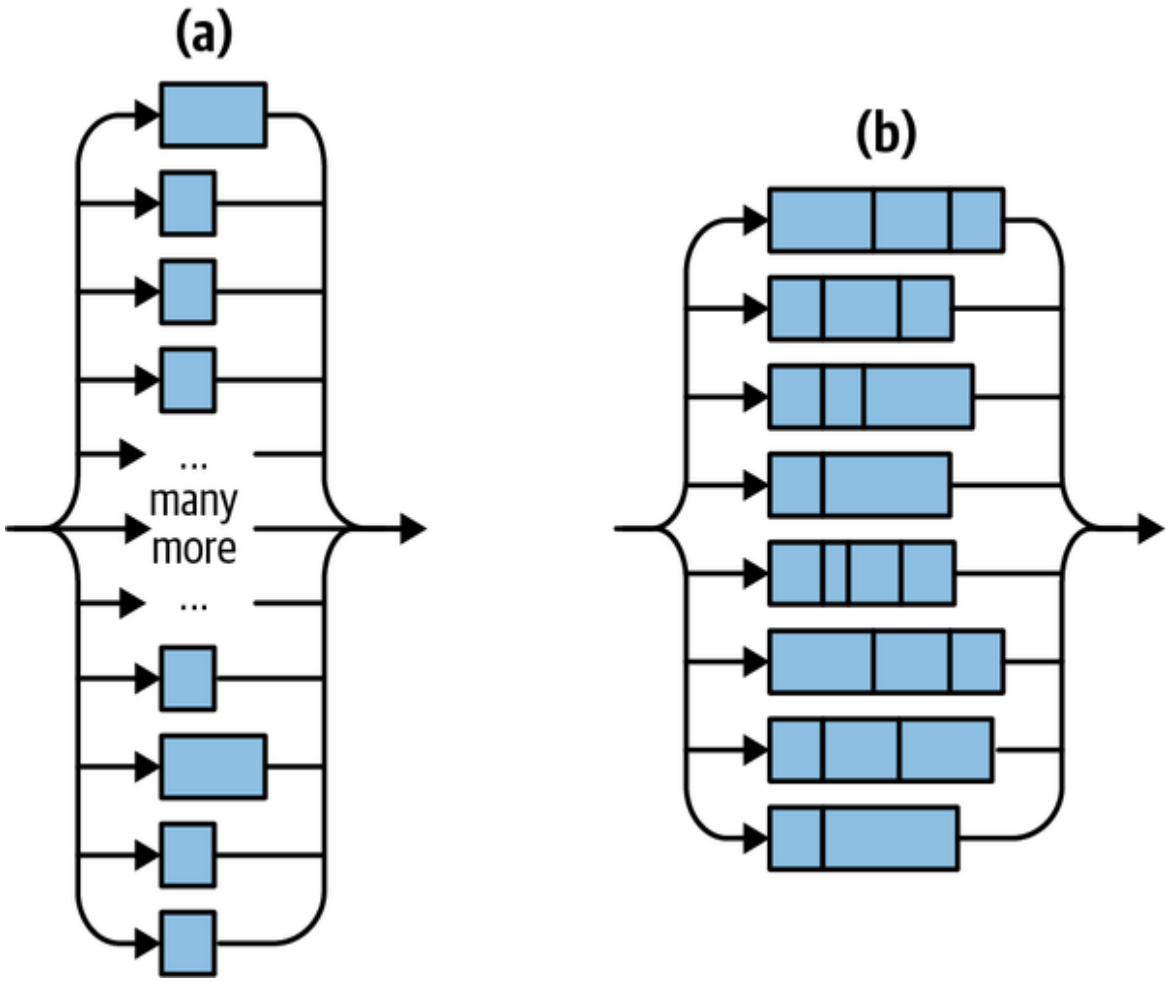


*Figure 19-3. Rayon in theory and practice*

Here's a version of `process_files_in_parallel` using Rayon and a `process_file` that takes, rather than `Vec<String>`, just a `&str`:

```
use rayon::prelude::*;

fn process_files_in_parallel(
    filenames: Vec<String>,
    glossary: &GigabyteMap,
) -> io::Result<()> {
    filenames
        .par_iter()
        .map(|filename| process_file(filename, glossary))
        .reduce_with(|r1, r2| {
            if r1.is_err() { r1 } else { r2 }
        })
        .unwrap_or(Ok(()))
}
```

This code is shorter and less tricky than the version using `std::thread::spawn`. Let's look at it line by line:

- First, we use `filenames.par_iter()` to create a parallel iterator.
- We use `.map()` to call `process_file` on each filename. This produces a `ParallelIterator` over a sequence of `io::Result<()>` values.
- We use `.reduce_with()` to combine the results. Here we're keeping the first error, if any, and discarding the rest. If we wanted to accumulate all the errors, or print them, we could do that here.

  The `.reduce_with()` method is also handy when you pass a `.map()` closure that returns a useful value on success. Then you can pass `.reduce_with()` a closure that knows how to combine two success results.
- `reduce_with` returns an `Option` that is `None` only if `filenames` was empty. We use the `Option`'s `.unwrap_or()` method to make the result `Ok(())` in that case.

Behind the scenes, Rayon balances workloads across threads dynamically, using a technique called *work-stealing*. It will typically do a better job keeping all the CPUs busy than we can do by manually dividing the work in advance, as in "spawn and join".

As a bonus, Rayon supports sharing references across threads. Any parallel processing that happens behind the scenes is guaranteed to be finished by the time `reduce_with` returns. This explains why we were able to pass `glossary` to `process_file` even though that closure will be called on multiple threads.

(Incidentally, it's no coincidence that we've used a `map` method and a `reduce` method. The MapReduce programming model, popularized by

Google and Apache Hadoop, has a lot in common with fork-join. It can be seen as a fork-join approach to querying distributed data.)

## Revisiting the Mandelbrot Set

Back in Chapter 2, we used fork-join concurrency to render the Mandelbrot set. This made rendering four times as fast—impressive, but not as impressive as it could be, considering that we had the program spawn eight worker threads and ran it on an eight-core machine!

The problem is that we didn't distribute the workload evenly. Computing one pixel of the image amounts to running a loop (see "What the Mandelbrot Set Actually Is"). It turns out that the pale gray parts of the image, where the loop quickly exits, are much faster to render than the black parts, where the loop runs the full 255 iterations. So although we split the area into equal-sized horizontal bands, we were creating unequal workloads, as Figure 19-4 shows.

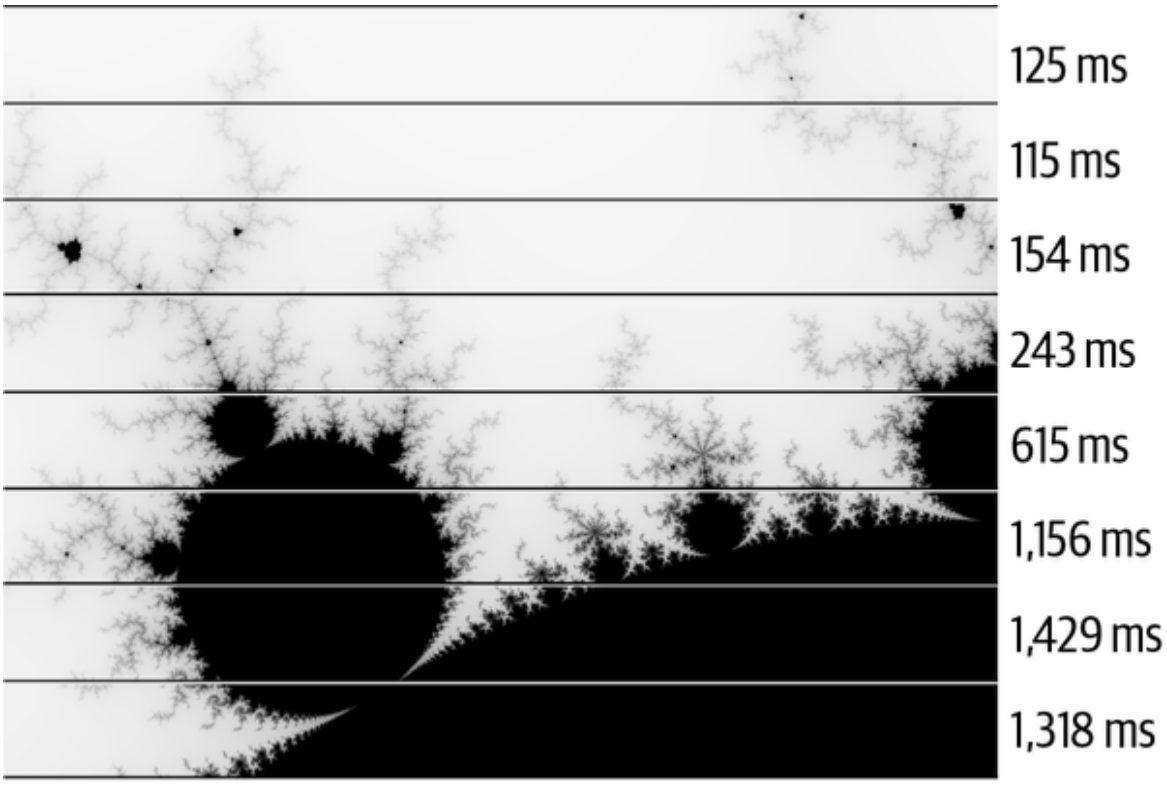


*Figure 19-4. Uneven work distribution in the Mandelbrot program*

This is easy to fix using Rayon. We can just fire off a parallel task for each row of pixels in the output. This creates several hundred tasks that Rayon can distribute across its threads. Thanks to work-stealing, it won't matter that the tasks vary in size. Rayon will balance the work as it goes.

To use Rayon, we must add this line to *main.rs*:

```
use rayon::prelude::*;
```

and this to *Cargo.toml*:

```
[dependencies]
rayon = "1.12.0"
```

Here is the code. The first line and the last line are part of the `main` function we showed back in "A Concurrent Mandelbrot Program", but we've changed the rendering code, which is everything in between:

```
let (width, height) = bounds;
let mut pixels = vec![0; width * height];

let bands: Vec<(usize, &mut [u8])> =
    pixels.chunks_mut(width).enumerate().collect();

bands.into_par_iter().for_each(|(i, band)| {
    let top = i;
    let band_bounds = (width, 1);
    let band_upper_left =
        pixel_to_point(bounds, (0, top), upper_left,
lower_right);
    let band_lower_right =
        pixel_to_point(bounds, (width, top + 1), upper_left,
lower_right);
    render(band, band_bounds, band_upper_left, band_lower_right);
});

write_image(&args[1], &pixels, bounds).expect("error writing PNG
file");
```

First, we create `bands`, the collection of tasks that we will be passing to Rayon. Each task is just a tuple of type `(usize, &mut [u8])`: the row

number, since the computation requires that, and the slice of `pixels` to fill in. We use the `chunks_mut` method to break the image buffer into rows, `enumerate` to attach a row number to each row, and `collect` to slurp all the number-slice pairs into a vector. (We need a vector because Rayon creates parallel iterators only out of arrays and vectors.)

Next, we turn `bands` into a parallel iterator and use the `.for_each()` method to tell Rayon what work we want done.

With these changes, the program now uses about 7.75 cores on an 8-core machine. It's 75% faster than before, when we were dividing the work manually. And the code is a little shorter, reflecting the benefits of letting a crate do a job (work distribution) rather than doing it ourselves.

## Channels

A *channel* is a one-way conduit for sending values from one thread to another. In other words, it's a thread-safe queue.

Figure 19-5 illustrates how channels are used. They're something like Unix pipes: one end is for sending data, and the other is for receiving. The two ends are typically owned by two different threads. But whereas Unix pipes are for sending bytes, channels are for sending Rust values. `sender.send(item)` puts a single value into the channel; `receiver.recv()` removes one. Ownership is transferred from the sending thread to the receiving thread. If the channel is empty, `receiver.recv()` blocks until a value is sent.

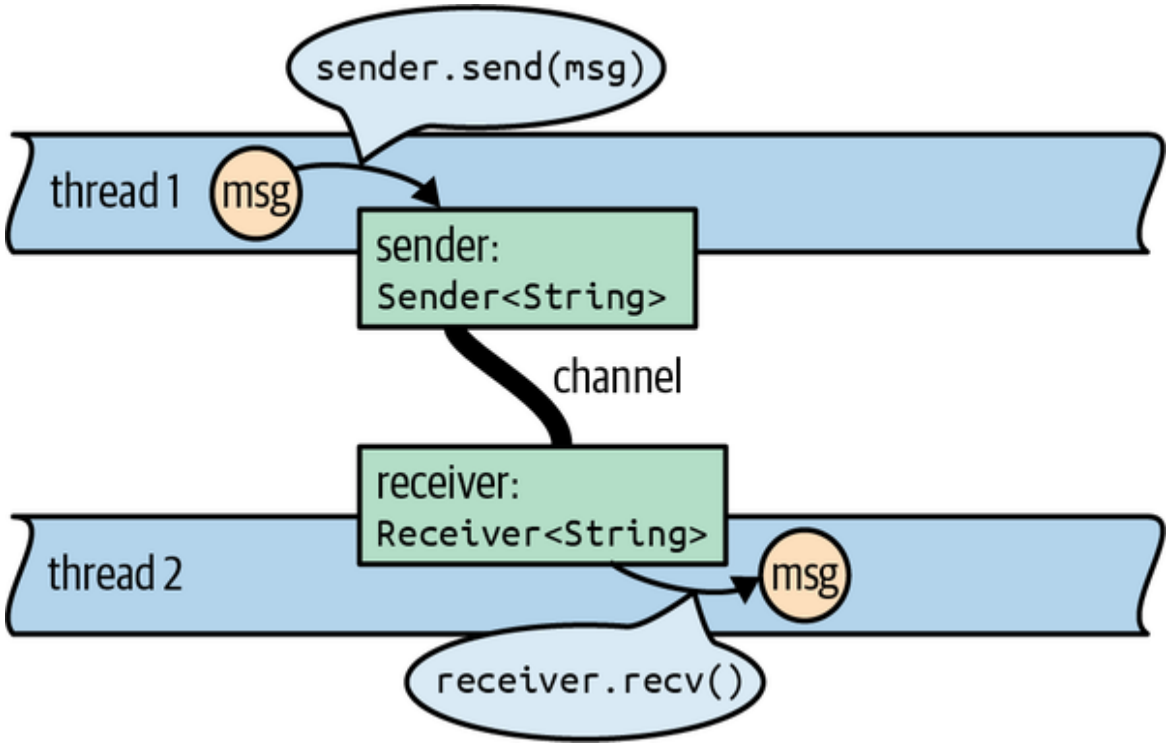


*Figure 19-5. A channel for `Strings`: ownership of the string msg is transferred from thread 1 to thread 2*

With channels, threads can communicate by passing values to one another. It's a simple way for threads to work together without using locking or shared memory.

This is not a new technique. Erlang has had isolated processes and message passing for 30 years now. Unix pipes have been around for almost 50 years. We tend to think of pipes as providing flexibility and composability, not concurrency, but in fact, they do all of the above. An example of a Unix pipeline is shown in Figure 19-6. It is certainly possible for all three programs to be working at the same time.

Rust channels are faster than Unix pipes. Sending a value moves it rather than copying it, and moves are fast even when you're moving data structures that contain many megabytes of data.

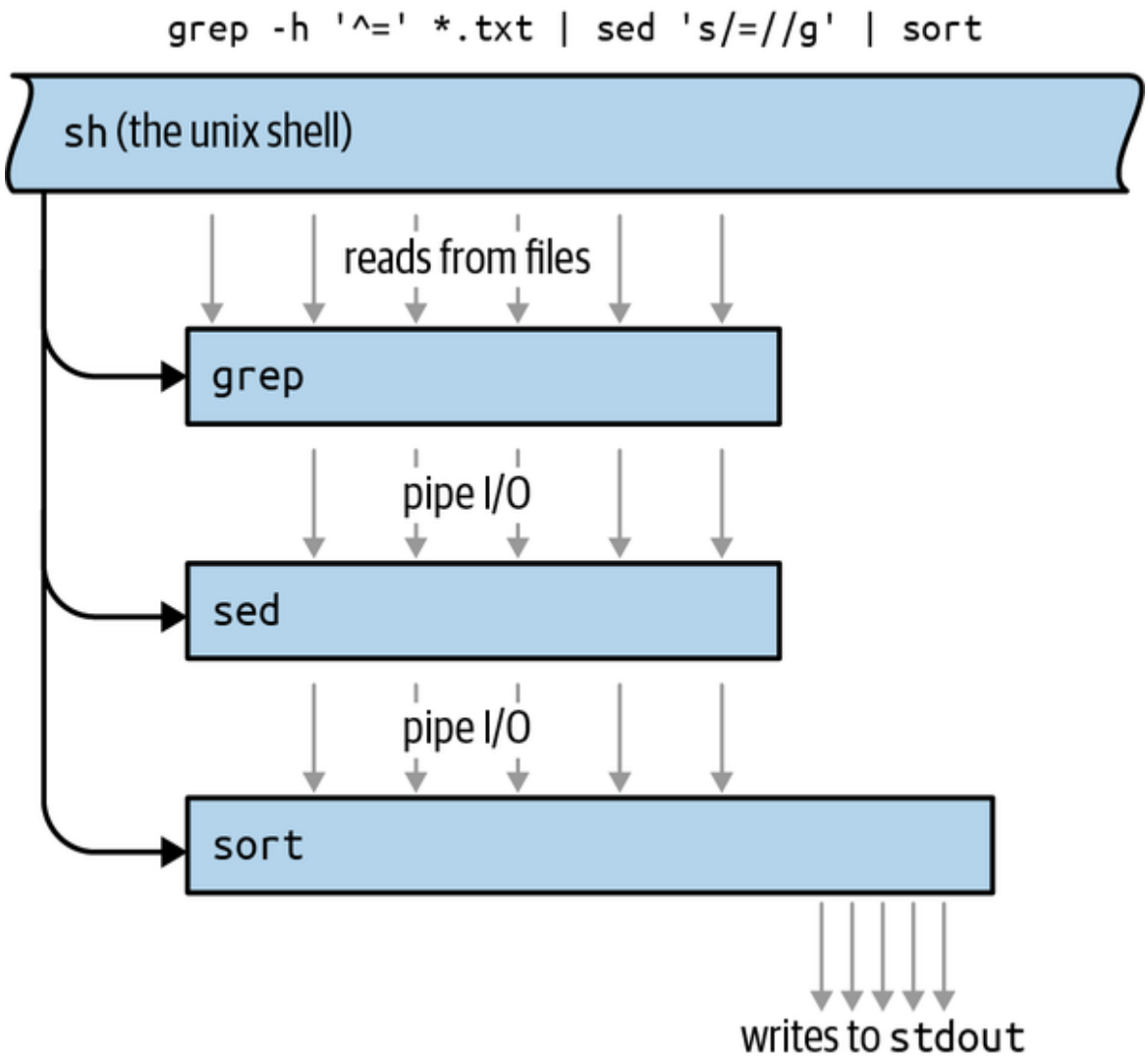


*Figure 19-6. Execution of a Unix pipeline*

## Sending Values

Over the next few sections, we'll use channels to build a concurrent program that creates an *inverted index,* one of the key ingredients of a search engine. Every search engine works on a particular collection of documents. The inverted index is the database that tells which words appear where.

We'll show the parts of the code that have to do with threads and channels. The complete program is short, about a thousand lines of code all told. Our program is structured as a pipeline, shown in Figure 19-7. Pipelines are only one of many ways to use channels—we'll discuss a few other uses

later—but they're a straightforward way to introduce concurrency into an existing single-threaded program.

We'll use a total of five threads, each doing a distinct task. Each thread produces output continually over the lifetime of the program. The first thread, for example, simply reads the source documents from disk into memory, one by one. (We want a thread to do this because we'll be writing the simplest possible code here, using `fs::read_to_string`, which is a blocking API. We don't want the CPU to sit idle whenever the disk is working.) The output of this stage is one long `String` per document, so this thread is connected to the next thread by a channel of `String`s.

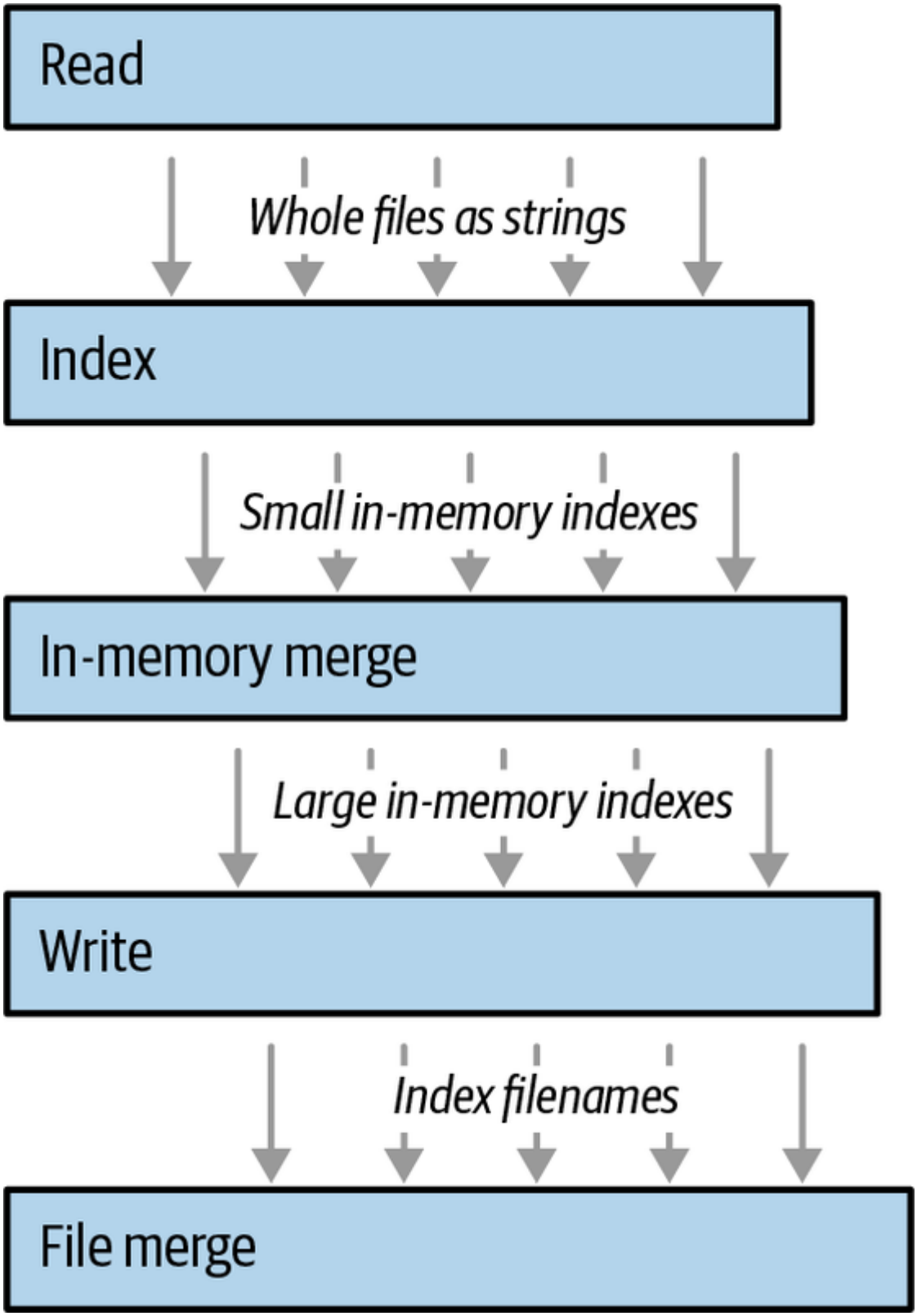


*Figure 19-7. The index builder pipeline, where the arrows represent values sent via a channel from one thread to another (disk I/O is not shown)*

Our program will begin by spawning the thread that reads files. Suppose `documents` is a `Vec<PathBuf>`, a vector of filenames. The code to start our file-reading thread looks like this:

```
use std::sync::mpsc;
use std::{fs, thread};

let (sender, receiver) = mpsc::channel();

let handle = thread::spawn(move || {
    for filename in documents {
        let text = fs::read_to_string(filename)?;

        if sender.send(text).is_err() {
            break;
        }
    }
    Ok(())
});
```

Channels are part of the `std::sync::mpsc` module. We'll explain what this name means later; first, let's look at how this code works. We start by creating a channel:

```
let (sender, receiver) = mpsc::channel();
```

The `channel` function returns a pair of values: a sender and a receiver. The underlying queue data structure is an implementation detail that the standard library does not expose.

Channels are typed. We're going to use this channel to send the text of each file, so we have a `sender` of type `Sender<String>` and a `receiver` of type `Receiver<String>`. We could have explicitly asked for a channel of strings by writing `mpsc::channel::<String>()`. Instead, we let Rust's type inference figure it out:

```
let handle = thread::spawn(move || {
```

As before, we're using `std::thread::spawn` to start a thread. Ownership of `sender` (but not `receiver`) is transferred to the new thread via this `move` closure.

The next few lines of code simply read files from disk:

```
        for filename in documents {
            let text = fs::read_to_string(filename)?;
```

After successfully reading a file, we send its text into the channel:

```
            if sender.send(text).is_err() {
                break;
            }
        }
```

`sender.send(text)` moves the value `text` into the channel. Ultimately, it will be moved again to whomever receives the value. Whether `text` contains 10 lines of text or 10 megabytes, this operation copies 3 machine words (the size of a `String` struct), and the corresponding `receiver.recv()` call will also copy 3 machine words.

The `send` and `recv` methods both return `Results`, but these methods fail only if the other end of the channel has been dropped. A `send` call fails if the `Receiver` has been dropped, because otherwise the value would sit in the channel forever: without a `Receiver`, there's no way for any thread to receive it. Likewise, a `recv` call fails if there are no values waiting in the channel and the `Sender` has been dropped, because otherwise `recv` would wait forever: without a `Sender`, there's no way for any thread to send the next value. Dropping your end of a channel is the normal way of "hanging up," closing the connection when you're done with it.

In our code, `sender.send(text)` will fail only if the receiver's thread has exited early. This is typical for code that uses channels. Whether that happened deliberately or due to an error, it's OK for our reader thread to quietly shut itself down.

When that happens or the thread finishes reading all the documents, it returns:

```
        Ok(())
    });
```

Note that this closure returns a `Result`. If the thread encounters an I/O error, it exits immediately, and the error is stored in the thread's `JoinHandle`.

Of course, just like any other programming language, Rust admits many other possibilities when it comes to error handling. When an error happens, we could just print it out using `println!` and move on to the next file. We could pass errors along via the same channel that we're using for data, making it a channel of `Results`—or create a second channel just for errors. The approach we've chosen here is both lightweight and responsible: we get to use the `?` operator, so there's not a bunch of boilerplate code, or even an explicit `try/catch` as you might see in Java, and yet errors won't pass silently.

For convenience, our program wraps all of this code in a function that returns both the `receiver` (which we haven't used yet) and the new thread's `JoinHandle`:

```
fn start_file_reader_thread(
    documents: Vec<PathBuf>,
) -> (mpsc::Receiver<String>, thread::JoinHandle<io::Result<()>>)
{
    let (sender, receiver) = mpsc::channel();

    let handle = thread::spawn(move || {
        ...
    });

    (receiver, handle)
}
```

Note that this function launches the new thread and immediately returns. We'll write a function like this for each stage of our pipeline.

## Receiving Values

Now we have a thread running a loop that sends values. We can spawn a second thread running a loop that calls `receiver.recv()`:

```
while let Ok(text) = receiver.recv() {
    do_something_with(text);
}
```

But `Receivers` are iterable, so there's a nicer way to write this:

```
for text in receiver {
    do_something_with(text);
}
```

These two loops are equivalent. Either way we write it, if the channel happens to be empty when control reaches the top of the loop, the receiving thread will block until some other thread sends a value. The loop will exit normally when the channel is empty and the `Sender` has been dropped. In our program, that happens naturally when the reader thread exits. That thread is running a closure that owns the variable `sender`; when the closure exits, `sender` is dropped. Now we can write code for the second stage of the pipeline:

```
fn start_file_indexing_thread(
    texts: mpsc::Receiver<String>,
) -> (mpsc::Receiver<InMemoryIndex>, thread::JoinHandle<()>) {
    let (sender, receiver) = mpsc::channel();

    let handle = thread::spawn(move || {
        for (doc_id, text) in texts.into_iter().enumerate() {
            let index =
InMemoryIndex::from_single_document(doc_id, text);
            if sender.send(index).is_err() {
                break;
            }
        }
    });

    (receiver, handle)
}
```

This function spawns a thread that receives `String` values from one channel (`texts`) and sends `InMemoryIndex` values to another channel (`sender`/`receiver`). This thread's job is to take each of the files loaded in the first stage and turn each document into a little one-file, in-memory inverted index.

The main loop of this thread is straightforward. All the work of indexing a document is done by the function `InMemoryIndex::from_single_document`. We won't show its source code here, but it splits the input string at word boundaries and then produces a map from words to lists of positions.

This stage doesn't perform I/O, so it doesn't have to deal with `io::Errors`. Instead of an `io::Result<()>`, it returns `()`.

## Running the Pipeline

The remaining three stages are similar in design. Each one consumes a `Receiver` created by the previous stage. Our goal for the rest of the pipeline is to merge all the small indexes into a single large index file on disk. The fastest way we found to do this is in three stages. We won't show the code here, just the type signatures of these three functions. The full source is online.

First, we merge indexes in memory until they get unwieldy (stage 3):

```
fn start_in_memory_merge_thread(
    file_indexes: mpsc::Receiver<InMemoryIndex>,
) -> (mpsc::Receiver<InMemoryIndex>, thread::JoinHandle<()>)
```

We write these large indexes to disk (stage 4):

```
fn start_index_writer_thread(
    big_indexes: mpsc::Receiver<InMemoryIndex>,
    output_dir: &Path,
) -> (mpsc::Receiver<PathBuf>,
thread::JoinHandle<io::Result<()>>)
```

Finally, if we have multiple large files, we merge them using a file-based merging algorithm (stage 5):

```
fn merge_index_files(
    files: mpsc::Receiver<PathBuf>,
    output_dir: &Path,
) -> io::Result<()>
```

This last stage doesn't return a `Receiver` because it's the end of the line. It produces a single output file on disk. It doesn't return a `JoinHandle` because we don't bother spawning a thread for this stage. The work is done on the caller's thread.

Now we come to the code that launches the threads and checks for errors:

```
fn run_pipeline(
    documents: Vec<PathBuf>,
    output_dir: PathBuf,
) -> io::Result<()> {
    // Launch all five stages of the pipeline.
    let (texts,   h1) = start_file_reader_thread(documents);
    let (pints,   h2) = start_file_indexing_thread(texts);
    let (gallons, h3) = start_in_memory_merge_thread(pints);
    let (files,   h4) = start_index_writer_thread(gallons,
&output_dir);
    let result = merge_index_files(files, &output_dir);

    // Wait for threads to finish, holding on to any errors that
they encounter.
    let r1 = h1.join().unwrap();
    h2.join().unwrap();
    h3.join().unwrap();
    let r4 = h4.join().unwrap();

    // Return the first error encountered, if any.
    // (As it happens, h2 and h3 can't fail: those threads
    // are pure in-memory data processing.)
    r1?;
    r4?;
    result
}
```

As before, we use `.join().unwrap()` to explicitly propagate panics from child threads to the main thread. The only other unusual thing here is that instead of using `?` right away, we set aside the `io::Result` values until we've joined all four threads.

This pipeline is 40% faster than the single-threaded equivalent. That's not bad for an afternoon's work, but it is paltry looking next to the 675% boost we got for the Mandelbrot program. We clearly haven't saturated either the system's I/O capacity or all the CPU cores. What's going on?

Pipelines are like assembly lines in a manufacturing plant: performance is limited by the throughput of the slowest stage. A brand-new, untuned assembly line may be as slow as unit production, but assembly lines reward targeted tuning. In our case, measurement shows that the second stage is the bottleneck. Our indexing thread uses `.to_lowercase()` and `.is_alphanumeric()`, so it spends a lot of time poking around in Unicode tables. The other stages downstream from indexing spend most of their time asleep in `Receiver::recv`, waiting for input.

This means we should be able to go faster. As we address the bottlenecks, the degree of parallelism will rise. Now that you know how to use channels and our program is made of isolated pieces of code, it's easy to see ways to address this first bottleneck. We could hand-optimize the code for the second stage, just like any other code; break up the work into two or more stages; or run multiple file-indexing threads at once.

## Channel Features and Performance

The `mpsc` part of `std::sync::mpsc` stands for *multiproducer, single-consumer,* a terse description of the kind of communication Rust's channels provide.

The channels in our sample program carry values from a single sender to a single receiver. This is a fairly common case. But Rust channels also support multiple senders in case you need, say, a single thread that handles requests from many client threads, as shown in Figure 19-8.

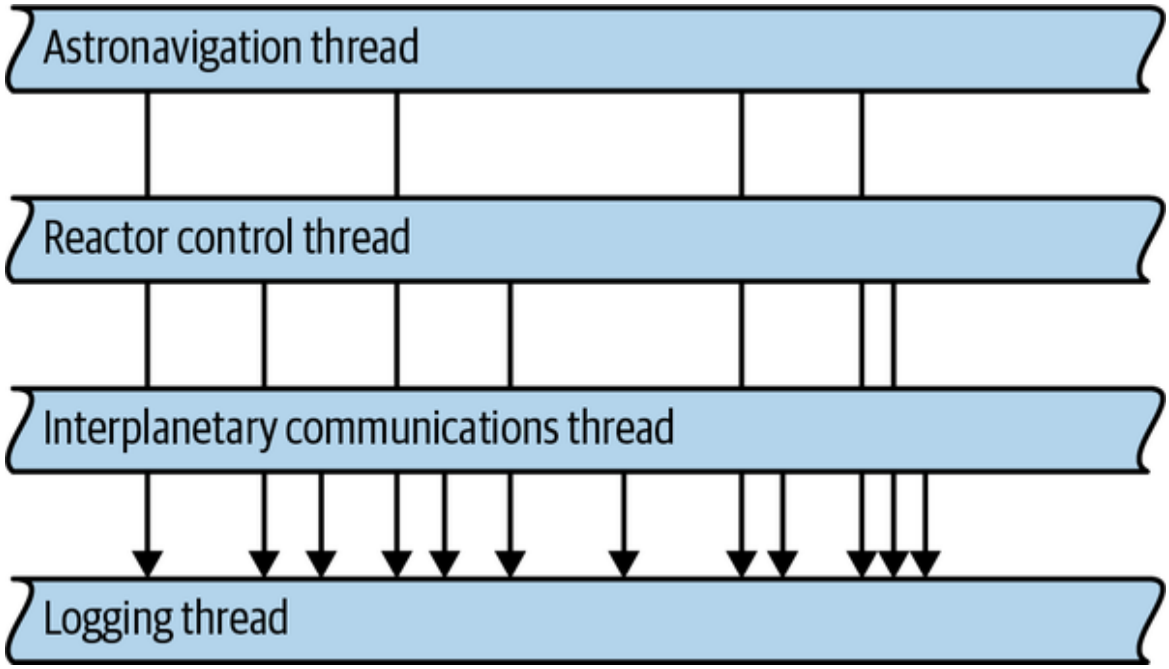


*Figure 19-8. A single channel receiving requests from many senders*

`Sender<T>` implements the `Clone` trait. To get a channel with multiple senders, simply create a regular channel and clone the sender as many times as you like. You can move each `Sender` value to a different thread.

A `Receiver<T>` can't be cloned, so if you need to have multiple threads receiving values from the same channel, you need a different kind of channel, a *multiconsumer* channel. The `flume` crate provides such a channel. We'll also show how to build your own later in this chapter.

Rust channels are carefully optimized. When a channel is first created, Rust uses a special "one-shot" queue implementation. If you only ever send one object through the channel, the overhead is minimal. If you send a second value, Rust switches to a different queue implementation. It's settling in for the long haul, really, preparing the channel to transfer many values while minimizing allocation overhead. If you clone the `Sender`, Rust must fall back on yet another implementation, one that is safe when multiple threads are trying to send values at once. But even the slowest of these three implementations is a lock-free queue, so sending or receiving a value is at most a few atomic operations and a heap allocation, plus the move itself. System calls are needed only when the queue is empty and the receiving

thread therefore needs to put itself to sleep. In this case, of course, traffic through your channel is not maxed out anyway.

Despite all that optimization work, there is one mistake that's easy for applications to make around channel performance: sending values faster than they can be received and processed. This causes an ever-growing backlog of values to accumulate in the channel. For example, in our program, we found that the file reader thread (stage 1) could load files much faster than the file indexing thread (stage 2) could index them. The result is that gigabytes of raw data would be read from disk and stuffed in the queue at once.

This is a serious bug. With a large enough document set, the file reader thread quickly fills up the system's memory. The operating system will eventually kill any process with such runaway memory usage.

Here Rust again takes a page from Unix pipes. Unix uses an elegant trick to provide some *backpressure* so that fast senders are forced to slow down: each pipe on a Unix system has a fixed size, and if a process tries to write to a pipe that's momentarily full, the system simply blocks that process until there's room in the pipe. The Rust equivalent is called a *synchronous channel*:

```
use std::sync::mpsc;

let (sender, receiver) = mpsc::sync_channel(1000);
```

A synchronous channel is exactly like a regular channel except that when you create it, you specify how many values it can hold. For a synchronous channel, `sender.send(value)` is potentially a blocking operation.

After all, the idea is that blocking is not always bad. In our example program, changing the `channel` in `start_file_reader_thread` to a `sync_channel` with room for a few dozen values keeps memory usage reasonable without decreasing throughput. When the channel is full, the file reader thread's call to `sender.send(content)` waits until there's room.

## Thread Safety: Send and Sync

So far we've been acting as though all values can be freely moved and shared across threads. This is mostly true, but Rust's full thread safety story hinges on two built-in traits, `std::marker::Send` and `std::marker::Sync`:

- Types that implement `Send` are safe to pass by value to another thread. They can be moved across threads.
- Types that implement `Sync` are safe to access by non-`mut` reference on multiple threads concurrently. They can be shared across threads.

By *safe* here, we mean the same thing we always mean: free from data races and other undefined behavior.

For example, in the `process_files_in_parallel` example "spawn and join", we used a closure to pass a `Vec<String>` from the parent thread to each child thread. We didn't point it out at the time, but this means the vector and its strings are allocated in the parent thread but freed in the child thread. The fact that `Vec<String>` implements `Send` is an API promise that this is OK: the allocator used internally by `Vec` and `String` is thread-safe.

(If you were to write your own `Vec` and `String` types with fast but non-thread-safe allocators, you would have to implement them using types that are not `Send`, such as raw pointers. Rust would then infer that your `CustomVec` and `CustomString` types are not `Send` and restrict them to single-threaded use. But that's a rare case.)

As Figure 19-9 illustrates, most types are both `Send` and `Sync`. You don't even have to use `#[derive]` to get these traits on structs and enums in your program. Rust does it for you. A struct or enum is `Send` if its fields are `Send`, and `Sync` if its fields are `Sync`.

Some types are `Send`, but not `Sync`. This has the effect of restricting access to one thread at a time, as in the case of `mpsc::Receiver`, the

"single-consumer" end of a multiproducer, single-consumer channel. Types that are `Sync` but not `Send` are even rarer and typically involve a `drop` method that for technical reasons must be called in the thread where the value was created. An example is `MutexGuard<T>`, a type that holds a mutex and automatically releases it when dropped. On some operating systems, `MutexGuard` is implemented using the C pthreads library, which requires locking and unlocking to happen on the same thread.

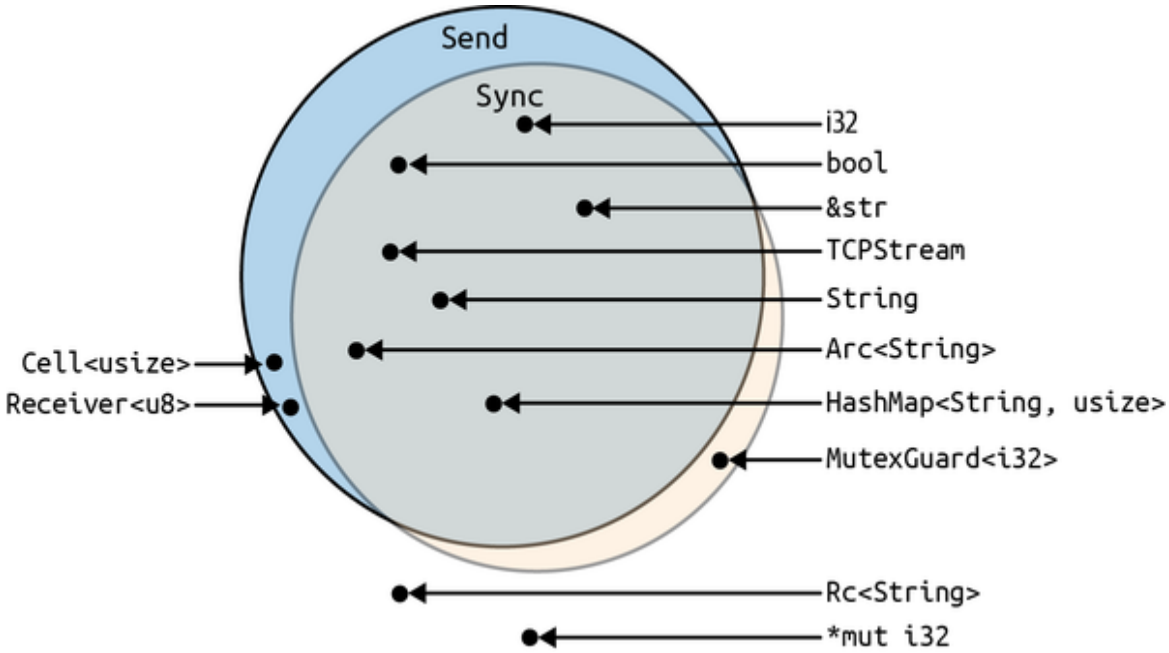


*Figure 19-9. Venn diagram of `Send` and `Sync` types*

The few types that are neither `Send` nor `Sync` are mostly those that use mutability in a way that isn't thread-safe. For example, consider `std::rc::Rc<T>`, the type of reference-counting smart pointers.

What would happen if `Rc<String>` were `Sync`, allowing threads to share a single `Rc` via shared references? If both threads happened to clone the `Rc` at the same time, as shown in Figure 19-10, we would have a data race as both threads increment the shared reference count. The reference count could become inaccurate, leading to a use-after-free or double free later—undefined behavior.

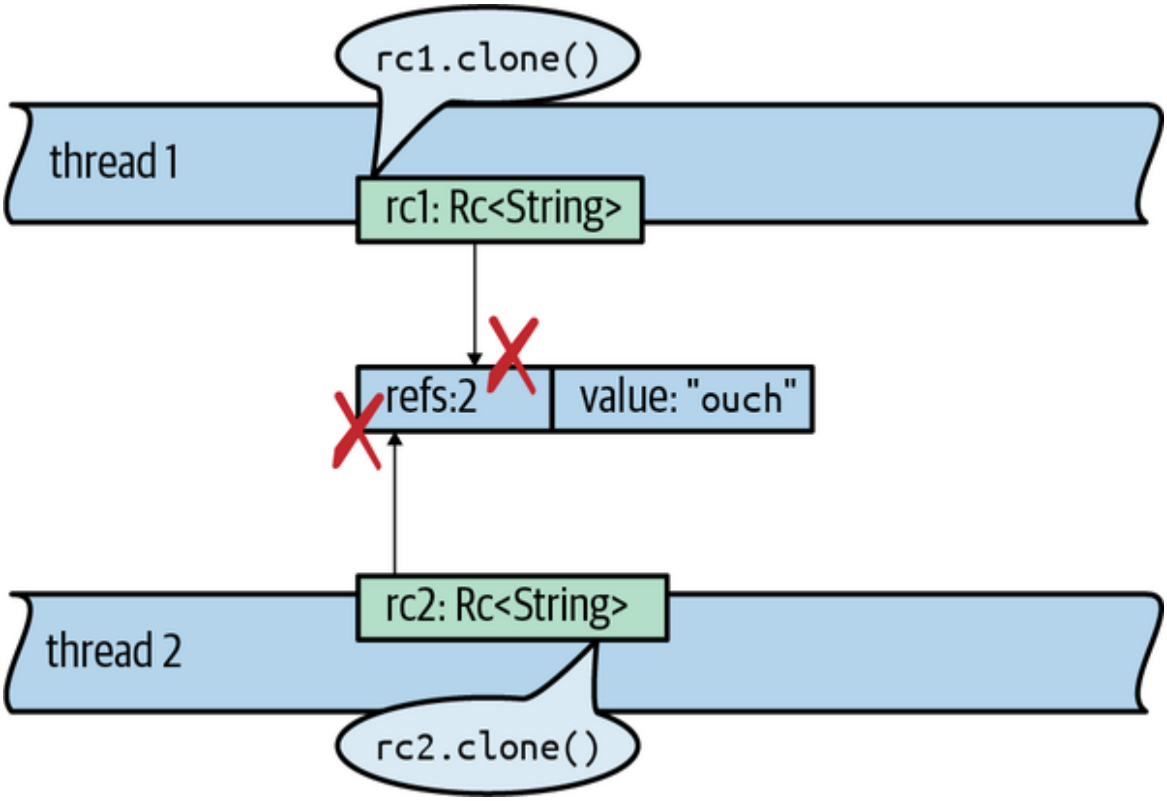


*Figure 19-10. Why `Rc<String>` is neither `Sync` nor `Send`*

Of course, Rust prevents this. Here's the code to set up this data race:

```
use std::rc::Rc;
use std::thread;

fn main() {
    let rc1 = Rc::new("ouch".to_string());
    let rc2 = rc1.clone();
    thread::spawn(move || {  // error
        rc2.clone();
    });
    rc1.clone();
}
```

Rust refuses to compile it, giving a detailed error message:

```
error: `Rc<String>` cannot be sent between threads safely
    |
10  |       thread::spawn(move || {  // error
    |       ------------- ^
    |       |             |
```

```
    |  _____|_____________|
    | |     |
    | |     required by a bound introduced by this call
11  | |         rc2.clone();
12  | |     });
    | |_____^ `Rc<String>` cannot be sent between threads safely
    |
    = help: the trait `Send` is not implemented for `Rc<String>`
note: required by a bound in `spawn`
    |
723 | pub fn spawn<F, T>(f: F) -> JoinHandle<T>
    |        ----- required by a bound in this function
...
726 |     F: Send + 'static,
    |        ^^^^ required by this bound in `spawn`
```

Now you can see how `Send` and `Sync` help Rust enforce thread safety. They appear as bounds in the type signature of functions that transfer data across thread boundaries. When you `spawn` a thread, the closure you pass must be `Send`, which means all the values it contains must be `Send`. `Sync` is used the same way, but for values that are shared across threads concurrently. For example, the parallel `map` method we used in "Rayon" takes a closure argument and calls it in parallel on many threads. That closure must therefore be `Sync`.

Fundamentally, the traits simply extend Rust's usual rules to multithreaded code:

- Types implement `Send` when the usual Rust practice of allowing exclusive `mut` access extends to multiple threads taking turns.
- Types implement `Sync` when the usual Rust practice of allowing shared `&` access extends to multiple threads running concurrently.

Most data types naturally satisfy these properties. Unless a type is doing something unusual and questionably thread-safe, like interior mutability, raw-pointer-based memory management, or calling into C code, all its fields will be `Send` and `Sync`, and it'll get both traits automatically.

In many languages, the word “thread-safe” is important but vague. It typically means a type supports *some* way of using it safely from multiple threads. But even for a so-called thread-safe type, there are often thread safety rules that users must learn and follow to avoid severe bugs. Where “thread-safe” is vague, `Sync` and `Send` are precise enough that the Rust can detect thread safety bugs at compile time. A funny consequence of learning Rust is that whenever we are debugging non-Rust code and we come across something named `ThreadSafe`, we know we’re in trouble. Nothing is called `ThreadSafe` in Rust.

## Piping Almost Any Iterator to a Channel

Our inverted index builder is built as a pipeline. The code is clear enough, but it has us manually setting up channels and launching threads. By contrast, the iterator pipelines we built in Chapter 15 seemed to pack a lot more work into just a few lines of code. Can we build something like that for thread pipelines?

In fact, it would be nice if we could unify iterator pipelines and thread pipelines. Then our index builder could be written as an iterator pipeline. It might start like this:

```
documents
    .into_iter()
    .map(read_whole_file)
    .errors_to(error_sender)    // filter out error results
    .off_thread()               // spawn a thread for the above
work
    .map(make_single_file_index)
    .off_thread()               // spawn another thread for stage
2
    ...
```

Traits allow us to add methods to standard library types, so we can actually do this. We start by writing a trait that declares the method we want:

```
use std::sync::mpsc;

pub trait OffThreadExt: Iterator {
```

```
    /// Transforms this iterator into an off-thread iterator: the
    /// `next()` calls happen on a separate worker thread, so the
    /// iterator and the body of your loop run concurrently.
    fn off_thread(self) -> mpsc::IntoIter<Self::Item>;
}
```

Then we implement this trait for iterator types. It helps that `mpsc::Receiver` is already iterable:

```
use std::thread;

impl<T> OffThreadExt for T
where
    T: Iterator + Send + 'static,
    T::Item: Send + 'static,
{
    fn off_thread(self) -> mpsc::IntoIter<Self::Item> {
        // Create a channel to transfer items from the worker
thread.
        let (sender, receiver) = mpsc::sync_channel(1024);

        // Move this iterator to a new worker thread and run it
there.
        thread::spawn(move || {
            for item in self {
                if sender.send(item).is_err() {
                    break;
                }
            }
        });

        // Return an iterator that pulls values from the channel.
        receiver.into_iter()
    }
}
```

The `where` clause in this code was determined via a process much like the one described in "Reverse-Engineering Bounds". At first, we just had this:

```
impl<T> OffThreadExt for T
```

That is, we wanted the implementation to work for all iterators. Rust was having none of it. Because we're using `spawn` to move an iterator of type

`T` to a new thread, we must specify `T: Iterator + Send + 'static`. Because we're sending the items back over a channel, we must specify `T::Item: Send + 'static`. With these changes, Rust was satisfied.

This is Rust's character in a nutshell: we're free to add a concurrency power tool to almost every iterator in the language—but not without first understanding and documenting the restrictions that make it safe to use.

## Beyond Pipelines

In this section, we used pipelines as our examples because pipelines are a nice, obvious way to use channels. Everyone understands them. They're concrete, practical, and deterministic. Channels are useful for more than just pipelines, though. They're also an easy way for one thread to offer a service to other threads in the same process.

For example, suppose you'd like to do logging on its own thread, as in Figure 19-8. Other threads could send log messages to the logging thread over a channel; since you can clone the channel's `Sender`, many client threads can have senders that ship log messages to the same logging thread.

Running a service like logging on its own thread has advantages. The logging thread can rotate log files whenever it needs to. It doesn't have to do any fancy coordination with the other threads. Those threads won't be blocked. Messages will accumulate harmlessly in the channel for a moment until the logging thread gets back to work.

Channels can also be used for cases where one thread sends a request to another thread and needs to get some sort of response. The first thread's request can be a struct or tuple that includes a `Sender`, a sort of self-addressed envelope that the second thread uses to send its reply. This doesn't mean the interaction must be synchronous. The first thread gets to decide whether to block and wait for the response or use the `.try_recv()` method to poll for it.

The tools we've presented so far—fork-join for highly parallel computation, channels for loosely connecting components—are sufficient for a wide range of applications. But we're not done.

# Shared Mutable State

In the months since you published the `fern_sim` crate in Chapter 8, your fern simulation software has really taken off. Now you're creating a multiplayer real-time strategy game in which eight players compete to grow mostly authentic period ferns in a simulated Jurassic landscape. The server for this game is a massively parallel app, with requests pouring in on many threads. How can these threads coordinate to start a game as soon as eight players are available?

The problem to be solved is that many threads need access to a shared list of players who are waiting to join a game. This data is necessarily both mutable and shared across all threads. If Rust doesn't have shared mutable state, where does that leave us?

You could solve this by creating a new thread whose whole job is to manage this list. Other threads would communicate with it via channels. Of course, this costs a thread, which has some operating system overhead.

Another option is to use the tools Rust provides for safely sharing mutable data. Such things do exist. They're low-level primitives that will be familiar to any system programmer who's worked with threads. In this section, we'll cover mutexes, read/write locks, condition variables, and atomic integers. Lastly, we'll show how to implement global mutable variables in Rust.

## What Is a Mutex?

A *mutex* (or *lock*) is used to force multiple threads to take turns when accessing certain data. We'll introduce Rust's mutexes in the next section. First, it makes sense to recall what mutexes are like in other languages. A simple use of a mutex in C++ might look like this:

```
// C++ code, not Rust
void FernEmpireApp::JoinWaitingList(PlayerId player) {
    mutex.Acquire();

    waitingList.push_back(player);

    // Start a game if we have enough players waiting.
    if (waitingList.size() >= GAME_SIZE) {
        vector<PlayerId> players;
        waitingList.swap(players);
        StartGame(players);
    }

    mutex.Release();
}
```

The calls `mutex.Acquire()` and `mutex.Release()` mark the beginning and end of a *critical section* in this code. For each `mutex` in a program, only one thread can be running inside a critical section at a time. If one thread is in a critical section, all other threads that call `mutex.Acquire()` will block until the first thread reaches `mutex.Release()`.

We say that the mutex *protects* the data: in this case, `mutex` protects `waitingList`. It is the programmer's responsibility, though, to make sure every thread always acquires the mutex before accessing the data and releases it afterward. Mutexes are helpful for several reasons:

- They prevent *data races,* situations where racing threads concurrently read and write the same memory. Data races are undefined behavior in C++ and Go. Managed languages like Java and C# promise not to crash, but the results of data races are still (to summarize) nonsense.
- Even if data races didn't exist, even if all reads and writes happened one by one in program order, without a mutex the actions of different threads could interleave in arbitrary ways. Imagine trying to write code that works even if other threads modify its data while it's running. Imagine trying to debug it. It would be like your program was haunted.

- Mutexes support programming with *invariants*: rules about protected data that are true by construction when set up and maintained by every critical section.

Of course, all of these are really the same reason: uncontrolled race conditions make programming intractable. Mutexes bring some order to the chaos (though not as much order as channels or fork-join).

However, in most languages, mutexes are easy to mess up. The data and the lock are separate objects. Ideally, comments explain that every thread must acquire the mutex before touching the data:

```
class FernEmpireApp {
    ...

private:
    // List of players waiting to join a game. Protected by
`mutex`.
    vector<PlayerId> waitingList;

    // Lock to acquire before reading or writing `waitingList`.
    Mutex mutex;
    ...
};
```

But even with such nice comments, the compiler can't enforce safe access here. When a piece of code neglects to acquire the mutex, we get undefined behavior. In practice, this means bugs that are extremely hard to reproduce and fix.

Even in Java, where there is some notional association between objects and mutexes, the relationship does not run very deep. The compiler makes no attempt to enforce it, and in practice, the data protected by a lock is rarely exactly the associated object's fields. It often includes data in several objects. Locking schemes are still tricky. Comments are still the main tool for enforcing them.

## Mutex<T>

Now we'll show an implementation of the waiting list in Rust. In our Fern Empire game server, each player has a unique ID:

```
type PlayerId = u32;
```

The waiting list is just a collection of players:

```
const GAME_SIZE: usize = 8;

/// A waiting list never grows to more than GAME_SIZE players.
type WaitingList = Vec<PlayerId>;
```

The waiting list is stored as a field of the `FernEmpireApp`, a singleton that's set up in an `Arc` during server startup. Each thread has an `Arc` pointing to it. It contains all the shared configuration and other flotsam our program needs. Most of that is read-only. Since the waiting list is both shared and mutable, it must be protected by a `Mutex`:

```
use std::sync::Mutex;

/// All threads have shared access to this big context struct.
struct FernEmpireApp {
    ...
    waiting_list: Mutex<WaitingList>,
    ...
}
```

Unlike C++, in Rust the protected data is stored *inside* the `Mutex`. Setting up the `Mutex` looks like this:

```
use std::sync::Arc;

let app = Arc::new(FernEmpireApp {
    ...
    waiting_list: Mutex::new(vec![]),
    ...
});
```

Creating a new `Mutex` looks like creating a new `Box` or `Arc`, but while `Box` and `Arc` signify heap allocation, `Mutex` is solely about locking. If you want your `Mutex` to be allocated in the heap, you have to say so, as we've done here by using `Arc::new` for the whole app and `Mutex::new` just for the protected data. These types are commonly used together: `Arc` is handy for sharing things across threads, and `Mutex` is handy for mutable data that's shared across threads. Now we can implement the `join_waiting_list` method that uses the mutex:

```
impl FernEmpireApp {
    /// Adds a player to the waiting list for the next game.
    /// Starts a new game immediately if enough players are
waiting.
    fn join_waiting_list(&self, player: PlayerId) {
        // Lock the mutex and gain access to the data inside.
        // The scope of `guard` is a critical section.
        let mut guard = self.waiting_list.lock().unwrap();

        // Now do the game logic.
        guard.push(player);
        if guard.len() == GAME_SIZE {
            let players = guard.split_off(0);
            self.start_game(players);
        }
    }
}
```

The only way to get at the data is to call the `.lock()` method:

```
let mut guard = self.waiting_list.lock().unwrap();
```

`self.waiting_list.lock()` blocks until the mutex can be acquired. Then it returns a `MutexGuard<WaitingList>`. The `MutexGuard` has two closely related responsibilities.

First, it provides access to the `WaitingList` protected by the lock. You can use `MutexGuard` to get shared or `mut` access to the lock data. Thanks to deref coercions, discussed in "Deref and DerefMut", we can even call `WaitingList` methods directly on the guard:

```
    guard.push(player);
```

Second, when `guard` is dropped, its `drop` method releases the lock. Ordinarily that happens at the end of the block, but you can also drop it manually:

```
    if guard.len() == GAME_SIZE {
        let players = guard.split_off(0);
        drop(guard);  // don't keep the list locked while starting a
    game
        self.start_game(players);
    }
```

`MutexGuard`'s two responsibilities work together to enforce thread safety. Like `Vec` or `Box`, the `MutexGuard` hands out references to the data it protects, but only for as long as its own lifetime. Rust's lifetime system ensures that access to protected data can't outlive the guard. There's no way to access the data in a `Mutex` except while holding the lock.

## mut and Mutex

It may seem odd—certainly it seemed odd to us at first—that our `join_waiting_list` method doesn't take `self` by `mut` reference. Its type signature is:

```
    fn join_waiting_list(&self, player: PlayerId)
```

The underlying collection, `Vec<PlayerId>`, *does* require a `mut` reference when you call its `push` method. Its type signature is:

```
    pub fn push(&mut self, item: T)
```

And yet this code compiles and runs fine. What's going on here?

In Rust, `&mut` means *exclusive access*. Plain `&` means *shared access*.

We're used to types passing `&mut` access along from the parent to the child, from the container to the contents. You only expect to be able to call `&mut`

`self` methods on `starships[id].engine` if you have a `mut` reference to `starships` to begin with. That's the default, because if you don't have exclusive access to the parent, Rust generally has no way of ensuring that you have exclusive access to the child.

But `Mutex` does have a way: the lock. In fact, a mutex is little more than a way to do exactly this, to provide *exclusive* (`mut`) access to the data inside, even though many threads may have *shared* (non-`mut`) access to the `Mutex` itself.

Rust's type system is telling us what `Mutex` does. It dynamically enforces exclusive access, something that's usually done statically, at compile time, by the Rust compiler.

(You may recall that `std::cell::RefCell` does the same, except without trying to support multiple threads. `Mutex` and `RefCell` are both flavors of interior mutability, which we covered "Interior Mutability".)

## Why Mutexes Are Not Always a Good Idea

Before we started on mutexes, we presented some approaches to concurrency that might have seemed weirdly easy to use correctly if you're coming from C++. This is no coincidence: these approaches are designed to provide strong guarantees against the most confusing aspects of concurrent programming. Programs that exclusively use fork-join parallelism are deterministic and can't deadlock. Programs that use channels are almost as well-behaved. Those that use channels exclusively for pipelining, like our index builder, are deterministic: the timing of message delivery can vary, but it won't affect the output. And so on. Guarantees about multithreaded programs are nice!

The design of Rust's `Mutex` will almost certainly have you using mutexes more systematically and more sensibly than you ever have before. But it's worth pausing and thinking about what Rust's safety guarantees can and can't help with.

Safe Rust code cannot trigger a *data race*, a specific kind of bug where multiple threads read and write the same memory concurrently, producing meaningless results. This is great: data races are always bugs, and they are not rare in real multithreaded programs.

However, threads that use mutexes are subject to some other problems that Rust doesn't fix for you:

- Valid Rust programs can't have data races, but they can have other *race conditions*—situations where a program's behavior depends on timing among threads and may therefore vary from run to run. Some race conditions are benign. Some manifest as general flakiness and incredibly hard-to-fix bugs. Using mutexes in an unstructured way invites race conditions. It's up to you to make sure they're benign.
- Shared mutable state also affects program design. Where channels serve as an abstraction boundary in your code, making it easy to separate isolated components for testing, mutexes encourage a "just-add-a-method" way of working that can lead to a monolithic blob of interrelated code.
- Lastly, mutexes are just not as simple as they seem at first, as the next two sections will show.

All of these problems are inherent in the tools. Use a more structured approach when you can; use a `Mutex` when you must.

## Deadlock

A thread can deadlock itself by trying to acquire a lock that it's already holding:

```
let mut guard1 = self.waiting_list.lock().unwrap();
let mut guard2 = self.waiting_list.lock().unwrap();  // deadlock
```

Suppose the first call to `self.waiting_list.lock()` succeeds, taking the lock. The second call sees that the lock is held, so it blocks, waiting for it to be released. It will be waiting forever. The waiting thread is the one that's holding the lock.

To put it another way, the lock in a `Mutex` is not a recursive lock.

Here the bug is obvious. In a real program, the two `lock()` calls might be in two different methods, one of which calls the other. The code for each method, taken separately, would look fine. There are other ways to get deadlock, too, involving multiple threads that each acquire multiple mutexes at once. Rust's borrow system can't protect you from deadlock. The best protection is to keep critical sections small: get in, do your work, and get out.

It's also possible to get deadlock with channels. For example, two threads might block, each one waiting to receive a message from the other. However, again, good program design can give you high confidence that this won't happen in practice. In a pipeline, like our inverted index builder, data flow is acyclic. Deadlock is as unlikely in such a program as in a Unix shell pipeline.

## Poisoned Mutexes

`Mutex::lock()` returns a `Result` for the same reason that `JoinHandle::join()` does: to fail gracefully if another thread has panicked. When we write `handle.join().unwrap()`, we're telling Rust to propagate panic from one thread to another. The idiom `mutex.lock().unwrap()` is similar.

If a thread panics while holding a `Mutex`, Rust marks the `Mutex` as *poisoned.* Any subsequent attempt to `lock` the poisoned `Mutex` will get an error result. Our `.unwrap()` call tells Rust to panic if that happens, propagating panic from the other thread to this one.

How bad is it to have a poisoned mutex? Poison sounds deadly, but this scenario is not necessarily fatal. As we said in Chapter 7, panic is safe. One

panicking thread leaves the rest of the program in a safe state.

The reason mutexes are poisoned on panic, then, is not for fear of undefined behavior. Rather, the concern is that you've probably been programming with invariants. Since your program panicked and bailed out of a critical section without finishing what it was doing, perhaps having updated some fields of the protected data but not others, it's possible that the invariants are now broken. Rust poisons the mutex to prevent other threads from blundering unwittingly into this broken situation and making it worse. You *can* still lock a poisoned mutex and access the data inside, with mutual exclusion fully enforced; see the documentation for `PoisonError::into_inner()`. But you won't do it by accident.

## Multiconsumer Channels Using Mutexes

We mentioned earlier that Rust's channels are multiple producer, single consumer. Or to put it more concretely, a channel has only one `Receiver`. We can't have a thread pool where many threads use a single `mpsc` channel as a shared worklist.

The `flume` crate provides fast multiproducer and multiconsumer channels. Alternatively, if you don't need the utmost performance, you can write your own. Adding a `Mutex` around the `Receiver` makes it safe to share across threads. Here's a module that does so:

```
pub mod shared_channel {
    use std::sync::{Arc, Mutex};
    use std::sync::mpsc::{channel, Sender, Receiver};

    /// A thread-safe wrapper around a `Receiver`.
    #[derive(Clone)]
    pub struct SharedReceiver<T>(Arc<Mutex<Receiver<T>>>);

    impl<T> Iterator for SharedReceiver<T> {
        type Item = T;

        /// Gets the next item from the wrapped receiver.
        fn next(&mut self) -> Option<T> {
            let guard = self.0.lock().unwrap();
            guard.recv().ok()
```

```
        }
    }

    /// Creates a new channel whose receiver can be shared across
threads.
    /// This returns a sender and a receiver, just like the
stdlib's
    /// `channel()`, and sometimes works as a drop-in
replacement.
    pub fn shared_channel<T>() -> (Sender<T>, SharedReceiver<T>)
{
        let (sender, receiver) = channel();
        (sender, SharedReceiver(Arc::new(Mutex::new(receiver))))
    }
}
```

We're using an `Arc<Mutex<Receiver<T>>>`. The generics have really piled up. This happens more often in Rust than in C++. It might seem this would get confusing, but often, as in this case, just reading off the names can help explain what's going on, as shown in Figure 19-11.

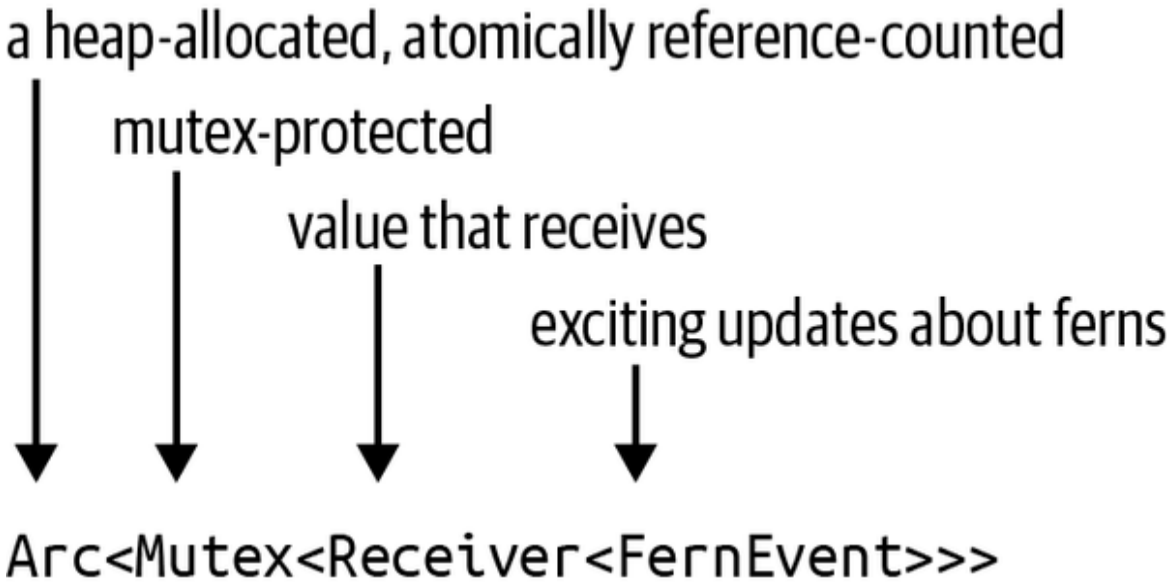


*Figure 19-11. How to read a complex type*

## Read/Write Locks (RwLock<T>)

Now let's move on from mutexes to the other tools provided in `std::sync`, Rust's standard library thread synchronization toolkit. We'll

move quickly, since a complete discussion of these tools is beyond the scope of this book.

Server programs often have configuration information that is loaded once and rarely ever changes. Most threads only query the configuration, but since the configuration *can* change—it may be possible to ask the server to reload its configuration from disk, for example—it must be protected by a lock anyway. In cases like this, a mutex can work, but it's an unnecessary bottleneck. Threads shouldn't have to take turns querying the configuration if it's not changing. This is a case for a *read/write lock*, or `RwLock`.

Whereas a mutex has a single `lock` method, a read/write lock has two locking methods, `read` and `write`. The `RwLock::write` method is like `Mutex::lock`. It waits for exclusive, `mut` access to the protected data. The `RwLock::read` method provides non-`mut` access, with the advantage that it is less likely to have to wait, because many threads can safely read at once. With a mutex, at any given moment, the protected data has only one reader or writer (or none). With a read/write lock, it can have either one writer or many readers, much like Rust references generally.

`FernEmpireApp` might have a struct for configuration, protected by an `RwLock`:

```
use std::sync::RwLock;

struct FernEmpireApp {
    ...
    config: RwLock<AppConfig>,
    ...
}
```

Methods that read the configuration would use `RwLock::read()`:

```
/// True if experimental fungus code should be used.
fn mushrooms_enabled(&self) -> bool {
    let config_guard = self.config.read().unwrap();
    config_guard.mushrooms_enabled
}
```

The method to reload the configuration would use `RwLock::write()`:

```
fn reload_config(&self) -> io::Result<()> {
    let new_config = AppConfig::load()?;
    let mut config_guard = self.config.write().unwrap();
    *config_guard = new_config;
    Ok(())
}
```

Rust is uniquely suited to enforce the safety rules on `RwLock` data. The single-writer-or-multiple-reader concept is the core of Rust's borrow system. `self.config.read()` returns a guard that provides non-`mut` (shared) access to the `AppConfig`; `self.config.write()` returns a different type of guard that provides `mut` (exclusive) access.

## Condition Variables (Condvar)

Often a thread needs to wait until a certain condition becomes true:

- During server shutdown, the main thread may need to wait until all other threads are finished exiting.
- When a worker thread has nothing to do, it needs to wait until there is some data to process.
- A thread implementing a distributed consensus protocol may need to wait until a quorum of peers have responded.

Sometimes, there's a convenient blocking API for the exact condition we want to wait on, like `JoinHandle::join` for the server shutdown example. In other cases, there is no built-in blocking API. Programs can use *condition variables* to build their own. In Rust, the `std::sync::Condvar` type implements condition variables. A `Condvar` has methods `.wait()` and `.notify_all()`; `.wait()` blocks until some other thread calls `.notify_all()`.

There's a bit more to it than that, since a condition variable is always about a particular true-or-false condition about some data protected by a particular

`Mutex`. This `Mutex` and the `Condvar` are therefore related. A full explanation is more than we have room for here, but for the benefit of programmers who have used condition variables before, we'll show the two key bits of code.

When the desired condition becomes true, we call `Condvar::notify_all` (or `notify_one`) to wake up any waiting threads:

```
    self.has_data_condvar.notify_all();
```

To go to sleep and wait for a condition to become true, we use `Condvar::wait()`:

```
    while !guard.has_data() {
        guard = self.has_data_condvar.wait(guard).unwrap();
    }
```

This `while` loop is a standard idiom for condition variables. However, the signature of `Condvar::wait` is unusual. It takes a `MutexGuard` object by value, consumes it, and returns a new `MutexGuard` on success. This captures the intuition that the `wait` method releases the mutex and then reacquires it before returning. Passing the `MutexGuard` by value is a way of saying, "I bestow upon you, `.wait()` method, my exclusive authority to release the mutex."

## Atomics

The `std::sync::atomic` module contains atomic types for lock-free concurrent programming. These types are almost the same as Standard C++ atomics, with some extras:

- `AtomicIsize` and `AtomicUsize` are shared integer types corresponding to the single-threaded `isize` and `usize` types.

- `AtomicI8`, `AtomicI16`, `AtomicI32`, `AtomicI64`, and their unsigned variants like `AtomicU8` are shared integer types that correspond to the single-threaded types `i8`, `i16`, etc.
- An `AtomicBool` is a shared `bool` value.
- An `AtomicPtr<T>` is a shared value of the raw pointer type `*mut T`.

The proper use of atomic data is beyond the scope of this book. Suffice it to say that multiple threads can read and write an atomic value at once without causing data races.

Instead of the usual arithmetic and logical operators, atomic types expose methods that perform *atomic operations,* individual loads, stores, exchanges, and arithmetic operations that happen safely, as a unit, even if other threads are also performing atomic operations that touch the same memory location. Incrementing an `AtomicIsize` named `atom` looks like this:

```
use std::sync::atomic::{AtomicIsize, Ordering};

let atom = AtomicIsize::new(0);
atom.fetch_add(1, Ordering::SeqCst);
```

These methods may compile to specialized machine language instructions. On the x86-64 architecture, this `.fetch_add()` call compiles to a `lock incq` instruction, where an ordinary `n += 1` might compile to a plain `incq` instruction or any number of variations on that theme. The Rust compiler also has to forgo some optimizations around the atomic operation, since—unlike a normal load or store—it can legitimately affect or be affected by other threads right away.

The argument `Ordering::SeqCst` is a *memory ordering.* Memory orderings are something like transaction isolation levels in a database. They tell the system how much you care about such philosophical notions as causes preceding effects and time not having loops, as opposed to

performance. Memory orderings are crucial to program correctness, and they are tricky to understand and reason about. Happily, the performance penalty for choosing sequential consistency, the strictest memory ordering, is often quite low—unlike the performance penalty for putting a SQL database into `SERIALIZABLE` mode. So when in doubt, use `Ordering::SeqCst`.

Rust inherits several other memory orderings from Standard C++ atomics, with various weaker guarantees about the nature of existence and causality. We won't discuss them here. However, one simple use of atomics is for cancellation. Suppose we have a thread that's doing some long-running computation, such as rendering a video, and we would like to be able to cancel it from another thread. The problem is to communicate to the thread that we want it to shut down. We can do this via a shared `AtomicBool`:

```
use std::sync::Arc;
use std::sync::atomic::AtomicBool;

let cancel_flag = Arc::new(AtomicBool::new(false));
let worker_cancel_flag = cancel_flag.clone();
```

This code creates two `Arc<AtomicBool>` smart pointers that point to the same heap-allocated `AtomicBool`, whose initial value is `false`. The first, named `cancel_flag`, will stay in the main thread. The second, `worker_cancel_flag`, will be moved to the worker thread.

Here is the code for the worker:

```
use std::sync::atomic::Ordering;
use std::thread;

let worker_handle = thread::spawn(move || {
    for pixel in animation.pixels_mut() {
        render(pixel);  // ray-tracing - this takes a few
microseconds
        if worker_cancel_flag.load(Ordering::SeqCst) {
            return None;
        }
    }
```

```
        Some(animation)
    });
```

After rendering each pixel, the thread checks the value of the flag by calling its `.load()` method:

```
worker_cancel_flag.load(Ordering::SeqCst)
```

If in the main thread we decide to cancel the worker thread, we store `true` in the `AtomicBool` and then wait for the thread to exit:

```
// Cancel rendering.
cancel_flag.store(true, Ordering::SeqCst);

// Discard the result, which is probably `None`.
worker_handle.join().unwrap();
```

Of course, there are other ways to implement this. The `AtomicBool` here could be replaced with a `Mutex<bool>` or a channel. The main difference is that atomics have minimal overhead. Atomic operations never use system calls. A load or store often compiles to a single CPU instruction. Atomics are a form of interior mutability, like `Mutex` or `RwLock`. Their methods take `self` by shared (non-`mut`) reference. This makes them useful as simple global variables.

## Global Variables

Suppose we are writing networking code. We would like to have a global variable, a counter that we increment every time we serve a packet:

```
/// Number of packets the server has successfully handled.
static PACKETS_SERVED: usize = 0;
```

This compiles fine. There's just one problem. `PACKETS_SERVED` is not mutable, so we can never change it.

Rust does everything it reasonably can to discourage global mutable state. Constants declared with `const` are, of course, immutable. Static variables are also immutable by default, so there is no way to get a `mut` reference to one. A `static` can be declared `mut`, but then accessing it is unsafe. Rust's insistence on thread safety is a major reason for all of these rules.

Global mutable state also has unfortunate software engineering consequences: it tends to make the various parts of a program more tightly coupled, harder to test, and harder to change later. Still, in some cases there's just no reasonable alternative, so we had better find a safe way to declare mutable static variables.

The simplest way to support incrementing `PACKETS_SERVED`, while keeping it thread-safe, is to make it an atomic integer:

```
use std::sync::atomic::AtomicUsize;

static PACKETS_SERVED: AtomicUsize = AtomicUsize::new(0);
```

Once this static is declared, incrementing the packet count is straightforward:

```
use std::sync::atomic::Ordering;

PACKETS_SERVED.fetch_add(1, Ordering::SeqCst);
```

Atomic globals are limited to simple integers and Booleans. Creating a global variable of any other type amounts to solving two problems.

First, the variable must be made thread-safe somehow, because otherwise it can't be global: for safety, static variables must be both `Sync` and non-`mut`. Fortunately, we've already seen the solution for this problem. Rust has types for safely sharing values that change: `Mutex`, `RwLock`, and the atomic types. These types can be modified even when declared as non-`mut`. It's what they do. (See "mut and Mutex".)

Second, static initializers can only call functions specifically marked as `const`, which the compiler can evaluate during compile time. Put another

way, their output is deterministic; it depends only on their arguments, not any other state or I/O. That way, the compiler can embed the results of that computation as a compile-time constant. This is similar to C++ `constexpr`.

The constructors for the `Atomic` types (`AtomicUsize`, `AtomicBool`, and so on) are all `const` functions, which allowed us to create a `static AtomicUsize` earlier. A few other types, like `String`, `Ipv4Addr`, and `Ipv6Addr`, have simple constructors that are `const` as well.

You can also define your own `const fn`s and use them in static initializers:

```
const fn mono_to_rgba(level: u8) -> Color {
    Color {
        red: level,
        green: level,
        blue: level,
        alpha: 0xFF,
    }
}

const WHITE: Color = mono_to_rgba(255);
const BLACK: Color = mono_to_rgba(0);
```

The code of a `const fn` is restricted in the same ways as a `const` or `static` initializer. It must stick to deterministic operations that Rust can compute at compile time. `const` code can use arithmetic, loops, and pattern-matching, but it can't allocate memory or call non-`const` functions. This means a `const fn` can't add items to a `Vec`. Nor can it use standard traits like `Clone`, `Into`, or `Iterator`: trait methods are never `const`.

A global variable protected by a `Mutex` can be initialized with any constant value:

```
static HOSTNAME: Mutex<String> = Mutex::new(String::new());
```

This works because `String::new()` and `Mutex::new()` are both `const fns`.

If we intend to initialize the `HOSTNAME` variable only once, on first use, the standard `LazyLock` type is more convenient than `Mutex`:

```
// Cargo.toml: hostname = "0.4.2"
use std::sync::LazyLock;

static HOSTNAME: LazyLock<String> = LazyLock::new(|| {
    hostname::get()
        .expect("getting the hostname should succeed")
        .into_string()
        .expect("hostname should be a valid UTF-8 string")
});

// Use the global's value like this:
let ip_addr = get_host_ip(&HOSTNAME);
```

We introduced `LazyLock` in "Building Regex Values Lazily". `LazyLock::new` takes a function pointer or closure that will be used to initialize the variable. At first, the function pointer is simply stored in the `LazyLock` value. The first time the variable is dereferenced, `LazyLock` calls the function. Whatever value it returns is then saved for all subsequent uses.

For more about what "dereferencing" means, see "Deref and DerefMut". `LazyLock<T>` implements `Deref<Target = T>`, and it is the `deref` method that actually triggers initialization. In this example, `HOSTNAME` implements `Deref<Target = String>`, and so `&HOSTNAME` can generally be used as a `&String`.

The similar `OnceLock` type supports deferred initialization in a slightly different way. `OnceLock` requires the closure to be provided each time the value is accessed:

```
use std::sync::OnceLock;

static HOSTNAME: OnceLock<String> = OnceLock::new();
```

```
// Use the global's value like this:
let hostname = HOSTNAME.get_or_init(|| {
    hostname::get()
        .expect("getting the hostname should succeed")
        .into_string()
        .expect("hostname should be a valid UTF-8 string")
});
let ip_addr = get_host_ip(&hostname);
```

`OnceLock` is a bit more flexible than `LazyLock`. For example, the initialization code can use local variables that didn't exist yet at the point where the lock was created. But when `LazyLock` works, it's usually more convenient.

The reason for the word `Lock` in `LazyLock` and `OnceLock` is that both behave a bit like a mutex if multiple threads try to initialize the value concurrently. One of those threads will call the closure to initialize the value; the other threads are blocked until initialization is complete. But unlike `Mutex`, these types have no `.lock()` method and no guard types analogous to `MutexGuard`. The locking is handled automatically by the methods that access or initialize the value.

`LazyLock` and `OnceLock` are implemented using `std::sync::Once`, a lower-level synchronization primitive designed for one-time initialization. `Once` is rather special purpose, so we will not cover it in detail. However, it is handy for initializing non-Rust libraries; for an example, see "A Safe Interface to libgit2".

The common locking code used for all three types is optimized for the case where the variable is initialized only once but accessed many times. After initialization, the overhead of accessing a `LazyLock` or `OnceLock` is minimal: a single atomic load to check that initialization has already occurred.

## Thread-Local Variables

Rust also supports *thread-local variables*, a special kind of `static` where, instead of having a single variable for the whole program, each thread gets

its own separate copy.

For example, a web service might have a request ID that's assigned to each unit of work it does. The program includes the request ID in every log entry so that it's easy to find all of a given request's entries in the log, using `grep`. But logging happens throughout the program; it's inconvenient to pass the request ID to every function that may generate log output. A single `static` global variable isn't appropriate either, since the program may have many threads, each one processing a different request. Really there should be one request ID per thread—a thread-local variable.

To declare a thread-local variable, use the `thread_local!` macro:

```
use std::cell::Cell;

thread_local! {
    static REQUEST_ID: Cell<u64> = Cell::new(0);
}
```

This looks like it defines a static of type `Cell<u64>`, but the actual type of `REQUEST_ID` is `std::thread::LocalKey<Cell<u64>>`. Each thread can access its own thread-local copy of the data using methods on the `LocalKey`:

```
/// Gets the current request ID for the calling thread.
pub fn request_id() -> u64 {
    REQUEST_ID.get()
}

/// Sets the current request ID for the calling thread.
pub fn set_request_id(id: u64) {
    REQUEST_ID.set(id);
}
```

Each thread's local copy is initialized on first use and dropped when the thread exits.

The `LocalKey` offers only non-`mut` access to the variable, like an `Rc`, `Arc`, or `static`. Uncontrolled `mut` access would be unsafe. Therefore,

just as a `static` is often a `Mutex` or `RwLock`, to allow controlled `mut` access to the data within, a thread-local variable is commonly wrapped with a `Cell` or `RefCell` for interior mutability. (A mutex would be overkill, since each copy of the variable will only used by the one thread that owns it.) The previous `set` example works because we declared `REQUEST_ID` using `Cell`.

Unfortunately, thread-local variables come with some inherent disadvantages.

Threads don't always map cleanly to your program's units of work. Suppose you have some working code and you decide to speed it up using Rayon. If this code uses the thread-local `REQUEST_ID` for logging, that will likely break.

Rayon's worker threads will see their own uninitialized copy of the variable. Similarly, in `async` code, the subject of our next chapter, running code is organized into *tasks* that can be scheduled arbitrarly onto threads. Thread-local variables don't work well with `async` code. You can use Tokio's *task-local variables* instead, but those work *only* with tasks, not threads.

Furthermore, the use of thread-local variables often shows through API boundaries. If you use a thread-local variable in a library, your users typically need to know about it to use the library correctly with threads and `async` code. A fine counterexample is the thread-local variable in the `rand` crate that holds each thread's default random number generator. This is necessary for performance and harmless because the only expectation users have about `rand`'s output is that it's unpredictable. Only in extreme cases do users care *which thread's* random number generator they are accessing.

But most crates are not `rand`. The popular `tracing` crate uses a thread-local variable to store "spans," collections of logging fields that are attached to each event, rather like `REQUEST_ID`. As a consequence, `tracing` is error-prone when spans are used with threads or `async` code. It is easy to accidentally end up generating log entries with the wrong spans attached.

The ease with which one can experiment with concurrency in Rust is one of the language's great strengths. When you reuse existing code from multiple threads or from asynchronous tasks, once you satisfy `rustc`, things mostly just work! But thread-local variables, by design, behave differently on different threads. Unfortunately, they are commonly used for the sort of contextual data, like `tracing` spans, that can be wrong without totally breaking your program. So bugs are not only easily introduced—they are also easy to miss. It's best to avoid thread-local variables where possible and pass most program state around explicitly.

## What Hacking Concurrent Code in Rust Is Like

We've shown three techniques for using threads in Rust: fork-join parallelism, channels, and shared mutable state with locks. Our aim has been to provide a good introduction to the pieces Rust provides, with a focus on how they can fit together into real programs.

Rust insists on safety, so from the moment you decide to write a multithreaded program, the focus is on building safe, structured communication. Keeping threads mostly isolated is a good way to convince Rust that what you're doing is safe. It happens that isolation is also a good way to make sure what you're doing is correct and maintainable. Again, Rust guides you toward good programs.

More importantly, Rust lets you combine techniques and experiment. You can iterate fast: arguing with the compiler gets you up and running correctly a lot faster than debugging data races.

# Chapter 20. Asynchronous Programming

In the previous chapter, we explained how to use threads in Rust to spread compute-intensive work across multiple processor cores, putting the entire machine to work. In this chapter and the next, we'll present an alternative to threads, offering more efficient concurrency for I/O-bound programs.

For CPU-bound programs, like our Mandelbrot example, the performance hinges entirely on efficient use of the available CPU time. The job requires so much processing that no other resource is under load. Threads are very good at putting CPUs to work.

A network service, though, has different performance characteristics. If it spawns a thread to handle each incoming request, that thread will spend almost all of its time blocked, waiting for I/O. The amount of CPU needed is so small that a single server can serve thousands or even hundreds of thousands of concurrent requests. Performance then depends on efficient use of memory and efficient task creation and switching. Threads use a lot of memory. Even a thread that's doing nothing weighs around 20 KB on most platforms (including kernel and user space memory), and once the thread starts doing real work, its call stack can soak up many times that. And creating threads can be slow.

Rust's *asynchronous code* is a cooperative multitasking system that offers the expressiveness of threaded code with lower overhead—sometimes much lower. The asynchronous counterpart of a thread is called a *task*. Asynchronous tasks in Rust are like tasks in C#, "goroutines" in Go, or "virtual threads" in Java. The facilities of those languages provide a smoother developer experience than Rust's asynchronous code, but they also require complex support from their language runtimes. Asynchronous Rust, in contrast, works well on servers and microcontrollers alike.

Without asynchronous code, each thread does one thing at a time. For example, consider a single-threaded program that calls `reqwest::blocking::get("https://red-bean.com")` to make an HTTP request. Figure 20-1 shows a simplified view of the function call stack as that program runs, from left to right. Each function call is a box, placed atop its caller. Obviously, the `get` function runs throughout the entire execution. It calls functions from the Rust standard library, like `TcpStream::connect` and `TcpStream`'s implementations of `write_all` and `read_to_string`. These call other functions in turn, but eventually the program makes *system calls*, requests to the operating system to actually get something done, like open a TCP connection, or read or write some data.

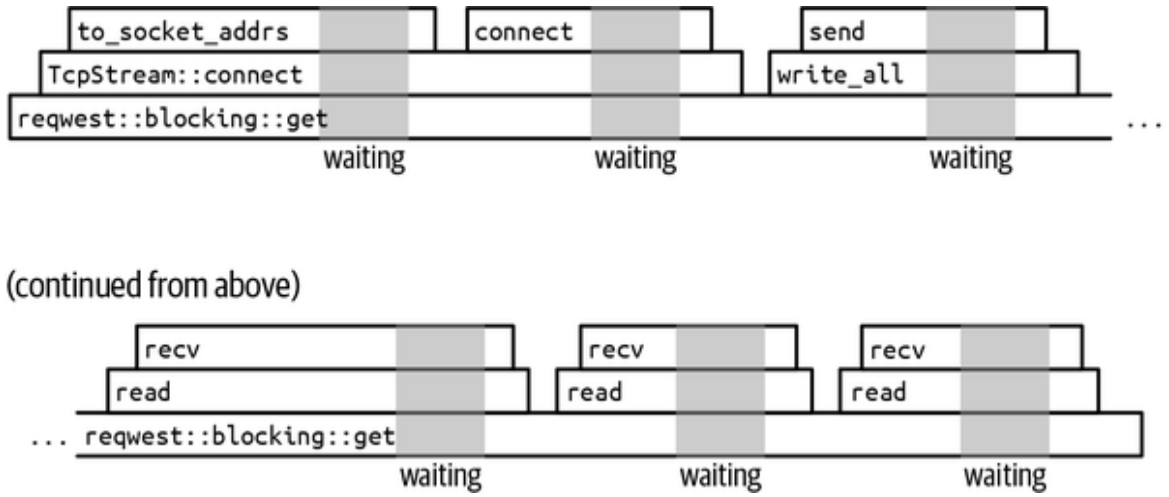


*Figure 20-1. Progress of a synchronous HTTP request (darker areas are waiting for the operating system)*

The darker backgrounds mark the times when the program is waiting for the operating system to finish the system call. This function spends almost all of its time waiting for the operating system; if we had drawn these times to scale, the execution of the actual Rust code would be narrow slivers of white between the system calls.

While this function is waiting for system calls to return, its single thread is *blocked*: it can't do anything else until the system call finishes. It's not unusual for a thread's stack to be tens or hundreds of kilobytes in size, so if this were a fragment of some larger system, with many threads working

away at similar jobs, the thread overhead alone could become quite expensive.

Asynchronous code lets a single thread do more than one thing. Figure 20-2 shows three asynchronous tasks, each running its own HTTP request using the asynchronous version of `reqwest::get`. In the top half of the figure, we see each task's perspective on its own execution.

Each one looks a lot like Figure 20-1. However, instead of blocking, asynchronous code is designed to take turns. The resulting interleaved execution pattern is shown at the bottom of the diagram.

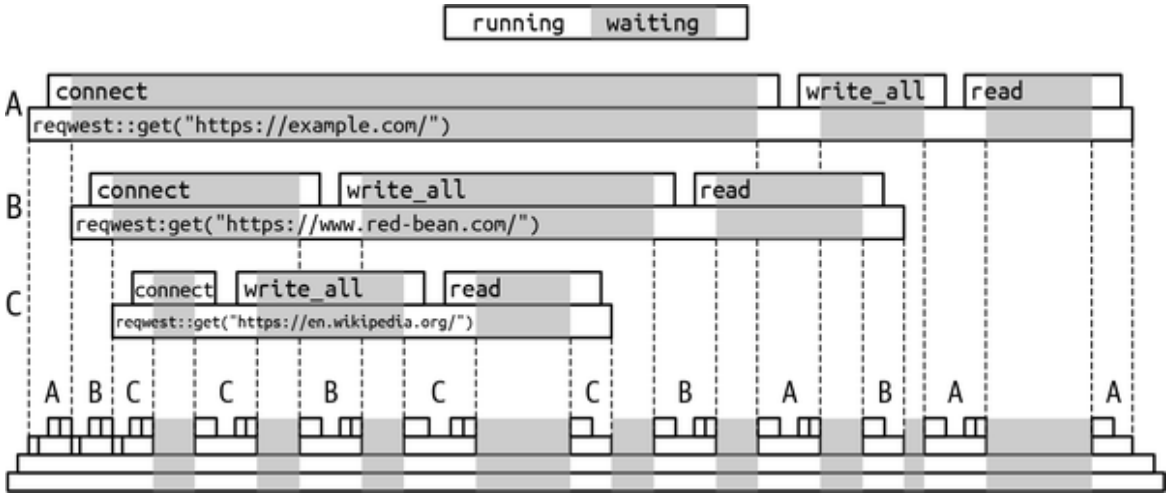


*Figure 20-2. Running three asynchronous tasks on a single thread*

Each request takes just as long as it would have in the synchronous version, but the periods during which the thread would simply be waiting for the network in the synchronous version get filled in with other work instead. This diagram still isn't to scale; you could fit many times more requests in before this thread fully occupied a single CPU core.

If you're doing compute-intensive work, you'll need to use threads to exploit your machine's parallelism. But for a given budget of memory and processor time, asynchronous code can handle many more I/O-bound tasks simultaneously. This is why most popular I/O-related crates in the Rust ecosystem provide asynchronous interfaces. But threads and asynchronous code are often used in combination to handle workloads that have a mix of interactive and computationally intensive tasks.

This chapter approaches asynchronous code from user's point of view: how to write it, how to use published crates with asynchronous interfaces, and how to work through common problems. The next chapter explains how asynchronous code works: exactly how it is suspended, scheduled, and resumed. You'll need those details to understand how asynchronous code will perform and extend the system with your own primitives. But in this chapter, we're concerned only with making stuff work.

## What Asynchronous Code Looks Like

Although asynchronous code shows its value best in applications that create many tasks, its essential features are easiest to understand in simpler situations. So while we'll see highly concurrent code later in the chapter, this section shows an example that offers fewer distractions.

Here's a program that uses the `reqwest` crate to fetch a web page:

```
use anyhow::Result;

async fn make_request() -> Result<String> {
    let url = "https://rust-lang.org/";
    let response = reqwest::get(url)
        .await?
        .text()
        .await?;
    Ok(response)
}

fn main() -> Result<()> {
    let runtime = tokio::runtime::Runtime::new()?;

    let response = runtime.block_on(make_request())?;
    println!("{response}");
    Ok(())
}
```

Here's our program's *Cargo.toml* file:

```
[package]
name = "reqwest-example"
```

```
version = "0.1.0"
edition = "2024"

[dependencies]
anyhow = "1.0.102"
reqwest = "0.13.4"
tokio = { version = "1.52.3", features = ["full"] }
```

When we run this, it writes the unprocessed HTML of the response to its standard output:

```
$ cargo run -p reqwest-example
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.31s
     Running `target/debug/reqwest-example`
<!doctype html>
<html lang="en-US">
  <head>
    <meta charset="utf-8">
    <title>
            Rust Programming Language
        </title>
...
```

This program's code doesn't look terribly different from ordinary Rust. And that's the idea: asynchronous code generally resembles classic, synchronous Rust, with a few additions to make the cooperative multitasking possible:

- An *asynchronous function*, defined with `async fn`, is one whose execution can be suspended while it waits for I/O or other blocking operations to complete. In our program, `make_request` is an asynchronous function. It calls `reqwest::get`, an asynchronous function provided by `reqwest`, a popular HTTP client crate.
- Within an asynchronous function, we can use *await expressions* to wait for asynchronous operations to complete. An await expression is written as `.await`, following the operation we want to wait for. (Although this looks like we're accessing a struct field named `await`, `.await` is actually a postfix operator built into Rust's grammar.)

The `make_request` function uses await expressions to wait for the result from `reqwest::get` and then for the result from calling the `text` method on its success value. The calls to `get` and `text` typically need to wait for the network, and when they do, the await expression suspends the execution of `make_request` itself, to be resumed when it can make progress again.

- In any program that uses asynchronous code, you must specify the *runtime* that will run your asynchronous tasks. An async runtime is Rust's analogue of the operating system's thread scheduler: it maintains a queue of runnable tasks and tracks tasks that are blocked on operations like I/O, waiting for a timer, or acquiring a mutex. When an await expression suspends an asynchronous function call, it is the runtime that resumes it later.

  Our program uses the `tokio` crate's runtime. We create a `Runtime` value and then call its `block_on` method to start an asynchronous task running the call to `make_request`. When the task is done, `block_on` returns `make_request`'s result, which we then print.

In addition to the `Runtime` type, the `tokio` crate provides asynchronous versions of the standard library's I/O and synchronization primitives and various frequently needed utilities. Tokio is by far the most widely used asynchronous support crate, so almost any other crate you find will be ready to work with it. That said, Tokio is just an ordinary third-party crate, not part of the Rust language. There's nothing about implementing a runtime that entails using internal, unstable, or nonportable Rust features. In fact, the next chapter shows how to implement several of a runtime's core features yourself.

It's nearly universal for programs that use asynchronous code to start, as we do here, by creating a runtime and then immediately using it to call some asynchronous function that does all the real work. This gets tedious, so

Tokio provides an attribute macro, `#[tokio::main]`, to package up all the boilerplate:

```
#[tokio::main]
async fn main() -> Result<()> {
    let url = "https://rust-lang.org/";
    let response = reqwest::get(url)
        .await?
        .text()
        .await?;
    println!("{response}");
    Ok(())
}
```

This is equivalent to our original code, but the runtime creation has been hidden away, and `main` itself has become an asynchronous function, so it can use `await` expressions itself. We don't need the `make_request` function any more, since `main` can now call `reqwest::get` directly. Tokio's interface is designed such that you rarely need to refer the runtime explicitly, so using `#[tokio::main]` is usually fine.

## Futures

In the first `reqwest` example, the call to `block_on` may look a little strange:

```
runtime.block_on(make_request())
```

As we said, calling `block_on` creates an asynchronous task to run the call to `make_request` and waits for it to complete. But hasn't `make_request` already returned? If it were an ordinary function, the work would already be done, and there would be nothing left to block on.

But `make_request` is not an ordinary function: it's asynchronous. When you call an asynchronous function, its body does not even begin execution. Instead, the function immediately returns a *future*, a Rust value that represents an asynchronous call in progress. A freshly created future just

records the call's arguments, but it has space for whatever local variables and temporaries the function body will need as it executes. Passing this future to `runtime.block_on` drives the asynchronous call to completion. Once it's done, `block_on` passes along the call's final return value—in this case, the body of the HTTP response. When you know that calling an asynchronous function produces a future, you can make better sense of code like this:

```
reqwest::get(url).await?
```

Here, too, the call to `reqwest::get` returns a future. The `await` expression takes ownership of that future and waits for it to produce a value. In this case, that's a `Result` to which the `?` operator is applied to see if the `get` succeeded.

Futures themselves are passive values; they don't do anything until you await them or pass them to some sort of task-starting function like `block_on`. For example, consider:

```
async fn announce(message: &str) {
    println!("{message}");
}

#[tokio::main]
async fn main() {
    let bonnie = announce("Bonnie");
    let clyde = announce("Clyde");

    println!("Starring:");
    clyde.await;
    println!("and");
    bonnie.await;
}
```

This produces the output:

```
Starring:
Clyde
and
Bonnie
```

Each call to `announce` returns a future, without executing the function's body, so the program's first output is `"Starring:"`. Only when we await the futures do the function calls they represent begin execution, so the two calls to `announce` run in the order we await them, not the order we created them: `"Clyde"` is printed before `"Bonnie"`. If, instead of awaiting a future, we simply drop it, the call that it represents never runs. (Rust prints a warning at compile time if you completely ignore the future of an asynchronous function call, so this rarely happens by mistake.)

Concretely, a future is any value that implements the standard library `Future` trait. The `Future` trait is generally not used directly, and doing so is tricky, so we'll put off examining its definition until the next chapter. For now, what matters is that a type that implements `Future` can be *polled* to let the computation it represents run for as long as it can without blocking. If the computation finishes, the future provides its final return value. Otherwise, the future saves its current state, and the blocking operation that halted its progress arranges to notify the runtime when it is ready so that the runtime can poll the future again to let it progress further.

The term "polling" is often associated with inefficient implementation techniques like busy waiting. That is not how asynchronous Rust works. Futures are polled only when there is actual progress to be made.

This is a good time to pin down a bit of terminology. Although calling an asynchronous function returns a future, that future is just an intermediate step toward what we really care about: the final return value produced by running the function's body to completion. In this book, when we talk about an asynchronous function's "return value," we mean this final return value, emphasizing the parallel with ordinary, synchronous functions. When we do need to talk about the future itself, we'll refer to "the future of the call," or say something similarly explicit.

## Asynchronous Function Future Types

The exact type of the future returned by an asynchronous function is anonymous and unique to that function. All you can say about it is that it implements the `Future` trait. This is analogous to the way Rust handles closures: each closure has its own anonymous, unique type, implementing some subset of the `Fn`, `FnMut`, and `FnOnce` traits. Like closure traits, the `Future` trait has an associated type, `Output`, indicating the type of the future's final value.

Since the future types produced by asynchronous functions are anonymous, if you want to write a function that accepts such a future as an argument, you must give it a generic type, and let type inference supply the details:

```
async fn credits(
    star: impl Future<Output = ()>,
    costar: impl Future<Output = ()>,
) {
    println!("Starring:");
    star.await;
    println!("and");
    costar.await;
}
```

This function permits `star` and `costar` to have any types that implement `Future`, as long as their return types are `()`: since `credits` only awaits them for their side effects, it doesn't expect them to return an interesting value.

You can return a future from a function like this:

```
fn star(star_index: usize) -> impl Future<Output = ()> {
    let name = match star_index {
        0 => "Bonnie",
        1 => "Clyde",
        2 => "Mephistopheles",
        _ => "some minor character",
    };
    announce(name)
}
```

Note that `star` is not an `async fn`: it's an ordinary, synchronous function that just happens to return a future, the one produced by calling the asynchronous function `announce`. Since we return the future immediately, `announce`'s body doesn't run here.

We can use `credits` and `star` like so:

```
#[tokio::main]
async fn main() {
    let bonnie = star(0);
    let clyde = star(1);

    credits(bonnie, clyde).await;
}
```

## async Blocks

In addition to asynchronous functions, Rust also has `async` blocks. The value of an `async` block is a future:

```
let my_future = async {
    println!("Starring:");
    bonnie.await;
    println!("and");
    clyde.await;
};
```

The code in the body of the `async` block does not run right away. Instead, the `async` block produces a future that will run that code when awaited. Like a closure, it can capture variables from the surrounding code. You can even write `async move { ... }` to force the block to take ownership of the variables it refers to, just like writing `move` in front of a closure.

This gives us a way to rewrite any asynchronous function into a synchronous function that just happens to return a future:

```
fn credits(
    star: impl Future<Output = ()>,
    costar: impl Future<Output = ()>,
```

```
) -> impl Future<Output = ()> {
    async {
        println!("Starring:");
        star.await;
        println!("and");
        costar.await;
    }
}
```

This version of `credits` uses different syntax to get the same effect as the original definition. A caller can't tell the difference between the two. But this one is a synchronous function that returns the future of an `async` block. (We could write `async move { ... }`, but Rust can infer from the await expressions that `star` and `costar` must be captured by moving, so it's not necessary.)

## Future Lifetimes

This all looks very neat. But to keep these examples simple, we've been avoiding some details that real-world code needs to worry about. Recall the definition of `announce`:

```
async fn announce(message: &str) {
    println!("{message}");
}
```

Like any asynchronous function, rather than using its arguments immediately, this returns a future that will use them later. Since that future holds the value of `message`, it must not outlive the `str` that `message` borrows. For example, the following is no good:

```
let future = {
    let credits = format!("{star} and {costar}");
    announce(&credits)
};
future.await;
```

The future produced by `announce` holds a reference to `credits`, but `credits` goes out of scope at the end of the block, so the `String` it owns gets dropped at that point.

When we try to use that future outside the block, Rust has concerns:

```
error: `credits` does not live long enough
   |
8  |     let future = {
   |         ------ borrow later stored here
9  |         let credits = format!("{star} and {costar}");
   |             ------- binding `credits` declared here
10 |         announce(&credits)
   |                  ^^^^^^^^ borrowed value does not live long
enough
11 |     };
   |     - `credits` dropped here while still borrowed
```

As an exercise, if we rewrite `announce` as a synchronous function with an `async` block, we can see what's going on a little better:

```
fn announce(message: &str) -> impl Future<Output = ()> {
    async move {
        println!("{message}");
    }
}
```

This returns a future that contains a copy of the reference `message` and perforce inherits its lifetime. If we fully wrote out all the lifetimes in the type signature, it would look like this:

```
fn announce<'m>(message: &'m str) -> impl Future<Output = ()> +
'm
```

The meaning is unchanged. The extra bound `+ 'm` on the return type declares that the result can't outlive the lifetime of `message`. This is the default in Rust, though. Recall that `impl SomeTrait` in the return type means "some type implementing `SomeTrait`, but we're not saying which

one.” This can be a type that depends on the function’s generic parameters, in this case `'m`.

When Rust’s defaults aren’t what we want, we can spell things out with an explicit lifetime bound. Here’s a variant of `announce` that makes a copy of its argument so that it can return a `'static` future:

```
fn copying_announce(message: &str) -> impl Future<Output = ()> +
'static {
    let owned_message = message.to_string();
    async move {
        println!("{owned_message}");
    }
}
```

The bound `+ 'static` declares our goal here: the future’s type “lasts as long as `'static`.” That is, the type itself doesn’t have a lifetime, so callers may keep the future around as long as they like. We achieve this by using `to_string` to turn the `&str` into a `String` and then use `async move` to ensure the future takes ownership of the `String`.

These examples have been a bit trite, to keep the explanations focused, but in the next section, we’ll look at a more developed, realistic example and show how asynchronous code helps manage highly concurrent code.

## Spawning Asynchronous Tasks

With the basics out of the way, we’re ready to put asynchronous Rust to work, running highly concurrent code without wasting resources.

In this section, we’ll write another program using `reqwest`, this time to find all the pages reachable from a given starting page within a given number of links. There are lots of ways to do this, but asynchronous code makes a simple design perfectly feasible: we simply spawn a fresh asynchronous task for every web page we visit. This can easily result in thousands of tasks running simultaneously—but because they’re

asynchronous tasks, not threads, our program's peak resource consumption is reasonable, not much different from a handwritten breadth-first traversal.

Here's the *Cargo.toml* file we'll be using:

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

[dependencies]
anyhow = "1.0.102"
reqwest = "0.13.4"
tokio = { version = "1.52.3", features = ["full"] }
netiquette = "0.1"
scraper = "0.27.0"
```

Most of these crates we've mentioned before. The error-handling crate `anyhow` was introduced in Chapter 7. We've been using `tokio` and the `reqwest` HTTP client in this chapter. The newcomers are `netiquette`, which we will use to crawl the web politely, limiting our program to a request per second per domain; and `scraper` for parsing HTML.

## Listing a Web Page's Outgoing Links

First, we'll take care of a bit of supporting code. The following function fetches a web page, finds the links in it, and returns them as a vector of absolute `Url`s:

```
use reqwest::{Client, Result, Url};
use scraper::{Html, Selector};

pub async fn page_links(client: &Client, url: &Url) ->
Result<Vec<Url>> {
    let body = client
        .get(url.clone())
        .send()
        .await?
        .error_for_status()?
        .text()
        .await?;
```

```
    let doc = Html::parse_document(&body);
    let link_selector = Selector::parse("a[href]").unwrap();
    Ok(doc
        .select(&link_selector)
        .flat_map(|a_elem| {
            let href = a_elem.attr("href").unwrap();
            url.join(href)
        })
        .collect())
}
```

The first half of this function uses `reqwest` to fetch the web page from the given `url`, returning an error if anything goes wrong. We will not dwell on the details of `reqwest`'s API, except to say that a `reqwest::Client` contains a connection pool, so it is better to use a `Client` than the plain `reqwest::get` function when you'll be doing more than one HTTP request.

A successful call to `client.get(url.clone()).send()` returns a `reqwest::Response` representing the HTTP response from the server, which may still be in the process of transmission. We check for HTTP error responses by calling `error_for_status`. If that succeeds, we call `text()` to fully receive the response body and check that it is valid UTF-8. At each point where an error could occur, we use the `?` operator to bail out.

The second half of the function uses `scraper::Html` to parse the response as HTML, finds all `<a href=>` tags in the document, uses `url.join` to resolve relative URLs to absolute URLs, and collects URLs in a vector. A real spider program should honor a few more HTML features, such as the `nofollow` attribute on links, but this will do for an example.

Note that `Html::parse_document` does not return a `Result`. The HTML standard specifies how every possible parse error in an HTML document can be handled (acknowledging the reality that finding botched markup on the web is like finding water in an especially wet ocean). Therefore, the only errors that can happen in this code are from `url.join(&href)`, which returns a `Result<Url,`

`url::ParseError>`. There is, it turns out, such a thing as a broken URL. Rather than treat them as fatal, we use the `flat_map` iterator method to keep the `Ok` results and ignore the errors.

If all goes well, `page_links` returns a vector of absolute URLs.

In the next section, we're going to use `page_links` as the workhorse in a concurrent traversal of the internet. But if you'd like to try it in isolation, here's a possible `main` function you could use:

```
#[tokio::main]
async fn main() -> anyhow::Result<()> {
    let Some(url) = std::env::args().nth(1) else {
        anyhow::bail!("Usage: list-links URL");
    };
    let url = Url::parse(&url)?;

    let link_urls = links::page_links(&Client::new(),
&url).await?;
    for link in link_urls {
        println!("{link}");
    }
    Ok(())
}
```

## Spidering the Web Concurrently

As we mentioned, we'll be using the simple strategy of spawning a task per web page. These tasks will share a few resources. Here's the struct that holds the common state for the traversal:

```
use std::collections::HashSet;
use std::sync::Mutex;

use netiquette::Limiter;
use reqwest::Client;

/// A traversal of the Internet, starting from a given page.
struct Traversal {
    /// HTTP client.
    client: Client,

    /// Set of all URLs we have seen so far. Note: `#fragment`s
```

```
are
    /// stripped, so that URLs pointing to two sections of the
same page
    /// aren't treated as different pages and fetched twice.
    seen: Mutex<HashSet<Url>>,

    /// Self-imposed rate limiter.
    limiter: Limiter,
}
```

We'll create an instance of this struct when we begin a traversal and give each asynchronous task its own `Arc` reference-counted pointer to it. It has three fields:

- `client` is the `reqwest` connection pool, which we will use every time we want to fetch a web page.
- `seen` is a set of all the pages we've visited so far. If we encounter a link to a page that's already in `seen`, we assume that some other task is taking care of enumerating its links and move on.
- `limiter` is used to avoid overloading websites by bombarding them with many requests concurrently or in rapid succession.

Since Tokio uses a thread pool to put all your processor cores to work running asynchronous tasks, we must assume that the fields of `Traversal` could be accessed by several different threads simultaneously. This means that `seen` needs to be protected by a `Mutex`. Although Tokio defines its own `Mutex` type, we don't need to use that here; the standard library's `std::sync::Mutex` will do fine and is slightly preferable. We'll discuss the difference between the two later in this chapter.

To create a fresh `Traversal` value, we provide a `new` function:

```
impl Traversal {
    fn new(client: Client, user_agent: String) -> Self {
        Self {
            seen: Mutex::new(HashSet::new()),
            client: client.clone(),
            limiter: Limiter::new(client, user_agent),
        }
```

```
    }
}
```

The code for the traversal itself is as follows:

```
use std::sync::Arc;
use tokio::task::JoinSet;

/// Visits all pages reachable from `page` within `depth` links.
async fn visit(traversal: Arc<Traversal>, mut url: Url, depth:
usize) {
    url.set_fragment(None);
    if !traversal.seen.lock().unwrap().insert(url.clone()) {
        return;
    }
    if depth == 0 {
        return;
    }

    // Rate limiting; and bail out if robots.txt prohibits
crawling this URL.
    let permit = match traversal.limiter.acquire(&url).await {
        Ok(permit) => permit,
        Err(err) => {
            eprintln!("Skipping <{url}>: {err}");
            return;
        }
    };

    // Fetch the document and find links.
    let links = match links::page_links(&traversal.client,
&url).await {
        Ok(links) => links,
        Err(err) => {
            eprintln!("Error visiting <{url}>: {err}");
            permit.note_error(&url, err);
            return;
        }
    };
    drop(permit); // done: allow crawling other URLs on this
domain

    // Crawl web pages linked from this document, recursively.
    let mut join_set = JoinSet::new();
    for link in links {
        spawn_visit(Arc::clone(&traversal), link, depth - 1, &mut
```

```
    join_set);
        }
        join_set.join_all().await;
}

fn spawn_visit(
        traversal: Arc<Traversal>,
        url: Url,
        depth: usize,
        join_set: &mut JoinSet<()>,
) {
        join_set.spawn(visit(traversal, url, depth));
}
```

We pass `visit` a URL and the number of links outward from that page we would like to explore. First we strip any `#fragment` from the end of the URL so that the spider correctly handles links that point to different sections of the same web page. The call to `HashSet::insert` records that this traversal has seen `url`. Conveniently, `insert` returns `false` if that page was already present in the set, indicating that some other task has already visited this page, so in that case our work is done. If `depth` is zero, then we are not responsible for exploring any further; again, our work is done.

Otherwise, the calling task is the first to reach this page and is thus responsible for enumerating its outgoing links. We call `page_links` to find them and record an error should one arise.

Now that we have our list of links, we have reached the moment where asynchronous code lets us do something that we cannot (or at least should not) do with threads: we simply spawn off a new asynchronous task for every one. If the page has a thousand outgoing links, this will spawn a thousand new asynchronous tasks.

Remember that an asynchronous task is nothing more than a future that the runtime is driving to completion. The future need only be large enough to save the computation's state at each await expression, including those in the callees, like `page_links` and `reqwest::get`. In this case, that's a little over a kilobyte. The runtime itself adds only a small amount of

overhead. And an asynchronous task requires no dedicated kernel resources. This is an order of magnitude less memory than needed for a thread that does nothing—and our asynchronous task does quite a bit more than nothing: it opens an HTTP connection, makes a request, and parses the HTML response body.

The upshot is that it is perfectly feasible to fire off a separate asynchronous task for every web page we want to visit. This frees us to write code that directly reflects the natural structure of the activity we're trying to carry out.

Of course, the exponential nature of the job eventually poses problems for any implementation approach. The internet is big. It's worth thinking about what resource would run out first if we ran our spider with a high depth and how you might redesign the program to scale up further. That's beyond the scope of our example, though.

The spawning loop uses a Tokio collection called a `JoinSet`, which is simply a collection of tasks with a convenient `join_all` method for waiting for them all to complete. `JoinSet::spawn` starts a new asynchronous task on the same runtime as the caller and adds it to the set. We call `Arc::clone` to give each new task its own `Arc` pointer to the `Traversal`.

Ideally, `spawn_visit` would not need to be a separate function; there's no good reason that `visit` should not simply recurse to obtain a future that visits `link` and call `join_set.spawn` itself.

However, as of this writing, there is a bug in the Rust compiler that causes it to believe that the future of `Traversal::visit`'s return value is not safe to move between threads if we do so. Isolating the recursive call to `visit` in its own synchronous function works around this bug.

## Extracting the Traversal's Results

Here's a `main` function that can set all this in motion:

```
#[tokio::main]
async fn main() -> Result<()> {
    let Some(url) = std::env::args().nth(1) else {
        anyhow::bail!("Usage: spider URL");
    };
    let start_url = Url::parse(&url)?;

    let client =
Client::builder().user_agent(USER_AGENT).build()?;
    let traversal = Arc::new(Traversal::new(client,
USER_AGENT.to_string()));
    visit(Arc::clone(&traversal), start_url, 2).await;

    let traversal = Arc::into_inner(traversal).unwrap();
    let seen = traversal.seen.into_inner().unwrap();

    let mut sorted = Vec::from_iter(seen.into_iter());
    sorted.sort();
    for page in sorted {
        println!("{page}");
    }

    Ok(())
}
```

This creates a fresh `Traversal` and prints all URLs reachable within two links from the provided starting URL. (For example, we discovered that starting from Rust's Wikipedia article, in two clicks you can reach articles for "Urediniospore," "Cranberry jelly," or "Hubble Space Telescope," or any of 150,000 other URLs across 7,000 domains.)

It's interesting to observe that this function is able to display the contents of the `Traversal` without locking any `Mutex`es. This is possible because we know that, since each call to `Traversal::visit` waits for all the tasks it has spawned to complete, by the time it returns, the `Arc` owned by `traversal` is the only `Arc` referring to that object in the entire program. Since no other thread has a clone of it, its reference count cannot increase without our knowledge. `Arc::into_inner` takes ownership of an `Arc`, verifies that its reference count is one, and then returns its referent by value. We effectively "unwrap" the `Arc` from around the `Traversal` and take full ownership of it.

A similar argument follows for `Mutex`: if one has ownership of a `Mutex`, not just a reference to it, then there must not be any other thread that can access it, so we can unwrap the `Mutex` from around the value it protects, giving us full ownership of the `seen` and `errors` tables.

## Waiting Versus Blocking

As written, our spider program calls `Html::parse_document` directly from `async` code. Parsing a web page often takes a few hundred milliseconds, and that's a problem. To understand why, we must dig a little deeper into how Tokio works.

The spider program can spawn thousands of tasks at once, but Tokio uses only a handful of system threads, by default one per CPU core, to run all asynchronous code. Fortunately, our tasks spend a fraction of their time running on a thread. The rest of the time, they are stopped at an `.await` point: either in `netiquette`, waiting for a polite interval before contacting a server, or in `reqwest`, waiting for network I/O.

When a task reaches an `.await` point and can't immediately proceed, it relinquishes control back to the runtime. Tokio sets the waiting task aside. If you could look inside the Tokio runtime while this program runs, you would see a small number of tasks actually running on system threads; a large number of tasks that are set aside, waiting; and possibly some tasks in queue, ready for a worker thread to pick them up and run them. This last set includes tasks for which data has just arrived from the network. (If you've ever peeked inside an operating system, this will be a familiar sight. An asynchronous runtime often acts like an operating system in miniature, managing your program's tasks the way an operating system manages threads and processes.)

This arrangement works smoothly if each task is well-behaved. If enough tasks run on a worker thread for long enough without an `.await`, they will hog all of Tokio's threads and prevent other tasks from running, degrading the responsiveness of the system.

In an excellent blog post, "Async: What is blocking?", Tokio maintainer Alice Rhyl wrote:

> *To give a sense of scale of how much time is too much, a good rule of thumb is no more than 10 to 100 microseconds between each* `.await`*. That said, this depends on the kind of application you are writing.*

When `Html::parse_document(body)` runs for 100 milliseconds, we are exceeding the high end of this rule-of-thumb limit by a factor of 1,000. The program will run, and as written, has no need for Tokio to stay responsive. But if we added, say, a graphical visualization of the spider's progress, also running in Tokio worker threads, this could cause dropped frames. If we added a terminal-based user interface, it might be slow to respond to keystrokes. In a production network service, the effect on response times would be even worse: a few bad tasks can crowd out thousands of other requests.

One partial fix is to use a *blocking task*, created with `tokio::task::spawn_blocking`. The second half of `page_links` can be replaced with this:

```
// Spawn a blocking task (not actually the best fix; see below)
let url = url.clone();
tokio::task::spawn_blocking(move || {
    let doc = Html::parse_document(&body);
    let link_selector = Selector::parse("a[href]").unwrap();
    Ok(...)
})
.await
.expect("HTML parsing task panicked")
```

Note that `spawn_blocking` takes a non-`async` closure as its argument. Tokio runs that closure on a separate thread, so it won't interfere with Tokio's responsiveness. `spawn_blocking` returns a future so that the `async` caller can wait for the blocking work to finish. The return value is an error if the task panicked.

However, there's a problem with this plan. Tokio spawns a system thread for each blocking task, up to a limit of several hundred by default. This

design is meant for code that uses blocking system calls, such as writing to a slow disk. But the work we're doing here is CPU-intensive; it would be counterproductive to spawn more threads for this work than the number of CPUs in the system.

We should, therefore, use a thread pool designed for CPU-intensive work:

```
use tokio::sync::oneshot;

// Spawn a Rayon task (the correct fix)
let (sender, receiver) = oneshot::channel();
let url = url.clone();
rayon::spawn(move || {
    let doc = Html::parse_document(&body);
    let links = ...;
    sender.send(links).unwrap();
});
Ok(receiver.await.unwrap())
```

The function `rayon::spawn()` runs a closure on Rayon's thread pool. However, this function doesn't support returning a value to the caller, so we must build that for ourselves, using Tokio's `oneshot` channel. Like the `std::mpsc::channel` and `sync_channel` functions we used in the previous chapter, `tokio::oneshot::channel()` returns a sender and a receiver, but a `oneshot` channel is designed to be used only once. The `send` method takes `self` by value so that the sender value is consumed when used; and instead of calling `receiver.recv()`, we simply use `receiver.await` to wait for a value to be delivered, consuming the receiver.

Oneshot channels often solve minor problems like this. Since the receiver is a future and the sender is a way to directly provide the receiver's value, `oneshot::channel()` can be used to turn any computation into a future.

This completes our spider program. The lesson to take away is that in an asynchronous program, there are several kinds of work, and getting the best performance requires implementing and running these workloads in different ways:

- CPU-light, nonblocking work only needs a fraction of a thread's time. It is written with `async` and `await` and runs on the Tokio worker pool.
- Code that uses blocking system calls should run in Tokio blocking tasks.
- CPU-intensive computation should run in a separate thread pool, such as Rayon.

`spawn_blocking`, `rayon::spawn`, and `oneshot` channels are the bridges that allow programs to span these different worlds.

## Asynchronous Versions of Blocking Tools

The rule, then, is that asynchronous code must avoid blocking the thread it runs on. That's easy to say, but the restriction cuts surprisingly deep. Many familiar APIs, such as `std::thread::sleep` and `std::net::TcpStream::connect`, block the calling thread. In asynchronous code, you must use the asynchronous equivalents, which are generally designed to work the same, except for needing extra `.await`s here and there.

For example, pausing for a second in regular blocking code looks like this:

```
std::thread::sleep(Duration::from_secs(1));
```

This asks the operating system to suspend the calling thread and wake it up after a second has passed.

Tokio offers a straightforward asynchronous equivalent:

```
tokio::time::sleep(Duration::from_secs(1)).await;
```

This asks Tokio to suspend our `async` code at `.await` and wake it up a second later.

Table 20-1 lists common features of the standard library and some other useful crates that have direct equivalents in Rust's `async` ecosystem. Tokio provides the `async` versions, with a few exceptions.

Any of these asynchronous APIs could be implemented in a few lines of code, using `spawn_blocking` to move the blocking operations off of asynchronous threads. In a default build, `tokio::fs` actually works that way. But the rest have custom futures-based implementations, because the performance advantage of asynchronous code comes from avoiding thread overhead, and these low-level I/O APIs are where the magic happens. We'll show how they're implemented in the next chapter.

*Table 20-1. Blocking APIs with direct asynchronous equivalents*

| Topic | Blocking API | Async API |
|---|---|---|
| **Concurrency** | `std::thread::spawn` | `tokio::spawn`, `tokio::task::spawn_blocking` |
| | `std::thread::scope` | `tokio::task::JoinSet` (a very rough equivalent) |
| | `rayon::join` (to run two closures in parallel) | `futures::future::join` (to await two futures concurrently) |
| **Time** | `std::thread::sleep` | `tokio::time::sleep` |
| **I/O** | `std::net::{TcpStream, ...}` | `tokio::net::{TcpStream, ...}` |
| | `reqwest::blocking::{get, Client, Request, ...}` | `reqwest::{get, Client, Request, ...}` |
| | `std::net::ToSocketAddrs` (domain name lookup) | `tokio::net::lookup_host` |
| | `std::io::{Read, Write}` (basic I/O traits) | `tokio::io::{AsyncRead, AsyncWrite, AsyncReadExt, AsyncWriteExt}` |
| | `std::fs::{File, ...}` | `tokio::fs::{File, ...}` (but see the text about this) |
| **Processes** | `std::process::Command` | `tokio::process::Command` |
| **Locking** | `std::sync::{Mutex, RwLock, ...}` | `tokio::sync::{Mutex, RwLock, ...}` (but see the text about this) |

| Topic | Blocking API | Async API |
| --- | --- | --- |
| **Channels** | `std::sync::mpsc::sync_channel` (limited queue size) | `tokio::sync::mpsc::channel` |
| | `std::sync::mpsc::channel` (unlimited queue size) | `tokio::sync::mpsc::unbounded_channel` |

Despite all our warnings, in two cases we recommend using blocking APIs instead of the asynchronous APIs listed in Table 20-1:

- `tokio::fs` is not like the other APIs listed in this table. The default implementation actually uses the blocking APIs from `std::fs`, wrapping each call in `spawn_blocking`. That imposes overhead on every operation. For large chunks of disk I/O work, you can get better performance by doing a single `spawn_blocking` of your own and using `std::fs` in the blocking task. For smaller jobs, like reading a configuration file, it's not unreasonable to call `std::fs` directly from `async` code.
- `std::sync::Mutex` and `RwLock` are better than their asynchronous equivalents for locks that are never held across an `.await` point, as long as contention is low. This is the case for most locks in practice.

The second recommendation is so counterintuitive that we must explain. There are two major differences between `std` locks and Tokio locks. One is that `std` locks and the operating system primitives they rely upon have been heroically fine-tuned over the course of decades. They use almost no memory, and the uncontended path through a mutex is a few machine instructions. The other difference is that Tokio's locks are designed for `async` code. Tokio's `Mutex::lock` method returns a future that the calling task must `.await`; if someone else is holding the mutex, the task is

suspended like any other waiting task, without blocking the worker thread. A `std` mutex would block the thread. That's a severe performance hazard if the lock is unobtainable for a long time, and that's why contention is the deciding factor.

Whatever your use case, holding a `std` lock across an `.await` point is usually a mistake, likely to cause other worker threads to block, and even deadlock, when they try to acquire the same lock. (Clippy, the Rust linter, can detect the most common forms of this bug.)

It's a little odd that `tokio::sync` is the name of the module that provides an `async` version of the `std::sync` toolkit. Both modules are named `sync` because they provide "synchronization primitives," tools for coordination and communication across multiple tasks or threads. This use of "synchronization" dates back to the 1970s, if not earlier. Meanwhile, "asynchronous I/O," the basis of `async` Rust, dates back to the 1980s, so the two similar-sounding but mostly unrelated terms were on a collision course for some 30 years before they met in `tokio::sync`! In any case, there's no contradiction in saying that `async` tasks need synchronization primitives. They need to coordinate.

## Tasks and 'static

Let's look at the type signature of Tokio's `spawn` function:

```
// in tokio::task
fn spawn<F>(future: F) -> JoinHandle<F::Output>
where
    F: Future + Send + 'static,
    F::Output: Send + 'static,
```

How does this compare to the standard library's function for spawning threads?

```
// in std::thread
fn spawn<F, T>(f: F) -> JoinHandle<T>
where
```

```
    F: FnOnce() -> T + Send + 'static,
    T: Send + 'static,
```

The `async` version takes a future instead of a closure, but otherwise these are very similar. The future or closure must be `Send` and `'static` so it's safe to run on another thread for as long as it takes to finish. The return type must be `Send` and `'static` so it's safe to transfer the return value back again when the `JoinHandle` is joined.

We keep stressing these similarities between `async` code and threads because it's easy to forget how similar they are. Again and again, when we have trouble with asynchronous code, we've found it illuminating to ask: what if we were using threads? Very often, the answer is that we'd have the same problem, for the same reasons, and can solve it the same way.

For instance, if you try to `spawn` a future that borrows a local variable, Rust complains:

```
let hosts = vec!["example.com", "example.org"];
tokio::task::spawn(async {
    // error: async block may outlive the current function, but
it
    // borrows `hosts`, which is owned by the current function
    for &host in &hosts {
        let result = reqwest::get(format!
("https://{host}/")).await;
        ...
    }
});
```

You'd get similar errors if you tried the same thing with `std::thread::spawn`, and the fix is similar: use an `async move` block to move the data into the new task instead of borrowing it. Like a thread, a task needs to own its data.

If you can't `move` the value, because the parent task still needs it, you must clone it. Then you can `move` the clone. This is a common technique; often the few lines of code leading up to an `async move` are local variables cloning data owned by the parent task. If a full copy is too expensive, wrap

it in an `Arc<T>`, which is cheaply cloneable. (And if that sounds familiar, it's because you were paying attention in "Sharing Immutable Data Across Threads", where we solved a thread-spawning problem using the same technique.)

## Tasks and Send

In addition to `'static`, a future spawned with Tokio must implement the `Send` marker trait. As we discussed in "Thread Safety: Send and Sync", types that implement `Send` can be safely moved from one thread to another. When a single task spawns a few hundred child tasks, Tokio distributes them among its worker threads. The futures must be `Send` to make this safe. (Tokio workers also practice work-stealing, moving tasks from thread to thread to balance load. This, too, requires `Send`.)

But how can you tell if your future implements `Send`? We said in Chapter 19 that a struct or enum implements `Send` if all its fields are `Send`. Closures and futures follow the same intuition, although the "fields" of those types aren't explicitly written down anywhere in your code. Each closure in your code has its own custom type. This type is `Send` if all the values the closure captures are `Send`.

Futures created by `async` code work the same way. They act as though they have private fields containing all the data they will need to run. A future created by an `async move` block contains each variable it captured, just like a `move` closure. Futures created by calling an `async fn` contain all the function arguments. And all `async` futures have additional private fields for storing the state of the `async` code at each `.await` point: all local variables in scope, and even anonymous temporary values in flight at the `.await`. If all these values are `Send`, the future is `Send`.

This list of types is never spelled out in code, so the `Send` restriction is easy to trip over by accident. For example, the following code looks innocent enough:

```
use std::rc::Rc;

async fn reluctant() -> String {
    let string = Rc::new("ref-counted string".to_string());

    some_asynchronous_thing().await;

    format!("Your splendid string: {string}")
}

tokio::spawn(reluctant());
```

In this case, `reluctant`'s future must use `string` after the `await`, so the future will, at least sometimes, contain an `Rc<String>` value. Since `Rc` pointers cannot be safely shared between threads, the future itself cannot be `Send`. And since `spawn` only accepts futures that are `Send`, Rust objects:

```
error: future cannot be sent between threads safely
    |
19  |     tokio::spawn(reluctant());
    |                  ^^^^^^^^^^^ future returned by `reluctant`
is not `Send`
    |
    = help: within `impl Future<Output = String>`, the trait
`Send` is not
            implemented for `Rc<String>`
note: future is not `Send` as this value is used across an await
    |
14  |         let string = Rc::new("ref-counted
string".to_string());
    |             ------ has type `Rc<String>` which is not
`Send`
...
16  |         some_asynchronous_thing().await;
    |                                   ^^^^^ await occurs here,
with `string`
                                              maybe used later
note: required by a bound in `tokio::spawn`
    |
174 |     pub fn spawn<F>(future: F) -> JoinHandle<F::Output>
    |            ----- required by a bound in this function
175 |     where
176 |         F: Future + Send + 'static,
    |                     ^^^^ required by this bound in `spawn`
```

This error message is long, but it has a lot of helpful detail:

- It explains why the future needs to be `Send`: `tokio::spawn` requires it.
- It explains which value is not `Send`: the local variable `string`, whose type is `Rc<String>`.
- It explains why `string` affects the future: it is in scope across the indicated `await`.

To fix the error, we just need to avoid holding an `Rc<String>` across an await point.[1]

One way to do this is to restrict the scope of the non-`Send` value so that it doesn't cover any `await` expressions and thus doesn't need to be saved in the function's future:

```
async fn reluctant() -> String {
    let return_value = {
        let string = Rc::new("ref-counted string".to_string());
        format!("Your splendid string: {string}")
        // The `Rc<String>` goes out of scope here...
    };

    // ... and thus is not around when we suspend here.
    some_asynchronous_thing().await;

    return_value
}
```

Another solution is simply to use `std::sync::Arc` instead of `Rc`. `Arc` uses atomic updates to manage its reference counts, so `Arc<String>` is `Send`.

Although eventually you'll learn to recognize and avoid non-`Send` types, they can be a bit surprising at first. (At least, your authors were often surprised.) For example, older Rust code sometimes uses generic result types like this:

```
// Not recommended!
type GenericError = Box<dyn std::error::Error>;
type GenericResult<T> = Result<T, GenericError>;
```

This `GenericError` type uses a boxed trait object to hold a value of any type that implements `std::error::Error`. But it doesn't place any further restrictions on it: if someone had a non-`Send` type that implemented `Error`, they could convert a boxed value of that type to a `GenericError`. Because of this possibility, `GenericError` is not `Send`, and a future that holds this kind of error value across an `.await` point isn't `Send` either.

This problem doesn't come up if you use stricter generic error types, like the ones we suggested in "Working with Multiple Error Types":

```
type GenericError = Box<dyn std::error::Error + Send + Sync +
'static>;
type GenericResult<T> = Result<T, GenericError>;
```

This `dyn` type explicitly requires the underlying error type to implement `Send`, so it is `Send` too, and it won't cause problems in `async` code.

For your own trait definitions, you can avoid this kind of trouble by writing `trait MyTrait: Send { ... }`, forcing all types that implement your trait to be `Send`. Then code using `dyn MyTrait` won't need to add `+ Send`. And, of course, you can extend this to `trait MyTrait: Send + Sync + 'static`, if needed.

You might be wondering why Rust lets you write non-`Send` code in the first place, if it isn't going to let you run it! But it's Tokio's multithreaded runtime that imposes the `Send` requirement, not Rust itself. In fact, Tokio's `Runtime::block_on` method does *not* require a `Send` future, because it doesn't use Tokio's thread pool. In general, though, if you use Tokio, most of your futures will need to be `Send`.

## Asynchronous Closures

There is not too much to say about `async` closures. They are just what you'd expect. They look like regular closures, but with an `async` keyword stuck on the front. Like an `async fn`, an `async` closure returns a future.

```
// spawn a task per user
let tasks = users
    .into_iter()
    .map(async |user| {
        add_to_group(user, group).await
    })
    .collect::<JoinSet<_>>();

let results = tasks.join_all().await;
```

In this example, we use the iterator `.map` method to call an `async` closure for each user in the vector `users`, producing a sequence of futures. Then we collect those futures into a `JoinSet`, which spawns one task per future. This is an easy way to run some tasks concurrently.

Just as ordinary closures are often used with iterators, asynchronous closures are often used with the asynchronous analogue of iterators: streams. The `futures` crate provides `Stream` and `StreamExt` traits. These traits are similar to `Iterator`, but they produce items asynchronously: the `next` method of a stream is an `async` method. `StreamExt` offers a smorgasbord of familiar methods (`map`, `filter`, `fold`, `collect`, and so on), many of which take asynchronous closures as arguments.

However, `StreamExt` also includes a few astonishing features that add an element of concurrency over what regular iterators can do. For example, `StreamExt::for_each` applies an asynchronous closure to each element of a stream, one at a time; but there's also `StreamExt::for_each_concurrent`, which processes multiple elements concurrently, up to a limit, which you specify as an argument:

```
// Rolling reboot of a set of servers, 8 at a time
futures::stream::iter(&servers)
    .for_each_concurrent(8, async |server| {
```

```
            server.reboot_and_wait_until_started().await;
        })
        .await;
```

This example creates a stream from an ordinary iterator using `futures::stream::iter`. Then it uses `for_each_concurrent` to call an asynchronous closure on each value, with up to eight closure calls running asynchronously at a time.

## AsyncFn

Analogous to `Fn`, `FnMut`, and `FnOnce`, there are three built-in traits for asynchronous closures: `AsyncFn`, `AsyncFnMut`, and `AsyncFnOnce`. These traits cover anything callable that returns a future: so, `async fn`s and `async` closures, certainly; but also regular closures and functions that return futures, like the `announce` and `copying_announce` examples earlier in this chapter.

Unfortunately, the `AsyncFn` traits do not promise to return a `Send + 'static` future. This means they can cause problems when you want to use a closure with `tokio::spawn` in generic code:

```
async fn kick_off_task<F>(closure: F)
where
    F: AsyncFn() + Send + 'static,
{
    tokio::spawn(async move {
        ...
        closure().await;  // error: awaits a future which is not
Send
        ...
    });
}
```

How can we work around this? We need to require the future type—not only the closure type `F`, but the type of future it returns—to be `Send + 'static`. It's possible to write a function signature that does this, but not

by using `AsyncFn()`. Use the trait `Fn() -> Fut` instead. This makes the future type explicit:

```
fn kick_off_task<F, Fut>(closure: F)
where
    F: Fn() -> Fut + Send + 'static,
    Fut: Future<Output = ()> + Send + 'static,
```

Once we've given the future's type a name in our code, `Fut`, we can easily spell out the requirements that will satisfy `tokio::spawn` in our function's `where` clause.

## Asynchronous Functions in Traits

Traits can include `async` functions, but by default those functions can't be run in Tokio's multithreaded runtime. There isn't an idiomatic way to declare an `async fn` type signature that says "this must return a future that is `Send`."

Two crates offer fixes for this problem:

- The `trait-variant` crate provides an attribute, `#[trait_variant::make]`, that you can use on a trait to declare a `Send` "variant" of that trait. The variant is like the original, but with its `async fn`s rewritten to return `Send` futures.
- The `async-trait` crate provides its own attribute, `#[async_trait::async_trait]`. This also rewrites your `async fn` signatures, but in a way that additionally makes your trait `dyn`-compatible.

The `Future` trait itself is `dyn`-compatible, so you can declare boxed `dyn` future types, similar to what we've seen earlier for closures and errors:

```
type BoxedFuture<T> = Box<dyn Future<Output = T> + Send>;
```

The `async-trait` crate works by transforming all your `async` methods' type signatures to return boxed futures like this. This imposes virtual method call overhead when the futures are polled, but that's necessary in order to make `async` methods `dyn`-compatible.

## Cancellation

There is no safe way to kill a single thread of a process. Safe cleanup is simply impossible, given that there's no way to tell precisely what the thread is doing. It might be holding locks, panicking, in the midst of dropping a large data structure, or even running non-Rust code, such as a system library. But `async` code is designed to yield frequently, at `.await` points, and every time it does so, all its variables and local state are neatly stored in the future. As a consequence, `async` code can be safely cancelled.

This capability has several uses:

- Killing a single running task (`tokio::task::JoinHandle::abort` and `JoinSet::abort_all`)
- Applying a timeout to an any future at all (`tokio::time::timeout`)
- Running any number of futures until we decide to cancel them (`tokio_util::sync::CancellationToken::run_until_cancelled`)
- Letting multiple futures race and handling whichever is ready first, cancelling the others (`tokio::select!`)

In the sections of this chapter, we'll touch on each of these features. To begin with, here is what a timeout looks like in Rust:

```
let result = tokio::time::timeout(
    Duration::from_secs(5),
```

```
        reqwest::get("https://example.com/"),
    ).await;
```

This snippet runs the `reqwest::get` future for up to 5 seconds. If the request finishes in time, the `result` will be an `Ok` wrapping the `reqwest::Result` produced by `get`, a nested `Result`. If time runs out, `result` will be `Err(Elapsed)`, a Tokio error type just for expired timeouts.

When you `tokio::spawn` or `await` a future or pass it by value to `tokio::time::timeout`, you're handing over ownership of that future. Later, if the Tokio runtime needs to cancel that future, it simply drops it. This in turn drops any local variables or other values wrapped up in the future, so any memory or resources it was using are cleaned up, a bit like panic unwinding.

This cleanup scheme is good and bad. Aborting a task is safe and won't normally leak memory. In the case of `reqwest::get`, `drop` methods inside `reqwest` will make sure the network connection is appropriately closed or returned to its connection pool. But in other cases, stopping your code at a random `.await` point can leave work half done, and that can cause bugs. In general, you shouldn't cancel asynchronous code unless you have some sense of what it's doing.

For example, if you abort a network server task, it won't gracefully stop accepting new requests, finish up serving the few in-flight requests, and then exit. Clients will get errors: their network connections will be closed with no response.

## Cancel Safety

Cancellation is like panic unwinding in another regard: if you're not careful, it can cause your code to break its invariants. Consider a function that reads a message from a channel and then updates a data structure. The code is naturally expected to maintain the invariant that the data structure reflects all messages received so far.

Now, between the moment a message is received and the moment the update is complete, the invariant does not quite hold. One message is in flight. This momentary discrepancy is unavoidable, and harmless, as it's only for the duration of the function. Since `mut` access to the data structure is exclusive, Rust can even guarantee that no other code can observe the discrepancy. But if the task panics or is cancelled at an await point before the update is complete, the invariant stays broken permanently.

The term for proper behavior in case of cancellation is "cancel safety." Making sure your code's invariants are intact at each `.await` point is the first step in making it cancel safe. Ultimately cancel safety is not a precisely defined term. The questions it poses are:

- If someone cancels this code, are they in for an unpleasant surprise?
- Have I treated not only `?` but every `.await` as a possible early exit point throughout this code?

If that sounds like too much work, don't do it. Plenty of asynchronous code makes no claim to be cancel safe. Just don't use `abort`, `timeout`, and so on to cancel that code. Don't leave the code running when you exit the program, either: the Tokio runtime cancels all remaining asynchronous tasks when it shuts down.

As with panic safety, enforcing cancel safety is beyond what Rust's type system can do for you. We therefore resort to documentation. Many asynchronous methods in Tokio have documentation with an explicit "Cancel safety" section. For example, `AsyncReadExt::read` promises not to consume any bytes in case of cancellation. Canceling code with no documented cancel safety guarantees is risky.

## Racing Futures with tokio::select!

So far, we've seen futures combined in sequence with `.await` and in parallel with `JoinSet`. There's one more common way to combine futures: *racing* them. This is not as scary as the name's association with

data races and race conditions might make it sound, but it does capture the same idea: racing futures means running several at once and responding only to the first one that completes. This pattern pops up all over the place. Any operation that can be cancelled by sending a message to a oneshot channel or a timeout is racing two futures against each other, and a server handling incoming connections on different ports or different protocols can be expressed as racing futures from each one.

Despite being a common pattern, writing code that actually drives futures this way by hand is pretty complicated, so Tokio provides a macro to help out, called `select!`. A `select!` invocation looks similar to a `match` statement:

```
tokio::select! {
    response = reqwest::get("http://ftp.se.debian.org/debian/ls-
lR.gz") => {
        println!("Sweden was faster. (Status {})",
response?.status());
    }
    response = reqwest::get("http://ftp.ca.debian.org/debian/ls-
lR.gz") => {
        println!("Canada was faster. (Status {})",
response?.status());
    }
}
```

Each arm of the `select!` consists of a variable name (`response`), a future, and then some code. All of the futures are polled until one of them completes; then, the code associated with that future is run, with the future's output bound to the provided name. The other futures are simply dropped and thus cancelled.

The futures in each arm of a `select!` invocation can have different `Output` types. This makes it possible to wait on all kinds of things at the same time. For instance, an asynchronous `timeout` function could be implemented like this:

```
async fn timeout<T, F>(future: F, t: Duration) -> Option<T>
where
```

```
    F: Future<Output = T> + Send + 'static,
{
    tokio::select! {
        _ = tokio::time::sleep(t) => None,
        value = future => Some(value)
    }
}
```

If the sleep duration elapses before the provided future completes, the function returns `None`, and the future the user passed in is cancelled.

Racing futures can be useful at a higher level, too. Many servers are essentially a single loop that spawns a task to deal each request and then goes back to listening for incoming connections. As long as all the futures involved are cancel-safe, `select!` makes this pattern simple to write:

```
use std::io;

use futures::channel::oneshot;
use tokio::net::{TcpListener, TcpStream, UnixListener,
UnixStream};

async fn serve(mut shutdown: oneshot::Receiver<()>) ->
io::Result<()> {
    let tcp_listener =
TcpListener::bind("127.0.0.1:9889").await?;
    let unix_listener =
UnixListener::bind("/tmp/mysocket.sock")?;
    loop {
        tokio::select! {
            tcp_result = tcp_listener.accept() => {
                let (stream, addr) = tcp_result?;
                println!("TCP connection from {addr:?}");
                tokio::spawn(handle_tcp(stream));
            }
            unix_result = unix_listener.accept() => {
                let (stream, addr) = unix_result?;
                println!("Unix domain socket connection from
{addr:?}");
                tokio::spawn(handle_unix(stream));
            }
            _ = &mut shutdown => {
                break;
            }
        }
```

```
        }
        handle_shutdown().await
    }
```

When the `select!` is reached, the `accept()` futures from each listener and the shutdown future are all run concurrently. `select!` picks which branch to poll first at random, to prevent a branch with a future that often completes immediately from hogging the available CPU time.

If one of the listeners receives a new connection, the other's future is cancelled. The winning branch spawns a new task to handle the incoming connection, and the loop starts over, calling `accept()` again to produce a new future for each listener. The shutdown channel, on the other hand, is passed to `select!` by mutable reference. The reference is dropped at the end of the loop, but the shutdown receiver itself is still available to be awaited again in the next iteration.

Each of the futures used in this `select!` loop explicitly documents its cancel safety. Without a guarantee that each one is designed with cancellation in mind, messages could be lost when the other branches' futures are dropped. This is a classic mistake in asynchronous code that is likely to lead to frustrating and difficult to diagnose problems.

## Shutdown

To close out this chapter, a few words on the subject of winding things down.

In general, programs that use threads should shut them down before exiting. Otherwise, when the program exits, every thread is instantly terminated, likely leaving some work unfinished.

The same goes for asynchronous programs. We won't fully describe Tokio shutdown here, but Tokio does cancel all tasks when you drop a `tokio::Runtime` or return from a `main` function marked `#[tokio::main]`. It drops those futures in an unspecified order. If a task tries to spawn more tasks while Tokio is trying to shut down, it panics. If

any blocking tasks don't finish promptly, Tokio leaves them running. So there are plenty of things that could go somewhat wrong if you don't shut down all tasks before exiting.

Calling `tokio::spawn` and ignoring the `JoinHandle` makes correct shutdown difficult. It's better to use `tokio::task::JoinSet` and call `.join_all().await` before exiting.

That alone is sufficient for programs like our spider, which has a finite amount of work to do and shuts down only when it's done. Other programs need to shut down on demand. We'll cover a few ways to do this in the following sections: aborting tasks, shutdown signals, and cancellation tokens.

## Aborting Tasks

The simplest way to stop a task is to call the `abort` method on the handle that `spawn` returns:

```
let handle = tokio::spawn(play_fugazi_forever());
tokio::time::sleep(ONE_HOUR).await;
// ...that's enough of that
handle.abort();
let result = handle.await;
assert!(result.unwrap_err().is_cancelled());
```

When this code calls `handle.abort()`, Tokio stops the spawned task and drops the future. There are a few caveats to keep in mind:

- Consider the cancel safety of the code being aborted. If `play_fugazi_forever()` is implemented via an audio library with `drop` methods that stop playback and leave the system in a reasonable state, this will behave as desired. Otherwise, you may be left listening to post-hardcore punk rock for some time.
- If the task is running on another CPU at the moment you abort it, Tokio will let it run until it yields before dropping it. This means

the task may still be running when `abort()` returns! To ensure the task has been fully cleaned up, we use `handle.await` on the next line.

- Aborting a task does not automatically abort any child tasks it spawns. However, when a `JoinSet` is dropped, any remaining tasks in the set are aborted. If you consistently use local `JoinSets` for spawning child tasks, then aborting one task will recursively tear down its descendants as well. However, all the tasks had better be cancel safe, since you're arranging for them to be automatically cancelled!
- Blocking tasks created with `tokio::task::spawn_blocking` are basically threads. They can't be aborted.

If we need to cancel a blocking task or we have any task at all that wants to run some code other than `drop` methods during shutdown, we need another plan.

## Shutdown Signals

Back in Chapter 2, we created an HTTP server using the `actix-web` crate:

```
let server = HttpServer::new(...);

println!("Serving on http://localhost:3000...");
server
    .bind("127.0.0.1:3000")
    .expect("error binding server to address")
    .run()
    .await
    .expect("error running server");
```

This server runs forever. The only way to stop it is to kill the process, which we did during development by running it in our terminal and hitting Ctrl+C. A real web service should shut down gracefully when the operating system

tells it to. Actix offers a couple of methods for configuring server shutdown:

```
...
server
    .shutdown_signal(shutdown_signal)
    .shutdown_timeout(5)  // seconds
    .bind("127.0.0.1:3000")
    ...
```

The `shutdown_signal` method specifies that in addition to serving requests, Actix should await the given argument, which must be a future satisfying `Future<Output = ()> + Send + 'static`.

When the shutdown signal resolves, the server begins to shut down. Any requests in flight are allowed to run for a time, specified by `shutdown_timeout`, so they have a chance to finish normally. Requests that don't finish in time are aborted. (Methods like `shutdown_timeout` should take `std::time::Duration` arguments. Actix's use of an integer here is a minor API botch.)

For example, if we were to run this service in production, we might want it to react to the `SIGTERM` signal, the standard way for a Unix system to tell a service to shut down. Tokio provides a Unix-only `Signal` type that supports this use case:

```
use tokio::signal::unix::{self, SignalKind};

let mut sigterm = unix::signal(SignalKind::terminate())
    .expect("error installing signal handler");
let shutdown_signal = async move {
    // Wait for the first SIGTERM to be delivered.
    let _ = sigterm.recv().await;
};

println!("Serving on http://localhost:3000...");
server
    .shutdown_signal(shutdown_signal)
    .shutdown_timeout(5)
    .bind("127.0.0.1:3000")
    ...
```

Shutdown signals don't necessarily have anything to do with Unix signals, though. Any future that waits for the desired shutdown-triggering event will do. Other Rust server implementations, such as Axum and Tonic, also provide APIs that follow this pattern. It's sometimes called "graceful shutdown."

## Cancellation Tokens

Now we have dispensed with all the easy shutdown cases. Cancellation tokens are for the more complicated ones.

In "Atomics", we showed how an `Arc<AtomicBool>` can be used to request cancellation across threads. Any thread can set the shared boolean value to true, and other threads can periodically check the value and exit if it's set. The `CancellationToken` type, supplied by `tokio-util` crate, is the deluxe version of `Arc<AtomicBool>`, with extra features for cancelling all kinds of code.

A cancellation token is like a boolean variable: it either is or isn't cancelled. `CancellationToken::new()` creates a new token. Cloning a `CancellationToken`, like cloning an `Arc<AtomicBool>`, creates another reference to the same boolean. Anyone holding one clone of a token can mark them all as cancelled by calling `token.cancel()`. This doesn't invasively stop any code from running; the idea is that you'll pass clones of a cancellation token to all your code that needs to shut down on demand. Different kinds of code will use the token to implement shutdown in different ways:

- Blocking or CPU-intensive code can periodically call `token.is_cancelled()` and exit when it returns `true`.
- A cancel-safe future `f` can be run using `token.run_until_cancelled(f).await`, which returns an `Option`. If the token is cancelled before the future completes, it returns `None`.

- Code that needs a shutdown signal can use `token.cancelled_owned()`. This returns a future that resolves to `()` when the token is cancelled.
- Other asynchronous code can wait for cancellation by calling `token.cancelled().await`. A task might use `select!` in its main loop to wait for a cancellation as one of several possible events:

```
loop {
    tokio::select! {
        // handle other events...
        tcp_result = tcp_listener.accept() => ...
        unix_result = unix_listener.accept() => ...

        // handle cancellation
        () = token.cancelled() => {
            eprintln!("canceled, exiting");
            break;
        }
    }
}
```

In addition, `CancellationToken` supports a hierarchy of "child tokens" to represent a hierarchy of chunks of work to be cancelled. The variety of features here makes cancellation tokens especially useful for adding cancellation to an existing codebase that already has a lot going on.

## Conclusion

Asynchronous code is ubiquitous in the Rust ecosystem; it's pretty much the way Rustaceans write servers or I/O-heavy code of any kind. To that end, we've built this chapter around Rust's asynchronous language features, the crates that work with them, and the tricks of the trade to make it all work. We've left the matter of how any of this is actually implemented completely untouched. In the next chapter, we'll look under the hood and see how asynchronous Rust actually works.

[1] Oddly, we don't need to change `reluctant`'s type signature. Auto traits, including `Send` and `Sync`, are inferred for all abstract return types, such as `-> impl Future<Output = String>`. An `async fn` is shorthand for that. So we need only fix the code inside `reluctant`, and Rust will know that `reluctant()` is now `Send`. This rule sits awkwardly with the rest of the language, since it means a function's type signature does not fully describe the types it produces. You can't tell from an `async fn`'s documentation whether it produces a `Send` future or not.

# Chapter 21. Futures

In Chapter 20, we covered how to use Rust's asynchronous programming system with `async`/`await` syntax and the Tokio runtime. Enabling asynchronous programming without either violating Rust's rules of ownership and memory safety or compromising on performance isn't trivial.

In this chapter, we'll cover three foundational elements of asynchronous programming in Rust:

*The `Future` trait*

Defines an interface between things that need to be waited for and things that wait

*The waker mechanism*

Allows futures to react to changes and I/O events without constantly polling

*Runtimes and reactors*

Tie futures, wakers, and operating system interfaces together into a functioning system

`async fn`s make it easy to create futures, but implementing futures by hand makes their exact size and layout visible in your code, makes it easier to understand exactly what they do, and, of course, is necessary for new operations and types of I/O that don't already have an asynchronous implementation available. Understanding how futures are constructed and used allows you to write your own, as well as to read and debug those you

encounter in the libraries your code depends on. In this chapter, we'll implement a few futures of our own, as well as the code to drive them.

## The Future Trait

The standard library's `Future` trait is defined like this:

```
trait Future {
    type Output;
    // For now, read `Pin<&mut Self>` as `&mut Self`.
    fn poll(self: Pin<&mut Self>, cx: &mut Context<'_>) ->
Poll<Self::Output>;
}

enum Poll<T> {
    Ready(T),
    Pending,
}
```

The first time `Future::poll` is called, it kicks off the execution of the future. On each call, it tries to make progress without blocking. If `poll` finds that the future's work is complete, it returns `Poll::Ready(output)`, where `output` is the future's final result. Otherwise, it returns `Poll::Pending` and promises to let the caller know when the the future is worth polling again by invoking a *waker*, a callback function supplied in the `Context`. We call this the "piñata model" of asynchronous programming: the only thing you can do with a future is whack it with a `poll` until a value falls out.

## Implementing and Instantiating Futures

All modern operating systems include variants of their system calls that we can use to implement this sort of polling interface. On Unix and Windows, for example, if you put a network socket in nonblocking mode, reads and writes return an error if they would block; you have to try again later. This nonblocking mode is the operating system's version of the `Future` trait. It

provides a way for the operating system to say, “please go away and come back later when I have bytes for you,” rather than blocking the calling thread.

The standard library’s `read_to_end` method, which is synchronous, has a signature like:

```
fn read_to_end(&mut self, buf: &mut Vec<u8>) -> Result<usize>;
```

On the other hand, an asynchronous version of `read_to_end` would have a signature roughly like this:

```
fn read_to_end(
    &mut self,
    buf: &mut Vec<u8>,
) -> impl Future<Output = Result<usize>>;
```

The future returned by an asynchronous method must hold all the information necessary to carry out the request made by the call. For example, the future returned by this `read_to_end` function must remember the input stream it was called on and the `Vec<u8>` to which it should append the incoming data.

Here’s what that might look like for an asynchronous read from a network socket:

```
use std::net::TcpStream;

pub struct ReadToEndFuture<'a> {
    stream: &'a mut TcpStream,
    buf: &'a mut Vec<u8>,
    bytes: usize,
}
```

Of course, Tokio implements its own futures for reading from network sockets, which are more complex, but this `ReadToEndFuture` contains all the information needed to make progress on the read operation. Constructing it isn’t difficult, either; all we need is a nonblocking

`TcpStream` and a buffer to write into. An asynchronous wrapper around `TcpStream` using this future might look like this:

```
use std::net::ToSocketAddrs;

/// Open handle to a read-only TCP stream.
struct AsyncStreamReader {
    stream: TcpStream,
}

impl AsyncStreamReader {
    /// Connects to the given address to receive only.
    async fn connect<A: ToSocketAddrs + Send + 'static>(addr: A)
-> io::Result<Self> {
        // We need a blocking task here because making a network
        // connection *blocks* until the connection is made.
        tokio::task::spawn_blocking(move || {
            let stream = TcpStream::connect(addr)?;
            // Tell the operating system to return an error if
there are no
            // bytes available when we try to read.
            stream.set_nonblocking(true)?;
            Ok(Self { stream })
        }).await.unwrap()
    }

    /// Asynchronously reads all data from the stream into `buf`.
    fn read_to_end<'a>(&'a mut self, buf: &'a mut Vec<u8>) ->
ReadToEndFuture<'a> {
        ReadToEndFuture {
            stream: &mut self.stream,
            buf,
            bytes: 0,
        }
    }
}
```

Here, `AsyncStreamReader::read_to_end` adds lifetimes to indicate that the returned future can live only as long as the values that `stream` and `buf` are borrowing. But if `read_to_end` itself just returns a new `ReadToEndFuture`, how does anything get done?

## How Do We Know When to Poll?

When a future is passed to an executor or running async code `.await`s one, it immediately calls `Future::poll()`. This first call will generally do some setup and then check if the underlying operation is ready. If so, `poll()` returns `Poll::Ready`, and the program moves on. If not, the future returns `Poll::Pending` and has to coordinate with the executor to poll it again at the right time. Think about what happens when we run code like this:

```
runtime.block_on(async {
    ...
    let mut buf = Vec::new();
    let response = reader.read_to_end(&mut buf).await?;
    ...
})
```

The first time `block_on` polls the `async` block's future, the network connection is almost certainly not ready immediately, so `block_on` goes to sleep. But when should it wake up? Somehow, once the network connection is ready, something needs to tell `block_on` that it should try polling the `async` block's future again.

When an executor like `block_on` polls a future, it must pass in a callback called a *waker*. If the future is not ready yet, the rules of the `Future` trait say that it must return `Poll::Pending` for now and arrange for the waker to be invoked later, if and when the future is worth polling again.

So, a handwritten implementation of `Future` often looks something like this:

```
use std::task::Waker;

struct MyPrimitiveFuture {
    ...
    waker: Option<Waker>,
}

impl Future for MyPrimitiveFuture {
```

```
    type Output = ...;

    fn poll(mut self: Pin<&mut Self>, cx: &mut Context<'_>) ->
Poll<...> {
        ...

        if ... future is ready ... {
            return Poll::Ready(final_value);
        }

        // Save the waker for later.
        self.waker = Some(cx.waker().clone());
        Poll::Pending
    }
}
```

In other words, if the future's value is ready, return it. Otherwise, stash a clone of the `Context`'s waker somewhere, and return `Poll::Pending`.

When the future is worth polling again, the future must notify the last executor that polled it by calling its waker's `wake` method:

```
// If we have a waker, invoke it, and clear `self.waker`.
if let Some(waker) = self.waker.take() {
    waker.wake();
}
```

Ideally, the executor and the future take turns polling and waking: the executor polls the future and goes to sleep; then the future invokes the waker, so the executor wakes up and polls the future again.

Futures of `async` functions and blocks don't deal with wakers themselves. They simply pass along the context they're given to the subfutures they await, delegating to them the obligation to save and invoke wakers. In the `read_to_end` example, the first poll of the `async` block's future just passes the context along when it awaits `ReadToEndFuture`. Subsequent polls similarly pass their context through to whatever future the block awaits next. (We'll see exactly what `ReadToEndFuture` does with the waker in "Reactors".)

`Waker` implements `Clone` and `Send`, so a future can always make its own copy of the waker and send it to other threads as needed. The `Waker::wake` method consumes the waker. There is a `wake_by_ref` method that does not, but some executors can implement the consuming version a bit more efficiently. (The difference is at most a `clone`.)

Although it's inefficient for an executor to overpoll a future, it's harmless. Futures, however, should be careful to invoke a waker only when polling would make actual progress: a cycle of spurious wakeups and polls can prevent an executor from ever sleeping at all, wasting power and leaving the processor less responsive to other tasks.

Now that we have shown how executors and primitive futures communicate, we'll implement a future ourselves and then walk through an implementation of the `block_on` executor.

## Invoking Wakers: spawn_blocking

In Chapter 20, we described the `spawn_blocking` function, which starts a given closure running on another thread and returns a future of its return value. We now have all the pieces we need to implement `spawn_blocking` ourselves. For simplicity, our version creates a fresh thread for each closure, rather than using a thread pool, as `tokio`'s version does.

Although `spawn_blocking` returns a future, we're not going to write it as an `async fn`. Rather, it'll be an ordinary, synchronous function that returns a struct, `SpawnBlocking`, on which we'll implement `Future` ourselves.

The signature of our `spawn_blocking` is as follows:

```
pub fn spawn_blocking<T, F>(closure: F) -> SpawnBlocking<T>
where
    F: FnOnce() -> T,
    F: Send + 'static,
    T: Send + 'static,
```

Since we need to send the closure to another thread and bring the return value back, both the closure `F` and its return value `T` must implement `Send`. And since we don't have any idea how long the thread will run, they must both be `'static` as well. These are the same bounds that `std::thread::spawn` itself imposes.

`SpawnBlocking<T>` is a future of the closure's return value. Here is its definition:

```
use std::sync::{Arc, Mutex};
use std::task::Waker;

pub struct SpawnBlocking<T>(Arc<Mutex<TaskState<T>>>);

struct TaskState<T> {
    value: Option<T>,
    waker: Option<Waker>,
}
```

The `TaskState` struct must serve as a rendezvous between the future and the thread running the closure, so it is owned by an `Arc` and protected with a `Mutex`. (A synchronous mutex is fine here.) Polling the future checks whether `value` is present and saves the waker in `waker` if not. The thread that runs the closure saves its return value in `value` and then invokes `waker`, if present.

Here's the full definition of `spawn_blocking`:

```
pub fn spawn_blocking<T, F>(closure: F) -> SpawnBlocking<T>
where
    F: FnOnce() -> T,
    F: Send + 'static,
    T: Send + 'static,
{
    let state = Arc::new(Mutex::new(TaskState {
        value: None,
        waker: None,
    }));

    std::thread::spawn({
        let state = state.clone();
```

```
            move || {
                let value = closure();

                let maybe_waker = {
                    let mut guard = state.lock().unwrap();
                    guard.value = Some(value);
                    guard.waker.take()
                };

                if let Some(waker) = maybe_waker {
                    waker.wake();
                }
            }
        });

        SpawnBlocking(state)
    }
```

After creating the `TaskState` value, this spawns a thread to run the closure, store the result in the `TaskState`'s `value` field, and invoke the waker, if any.

We can implement `Future` for `SpawnBlocking` as follows:

```
use std::pin::Pin;
use std::task::{Context, Poll};

impl<T: Send> Future for SpawnBlocking<T> {
    type Output = T;

    fn poll(self: Pin<&mut Self>, cx: &mut Context<'_>) ->
Poll<T> {
        let mut guard = self.0.lock().unwrap();
        if let Some(value) = guard.value.take() {
            return Poll::Ready(value);
        }

        guard.waker = Some(cx.waker().clone());
        Poll::Pending
    }
}
```

Polling a `SpawnBlocking` checks if the closure's value is ready, taking ownership and returning it if so. Otherwise, the future is still pending, so it

saves a clone of the context's waker in the future's `waker` field.

Once a `Future` has returned `Poll::Ready`, you're not supposed to poll it again. The usual ways of consuming futures, like `await` and `block_on`, all respect this rule. If a `SpawnBlocking` future is overpolled, nothing especially terrible happens, but it doesn't go to any effort to handle that case, either. This is typical for handwritten futures.

## Implementing block_on

In addition to being able to implement primitive futures, we also have all the pieces we need to build a simple executor. In this section, we'll write our own version of `block_on`. It will be quite a bit simpler than Tokio's version; for example, it won't support task-local variables or nested invocations (calling `block_on` from asynchronous code). But it is sufficient to run our `read_to_end` future.

Here's the code:

```
use std::pin::pin;
use std::task::{Context, Poll};
use std::thread;

use waker_fn::waker_fn;       // Cargo.toml: waker-fn = "1.2.0"

fn block_on<F: Future>(future: F) -> F::Output {
    let executor_thread = thread::current();
    let waker = waker_fn(move || executor_thread.unpark());
    let mut context = Context::from_waker(&waker);

    let mut future = pin!(future);

    loop {
        match future.as_mut().poll(&mut context) {
            Poll::Ready(value) => return value,
            Poll::Pending => thread::park(),
        }
    }
}
```

This is pretty short, but there's a lot going on, so let's take it one piece at a time. The standard library equips every thread with a simple blocking mechanism. Calling `std::thread::park()` blocks the thread until someone else calls `.unpark()` on the corresponding `Thread`, which you obtain beforehand, either from a `JoinHandle` for a thread you've spawned or from `std::thread::current()` for the current thread:

```
let executor_thread = thread::current();
```

If you `unpark` a thread that isn't parked yet, its next call to `park` returns immediately, without blocking. Our `block_on` will use the `std::thread::park` to wait whenever the future isn't ready, and the waker we pass to futures will unpark it. The `waker_fn` function, from the crate of the same name, creates a `Waker` from a given closure. Here, we make a `Waker` that, when invoked, calls the closure `move || thread.unpark()`. You can also create wakers by implementing the `std::task::Wake` trait, but `waker_fn` is more convenient here:

```
let waker = waker_fn(move || executor_thread.unpark());
```

This gives us the `Pin<&mut Self>` required by the `poll` method (we'll discuss this in depth in "Pinning"):

```
let mut future = pin!(future);
```

Finally, the polling loop is quite simple. Passing a context carrying our waker, we poll the future until it returns `Poll::Ready`. If it returns `Poll::Pending`, we park the thread, which blocks until `waker` is invoked. Then we try again:

```
loop {
    match future.as_mut().poll(&mut context) {
        Poll::Ready(value) => return value,
        Poll::Pending => thread::park(),
    }
}
```

The `as_mut` call lets us poll `future` without giving up ownership; we'll explain this more in "Pinned Pointers".

# The Role of Runtimes

It's entirely possible to write an efficient program using `async` without relying on any external libraries or to use a patchwork of libraries that each provide just one component, but most asynchronous programs in Rust use an integrated runtime library. Runtimes provide an executor alongside I/O and synchronization facilities that are designed to work well with it. In this book, we've used the Tokio library, which provides a broad set of I/O operations, channels, and locks alongside a work-stealing executor designed to make efficient use of multiple threads. Other runtimes exist for specific use cases, like software running on embedded systems with limited concurrency facilities.

To understand exactly what Tokio provides, let's implement an I/O future ourselves.

## Implementing I/O Futures

As we saw in "Asynchronous Versions of Blocking Tools", it's entirely possible to make I/O operations asynchronous by simply spawning a thread to deal with each one, but in many cases, we can do better.

Remember the `ReadToEndFuture` we briefly discussed in "Implementing and Instantiating Futures"? Implementing `Future` for it is mostly straightforward:

```
use std::io::{self, ErrorKind, prelude::*};
use std::pin::Pin;
use std::task::{Context, Poll};

impl<'a> Future for ReadToEndFuture<'a> {
    type Output = io::Result<usize>;

    fn poll(
        mut self: Pin<&mut Self>,
```

```
            cx: &mut Context<'_>
        ) -> Poll<Self::Output> {
            let mut buf = [0; 4096];
            loop {
                match self.stream.read(&mut buf) {
                    Ok(0) => return Poll::Ready(Ok(self.bytes)),
                    Ok(n) => {
                        self.buf.extend_from_slice(&buf[0..n]);
                        self.bytes += n;
                        // Repeat the loop and try to make more
progress.
                    }
                    Err(e) if e.kind() == ErrorKind::WouldBlock => {
                        todo!("Uh oh! How do we know when to poll()
again?");
                        return Poll::Pending;
                    }
                    Err(e) => return Poll::Ready(Err(e)),
                }
            }
        }
    }
```

Each time `poll()` is called, it tries to `read()` some bytes into an intermediate buffer in a loop, which keeps running as long as `read()` is making progress. If `read()` returns `Ok(0)`, the TCP connection is closed, and the future can return `Poll::Ready` with the total number of bytes read. If `read()` returns an `Error` with any `ErrorKind` other than `WouldBlock`, we want to stop and return that error immediately, so that results in a `Poll::Ready` too.

When `read()` returns an `Error` with `ErrorKind::WouldBlock`, the operating system is telling our program that there's no data available to read right now, but there might be some data in the future. We can't `wake()` the waker immediately, because it's very likely that calling `poll()` again will have exactly the same result: nothing. This would lead to the executor simply `poll()`ing the same future over and over again, wasting time.

On the other hand, we can't return `Pending` and never call `wake_by_ref()`, because our future would never be woken up again. Unlike `spawn_blocking`, there's no convenient thread to send `Waker`

to. We don't want to spawn a new thread for every stream being read, since that would be no more efficient than simply using `std::thread::spawn()` without a future. So, how does our code know when to call its waker?

## Reactors

One of the key features of Rust's asynchronous programming ecosystem isn't actually part of the language or its standard library at all. A *reactor* is a single thread that interacts with the operating system on behalf of other parts of an asynchronous program. It allows futures to register their interest in certain events, such as time passing, signals or errors being raised by the operating system, or I/O events, and runs callbacks when those events occur. That's exactly what `ReadToEndFuture` needs in order to work properly in an asynchronous program.

Reactors aren't unique to Rust. NodeJS, for example, is based on an event loop that drives the I/O operations represented in JavaScript programs as `Promises`. The operating system machinery to support this paradigm has existed since the 1980s, and most high-performance servers use it. Asynchronous Rust is just an ergonomic way to program in this style.

Next, we will describe how reactors work and then show a Unix implementation of a reactor that can handle network reads. Before we begin, we need a little vocabulary about how I/O works on Unix. A *file descriptor* is an integer that acts as a handle to some system resource, usually something you can read or write: a file, pipe, network socket, or terminal. The `poll` API takes an array of file descriptors as an argument, waits until one or more are ready for reading or writing, and then tells us which ones need attention.

Throughout this example, we will use Rust's Unix-only file descriptor types: `std::os::fd::RawFd`, `BorrowedFd`, and `OwnedFd`. All three are just newtypes wrapping integers returned by the operating system in response to system calls like `open`, `dup`, and so forth. Types like `File`, `TcpStream`, and `PipeReader` are also just wrappers around these

integers of special origin, with helpful methods attached. The `AsFd` and `AsRawFd` traits provide access to the underlying file descriptors.

Figure 21-1 shows a `poll`-based reactor in action.

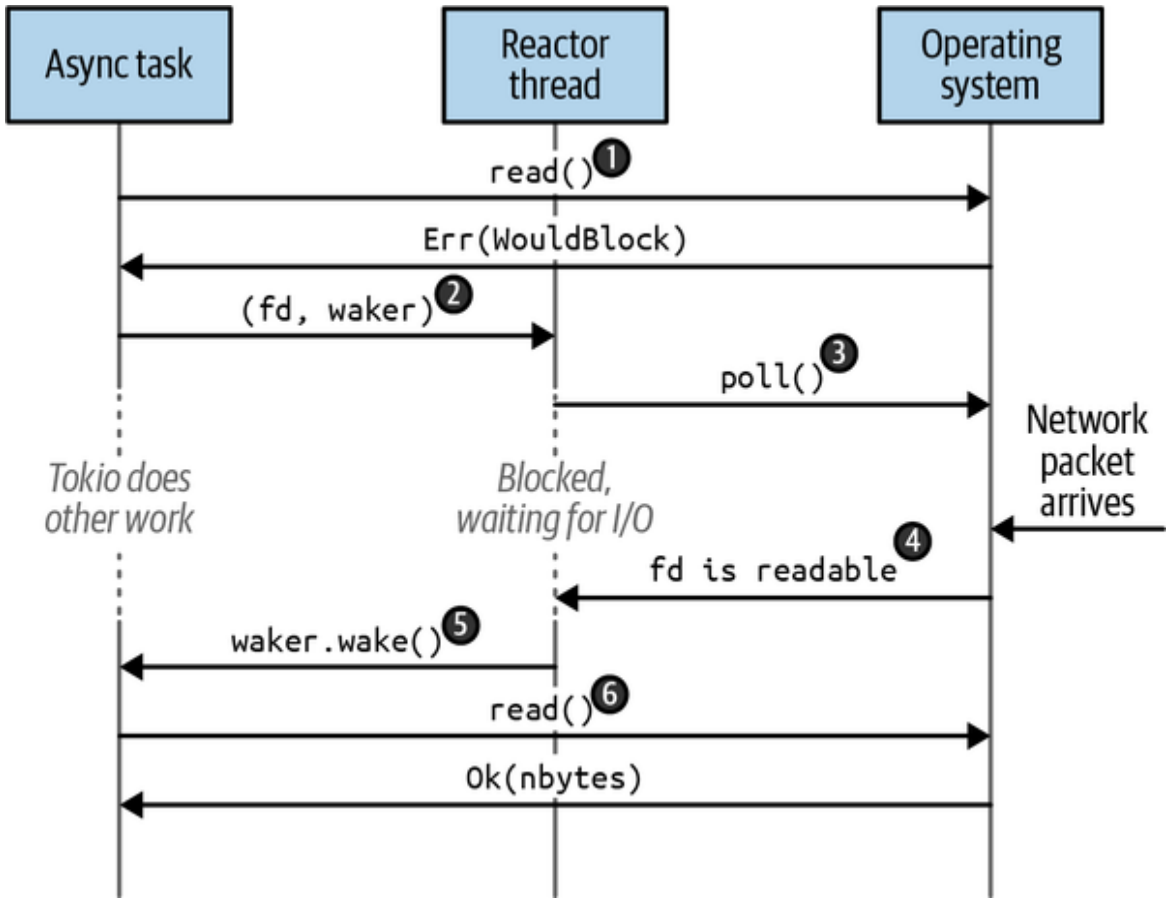


*Figure 21-1. A reactor participates in an asynchronous read*

Let's take a closer look:

1. First, the asynchronous task enters `ReadToEndFuture::poll` and tries to `read()` data from the network (❶). This is the part we already implemented in the last section. If this read succeeded right away, the reactor wouldn't need to get involved. In the story this figure is telling, however, the operating system returns an error, saying that there's no data ready and the read would therefore block. (Remember, earlier we called `set_nonblocking` on the socket specifically to request this error so that we don't block in asynchronous code.)

2. The task handles this error by passing the network connection's file descriptor (`fd`) and its waker to the reactor (❷). The gist of this message is, "wake me up when this connection has data to read." The task then generally won't have anything to do until it's awakened, so it returns `Pending` to the executor. The executor can go do other work.

3. The reactor adds `fd` to the list of connections it's monitoring. As we mentioned, it might be responsible for monitoring connections for thousands of tasks, not just the one shown here. The reactor uses the `poll()` system call to wait for I/O on any of those connections (❸). This blocks the reactor thread.

4. Eventually, a network packet arrives on the connection. The operating system returns from `poll` to the reactor thread (❹), telling the reactor that `fd` is now ready to read.

5. The reactor then calls `waker.wake()` to wake up the task (❺). Its work for this task is now done, so it can drop the waker and its handle to the file descriptor.

6. The executor now polls the task again, and this time the `read` succeeds (❻).

This is the arrangement that enables a small number of threads to service a large number of connections.

## Implementing a Reactor

Our simple reactor is about a hundred lines of code, so we'll show it in pieces.

First, we need a way for our asynchronous tasks to send requests to the reactor (step ❷ in Figure 21-1). We'll use a channel. Since there's just one reactor thread, we'll create a single, global handle to it, which looks like this:

```rust
use std::io::PipeWriter;
use std::os::fd::OwnedFd;
use std::sync::{Arc, Mutex, mpsc};
use std::task::Waker;

#[derive(Clone)]
pub struct ReactorHandle {
    fd_sender: mpsc::Sender<(OwnedFd, Waker)>,
    interrupt_writer: Arc<Mutex<PipeWriter>>,
}
```

This `ReactorHandle` is just a way for asynchronous tasks to send `(fd, waker)` pairs to the reactor. We'll see in a moment how it works and what the `interrupt_writer` is for.

Creating the `ReactorHandle` is simple:

```rust
use std::sync::OnceLock;

static REACTOR: OnceLock<ReactorHandle> = OnceLock::new();

pub fn get_reactor() -> ReactorHandle {
    REACTOR
        .get_or_init(|| {
            let (reader, writer) = std::io::pipe().expect("Could
not open pipe");
            let (sender, receiver) = mpsc::channel::<(OwnedFd,
Waker)>();
            std::thread::spawn(move || reactor_loop(reader,
receiver));

            ReactorHandle {
                fd_sender: sender,
                interrupt_writer: Arc::new(Mutex::new(writer)),
            }
        })
        .clone()
}
```

When `get_reactor` is called, it tries to return a clone of the `ReactorHandle` stored in the global `REACTOR` variable. If there isn't one yet, the reactor hasn't been started, so it creates all of the requisite parts and starts `reactor_loop` in a new thread.

We use `std::io::pipe()` to create a Unix pipe, a pair of file descriptors that transport bytes between them. We'll use this to notify the reactor thread when there's something new in the channel. Since the reactor's whole purpose is to wait for new data from file descriptors, a pipe is a form of notification it'll find easy to handle.

The `ReactorHandle` doesn't provide a way to remove handles from the reactor explicitly, and we don't need one. Once they have bytes available, their associated task will be woken up, and they'll be removed.

Having created both ends of the channel and pipe, `get_reactor` passes them into `reactor_loop`, which is spawned on a new thread. That's where the core of the reactor lives:

```
use std::collections::HashMap;
use std::io::PipeReader;
use std::os::fd::{AsFd, AsRawFd, RawFd};

use nix::poll::{PollFd, PollFlags, PollTimeout, poll};

fn reactor_loop(
    mut interrupt_reader: PipeReader,
    handle_receiver: mpsc::Receiver<(OwnedFd, Waker)>,
) {
    let mut fds = HashMap::<RawFd, (OwnedFd, Waker)>::new();
    loop {
        let interrupt_poller =
PollFd::new(interrupt_reader.as_fd(), PollFlags::POLLIN);
        let mut pollers = vec![interrupt_poller];

        for (fd, _) in fds.values() {
            pollers.push(PollFd::new(fd.as_fd(),
PollFlags::POLLIN));
        }

        // Wait for one of the configured pollers to have data
available
        poll(&mut pollers, PollTimeout::NONE).expect("Unable to
poll()");

        // Find out which file descriptors have data to read
        let awoken_fds: Vec<_> = pollers
            .iter()
            .filter_map(|p| match p.revents() {
```

```
                    Some(e) if !e.is_empty() =>
Some(p.as_fd().as_raw_fd()),
                    _ => None,
                })
                .collect();

            // Handle waking up the tasks for each fd
            awoken_fds.iter().for_each(|fd| {
                if let Some((_, waker)) = fds.remove(fd) {
                    waker.wake();
                } else if *fd == interrupt_reader.as_raw_fd() {
                    let mut buf = [0_u8; 1024];
                    interrupt_reader
                        .read(&mut buf)
                        .expect("Interrupt pipe closed");
                }
            });

            // Insert newly queued files, if any, into the hashmap
            for (fd, waker) in handle_receiver.try_iter() {
                fds.insert(fd.as_raw_fd(), (fd, waker));
            }
        }
}
```

The reactor maintains its internal state as a map of `RawFd`s, the underlying representation of a file descriptor, to their associated `Waker`s. Within a process, currently open file descriptors are guaranteed to be unique, so there's no danger of a collision.

The rest of the reactor is one big loop. First, the reactor constructs the `PollFd` structs that indicate interest in particular events to the operating system. Each `PollFd` contains the file descriptor and `PollFlags::POLLIN`, which tells the operating system we only care about input. The first of these `PollFd` structs registers interest in the interrupt pipe, so writing to it will wake the reactor up and start another iteration of the loop.

Those `PollFd`s are then passed to `poll`. We're using `nix::poll::poll`, a thin, safe wrapper around the `poll` system call. It blocks the reactor thread until one or more of the file descriptors has had

something written to it. This call to `poll` is step ❸ of Figure 21-1; returning from it is step ❹.

Before it returns, the operating system updates the `PollFd` structs with some flags, accessible in `nix` through the `revents` method. The reactor checks all the `PollFd`s, selecting only those `poll` marked as readable. It removes their entries from the file descriptor map, taking ownership of each associated `Waker` and calling `wake()` on it (step ❺). The executor will take care of step ❻, calling `Future::poll()` on the awakened tasks.

The reactor then reads from the interrupt pipe to to clear it out. We aren't interested in the values written to it, just the fact that something was written. Finally, the reactor checks for any newly submitted files to be watched and adds them to the map. Then it's time to do the whole dance again.

The last piece of the puzzle is actually getting the `(OwnedFd, Waker)` pairs sent to the reactor when they're ready to be waited on, which happens in two parts. There's a method on the `ReactorHandle` that accepts a `TcpStream` and a `Waker`:

```
impl ReactorHandle {
    pub fn request_wakeup(&self, stream: &TcpStream, waker:
Waker) {
        let fd = stream.as_fd().try_clone_to_owned().unwrap();
        let mut interrupt_writer =
self.interrupt_writer.lock().unwrap();
        self.fd_sender
            .send((fd, waker))
            .expect("Failed to send new subscription to
reactor");
        interrupt_writer
            .write_all(b"\0")
            .expect("Failed to interrupt reactor");
    }
}
```

First, `request_wakeup` has to get an `OwnedFd` from the borrowed `TcpStream`. The standard library allows us to get a `BorrowedFd` from a reference to a `TcpStream`, and a `BorrowedFd` can be turned into an

`OwnedFd` by asking the operating system to make a new file descriptor, with a new number and its own open/closed state, which points to the same I/O object internally. This `OwnedFd` will be dropped and closed if the reactor wakes up the future that created it, but that won't affect the file descriptor held by that future.

With the `OwnedFd` in hand, `request_wakeup` adds the future's `Waker` to the reactor's queue along with its corresponding file descriptor and then writes a single byte to the interrupt pipe. This makes the reactor wake up, check if any of the already-registered streams are readable, and check the channel for new `Wakers` to add to its `HashMap`.

So, we can finally properly implement that last match arm in `ReadToEndFuture::poll`:

```
Err(e) if e.kind() == ErrorKind::WouldBlock => {
    get_reactor().request_wakeup(self.stream,
cx.waker().clone());
    return Poll::Pending;
}
```

If the future sees that it can't make more progress at the moment, it simply asks the reactor for a wake-up call and returns `Poll::Pending`.

Writing reactors that handle I/O efficiently can be complex. For example, using unsafe code, it's possible to avoid the call to `try_clone_to_owned` in `request_wakeup`. With some additional setup, the number of allocations within each iteration of the reactor's loop can also be reduced, and we'll see how to remove the intermediate buffer allocation in `poll` later in this chapter.

Tokio provides a broad set of I/O futures that use a single, well-optimized event loop. They also have the advantage of being designed with the inner workings of Tokio's runtime in mind.

## Cooperative Multitasking

In addition to responding to I/O events, Tokio keeps track of how active each task has been and balances time between them, ensuring that newly ready tasks don't sit around waiting on tasks that have been consistently making progress. This mechanism is similar to the preemptive multitasking employed by an operating system's scheduler, but Tokio can't just pause a future whenever it likes. In its *cooperative multitasking* scheme, Tokio has to rely on every future that does long-running work to occasionally yield control.

If you do long computations in a future or bring in a non-Tokio library to do I/O, this can become a problem. Consider this asynchronous message-counting middleware:

```
// Count the messages passed from one FTL communicator to
another.
async fn count(inbox: &mut Ansible, outbox: &mut Ansible) ->
usize {
    let mut n = 0;

    while let Some(msg) = inbox.read_message().await {
        outbox.send_message(msg).await;
        n += 1;
    }

    n
}
```

If the futures returned by `read_message` and `send_message` usually —or, worse, always—return `Poll::Ready`, running this future under Tokio will cause other work on that thread to grind to a halt, because Tokio won't have an opportunity to schedule anything else to run. Even though execution is passing through `.await` points, it never yields control back to the executor. Fortunately, Tokio provides a way to opt in to the cooperative multitasking system in `consume_budget`:

```
while let Some(msg) = inbox.read_message().await {
    outbox.send_message(msg).await;
    n += 1;
    tokio::task::consume_budget().await;
}
```

Polling the future returned by `consume_budget` updates the runtime's understanding of how much work the awaiting task has done. The caller then receives `Poll::Ready` if the runtime is ready for the task to do some more work immediately, or `Poll::Pending` if Tokio wants to run something else and wake this task up again later.

As a user of Tokio, you won't usually need to call `consume_budget` yourself, because many of the futures returned by Tokio's APIs, and the libraries that use them (like `reqwest`), participate in this system. Every time you `await` an I/O future under Tokio, your code is implicitly participating in cooperative multitasking already.

### Tokio's Executor

You may remember from "Tasks and Send" that tasks spawned in Tokio must be `Send`, because Tokio's executor is multithreaded. Like Rayon, Tokio uses work-stealing to balance work across multiple threads. Tasks that are ready to run are placed in a queue and polled on whichever thread is available until they return either `Poll::Ready` or `Poll::Pending`. Periodically, and whenever there aren't any tasks in the queue, Tokio checks for new I/O events that might wake up some tasks.

Tokio also provides a single-threaded option in the current-thread executor, which is what you get if you call `block_on`. It works similarly to the work-stealing executor, but with just one thread, queueing work to be done and checking for new I/O events periodically. `block_on` can run a non-`Send` future but still requires futures spawned from within that future to be `Send`.

## Pinning

Most things in Rust don't care where they're stored. You're free to pass an `i32` or a `String` by value, return it, put it in a `Box`, and so forth, without worrying that accessing that value will cause undefined behavior. Not every value is like this, though. *Address-sensitive* values, whose validity depends

on being at a particular address in memory, can't be moved. Some futures are address-sensitive.

In this section, we'll show why futures of asynchronous function calls and blocks are address-sensitive and why they can't be handled as freely as ordinary Rust values. Then we'll show how the `Pin` type serves as a "seal of approval" on pointers that can be counted on to manage such futures safely and how the `Unpin` trait allows the compiler to tell which types need special handling. Finally, we'll show a few ways to work with `Pin` values.

## The Two Life Stages of a Future

Consider this simple asynchronous function:

```
use std::io;

use tokio::io::AsyncReadExt;
use tokio::net::TcpStream;

async fn fetch_string(address: &str) -> io::Result<String> {
    ❶
    let mut socket = TcpStream::connect(address).await❷?;
    let mut buf = String::new();
    socket.read_to_string(&mut buf).await❸?;
    Ok(buf)
}
```

This opens a TCP connection to the given address and returns, as a `String`, whatever the server there wants to send. The points labeled ❶, ❷, and ❸ are the *resumption points*, the points in the `async fn`'s code at which execution may be suspended.

Suppose you call it, without awaiting, like so:

```
let response_future = fetch_string("localhost:6502");
```

Now `response_future` is a future ready to begin execution at the start of `fetch_string`, with the given argument. In memory, the future looks something like Figure 21-2.

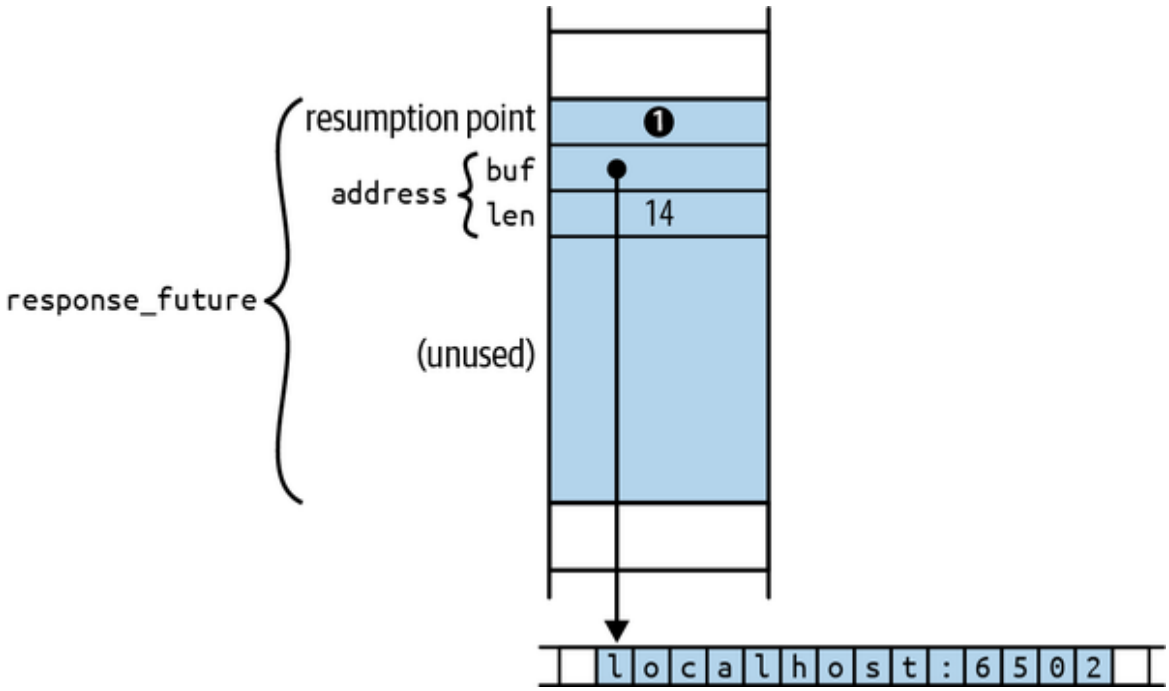


*Figure 21-2. The future constructed for a call to `fetch_string`*

Since we just created this future, it says that execution should begin at resumption point ❶, at the top of the function body. In this state, the only values a future needs to proceed are the function arguments.

Now suppose that you poll `response_future` a few times and it reaches this point in the `async` code:

```
socket.read_to_string(&mut buf).await❸?;
```

Suppose further that the result of `read_to_string` isn't ready, so the poll returns `Poll::Pending`. At this point, the future looks like Figure 21-3.

A future must always hold all the information needed to resume execution the next time it is polled. In this case that is:

- Resumption point ❸, saying that execution should resume in the `await` polling `read_to_string`'s future.
- The values `socket` and `buf` are alive at that resumption point. The value of `address` is no longer present in the future, since the

function no longer needs it.

- The `read_to_string` subfuture, which the `await` expression is in the midst of polling.

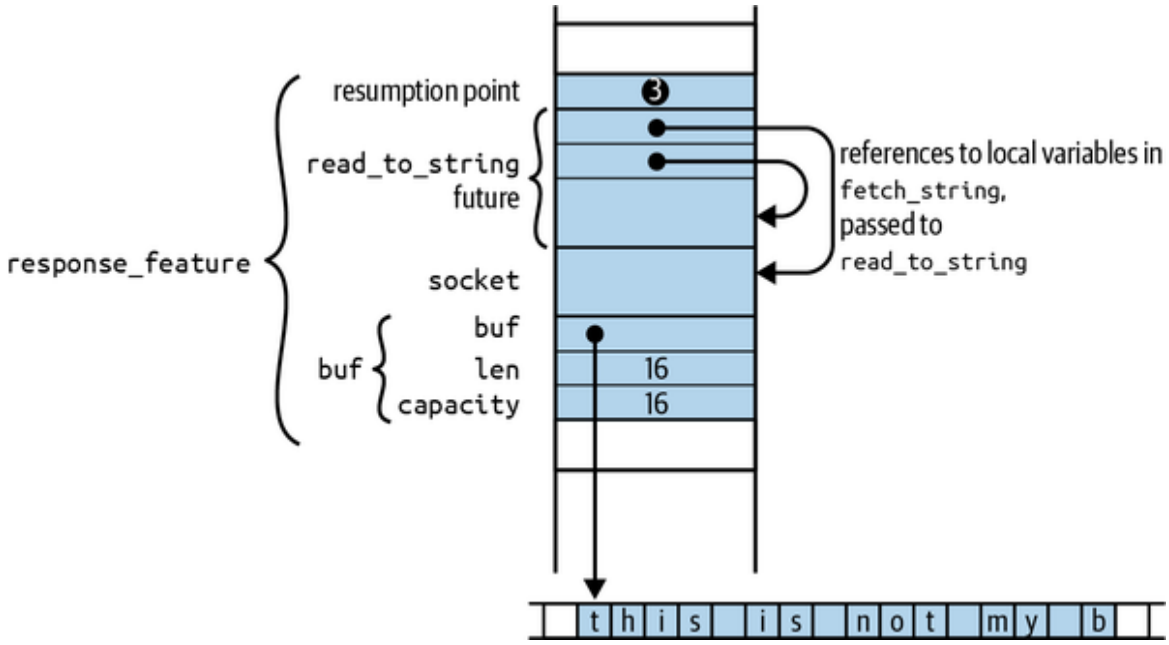


*Figure 21-3. The same future, in the midst of awaiting `read_to_string`*

Note that the call to `read_to_string` has borrowed references to `socket` and `buf`. In a synchronous function, all local variables live on the stack, but in an `async` function, local variables that are alive across an `await` must be located in the future, so they'll be available when it is polled again. Borrowing a reference to such a variable borrows a part of the future.

However, Rust requires that values not be moved while they are borrowed. Suppose you were to move this future to a new location:

```
let new_variable = response_future;
```

Rust has no means to find all the active references and adjust them accordingly. Instead of pointing to `socket` and `buf` at their new locations, the references continue to point at their old locations in the now-

uninitialized `response_future`. They have become dangling pointers, as shown in Figure 21-4.

Preventing borrowed values from being moved is generally the borrow checker's responsibility. The borrow checker treats variables as the roots of ownership trees, but unlike variables stored on the stack, variables stored in futures get moved if the future itself moves. This means the borrows of `socket` and `buf` affect not just what `fetch_string` can do with its own variables, but what its caller can safely do with `response_future`, the future that holds them. Futures of `async` functions are a blind spot for the borrow checker, which Rust must cover somehow if it wants to keep its memory safety promises.

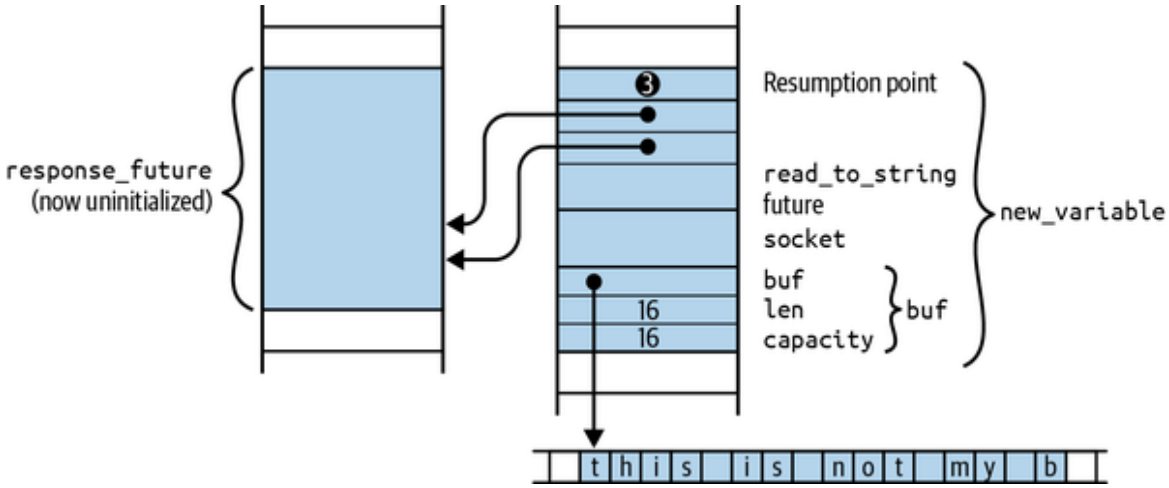


*Figure 21-4. `fetch_string`'s future, moved while borrowed (Rust prevents this)*

Rust's solution to this problem rests on the insight that futures are always safe to move when they are first created and only become unsafe to move when they are polled. A future that has just been created by calling an `async` function simply holds a resumption point and the function's arguments' values, while one created by evaluating an `async` block holds a resumption point and the values it captures. These are only in scope within the `async` function or block, which has not yet begun execution. Only polling a future can borrow its contents.

From this, we can see that every future has two life stages:

- The first stage begins when the future is created. Because the `async` code hasn't begun execution, no part of it could possibly be borrowed yet. At this point, it's as safe to move as any other Rust value.
- The second stage begins the first time the future is polled. Once the `async` code has begun execution, it could borrow references to variables stored in the future and then await, leaving that part of the future borrowed. Starting after its first poll, we must assume the future might not be safe to move.

The flexibility of the first life stage is what lets us pass futures to `block_on` and `spawn` and call adapter methods like `race` and `fuse`, all of which take futures by value. In fact, even the `async` function call that created the future in the first place had to return it to the caller; that was a move as well.

To enter its second life stage, the future must be polled. The `poll` method requires the future be passed as a `Pin<&mut Self>` value. `Pin` is a wrapper for pointer types (like `&mut Self`) that restricts how the pointers can be used, ensuring that their referents (like `Self`) cannot ever be moved again. So you must produce a `Pin`-wrapped pointer to the future before you can poll it.

This, then, is Rust's strategy for keeping futures safe: a future can't become dangerous to move until it's polled. You can't poll a future until you've constructed a `Pin`-wrapped pointer to it, and once you've done that, the future can't be moved.

"A value you can't move" sounds impossible: moves are everywhere in Rust. We'll explain exactly how `Pin` protects futures in the next section.

## Pinned Pointers

The `Pin` type is a wrapper for pointers that prevents the pointer's referent from being moved. It was introduced at the same time as `async`, `await`,

and `Future`, specifically to solve the problems caused by address-sensitive futures.

By *pointer*, we mean any type that implements `Deref`, and possibly `DerefMut`. A `Pin` wrapped around a pointer is called a *pinned pointer*. `Pin<&mut T>` and `Pin<Box<T>>` are typical.

The definition of `Pin` in the standard library is simple:

```
pub struct Pin<P> {
    pointer: P,
}
```

Note that the `pointer` field is *not* `pub`. This means that the only way to construct a `Pin` is to get the standard library to make it for you. There are a few features that do so, and each one is carefully designed to ensure that once a pinned pointer exists, you can't move the value:

- The `pin!` macro takes a value of type `T`, stores it in a hidden local variable, and returns a pinned pointer to that variable, a `Pin<&mut T>`. Simply putting the value in a variable that you can't name is sufficient to keep you from moving it again. It'll be dropped when control reaches the end of the current block. We used `pin!` in our `block_on` implementation to pin the future we wanted to poll.
- The standard library's `Box::pin` constructor takes ownership of a value of any type `T`, moves it into the heap, and returns a `Pin<Box<T>>`.
- `Pin<Box<T>>` implements `From<Box<T>>`, so `Pin::from(boxed)` takes ownership of `boxed` and gives you back a pinned box pointing at the same `T` in the heap.

Every way to obtain a pinned pointer entails giving up ownership of the value being pinned, and there is no way to get it back out. The pinned pointer itself can be moved in any way you please, of course, but moving a

pointer doesn't move its referent. So possession of a pinned pointer to a future serves as proof that you have permanently given up the ability to move that future. This is all we need to know that it can be polled safely.

Once you've pinned a future, if you'd like to poll it, all `Pin<pointer to T>` types have an `as_mut` method that dereferences the pointer and returns the `Pin<&mut T>` that `poll` requires The `as_mut` method can also help you poll a future without giving up ownership. Our `block_on` implementation used it in this role:

```
let mut future = pin!(future);

loop {
    match future.as_mut().poll(&mut context) {
        Poll::Ready(value) => return value,
        Poll::Pending => thread::park(),
    }
}
```

Here, the `pin!` macro has redeclared `future` as a `Pin<&mut F>`, so we could pass that to `poll`. Mutable references are not `Copy`, so `Pin<&mut F>` cannot be `Copy` either, meaning that calling `future.poll()` would directly take ownership of `future`, leaving the next iteration of the loop with an uninitialized variable. To avoid this, call `future.as_mut()` to reborrow a fresh `Pin<&mut F>` for each loop iteration. There is no way to get a `&mut` reference to a pinned future. If you could, you'd use `std::mem::replace` or `std::mem::swap` to move it out and put a different future in its place.

The reason we don't have to worry about pinning futures in ordinary asynchronous code is that the most common ways to obtain a future's value —awaiting it or passing to an executor—all take ownership of the future and manage the pinning internally. For example, our `block_on` implementation takes ownership of the future and uses the `pin!` macro to produce the `Pin<&mut F>` needed to poll. An `await` expression also takes ownership of the future and uses an approach similar to the `pin!` macro internally.

## The Unpin Trait

Not all futures require this kind of careful handling. For any handwritten implementation of `Future` for an ordinary type, like our `SpawnBlocking` type mentioned earlier, the restrictions on constructing and using pinned pointers are unnecessary.

Such durable types implement the `Unpin` marker trait:

```
trait Unpin {}
```

Almost all types in Rust automatically implement `Unpin`, using special support in the compiler. `async` futures are the exceptions to this rule. For `Unpin` types, `Pin` imposes no restrictions whatsoever. You can make a pinned pointer from an ordinary pointer with `Pin::new` and get the pointer back out with `Pin::into_inner`. The `Pin` itself passes along the pointer's own `Deref` and `DerefMut` implementations.

For example, `String` implements `Unpin`, so we can write:

```
let mut string = "Pinned?".to_string();
let mut pinned: Pin<&mut String> = Pin::new(&mut string);

pinned.push_str(" Not");
Pin::into_inner(pinned).push_str(" so much.");

let new_home = string;
assert_eq!(new_home, "Pinned? Not so much.");
```

Even after making a `Pin<&mut String>`, we have full mutable access to the string and can move it to a new variable once the `Pin` has been consumed by `into_inner` and the mutable reference is gone. So for types that are `Unpin`—which is almost all of them—`Pin` is mostly just a boring wrapper around pointers to that type.

When you implement `Future` for your own `Unpin` types, your `poll` implementation can treat `self` as if it were `&mut Self`, not `Pin<&mut Self>`. Pinning becomes something you can mostly ignore, unless you

need to make disjoint mutable borrows of the fields of the future, like, for example, a buffer and a file, as in `ReadToEndFuture`.

The `ReadToEndFuture::poll` method that we implemented earlier reads into an intermediate buffer and then copies its contents into the future's output buffer. It would be more natural to skip the intermediate buffer and write straight into the output vector, and the crate `rustix` provides a wrapper type for `Vec` that allows us to do just that:

```
use rustix::buffer::spare_capacity; // Cargo.toml: rustix = "1"

...
fn poll(mut self: Pin<&mut Self>, cx: &mut Context<'_>) ->
Poll<Self::Output> {
    loop {
        if self.buf.capacity() == self.buf.len() {
            self.buf.reserve(4096);
        }

        match rustix::io::read(&mut self.stream,
spare_capacity(self.buf)) {
        ...
```

`rustix::io::read` can read bytes into a variety of places in memory. Using `spare_capacity`, we're telling it to write into the unused capacity of `self.buf`. This requires two mutable borrows of `self`: one for `self.stream` and one for `self.buf`.

The Rust compiler is smart enough to know that these fields are not the same—unless those fields are being accessed through `DerefMut`, which is how `Pin` works. And indeed, this code does not compile:

```
error: cannot borrow `self` as mutable more than once at a time
    match rustix::io::read(&mut self.stream,
spare_capacity(self.buf)) {
          ----------------      ----                        ^^^^
          |                     |
second mutable
          |                     |
borrow occurs here
          |                     |
```

```
            |                       first mutable borrow occurs here
            first borrow later used by call
```

Fortunately, `ReadToEndFuture` is `Unpin`, so all we need to do is call `Pin::into_inner`:

```
use rustix::io::read; // Cargo.toml: rustix = "1"
use rustix::buffer::spare_capacity;

impl<'a> Future for ReadToEndFuture<'a> {
    type Output = io::Result<usize>;


    fn poll(
        self: Pin<&mut Self>,
        cx: &mut Context<'_>
    ) -> Poll<Self::Output> {
        let unpinned = Pin::into_inner(self);
        loop {
            if unpinned.buf.capacity() == unpinned.buf.len() {
                unpinned.buf.reserve(4096);
            }

            match read(&mut unpinned.stream,
spare_capacity(unpinned.buf)) {
                Ok(0) => return Poll::Ready(Ok(unpinned.bytes)),
                Ok(n) => {
                    unpinned.bytes += n;
                }
                Err(e) if e.kind() == ErrorKind::WouldBlock => {
                    get_reactor().request_wakeup(unpinned.stream,
cx.waker().clone());
                    return Poll::Pending;
                }
                Err(e) => return Poll::Ready(Err(e.into())),
            }
        }
    }
}
```

Pinning shows up whenever you have a reference to a future. Most of the time, this is in `Future::poll` or when using `select!` in a loop, as we showed in “Racing Futures with tokio::select!”.

## Conclusion

If you look inside something like the HTTP library `hyper`, you will find futures carefully handcoded to ensure cancel safety, memory efficiency, and low latency. The work that goes into designing and refining these smallest units of code is justified because of the massive leverage they offer. A decrease in the time it takes to poll a future in `hyper` translates directly to web applications, proxies, and caches across the ecosystem handling more requests per second, on the same hardware, for the same power consumption.

# Chapter 22. Macros

> *A cento (from the Latin for "patchwork") is a poem made up entirely of lines quoted from another poet.*
>
> —Matt Madden

Rust supports *macros*, a way to extend the language in ways that go beyond what you can do with functions alone. For example, we've seen the `assert_eq!` macro, which is handy for tests:

```
assert_eq!(gcd(6, 10), 2);
```

This could have been written as a generic function, but the `assert_eq!` macro does several things that functions can't do. One is that when an assertion fails, `assert_eq!` prints an error message using a format string that the user can provide by passing extra arguments to the macro. Functions in Rust can't take a variable number of arguments. Macros can, because the way they work is completely different.

Macros are a kind of shorthand. During compilation, before types are checked and long before any machine code is generated, each macro call is *expanded*—that is, it's replaced with some Rust code. The preceding macro call expands to something roughly like this:

```
match (&gcd(6, 10), &2) {
    (left_val, right_val) => {
        if !(*left_val == *right_val) {
            panic!(
                "assertion `left == right` failed\
                \n  left: {left_val:?}\
                \n right: {right_val:?}",
            );
        }
    }
}
```

`panic!` is also a macro, which itself expands to yet more Rust code (not shown here). That code uses two other macros, `file!()` and `line!()`. Once every macro call in the crate is fully expanded, Rust moves on to the next phase of compilation.

At run time, an assertion failure would look like this (and would indicate a bug in the `gcd()` function, since `2` is the correct answer):

```
thread 'main' panicked at gcd.rs:7:5:
assertion `left == right` failed
  left: 17
 right: 2
```

If you're coming from C++, you may have had some bad experiences with macros. Rust macros take a different approach, similar to Scheme's `syntax-rules`. Compared to C++ macros, Rust macros are better integrated with the rest of the language and therefore less error-prone. Macro calls are always marked with an exclamation point, so they stand out when you're reading code, and they can't be called accidentally when you meant to call a function. Rust macros never insert unmatched brackets or parentheses. And Rust macros come with pattern matching, making it easier to write macros that are both maintainable and appealing to use.

In this chapter, we'll show how to write macros using several simple examples. But like much of Rust, macros reward deep understanding, so we'll walk through the design of a more complicated macro that lets us embed JSON literals directly in our programs.

## Macro Basics

Figure 22-1 shows part of the source code for the `assert_eq!` macro.

`macro_rules!` is the main way to define macros in Rust. Note that there is no `!` after `assert_eq` in this macro definition: the `!` is only included when calling a macro, not when defining it.

Not all macros are defined this way: a few, like `file!`, `line!`, and `macro_rules!` itself, are built into the compiler, and we'll talk about another approach, called procedural macros, at the end of this chapter. But for the most part, we'll focus on `macro_rules!`, which is (so far) the easiest way to write your own.

A macro defined with `macro_rules!` works entirely by pattern matching. The body of a macro is just a series of rules:

```
( pattern1 ) => ( template1 );

( pattern2 ) => ( template2 );

...
```

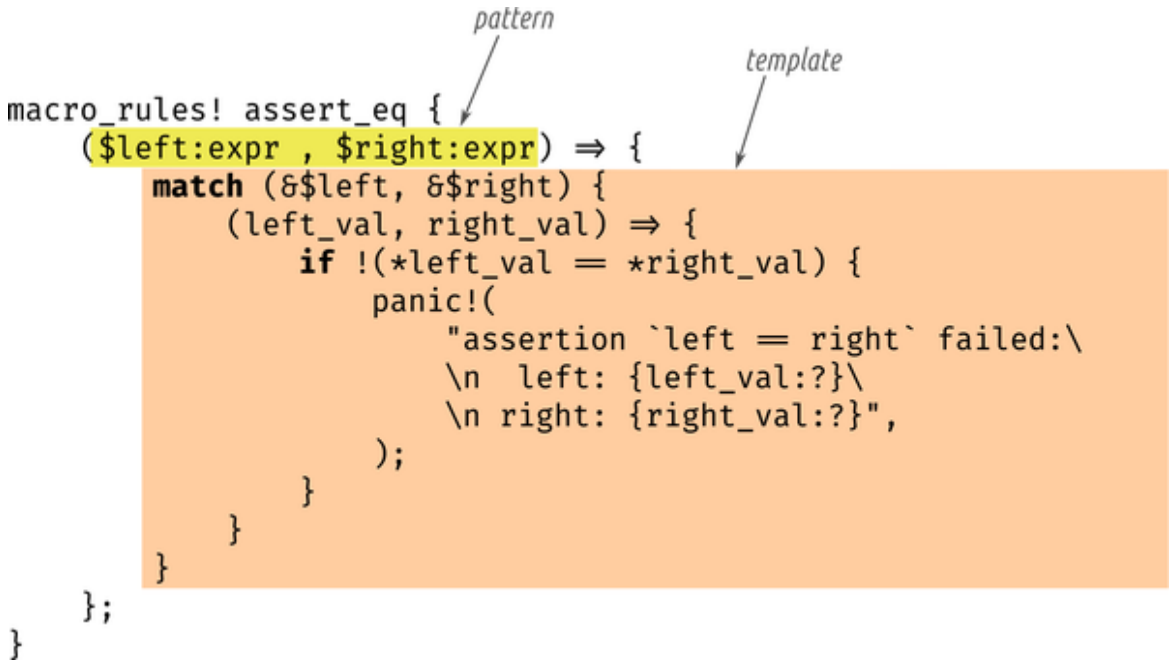


*Figure 22-1. The `assert_eq!` macro*

The version of `assert_eq!` in Figure 22-1 has just one pattern and one template.

Incidentally, you can use square brackets or curly braces instead of parentheses around the pattern or the template; it makes no difference to Rust. Likewise, when you call a macro, these are all equivalent:

```
assert_eq!(gcd(6, 10), 2);
assert_eq![gcd(6, 10), 2];
assert_eq!{gcd(6, 10), 2}
```

The only difference is that semicolons are usually optional after curly braces. By convention, we use parentheses when calling `assert_eq!`, square brackets for `vec!`, and curly braces for `macro_rules!`.

Now that we've shown a simple example of a macro's expansion and the definition that generated it, we can get into the details necessary to put this to work:

- We'll explain exactly how Rust goes about finding and expanding macro definitions in your program.
- We'll point out some subtleties inherent in the process of generating code from macro templates.
- Finally, we'll show how macros handle repeating patterns, such as the list of expressions in a `vec![]`.

## Basics of Macro Expansion

Rust expands macros very early during compilation. The compiler reads your source code from beginning to end, defining and expanding macros as it goes. You can't call a macro before it is defined, because Rust expands each macro call before it even looks at the rest of the program. (By contrast, functions and other items don't have to be in any particular order. It's OK to call a function that won't be defined until later in the crate.)

When Rust expands an `assert_eq!` macro call, what happens is a lot like evaluating a `match` expression. Rust first matches the arguments against the pattern, as shown in Figure 22-2.

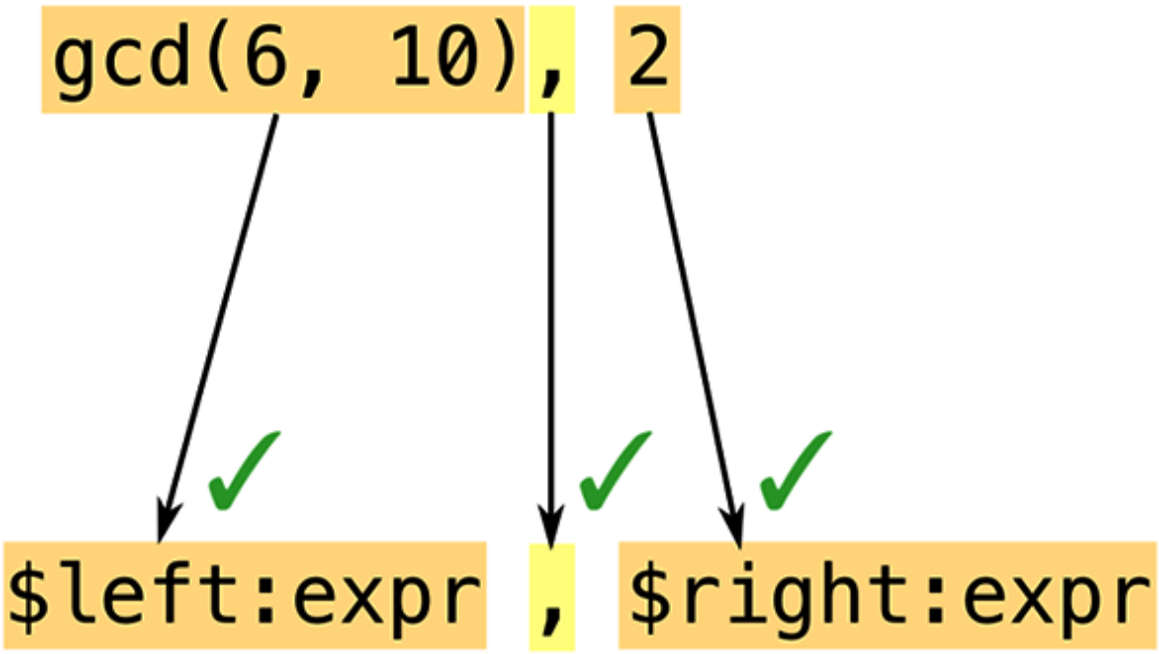


*Figure 22-2. Expanding a macro, part 1: pattern-matching the arguments*

Macro patterns are a mini-language within Rust. They're essentially regular expressions for matching code. But where regular expressions operate on characters, patterns operate on *tokens*—the numbers, names, punctuation marks, and so forth that are the building blocks of Rust programs. This means you can use comments and whitespace freely in macro patterns to make them as readable as possible. Comments and whitespace aren't tokens, so they don't affect matching.

Another important difference between regular expressions and macro patterns is that parentheses, brackets, and braces always occur in matched pairs in Rust. This is checked before macros are expanded, not only in macro patterns but throughout the language.

In this example, our pattern contains the *fragment* `$left:expr`, which tells Rust to match an expression (in this case, `gcd(6, 10)`) and assign it the name `$left`. Rust then matches the comma in the pattern with the comma following `gcd`'s arguments. Just like regular expressions, patterns have only a few special characters that trigger interesting matching behavior; everything else, like this comma, has to match verbatim or else matching fails. Lastly, Rust matches the expression `2` and gives it the name `$right`.

Both code fragments in this pattern are of type `expr`: they expect expressions. We'll see other types of code fragments in "Fragment Types".

Since this pattern matched all of the arguments, Rust expands the corresponding *template* (Figure 22-3).

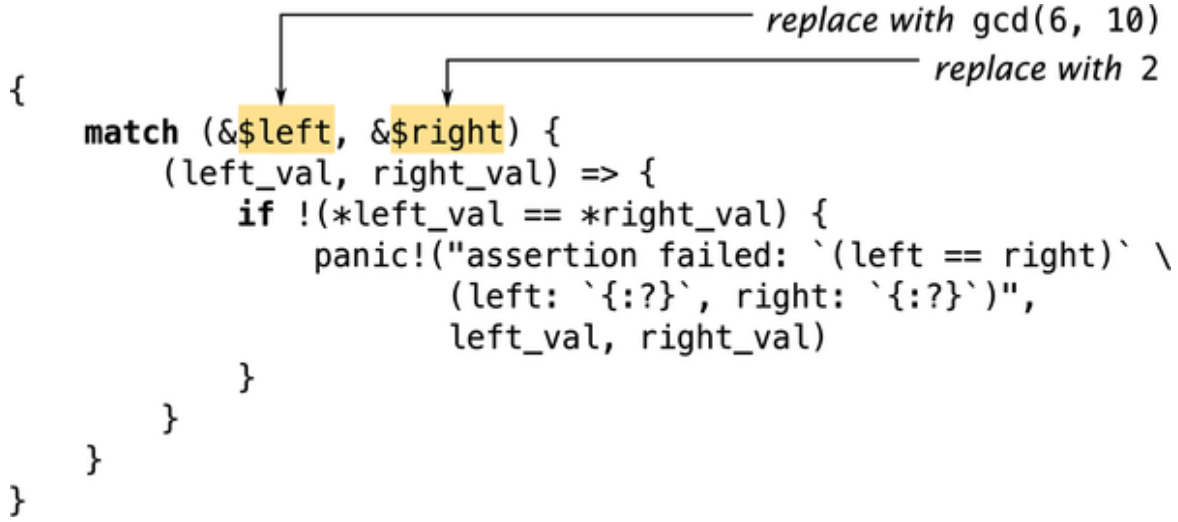


*Figure 22-3. Expanding a macro, part 2: filling in the template*

Rust replaces `$left` and `$right` with the code fragments it found during matching.

It's a common mistake to include the fragment type in the output template: writing `$left:expr` rather than just `$left`. Rust does not immediately detect this kind of error. It sees `$left` as a substitution, and then it treats `:expr` just like everything else in the template: tokens to be included in the macro's output. So the errors won't happen until you *call* the macro; then it will generate bogus output that won't compile. If you get error messages like "`cannot find type `expr` in this scope`" and "`help: maybe you meant to use a path separator here`" when using a new macro, check it for this mistake. ("Debugging Macros" offers more general advice for situations like this.)

Macro templates aren't much different from any of a dozen template languages commonly used in web programming. The only difference—and it's a significant one—is that the output is Rust code.

## Unintended Consequences

Plugging fragments of code into templates is subtly different from regular code that works with values. These differences aren't always obvious at first. The macro we've been looking at, `assert_eq!`, contains some slightly strange bits of code for reasons that say a lot about macro programming. Let's look at two funny bits in particular.

First, why does this macro create the variables `left_val` and `right_val`? Is there some reason we can't simplify the template to look like this?

```
if !($left == $right) {
    panic!(
        "assertion `left == right` failed\n  left: {:?}\n right:
{:?}",
        $left, $right,
    );
}
```

To answer this question, try mentally expanding the macro call `assert_eq!(letters.pop(), Some('z'))`. What would the output be? Naturally, Rust would plug the matched expressions into the template in multiple places. It seems like a bad idea to evaluate the expressions all over again when building the error message, though, and not just because it would take twice as long: since `letters.pop()` removes a value from a vector, it'll produce a different value the second time we call it! That's why the real macro computes `$left` and `$right` only once and stores their values.

Moving on to the second question: why does this macro borrow references to the values of `$left` and `$right`? Why not just store the values in variables, like this?

```
macro_rules! bad_assert_eq {
    ($left:expr, $right:expr) => {
        match ($left, $right) {
            (left_val, right_val) => {
                if !(left_val == right_val) {
```

```
                    panic!("assertion failed" /* ... */);
                }
            }
        }
    };
}
```

For the particular case we've been considering, where the macro arguments are integers, this would work fine. But if the caller passed, say, a `String` variable as `$left` or `$right`, this code would move the value out of the variable!

```
fn main() {
    let s = "a rose".to_string();
    bad_assert_eq!(s, "a rose");
    println!("confirmed: {s} is a rose");  // error: use of moved
value "s"
}
```

Since we don't want assertions to move values, the macro borrows references instead.

(You may have wondered why the macro uses `match` rather than `let` to define the variables. We wondered too. It turns out there's no particular reason for this. `let` would have been equivalent.) In short, macros can do surprising things. If strange things happen around a macro you've written, it's a good bet that the macro is to blame.

One bug that you *won't* see is this classic C++ macro bug:

```
// buggy C++ macro to add 1 to a number
#define ADD_ONE(n)  n + 1
```

For reasons familiar to most C++ programmers and not worth explaining fully here, unremarkable code like `ADD_ONE(1) * 10` or `ADD_ONE(1 << 4)` produces surprising results with this macro. To fix it, you'd add more parentheses to the macro definition. This isn't necessary in Rust, because Rust macros are better integrated with the language. Rust knows

when it's handling expressions, so it effectively adds parentheses whenever it pastes one expression into another.

## Repetition

The standard `vec!` macro comes in three forms:

```
// New empty Vec
let unicorns = vec![];

// Repeat a value N times
let buffer = vec![0_u8; 1000];

// A list of values, separated by commas
let noodles = vec!["udon", "ramen", "soba"];
```

It can be implemented like this:

```
macro_rules! vec {
    () => {
        ::std::vec::Vec::new()
    };
    ($elem:expr ; $n:expr) => {
        ::std::vec::from_elem($elem, $n)
    };
    ( $( $x:expr ),* ) => {
        <[_]>::into_vec(Box::new([ $( $x ),* ]))
    };
}
```

There are three rules here. Whenever Rust encounters a call to this macro, it will try each rule in turn. If no rule matches, it's an error.

The first rule in the macro has an empty pattern, so it matches only macro calls with no arguments: `vec![]`. These expand to a regular function call to `Vec::new()`.

The second rule handles uses like `vec![0u8; 1000]`. It happens that there is a standard (but undocumented) function, `std::vec::from_elem`, that does exactly what's needed here, so this rule is also straightforward.

The third rule handles `vec!["udon", "ramen", "soba"]`. The first part of the pattern, `$( $x:expr ),*`, uses a feature we haven't seen before: repetition. It matches 0 or more expressions, separated by commas. More generally, the syntax `$( PATTERN ),*` is used to match any comma-separated list, where each item in the list matches `PATTERN`.

The `*` here has the same meaning as in regular expressions ("0 or more") although admittedly regular expressions do not have a special `,*` repeater. You can also use `+` to require at least one match, or `?` for zero or one match. Other tokens can be used as separators in place of the comma. For example, `$( PATTERN );*` would match a semicolon-separated list. Table 22-1 gives the full suite of repetition patterns.

*Table 22-1. Repetition patterns*

| Pattern | Meaning |
|---|---|
| `$( ... )*` | Match 0 or more times with no separator |
| `$( ... ),*` | Match 0 or more times, separated by commas |
| `$( ... )separator*` | Match 0 or more times, separated by some other token |
| `$( ... )+` | Match 1 or more times with no separator |
| `$( ... ),+` | Match 1 or more times, separated by commas |
| `$( ... )separator+` | Match 1 or more times, separated by some other token |
| `$( ... )?` | Match 0 or 1 times |

The code fragment `$x` is not just a single expression but a list of expressions. The template for this rule uses repetition syntax too:

```
<[_]>::into_vec(Box::new([ $( $x ),* ]))
```

Again, there are standard methods that do exactly what we need. This code creates a boxed array and then uses the `[T]::into_vec` method to convert the boxed array to a vector.

The first bit, `<[_]>`, is an unusual way to write the type "slice of something," while expecting Rust to infer the element type. Types whose names are plain identifiers can be used in expressions without any fuss, but types like `fn()`, `&str`, or `[_]` must be wrapped in angle brackets.

Repetition comes in at the end of the template, where we have `$($x),*`. This `$(...),*` is the same syntax we saw in the pattern. It iterates over the list of expressions that we matched for `$x` and inserts them all into the template, separated by commas.

In this case, the repeated output looks just like the input. But that doesn't have to be the case. We could have written the rule like this:

```
( $( $x:expr ),* ) => {
    {
        let mut v = Vec::new();
        $( v.push($x); )*
        v
    }
};
```

Here, the part of the template that reads `$( v.push($x); )*` inserts a call to `v.push()` for each expression in `$x`. A macro arm can expand to a sequence of expressions, but here we need just a single expression, so we wrap the assembly of the vector in a block.

Our `vec` macro has one minor bug, though. Unlike virtually everything else in the language, patterns using `$( ... ),*` do not automatically accept the optional trailing comma in `vec![1, 2,]`. Users expect this to work in macros. We can support it by adding `$( , )?` to the end of the third pattern, like this:

```
( $( $x:expr ),* $( , )? ) => ...
```

## Built-In Macros

The Rust compiler supplies several macros that are helpful when you're defining your own macros. None of these could be implemented using `macro_rules!` alone. They're hardcoded in `rustc`:

`file!()`, `line!()`, `column!()`

> `file!()` expands to a string literal: the current filename. `line!()` and `column!()` expand to `u32` literals giving the current line and column (counting from 1).
>
> If one macro calls another, which calls another, all in different files, and the last macro calls `file!()`, `line!()`, or `column!()`, it will expand to indicate the location of the *first* macro call.

*module_path!()*

> This expands to a string, the Rust path to the current module, such as `"fernlib::fronds"`, as opposed to the file path `"/home/fernando/fernlib/src/fronds.rs"`.

`stringify!(...tokens...)`

> Expands to a string literal containing the given tokens. The `assert!` macro uses this to generate an error message that includes the code of the assertion.
>
> Macro calls in the argument are *not* expanded: `stringify!(line!())` expands to the string `"line!()"`. Rust constructs the string from the tokens, so there are no line breaks or comments in the string.

`concat!(str0, str1, ...)`

> Expands to a single string literal made by concatenating its arguments.

`compile_error!(message)`

> Stops compilation with the given error message.

One of the disadvantages of macros is that when user code calls a macro incorrectly, the compiler doesn't have enough information to report a useful error. Rust often says something like "`error: no rules expected ``,``.`" A macro can help by including a pattern that matches common user errors and produces a `compiler_error!` with a custom message.

## Debugging Macros

Debugging a wayward macro can be challenging. The biggest problem is the lack of visibility into the process of macro expansion. Rust will often expand all macros, find some kind of error, and then print an error message that does not show the fully expanded code that contains the error!

Here are three tools to help troubleshoot macros. All three rely on experimental features of Rust, so they require the nightly version of Rust to be installed. You can do this with `rustup toolchain install nightly` and then compile your code with `cargo +nightly build`.

First and simplest, you can ask Rust to show what your code looks like after expanding all macros. Most Rust IDEs offer a menu option to do this for any given macro call. Alternatively, you can install the `cargo-expand` extension using `cargo install cargo-expand`. Then use `cargo expand path::to::module` to inspect any module in your project. The fully expanded code is pretty-printed and dumped to your terminal. Unfortunately, this works only if your code is free of syntax errors.

Second, Rust provides a `log_syntax!()` macro that simply prints its arguments to the terminal at compile time. You can use this for `println!`-style debugging of your macro as it's being expanded. This macro requires the `#![feature(log_syntax)]` feature flag.

Third, you can ask the Rust compiler to log all macro calls to the terminal. Insert `trace_macros!(true);` somewhere in your code. From that point on, each time Rust expands a macro, it will print the macro name and arguments. For example, consider this program:

```
#![feature(trace_macros)]

fn main() {
    trace_macros!(true);
    let buffer = vec![0u8; 64];
    trace_macros!(false);
    assert_eq!(buffer.len(), 64);
}
```

It produces this output:

```
$ cargo +nightly build
note: trace_macro
 --> src/main.rs:7:18
  |
7 |     let buffer = vec![0u8; 64];
  |                  ^^^^^^^^^^^^^
  |
  = note: expanding `vec! { 0u8; 64 }`
  = note: to `$crate :: vec :: from_elem(0u8, 64)`
```

The compiler shows the code of each macro call, both before and after expansion. The line `trace_macros!(false);` turns tracing off again, so the call to `println!()` is not traced.

## Building the json! Macro

We've now discussed the core features of `macro_rules!`. In this section, we'll incrementally develop a macro for building JSON data. We'll use this example to show what it's like to develop a macro, present the few remaining pieces of `macro_rules!`, and offer some advice on how to make sure your macros behave as desired.

In Chapter 10, we presented this enum for representing JSON data:

```
#[derive(Clone, PartialEq, Debug)]
enum Json {
    Null,
    Boolean(bool),
    Number(f64),
    String(String),
```

```
    Array(Vec<Json>),
    Object(Box<HashMap<String, Json>>),
}
```

The syntax for writing out `Json` values is unfortunately rather verbose:

```
let students = Json::Array(vec![
    Json::Object(Box::new(vec![
        ("name".to_string(), Json::String("Jim
Blandy".to_string())),
        ("class_of".to_string(), Json::Number(1926.0)),
        ("major".to_string(), Json::String("Tibetan throat
singing".to_string())),
    ].into_iter().collect())),
    Json::Object(Box::new(vec![
        ("name".to_string(), Json::String("Jason
Orendorff".to_string())),
        ("class_of".to_string(), Json::Number(1702.0)),
        ("major".to_string(), Json::String("Knots".to_string())),
    ].into_iter().collect())),
]);
```

We would like to be able to write this using a more JSON-like syntax:

```
let students = json!([
    {
        "name": "Jim Blandy",
        "class_of": 1926,
        "major": "Tibetan throat singing"
    },
    {
        "name": "Jason Orendorff",
        "class_of": 1702,
        "major": "Knots"
    }
]);
```

What we want is a `json!` macro that takes a JSON value as an argument and expands to a Rust expression like the one in the previous example.

## Fragment Types

The first job in writing any complex macro is figuring out how to match, or *parse*, the desired input.

We can already see that the macro will have several rules, because there are several different sorts of things in JSON data: objects, arrays, numbers, and so forth. In fact, we might guess that we'll have one rule for each JSON type:

```
macro_rules! json {
    (null)    => { Json::Null };
    ([ ... ]) => { Json::Array(...) };
    ({ ... }) => { Json::Object(...) };
    (???)     => { Json::Boolean(...) };
    (???)     => { Json::Number(...) };
    (???)     => { Json::String(...) };
}
```

This is not quite correct, as macro patterns offer no way to tease apart the last three cases, but we'll see how to deal with that later. The first three cases, at least, clearly begin with different tokens, so let's start with those.

The first rule already works:

```
macro_rules! json {
    (null) => {
        Json::Null
    };
}

#[test]
fn json_null() {
    assert_eq!(json!(null), Json::Null);  // passes!
}
```

To add support for JSON arrays, we might try matching the elements as `exprs`:

```
macro_rules! json {
    (null) => {
        Json::Null
    };
    ([ $( $element:expr ),* ]) => {
```

```
            Json::Array(vec![ $( $element ),* ])
        };
    }
```

Unfortunately, this does not match all JSON arrays. Here's a test that illustrates the problem:

```
#[test]
fn json_array_with_json_element() {
    let macro_generated_value = json!(
        [
            // valid JSON that doesn't match `$element:expr`
            {
                "pitch": 440.0
            }
        ]
    );
    let hand_coded_value =
        Json::Array(vec![
            Json::Object(Box::new(vec![
                ("pitch".to_string(), Json::Number(440.0)),
            ].into_iter().collect())),
        ]);
    assert_eq!(macro_generated_value, hand_coded_value);
}
```

The pattern `$( $element:expr ),*` means "a comma-separated list of Rust expressions." But many JSON values, particularly objects, aren't valid Rust expressions. They won't match.

Since not every bit of code you want to match is an expression, Rust supports several other fragment types, listed in Table 22-2.

*Table 22-2. Fragment types supported by `macro_rules!`*

| Fragment type | Matches (with examples) | Can be followed by... |
|---|---|---|
| `expr` | An expression:<br>`2 + 2`, `"udon"`, `x.len()` | `=> , ;` |
| `stmt` | An expression or declaration, not including any trailing semicolon<br>(hard to use; try `expr` or `block` instead) | `=> , ;` |
| `ty` | A type:<br>`String`, `Vec<u8>`, `(&str, bool)`, `dyn Read + Send` | `=> , ; = \| { [ : > as where` |
| `path` | A path (discussed in "Paths and Imports"):<br>`ferns`, `::std::sync::mpsc` | `=> , ; = \| { [ : > as where` |
| `pat` | A pattern (discussed in "Patterns"):<br>`_`, `Some(ref x)` | `=> , = \| if in` |
| `item` | An item (discussed in "Declarations"):<br>`struct Point { x: f64, y: f64 }`, `mod ferns;` | Anything |

| Fragment type | Matches (with examples) | Can be followed by... |
|---|---|---|
| `block` | A block (discussed in "Blocks"):<br>`{ s += "ok\n"; true }` | Anything |
| `meta` | The body of an attribute (discussed in "Attributes"):<br>`inline`, `derive(Copy, Clone)`, `doc="3D models."` | Anything |
| `literal` | A literal value:<br>`1024`, `"Hello, world!"`, `1_000_000f64` | Anything |
| `lifetime` | A lifetime:<br>`'a`, `'item`, `'static` | Anything |
| `vis` | An optional visibility specifier:<br>`pub`, `pub(crate)`, `pub(in module::submodule)` | Anything |
| `ident` | An identifier:<br>`std`, `Json`, `longish_variable_name` | Anything |
| `tt` | A token tree (discussed in this section):<br>`;`, `>=`, `{}`, `[0 1 (+ 0 1)]` | Anything |

Most of the options in this table strictly enforce Rust syntax. The `expr` type matches only Rust expressions (not JSON values), `ty` matches only Rust types, and so on. They're not extensible: there's no way to define new arithmetic operators or new keywords that `expr` would recognize. We won't be able to make any of these match arbitrary JSON data.

The last two, `ident` and `tt`, support matching macro arguments that don't look like Rust code. `ident` matches any identifier. `tt` matches a single *token tree*: either a properly matched pair of brackets, `(...)`, `[...]`, or `{...}`, and everything in between, including nested token trees, or a single token that isn't a bracket, like `1926` or `"Knots"`.

Token trees are exactly what we need for our `json!` macro. Every JSON value is a single token tree: numbers, strings, Boolean values, and `null` are all single tokens; objects and arrays are bracketed. So we can write the patterns like this:

```
macro_rules! json {
    (null) => {
        Json::Null
    };
    ([ $( $element:tt ),* ]) => {
        Json::Array(...)
    };
    ({ $( $key:tt : $value:tt ),* }) => {
        Json::Object(...)
    };
    ($other:tt) => {
        ...  // TODO: Return Number, String, or Boolean
    };
}
```

This version of the `json!` macro can match all JSON data. Now we just need to produce correct Rust code.

To make sure Rust can gain new syntactic features in the future without breaking any macros you write today, Rust restricts tokens that appear in patterns right after a fragment. The "Can be followed by..." column of Table 22-2 shows which tokens are allowed. For example, the pattern

`$x:expr ~ $y:expr` is an error, because ~ isn't allowed after an `expr`. The pattern `$vars:pat => $handler:expr` is OK, because `$vars:pat` is followed by the arrow =>, one of the allowed tokens for a `pat`, and `$handler:expr` is followed by nothing, which is always allowed.

## Recursion in Macros

You've already seen one trivial case of a macro calling itself: our implementation of `vec!` uses recursion to support trailing commas. Here we can show a more significant example: `json!` needs to call itself recursively.

We might try supporting JSON arrays without using recursion, like this:

```
([ $( $element:tt ),* ]) => {
    Json::Array(vec![ $( $element ),* ])
};
```

But this wouldn't work. We'd be pasting JSON data (the `$element` token trees) right into a Rust expression. They're two different languages.

We need to convert each element of the array from JSON form to Rust. Fortunately, there's a macro that does this: the one we're writing!

```
([ $( $element:tt ),* ]) => {
    Json::Array(vec![ $( json!($element) ),* ])
};
```

Objects can be supported in the same way:

```
({ $( $key:tt : $value:tt ),* }) => {
    Json::Object(Box::new(vec![
        $( ($key.to_string(), json!($value)) ),*
    ].into_iter().collect()))
};
```

The compiler imposes a recursion limit on macros: 128 calls, by default. That's more than enough for normal uses of `json!`, but complex recursive macros sometimes hit the limit. You can adjust it by adding this attribute at the top of the crate where the macro is used:

```
#![recursion_limit = "256"]
```

Our `json!` macro is nearly complete. All that remains is to support Boolean, number, and string values.

## Using Traits with Macros

Writing complex macros always poses puzzles. It's important to remember that macros themselves are not the only puzzle-solving tool at your disposal.

Here, we need to support `json!(true)`, `json!(1.0)`, and `json!("yes")`, converting the value, whatever it may be, to the appropriate kind of `Json` value. But macros are not good at distinguishing types. We can imagine writing:

```
macro_rules! json {
    (true) => {
        Json::Boolean(true)
    };
    (false) => {
        Json::Boolean(false)
    };
    ...
}
```

This approach breaks down right away. There are only two Boolean values, but rather more numbers than that, and even more strings.

Fortunately, there is a standard way to convert values of various types to one specified type: the `From` trait, covered "From and Into". We simply need to implement this trait for a few types:

```
impl From<bool> for Json {
    fn from(b: bool) -> Json {
        Json::Boolean(b)
    }
}

impl From<i32> for Json {
    fn from(i: i32) -> Json {
        Json::Number(i as f64)
    }
}

impl From<String> for Json {
    fn from(s: String) -> Json {
        Json::String(s)
    }
}

impl<'a> From<&'a str> for Json {
    fn from(s: &'a str) -> Json {
        Json::String(s.to_string())
    }
}
...
```

In fact, all 12 numeric types should have similar implementations, so it might make sense to write a macro, just to avoid the copy and paste:

```
macro_rules! impl_from_num_for_json {
    ( $( $t:ident )* ) => {
        $(
            impl From<$t> for Json {
                fn from(n: $t) -> Json {
                    Json::Number(n as f64)
                }
            }
        )*
    };
}

impl_from_num_for_json!(u8 i8 u16 i16 u32 i32 u64 i64 u128 i128
                        usize isize f32 f64);
```

Now we can use `Json::from(value)` to convert a `value` of any supported type to `Json`. In our macro, it'll look like this:

```
    ( $other:tt ) => {
        Json::from($other)  // Handle Boolean/number/string
    };
```

Adding this rule to our `json!` macro makes it pass all the tests we've written so far. Putting together all the pieces, it currently looks like this:

```
macro_rules! json {
    (null) => {
        Json::Null
    };
    ([ $( $element:tt ),* ]) => {
        Json::Array(vec![ $( json!($element) ),* ])
    };
    ({ $( $key:tt : $value:tt ),* }) => {
        Json::Object(Box::new(vec![
            $( ($key.to_string(), json!($value)) ),*
        ].into_iter().collect()))
    };
    ( $other:tt ) => {
        Json::from($other)  // Handle Boolean/number/string
    };
}
```

As it turns out, the macro unexpectedly supports the use of variables and even arbitrary Rust expressions inside the JSON data, a handy extra feature:

```
let width = 4.0;
let desc =
    json!({
        "width": width,
        "height": (width * 9.0 / 4.0)
    });
```

Because `(width * 9.0 / 4.0)` is parenthesized, it's a single token tree, so the macro successfully matches it with `$value:tt` when parsing the object.

## Scoping and Hygiene

A surprisingly tricky aspect of writing macros is that they involve pasting code from different scopes together. So the next few pages cover the two ways Rust handles scoping: one way for local variables and arguments, and one way for everything else.

To show why this matters, let's rewrite our rule for parsing JSON objects (the third rule in the `json!` macro shown previously) to eliminate the temporary vector. We can write it like this:

```
({ $($key:tt : $value:tt),* }) => {
    {
        let mut fields = Box::new(HashMap::new());
        $( fields.insert($key.to_string(), json!($value)); )*
        Json::Object(fields)
    }
};
```

Now we're populating the `HashMap` not by using `collect()` but by repeatedly calling the `.insert()` method. This means we need to store the map in a temporary variable, which we've called `fields`.

But then what happens if the code that calls `json!` happens to use a variable of its own, also named `fields`?

```
let fields = "Fields, W.C.";
let role = json!({
    "name": "Larson E. Whipsnade",
    "actor": fields
});
```

Expanding the macro would paste together two bits of code, both using the name `fields` for different things!

```
let fields = "Fields, W.C.";
let role = {
    let mut fields = Box::new(HashMap::new());
    fields.insert("name".to_string(), Json::from("Larson E.
Whipsnade"));
    fields.insert("actor".to_string(), Json::from(fields));
    Json::Object(fields)
};
```

This may seem like an unavoidable pitfall whenever macros use temporary variables, and you may already be thinking through the possible fixes. Perhaps we should rename the variable that the `json!` macro defines to something that its callers aren't likely to pass in: instead of `fields`, we could call it `__json$fields`.

The surprise here is that *the macro works as is*. Rust renames the variable for you! This feature, first implemented in Scheme macros, is called *hygiene*, and so Rust is said to have *hygienic macros*.

The easiest way to understand macro hygiene is to imagine that every time a macro is expanded, the parts of the expansion that come from the macro itself are painted a different color.

Variables of different colors, then, are treated as if they had different names:

```
let fields = "Fields, W.C.";
let role = {
    let mut fields = Box::new(HashMap::new());
    fields.insert("name".to_string(), Json::from("Larson E.
Whipsnade"));
    fields.insert("actor".to_string(), Json::from(fields));
    Json::Object(fields)
};
```

Note that bits of code that were passed in by the macro caller and pasted into the output, such as `"name"` and `"actor"`, keep their original color (black). Only tokens that originate from the macro template are painted.

Now there's one variable named `fields` (declared in the caller) and a separate variable named **`fields`** (introduced by the macro). Since the names are different colors, the two variables don't get confused.

If a macro really does need to refer to a variable in the caller's scope, the caller has to pass the name of the variable to the macro.

(The paint metaphor isn't meant to be an exact description of how hygiene works. The real mechanism is even a little smarter than that, recognizing

two identifiers as the same, regardless of "paint," if they refer to a common variable that's in scope for both the macro and its caller. But cases like this are rare in Rust. If you understand the preceding example, you know enough to use hygienic macros.)

You may have noticed that many other identifiers were painted one or more colors as the macros were expanded: `Box`, `HashMap`, and `Json`, for example. Despite the paint, Rust had no trouble recognizing these type names. That's because hygiene in Rust is limited to local variables and arguments. When it comes to constants, types, methods, modules, statics, and macro names, Rust is "colorblind."

This means that if our `json!` macro is used in a module where `Box`, `HashMap`, or `Json` is not in scope, the macro won't work. We'll show how to avoid this problem in the next section.

First, we'll consider a case where Rust's strict hygiene gets in the way, and we need to work around it. Suppose we have many functions that contain this line of code:

```
let req = ServerRequest::new(server_socket.session());
```

Copying and pasting that line is a pain. Can we use a macro instead?

```
macro_rules! setup_req {
    () => {
        let req = ServerRequest::new(server_socket.session());
    };
}

fn handle_http_request(server_socket: &ServerSocket) {
    setup_req!();  // declares `req`, uses `server_socket`
    ...  // code that uses `req`
}
```

As written, this doesn't work. It requires the name `server_socket` in the macro to refer to the local `server_socket` declared in the function, and vice versa for the variable `req`. But hygiene prevents names in macros from "colliding" with names in other scopes—even in cases like this, where

that's what you want. The solution is to pass the macro any identifiers you plan on using both inside and outside the macro code:

```
macro_rules! setup_req {
    ($req:ident, $server_socket:ident) => {
        let $req = ServerRequest::new($server_socket.session());
    };
}

fn handle_http_request(server_socket: &ServerSocket) {
    setup_req!(req, server_socket);
    ...  // code that uses `req`
}
```

Since `req` and `server_socket` are now provided by the function, they're the right "color" for that scope.

Hygiene makes this macro a little wordier to use, but that's a feature, not a bug: it's easier to reason about hygienic macros knowing that they can't mess with local variables behind your back. If you search for an identifier like `server_socket` in a function, you'll find all the places where it's used, including macro calls.

## Importing and Exporting Macros

Since macros are expanded early in compilation, before Rust knows the full module structure of your project, the rules for their scope and for importing and exporting them are a bit unusual.

By default, a macro is visible from the point of its declaration to the end of the enclosing scope. To declare a macro in one module and access it from other modules within the same crate, declare a `pub(crate)` alias for the macro:

```
macro_rules! ping {
    ...
}

pub(crate) use ping;
```

Other modules can then use the macro just like any other `pub(crate)` feature of that module. If the previous code is in the `sonar` module, in another module you can write `use crate::sonar::ping;` to import it and then call `ping!()`. Or, if you prefer, you can use the macro without importing it by writing out its full path: `crate::sonar::ping!()`.

Importing a macro from another crate works much the same way. You can write `use tokio::select;` to import the `select!` macro from the `tokio` crate or use `tokio::select! {...}` directly.

To export a macro, mark its definition with the `#[macro_export]` attribute:

```
/// ...documentation for `select!` macro...
#[macro_export]
macro_rules! select {
    ...
}
```

This causes the macro to be exported from your crate's root module, regardless of where the macro is defined. For example, Tokio's `select!` macro is defined in the file *src/macros/select.rs*, but it is nonetheless exported as `tokio::select!`, not `tokio::macros::select::select!`.

If you do want to export a macro from a submodule of your crate, it's possible, but it requires a slightly ugly hack. First export the macro from the crate root, but undocumented, with an obscure name. Then, in the same file, declare a public alias for the macro with `pub use`:

```
#[doc(hidden)]
#[macro_export]
macro_rules! _secret_macro_sweep {
    ...
}

/// ...documentation for `sweep!`...
pub use _secret_macro_sweep as sweep;
```

If this code is in *src/monsters/broom.rs*, and `monsters` and `monsters::broom` are both public, then the macro is accessible from outside the crate as `my_crate_name::monsters::broom::sweep!` and inside the crate as `crate::monsters::broom::sweep!`.

Of course, exporting a module means it can be expanded within user code that you don't control. A macro therefore shouldn't rely on anything being in scope—there's no telling what will be in scope where it's used. Even features of the standard prelude can be shadowed.

Instead, the macro should use absolute paths to any names it uses. `macro_rules!` provides the special fragment `$crate` to help with this. This is not the same as `crate`, which is a keyword that can be used in paths anywhere, not just in macros. `$crate` acts like an absolute path to the root module of the crate where the macro was defined.

Instead of `Json`, we can write `$crate::Json`, which works even if `Json` was not imported. `HashMap` can be changed to either `::std::collections::HashMap` or `$crate::macros::HashMap`. In the latter case, we'll have to re-export `HashMap`, because `$crate` can't be used to access private features of a crate. It really just expands to something like `::jsonlib`, an ordinary path. Visibility rules are unaffected.

After moving the macro to its own module `macros` and modifying it to use `$crate`, it looks like this. This is the final version:

```
// macros.rs
pub use std::boxed::Box;
pub use std::collections::HashMap;
pub use std::string::ToString;

#[macro_export]
macro_rules! json {
    (null) => {
        $crate::Json::Null
    };
    ([ $( $element:tt ),* ]) => {
```

```
            $crate::Json::Array(vec![ $( $crate::json!($element) ),*
])
    };
    ({ $( $key:tt : $value:tt ),* }) => {
        {
            let mut fields = $crate::macros::Box::new(
                $crate::macros::HashMap::new());
            $(
                fields.insert(
                    $crate::macros::ToString::to_string($key),
                    $crate::json!($value),
                );
            )*
            $crate::Json::Object(fields)
        }
    };
    ($other:tt) => {
        $crate::Json::from($other)
    };
}
```

Since the `.to_string()` method is part of the standard `ToString` trait, we use `$crate` to refer to that as well, using syntax we introduced in "Fully Qualified Method Calls": `$crate::macros::ToString::to_string($key)`. In our case, this isn't strictly necessary to make the macro work, because `ToString` is in the standard prelude. But if you're calling methods of a trait that may not be in scope at the point where the macro is called, a fully qualified method call is the best way to do it.

## Beyond macro_rules!

Macro patterns can parse input that's even more intricate than JSON, but the complexity quickly gets out of hand. As an alternative, Rust offers *procedural macros*, a more general mechanism for expanding code at build time. Procedural macros can't use `macro_rules!` pattern-matching. They are more like extensions to the compiler. Each one is implemented as a regular Rust function, operating on Rust tokens, and the compiler calls the function each time it needs to expand the macro.

Any `macro_rules!` macro could be implemented as a procedural macro, but procedural macros can also do things that `macro_rules!` can't, like access files and the network at build time. For example, the `diesel` database library uses procedural macros to connect to a database and generate code based on the schema of that database at compile time. Procedural macros can also extend the Rust language in two ways that `macro_rules!` can't. They can extend the `#[derive]` attribute, as we've seen with `#[derive(serde::Serialize)]`. They can also be used to implement custom attributes like `#[tokio::test]`.

The details are beyond the scope of this book. To get started, see the documentation and examples for the `syn` crate.

If your code generation needs outgrow macros, you can use a build script instead. The Cargo documentation shows how. It involves writing a program that generates the Rust code you want, adding a line to *Cargo.toml* to run that program as part of the build process, and using `include!` to get the generated code into your crate.

# Chapter 23. Unsafe Code

*Let no one think of me that I am humble or weak or passive;*
*Let them understand I am of a different kind:*
*dangerous to my enemies, loyal to my friends.*
*To such a life glory belongs.*

—Euripides, *Medea*

The secret joy of systems programming is that underneath every single safe language and carefully designed abstraction is a swirling maelstrom of wildly unsafe machine language and bit fiddling. You can write that in Rust, too.

The language we've presented up to this point in the book ensures your programs are free of memory errors and data races entirely automatically, through types, lifetimes, bounds checks, and so on. But this sort of automated reasoning has its limits; there are many valuable techniques that Rust cannot recognize as safe.

*Unsafe code* lets you tell Rust, "I am opting to use features whose safety you cannot guarantee." By marking off a block of code as unsafe, you acquire the ability to call `unsafe` functions in the standard library, dereference raw pointers, and call functions written in other languages like C and C++, among other powers. Rust's other safety checks still apply: type checks, lifetime checks, and bounds checks on indices all occur normally. Unsafe code just enables a small set of additional features.

This ability to step outside the boundaries of safe Rust is what makes it possible to implement many of Rust's most fundamental features in Rust itself, just as C and C++ are used to implement their own standard libraries. Unsafe code is what allows the `Vec` type to manage its buffer efficiently, the `std::io` module to talk to the operating system, and the `std::thread` and `std::sync` modules to provide concurrency primitives.

This chapter covers the essentials of working with unsafe features:

- Intentionally skip consistency and bounds checks when you know they're unnecessary and hurting performance by calling unsafe functions like `from_utf8_unchecked`.
- Bypass the type system to do things like reinterpreting a `&[u8]` as a `&[u32]`.
- Write your own memory management and concurrency primitives, like `Vec` and `Arc`, without relying on Rust's standard library.
- Use advanced, CPU-specific instructions, compiler intrinsics, and other features the compiler can't prove are safe.
- Wrap your unsafe code in a safe API that ensures end users—and your future self—can take advantage of the benefits of your work without violating Rust's safety guarantees.

## Unsafe from What?

At the start of this book, we showed a C program that crashes in a surprising way because it fails to follow one of the rules prescribed by the C standard. A similar program can be written in Rust:

```
fn main() {
    let mut a: usize = 0;
    let ptr = &raw mut a;
    unsafe {
        *ptr.add(4) = 0x7ffff7d48a38;
    }
}
```

Running this program results in similarly surprising results:

```
$ cargo build
   Compiling unsafe-samples v0.1.0
    Finished debug [unoptimized + debuginfo] target(s) in 0.44s
$ ../../target/debug/crash
```

```
crash: Error: .netrc file is readable by others.
crash: Remove password or make file unreadable by others.
Segmentation fault (core dumped)
$
```

This program uses the `&raw mut` operator to get a raw pointer of type `*mut usize` pointing to the local variable `a` and then uses the `add` method to produce a pointer four words further along in memory. This happens to be where `main`'s return address is stored. The program overwrites the return address with a constant, such that returning from `main` behaves in a surprising way. What makes this crash possible is the program's incorrect use of unsafe features—in this case, the ability to dereference raw pointers. An unsafe feature is one that imposes a *contract*: rules that Rust cannot enforce automatically, but which you must nonetheless follow to avoid *undefined behavior*.

A contract goes beyond the usual type checks and lifetime checks, imposing further rules specific to that unsafe feature. Typically, Rust itself doesn't know about the contract at all; it's just explained in the feature's documentation. For example, the raw pointer type has a contract forbidding you to dereference a pointer that has been advanced beyond the end of its original referent. The expression `*ptr.add(3) = ...` in this example breaks this contract. But, as the transcript shows, Rust compiles the program without complaint: its safety checks do not detect this violation. When you use unsafe features, you, as the programmer, bear the responsibility for checking that your code adheres to their contracts.

Lots of features have rules you should follow to use them correctly, but such rules are not contracts in the sense we mean here unless the possible consequences include undefined behavior. Undefined behavior is behavior Rust assumes will never happen, like overwriting a function call's return address with something else. Code that passes Rust's usual safety checks and complies with the contracts of the unsafe features it uses cannot possibly do such a thing. Since the program violates the raw pointer contract, its behavior is undefined, and it goes off the rails.

If your code exhibits undefined behavior, you have broken your half of your bargain with Rust, and Rust declines to predict the consequences. Dredging up irrelevant error messages from the depths of system libraries and crashing is one possible consequence; handing control of your computer over to an attacker is another. The effects could vary from one release of Rust to the next, without warning. Sometimes, however, undefined behavior has no visible consequences. For example, if the `main` function never returned (if, perhaps, it called `std::process::exit` to terminate the program early), then the corrupted return address probably wouldn't matter.

You may only use unsafe features within an `unsafe` block or an `unsafe` function; we'll explain both in the sections that follow. This makes it harder to use unsafe features unknowingly: by forcing you to write an `unsafe` block or function, Rust makes sure you have acknowledged that your code may have additional rules to follow.

## unsafe Blocks

An `unsafe` block looks just like an ordinary Rust block preceded by the `unsafe` keyword, with the difference that you can use unsafe features in the block:

```
unsafe {
    String::from_utf8_unchecked(ascii)
}
```

Without the `unsafe` keyword in front of the block, Rust would object to the use of `from_utf8_unchecked`, which is an `unsafe` function. Blocks marked with `unsafe` segregate code that requires extra scrutiny due to its ability to cause undefined behavior from the rest of the program.

Small amounts of unsafe code can be wrapped in safe interfaces that enable their use without fearing undefined behavior, at a reduced cost in time and effort compared to simply using `unsafe` everywhere.

Like an ordinary Rust block, the value of an `unsafe` block is that of its final expression, or `()` if it doesn't have one. The call to `String::from_utf8_unchecked` in this example provides the value of the block.

An `unsafe` block unlocks five additional options for you:

- You can call `unsafe` functions. Each `unsafe` function must specify its own contract, depending on its purpose.
- You can dereference raw pointers. Safe code can pass raw pointers around, compare them, and create them by conversion from references (or even from integers), but only unsafe code can actually use them to access memory. We'll cover raw pointers in detail and explain how to use them safely in "Raw Pointers".
- You can access the fields of `unions`, which are unsafe because, unlike `enums`, the compiler can't be sure they contain valid bit patterns for their respective types.
- You can access mutable `static` variables. As explained in "Global Variables", Rust can't be sure when threads are using mutable `static` variables, so their contract requires you to ensure all access is properly synchronized.
- You can access functions and variables declared through Rust's foreign function interface. These are considered `unsafe` even when immutable, since they are visible to code written in other languages that may not respect Rust's safety rules.

Restricting unsafe features to `unsafe` blocks doesn't really prevent you from doing whatever you want. It's perfectly possible to just stick an `unsafe` block into your code and move on. The benefit of the rule lies mainly in drawing human attention to code whose safety Rust can't guarantee:

- You won't accidentally use unsafe features and then discover you were responsible for contracts you didn't even know existed.
- An `unsafe` block attracts more attention from reviewers. Some projects even have automation to ensure this, flagging code changes that affect `unsafe` blocks for special attention.
- When you're considering writing an `unsafe` block, you can take a moment to ask yourself whether your task really requires such measures. If it's for performance, do you have measurements to show that this is actually a bottleneck? Perhaps there is a good way to accomplish the same thing in safe Rust.

## Example: An Efficient ASCII String Type

Here's the definition of `Ascii`, a string type that ensures its contents are always valid ASCII. This type uses an unsafe feature to provide zero-cost conversion into `String`:

```
mod my_ascii {
    /// An ASCII-encoded string.
    #[derive(Debug, Eq, PartialEq)]
    pub struct Ascii(
        // This must hold only well-formed ASCII text:
        // bytes from `0` to `0x7f`.
        Vec<u8>,
    );

    impl Ascii {
        /// Creates an `Ascii` from the ASCII text in `bytes`.
Returns a
        /// `NotAsciiError` error if `bytes` contains any non-
ASCII
        /// characters.
        pub fn from_bytes(bytes: Vec<u8>) -> Result<Ascii,
NotAsciiError> {
            if bytes.iter().any(|&byte| !byte.is_ascii()) {
                return Err(NotAsciiError(bytes));
            }
            Ok(Ascii(bytes))
        }
```

```
    }

    // When conversion fails, we give back the vector we couldn't
convert.
    // This should implement `std::error::Error`; omitted for
brevity.
    #[derive(Debug, Eq, PartialEq)]
    pub struct NotAsciiError(pub Vec<u8>);

    // Safe, efficient conversion, implemented using unsafe code.
    impl From<Ascii> for String {
        fn from(ascii: Ascii) -> String {
            // SAFETY: This module enforces the invariant that
`ascii.0`
            // is ASCII, and all ASCII text is well-formed UTF-8.
            unsafe { String::from_utf8_unchecked(ascii.0) }
        }
    }
    ...
}
```

The key to this module is the definition of the `Ascii` type. The type itself is marked `pub` to make it visible outside the `my_ascii` module. But the type's `Vec<u8>` element is *not* public, so only the `my_ascii` module can construct an `Ascii` value or refer to its element. This leaves the module's code in complete control over what may or may not appear there. As long as the public constructors and methods ensure that freshly created `Ascii` values are well-formed and remain so throughout their lives, then the rest of the program cannot violate that rule. And indeed, the public constructor `Ascii::from_bytes` carefully checks the vector it's given before agreeing to construct an `Ascii` from it. For brevity's sake, we don't show any methods, but you can imagine a set of text-handling methods that ensure `Ascii` values always contain proper ASCII text, just as a `String`'s methods ensure that its contents remain well-formed UTF-8.

This arrangement lets us implement `From<Ascii>` for `String` very efficiently. The unsafe function `String::from_utf8_unchecked` takes a byte vector and builds a `String` from it without checking whether its contents are well-formed UTF-8 text; the function's contract holds its caller responsible for that. Fortunately, the rules enforced by the `Ascii`

type are what we need to satisfy `from_utf8_unchecked`'s contract. As we explained in "UTF-8", any block of ASCII text is also well-formed UTF-8, so an `Ascii`'s underlying `Vec<u8>` is immediately ready to serve as a `String`'s buffer.

Nonetheless, we have marked the `unsafe` block in the `from` method with a `// SAFETY:` comment, as is customary, explaining why we think that particular use of unsafe code is correct. With the preceding definitions in place, we can take our `Ascii` string type for a spin:

```
use my_ascii::Ascii;

let bytes: Vec<u8> = b"ASCII and ye shall receive".to_vec();

// This call entails no allocation or text copies, just a scan.
let ascii: Ascii = Ascii::from_bytes(bytes)
    .unwrap();  // We know these chosen bytes are ok.

// This call is zero-cost: no allocation, copies, or scans.
let string = String::from(ascii);

assert_eq!(string, "ASCII and ye shall receive");
```

No `unsafe` blocks are required to use `Ascii`. We have implemented a safe interface using unsafe operations and arranged to meet their contracts depending only on the module's own code, not on its users' behavior.

An `Ascii` is nothing more than a wrapper around a `Vec<u8>`, hidden inside a module that enforces extra rules about its contents. A type of this sort is called a *newtype*, a common pattern in Rust. Rust's own `String` type is defined in exactly the same way, except that its contents are restricted to be UTF-8, not ASCII. In fact, here's the definition of `String` from the standard library:

```
pub struct String {
    vec: Vec<u8>,
}
```

This pattern, in which unsafe operations are wrapped in safe interfaces, is the mechanism that enables most Rust programs to avoid `unsafe` entirely while still allocating memory, interacting with filesystem APIs, and so forth. It is typically very efficient; at the machine level, with Rust's types out of the picture, a newtype and its element have identical representations in memory, so constructing a newtype doesn't require any machine instructions at all. In `Ascii::from_bytes`, the expression `Ascii(bytes)` simply deems the `Vec<u8>`'s representation to now hold an `Ascii` value. Similarly, `String::from_utf8_unchecked` probably requires no machine instructions when inlined: the `Vec<u8>` is now considered to be a `String`.

## Unsafe Functions

An `unsafe` function definition looks like an ordinary function definition preceded by the `unsafe` keyword.

Marking a function `unsafe` warns its callers that the function has a contract they must satisfy to avoid undefined behavior. You may call `unsafe` functions only within `unsafe` blocks.

For example, here's a new constructor for the `Ascii` type we introduced before that builds an `Ascii` from a byte vector without checking if its contents are valid ASCII:

```
// This must be placed inside the `my_ascii` module.
impl Ascii {
    /// Constructs an `Ascii` value from `bytes`, without
checking
    /// whether `bytes` actually contains well-formed ASCII.
    ///
    /// This constructor is infallible, and returns an `Ascii`
directly,
    /// rather than a `Result<Ascii, NotAsciiError>` as the
`from_bytes`
    /// constructor does.
    ///
    /// # Safety
```

```
    ///
    /// The caller must ensure that `bytes` contains only ASCII
    /// characters: bytes no greater than 0x7f. Otherwise, the
effect is
    /// undefined.
    pub unsafe fn from_bytes_unchecked(bytes: Vec<u8>) -> Ascii {
        Ascii(bytes)
    }
}
```

Presumably, code calling `Ascii::from_bytes_unchecked` already knows somehow that the vector in hand contains only ASCII characters, so the check that `Ascii::from_bytes` insists on carrying out would be a waste of time, and the caller would have to write code to handle `Err` results that it knows will never occur. `Ascii::from_bytes_unchecked` lets such a caller sidestep the checks and the error handling.

But earlier we emphasized the importance of `Ascii`'s public constructors and methods ensuring that `Ascii` values are well-formed. Doesn't `from_bytes_unchecked` fail to meet that responsibility?

Not quite: `from_bytes_unchecked` meets its obligations by passing them on to its caller via its contract. The presence of this contract is what makes it correct to mark this function `unsafe`: despite the fact that the function itself carries out no unsafe operations, its callers must follow rules Rust cannot enforce automatically to avoid undefined behavior.

Can you really cause undefined behavior by breaking the contract of `Ascii::from_bytes_unchecked`? Yes. You can construct a `String` holding ill-formed UTF-8 as follows:

```
// Imagine that this vector is the result of some complicated
process
// that we expected to produce ASCII. Something went wrong!
let bytes = vec![0xf7, 0xbf, 0xbf, 0xbf];

let ascii = unsafe {
    // This unsafe function's contract is violated
    // when `bytes` holds non-ASCII bytes.
    Ascii::from_bytes_unchecked(bytes)
};
```

```
let bogus: String = ascii.into();

// `bogus` now holds ill-formed UTF-8. Parsing its first
character produces
// a `char` that is not a valid Unicode code point. That's
undefined
// behavior, so the language doesn't say how this assertion
should behave.
assert_eq!(bogus.chars().next().unwrap() as u32, 0x1fffff);
```

As it happens, the standard library's `chars` iterator contains a debug-only check that detects the undefined behavior and aborts the process:

```
thread 'bad_ascii' panicked at
rust/library/core/src/char/methods.rs:239:18:
unsafe precondition(s) violated: invalid value for `char`

This indicates a bug in the program. This Undefined Behavior
check is optional,
and cannot be relied on for safety.
thread caused non-unwinding panic. aborting.
```

Checks like this one are disabled in release builds, for performance, and some kinds of undefined behavior are not subject to run-time checking at all. In those cases the consequences are truly unpredictable. In one version of Rust, this example produced the following entertaining error message:

```
thread 'main' panicked at 'assertion failed: `(left == right)`
  left: `2097151`,
 right: `2097151`', src/main.rs:42:5
```

Those two numbers seem equal to us, but this is not Rust's fault; it's the fault of the previous `unsafe` block. When we say that undefined behavior leads to unpredictable results, this is the kind of thing we mean.

This illustrates two critical facts about bugs and unsafe code:

- *Bugs that occur before the `unsafe` block can break contracts.* Whether an `unsafe` block causes undefined behavior can depend not just on the code in the block itself, but also on the code that

supplies the values it operates on. Everything that your `unsafe` code relies on to satisfy contracts is safety-critical. The conversion from `Ascii` to `String` based on `String::from_utf8_unchecked` is well-defined only if the rest of the module properly maintains `Ascii`'s invariants.

- *The consequences of breaking a contract may appear after you leave the `unsafe` block.* The undefined behavior courted by failing to comply with an unsafe feature's contract often does not occur within the `unsafe` block itself. Constructing a bogus `String` as shown before may not cause problems until much later in the program's execution.

Essentially, Rust's type checker, borrow checker, and other static checks are inspecting your program and trying to construct proof that it cannot exhibit undefined behavior. When Rust compiles your program successfully, that means it succeeded in proving your code sound. An `unsafe` block is a gap in this proof: "This code," you are saying to Rust, "is fine, trust me." Whether your claim is true could depend on any part of the program that influences what happens in the `unsafe` block, and the consequences of being wrong could appear anywhere influenced by the `unsafe` block. Writing the `unsafe` keyword amounts to a reminder that you are not getting the full benefit of the language's safety checks.

Given the choice, you should naturally prefer to create safe interfaces, without contracts. These are much easier to work with, since users can count on Rust's safety checks to ensure their code is free of undefined behavior. Even if your implementation uses unsafe features, it's best to use Rust's types, lifetimes, and module system to meet their contracts while using only what you can guarantee yourself, rather than passing responsibilities on to your callers.

Unfortunately, it's not unusual to come across unsafe functions in the wild whose documentation does not bother to explain their contracts. You are expected to infer the rules yourself, based on your experience and knowledge of how the code behaves. If you've ever uneasily wondered

whether what you're doing with a C or C++ API is OK, then you know what that's like.

## Marking Unsafe Code

On most topics, the Rust compiler is happy to offer guidance, but on the subject of whether a function should be marked `unsafe`, Rust is silent. You can usually delete the `unsafe` from an `unsafe fn` without so much as a warning. When using unsafe code, it's up to you to categorize functions correctly:

- If it's possible to misuse the function in a way that compiles fine but still causes undefined behavior, you must mark it as unsafe. The rules for using the function correctly are its contract; the existence of a contract is what makes the function unsafe.
- Otherwise, the function is safe: no well-typed call to it can cause undefined behavior. It should not be marked `unsafe`.

Whether the function uses unsafe features in its body is irrelevant; what matters is the presence of a contract. Before, we showed an unsafe function that uses no unsafe features and a safe function that does use unsafe features.

Marking a function `unsafe` means you're providing a dangerous tool. It should come with a `# Safety` section in the documentation, explaining how to use it correctly. An `unsafe` block means you're using dangerous tools, ideally with a `// SAFETY:` comment explaining why your usage is correct. These are two different messages. Sometimes both messages (and both kinds of comment) are appropriate, so even in an `unsafe fn`, it makes sense to wrap unsafe code in an `unsafe` block. Rust warns if you don't. You can upgrade the warning to an error with `#![deny(unsafe_op_in_unsafe_fn)]` in your crate root.

# Undefined Behavior

In the introduction, we said that the term *undefined behavior* refers to behavior that Rust assumes will never happen. Of course, we know from our experience with other languages that this kind of behavior happens all the time, by accident. The compiler's authors are not naïve to this fact, but choosing to draw boundaries around what the compiler expects to happen allows it to produce much more efficient code.

A compiler is a translator from one programming language to another. The Rust compiler takes a Rust program and translates it into an equivalent machine language program; that is, one that has the same visible behavior when executed, makes the same system calls, interacts with foreign libraries in equivalent ways, and so on. It's a bit like a Turing test for programs: if you can't tell whether you're interacting with the original or the translation, then they're equivalent.

Optimizing compilers, like `rustc`, do their work by incrementally transforming your code. At every step, the compiler is trying to change the program behavior in good ways (making it run faster or use less memory) but not in bad ways (introducing bugs).

Let's look at an example of what happens when this process goes wrong. Consider the following code:

```
let i = 10;
very_trustworthy(&i);
println!("{}", i * 100);
```

Even knowing nothing about the definition of `very_trustworthy`, we can see that it receives only a shared reference to `i`, so the call cannot change `i`'s value. Since the value passed to `println!` will always be `1000`, Rust can translate this code into machine language as if we had written:

```
very_trustworthy(&10);
println!("{}", 1000);
```

This transformed version has the same visible behavior as the original, and it's probably a bit faster. But it makes sense to consider the performance of this version only if we agree it has the same meaning as the original. What if `very_trustworthy` were defined as follows?

```
// This function takes a non-mut reference...
fn very_trustworthy(shared: &i32) {
    unsafe {
        // ... and breaks the rules by turning it into a mut
reference
        // via pointers. This is undefined behavior.
        let mutable = shared as *const i32 as *mut i32;
        *mutable = 20;
    }
}
```

This code breaks the rules for shared references: it changes the value of `i` to `20`, even though it should be frozen because `i` is borrowed for sharing. As it happens, Rust is smart enough to catch this particular ill-conceived hack and, by default, refuses to compile it. But Rust can't detect all rule-breaking in unsafe code. What would happen if Rust couldn't detect the problem here, and it simply compiled the code as usual? The transformation we made to the caller would have a very visible effect: if Rust transformed the code, the program would print `1000`; if it left the code alone and used the new value of `i`, it would print `2000`. Breaking the rules for shared references in `very_trustworthy` means that shared references won't behave as expected in its callers.

This sort of problem arises with almost every kind of transformation Rust might attempt. Even inlining a function into its call site assumes, among other things, that when the callee finishes, control flow returns to the call site. But we opened the chapter with an example of ill-behaved code that violates even that assumption.

It's basically impossible for Rust (or any other language) to assess whether a transformation to a program preserves its meaning unless it can trust the fundamental features of the language to behave as designed. And whether they do or not can depend not just on the code at hand but on other,

potentially distant, parts of the program. To do anything at all with your code, Rust must assume that the rest of your program is well-behaved.

Here, then, are Rust's rules for well-behaved programs:

- The program must not read uninitialized memory.
- The program must not create invalid primitive values:
  - References, boxes, or `fn` pointers that are `null`
  - `bool` values that are not either a `0` or `1`
  - `enum` values with invalid discriminant values
  - `char` values that are not valid, nonsurrogate Unicode code points
  - `str` values that are not well-formed UTF-8
  - Fat pointers with invalid vtables/slice lengths
  - Any value of the "never" type, written `!`, for functions that don't return
- The rules for references explained in Chapter 5 must be followed. No reference may outlive its referent; shared access is read-only access; and mutable access is exclusive access.
- The program must not dereference null, incorrectly aligned, or dangling pointers.
- The program must not use a pointer to access memory outside the allocation with which the pointer is associated. We will explain this rule in detail in "Dereferencing Raw Pointers Safely".
- The program must be free of data races. A data race occurs when two threads access the same memory location without synchronization, and at least one of the accesses is a write.

- The program must not unwind across a call made from another language, via the foreign function interface, as explained in "Unwinding".
- If the program uses any `unsafe` standard library features, it must comply with their contracts.

Any violation of these rules constitutes undefined behavior and renders Rust's efforts to optimize your program and translate it into machine language untrustworthy. If you break the last rule and pass ill-formed UTF-8 to `String::from_utf8_unchecked`, perhaps `2097151` is not so equal to `2097151` after all.

In safe Rust code, the compiler enforces all of these rules. If your program compiles, you're in good shape. Only when you use unsafe features do the rules become your responsibility.

In C and C++, the fact that your program compiles without errors or warnings means much less. As we mentioned in the introduction to this book, even the best C and C++ programs written by well-respected projects that hold their code to high standards exhibit undefined behavior in practice.

## Unsafe Traits

An *unsafe trait* is a trait that has a contract Rust cannot check or enforce that implementers must satisfy to avoid undefined behavior. To implement an unsafe trait, you must mark the implementation as unsafe. It is up to you to understand the trait's contract and make sure your type satisfies it.

`std::marker::Send` and `std::marker::Sync` are the classic examples of unsafe traits. These traits don't define any methods, so they're trivial to implement for any type you like. But they do have contracts: `Send` requires implementers to be safe to move to another thread, and `Sync` requires them to be safe to share among threads via shared

references. Implementing `Send` for an inappropriate type, for example, would make `std::sync::Mutex` no longer safe from data races.

The `bytemuck` crate provides some additional capabilities for "plain old data" types—that is, types for which there aren't complex initialization and validity requirements. It does this partly through a trait called `Zeroable`, for types that can be safely initialized by setting all their bytes to zero. Clearly, zeroing a `usize` is fine, but zeroing a `&T` gives you a null reference, which will cause a crash if dereferenced. For types that are `Zeroable`, some optimizations are possible: you can initialize an array of them quickly with the `write_bytes` method (Rust's equivalent of `memset`) or use operating system calls that allocate zeroed pages.

Like most marker traits, implementing `Zeroable` doesn't require implementing any methods:

```
unsafe impl Zeroable for u8 {}
unsafe impl Zeroable for i32 {}
unsafe impl Zeroable for usize {}
// and so on for all the integer types
```

With these definitions, we can write a function that quickly allocates a vector of a given length containing a `Zeroable` type:

```
use bytemuck::Zeroable;

fn zeroed_vector<T>(len: usize) -> Vec<T>
where
    T: Zeroable,
{
    let mut vec = Vec::<T>::with_capacity(len);
    // SAFETY: Writing to the spare capacity of vec is safe. Once
we've
    // initialized the storage with valid T values, set_len is
OK.
    // We know zero bytes make valid values because T is
Zeroable.
    unsafe {
        vec.as_mut_ptr().write_bytes(0, len);
        vec.set_len(len);
    }
```

```
    vec
}
```

This function starts by creating an empty `Vec` with the required capacity. Then it obtains a pointer of type `*mut T` pointing to the unoccupied buffer and calls the pointer's `write_bytes` method to fill it with zeros. (The `write_bytes` method treats `len` as a number of `T` elements, not a number of bytes, so this call does fill the entire buffer.)

A vector's `set_len` method changes its length without doing anything to the buffer; this is unsafe because you must ensure that the newly enclosed buffer space actually contains properly initialized values of type `T`. But this is exactly what the `T: Zeroable` bound establishes: a block of zero bytes represents a valid `T` value. Our use of `set_len` is safe.

Here, we put it to use:

```
let v: Vec<usize> = zeroed_vector(100_000);
assert!(v.iter().all(|&u| u == 0));
```

Clearly, `Zeroable` must be an unsafe trait, since an implementation that doesn't respect its contract can lead to undefined behavior:

```
struct HoldsRef<'a>(&'a mut i32);

unsafe impl<'a> Zeroable for HoldsRef<'a> {}

let mut v: Vec<HoldsRef> = zeroed_vector(1);
*v[0].0 = 1;   // crashes: dereferences null pointer
```

Rust has no idea what `Zeroable` is meant to signify, so it can't tell when it's being implemented for an inappropriate type. As with any other unsafe feature, it's up to you to understand and adhere to an unsafe trait's contract.

Note that unsafe code must not depend on ordinary, safe traits being implemented correctly. For example, suppose there was an implementation of the `std::hash::Hasher` trait that simply returned a random hash value, with no relation to the values being hashed. The trait requires that

hashing the same bits twice must produce the same hash value, but this implementation doesn't meet that requirement; it's simply incorrect. But because `Hasher` is not an unsafe trait, unsafe code must not exhibit undefined behavior when it uses this hasher. The `std::collections::HashMap` type is carefully written to respect the contracts of the unsafe features it uses, regardless of how the hasher behaves. Certainly, the table won't function correctly: lookups will fail, and entries will appear and disappear at random. But the table will not exhibit undefined behavior.

## Raw Pointers

A *raw pointer* in Rust is an unconstrained pointer. You can use raw pointers to form all sorts of structures that Rust's checked pointer types cannot, like doubly linked lists or arbitrary graphs of objects. But because raw pointers are so flexible, Rust cannot tell whether you are using them safely or not, so you can dereference them only in an `unsafe` block.

Raw pointers are equivalent to C or C++ pointers, so they're also useful for interacting with code written in those languages.

There are two kinds of raw pointers:

- A `*mut T` is a raw pointer to a `T` that permits modifying its referent.
- A `*const T` is a raw pointer to a `T` that only permits reading its referent.

(There is no plain `*T` type; you must always specify either `const` or `mut`.)

You can create a raw pointer using `&raw const` or `&raw mut`, the pointer versions of the borrowing operators `&` and `&mut`; or by conversion from the corresponding reference type. To dereference a raw pointer, use the `*` operator:

```
let mut x = 10;
let ptr_x = &raw mut x;  // using the `&raw mut` operator

let y = Box::new(20);
let ptr_y: *const i32 = &*y;  // using conversion

unsafe {
    *ptr_x += *ptr_y;
}
assert_eq!(x, 30);
```

No explicit conversion is needed to assign the reference `&*y` to the pointer variable `ptr_y`; just specifying the type is enough. Rust implicitly coerces references to raw pointers (but not the other way around, of course). Unlike boxes and references, raw pointers can be null, like `NULL` in C or `nullptr` in C++:

```
fn option_to_raw<T>(opt: Option<&T>) -> *const T {
    match opt {
        None => std::ptr::null(),
        Some(r) => r as *const T,
    }
}

assert!(!option_to_raw(Some(&("pea", "pod"))).is_null());
assert_eq!(option_to_raw::<i32>(None), std::ptr::null());
```

This example has no `unsafe` blocks: creating raw pointers, passing them around, and comparing them are all safe. Only dereferencing a raw pointer is unsafe.

A raw pointer to a dynamically sized type is a fat pointer, just as the corresponding reference or `Box` type would be. A `*const [u8]` pointer includes a length along with the address, and a `*mut dyn Write` includes a pointer to the vtable.

Although Rust implicitly dereferences safe pointer types in various situations, raw pointer dereferences must be explicit:

- The `.` operator will not implicitly dereference a raw pointer; you must write `(*raw).field` or `(*raw).method(...)`.

- Raw pointers do not implement `Deref`, so deref coercions do not apply to them.
- Operators like == and < compare raw pointers as addresses: two raw pointers are equal if they point to the same location in memory. Similarly, hashing a raw pointer hashes the address it points to, not the value of its referent.
- Formatting traits like `std::fmt::Display` follow references automatically but don't handle raw pointers at all. The exceptions are `std::fmt::Debug` and `std::fmt::Pointer`, which show raw pointers as hexadecimal addresses, without dereferencing them.

The `as` operator permits almost every plausible conversion from references to raw pointers or between two raw pointer types. However, you may need to break up a complex conversion into a series of simpler steps. For example:

```
&vec![42_u8] as *const String;  // error: invalid conversion
&vec![42_u8] as *const Vec<u8> as *const String;  // permitted
```

Note that the `as` operator doesn't work in the other direction, converting raw pointers to references. Such conversions would be unsafe, and `as` is a safe operation. Instead, you must dereference the raw pointer (in an `unsafe` block) and then borrow the resulting value. This makes it clear where the reference is being borrowed.

Be very careful when you do this: a reference produced this way has an unconstrained lifetime: there's no limit on how long it can live, since the raw pointer gives Rust nothing to base such a decision on. In "A Safe Interface to libgit2", we show several examples of how to properly constrain lifetimes.

Many types have `as_ptr` and `as_mut_ptr` methods that return a raw pointer to their contents. For example, array slices and strings return pointers to their first elements. Owning pointer types like `Box`, `Rc`, and

`Arc` have `into_raw` and `from_raw` functions that convert to and from raw pointers. Some of these methods' contracts impose surprising requirements, so check their documentation before using them.

You can also construct raw pointers by conversion from integers, although the only integers you can trust for this are generally those you got from a pointer in the first place. Raw pointers are neither `Send` nor `Sync`. Rust assumes that types containing raw pointers are not thread-safe unless you explicitly implement `Send` and/or `Sync`, as discussed in "Unsafe Traits".

## Dereferencing Raw Pointers Safely

Here are some common-sense guidelines for using raw pointers safely:

- Dereferencing null pointers or dangling pointers is undefined behavior.
- Dereferencing pointers that are not properly aligned for their referent type is undefined behavior.
- Reading uninitialized memory is always undefined behavior. Assigning to uninitialized memory, `*ptr = value`, is undefined behavior too, if the type of `*ptr` has a destructor! You can initialize the memory safely using `ptr.write(value)`, as we'll see later in this chapter.
- You may borrow values out of a dereferenced raw pointer only if doing so obeys the rules for reference safety explained in Chapter 5: no reference may outlive its referent, shared access is read-only access, and mutable access is exclusive access. (This rule is easy to violate by accident, since raw pointers are often used to create data structures with nonstandard sharing or ownership.)
- You may use a raw pointer's referent only if it is a well-formed value of its type. For example, you must ensure that dereferencing a `*const char` yields a proper, nonsurrogate Unicode code point.

- If you assign to a raw pointer's referent, you must not violate the invariants of any type of which the referent is a part. For example, if you have a `*mut u8` pointing to a byte of a `String`, you may only store values in that `u8` that leave the `String` holding well-formed UTF-8.
- A pointer's `add` and `sub` methods must only be used to produce new pointers within the same variable or heap allocation, or one byte past the end. Going outside the bounds of the allocation is undefined behavior. (This is the rule we broke in the crashing example at the beginning of this chapter. We'll discuss `add` in detail later and show how to use it constructively.)
- Likewise, if you do pointer arithmetic by converting a pointer to an integer, doing arithmetic on the integer, and then converting it back to a pointer, the result must point into the same allocation. If it doesn't, dereferencing it is undefined behavior.

These are essentially the same rules you must follow when using pointers in C or C++, and the same rules that Rust enforces automatically when you use references.

The reason for not violating types' invariants should be clear. Many of Rust's standard types use unsafe code in their implementation but still provide safe interfaces on the assumption that Rust's safety checks, module system, and visibility rules will be respected. Using raw pointers to circumvent these protective measures can lead to undefined behavior.

The complete, exact contract for raw pointers is not easily stated and may change as the language evolves. But the principles outlined here should keep you in safe territory.

## Example: RefWithFlag

Here's an example of how to take a classic[1] bit-level hack made possible by raw pointers and wrap it up as a completely safe Rust type. This module defines a type, `RefWithFlag<'a, T>`, that holds both a `&'a T` and a

`bool`, like the tuple `(&'a T, bool)` and yet still manages to occupy only one machine word instead of two. This sort of technique is used regularly in garbage collectors and virtual machines, where certain types—say, the type representing an object—are so numerous that adding even a single word to each value would drastically increase memory use:

```
mod ref_with_flag {
    use std::marker::PhantomData;

    /// A `&T` and a `bool`, wrapped up in a single word.
    /// The type `T` must require at least two-byte alignment.
    ///
    /// If you're the kind of programmer who's never met a
pointer whose
    /// 2⁰-bit you didn't want to steal, well, now you can do it
safely!
    /// ("But it's not nearly as exciting this way...")
    pub struct RefWithFlag<'a, T> {
        ptr_and_bit: *const T,
        behaves_like: PhantomData<&'a T>,  // occupies no space
    }

    impl<'a, T: 'a> RefWithFlag<'a, T> {
        pub fn new(ptr: &'a T, flag: bool) -> Self {
            const {
                assert!(align_of::<T>().is_multiple_of(2));
            }
            let ptr = ptr as *const T;
            RefWithFlag {
                ptr_and_bit: ptr.map_addr(|addr| addr | flag as
usize),
                behaves_like: PhantomData,
            }
        }

        pub fn get_ref(&self) -> &'a T {
            let ptr = self.ptr_and_bit.map_addr(|addr| addr &
!1);
            // SAFETY: We have just recreated the original `ptr`
from the constructor.
            // Now we will reborrow the original reference. We
know the value is still
            // there, since the original reference had lifetime
'a, and borrows
            // prevent moves and drops. (We know 'a hasn't
```

```
expired; Rust ensures that
            // no lifetime in scope is ever expired. It's an
error to call this
            // method on `self` after the 'a in its type
expires.)
            unsafe { &*ptr }
        }

        pub fn get_flag(&self) -> bool {
            self.ptr_and_bit.addr() & 1 != 0
        }
    }
}
```

This code takes advantage of the fact that many types must be placed at even addresses in memory: since an even address's least significant bit is always zero, we can store something else there and then reliably reconstruct the original address just by masking off the bottom bit. Not all types qualify; for example, the types `u8` and `(bool, [i8; 2])` can be placed at any address. But we can check the type's alignment on construction and refuse types that won't work.

You can use `RefWithFlag` like this:

```
use ref_with_flag::RefWithFlag;

let vec = vec![10, 20, 30];
let flagged = RefWithFlag::new(&vec, true);
assert_eq!(flagged.get_ref()[1], 20);
assert_eq!(flagged.get_flag(), true);
```

The constructor `RefWithFlag::new` takes a reference and a `bool` value and begins by asserting that the type `T` is does in fact require alignment to even addresses. The `const` block around the assertion ensures that it is evaluated at compile time so that using `RefWithFlag` incorrectly is a compilation error, not a run-time panic. Having established that the type is OK, the constructor then converts the reference to a raw pointer and uses `map_addr` and the `|` bitwise-or operator to add the integer value of `flag` to the pointer's address.

The `get_flag` method extracts the `bool` component of a `RefWithFlag`. It's simple: just mask off the bottom bit of the address and check if it's nonzero.

The `get_ref` method extracts the reference from a `RefWithFlag`. First, it uses the `map_addr` method once again to mask off the `usize`'s bottom bit, reproducing the original pointer value. The `as` operator will not convert raw pointers to references, but we can dereference the raw pointer (in an `unsafe` block, naturally) and borrow that. Borrowing a raw pointer's referent gives you a reference with an unbounded lifetime: Rust will accord the reference whatever lifetime would make the code around it check, if there is one. Usually, though, there is some specific lifetime that is more accurate and would thus catch more mistakes. In this case, since `get_ref`'s return type is `&'a T`, Rust sees that the reference's lifetime is the same as `RefWithFlag`'s lifetime parameter `'a`, which is just what we want: that's the lifetime of the reference we started with.

These methods use `addr` to get the address of the pointer as a `usize` and `map_addr` to modify it. These methods are part of Rust's *strict pointer provenance* system, which tracks when, where, and how pointers are created and used. Usually, this happens entirely at compile time, providing Rust with more information it can use to optimize programs, but some new CPUs and operating systems can use this information at runtime to enforce invariants about how programs access memory. Exactly how this works is an area of active research in projects like CheriABI.

In `RefWithFlag`, all we're doing is modifying an address that came from a pointer in the first place, so it's enough to use `map_addr`, which keeps the modified address associated with the original pointer's provenance information. If you ever do have to create a pointer from an integer with `as *const T` or similar, you're using *exposed provenance* instead, which is even less well-defined.

In memory, a `RefWithFlag` looks just like a `usize`: since `PhantomData` is a zero-sized type, the `behaves_like` field takes up no space in the structure. But the `PhantomData` is necessary for Rust to

know how to treat lifetimes in code that uses `RefWithFlag`. Imagine what the type would look like without the `behaves_like` field:

```
// This won't compile.
pub struct RefWithFlag<'a, T: 'a> {
    ptr_and_bit: *const T,
}
```

In Chapter 5, we pointed out that any structure containing references must not outlive the values they borrow, lest the references become dangling pointers. The structure must abide by the restrictions that apply to its fields. This certainly applies to `RefWithFlag`: in the example code we just looked at, `flagged` must not outlive `vec`, since `flagged.get_ref()` returns a reference to it. But our reduced `RefWithFlag` type contains no references at all and never uses its lifetime parameter `'a`. It's just a `usize`. How should Rust know that any restrictions apply to `flagged`'s lifetime? Including a `PhantomData<&'a T>` field tells Rust to treat `RefWithFlag<'a, T>` *as if* it contained a `&'a T`, without actually affecting the struct's representation.

Specifically, this fictional `&'a T` field helps determine whether the type `T` is implicitly required to live at least as long as `'a` (it is, since the reference type `&'a T` has that requirement); whether `RefWithFlag` is covariant in `'a` and `T` (it is); and whether it's `Sync` and `Send` (although in this case the pointer field prevents both). These are esoteric questions, but Rust needs them answered somehow. If you omit the `behaves_like` field, Rust will complain that the parameter `'a` is unused and suggest adding a `PhantomData`.

`RefWithFlag` uses the same tactics as the `Ascii` type we presented earlier to avoid undefined behavior in its `unsafe` block. The type itself is `pub`, but its fields are not, meaning that only code within the `ref_with_flag` module can create or look inside a `RefWithFlag` value. You don't have to inspect much code to have confidence that the `ptr_and_bit` field is well constructed.

## Null Pointers

A null pointer in Rust is a raw pointer with an address of zero, just as in C and C++. For any type `T`, the `std::ptr::null<T>` function returns a `*const T` null pointer, and `std::ptr::null_mut<T>` returns a `*mut T` null pointer.

There are a few ways to check whether a raw pointer is null. The simplest is the `is_null` method, but the `as_ref` method may be more convenient: it takes a `*const T` pointer and returns an `Option<&'a T>`, turning a null pointer into a `None`. Similarly, the `as_mut` method converts `*mut T` pointers into `Option<&'a mut T>` values.

## Type Sizes and Alignments

A value of any `Sized` type occupies a constant number of bytes in memory and must be placed at an address that is a multiple of some *alignment* value, determined by the machine architecture. For example, an `(i32, i32)` tuple occupies 8 bytes, and most processors prefer it to be placed at an address that is a multiple of four.

The generic function `size_of::<T>()` returns the size of a value of type `T`, in bytes, and `align_of::<T>()` returns its required alignment. For example:

```
struct Seat {
    row_number: u32,
    seat_number: u32,
}

assert_eq!(size_of::<Seat>(), 8);
assert_eq!(align_of::<Seat>(), 4);
```

Any type's alignment is always a power of two. A type's size is always rounded up to a multiple of its alignment, even if it technically could fit in less space. For example, even though a tuple like `(f32, u8)` requires only five bytes, `size_of::<(f32, u8)>()` is `8`, because `align_of::<(f32, u8)>()` is `4`. This ensures that if you have an

array, the size of the element type always reflects the spacing between one element and the next.

For dynamically sized types, the size and alignment depend on the value at hand. Given a reference to a dynamically sized value, the `size_of_val` and `align_of_val` functions return the value's size and alignment. These functions can operate on references to both `Sized` and dynamically sized types:

```
// Fat pointers to slices carry their referent's length.
let slice: &[i32] = &[1, 3, 9, 27, 81];
assert_eq!(size_of_val(slice), 20);

let text: &str = "alligator";
assert_eq!(size_of_val(text), 9);

use std::fmt::Display;
let unremarkable: &dyn Display = &193_u8;
let remarkable: &dyn Display = &0.0072973525664;

// These return the size/alignment of the referent,
// not those of the dyn reference itself. The answers
// come from the vtable the dyn reference points to.
assert_eq!(size_of_val(unremarkable), 1);
assert_eq!(align_of_val(remarkable), 8);
```

All four functions are included in the standard prelude.

## Pointer Arithmetic

Rust lays out the elements of an array, slice, or vector as a single contiguous block of memory, as shown in Figure 23-1. Elements are regularly spaced, so that if each element occupies `size` bytes, then the `i`th element starts with the `i * size`th byte.

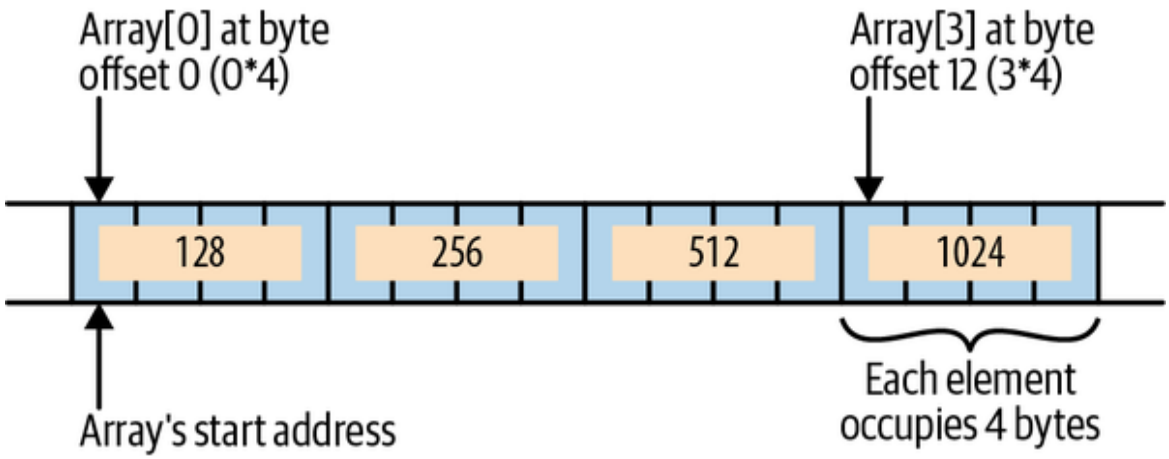


*Figure 23-1. An array in memory*

One nice consequence of this is that if you have two raw pointers to elements of an array, comparing the pointers gives the same results as comparing the elements' indices: if `i < j`, then a raw pointer to the `i`th element is less than a raw pointer to the `j`th element. This makes raw pointers useful as bounds on array traversals. In fact, the standard library's simple iterator over a slice was originally defined like this:

```
struct Iter<'a, T> {
    ptr: *const T,
    end: *const T,
    ...
}
```

The `ptr` field points to the next element iteration should produce, and the `end` field serves as the limit: when `ptr == end`, the iteration is complete.

Another nice consequence of array layout is that the address of any array element is easy to compute. If `element_ptr` is a `*const T` or `*mut T` raw pointer to element `arr[i]` of some array, then `element_ptr.add(j)` is a raw pointer to `arr[i + j]`. The definition of the `add` method is something like this:

```
fn add<T>(ptr: *const T, count: usize) -> *const T
where
    T: Sized,
```

```
{
    let bytes_per_element = size_of::<T>();
    ptr.map_addr(|addr| addr + count * bytes_per_element)
}
```

As in "Example: RefWithFlag", `map_addr` allows us to convert the base pointer to a `usize`, do arithmetic on that value, then convert the result back to a pointer.

This is called *pointer arithmetic*, and it's usually done via the `add`, `sub`, `wrapping_add`, and `wrapping_sub` methods on raw pointer types, all of which preserve provenance. Inversely, the `offset_from` method gives the number of array elements between two pointers, though we're responsible for making sure the beginning and end are in the same memory region (the same `Vec`, for instance):

```
let trucks = vec!["garbage truck", "dump truck", "moonstruck"];
let first = &raw const trucks[0];
let last = &raw const trucks[2];
assert_eq!(unsafe { last.offset_from(first) }, 2);
assert_eq!(unsafe { first.offset_from(last) }, -2);
```

It's fine to produce a pointer to the first byte after the end of an array. You cannot dereference such a pointer, but it can be useful to represent the limit of a loop or for bounds checks.

However, it is undefined behavior to use `add` (or `sub`) to produce a pointer beyond that point or before the start of the array, even if you never dereference it. For the sake of optimization, Rust would like to assume that `ptr.add(i) > ptr` and that `ptr.sub(i) < ptr`. This assumption seems safe, but it may not hold if the arithmetic in `add` or `sub` overflows a `usize` value. If `i` is constrained to stay within the same array as `ptr`, no overflow can occur, because the array itself cannot overflow the bounds of the address space. (To make pointers to the first byte after the end safe, Rust never places values at the upper end of the address space.)

If you do need to offset pointers beyond the limits of the array they are associated with, you can use the `wrapping_add` and `wrapping_sub`

methods. These are equivalent to `add` and `sub`, but Rust makes no assumptions about the relative ordering of `ptr.wrapping_add(i)` and `ptr` itself. Of course, you still can't dereference such pointers unless they fall within the array.

## Moving Into and Out of Memory

If you are implementing a type that manages its own memory, you will need to track which parts of your memory hold values and which do not, just as Rust does with local variables. Consider this code:

```
let pot = "pasta".to_string();
let plate = pot;
```

After this code has run, the situation looks like Figure 23-2.

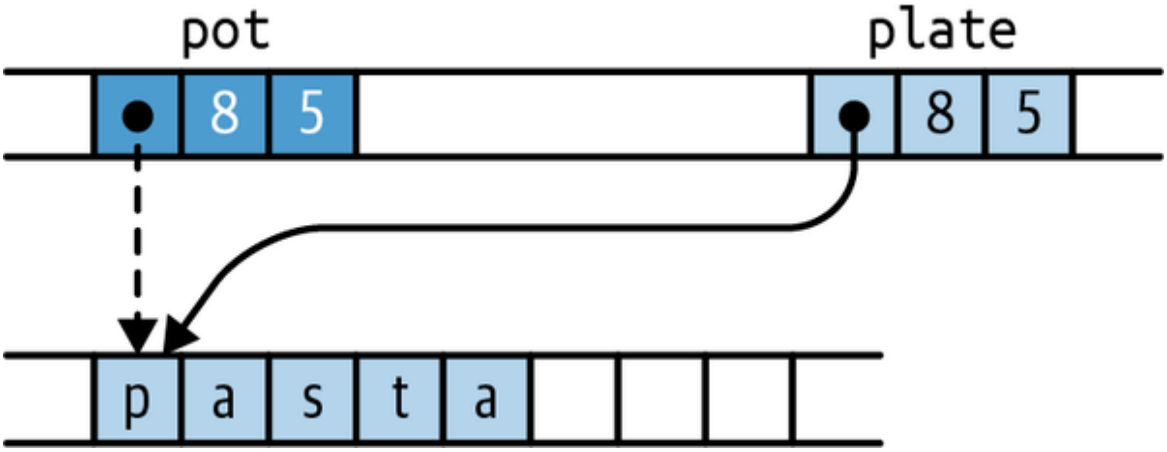


*Figure 23-2. Moving a string from one local variable to another*

After the assignment, `pot` no longer contains a value. Now `plate` is the owner of the string. We will call memory locations "occupied" while they hold and own values; and "vacant" if they're uninitialized or have had their values moved.

At the machine level, it's not specified what this move does to the memory storing `pot`, but in practice it usually does nothing at all. The assignment probably leaves `pot` still holding a pointer, capacity, and length for the

string. It could be disastrous to continue using this leftover data, though, especially the pointer; so Rust forbids the use of vacant variables.

The same considerations apply to data structures that manage their own memory. Suppose you run this code:

```
let mut noodles = vec!["udon".to_string()];
let soba = "soba".to_string();
let last;
```

In memory, the state looks like Figure 23-3.

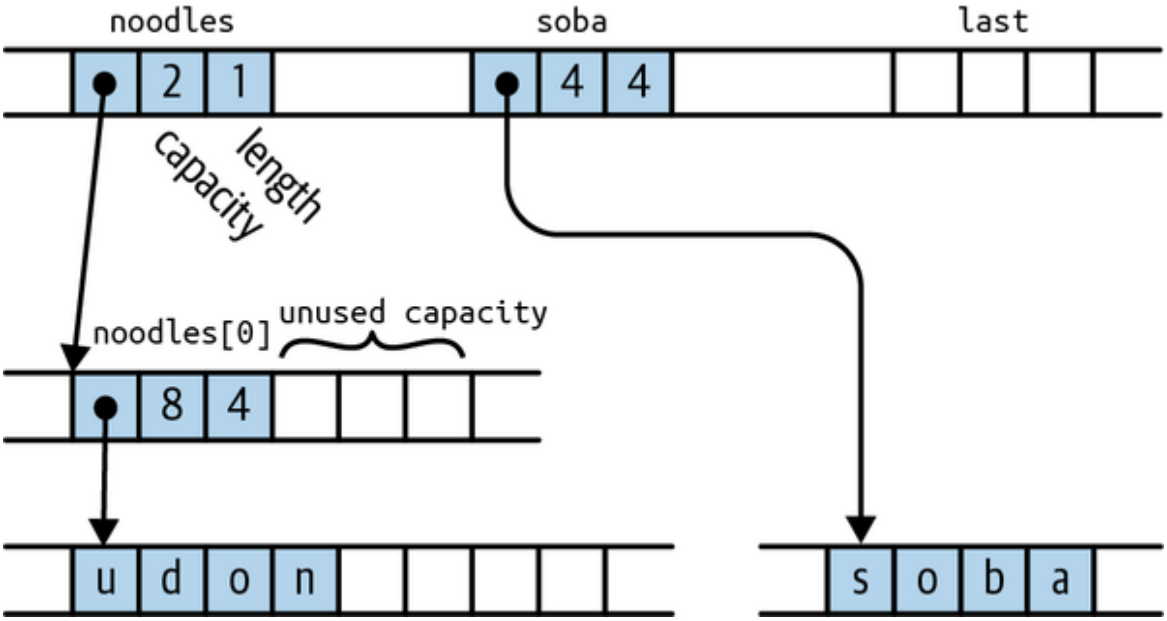


*Figure 23-3. A vector with uninitialized, spare capacity*

The vector has the spare capacity to hold one more element, but its contents are junk, probably whatever that memory held previously. Suppose you then run this code:

```
noodles.push(soba);
```

Pushing the string onto the vector transforms that uninitialized memory into a new element, as illustrated in Figure 23-4.

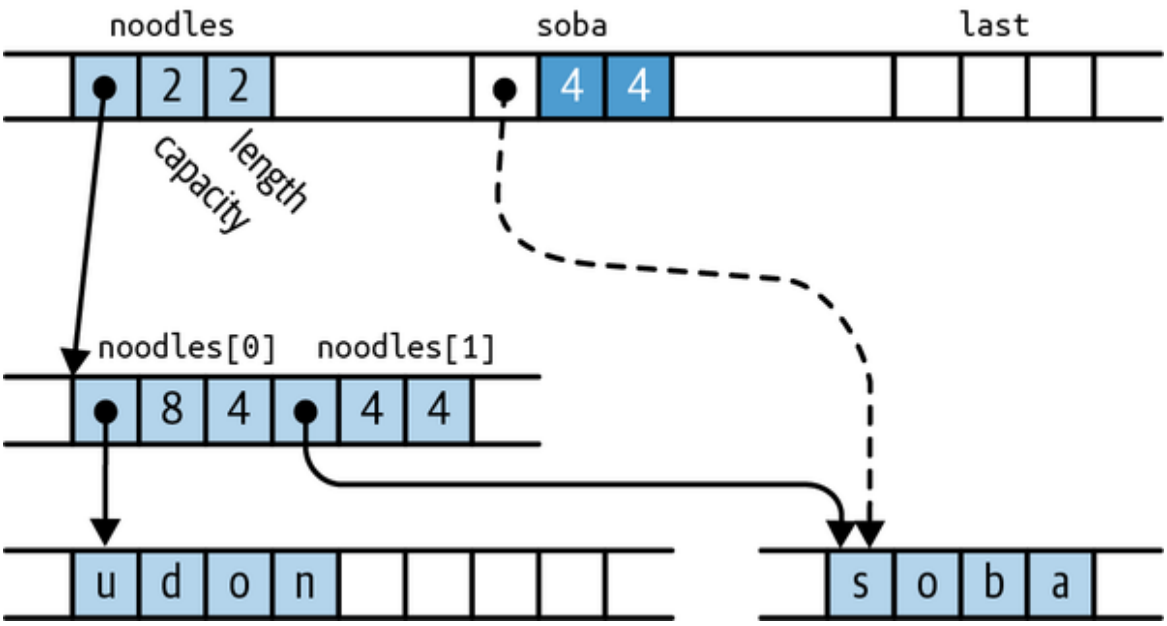


*Figure 23-4. After pushing `soba`'s value onto the vector*

The vector has initialized its empty space to own the string and incremented its length to mark that space as occupied. The vector is now the owner of the string; you can refer to its second element with `noodles[1]`, and dropping the vector would free both strings. And the variable `soba` is now vacant.

Finally, consider what happens when we pop a value from the vector:

```
last = noodles.pop().unwrap();
```

In memory, things now look like Figure 23-5.

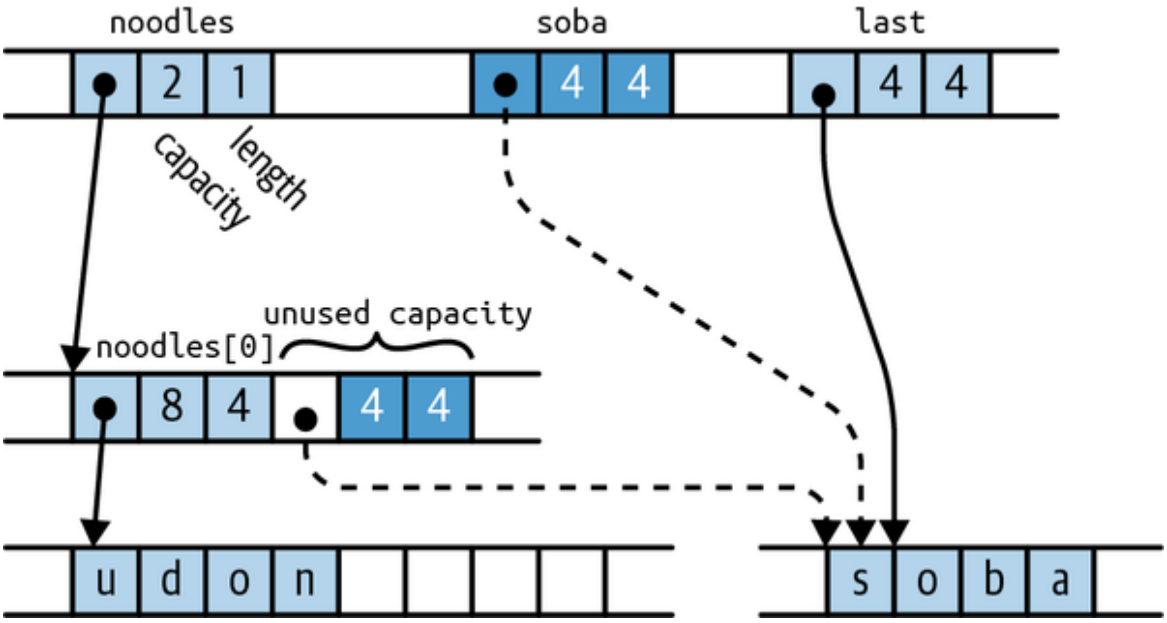


*Figure 23-5. After popping an element from the vector into `last`*

The variable `last` has taken ownership of the string. The vector has decremented its length to indicate that the space that used to hold the string is now vacant.

Just as with `pot` and `pasta` earlier, all three of `soba`, `last`, and the vector's free space probably hold identical bit patterns. But only `last` is considered to own the value. Treating either of the other two locations as occupied would be a mistake. For local variables, Rust tracks initialization and moves at compile time. Types like `Vec` and `HashMap` track occupancy for their buffers dynamically. If you implement a type that manages its own memory, you will need to do the same.

Raw pointers provide two essential unsafe methods for implementing such types:

`ptr.read()`

> Moves or copies a value out of the location `ptr` points to. `ptr` can be either a `*const T` or a `*mut T` raw pointer, where `T` is a sized type. The method returns a `T`.
>
> After calling this method, the contents of `*ptr` are unchanged, but unless `T` is `Copy`, you typically shouldn't treat that memory as occupied

anymore. If your program `read()`s the same pointer again, for example, it will create a second byte-for-byte copy of the same non-`Copy` value. That often means a double free when both values are dropped.

This is the operation behind `Vec::pop`. Popping a value calls `read` to move the value out of the buffer and then decrements the length to mark that memory as vacant.

`ptr.write(value)`

Moves `value` into the location `ptr` points to. Whatever was in that memory before is simply overwritten, without calling destructors, so this is suitable for writing to uninitialized memory. Here, `ptr` must be a `*mut T` raw pointer and `value` a `T` value, where `T` is a sized type.

You can think of `*ptr` as owning the value afterward. If the value has a destructor, it's your responsibility to make sure `*ptr` is a location where the value will be dropped later.

This is the operation behind `Vec::push`. Pushing a value calls `write` to move the value into the next available space and then increments the length to mark that memory as occupied.

The standard library also provides methods for moving arrays of values from one block of memory to another:

`src.copy_to(dst, count)`

Moves `count` values stored in memory starting at `src` to the memory starting at `dst`. The `src` and `dest` arguments must be `*const T` and `*mut T` raw pointers, and `count` must be a `usize`. The regions may overlap.

This is similar to a loop that uses `read` and `write` calls to move the values one at a time, except that `read` requires the memory to contain a valid value, and `copy_to` doesn't care. The memory being moved can even be uninitialized.

`src.copy_to_nonoverlapping(dst, count)`

> Like `copy_to`, except its contract further requires that the source and destination regions must not overlap. This may be slightly faster than calling `copy_to`.

C programmers will recognize these methods as Rust's versions of `memmove` and `memcpy`.

There are two other families of `read` and `write` pointer methods:

`ptr.read_unaligned(), ptr.write_unaligned(value)`

> These methods are like `read` and `write`, except that the pointer need not be aligned as normally required for the referent type. These functions may be slower than the plain `read` and `write` functions.

`ptr.read_volatile(), ptr.write_volatile(value)`

> These functions are the equivalent of volatile reads and writes in C or C++.

The standard library documentation covers all pointer methods under "Primitive type pointer".

## Example: GapBuffer

Here's an example that puts the raw pointer methods just described to use.

Suppose you're writing a text editor, and you're looking for a type to represent the text. You could choose `String` and use the `insert` and `remove` methods to insert and delete characters as the user types. But if they're editing text at the beginning of a large file, those methods can be expensive: inserting a new character involves shifting the entire rest of the string to the right in memory, and deletion shifts it all back to the left. You'd like such common operations to be cheaper.

The Emacs text editor uses a simple data structure called a *gap buffer* that can insert and delete characters in constant time. Whereas a `String` keeps all its spare capacity at the end of the text, which makes `push` and `pop` cheap, a gap buffer keeps its spare capacity in the midst of the text, at the point where editing is taking place. This spare capacity is called the *gap*. Inserting or deleting elements at the gap is cheap: you simply shrink or enlarge the gap as needed. You can move the gap to any location you like by shifting text from one side of the gap to the other. When the gap is empty, you migrate to a larger buffer.

While insertion and deletion in a gap buffer are fast, changing the position at which they take place entails moving the gap to the new position. Shifting the elements requires time proportional to the distance being moved.

In this section we'll implement a gap buffer in Rust. To avoid being distracted by UTF-8, we'll make our buffer store `char` values directly, but the principles of operation would be the same if we stored the text in some other form.

First, we'll show a gap buffer in action. This code creates a `GapBuffer`, inserts some text in it, and then moves the insertion point to sit just before the last word:

```
let mut buf = GapBuffer::new();
buf.insert_iter("Lord of the Rings".chars());
buf.set_position(12);
```

After running this code, the buffer looks as shown in Figure 23-6.

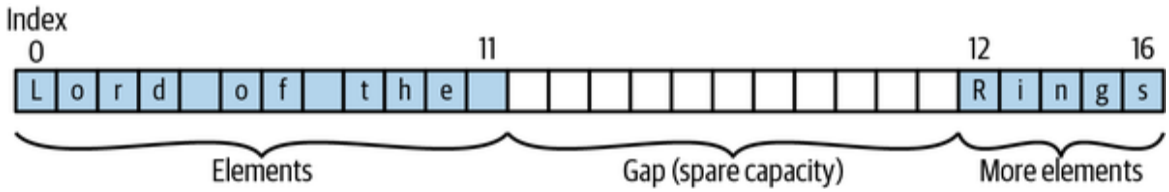


*Figure 23-6. A gap buffer containing some text*

Insertion is a matter of filling in the gap with new text. This code adds a word and ruins the film:

```
buf.insert_iter("Onion ".chars());
```

This results in the state shown in Figure 23-7.

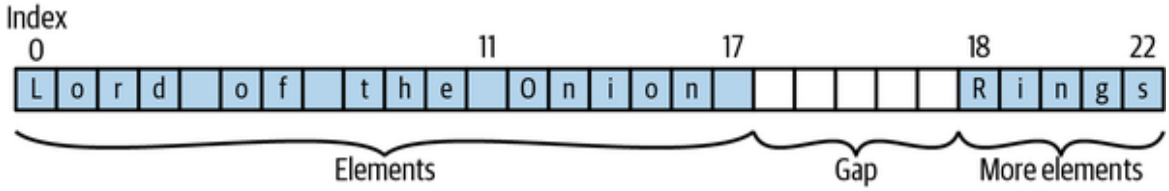


*Figure 23-7. A gap buffer containing some more text*

Here's our `GapBuffer` type:

```
use std::ops::Range;

pub struct GapBuffer<T> {
    // Storage for elements. This has the capacity we need, but
its length
    // always remains zero. GapBuffer puts its elements and the
gap in this
    // `Vec`'s "unused" capacity.
    storage: Vec<T>,

    // Range of uninitialized elements in the middle of
`storage`.
    // Elements before and after this range are always
initialized.
    gap: Range<usize>,
}
```

`GapBuffer` uses its `storage` field in a strange way. It never actually stores any elements in the vector—or not quite. It simply calls `Vec::with_capacity(n)` to get a block of memory large enough to hold `n` values, obtains raw pointers to that memory via the vector's `as_ptr` and `as_mut_ptr` methods, and then uses the buffer directly for its own purposes. The vector's length always remains zero.

When the `Vec` gets dropped, it doesn't try to free its elements because it doesn't know it has any, but it does free the block of memory. This is what `GapBuffer` wants; it has its own `Drop` implementation that knows where

the elements are and drops them correctly. `GapBuffer`'s simplest methods are what you'd expect:

```
impl<T> GapBuffer<T> {
    pub fn new() -> GapBuffer<T> {
        GapBuffer {
            storage: Vec::new(),
            gap: 0..0,
        }
    }

    /// Returns the number of elements this GapBuffer could hold
without
    /// reallocation.
    pub fn capacity(&self) -> usize {
        self.storage.capacity()
    }

    /// Returns the number of elements this GapBuffer currently
holds.
    pub fn len(&self) -> usize {
        self.capacity() - self.gap.len()
    }

    /// Returns the current insertion position.
    pub fn position(&self) -> usize {
        self.gap.start
    }

    ...
}
```

It cleans up many of the following functions to have a utility method that returns a raw pointer to the buffer element at a given index. This being Rust, we end up needing one method for `mut` pointers and one for `const`. Unlike the preceding methods, these are not public. Continuing this `impl` block:

```
/// Returns a pointer to the `index`th element of the underlying
storage,
/// regardless of the gap.
///
/// # Safety
```

```
    /// `index` must be a valid index into `self.storage`.
    unsafe fn space(&self, index: usize) -> *const T {
        // SAFETY: The caller must ensure `index` is in range.
        unsafe { self.storage.as_ptr().add(index) }
    }

    /// Returns a mutable pointer to the `index`th element of the
    underlying
    /// storage, regardless of the gap.
    ///
    /// # Safety
    /// `index` must be a valid index into `self.storage`.
    unsafe fn space_mut(&mut self, index: usize) -> *mut T {
        // SAFETY: Same as space().
        unsafe { self.storage.as_mut_ptr().add(index) }
    }
```

You'll see this pattern frequently in unsafe Rust: the `unsafe` code inside these methods is safe *if and only if* the caller holds up their end of the deal. To find the element at a given index, you must consider if the index falls before or after the gap and adjust appropriately:

```
    /// Returns the offset in the buffer of the `index`th element,
    taking
    /// the gap into account. This does not check whether index is in
    range,
    /// but it never returns an index in the gap.
    fn index_to_raw(&self, index: usize) -> usize {
        if index < self.gap.start {
            index
        } else {
            index + self.gap.len()
        }
    }

    /// Returns a reference to the `index`th element,
    /// or `None` if `index` is out of bounds.
    pub fn get(&self, index: usize) -> Option<&T> {
        let raw = self.index_to_raw(index);
        if raw < self.capacity() {
            // SAFETY: We just checked `raw` against self.capacity(),
            // and index_to_raw skips the gap, so this is safe.
            Some(unsafe { &*self.space(raw) })
        } else {
            None
```

```
    }
}
```

When we start making insertions and deletions in a different part of the buffer, we need to move the gap to the new location. Moving the gap to the right entails shifting elements to the left, and vice versa, just as the bubble in a spirit level moves in one direction when the fluid flows in the other:

```
/// Sets the current insertion position to `pos`.
/// If `pos` is out of bounds, this panics.
pub fn set_position(&mut self, pos: usize) {
    if pos > self.len() {
        panic!("index {pos} out of range for GapBuffer");
    }

    let gap = self.gap.clone();
    if pos > gap.start {
        // `pos` falls after the gap. Move the gap right
        // by shifting elements after the gap to before it.
        let count = pos - gap.start;
        // SAFETY: If our arithmetic is right, these pointer
ranges are all
        // inside the buffer. They may overlap, but `copy_to`
supports that.
        // Copying is OK, even if `T` is not `Copy`, because
we're really
        // moving the values, not making copies.
        unsafe {
            self.space(gap.end)
                .copy_to(self.space_mut(gap.start), count);
        }
    } else if pos < gap.start {
        // `pos` falls before the gap. Move the gap left
        // by shifting elements before the gap to after it.
        let count = gap.start - pos;
        // SAFETY: Same as above.
        unsafe {
            self.space(pos)
                .copy_to(self.space_mut(gap.end - count), count);
        }
    }

    self.gap = pos..pos + gap.len();
}
```

This function uses the `copy_to` method to shift the elements. Note that `copy_to` doesn't care what location in memory "owns" a value or which locations are "occupied" and which are "vacant." It simply copies the raw bytes from one region to the other, as fast as possible, like `memmove` in C. It's up to us to make sure `GapBuffer` consistently applies its own rules about which locations are occupied.

Element insertion and removal are relatively simple. Insertion takes over one space from the gap for the new element, whereas removal moves one value out and enlarges the gap to cover the space it used to occupy:

```
    /// Inserts `elt` at the current insertion position,
    /// and leaves the insertion position after it.
    pub fn insert(&mut self, elt: T) {
        if self.gap.len() == 0 {
            self.enlarge_gap();
        }

        // SAFETY: The code above ensures there's room in the gap.
        unsafe {
            let index = self.gap.start;
            self.space_mut(index).write(elt);
        }
        self.gap.start += 1;
    }

    /// Inserts the elements produced by `iter` at the current
    insertion
    /// position, and leaves the insertion position after them.
    pub fn insert_iter<I>(&mut self, iterable: I)
    where
        I: IntoIterator<Item = T>,
    {
        for item in iterable {
            self.insert(item);
        }
    }

    /// Removes the element just after the insertion position
    /// and returns it, or returns `None` if the insertion position
    /// is at the end of the GapBuffer.
    pub fn remove(&mut self) -> Option<T> {
        if self.gap.end == self.capacity() {
            return None;
```

```
        }

        let element = unsafe { self.space(self.gap.end).read() };
        self.gap.end += 1;
        Some(element)
    }
```

Similar to the way `Vec` uses a pointer `write` for `push` and a pointer `read` for `pop`, `GapBuffer` uses `write` for `insert` and `read` for `remove`. And just as `Vec` must adjust its length to maintain the boundary between occupied and vacant memory, `GapBuffer` adjusts its gap.

When the gap has been filled in, the `insert` method must grow the buffer to acquire more free space. The `enlarge_gap` method (the last in the `impl` block) handles this:

```
    /// Doubles the capacity of `self.storage`.
    fn enlarge_gap(&mut self) {
        let mut new_capacity = self.capacity() * 2;
        if new_capacity == 0 {
            // The existing vector is empty.
            // Choose a reasonable starting capacity.
            new_capacity = 4;
        }

        // We have no idea what resizing a Vec does with its "unused"
        // capacity. So just create a new vector and move over the
    elements.
        let mut new = Vec::with_capacity(new_capacity);
        let after_gap = self.capacity() - self.gap.end;
        let new_gap = self.gap.start..new.capacity() - after_gap;

        unsafe {
            // Move the elements that fall before the gap.
            self.space(0)
                .copy_to_nonoverlapping(new.as_mut_ptr(),
    self.gap.start);

            // Move the elements that fall after the gap.
            let new_gap_end = new.as_mut_ptr().add(new_gap.end);
            self.space(self.gap.end)
                .copy_to_nonoverlapping(new_gap_end, after_gap);
        }
```

```
        // This frees the old Vec, but drops no elements,
        // because the Vec's length is zero.
        self.storage = new;
        self.gap = new_gap;
    }
```

Whereas `set_position` must use `copy_to` to move elements back and forth in the gap, `enlarge_gap` can use `copy_to_nonoverlapping`, since it is moving elements to an entirely new buffer.

Moving the new vector into `self.storage` drops the old vector. Since its length is zero, the old vector believes it has no elements to drop and simply frees its buffer. Neatly, we have moved all the values, so the old vector is correct in this belief: all the elements are now owned by the new vector.

Finally, we need to make sure that dropping a `GapBuffer` drops all its elements:

```
impl<T> Drop for GapBuffer<T> {
    fn drop(&mut self) {
        // SAFETY: GapBuffer maintains the invariant that the
        // spaces in these two ranges contain valid T values.
        unsafe {
            for i in 0..self.gap.start {
                self.space_mut(i).drop_in_place();
            }
            for i in self.gap.end..self.capacity() {
                self.space_mut(i).drop_in_place();
            }
        }
    }
}
```

The elements lie before and after the gap, so we iterate over each region and use the `drop_in_place` pointer method to drop each one. The `drop_in_place` method is a utility that behaves like `drop(ptr.read())` but doesn't bother moving the value before dropping it. And just as in `enlarge_gap`, by the time the vector `self.storage` is dropped, its buffer really is entirely vacant.

Like the other types we've shown in this chapter, `GapBuffer` ensures that its own invariants are sufficient to ensure that the contract of every unsafe feature it uses is followed, so none of its public methods needs to be marked unsafe. `GapBuffer` implements a safe interface for a feature that cannot be written efficiently in safe code.

## Panic Safety in Unsafe Code

In Rust, panics can't usually cause undefined behavior; the `panic!` macro is not an unsafe feature. But when you decide to work with unsafe code, panic safety becomes part of your job.

Consider the `GapBuffer::remove` method from the previous section:

```
pub fn remove(&mut self) -> Option<T> {
    if self.gap.end == self.capacity() {
        return None;
    }

    let element = unsafe { self.space(self.gap.end).read() };
    self.gap.end += 1;
    Some(element)
}
```

The call to `read` produces a value of type `T` by reading the space immediately following the gap. But it also leaves the original bytes unchanged. If we were to drop both copies of the value, it could be undefined behavior. Fortunately, the very next statement enlarges the gap to mark that space as vacant, so by the time we return, there is again only one live copy of the value.

But consider what would happen if, after the call to `read` but before the adjustment to `self.gap.end`, this code tried to use a feature that might panic—say, indexing a slice. Exiting the method abruptly anywhere between those two actions would drop `element` and leave the `GapBuffer` with a copy of the same value outside the gap. The next call to `remove` could try to `read` it again; even simply dropping the `GapBuffer` would try to drop it. Unless `T` happens to be `Copy`, dropping

multiple byte-for-byte copies of a value like this is likely to be undefined behavior.

It's all but unavoidable for a type's methods to momentarily relax the type's invariants while they do their job and then put everything back to rights before they return. A panic mid-method could cut that cleanup process short, leaving the type in an inconsistent state.

If the type uses only safe code, then this inconsistency may make the type misbehave, but it can't introduce undefined behavior. But code using unsafe features is usually counting on its invariants to meet the contracts of those features. Broken invariants lead to broken contracts, which lead to undefined behavior.

When working with unsafe features, you must take special care to identify these sensitive regions of code where invariants are temporarily relaxed and ensure that they do nothing that might panic.

## Unions

Rust also has *unions*, a kind of user-defined type inherited from C.

The Rust standard library documentation says that a union is like a struct, but instead of all the fields being stored at different offsets within the struct value, they are all stored at the *same* memory location. This is fantastical but true.

```
union UnspecifiedShape {
    circle: *mut Circle,
    rectangle: *mut Rectangle,
}
```

This type is large enough to hold a single pointer, not two. You can create values of this type by writing either `UnspecifiedShape { circle: &mut c }` or `UnspecifiedShape { rectangle: &mut r }`. Specifying both fields is not permitted, as one would simply overwrite the other.

Unlike an `enum`, whose tag indicates which variant is present, an `UnspecifiedShape` carries no indication of which field is initialized, so reading from any field of a union is unsafe.

When a union is dropped, Rust again has no way to tell which field is in use. Therefore, unions can't have fields that implement `Drop`.

Unions are useful in very narrow circumstances:

- They can be used to roll your own `enum`-like types. Sometimes an `enum` with several fields can be reimplemented using a `union` in a way that saves a whole machine word and has a safe API. There's rarely more than one type in your program that merits this amount of effort, but when a program uses a hundred million values of a single type, the savings add up.
- Unions provide a way to reinterpret raw bytes as struct types, or vice versa: declare a union where one field is an array of `u8`, and the other is the desired struct. (This can be handy when interpreting a binary file or network packet. When possible, though, it's better to do this safely using the `bytemuck` crate.)
- Sometimes, when Rust needs to call or be called from code in another language, unions can be a way of sharing data across the language boundary. C doesn't have Rust-style enums with fields, for instance, but it does have unions.

Calling back and forth between Rust and other languages is the topic of the next chapter. As we'll see, Rust helps you build safe interfaces not only for your own unsafe code but also for code written in other languages.

---

[1] Well, it's a classic where we come from.

# Chapter 24. Foreign Functions

> *Cyberspace. Unthinkable complexity. Lines of light ranged in the non-space of the mind, clusters and constellations of data. Like city lights, receding . . .*
>
> —William Gibson, *Neuromancer*

Tragically, not every program in the world is written in Rust. There are many critical libraries and interfaces implemented in other languages that we would like to be able to use in our Rust programs. Rust's *foreign function interface* (FFI) lets Rust code call functions written in C, and in some cases C++. Since most operating systems offer C interfaces, Rust's FFI allows immediate access to all sorts of low-level facilities.

In this chapter, we'll write a program that links with `libgit2`, a C library for working with the Git version control system. First, we'll show what it's like to use C functions directly from Rust, using the unsafe features demonstrated in the previous chapter. Then, we'll show how to construct a safe interface to `libgit2`, taking inspiration from the open source `git2-rs` crate.

We'll assume that you're familiar with C and the mechanics of compiling and linking C programs. Working with C++ is similar. We'll also assume that you're somewhat familiar with the Git version control system.

There do exist Rust crates for communicating with many other languages, including Python, JavaScript, Lua, and Java. We don't have room to cover them here, but ultimately, all these interfaces are built using the C FFI, so this chapter should give you a head start no matter which language you need to work with.

## Finding Common Data Representations

The common denominator of Rust and C is machine language, so to anticipate what Rust values look like to C code, or vice versa, you need to consider their machine-level representations. Throughout the book, we've made a point of showing how values are actually represented in memory, so you've probably noticed that the data worlds of C and Rust have a lot in common: a Rust `usize` and a C `size_t` are identical, for example, and structs are fundamentally the same idea in both languages. To establish a correspondence between Rust and C types, we'll start with primitives and then work our way up to more complicated types.

Given its primary use as a systems programming language, C has always been surprisingly loose about its types' representations: an `int` is typically 32 bits long, but could be longer, or as short as 16 bits; a C `char` may be signed or unsigned; and so on. To cope with this variability, Rust's `std::ffi` module defines a set of Rust types that are guaranteed to have the same representation as certain C types (Table 24-1). These cover the primitive integer and character types.

*Table 24-1. `std::ffi` types in Rust*

| C type | Corresponding `std::ffi` type |
|---|---|
| `short` | `c_short` |
| `int` | `c_int` |
| `long` | `c_long` |
| `long long` | `c_longlong` |
| `unsigned short` | `c_ushort` |
| `unsigned`, `unsigned int` | `c_uint` |
| `unsigned long` | `c_ulong` |
| `unsigned long long` | `c_ulonglong` |
| `char` | `c_char` |
| `signed char` | `c_schar` |
| `unsigned char` | `c_uchar` |
| `float` | `c_float` |
| `double` | `c_double` |
| `void *`, `const void *` | `*mut c_void`, `*const c_void` |

Some notes about Table 24-1:

- Except for `c_void`, all the Rust types here are aliases for some primitive Rust type: `c_char`, for example, is either `i8` or `u8`.
- A Rust `bool` is equivalent to a C or C++ `bool`.

- Rust's 32-bit `char` type is not the analogue of `wchar_t`, whose width and encoding vary from one implementation to another. C's `char32_t` type is closer, but its encoding is still not guaranteed to be Unicode.
- Rust's primitive `usize` and `isize` types have the same representations as C's `size_t` and `ptrdiff_t`.
- C and C++ pointers and C++ references correspond to Rust's raw pointer types, `*mut T` and `*const T`.
- Technically, the C standard permits implementations to use representations for which Rust has no corresponding type: 36-bit integers, sign-and-magnitude representations for signed values, and so on. In practice, on every platform Rust has been ported to, every common C integer type has a match in Rust.

For defining Rust struct types compatible with C structs, you can use the `#[repr(C)]` attribute. Placing `#[repr(C)]` above a struct definition asks Rust to lay out the struct's fields in memory the same way a C compiler would lay out the analogous C struct type. For example, `libgit2`'s *git2/errors.h* header file defines the following C struct to provide details about a previously reported error:

```
typedef struct {
    char *message;
    int klass;
} git_error;
```

You can define a Rust type with an identical representation as follows:

```
use std::ffi::{c_char, c_int};

#[repr(C)]
pub struct git_error {
    pub message: *const c_char,
    pub klass: c_int,
}
```

The `#[repr(C)]` attribute affects only the layout of the struct itself, not the representations of its individual fields, so to match the C struct, each field must use the C-like type as well: `*const c_char` for `char *`, `c_int` for `int`, and so on.

In this particular case, the `#[repr(C)]` attribute probably doesn't change the layout of `git_error`. There really aren't too many interesting ways to lay out a pointer and an integer. But whereas C and C++ guarantee that a structure's members appear in memory in the order they're declared, each at a distinct address, Rust reorders fields to minimize the overall size of the struct, and zero-sized types take up no space. The `#[repr(C)]` attribute tells Rust to follow C's rules for the given type.

You can also use `#[repr(C)]` to declare C-compatible enums, but it's not recommended:

```
#[repr(C)]
#[allow(non_camel_case_types)]
enum git_error_code {  // NOT recommended
    GIT_OK          =  0,
    GIT_ERROR       = -1,
    GIT_ENOTFOUND   = -3,
    GIT_EEXISTS     = -4,
    ...
}
```

This is dangerous, because Rust is strict about enum values, and C is not. In C, there's nothing wrong with having a `git_error_code` whose value is 1, or 2, or 300000, whether those values are listed in the definition of `enum git_error_code` or not. In Rust, an enum whose value doesn't match one of the variants in the `enum` declaration is invalid. Returning such a value from C code to Rust is undefined behavior. (Feeding an invalid enum value to a `match` expression is especially likely to go off the rails. This happens implicitly in derived `Debug` implementations. But creating the invalid value in Rust at all is what invalidates `rustc`'s assumptions; nothing can make that safe.)

The safe alternative is to declare `git_error_code` to be an alias for `c_int`, and declare the enumerators as constants:

```
type git_error_code = c_int;

const GIT_OK: git_error_code = 0;
const GIT_ERROR: git_error_code = -1;
...
```

Bindgen applies this workaround automatically.

As long as the behavior of the code on the other side of the FFI boundary is well-understood, it's possible to pass even complex values back and forth.

Passing strings between Rust and C is a little harder. C represents a string as a pointer to an array of characters, terminated by a null character. Rust, on the other hand, stores the length of a string explicitly, either as a field of a `String` or as the second word of a fat reference `&str`. Rust strings are not null-terminated; in fact, they may include null characters in their contents, like any other character.

This means that you can't borrow a Rust string as a C string: if you pass C code a pointer into a Rust string, it could mistake an embedded null character for the end of the string or run off the end looking for a terminating null that isn't there. Going the other direction, you may be able to borrow a C string as a Rust `&str`, as long as its contents are well-formed UTF-8.

This situation effectively forces Rust to treat C strings as types entirely distinct from `String` and `&str`. In the `std::ffi` module, the `CString` and `CStr` types represent owned and borrowed null-terminated arrays of bytes. Compared to `String` and `str`, the methods on `CString` and `CStr` are quite limited, restricted to construction and conversion to other types. We'll show these types in action in the next section.

## Declaring Foreign Functions and Variables

An `extern` block declares functions or variables defined in some other library that the final Rust executable will be linked with. For example, on most platforms, every Rust program is linked against the standard C library, so we can tell Rust about the C library's `strlen` function like this:

```
use std::ffi::c_char;

unsafe extern "C" {
    fn strlen(s: *const c_char) -> usize;
}
```

This gives Rust the function's name and type, while leaving the definition to be linked in later.

Rust assumes that functions declared inside `unsafe extern "C"` blocks use C conventions for passing arguments and accepting return values. They are defined as `unsafe` functions. These are the right choices for `strlen`: it is indeed a C function, and its specification in C requires that you pass it a valid pointer to a properly terminated string, which is a contract that Rust cannot enforce. (Almost any function that takes a raw pointer must be `unsafe`: safe Rust can construct raw pointers from arbitrary integers, and dereferencing such a pointer would be undefined behavior.)

With this `extern` block, we can call `strlen` like any other Rust function, although its type gives it away as a tourist:

```
use std::ffi::CString;

let rust_str = "I'll be back";
let null_terminated = CString::new(rust_str).unwrap();
unsafe {
    assert_eq!(strlen(null_terminated.as_ptr()), 12);
}
```

The `CString::new` function builds a null-terminated C string. It first checks its argument for embedded null characters, since those cannot be represented in a C string, and returns an error if it finds any (hence the need

to `unwrap` the result). Otherwise, it adds a null byte to the end and returns a `CString` owning the resulting characters.

The cost of `CString::new` depends on what type you pass it. It accepts anything that implements `Into<Vec<u8>>`. Passing a `&str` entails an allocation and a copy, as the conversion to `Vec<u8>` builds a heap-allocated copy of the string for the vector to own. But passing a `String` by value simply consumes the string and takes over its buffer, so unless appending the null character forces the buffer to be resized, the conversion requires no copying of text or allocation at all. Like `&[u8]` and `&str`, `&CStr` can be written as a literal, like `c"Hello, world."`.

`CString` dereferences to `CStr`, whose `as_ptr` method returns a `*const c_char` pointing at the start of the string. This is the type that `strlen` expects. In the example, `strlen` runs down the string, finds the null character that `CString::new` placed there, and returns the length as a byte count. You can also declare global variables in `extern` blocks. POSIX systems have a global variable named `environ` that holds the values of the process's environment variables. In C, it's declared:

```
extern char **environ;
```

In Rust, you would say:

```
use std::ffi::{CStr, c_char};

unsafe extern "C" {
    static environ: *mut *mut c_char;
}
```

To print the environment's first element, you could write:

```
unsafe {
    if !environ.is_null() && !(*environ).is_null() {
        let var = CStr::from_ptr(*environ);
        println!("first environment variable: {}",
var.to_string_lossy());
```

```
    }
}
```

After making sure `environ` has a first element, the code calls `CStr::from_ptr` to build a `CStr` that borrows it. The `to_string_lossy` method returns a `Cow<str>`: if the C string contains well-formed UTF-8, the `Cow` borrows its content as a `&str`, not including the terminating null byte. Otherwise, `to_string_lossy` makes a copy of the text in the heap, replaces the ill-formed UTF-8 sequences with the official Unicode replacement character, `�`, and builds an owning `Cow` from that. Either way, the result implements `Display`, so you can print it with the `{}` format parameter.

## Using Functions from Libraries

To use functions provided by a particular library, you can place a `#[link]` attribute atop the `extern` block that names the library Rust should link the executable with. For example, here's a program that calls `libgit2`'s initialization and shutdown methods but does nothing else:

```
use std::ffi::c_int;

#[link(name = "git2")]
unsafe extern "C" {
    pub fn git_libgit2_init() -> c_int;
    pub fn git_libgit2_shutdown() -> c_int;
}

fn main() {
    unsafe {
        git_libgit2_init();
        git_libgit2_shutdown();
    }
}
```

The `unsafe extern "C"` block declares the extern functions as before. The `#[link(name = "git2")]` attribute leaves a note in the crate to the effect that, when Rust creates the final executable or shared library, it

should link against the `git2` library. Rust uses the system linker to build executables; on Unix, this passes the argument `-lgit2` on the linker command line; on Windows, it passes `git2.LIB`.

`#[link]` attributes work in library crates, too. When you build a program that depends on other crates, Cargo gathers together the link notes from the entire dependency graph and includes them all in the final link.

In this example, if you would like to follow along on your own machine, you'll need to build `libgit2` for yourself. We used `libgit2` version 1.8.1. To compile `libgit2`, you will need to install the CMake build tool and the Python language; we used CMake version 3.28.3 and Python version 3.12.3.

The full instructions for building `libgit2` are available on its website, but they're simple enough that we'll show the essentials here. On Linux, assume you've already unzipped the library's source into the directory */home/jimb/libgit2-1.8.1*:

```
$ cd /home/jimb/libgit2-1.8.1
$ mkdir build
$ cd build
$ cmake ..
$ cmake --build .
```

On Linux, this produces a shared library */home/jimb/libgit2-1.8.1/build/libgit2.so.1.8.1* with the usual nest of symlinks pointing to it, including one named *libgit2.so*. On macOS, the results are similar, but the library is named *libgit2.dylib*.

On Windows, things are also straightforward. Assume you've unzipped the source into the directory *C:\Users\JimB\libgit2-1.8.1*. In a Visual Studio command prompt:

```
> cd C:\Users\JimB\libgit2-1.8.1
> mkdir build
> cd build
> cmake -A x64 ..
> cmake --build .
```

These are the same commands as used on Linux, except that you must request a 64-bit build when you run CMake the first time to match your Rust compiler. (If you have installed the 32-bit Rust toolchain, then you should omit the `-A x64` flag to the first `cmake` command.) This produces an import library *git2.LIB* and a dynamic-link library *git2.DLL*, both in the directory *C:\Users\JimB\libgit2-1.8.1\build\Debug*. (The remaining instructions are shown for Unix, except where Windows is substantially different.)

Create the Rust program in a separate directory:

```
$ cd /home/jimb
$ cargo new --bin git-toy
    Creating binary (application) `git-toy` package
```

Take the code shown earlier and put it in *src/main.rs*. Naturally, if you try to build this, Rust has no idea where to find the `libgit2` you built:

```
$ cd git-toy
$ cargo run
   Compiling git-toy v0.1.0 (/home/jimb/git-toy)
error: linking with `cc` failed: exit status: 1
  |
  = note: rust-lld: error: unable to find library -lgit2
          collect2: error: ld returned 1 exit status


error: could not compile `git-toy` (bin "git-toy") due to 1
previous error
```

You can tell Rust where to search for libraries by writing a build script that tells Cargo to add a library search path to the executable's link command. Cargo parses the build script's output for information of this sort, so the build script simply needs to print the right magic to its standard output. For more on build scripts in general, see "Build Scripts".

To create your build script, add a file named *build.rs* in the same directory as the *Cargo.toml* file, with the following contents:

```
fn main() {
    println!(r"cargo:rustc-link-search=native=/home/jimb/libgit2-
1.8.1/build");
}
```

This is the right path for Linux; on Windows, you would change the path following the text `native=` to `C:\Users\JimB\libgit2-1.8.1\build\Debug`. (We're cutting some corners to keep this example simple; in a real application, you should avoid using absolute paths in your build script. We cite documentation that shows how to do it right at the end of this section.)

Now you can almost run the program. On macOS it may work immediately; on a Linux system you will probably see something like the following:

```
$ cargo run
   Compiling git-toy v0.1.0 (/home/jimb/git-toy)
    Finished `dev` profile [unoptimized + debuginfo] target(s)
     Running `target/debug/git-toy`
target/debug/git-toy: error while loading shared libraries:
libgit2.so.25: cannot open shared object file: No such file or
directory
```

This means that although Cargo succeeded in linking the executable against the library, it doesn't know where to find the shared library at run time. Windows reports this failure by popping up a dialog box. On Linux, you must set the `LD_LIBRARY_PATH` environment variable:

```
$ export LD_LIBRARY_PATH=/home/jimb/libgit2-
1.8.1/build:$LD_LIBRARY_PATH
$ cargo run
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.0 secs
     Running `target/debug/git-toy`
```

On macOS, you may need to set `DYLD_LIBRARY_PATH` instead.

On Windows, you must set the `PATH` environment variable:

```
> set PATH=C:\Users\JimB\libgit2-1.8.1\build\Debug;%PATH%
> cargo run
    Finished `dev` profile [unoptimized + debuginfo] target(s) in
0.0 secs
     Running `target/debug/git-toy`
>
```

Naturally, in a deployed application you'd want to avoid having to set environment variables just to find your library's code. One alternative is to statically link the C library into your crate. This copies the library's object files into the crate's *.rlib* file, alongside the object files and metadata for the crate's Rust code. The entire collection then participates in the final link.

It is a Cargo convention that a crate that provides access to a C library should be named `LIB-sys`, where `LIB` is the name of the C library. A `-sys` crate should contain nothing but the statically linked library and Rust modules containing `extern` blocks and type definitions. Higher-level interfaces then belong in crates that depend on the `-sys` crate. This allows multiple upstream crates to depend on the same `-sys` crate, assuming there is a single version of the `-sys` crate that meets everyone's needs.

For the full details on Cargo's support for build scripts and linking with system libraries, see the online Cargo documentation. It shows how to avoid absolute paths in build scripts, control compilation flags, use tools like `pkg-config`, and so on. The `git2-rs` crate also provides good examples to emulate; its build script handles some complex situations.

## A Raw Interface to libgit2

Figuring out how to use `libgit2` properly breaks down into two questions:

- What does it take to use `libgit2` functions in Rust?
- How can we build a safe Rust interface around them?

We'll take these questions one at a time. In this section, we'll write a program that's essentially a single giant `unsafe` block filled with

nonidiomatic Rust code, reflecting the clash of type systems and conventions that is inherent in mixing languages. We'll call this the *raw* interface. The code will be messy, but it will make plain all the steps that must occur for Rust code to use `libgit2`.

Then, in the next section, we'll build a safe interface to `libgit2` that puts Rust's types to use enforcing the rules `libgit2` imposes on its users. Fortunately, `libgit2` is an exceptionally well-designed C library, so the questions that Rust's safety requirements force us to ask all have pretty good answers, and we can construct an idiomatic Rust interface with no `unsafe` functions.

The program we'll write is simple: it takes a path as a command-line argument, opens the Git repository there, and prints out the head commit. But this is enough to illustrate the key strategies for building safe and idiomatic Rust interfaces.

For the raw interface, the program will end up needing a somewhat larger collection of functions and types from `libgit2` than we used before, so it makes sense to move the `extern` block into its own module. We'll create a file named *raw.rs* in *git-toy/src* whose contents are as follows:

```
#![allow(non_camel_case_types)]

use std::ffi::{c_int, c_char, c_uchar};

#[link(name = "git2")]
unsafe extern "C" {
    pub fn git_libgit2_init() -> c_int;
    pub fn git_libgit2_shutdown() -> c_int;
    pub fn giterr_last() -> *const git_error;

    pub fn git_repository_open(
        out: *mut *mut git_repository,
        path: *const c_char,
    ) -> c_int;
    pub fn git_repository_free(repo: *mut git_repository);

    pub fn git_reference_name_to_id(
        out: *mut git_oid,
        repo: *mut git_repository,
```

```
        reference: *const c_char,
    ) -> c_int;

    pub fn git_commit_lookup(
        out: *mut *mut git_commit,
        repo: *mut git_repository,
        id: *const git_oid,
    ) -> c_int;

    pub fn git_commit_author(commit: *const git_commit) -> *const
git_signature;
    pub fn git_commit_message(commit: *const git_commit) ->
*const c_char;
    pub fn git_commit_free(commit: *mut git_commit);
}

#[repr(C)]
pub struct git_repository {
    _private: [u8; 0],
}

#[repr(C)]
pub struct git_commit {
    _private: [u8; 0],
}

#[repr(C)]
pub struct git_error {
    pub message: *const c_char,
    pub klass: c_int,
}

pub const GIT_OID_RAWSZ: usize = 20;

#[repr(C)]
pub struct git_oid {
    pub id: [c_uchar; GIT_OID_RAWSZ],
}

pub type git_time_t = i64;

#[repr(C)]
pub struct git_time {
    pub time: git_time_t,
    pub offset: c_int,
}

#[repr(C)]
```

```
pub struct git_signature {
    pub name: *const c_char,
    pub email: *const c_char,
    pub when: git_time,
}
```

Each item here is modeled on a declaration from `libgit2`'s own header files. For example, *libgit2-1.8.1/include/git2/repository.h* includes this declaration:

```
extern int git_repository_open(git_repository **out, const char
*path);
```

This function tries to open the Git repository at `path`. If all goes well, it creates a `git_repository` object and stores a pointer to it in the location pointed to by `out`. The equivalent Rust declaration is the following:

```
pub fn git_repository_open(
    out: *mut *mut git_repository,
    path: *const c_char,
) -> c_int;
```

The `libgit2` public header files define the `git_repository` type as a `typedef` for an incomplete `struct` type:

```
typedef struct git_repository git_repository;
```

Since the details of this type are private to the library, so the public headers never define `struct git_repository`, ensuring that the library's users can never build an instance of this type themselves. A possible analogue to an incomplete struct type in Rust is:

```
#[repr(C)]
pub struct git_repository {
    _private: [u8; 0],
}
```

This is a struct type containing an array with no elements. Since the `_private` field isn't `pub`, values of this type cannot be constructed outside this module, which is perfect as the reflection of a C type that only `libgit2` should ever construct, and which is manipulated solely through raw pointers.

Writing large `extern` blocks by hand can be a chore. If you are creating a Rust interface to a complex C library, you may want to try using the `bindgen` crate, which has functions you can use from your build script to parse C header files and generate the corresponding Rust declarations automatically. We don't have space to show `bindgen` in action here, but `bindgen`'s page on crates.io includes links to its documentation.

Next we'll rewrite *main.rs* completely. First, we need to declare the `raw` module:

```
mod raw;
```

According to `libgit2`'s conventions, fallible functions return an integer code that is positive or zero on success, and negative on failure. If an error occurs, the `giterr_last` function will return a pointer to a `git_error` structure providing more details about what went wrong. `libgit2` owns this structure, so we don't need to free it ourselves, but it could be overwritten by the next library call we make. A proper Rust interface would use `Result`, but for now, we want to use the `libgit2` functions just as they are, so we'll roll our own function for handling errors:

```
use std::ffi::{CStr, c_int};

fn check(activity: &'static str, status: c_int) -> c_int {
    if status < 0 {
        unsafe {
            let error = &*raw::giterr_last();
            println!(
                "error while {activity}: {} ({})",
                CStr::from_ptr(error.message).to_string_lossy(),
                error.klass,
            );
```

```
                std::process::exit(1);
            }
        }

        status
    }
```

We'll use this function to check the results of `libgit2` calls like this:

```
    check("initializing library", raw::git_libgit2_init());
```

This uses the same `CStr` methods used earlier: `from_ptr` to construct the `CStr` from a C string, and `to_string_lossy` to turn that into something Rust can print.

Next, we need a function to print out a commit:

```
    unsafe fn show_commit(commit: *const raw::git_commit) {
        // SAFETY: Lifetimes of `name` and `email` are tied to
    `commit`.
        // The commit message is cloned and non-UTF-8 data is
    removed.
        unsafe {
            let author = raw::git_commit_author(commit);

            let name =
    CStr::from_ptr((*author).name).to_string_lossy();
            let email =
    CStr::from_ptr((*author).email).to_string_lossy();
            println!("{name} <{email}>\n");

            let message = raw::git_commit_message(commit);
            println!("{}",
    CStr::from_ptr(message).to_string_lossy());
        }
    }
```

Given a pointer to a `git_commit`, `show_commit` calls `git_commit_author` and `git_commit_message` to retrieve the information it needs. These two functions follow a convention that the `libgit2` documentation explains as follows:

*If a function returns an object as a return value, that function is a getter and the object's lifetime is tied to the parent object.*

In Rust terms, `author` and `message` are borrowed from `commit`: `show_commit` doesn't need to free them itself, but it must not hold on to them after `commit` is freed. Since this API uses raw pointers, Rust won't check their lifetimes for us: if we do accidentally create dangling pointers, we probably won't find out about it until the program crashes.

The preceding code assumes these fields hold UTF-8 text, which is not always correct. Git permits other encodings as well. Interpreting these strings properly would probably entail using the `encoding` crate. For brevity's sake, we'll gloss over those issues here.

Our program's `main` function reads as follows:

```
use std::ffi::CString;
use std::mem::MaybeUninit;
use std::ptr;

fn main() {
    let path = std::env::args()
        .nth(1)
        .expect("usage: git-toy PATH");
    let path = CString::new(path)
        .expect("path contains null characters");

    unsafe {
        check("initializing library", raw::git_libgit2_init());

        let mut repo = ptr::null_mut();
        check(
            "opening repository",
            raw::git_repository_open(&mut repo, path.as_ptr()),
        );

        let c_name = c"HEAD";
        let oid = {
            let mut oid = MaybeUninit::uninit();
            check(
                "looking up HEAD",
                raw::git_reference_name_to_id(oid.as_mut_ptr(),
repo, c_name.as_ptr()),
            );
```

```
            oid.assume_init()
        };

        let mut commit = ptr::null_mut();
        check(
            "looking up commit",
            raw::git_commit_lookup(&mut commit, repo, &oid),
        );

        show_commit(commit);

        raw::git_commit_free(commit);

        raw::git_repository_free(repo);

        check("shutting down library",
raw::git_libgit2_shutdown());
    }
}
```

This starts with code to handle the path argument and initialize the library, all of which we've seen before. The first novel code is this:

```
let mut repo = ptr::null_mut();
check(
    "opening repository",
    raw::git_repository_open(&mut repo, path.as_ptr()),
);
```

The call to `git_repository_open` tries to open the Git repository at the given path. If it succeeds, it allocates a new `git_repository` object for it and sets `repo` to point to that. Rust implicitly coerces references into raw pointers, so passing `&mut repo` here provides the `*mut *mut git_repository` the call expects.

This shows another `libgit2` convention in use (from the `libgit2` documentation):

> *Objects which are returned via the first argument as a pointer-to-pointer are owned by the caller and it is responsible for freeing them.*

In Rust terms, functions like `git_repository_open` pass ownership of the new value to the caller.

Next, consider the code that looks up the object hash of the repository's current head commit:

```
let oid = {
    let mut oid = MaybeUninit::uninit();
    check(
        "looking up HEAD",
        raw::git_reference_name_to_id(oid.as_mut_ptr(), repo,
c_name.as_ptr()),
    );
    oid.assume_init()
};
```

The `git_oid` type stores an object identifier—a 160-bit hash code that Git uses internally (and throughout its delightful user interface) to identify commits, individual versions of files, and so on. This call to `git_reference_name_to_id` looks up the object identifier of the current `"HEAD"` commit.

In C it's perfectly normal to initialize a variable by passing a pointer to it to some function that fills in its value; this is how `git_reference_name_to_id` expects to treat its first argument. But Rust won't let us borrow a reference to an uninitialized variable. We could initialize `oid` with zeros, but this is a waste: any value stored there will simply be overwritten.

It is possible to ask Rust to give us uninitialized memory, but because reading uninitialized memory at any time is instant undefined behavior, Rust provides an abstraction, `MaybeUninit`, to ease its use. `MaybeUninit<T>` tells the compiler to set aside enough memory for your type `T`, but not to touch it until you say that it's safe to do so. While this memory is owned by the `MaybeUninit`, the compiler will also avoid certain optimizations that could otherwise cause undefined behavior even without any explicit access to the uninitialized memory in your code.

`MaybeUninit` provides a method, `as_mut_ptr()`, that produces a `*mut T` pointing to the potentially uninitialized memory it wraps. By passing that pointer to a foreign function that initializes the memory and then calling the unsafe method `assume_init` on the `MaybeUninit` to produce a fully initialized `T`, you can avoid undefined behavior without the additional overhead that comes from initializing and immediately throwing away a value. `assume_init` is unsafe because calling it on a `MaybeUninit` without being certain that the memory is actually initialized will immediately cause undefined behavior.

In this case, it is safe because `git_reference_name_to_id` initializes the memory owned by the `MaybeUninit`. We could use `MaybeUninit` for the `repo` and `commit` variables as well, but since these are just single words, we just go ahead and initialize them to null:

```
let mut commit = ptr::null_mut();
check(
    "looking up commit",
    raw::git_commit_lookup(&mut commit, repo, &oid),
);
```

This takes the commit's object identifier and looks up the actual commit, storing a `git_commit` pointer in `commit` on success.

The remainder of the `main` function should be self-explanatory. It calls the `show_commit` function defined earlier, frees the commit and repository objects, and shuts down the library.

Now we can try out the program on any Git repository ready at hand:

```
$ cargo run /home/jimb/rbattle
    Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
     Running `target/debug/git-toy /home/jimb/rbattle`
Jim Blandy <jimb@red-bean.com>

Animate goop a bit.
```

## A Safe Interface to libgit2

The raw interface to `libgit2` is a perfect example of an unsafe feature: it certainly can be used correctly (as we do here, so far as we know), but Rust can't enforce the rules you must follow. Designing a safe API for a library like this is a matter of identifying all these rules and then finding ways to turn any violation of them into a type or borrow-checking error.

Here, then, are `libgit2`'s rules for the features the program uses:

- You must call `git_libgit2_init` before using any other library function. You must not use any library function after calling `git_libgit2_shutdown`.
- All values passed to `libgit2` functions must be fully initialized, except for output parameters.
- When a call fails, output parameters passed to hold the results of the call are left uninitialized, and you must not use their values.
- A `git_commit` object refers to the `git_repository` object it is derived from, so the former must not outlive the latter. (This isn't spelled out in the `libgit2` documentation; we inferred it from the presence of certain functions in the interface and then verified it by reading the source code.)
- Similarly, a `git_signature` is always borrowed from a given `git_commit`, and the former must not outlive the latter. (The documentation does cover this case.)
- The message associated with a commit and the name and email address of the author are all borrowed from the commit and must not be used after the commit is freed.
- Once a `libgit2` object has been freed, it must never be used again.

As it turns out, you can build a Rust interface to `libgit2` that enforces all of these rules, either through Rust's type system or by managing details internally.

Before we get started, let's restructure the project a little bit. We'd like to have a `git` module that exports the safe interface, of which the raw interface from the previous program is a private submodule.

The whole source tree will look like this:

```
git-toy/
├── Cargo.toml
├── build.rs
└── src/
    ├── main.rs
    └── git/
        ├── mod.rs
        └── raw.rs
```

Following the rules we explained in "Modules in Separate Files", the source for the `git` module appears in *git/mod.rs*, and the source for its `git::raw` submodule goes in *git/raw.rs*.

Once again, we're going to rewrite *main.rs* completely. It should start with a declaration of the `git` module:

```
mod git;
```

Then, we'll need to create the *git* subdirectory and move *raw.rs* into it:

```
$ cd /home/jimb/git-toy
$ mkdir src/git
$ mv src/raw.rs src/git/raw.rs
```

The `git` module needs to declare its `raw` submodule. The file *src/git/mod.rs* must say:

```
mod raw;
```

Since it's not `pub`, this submodule is not visible to the main program.

In a bit we'll need to use some functions from the `libc` crate, so we must add a dependency in *Cargo.toml*. The full file now reads:

```
[package]
name = "git-toy"
version = "0.1.0"
authors = ["You <you@example.com>"]
edition = "2024"

[dependencies]
libc = "0.2.186"
```

Now that we've restructured our modules, let's consider error handling. Even `libgit2`'s initialization function can return an error code, so we'll need to have this sorted out before we can get started. An idiomatic Rust interface needs its own `Error` type that captures the `libgit2` failure code as well as the error message and class from `giterr_last`. A proper error type must implement the usual `Error`, `Debug`, and `Display` traits. Then, it needs its own `Result` type that uses this `Error` type. Here are the necessary definitions in *src/git/mod.rs*:

```
use std::error;
use std::fmt;
use std::result;

#[derive(Debug)]
pub struct Error {
    code: i32,
    message: String,
    class: i32,
}

impl fmt::Display for Error {
    fn fmt(&self, f: &mut fmt::Formatter) -> result::Result<(),
fmt::Error> {
        // Displaying an `Error` simply displays the message from
libgit2.
        self.message.fmt(f)
    }
}

impl error::Error for Error {}

pub type Result<T> = result::Result<T, Error>;
```

To check the result from raw library calls, the module needs a function that turns a `libgit2` return code into a `Result`:

```
use std::ffi::{CStr, c_int};

fn check(code: c_int) -> Result<c_int> {
    if code >= 0 {
        return Ok(code);
    }

    unsafe {
        let error = raw::giterr_last();

        // libgit2 ensures that (*error).message is always non-
null and null
        // terminated, so this call is safe.
        let message = CStr::from_ptr((*error).message)
            .to_string_lossy()
            .into_owned();

        Err(Error {
            code,
            message,
            class: (*error).klass,
        })
    }
}
```

The main difference between this and the `check` function from the raw version is that this constructs an `Error` value instead of printing an error message and exiting immediately.

Now we're ready to tackle `libgit2` initialization. The safe interface will provide a `Repository` type that represents an open Git repository, with methods for resolving references, looking up commits, and so on. Continuing in *git/mod.rs*, here's the definition of `Repository`:

```
/// A Git repository.
pub struct Repository {
    // This must always be a pointer to a live `git_repository`
structure.
    // No other `Repository` may point to it.
```

```
    raw: *mut raw::git_repository,
}
```

A `Repository`'s `raw` field is not public. Since only code in this module can access the `raw::git_repository` pointer, getting this module right should ensure the pointer is always used correctly.

If the only way to create a `Repository` is to successfully open a fresh Git repository, that will ensure that each `Repository` points to a distinct `git_repository` object:

```
use std::path::Path;
use std::ptr;

impl Repository {
    pub fn open<P: AsRef<Path>>(path: P) -> Result<Repository> {
        ensure_initialized();

        let path = path_to_cstring(path.as_ref())?;
        let mut repo = ptr::null_mut();
        unsafe {
            check(raw::git_repository_open(&mut repo,
path.as_ptr()))?;
        }
        Ok(Repository { raw: repo })
    }
}
```

Since the only way to do anything with the safe interface is to start with a `Repository` value, and `Repository::open` starts with a call to `ensure_initialized`, we can be confident that `ensure_initialized` will be called before any `libgit2` functions. Its definition is as follows:

```
fn ensure_initialized() {
    static ONCE: std::sync::Once = std::sync::Once::new();
    ONCE.call_once(|| {
        unsafe {
            check(raw::git_libgit2_init())
                .expect("initializing libgit2 failed");
            assert_eq!(libc::atexit(shutdown), 0);
        }
```

```
    });
}

extern "C" fn shutdown() {
    unsafe {
        check(raw::git_libgit2_shutdown())
            .expect("shutting down libgit2 failed");
    }
}
```

The `std::sync::Once` type helps run initialization code in a thread-safe way. Only the first thread to call `ONCE.call_once` runs the given closure. Any subsequent calls, by this thread or any other, block until the first has completed and then return immediately, without running the closure again. Once the closure has finished, calling `ONCE.call_once` is cheap, requiring nothing more than an atomic load of a flag stored in `ONCE`.

In the preceding code, the initialization closure calls `git_libgit2_init` and checks the result. It punts a bit and just uses `expect` to make sure initialization succeeded, instead of trying to propagate errors back to the caller.

To make sure the program calls `git_libgit2_shutdown`, the initialization closure uses the C library's `atexit` function, which takes a pointer to a function to invoke before the process exits. Rust closures cannot serve as C function pointers: a closure is a value of some anonymous type carrying the values of whatever variables it captures or references to them; a C function pointer is just a pointer. However, Rust `fn` types work fine, as long as you declare them `extern "C"` so that Rust knows to use the C calling conventions. The local function `shutdown` fits the bill and ensures `libgit2` gets shut down properly.

In "Unwinding", we mentioned that Rust aborts the process immediately if a panic is about to cross language boundaries. The call from `atexit` to `shutdown` is such a boundary, so if `shutdown` panics, there will be no chance to catch the panic higher up the stack. Rust provides an alternative ABI, called `"C-unwind"`, which specifies behavior for unwinding into C, as long as the panic eventually reaches Rust code again afterward. Using

`"C-unwind"` isn't possible in this case, as there is no Rust code on the other side of `atexit` to catch the panic.

It might be possible to arrange to call `git_libgit2_shutdown` sooner—say, when the last `Repository` value is dropped. But no matter how we arrange things, calling `git_libgit2_shutdown` must be the safe API's responsibility. The moment it is called, any extant `libgit2` objects become unsafe to use, so a safe API must not expose this function directly.

A `Repository`'s raw pointer must always point to a live `git_repository` object. This implies that the only way to close a repository is to drop the `Repository` value that owns it:

```
impl Drop for Repository {
    fn drop(&mut self) {
        unsafe {
            raw::git_repository_free(self.raw);
        }
    }
}
```

By calling `git_repository_free` only when the sole pointer to the `raw::git_repository` is about to go away, the `Repository` type also ensures the pointer will never be used after it's freed.

The `Repository::open` method uses a private function called `path_to_cstring`, which has two definitions—one for Unix-like systems and one for Windows:

```
use std::ffi::CString;

#[cfg(unix)]
fn path_to_cstring(path: &Path) -> Result<CString> {
    // The `as_bytes` method exists only on Unix-like systems.
    use std::os::unix::ffi::OsStrExt;

    Ok(CString::new(path.as_os_str().as_bytes())?)
}

#[cfg(windows)]
fn path_to_cstring(path: &Path) -> Result<CString> {
```

```
    // Try to convert to UTF-8. If this fails, libgit2 can't
handle the path
    // anyway.
    match path.to_str() {
        Some(s) => Ok(CString::new(s)?),
        None => {
            let message = format!(
                "Couldn't convert path '{}' to UTF-8",
                path.display(),
            );
            Err(message.into())
        }
    }
}
```

The `libgit2` interface makes this code a little tricky. On all platforms, `libgit2` accepts paths as null-terminated C strings. On Windows, `libgit2` assumes these C strings hold well-formed UTF-8 and converts them internally to the 16-bit paths Windows actually requires. This usually works, but it's not ideal. Windows permits filenames that are not well-formed Unicode and thus cannot be represented in UTF-8. If you have such a file, it's impossible to pass its name to `libgit2`.

In Rust, the proper representation of a filesystem path is a `std::path::Path`, carefully designed to handle any path that can appear on Windows or POSIX. This means that there are `Path` values on Windows that one cannot pass to `libgit2`, because they are not well-formed UTF-8. So although `path_to_cstring`'s behavior is less than ideal, it's actually the best we can do given `libgit2`'s interface.

The two `path_to_cstring` definitions just shown rely on conversions to our `Error` type: the `?` operator attempts such conversions, and the Windows version explicitly calls `.into()`. These conversions are unremarkable:

```
impl From<String> for Error {
    fn from(message: String) -> Error {
        Error {
            code: -1,
            message,
```

```
                class: 0,
            }
        }
    }

    // NulError is what `CString::new` returns if a string
    // has embedded zero bytes.
    impl From<std::ffi::NulError> for Error {
        fn from(e: std::ffi::NulError) -> Error {
            Error {
                code: -1,
                message: e.to_string(),
                class: 0,
            }
        }
    }
```

Let's figure out how to resolve a Git reference to an object identifier. Since an object identifier is just a 20-byte hash value, it's perfectly fine to expose it in the safe API:

```
    /// The identifier of some sort of object stored in the Git
    object
    /// database: a commit, tree, blob, tag, etc. This is a wide hash
    of the
    /// object's contents.
    pub struct Oid {
        pub raw: raw::git_oid,
    }
```

We'll add a method to `Repository` to perform the lookup:

```
    use std::ffi::c_char;
    use std::mem::MaybeUninit;

    impl Repository {
        pub fn reference_name_to_id(&self, name: &str) -> Result<Oid>
    {
            let name = CString::new(name)?;
            unsafe {
                let oid = {
                    let mut oid = MaybeUninit::uninit();
                    check(raw::git_reference_name_to_id(
                        oid.as_mut_ptr(),
```

```
                    self.raw,
                    name.as_ptr() as *const c_char,
                ))?;
                oid.assume_init()
            };
            Ok(Oid { raw: oid })
        }
    }
}
```

Although `oid` is left uninitialized when the lookup fails, this function guarantees that its caller can never see the uninitialized value simply by following Rust's `Result` idiom: either the caller gets an `Ok` carrying a properly initialized `Oid` value, or it gets an `Err`.

Next, the module needs a way to retrieve commits from the repository. We'll define a `Commit` type as follows:

```
use std::marker::PhantomData;

pub struct Commit<'repo> {
    // This must always be a pointer to a usable `git_commit`
structure.
    raw: *mut raw::git_commit,
    _marker: PhantomData<&'repo Repository>,
}
```

As we mentioned earlier, a `git_commit` object must never outlive the `git_repository` object it was retrieved from. Rust's lifetimes let the code capture this rule precisely.

In "Example: RefWithFlag", we used a `PhantomData` field to tell Rust to treat a type as if it contained a reference with a given lifetime, even though the type apparently contained no such reference. The `Commit` type needs to do something similar. In this case, the `_marker` field's type is `PhantomData<&'repo Repository>`, indicating that Rust should treat `Commit<'repo>` as if it held a reference with lifetime `'repo` to some `Repository`.

The method for looking up a commit is as follows:

```
impl Repository {
    pub fn find_commit(&self, oid: &Oid) -> Result<Commit<'_>> {
        let mut commit = ptr::null_mut();
        unsafe {
            check(raw::git_commit_lookup(&mut commit, self.raw,
&oid.raw))?;
        }
        Ok(Commit {
            raw: commit,
            _marker: PhantomData,
        })
    }
}
```

How does this relate the `Commit`'s lifetime to the `Repository`'s? The signature of `find_commit` omits the lifetimes of the references involved according to the rules outlined in "Omitting Lifetime Parameters". If we were to write the lifetimes out, the full signature would read:

```
fn find_commit<'repo, 'id>(&'repo self, oid: &'id Oid) ->
Result<Commit<'repo>>
```

This is exactly what we want: Rust treats the returned `Commit` as if it borrows something from `self`, which is the `Repository`.

When a `Commit` is dropped, it must free its `raw::git_commit`:

```
impl Drop for Commit<'_> {
    fn drop(&mut self) {
        unsafe {
            raw::git_commit_free(self.raw);
        }
    }
}
```

From a `Commit`, you can borrow a `Signature` (a name and email address) and the text of the commit message:

```
impl Commit<'_> {
    pub fn author(&self) -> Signature<'_> {
        unsafe {
            Signature {
```

```
                raw: raw::git_commit_author(self.raw),
                _marker: PhantomData,
            }
        }
    }

    pub fn message(&self) -> Option<&str> {
        unsafe {
            let message = raw::git_commit_message(self.raw);
            char_ptr_to_str(self, message)
        }
    }
}
```

Here's the `Signature` type:

```
pub struct Signature<'text> {
    raw: *const raw::git_signature,
    _marker: PhantomData<&'text str>,
}
```

A `git_signature` object always borrows its text from elsewhere; in particular, signatures returned by `git_commit_author` borrow their text from the `git_commit`. So our safe `Signature` type includes a `PhantomData<&'text str>` to tell Rust to behave as if it contained a `&str` with a lifetime of `'text`. Just as before, `Commit::author` properly connects this `'text` lifetime of the `Signature` it returns to that of the `Commit` without us needing to write a thing. The `Commit::message` method does the same with the `Option<&str>` holding the commit message.

A `Signature` includes methods for retrieving the author's name and email address:

```
impl Signature<'_> {
    /// Returns the author's name as a `&str`,
    /// or `None` if it is not well-formed UTF-8.
    pub fn name(&self) -> Option<&str> {
        unsafe {
            char_ptr_to_str(self, (*self.raw).name)
        }
```

```
    }

    /// Returns the author's email as a `&str`,
    /// or `None` if it is not well-formed UTF-8.
    pub fn email(&self) -> Option<&str> {
        unsafe {
            char_ptr_to_str(self, (*self.raw).email)
        }
    }
}
```

The preceding methods depend on a private utility function `char_ptr_to_str`:

```
/// Tries to borrow a `&str` from `ptr`, given that `ptr` may be
null or
/// refer to ill-formed UTF-8. The result gets a lifetime as if
it were
/// borrowed from `_owner`.
///
/// Safety: if `ptr` is non-null, it must point to a null-
terminated C
/// string that is both safe to access and whose contents are not
modified
/// for at least as long as the lifetime of `_owner`.
unsafe fn char_ptr_to_str<T>(_owner: &T, ptr: *const c_char) ->
Option<&str> {
    if ptr.is_null() {
        None
    } else {
        unsafe {
            CStr::from_ptr(ptr).to_str().ok()
        }
    }
}
```

The `_owner` parameter's value is never used, but its lifetime is. Making the lifetimes in this function's signature explicit gives us:

```
fn char_ptr_to_str<'o, T: 'o>(
    _owner: &'o T,
    ptr: *const c_char,
) -> Option<&'o str>
```

The `CStr::from_ptr` function returns a `&CStr` whose lifetime is completely unbounded, since it was borrowed from a dereferenced raw pointer. Unbounded lifetimes are almost always inaccurate, so it's good to constrain them as soon as possible. Including the `_owner` parameter causes Rust to attribute its lifetime to the return value's type, so callers can receive a more accurately bounded reference.

It is not clear from the `libgit2` documentation whether a `git_signature`'s `email` and `author` pointers can be null, despite the documentation for `libgit2` being quite good. Your authors dug around in the source code for some time without being able to persuade themselves one way or the other and finally decided that `char_ptr_to_str` had better be prepared for null pointers just in case. In Rust, this sort of question is answered immediately by the type: if it's `&str`, you can count on the string to be there; if it's `Option<&str>`, it's optional.

Finally, we've provided safe interfaces for all the functionality we need. The new `main` function in *src/main.rs* is slimmed down quite a bit and looks like real Rust code:

```
fn main() {
    let path = std::env::args_os()
        .nth(1)
        .expect("usage: git-toy PATH");

    let repo = git::Repository::open(&path)
        .expect("opening repository");

    let commit_oid = repo
        .reference_name_to_id("HEAD")
        .expect("looking up 'HEAD' reference");

    let commit = repo
        .find_commit(&commit_oid)
        .expect("looking up commit");

    let author = commit.author();
    println!(
        "{} <{}>\n",
        author.name().unwrap_or("(none)"),
        author.email().unwrap_or("none"),
```

```
        );

        println!("{}", commit.message().unwrap_or("(none)"));
    }
```

In this chapter, we've gone from simplistic interfaces that don't provide many safety guarantees to a safe API wrapping an inherently unsafe API by arranging for any violation of the latter's contract to be a Rust type error. The result is an interface that Rust can ensure you use correctly. For the most part, the rules we've made Rust enforce are the sorts of rules that C and C++ programmers end up imposing on themselves anyway. What makes Rust feel so much stricter than C and C++ is not that the rules are so foreign but that this enforcement is mechanical and comprehensive.

## Conclusion

Rust is not a simple language. Its goal is to span two different worlds. It's a modern programming language, safe by design, with conveniences like closures and iterators, yet it aims to put you in control of the raw capabilities of the machine it runs on, with minimal run-time overhead.

The contours of the language are determined by these goals. Rust manages to bridge most of the gap with safe code. Its borrow checker and zero-cost abstractions put you as close to the bare metal as possible without risking undefined behavior. When that's not enough or when you want to leverage existing C code, unsafe code and the foreign function interface stand ready. But again, the language doesn't just offer you these unsafe features and wish you luck. The goal is always to use unsafe features to build safe APIs. That's what we did with `libgit2`. It's also what the Rust team has done with `Box`, `Vec`, the other collections, channels, and more: the standard library is full of safe abstractions, implemented with some unsafe code behind the scenes.

A language with Rust's ambitions was, perhaps, not destined to be the simplest of tools. But Rust is safe, fast, concurrent—and effective. Use it to

build large, fast, secure, robust systems that take advantage of the full power of the hardware they run on. Use it to make software better.

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## About the Authors

**Jim Blandy** has been programming since 1981 and writing free software since 1990. He has worked on GNU Emacs, GNU Guile, and the GNU Debugger, and now works on Firefox at Mozilla.

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## Colophon

The animal on the cover of *Programming Rust* is a Montagu's crab (*Xantho hydrophilus*). Montagu's crab has been found in the northeastern Atlantic Ocean and in the Mediterranean Sea. It lives under rocks and boulders during low tide. If one is exposed when a rock is lifted, it will aggressively hold its pincers up and spread them wide open to make itself appear bigger.

This robust-looking crab has a muscly appearance with a broad carapace about 70 mm wide. The edge of the carapace is furrowed, and the color is yellowish or reddish-brown. It has 10 legs: the front pair (the chelipeds) are equal in size with black-tipped claws or pincers; then there are three pairs of walking legs that are stout and relatively short; and the last pair of legs are for swimming. They walk and swim sideways.

This crab is an omnivore. They eat mostly algae, snails, and crabs of other species. They are mostly active at night. Egg-bearing females are found from March through July, and the larvae are present in plankton for most of the summer.

Many of the animals on O'Reilly covers are endangered; all of them are important to the world.

The cover illustration is by Karen Montgomery, based on an image from *Wood's Natural History*. The cover fonts are Gilroy Semibold and Guardian Sans. The text font is Adobe Minion Pro; the heading font is Adobe Myriad Condensed; and the code font is Dalton Maag's Ubuntu Mono.