

# The Rust Programming Language

The Rust Team

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# 1

## Introduction

Welcome! This book will teach you about the Rust Programming Language<sup>1</sup>. Rust is a systems programming language focused on three goals: safety, speed, and concurrency. It maintains these goals without having a garbage collector, making it a useful language for a number of use cases other languages aren't good at: embedding in other languages, programs with specific space and time requirements, and writing low-level code, like device drivers and operating systems. It improves on current languages targeting this space by having a number of compile-time safety checks that produce no runtime overhead, while eliminating all data races. Rust also aims to achieve 'zero-cost abstractions' even though some of these abstractions feel like those of a high-level language. Even then, Rust still allows precise control like a low-level language would.

"The Rust Programming Language" is split into seven sections. This introduction is the first. After this:

- Getting started (chapter 2, page 15) - Set up your computer for Rust development.
- Learn Rust (chapter 3, page 23) - Learn Rust programming through small projects.
- Effective Rust (chapter 4, page 59) - Higher-level concepts for writing excellent Rust code.
- Syntax and Semantics (chapter 5, page 119) - Each bit of Rust, broken down into small chunks.
- Nightly Rust (chapter 6, page 239) - Cutting-edge features that aren't in stable builds yet.
- Glossary (chapter 7, page 261) - A reference of terms used in the book.
- Academic Research (chapter 8, page 263) - Literature that influenced Rust.

After reading this introduction, you'll want to dive into either 'Learn Rust' or 'Syntax and Semantics', depending on your preference: 'Learn Rust' if you want to dive in with a project, or 'Syntax and Semantics' if you prefer to start small, and learn a single concept thoroughly before moving onto the next. Copious cross-linking connects these parts together.

---

<sup>1</sup><http://rust-lang.org>

## 1.1 Contributing

The source files from which this book is generated can be found on Github: [github.com/rust-lang/rust/tree/master/src/doc/trpl](https://github.com/rust-lang/rust/tree/master/src/doc/trpl)<sup>2</sup>

## 1.2 A brief introduction to Rust

Is Rust a language you might be interested in? Let's examine a few small code samples to show off a few of its strengths.

The main concept that makes Rust unique is called 'ownership'. Consider this small example:

```
fn main() {  
    let mut x = vec!["Hello", "world"];  
}
```

This program makes a variable binding (section 5.1, page 119) named `x`. The value of this binding is a `Vec<T>`, a 'vector', that we create through a macro (section 5.35, page 219) defined in the standard library. This macro is called `vec`, and we invoke macros with a `!`. This follows a general principle of Rust: make things explicit. Macros can do significantly more complicated things than function calls, and so they're visually distinct. The `!` also helps with parsing, making tooling easier to write, which is also important.

We used `mut` to make `x` mutable: bindings are immutable by default in Rust. We'll be mutating this vector later in the example.

It's also worth noting that we didn't need a type annotation here: while Rust is statically typed, we didn't need to explicitly annotate the type. Rust has type inference to balance out the power of static typing with the verbosity of annotating types.

Rust prefers stack allocation to heap allocation: `x` is placed directly on the stack. However, the `Vec<T>` type allocates space for the elements of the vector on the heap. If you're not familiar with this distinction, you can ignore it for now, or check out 'The Stack and the Heap' (section 4.1, page 59). As a systems programming language, Rust gives you the ability to control how your memory is allocated, but when we're getting started, it's less of a big deal.

Earlier, we mentioned that 'ownership' is the key new concept in Rust. In Rust parlance, `x` is said to 'own' the vector. This means that when `x` goes out of scope, the vector's memory will be deallocated. This is done deterministically by the Rust compiler, rather than through a mechanism such as a garbage collector. In other words, in Rust, you don't call functions like `malloc` and `free` yourself: the compiler statically determines when you need to allocate or deallocate memory, and inserts those calls itself. To err is to be human, but compilers never forget.

Let's add another line to our example:

```
fn main() {  
    let mut x = vec!["Hello", "world"];
```

---

<sup>2</sup><https://github.com/rust-lang/rust/tree/master/src/doc/trpl>

```
let y = &x[0];
}
```

We've introduced another binding, `y`. In this case, `y` is a 'reference' to the first element of the vector. Rust's references are similar to pointers in other languages, but with additional compile-time safety checks. References interact with the ownership system by 'borrowing' (section 5.9, page 138) what they point to, rather than owning it. The difference is, when the reference goes out of scope, it will not deallocate the underlying memory. If it did, we'd de-allocate twice, which is bad!

Let's add a third line. It looks innocent enough, but causes a compiler error:

```
fn main() {
    let mut x = vec!["Hello", "world"];

    let y = &x[0];

    x.push("foo");
}
```

`push` is a method on vectors that appends another element to the end of the vector. When we try to compile this program, we get an error:

```
error: cannot borrow `x` as mutable because it is also borrowed as immutable
    x.push("foo");
    ^
note: previous borrow of `x` occurs here; the immutable borrow prevents
subsequent moves or mutable borrows of `x` until the borrow ends
    let y = &x[0];
    ^
note: previous borrow ends here
fn main() {

}
^
```

Whew! The Rust compiler gives quite detailed errors at times, and this is one of those times. As the error explains, while we made our binding mutable, we still cannot call `push`. This is because we already have a reference to an element of the vector, `y`. Mutating something while another reference exists is dangerous, because we may invalidate the reference. In this specific case, when we create the vector, we may have only allocated space for three elements. Adding a fourth would mean allocating a new chunk of memory for all those elements, copying the old values over, and updating the internal pointer to that memory. That all works just fine. The problem is that `y` wouldn't get updated, and so we'd have a 'dangling pointer'. That's bad. Any use of `y` would be an error in this case, and so the compiler has caught this for us.

So how do we solve this problem? There are two approaches we can take. The first is making a copy rather than using a reference:

```
fn main() {  
    let mut x = vec!["Hello", "world"];  
  
    let y = x[0].clone();  
  
    x.push("foo");  
}
```

Rust has move semantics (subsection 5.8.3, page 136) by default, so if we want to make a copy of some data, we call the `clone()` method. In this example, `y` is no longer a reference to the vector stored in `x`, but a copy of its first element, "Hello". Now that we don't have a reference, our `push()` works just fine.

If we truly want a reference, we need the other option: ensure that our reference goes out of scope before we try to do the mutation. That looks like this:

```
fn main() {  
    let mut x = vec!["Hello", "world"];  
  
    {  
        let y = &x[0];  
    }  
  
    x.push("foo");  
}
```

We created an inner scope with an additional set of curly braces. `y` will go out of scope before we call `push()`, and so we're all good.

This concept of ownership isn't just good for preventing dangling pointers, but an entire set of related problems, like iterator invalidation, concurrency, and more.

# 2

## Getting Started

This first section of the book will get you going with Rust and its tooling. First, we'll install Rust. Then, the classic 'Hello World' program. Finally, we'll talk about Cargo, Rust's build system and package manager.

### 2.1 Installing Rust

The first step to using Rust is to install it! There are a number of ways to install Rust, but the easiest is to use the `rustup` script. If you're on Linux or a Mac, all you need to do is this (note that you don't need to type in the `$`s, they just indicate the start of each command):

```
$ curl -sf -L https://static.rust-lang.org/rustup.sh | sh
```

If you're concerned about the potential insecurity<sup>1</sup> of using `curl | sh`, please keep reading and see our disclaimer below. And feel free to use a two-step version of the installation and examine our installation script:

```
$ curl -f -L https://static.rust-lang.org/rustup.sh -O  
$ sh rustup.sh
```

If you're on Windows, please download either the 32-bit installer<sup>2</sup> or the 64-bit installer<sup>3</sup> and run it.

---

<sup>1</sup><http://curlpipesh.tumblr.com>

<sup>2</sup><https://static.rust-lang.org/dist/rust-1.0.0-beta-i686-pc-windows-gnu.msi>

<sup>3</sup>[https://static.rust-lang.org/dist/rust-1.0.0-beta-x86\\_64-pc-windows-gnu.msi](https://static.rust-lang.org/dist/rust-1.0.0-beta-x86_64-pc-windows-gnu.msi)

## Uninstalling

If you decide you don't want Rust anymore, we'll be a bit sad, but that's okay. Not every programming language is great for everyone. Just run the uninstall script:

```
$ sudo /usr/local/lib/rustlib/uninstall.sh
```

If you used the Windows installer, just re-run the `.msi` and it will give you an uninstall option.

Some people, and somewhat rightfully so, get very upset when we tell you to `curl | sh`. Basically, when you do this, you are trusting that the good people who maintain Rust aren't going to hack your computer and do bad things. That's a good instinct! If you're one of those people, please check out the documentation on building Rust from Source<sup>4</sup>, or the official binary downloads<sup>5</sup>.

Oh, we should also mention the officially supported platforms:

- Windows (7, 8, Server 2008 R2)
- Linux (2.6.18 or later, various distributions), x86 and x86-64
- OSX 10.7 (Lion) or greater, x86 and x86-64

We extensively test Rust on these platforms, and a few others, too, like Android. But these are the ones most likely to work, as they have the most testing.

Finally, a comment about Windows. Rust considers Windows to be a first-class platform upon release, but if we're honest, the Windows experience isn't as integrated as the Linux/OS X experience is. We're working on it! If anything does not work, it is a bug. Please let us know if that happens. Each and every commit is tested against Windows just like any other platform.

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

```
$ rustc --version
```

You should see the version number, commit hash, commit date and build date:

```
rustc 1.0.0-beta (9854143cb 2015-04-02) (built 2015-04-02)
```

If you did, Rust has been installed successfully! Congrats!

This installer also installs a copy of the documentation locally, so you can read it offline. On UNIX systems, `/usr/local/share/doc/rust` is the location. On Windows, it's in a `share/doc` directory, inside wherever you installed Rust to.

If not, there are a number of places where you can get help. The easiest is the `#rust` IRC channel on `irc.mozilla.org`<sup>6</sup>, which you can access through Mibbit<sup>7</sup>. Click that link, and you'll be chatting with other Rustaceans (a silly nickname we call ourselves), and we can help you out. Other great resources include the user's forum<sup>8</sup>, and Stack Overflow<sup>9</sup>.

<sup>4</sup><https://github.com/rust-lang/rust#building-from-source>

<sup>5</sup><http://www.rust-lang.org/install.html>

<sup>6</sup><irc://irc.mozilla.org/#rust>

<sup>7</sup><http://chat.mibbit.com/?server=irc.mozilla.org&channel=%23rust>

<sup>8</sup><http://users.rust-lang.org/>

<sup>9</sup><http://stackoverflow.com/questions/tagged/rust>



## 2.2 Hello, world!

Now that you have Rust installed, let's write your first Rust program. It's traditional to make your first program in any new language one that prints the text "Hello, world!" to the screen. The nice thing about starting with such a simple program is that you can verify that your compiler isn't just installed, but also working properly. And printing information to the screen is a pretty common thing to do.

The first thing that we need to do is make a file to put our code in. I like to make a **projects** directory in my home directory, and keep all my projects there. Rust does not care where your code lives.

This actually leads to one other concern we should address: this guide will assume that you have basic familiarity with the command line. Rust itself makes no specific demands on your editing tooling, or where your code lives. If you prefer an IDE to the command line, you may want to check out SolidOak<sup>10</sup>, or wherever plugins are for your favorite IDE. There are a number of extensions of varying quality in development by the community. The Rust team also ships plugins for various editors<sup>11</sup>. Configuring your editor or IDE is out of the scope of this tutorial, so check the documentation for your setup, specifically.

With that said, let's make a directory in our projects directory.

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

If you're on Windows and not using PowerShell, the ~ may not work. Consult the documentation for your shell for more details.

Let's make a new source file next. We'll call our file `main.rs`. Rust files always end in a `.rs` extension. If you're using more than one word in your filename, use an underscore: `hello_world.rs` rather than `helloworld.rs`.

Now that you've got your file open, type this in:

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

Save the file, and then type this into your terminal window:

```
$ rustc main.rs
$ ./main # or main.exe on Windows
Hello, world!
```

Success! Let's go over what just happened in detail.

---

<sup>10</sup><https://github.com/oakes/SolidOak>

<sup>11</sup><https://github.com/rust-lang/rust/blob/master/src/etc/CONFIGS.md>

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

These lines define a *function* in Rust. The `main` function is special: it's the beginning of every Rust program. The first line says "I'm declaring a function named `main` which takes no arguments and returns nothing." If there were arguments, they would go inside the parentheses (`(` and `)`), and because we aren't returning anything from this function, we can omit the return type entirely. We'll get to it later.

You'll also note that the function is wrapped in curly braces (`{` and `}`). Rust requires these around all function bodies. It is also considered good style to put the opening curly brace on the same line as the function declaration, with one space in between.

Next up is this line:

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

This line does all of the work in our little program. There are a number of details that are important here. The first is that it's indented with four spaces, not tabs. Please configure your editor of choice to insert four spaces with the tab key. We provide some sample configurations for various editors<sup>12</sup>.

The second point is the `println!()` part. This is calling a Rust macro (section 5.35, page 219), which is how metaprogramming is done in Rust. If it were a function instead, it would look like this: `println()`. For our purposes, we don't need to worry about this difference. Just know that sometimes, you'll see a `!`, and that means that you're calling a macro instead of a normal function. Rust implements `println!` as a macro rather than a function for good reasons, but that's an advanced topic. One last thing to mention: Rust's macros are significantly different from C macros, if you've used those. Don't be scared of using macros. We'll get to the details eventually, you'll just have to trust us for now.

Next, `"Hello, world!"` is a 'string'. Strings are a surprisingly complicated topic in a systems programming language, and this is a 'statically allocated' string. If you want to read further about allocation, check out the stack and the heap (section 4.1, page 59), but you don't need to right now if you don't want to. We pass this string as an argument to `println!`, which prints the string to the screen. Easy enough!

Finally, the line ends with a semicolon (`;`). Rust is an 'expression oriented' language, which means that most things are expressions, rather than statements. The `;` is used to indicate that this expression is over, and the next one is ready to begin. Most lines of Rust code end with a `;`.

Finally, actually compiling and running our program. We can compile with our compiler, `rustc`, by passing it the name of our source file:

```
$ rustc main.rs
```

This is similar to `gcc` or `clang`, if you come from a C or C++ background. Rust will output a binary executable. You can see it with `ls`:

---

<sup>12</sup><https://github.com/rust-lang/rust/tree/master/src/etc/CONFIGS.md>

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

Or on Windows:

```
$ dir
main.exe  main.rs
```

There are now two files: our source code, with the `.rs` extension, and the executable (`main.exe` on Windows, `main` everywhere else)

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

This prints out our `Hello, world!` text to our terminal.

If you come from a dynamic language like Ruby, Python, or JavaScript, you may not be used to these two steps being separate. Rust is an ‘ahead-of-time compiled language’, which means that you can compile a program, give it to someone else, and they don’t need to have Rust installed. If you give someone a `.rb` or `.py` or `.js` file, they need to have a Ruby/Python/JavaScript implementation installed, but you just need one command to both compile and run your program. Everything is a tradeoff in language design, and Rust has made its choice.

Congratulations! You have officially written a Rust program. That makes you a Rust programmer! Welcome. ☒☒☒

Next, I’d like to introduce you to another tool, Cargo, which is used to write real-world Rust programs. Just using `rustc` is nice for simple things, but as your project grows, you’ll want something to help you manage all of the options that it has, and to make it easy to share your code with other people and projects.

## 2.3 Hello, Cargo!

Cargo<sup>13</sup> is a tool that Rustaceans use to help manage their Rust projects. Cargo is currently in a pre-1.0 state, and so it is still a work in progress. However, it is already good enough to use for many Rust projects, and so it is assumed that Rust projects will use Cargo from the beginning.

Cargo manages three things: building your code, downloading the dependencies your code needs, and building those dependencies. At first, your program doesn’t have any dependencies, so we’ll only be using the first part of its functionality. Eventually, we’ll add more. Since we started off by using Cargo, it’ll be easy to add later.

If you installed Rust via the official installers you will also have Cargo. If you installed Rust some other way, you may want to check the Cargo README<sup>14</sup> for specific instructions about installing it.

---

<sup>13</sup><http://doc.crates.io>

<sup>14</sup><https://github.com/rust-lang/cargo#installing-cargo-from-nightlies>

## Converting to Cargo

Let's convert Hello World to Cargo.

To Cargo-ify our project, we need to do two things: Make a `Cargo.toml` configuration file, and put our source file in the right place. Let's do that part first:

```
$ mkdir src
$ mv main.rs src/main.rs
```

Note that since we're creating an executable, we used `main.rs`. If we want to make a library instead, we should use `lib.rs`. Custom file locations for the entry point can be specified with a `[[lib]]` or `[[bin]]`<sup>15</sup> key in the TOML file described below.

Cargo expects your source files to live inside a `src` directory. That leaves the top level for other things, like READMEs, license information, and anything not related to your code. Cargo helps us keep our projects nice and tidy. A place for everything, and everything in its place.

Next, our configuration file:

```
$ editor Cargo.toml
```

Make sure to get this name right: you need the capital C!

Put this inside:

```
[package]

name = "hello_world"
version = "0.0.1"
authors = [ "Your name <you@example.com>" ]
```

This file is in the TOML<sup>16</sup> format. Let's let it explain itself to you:

TOML aims to be a minimal configuration file format that's easy to read due to obvious semantics. TOML is designed to map unambiguously to a hash table. TOML should be easy to parse into data structures in a wide variety of languages.

TOML is very similar to INI, but with some extra goodies.

Once you have this file in place, we should be ready to build! Try this:

```
$ cargo build
   Compiling hello_world v0.0.1 (file:///home/yourname/projects/hello_world)
$ ./target/debug/hello_world
Hello, world!
```

---

<sup>15</sup><http://doc.crates.io/manifest.html#configuring-a-target>

<sup>16</sup><https://github.com/toml-lang/toml>

Bam! We build our project with `cargo build`, and run it with `./target/debug/hello_world`. We can do both in one step with `cargo run`:

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

Notice that we didn't re-build the project this time. Cargo figured out that we hadn't changed the source file, and so it just ran the binary. If we had made a modification, we would have seen it do both:

```
$ cargo run
    Compiling hello_world v0.0.1 (file:///home/yourname/projects/hello_world)
    Running `target/debug/hello_world`
Hello, world!
```

This hasn't bought us a whole lot over our simple use of `rustc`, but think about the future: when our project gets more complex, we would need to do more things to get all of the parts to properly compile. With Cargo, as our project grows, we can just `cargo build`, and it'll work the right way.

When your project is finally ready for release, you can use `cargo build --release` to compile your project with optimizations.

You'll also notice that Cargo has created a new file: `Cargo.lock`.

```
[root]
name = "hello_world"
version = "0.0.1"
```

This file is used by Cargo to keep track of dependencies in your application. Right now, we don't have any, so it's a bit sparse. You won't ever need to touch this file yourself, just let Cargo handle it.

That's it! We've successfully built `hello_world` with Cargo. Even though our program is simple, it's using much of the real tooling that you'll use for the rest of your Rust career. You can expect to do this to get started with virtually all Rust projects:

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

## A New Project

You don't have to go through this whole process every time you want to start a new project! Cargo has the ability to make a bare-bones project directory in which you can start developing right away.

To start a new project with Cargo, use `cargo new`:

```
$ cargo new hello_world --bin
```

We’re passing `--bin` because we’re making a binary program: if we were making a library, we’d leave it off.

Let’s check out what Cargo has generated for us:

```
$ cd hello_world
$ tree .
.
├── Cargo.toml
└── src
    └── main.rs
```

1 directory, 2 files

If you don’t have the `tree` command, you can probably get it from your distribution’s package manager. It’s not necessary, but it’s certainly useful.

This is all we need to get started. First, let’s check out `Cargo.toml`:

```
[package]

name = "hello_world"
version = "0.0.1"
authors = ["Your Name <you@example.com>"]
```

Cargo has populated this file with reasonable defaults based off the arguments you gave it and your `git` global configuration. You may notice that Cargo has also initialized the `hello_world` directory as a `git` repository.

Here’s what’s in `src/main.rs`:

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

Cargo has generated a “Hello World!” for us, and you’re ready to start coding! Cargo has its own guide<sup>17</sup> which covers Cargo’s features in much more depth.

Now that you’ve got the tools down, let’s actually learn more about the Rust language itself. These are the basics that will serve you well through the rest of your time with Rust.

You have two options: Dive into a project with ‘Learn Rust (chapter 3, page 23)’, or start from the bottom and work your way up with ‘Syntax and Semantics (chapter 5, page 119)’. More experienced systems programmers will probably prefer ‘Learn Rust’, while those from dynamic backgrounds may enjoy either. Different people learn differently! Choose whatever’s right for you.

---

<sup>17</sup><http://doc.crates.io/guide.html>

# 3

## Learn Rust

Welcome! This section has a few tutorials that teach you Rust through building projects. You'll get a high-level overview, but we'll skim over the details.

If you'd prefer a more 'from the ground up'-style experience, check out Syntax and Semantics (chapter 5, page 119).

### 3.1 Guessing Game

For our first project, we'll implement a classic beginner programming problem: the guessing game. Here's how it works: Our program will generate a random integer between one and a hundred. It will then prompt us to enter a guess. Upon entering our guess, it will tell us if we're too low or too high. Once we guess correctly, it will congratulate us. Sounds good?

#### 3.1.1 Set up

Let's set up a new project. Go to your projects directory. Remember how we had to create our directory structure and a `Cargo.toml` for `hello_world`? Cargo has a command that does that for us. Let's give it a shot:

```
$ cd ~/projects
$ cargo new guessing_game --bin
$ cd guessing_game
```

We pass the name of our project to `cargo new`, and then the `--bin` flag, since we're making a binary, rather than a library.

Check out the generated `Cargo.toml`:

```
[package]

name = "guessing_game"
version = "0.0.1"
authors = ["Your Name <you@example.com>"]
```

Cargo gets this information from your environment. If it's not correct, go ahead and fix that. Finally, Cargo generated a 'Hello, world!' for us. Check out `src/main.rs`:

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

Let's try compiling what Cargo gave us:

```
$ cargo build
   Compiling guessing_game v0.0.1 (file:///home/you/projects/guessing_game)
```

Excellent! Open up your `src/main.rs` again. We'll be writing all of our code in this file.

Before we move on, let me show you one more Cargo command: `run`. `cargo run` is kind of like `cargo build`, but it also then runs the produced executable. Try it out:

```
$ cargo run
   Compiling guessing_game v0.0.1 (file:///home/you/projects/guessing_game)
   Running `target/debug/guessing_game`
Hello, world!
```

Great! The `run` command comes in handy when you need to rapidly iterate on a project. Our game is just such a project, we need to quickly test each iteration before moving on to the next one.

### 3.1.2 Processing a Guess

Let's get to it! The first thing we need to do for our guessing game is allow our player to input a guess. Put this in your `src/main.rs`:

```
use std::io;

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

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

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



```

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

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

```

There's a lot here! Let's go over it, bit by bit.

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

We'll need to take user input, and then print the result as output. As such, we need the `io` library from the standard library. Rust only imports a few things into every program, the 'prelude'<sup>1</sup>. If it's not in the prelude, you'll have to `use` it directly.

```
fn main() {
```

As you've seen before, the `main()` function is the entry point into your program. The `fn` syntax declares a new function, the `()`s indicate that there are no arguments, and `{` starts the body of the function. Because we didn't include a return type, it's assumed to be `()`, an empty tuple<sup>2</sup>.

```

    println!("Guess the number!");

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

```

We previously learned that `println!()` is a macro (section 5.35, page 219) that prints a string (section 5.18, page 169) to the screen.

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

Now we're getting interesting! There's a lot going on in this little line. The first thing to notice is that this is a `let` statement (section 5.1, page 119), which is used to create 'variable bindings'. They take this form:

```
let foo = bar;
```

This will create a new binding named `foo`, and bind it to the value `bar`. In many languages, this is called a 'variable', but Rust's variable bindings have a few tricks up their sleeves.

For example, they're immutable (section 5.11, page 150) by default. That's why our example uses `mut`: it makes a binding mutable, rather than immutable. `let` doesn't take a name on the left hand side, it actually accepts a 'pattern' (section 5.15, page 159)<sup>3</sup>. We'll use patterns more later. It's easy enough to use for now:

```

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

```

<sup>1</sup><http://doc.rust-lang.org/std/prelude/index.html>

<sup>2</sup>[primitive-types.html#tuples](http://doc.rust-lang.org/std/primitive-types.html#tuples)

Oh, and `//` will start a comment, until the end of the line. Rust ignores everything in comments (section 5.4, page 131).

So now we know that `let mut guess` will introduce a mutable binding named `guess`, but we have to look at the other side of the `=` for what it's bound to: `String::new()`.

`String` is a string type, provided by the standard library. A `String`<sup>3</sup> is a growable, UTF-8 encoded bit of text.

The `::new()` syntax uses `::` because this is an 'associated function' of a particular type. That is to say, it's associated with `String` itself, rather than a particular instance of a `String`. Some languages call this a 'static method'.

This function is named `new()`, because it creates a new, empty `String`. You'll find a `new()` function on many types, as it's a common name for making a new value of some kind.

Let's move forward:

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

That's a lot more! Let's go bit-by-bit. The first line has two parts. Here's the first:

```
io::stdin()
```

Remember how we used `std::io` on the first line of the program? We're now calling an associated function on it. If we didn't use `std::io`, we could have written this line as `std::io::stdin()`.

This particular function returns a handle to the standard input for your terminal. More specifically, a `std::io::Stdin`<sup>4</sup>.

The next part will use this handle to get input from the user:

```
.read_line(&mut guess)
```

Here, we call the `read_line()`<sup>5</sup> method on our handle. Methods (section 5.16, page 164) are like associated functions, but are only available on a particular instance of a type, rather than the type itself. We're also passing one argument to `read_line()`: `&mut guess`.

Remember how we bound `guess` above? We said it was mutable. However, `read_line` doesn't take a `String` as an argument: it takes a `&mut String`. Rust has a feature called 'references' (section 5.9, page 138), which allows you to have multiple references to one piece of data, which can reduce copying. References are a complex feature, as one of Rust's major selling points is how safe and easy it is to use references. We don't need to know a lot of those details to finish our program right now, though. For now, all we need to know is that like `let` bindings, references are immutable by default. Hence, we need to write `&mut guess`, rather than `&guess`.

Why does `read_line()` take a mutable reference to a string? Its job is to take what the user types into standard input, and place that into a string. So it takes that string as an argument, and in order to add the input, it needs to be mutable.

<sup>3</sup><http://doc.rust-lang.org/std/string/struct.String.html>

<sup>4</sup><http://doc.rust-lang.org/std/io/struct.Stdin.html>

<sup>5</sup>[http://doc.rust-lang.org/std/io/struct.Stdin.html#method.read\\_line](http://doc.rust-lang.org/std/io/struct.Stdin.html#method.read_line)

But we're not quite done with this line of code, though. While it's a single line of text, it's only the first part of the single logical line of code:

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

When you call a method with the `.foo()` syntax, you may introduce a newline and other whitespace. This helps you split up long lines. We *could* have done:

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

But that gets hard to read. So we've split it up, three lines for three method calls. We already talked about `read_line()`, but what about `ok()` and `expect()`? Well, we already mentioned that `read_line()` puts what the user types into the `&mut String` we pass it. But it also returns a value: in this case, an `io::Result`<sup>6</sup>. Rust has a number of types named `Result` in its standard library: a generic `Result`<sup>7</sup>, and then specific versions for sub-libraries, like `io::Result`.

The purpose of these `Result` types is to encode error handling information. Values of the `Result` type, like any type, have methods defined on them. In this case, `io::Result` has an `ok()` method, which says 'we want to assume this value is a successful one. If not, just throw away the error information'. Why throw it away? Well, for a basic program, we just want to print a generic error, as basically any issue means we can't continue. The `ok()` method<sup>8</sup> returns a value which has another method defined on it: `expect()`. The `expect()` method<sup>9</sup> takes a value it's called on, and if it isn't a successful one, `panic!` (section 4.7, page 100)s with a message you passed it. A `panic!` like this will cause our program to crash, displaying the message.

If we leave off calling these two methods, our program will compile, but we'll get a warning:

```
$ cargo build
   Compiling guessing_game v0.1.0 (file:///home/you/projects/guessing_game)
src/main.rs:10:5: 10:39 warning: unused result which must be used,
#[warn(unused_must_use)] on by default
src/main.rs:10      io::stdin().read_line(&mut guess);
                   ^~~~~~
```

Rust warns us that we haven't used the `Result` value. This warning comes from a special annotation that `io::Result` has. Rust is trying to tell you that you haven't handled a possible error. The right way to suppress the error is to actually write error handling. Luckily, if we just want to crash if there's a problem, we can use these two little methods. If we can recover from the error somehow, we'd do something else, but we'll save that for a future project.

There's just one line of this first example left:

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

<sup>6</sup><http://doc.rust-lang.org/std/io/type.Result.html>

<sup>7</sup><http://doc.rust-lang.org/std/result/enum.Result.html>

<sup>8</sup><http://doc.rust-lang.org/std/result/enum.Result.html#method.ok>

<sup>9</sup><http://doc.rust-lang.org/std/option/enum.Option.html#method.expect>

This prints out the string we saved our input in. The {}s are a placeholder, and so we pass it `guess` as an argument. If we had multiple {}s, we would pass multiple arguments:

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

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

Easy.

Anyway, that's the tour. We can run what we have with `cargo run`:

```
$ cargo run
   Compiling guessing_game v0.1.0 (file:///home/you/projects/guessing_game)
   Running `target/debug/guessing_game`
Guess the number!
Please input your guess.
6
You guessed: 6
```

All right! Our first part is done: we can get input from the keyboard, and then print it back out.

### 3.1.3 Generating a secret number

Next, we need to generate a secret number. Rust does not yet include random number functionality in its standard library. The Rust team does, however, provide a `rand` crate<sup>10</sup>. A 'crate' is a package of Rust code. We've been building a 'binary crate', which is an executable. `rand` is a 'library crate', which contains code that's intended to be used with other programs.

Using external crates is where Cargo really shines. Before we can write the code using `rand`, we need to modify our `Cargo.toml`. Open it up, and add these few lines at the bottom:

```
[dependencies]

rand="0.3.0"
```

The `[dependencies]` section of `Cargo.toml` is like the `[package]` section: everything that follows it is part of it, until the next section starts. Cargo uses the dependencies section to know what dependencies on external crates you have, and what versions you require. In this case, we've used version `0.3.0`. Cargo understands Semantic Versioning<sup>11</sup>, which is a standard for writing version numbers. If we wanted to use the latest version we could use `*` or we could use a range of versions. Cargo's documentation<sup>12</sup> contains more details.

Now, without changing any of our code, let's build our project:

---

<sup>10</sup><https://crates.io/crates/rand>

<sup>11</sup><http://semver.org>

<sup>12</sup><http://doc.crates.io/crates-io.html>

```
$ cargo build
  Updating registry `https://github.com/rust-lang/crates.io-index`
  Downloading rand v0.3.8
  Downloading libc v0.1.6
   Compiling libc v0.1.6
   Compiling rand v0.3.8
   Compiling guessing_game v0.1.0 (file:///home/you/projects/guessing_game)
```

(You may see different versions, of course.)

Lots of new output! Now that we have an external dependency, Cargo fetches the latest versions of everything from the registry, which is a copy of data from Crates.io<sup>13</sup>. Crates.io is where people in the Rust ecosystem post their open source Rust projects for others to use.

After updating the registry, Cargo checks our [dependencies] and downloads any we don't have yet. In this case, while we only said we wanted to depend on `rand`, we've also grabbed a copy of `libc`. This is because `rand` depends on `libc` to work. After downloading them, it compiles them, and then compiles our project.

If we run `cargo build` again, we'll get different output:

```
$ cargo build
```

That's right, no output! Cargo knows that our project has been built, and that all of its dependencies are built, and so there's no reason to do all that stuff. With nothing to do, it simply exits. If we open up `src/main.rs` again, make a trivial change, and then save it again, we'll just see one line:

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

So, we told Cargo we wanted any `0.3.x` version of `rand`, and so it fetched the latest version at the time this was written, `v0.3.8`. But what happens when next week, version `v0.3.9` comes out, with an important bugfix? While getting bugfixes is important, what if `0.3.9` contains a regression that breaks our code?

The answer to this problem is the `Cargo.lock` file you'll now find in your project directory. When you build your project for the first time, Cargo figures out all of the versions that fit your criteria, and then writes them to the `Cargo.lock` file. When you build your project in the future, Cargo will see that the `Cargo.lock` file exists, and then use that specific version rather than do all the work of figuring out versions again. This lets you have a repeatable build automatically. In other words, we'll stay at `0.3.8` until we explicitly upgrade, and so will anyone who we share our code with, thanks to the lock file.

What about when we *do* want to use `v0.3.9`? Cargo has another command, `update`, which says 'ignore the lock, figure out all the latest versions that fit what we've specified. If that works, write those versions out to the lock file'. But, by default, Cargo will only look for versions larger than `0.3.0` and smaller than `0.4.0`. If we want to move to `0.4.x`, we'd have to update the

---

<sup>13</sup><https://crates.io>

`Cargo.toml` directly. When we do, the next time we `cargo build`, Cargo will update the index and re-evaluate our `rand` requirements.

There's a lot more to say about Cargo<sup>14</sup> and its ecosystem<sup>15</sup>, but for now, that's all we need to know. Cargo makes it really easy to re-use libraries, and so Rustaceans tend to write smaller projects which are assembled out of a number of sub-packages.

Let's get on to actually *using* `rand`. Here's our next step:

```
extern crate rand;

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

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

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

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

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

    let mut guess = String::new();

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

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

The first thing we've done is change the first line. It now says `extern crate rand`. Because we declared `rand` in our [dependencies], we can use `extern crate` to let Rust know we'll be making use of it. This also does the equivalent of a `use rand`; as well, so we can make use of anything in the `rand` crate by prefixing it with `rand::`.

Next, we added another `use` line: `use rand::Rng`. We're going to use a method in a moment, and it requires that `Rng` be in scope to work. The basic idea is this: methods are defined on something called 'traits', and for the method to work, it needs the trait to be in scope. For more about the details, read the traits (section 5.20, page 173) section.

There are two other lines we added, in the middle:

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

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

---

<sup>14</sup><http://doc.crates.io>

<sup>15</sup><http://doc.crates.io/crates-io.html>

We use the `rand::thread_rng()` function to get a copy of the random number generator, which is local to the particular thread (section 4.6, page 94) of execution we're in. Because we use `rand::Rng`'d above, it has a `gen_range()` method available. This method takes two arguments, and generates a number between them. It's inclusive on the lower bound, but exclusive on the upper bound, so we need 1 and 101 to get a number between one and a hundred.

The second line just prints out the secret number. This is useful while we're developing our program, so we can easily test it out. But we'll be deleting it for the final version. It's not much of a game if it prints out the answer when you start it up!

Try running our new program a few times:

```
$ cargo run
  Compiling guessing_game v0.1.0 (file:///home/you/projects/guessing_game)
    Running `target/debug/guessing_game`
Guess the number!
The secret number is: 7
Please input your guess.
4
You guessed: 4
$ cargo run
    Running `target/debug/guessing_game`
Guess the number!
The secret number is: 83
Please input your guess.
5
You guessed: 5
```

Great! Next up: let's compare our guess to the secret guess.

### 3.1.4 Comparing guesses

Now that we've got user input, let's compare our guess to the random guess. Here's our next step, though it doesn't quite work yet:

```
extern crate rand;

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

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

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

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

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

```

let mut guess = String::new();

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

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

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

```

A few new bits here. The first is another use. We bring a type called `std::cmp::Ordering` into scope. Then, five new lines at the bottom that use it:

```

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

```

The `cmp()` method can be called on anything that can be compared, and it takes a reference to the thing you want to compare it to. It returns the `Ordering` type we used earlier. We use a `match` (section 5.14, page 157) statement to determine exactly what kind of `Ordering` it is. `Ordering` is an enum (section 5.13, page 156), short for ‘enumeration’, which looks like this:

```

enum Foo {
    Bar,
    Baz,
}

```

With this definition, anything of type `Foo` can be either a `Foo::Bar` or a `Foo::Baz`. We use the `::` to indicate the namespace for a particular enum variant.

The `Ordering`<sup>16</sup> enum has three possible variants: `Less`, `Equal`, and `Greater`. The `match` statement takes a value of a type, and lets you create an ‘arm’ for each possible value. Since we have three types of `Ordering`, we have three arms:

```

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

```

<sup>16</sup><http://doc.rust-lang.org/std/cmp/enum.Ordering.html>



If it's Less, we print `Too small!`, if it's Greater, `Too big!`, and if Equal, `You win!`. `match` is really useful, and is used often in Rust.

I did mention that this won't quite work yet, though. Let's try it:

```
$ cargo build
   Compiling guessing_game v0.1.0 (file:///home/you/projects/guessing_game)
src/main.rs:28:21: 28:35 error: mismatched types:
  expected `collections::string::String`,
    found `&_`
(expected struct `collections::string::String`,
  found integral variable) [E0308]
src/main.rs:28      match guess.cmp(&secret_number) {
                                ^~~~~~
error: aborting due to previous error
Could not compile `guessing_game`.
```

Whew! This is a big error. The core of it is that we have 'mismatched types'. Rust has a strong, static type system. However, it also has type inference. When we wrote `let guess = String::new()`, Rust was able to infer that `guess` should be a `String`, and so it doesn't make us write out the type. And with our `secret_number`, there are a number of types which can have a value between one and a hundred: `i32`, a thirty-two-bit number, or `u32`, an unsigned thirty-two-bit number, or `i64`, a sixty-four-bit number. Or others. So far, that hasn't mattered, and so Rust defaults to an `i32`. However, here, Rust doesn't know how to compare the `guess` and the `secret_number`. They need to be the same type. Ultimately, we want to convert the `String` we read as input into a real number type, for comparison. We can do that with three more lines. Here's our new program:

```
extern crate rand;

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

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

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

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

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

    let mut guess = String::new();

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

```

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

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

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

```

The new three lines:

```

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

```

Wait a minute, I thought we already had a `guess`? We do, but Rust allows us to ‘shadow’ the previous `guess` with a new one. This is often used in this exact situation, where `guess` starts as a `String`, but we want to convert it to an `u32`. Shadowing lets us re-use the `guess` name, rather than forcing us to come up with two unique names like `guess_str` and `guess`, or something else.

We bind `guess` to an expression that looks like something we wrote earlier:

```
guess.trim().parse()
```

Followed by an `ok().expect()` invocation. Here, `guess` refers to the old `guess`, the one that was a `String` with our input in it. The `trim()` method on `Strings` will eliminate any white space at the beginning and end of our string. This is important, as we had to press the ‘return’ key to satisfy `read_line()`. This means that if we type 5 and hit return, `guess` looks like this: `5\n`. The `\n` represents ‘newline’, the enter key. `trim()` gets rid of this, leaving our string with just the 5. The `parse()` method on strings<sup>17</sup> parses a string into some kind of number. Since it can parse a variety of numbers, we need to give Rust a hint as to the exact type of number we want. Hence, `let guess: u32`. The colon (`:`) after `guess` tells Rust we’re going to annotate its type. `u32` is an unsigned, thirty-two bit integer. Rust has a number of built-in number types<sup>18</sup>, but we’ve chosen `u32`. It’s a good default choice for a small positive number.

Just like `read_line()`, our call to `parse()` could cause an error. What if our string contained `A %`? There’d be no way to convert that to a number. As such, we’ll do the same thing we did with `read_line()`: use the `ok()` and `expect()` methods to crash if there’s an error.

Let’s try our program out!

```

$ cargo run
  Compiling guessing_game v0.0.1 (file:///home/you/projects/guessing_game)

```

<sup>17</sup><http://doc.rust-lang.org/std/primitive.str.html#method.parse>

<sup>18</sup>[primitive-types.html#numeric-types](http://doc.rust-lang.org/std/primitive.html#numeric-types)

```

Running `target/guessing_game`
Guess the number!
The secret number is: 58
Please input your guess.
  76
You guessed: 76
Too big!

```

Nice! You can see I even added spaces before my guess, and it still figured out that I guessed 76. Run the program a few times, and verify that guessing the number works, as well as guessing a number too small.

Now we've got most of the game working, but we can only make one guess. Let's change that by adding loops!

### 3.1.5 Looping

The `loop` keyword gives us an infinite loop. Let's add that in:

```

extern crate rand;

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

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

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

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

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

        let mut guess = String::new();

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

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

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

        match guess.cmp(&secret_number) {

```

```

        Ordering::Less    => println!("Too small!"),
        Ordering::Greater => println!("Too big!"),
        Ordering::Equal   => println!("You win!"),
    }
}
}

```

And try it out. But wait, didn't we just add an infinite loop? Yup. Remember our discussion about `parse()`? If we give a non-number answer, we'll return and quit. Observe:

```

$ cargo run
   Compiling guessing_game v0.0.1 (file:///home/you/projects/guessing_game)
   Running `target/guessing_game`
Guess the number!
The secret number is: 59
Please input your guess.
45
You guessed: 45
Too small!
Please input your guess.
60
You guessed: 60
Too big!
Please input your guess.
59
You guessed: 59
You win!
Please input your guess.
quit
thread '<main>' panicked at 'Please type a number!'

```

Ha! `quit` actually quits. As does any other non-number input. Well, this is suboptimal to say the least. First, let's actually quit when you win the game:

```

extern crate rand;

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

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

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

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

    loop {

```

```

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

let mut guess = String::new();

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

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

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

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

```

By adding the `break` line after the `You win!`, we'll exit the loop when we win. Exiting the loop also means exiting the program, since it's the last thing in `main()`. We have just one more tweak to make: when someone inputs a non-number, we don't want to quit, we just want to ignore it. We can do that like this:

```

extern crate rand;

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

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

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

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

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

        let mut guess = String::new();

        io::stdin().read_line(&mut guess)

```

```

        .ok()
        .expect("failed to read line");

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

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

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

```

These are the lines that changed:

```

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

```

This is how you generally move from ‘crash on error’ to ‘actually handle the error’, by switching from `ok().expect()` to a `match` statement. The `Result` returned by `parse()` is an enum just like `Ordering`, but in this case, each variant has some data associated with it: `Ok` is a success, and `Err` is a failure. Each contains more information: the successful parsed integer, or an error type. In this case, we `match` on `Ok(num)`, which sets the inner value of the `Ok` to the name `num`, and then we just return it on the right-hand side. In the `Err` case, we don’t care what kind of error it is, so we just use `_` instead of a name. This ignores the error, and `continue` causes us to go to the next iteration of the `loop`.

Now we should be good! Let’s try:

```

$ cargo run
   Compiling guessing_game v0.0.1 (file:///home/you/projects/guessing_game)
   Running `target/guessing_game`
Guess the number!
The secret number is: 61
Please input your guess.
10
You guessed: 10
Too small!

```

```
Please input your guess.  
99  
You guessed: 99  
Too big!  
Please input your guess.  
foo  
Please input your guess.  
61  
You guessed: 61  
You win!
```

Awesome! With one tiny last tweak, we have finished the guessing game. Can you think of what it is? That's right, we don't want to print out the secret number. It was good for testing, but it kind of ruins the game. Here's our final source:

```
extern crate rand;

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

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

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

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

        let mut guess = String::new();

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

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

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

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

```
    }  
  }  
}
```

### 3.1.6 Complete!

At this point, you have successfully built the Guessing Game! Congratulations!

This first project showed you a lot: `let`, `match`, methods, associated functions, using external crates, and more. Our next project will show off even more.

## 3.2 Dining Philosophers

For our second project, let's look at a classic concurrency problem. It's called 'the dining philosophers'. It was originally conceived by Dijkstra in 1965, but we'll use the version from this paper<sup>19</sup> by Tony Hoare in 1985.

In ancient times, a wealthy philanthropist endowed a College to accommodate five eminent philosophers. Each philosopher had a room in which he could engage in his professional activity of thinking; there was also a common dining room, furnished with a circular table, surrounded by five chairs, each labelled by the name of the philosopher who was to sit in it. They sat anticlockwise around the table. To the left of each philosopher there was laid a golden fork, and in the centre stood a large bowl of spaghetti, which was constantly replenished. A philosopher was expected to spend most of his time thinking; but when he felt hungry, he went to the dining room, sat down in his own chair, picked up his own fork on his left, and plunged it into the spaghetti. But such is the tangled nature of spaghetti that a second fork is required to carry it to the mouth. The philosopher therefore had also to pick up the fork on his right. When we was finished he would put down both his forks, get up from his chair, and continue thinking. Of course, a fork can be used by only one philosopher at a time. If the other philosopher wants it, he just has to wait until the fork is available again.

This classic problem shows off a few different elements of concurrency. The reason is that it's actually slightly tricky to implement: a simple implementation can deadlock. For example, let's consider a simple algorithm that would solve this problem:

1. A philosopher picks up the fork on their left.
2. They then pick up the fork on their right.
3. They eat.
4. They return the forks.

Now, let's imagine this sequence of events:

---

<sup>19</sup><http://www.usingcsp.com/cspbook.pdf>



1. Philosopher 1 begins the algorithm, picking up the fork on their left.
2. Philosopher 2 begins the algorithm, picking up the fork on their left.
3. Philosopher 3 begins the algorithm, picking up the fork on their left.
4. Philosopher 4 begins the algorithm, picking up the fork on their left.
5. Philosopher 5 begins the algorithm, picking up the fork on their left.
6. ... ? All the forks are taken, but nobody can eat!

There are different ways to solve this problem. We'll get to our solution in the tutorial itself. For now, let's get started modelling the problem itself. We'll start with the philosophers:

```
struct Philosopher {
    name: String,
}

impl Philosopher {
    fn new(name: &str) -> Philosopher {
        Philosopher {
            name: name.to_string(),
        }
    }
}

fn main() {
    let p1 = Philosopher::new("Baruch Spinoza");
    let p2 = Philosopher::new("Gilles Deleuze");
    let p3 = Philosopher::new("Karl Marx");
    let p4 = Philosopher::new("Friedrich Nietzsche");
    let p5 = Philosopher::new("Michel Foucault");
}
```

Here, we make a `struct` (section 5.12, page 153) to represent a philosopher. For now, a name is all we need. We choose the `String` (section 5.18, page 169) type for the name, rather than `&str`. Generally speaking, working with a type which owns its data is easier than working with one that uses references.

Let's continue:

```
impl Philosopher {
    fn new(name: &str) -> Philosopher {
        Philosopher {
            name: name.to_string(),
        }
    }
}
```

This `impl` block lets us define things on `Philosopher` structs. In this case, we define an 'associated function' called `new`. The first line looks like this:

```
fn new(name: &str) -> Philosopher {
```

We take one argument, a `name`, of type `&str`. This is a reference to another string. It returns an instance of our `Philosopher` struct.

```
Philosopher {  
    name: name.to_string(),  
}
```

This creates a new `Philosopher`, and sets its `name` to our `name` argument. Not just the argument itself, though, as we call `.to_string()` on it. This will create a copy of the string that our `&str` points to, and give us a new `String`, which is the type of the `name` field of `Philosopher`.

Why not accept a `String` directly? It's nicer to call. If we took a `String`, but our caller had a `&str`, they'd have to call this method themselves. The downside of this flexibility is that we *always* make a copy. For this small program, that's not particularly important, as we know we'll just be using short strings anyway.

One last thing you'll notice: we just define a `Philosopher`, and seemingly don't do anything with it. Rust is an 'expression based' language, which means that almost everything in Rust is an expression which returns a value. This is true of functions as well, the last expression is automatically returned. Since we create a new `Philosopher` as the last expression of this function, we end up returning it.

This name, `new()`, isn't anything special to Rust, but it is a convention for functions that create new instances of structs. Before we talk about why, let's look at `main()` again:

```
fn main() {  
    let p1 = Philosopher::new("Baruch Spinoza");  
    let p2 = Philosopher::new("Gilles Deleuze");  
    let p3 = Philosopher::new("Karl Marx");  
    let p4 = Philosopher::new("Friedrich Nietzsche");  
    let p5 = Philosopher::new("Michel Foucault");  
}
```

Here, we create five variable bindings with five new philosophers. These are my favorite five, but you can substitute anyone you want. If we *didn't* define that `new()` function, it would look like this:

```
fn main() {  
    let p1 = Philosopher { name: "Baruch Spinoza".to_string() };  
    let p2 = Philosopher { name: "Gilles Deleuze".to_string() };  
    let p3 = Philosopher { name: "Karl Marx".to_string() };  
    let p4 = Philosopher { name: "Friedrich Nietzsche".to_string() };  
    let p5 = Philosopher { name: "Michel Foucault".to_string() };  
}
```

That's much noisier. Using `new` has other advantages too, but even in this simple case, it ends up being nicer to use.

Now that we've got the basics in place, there's a number of ways that we can tackle the broader problem here. I like to start from the end first: let's set up a way for each philosopher to finish eating. As a tiny step, let's make a method, and then loop through all the philosophers, calling it:

```
struct Philosopher {
    name: String,
}

impl Philosopher {
    fn new(name: &str) -> Philosopher {
        Philosopher {
            name: name.to_string(),
        }
    }

    fn eat(&self) {
        println!("{}", self.name);
    }
}

fn main() {
    let philosophers = vec![
        Philosopher::new("Baruch Spinoza"),
        Philosopher::new("Gilles Deleuze"),
        Philosopher::new("Karl Marx"),
        Philosopher::new("Friedrich Nietzsche"),
        Philosopher::new("Michel Foucault"),
    ];

    for p in &philosophers {
        p.eat();
    }
}
```

Let's look at `main()` first. Rather than have five individual variable bindings for our philosophers, we make a `Vec<T>` of them instead. `Vec<T>` is also called a 'vector', and it's a growable array type. We then use a `for` (section 5.6, page 133) loop to iterate through the vector, getting a reference to each philosopher in turn.

In the body of the loop, we call `p.eat()`, which is defined above:

```
fn eat(&self) {
    println!("{}", self.name);
}
```

In Rust, methods take an explicit `self` parameter. That's why `eat()` is a method, but `new` is an associated function: `new()` has no `self`. For our first version of `eat()`, we just print out the name of the philosopher, and mention they're done eating. Running this program should give you the following output:

Baruch Spinoza is done eating.  
Gilles Deleuze is done eating.  
Karl Marx is done eating.  
Friedrich Nietzsche is done eating.  
Michel Foucault is done eating.

Easy enough, they're all done! We haven't actually implemented the real problem yet, though, so we're not done yet!

Next, we want to make our philosophers not just finish eating, but actually eat. Here's the next version:

```
use std::thread;

struct Philosopher {
    name: String,
}

impl Philosopher {
    fn new(name: &str) -> Philosopher {
        Philosopher {
            name: name.to_string(),
        }
    }

    fn eat(&self) {
        println!("{}", self.name);

        thread::sleep_ms(1000);

        println!("{}", self.name);
    }
}

fn main() {
    let philosophers = vec![
        Philosopher::new("Baruch Spinoza"),
        Philosopher::new("Gilles Deleuze"),
        Philosopher::new("Karl Marx"),
        Philosopher::new("Friedrich Nietzsche"),
        Philosopher::new("Michel Foucault"),
    ];

    for p in &philosophers {
        p.eat();
    }
}
```

Just a few changes. Let's break it down.

```
use std::thread;
```

`use` brings names into scope. We're going to start using the `thread` module from the standard library, and so we need to use it.

```
fn eat(&self) {
    println!("{}", self.name);

    thread::sleep_ms(1000);

    println!("{}", self.name);
}
```

We now print out two messages, with a `sleep_ms()` in the middle. This will simulate the time it takes a philosopher to eat.

If you run this program, You should see each philosopher eat in turn:

```
Baruch Spinoza is eating.
Baruch Spinoza is done eating.
Gilles Deleuze is eating.
Gilles Deleuze is done eating.
Karl Marx is eating.
Karl Marx is done eating.
Friedrich Nietzsche is eating.
Friedrich Nietzsche is done eating.
Michel Foucault is eating.
Michel Foucault is done eating.
```

Excellent! We're getting there. There's just one problem: we aren't actually operating in a concurrent fashion, which is a core part of the problem!

To make our philosophers eat concurrently, we need to make a small change. Here's the next iteration:

```
use std::thread;

struct Philosopher {
    name: String,
}

impl Philosopher {
    fn new(name: &str) -> Philosopher {
        Philosopher {
            name: name.to_string(),
        }
    }
}
```

```

fn eat(&self) {
    println!("{}", self.name);

    thread::sleep_ms(1000);

    println!("{}", self.name);
}

fn main() {
    let philosophers = vec![
        Philosopher::new("Baruch Spinoza"),
        Philosopher::new("Gilles Deleuze"),
        Philosopher::new("Karl Marx"),
        Philosopher::new("Friedrich Nietzsche"),
        Philosopher::new("Michel Foucault"),
    ];

    let handles: Vec<_> = philosophers.into_iter().map(|p| {
        thread::spawn(move || {
            p.eat();
        })
    }).collect();

    for h in handles {
        h.join().unwrap();
    }
}

```

All we've done is change the loop in `main()`, and added a second one! Here's the first change:

```

let handles: Vec<_> = philosophers.into_iter().map(|p| {
    thread::spawn(move || {
        p.eat();
    })
}).collect();

```

While this is only five lines, they're a dense five. Let's break it down.

```
let handles: Vec<_> =
```

We introduce a new binding, called `handles`. We've given it this name because we are going to make some new threads, and that will return some handles to those threads that let us control their operation. We need to explicitly annotate the type here, though, due to an issue we'll talk about later. The `_` is a type placeholder. We're saying "`handles` is a vector of something, but you can figure out what that something is, Rust."

```
philosophers.into_iter().map(|p| {
```

We take our list of philosophers and call `into_iter()` on it. This creates an iterator that takes ownership of each philosopher. We need to do this to pass them to our threads. We take that iterator and call `map` on it, which takes a closure as an argument and calls that closure on each element in turn.

```
    thread::spawn(move || {
        p.eat();
    })
```

Here's where the concurrency happens. The `thread::spawn` function takes a closure as an argument and executes that closure in a new thread. This closure needs an extra annotation, `move`, to indicate that the closure is going to take ownership of the values it's capturing. Primarily, the `p` variable of the `map` function.

Inside the thread, all we do is call `eat()` on `p`.

```
}).collect();
```

Finally, we take the result of all those `map` calls and collect them up. `collect()` will make them into a collection of some kind, which is why we needed to annotate the return type: we want a `Vec<T>`. The elements are the return values of the `thread::spawn` calls, which are handles to those threads. Whew!

```
for h in handles {
    h.join().unwrap();
}
```

At the end of `main()`, we loop through the handles and call `join()` on them, which blocks execution until the thread has completed execution. This ensures that the threads complete their work before the program exits.

If you run this program, you'll see that the philosophers eat out of order! We have multi-threading!

```
Gilles Deleuze is eating.
Gilles Deleuze is done eating.
Friedrich Nietzsche is eating.
Friedrich Nietzsche is done eating.
Michel Foucault is eating.
Baruch Spinoza is eating.
Baruch Spinoza is done eating.
Karl Marx is eating.
Karl Marx is done eating.
Michel Foucault is done eating.
```

But what about the forks? We haven't modeled them at all yet.

To do that, let's make a new `struct`:

```
use std::sync::Mutex;

struct Table {
    forks: Vec<Mutex<()>>,
}
```

This `Table` has an vector of `Mutexes`. A mutex is a way to control concurrency: only one thread can access the contents at once. This is exactly the property we need with our forks. We use an empty tuple, `()`, inside the mutex, since we're not actually going to use the value, just hold onto it.

Let's modify the program to use the `Table`:

```
use std::thread;
use std::sync::{Mutex, Arc};

struct Philosopher {
    name: String,
    left: usize,
    right: usize,
}

impl Philosopher {
    fn new(name: &str, left: usize, right: usize) -> Philosopher {
        Philosopher {
            name: name.to_string(),
            left: left,
            right: right,
        }
    }

    fn eat(&self, table: &Table) {
        let _left = table.forks[self.left].lock().unwrap();
        let _right = table.forks[self.right].lock().unwrap();

        println!("{}", self.name);

        thread::sleep_ms(1000);

        println!("{}", self.name);
    }
}

struct Table {
    forks: Vec<Mutex<()>>,
}

fn main() {
    let table = Arc::new(Table { forks: vec![
```



```

        Mutex::new(()),
        Mutex::new(()),
        Mutex::new(()),
        Mutex::new(()),
        Mutex::new(()),
    ]});

    let philosophers = vec![
        Philosopher::new("Baruch Spinoza", 0, 1),
        Philosopher::new("Gilles Deleuze", 1, 2),
        Philosopher::new("Karl Marx", 2, 3),
        Philosopher::new("Friedrich Nietzsche", 3, 4),
        Philosopher::new("Michel Foucault", 0, 4),
    ];

    let handles: Vec<_> = philosophers.into_iter().map(|p| {
        let table = table.clone();

        thread::spawn(move || {
            p.eat(&table);
        })
    }).collect();

    for h in handles {
        h.join().unwrap();
    }
}

```

Lots of changes! However, with this iteration, we've got a working program. Let's go over the details:

```
use std::sync::{Mutex, Arc};
```

We're going to use another structure from the `std::sync` package: `Arc<T>`. We'll talk more about it when we use it.

```

struct Philosopher {
    name: String,
    left: usize,
    right: usize,
}

```

We need to add two more fields to our `Philosopher`. Each philosopher is going to have two forks: the one on their left, and the one on their right. We'll use the `usize` type to indicate them, as it's the type that you index vectors with. These two values will be the indexes into the `forks` our `Table` has.

```
fn new(name: &str, left: usize, right: usize) -> Philosopher {
    Philosopher {
        name: name.to_string(),
        left: left,
        right: right,
    }
}
```

We now need to construct those `left` and `right` values, so we add them to `new()`.

```
fn eat(&self, table: &Table) {
    let _left = table.forks[self.left].lock().unwrap();
    let _right = table.forks[self.right].lock().unwrap();

    println!("{}", self.name);

    thread::sleep_ms(1000);

    println!("{}", self.name);
}
```

We have two new lines. We've also added an argument, `table`. We access the `Table`'s list of forks, and then use `self.left` and `self.right` to access the fork at that particular index. That gives us access to the `Mutex` at that index, and we call `lock()` on it. If the mutex is currently being accessed by someone else, we'll block until it becomes available.

The call to `lock()` might fail, and if it does, we want to crash. In this case, the error that could happen is that the mutex is 'poisoned'<sup>20</sup>, which is what happens when the thread panics while the lock is held. Since this shouldn't happen, we just use `unwrap()`.

One other odd thing about these lines: we've named the results `_left` and `_right`. What's up with that underscore? Well, we aren't planning on *using* the value inside the lock. We just want to acquire it. As such, Rust will warn us that we never use the value. By using the underscore, we tell Rust that this is what we intended, and it won't throw a warning.

What about releasing the lock? Well, that will happen when `_left` and `_right` go out of scope, automatically.

```
let table = Arc::new(Table { forks: vec![
    Mutex::new(),
    Mutex::new(),
    Mutex::new(),
    Mutex::new(),
    Mutex::new(),
    Mutex::new(),
] });
```

Next, in `main()`, we make a new `Table` and wrap it in an `Arc<T>`. 'arc' stands for 'atomic reference count', and we need that to share our `Table` across multiple threads. As we share it, the reference count will go up, and when each thread ends, it will go back down.

<sup>20</sup><http://doc.rust-lang.org/std/sync/struct.Mutex.html#poisoning>

```
let philosophers = vec![
    Philosopher::new("Baruch Spinoza", 0, 1),
    Philosopher::new("Gilles Deleuze", 1, 2),
    Philosopher::new("Karl Marx", 2, 3),
    Philosopher::new("Friedrich Nietzsche", 3, 4),
    Philosopher::new("Michel Foucault", 0, 4),
];
```

We need to pass in our `left` and `right` values to the constructors for our `Philosophers`. But there's one more detail here, and it's *very* important. If you look at the pattern, it's all consistent until the very end. Monsieur Foucault should have `4, 0` as arguments, but instead, has `0, 4`. This is what prevents deadlock, actually: one of our philosophers is left handed! This is one way to solve the problem, and in my opinion, it's the simplest.

```
let handles: Vec<_> = philosophers.into_iter().map(|p| {
    let table = table.clone();

    thread::spawn(move || {
        p.eat(&table);
    })
}).collect();
```

Finally, inside of our `map()/collect()` loop, we call `table.clone()`. The `clone()` method on `Arc<T>` is what bumps up the reference count, and when it goes out of scope, it decrements the count. You'll notice we can introduce a new binding to `table` here, and it will shadow the old one. This is often used so that you don't need to come up with two unique names.

With this, our program works! Only two philosophers can eat at any one time, and so you'll get some output like this:

```
Gilles Deleuze is eating.
Friedrich Nietzsche is eating.
Friedrich Nietzsche is done eating.
Gilles Deleuze is done eating.
Baruch Spinoza is eating.
Karl Marx is eating.
Baruch Spinoza is done eating.
Michel Foucault is eating.
Karl Marx is done eating.
Michel Foucault is done eating.
```

Congrats! You've implemented a classic concurrency problem in Rust.

### 3.3 Rust inside other languages

For our third project, we're going to choose something that shows off one of Rust's greatest strengths: a lack of a substantial runtime.

As organizations grow, they increasingly rely on a multitude of programming languages. Different programming languages have different strengths and weaknesses, and a polyglot stack lets you use a particular language where its strengths make sense, and use a different language where it's weak.

A very common area where many programming languages are weak is in runtime performance of programs. Often, using a language that is slower, but offers greater programmer productivity is a worthwhile trade-off. To help mitigate this, they provide a way to write some of your system in C, and then call the C code as though it were written in the higher-level language. This is called a 'foreign function interface', often shortened to 'FFI'.

Rust has support for FFI in both directions: it can call into C code easily, but crucially, it can also be called *into* as easily as C. Combined with Rust's lack of a garbage collector and low runtime requirements, this makes Rust a great candidate to embed inside of other languages when you need some extra oomph.

There is a whole chapter devoted to FFI (section 4.8, page 106) and its specifics elsewhere in the book, but in this chapter, we'll examine this particular use-case of FFI, with three examples, in Ruby, Python, and JavaScript.

### 3.3.1 The problem

There are many different projects we could choose here, but we're going to pick an example where Rust has a clear advantage over many other languages: numeric computing and threading.

Many languages, for the sake of consistency, place numbers on the heap, rather than on the stack. Especially in languages that focus on object-oriented programming and use garbage collection, heap allocation is the default. Sometimes optimizations can stack allocate particular numbers, but rather than relying on an optimizer to do its job, we may want to ensure that we're always using primitive number types rather than some sort of object type.

Second, many languages have a 'global interpreter lock', which limits concurrency in many situations. This is done in the name of safety, which is a positive effect, but it limits the amount of work that can be done at the same time, which is a big negative.

To emphasize these two aspects, we're going to create a little project that uses these two aspects heavily. Since the focus of the example is the embedding of Rust into the languages, rather than the problem itself, we'll just use a toy example:

Start ten threads. Inside each thread, count from one to five million. After All ten threads are finished, print out 'done!'.

I chose five million based on my particular computer. Here's an example of this code in Ruby:

```
threads = []

10.times do
  threads << Thread.new do
    count = 0

    5_000_000.times do
```

```

        count += 1
    end
end
end

threads.each {|t| t.join }
puts "done!"

```

Try running this example, and choose a number that runs for a few seconds. Depending on your computer's hardware, you may have to increase or decrease the number.

On my system, running this program takes 2.156 seconds. And, if I use some sort of process monitoring tool, like `top`, I can see that it only uses one core on my machine. That's the GIL kicking in.

While it's true that this is a synthetic program, one can imagine many problems that are similar to this in the real world. For our purposes, spinning up some busy threads represents some sort of parallel, expensive computation.

### 3.3.2 A Rust library

Let's re-write this problem in Rust. First, let's make a new project with Cargo:

```

$ cargo new embed
$ cd embed

```

This program is fairly easy to write in Rust:

```

use std::thread;

fn process() {
    let handles: Vec<_> = (0..10).map(|_| {
        thread::spawn(|| {
            let mut _x = 0;
            for _ in (0..5_000_001) {
                _x += 1
            }
        })
    }).collect();

    for h in handles {
        h.join().ok().expect("Could not join a thread!");
    }
}

```

Some of this should look familiar from previous examples. We spin up ten threads, collecting them into a `handles` vector. Inside of each thread, we loop five million times, and add one to `_x` each time. Why the underscore? Well, if we remove it and compile:

```
$ cargo build
   Compiling embed v0.1.0 (file:///home/steve/src/embed)
src/lib.rs:3:1: 16:2 warning: function is never used: `process`, #[warn(dead_code)] on by default
src/lib.rs:3 fn process() {
src/lib.rs:4     let handles: Vec<_> = (0..10).map(|_| {
src/lib.rs:5         thread::spawn(|| {
src/lib.rs:6             let mut x = 0;
src/lib.rs:7             for _ in (0..5_000_001) {
src/lib.rs:8                 x += 1
...
src/lib.rs:6:17: 6:22 warning: variable `x` is assigned to, but never used, #[warn(unused_variables)] on
src/lib.rs:6         let mut x = 0;
                ^~~~~
```

That first warning is because we are building a library. If we had a test for this function, the warning would go away. But for now, it's never called.

The second is related to `x` versus `_x`. Because we never actually *do* anything with `x`, we get a warning about it. In our case, that's perfectly okay, as we're just trying to waste CPU cycles. Prefixing `x` with the underscore removes the warning.

Finally, we join on each thread.

Right now, however, this is a Rust library, and it doesn't expose anything that's callable from C. If we tried to hook this up to another language right now, it wouldn't work. We only need to make two small changes to fix this, though. The first is modify the beginning of our code:

```
#[no_mangle]
pub extern fn process() {
```

We have to add a new attribute, `no_mangle`. When you create a Rust library, it changes the name of the function in the compiled output. The reasons for this are outside the scope of this tutorial, but in order for other languages to know how to call the function, we need to not do that. This attribute turns that behavior off.

The other change is the `pub extern`. The `pub` means that this function should be callable from outside of this module, and the `extern` says that it should be able to be called from C. That's it! Not a whole lot of change.

The second thing we need to do is to change a setting in our `Cargo.toml`. Add this at the bottom:

```
[lib]
name = "embed"
crate-type = ["dylib"]
```

This tells Rust that we want to compile our library into a standard dynamic library. By default, Rust compiles into an 'rlib', a Rust-specific format.

Let's build the project now:

```
$ cargo build --release
   Compiling embed v0.1.0 (file:///home/steve/src/embed)
```

We've chosen `cargo build --release`, which builds with optimizations on. We want this to be as fast as possible! You can find the output of the library in `target/release`:

```
$ ls target/release/  
build  deps  examples  libembed.so  native
```

That `libembed.so` is our 'shared object' library. We can use this file just like any shared object library written in C! As an aside, this may be `embed.dll` or `libembed.dylib`, depending on the platform.

Now that we've got our Rust library built, let's use it from our Ruby.

### 3.3.3 Ruby

Open up a `embed.rb` file inside of our project, and do this:

```
require 'ffi'  
  
module Hello  
  extend FFI::Library  
  ffi_lib 'target/release/libembed.so'  
  attach_function :process, [], :void  
end  
  
Hello.process  
  
puts "done!"
```

Before we can run this, we need to install the `ffi` gem:

```
$ gem install ffi # this may need sudo  
Fetching: ffi-1.9.8.gem (100%)  
Building native extensions. This could take a while...  
Successfully installed ffi-1.9.8  
Parsing documentation for ffi-1.9.8  
Installing ri documentation for ffi-1.9.8  
Done installing documentation for ffi after 0 seconds  
1 gem installed
```

And finally, we can try running it:

```
$ ruby embed.rb  
done!  
$
```

Whoah, that was fast! On my system, this took `0.086` seconds, rather than the two seconds the pure Ruby version took. Let's break down this Ruby code:

```
require 'ffi'
```

We first need to require the `ffi` gem. This lets us interface with our Rust library like a C library.

```
module Hello
  extend FFI::Library
  ffi_lib 'target/release/libembed.so'
```

The `ffi` gem's authors recommend using a module to scope the functions we'll import from the shared library. Inside, we `extend` the necessary `FFI::Library` module, and then call `ffi_lib` to load up our shared object library. We just pass it the path that our library is stored, which as we saw before, is `target/release/libembed.so`.

```
attach_function :process, [], :void
```

The `attach_function` method is provided by the FFI gem. It's what connects our `process()` function in Rust to a Ruby function of the same name. Since `process()` takes no arguments, the second parameter is an empty array, and since it returns nothing, we pass `:void` as the final argument.

```
Hello.process
```

This is the actual call into Rust. The combination of our `module` and the call to `attach_function` sets this all up. It looks like a Ruby function, but is actually Rust!

```
puts "done!"
```

Finally, as per our project's requirements, we print out `done!`.

That's it! As we've seen, bridging between the two languages is really easy, and buys us a lot of performance.

Next, let's try Python!

### 3.3.4 Python

Create an `embed.py` file in this directory, and put this in it:

```
from ctypes import cdll

lib = cdll.LoadLibrary("target/release/libembed.so")

lib.process()

print("done!")
```

Even easier! We use `cdll` from the `ctypes` module. A quick call to `LoadLibrary` later, and we can call `process()`.

On my system, this takes `0.017` seconds. Speedy!



### 3.3.5 Node.js

Node isn't a language, but it's currently the dominant implementation of server-side JavaScript.

In order to do FFI with Node, we first need to install the library:

```
$ npm install ffi
```

After that installs, we can use it:

```
var ffi = require('ffi');

var lib = ffi.Library('target/release/libembed', {
  'process': [ 'void', [] ]
});

lib.process();

console.log("done!");
```

It looks more like the Ruby example than the Python example. We use the `ffi` module to get access to `ffi.Library()`, which loads up our shared object. We need to annotate the return type and argument types of the function, which are 'void' for return, and an empty array to signify no arguments. From there, we just call it and print the result.

On my system, this takes a quick 0.092 seconds.

### 3.3.6 Conclusion

As you can see, the basics of doing this are *very* easy. Of course, there's a lot more that we could do here. Check out the FFI (section 4.8, page 106) chapter for more details.



# 4

## Effective Rust

So you've learned how to write some Rust code. But there's a difference between writing *any* Rust code and writing *good* Rust code.

This section consists of relatively independent tutorials which show you how to take your Rust to the next level. Common patterns and standard library features will be introduced. Read these sections in any order of your choosing.

### 4.1 The Stack and the Heap

As a systems language, Rust operates at a low level. If you're coming from a high-level language, there are some aspects of systems programming that you may not be familiar with. The most important one is how memory works, with a stack and a heap. If you're familiar with how C-like languages use stack allocation, this chapter will be a refresher. If you're not, you'll learn about this more general concept, but with a Rust-y focus.

#### 4.1.1 Memory management

These two terms are about memory management. The stack and the heap are abstractions that help you determine when to allocate and deallocate memory.

Here's a high-level comparison:

The stack is very fast, and is where memory is allocated in Rust by default. But the allocation is local to a function call, and is limited in size. The heap, on the other hand, is slower, and is explicitly allocated by your program. But it's effectively unlimited in size, and is globally accessible.

### 4.1.2 The Stack

Let's talk about this Rust program:

```
fn main() {  
    let x = 42;  
}
```

This program has one variable binding, `x`. This memory needs to be allocated from somewhere. Rust 'stack allocates' by default, which means that basic values 'go on the stack'. What does that mean?

Well, when a function gets called, some memory gets allocated for all of its local variables and some other information. This is called a 'stack frame', and for the purpose of this tutorial, we're going to ignore the extra information and just consider the local variables we're allocating. So in this case, when `main()` is run, we'll allocate a single 32-bit integer for our stack frame. This is automatically handled for you, as you can see, we didn't have to write any special Rust code or anything.

When the function is over, its stack frame gets deallocated. This happens automatically, we didn't have to do anything special here.

That's all there is for this simple program. The key thing to understand here is that stack allocation is very, very fast. Since we know all the local variables we have ahead of time, we can grab the memory all at once. And since we'll throw them all away at the same time as well, we can get rid of it very fast too.

The downside is that we can't keep values around if we need them for longer than a single function. We also haven't talked about what that name, 'stack' means. To do that, we need a slightly more complicated example:

```
fn foo() {  
    let y = 5;  
    let z = 100;  
}  
  
fn main() {  
    let x = 42;  
  
    foo();  
}
```

This program has three variables total: two in `foo()`, one in `main()`. Just as before, when `main()` is called, a single integer is allocated for its stack frame. But before we can show what happens when `foo()` is called, we need to visualize what's going on with memory. Your operating system presents a view of memory to your program that's pretty simple: a huge list of addresses, from 0 to a large number, representing how much RAM your computer has. For example, if you have a gigabyte of RAM, your addresses go from 0 to 1,073,741,824. That number comes from 230, the number of bytes in a gigabyte.

This memory is kind of like a giant array: addresses start at zero and go up to the final number. So here's a diagram of our first stack frame:

Address	Name	Value
0	x	42

We've got `x` located at address `0`, with the value `42`.

When `foo()` is called, a new stack frame is allocated:

Address	Name	Value
2	z	100
1	y	5
0	x	42

Because `0` was taken by the first frame, `1` and `2` are used for `foo()`'s stack frame. It grows upward, the more functions we call.

There's some important things we have to take note of here. The numbers `0`, `1`, and `2` are all solely for illustrative purposes, and bear no relationship to the actual numbers the computer will actually use. In particular, the series of addresses are in reality going to be separated by some number of bytes that separate each address, and that separation may even exceed the size of the value being stored.

After `foo()` is over, its frame is deallocated:

Address	Name	Value
0	x	42

And then, after `main()`, even this last value goes away. Easy!

It's called a 'stack' because it works like a stack of dinner plates: the first plate you put down is the last plate to pick back up. Stacks are sometimes called 'last in, first out queues' for this reason, as the last value you put on the stack is the first one you retrieve from it.

Let's try a three-deep example:

```
fn bar() {  
    let i = 6;  
}  
  
fn foo() {  
    let a = 5;  
    let b = 100;  
    let c = 1;  
  
    bar();  
}  
  
fn main() {
```

```

let x = 42;

foo();
}

```

Okay, first, we call `main()`:

Address	Name	Value
0	x	42

Next up, `main()` calls `foo()`:

Address	Name	Value
3	c	1
2	b	100
1	a	5
0	x	42

And then `foo()` calls `bar()`:

Address	Name	Value
4	i	6
3	c	1
2	b	100
1	a	5
0	x	42

Whew! Our stack is growing tall.

After `bar()` is over, its frame is deallocated, leaving just `foo()` and `main()`:

Address	Name	Value
3	c	1
2	b	100
1	a	5
0	x	42

And then `foo()` ends, leaving just `main()`

Address	Name	Value
0	x	42

And then we're done. Getting the hang of it? It's like piling up dishes: you add to the top, you take away from the top.

### 4.1.3 The Heap

Now, this works pretty well, but not everything can work like this. Sometimes, you need to pass some memory between different functions, or keep it alive for longer than a single function's execution. For this, we can use the heap.

In Rust, you can allocate memory on the heap with the `Box<T>` type<sup>1</sup>. Here's an example:

```
fn main() {
    let x = Box::new(5);
    let y = 42;
}
```

Here's what happens in memory when `main()` is called:

Address	Name	Value
1	y	42
0	x	?????

We allocate space for two variables on the stack. `y` is 42, as it always has been, but what about `x`? Well, `x` is a `Box<i32>`, and boxes allocate memory on the heap. The actual value of the box is a structure which has a pointer to 'the heap'. When we start executing the function, and `Box::new()` is called, it allocates some memory for the heap, and puts 5 there. The memory now looks like this:

Address	Name	Value
230		5
...	...	...
1	y	42
0	x	230

We have 230 in our hypothetical computer with 1GB of RAM. And since our stack grows from zero, the easiest place to allocate memory is from the other end. So our first value is at the highest place in memory. And the value of the struct at `x` has a raw pointer (section 5.36, page 233) to the place we've allocated on the heap, so the value of `x` is 230, the memory location we've asked for.

We haven't really talked too much about what it actually means to allocate and deallocate memory in these contexts. Getting into very deep detail is out of the scope of this tutorial, but what's important to point out here is that the heap isn't just a stack that grows from the opposite end. We'll have an example of this later in the book, but because the heap can be

<sup>1</sup><http://doc.rust-lang.org/std/boxed/index.html>

allocated and freed in any order, it can end up with ‘holes’. Here’s a diagram of the memory layout of a program which has been running for a while now:

Address	Name	Value
230		5
(230) - 1		
(230) - 2		
(230) - 3		42
...	...	...
3	y	(230) - 3
2	y	42
1	y	42
0	x	230

In this case, we’ve allocated four things on the heap, but deallocated two of them. There’s a gap between 230 and (230) - 3 which isn’t currently being used. The specific details of how and why this happens depends on what kind of strategy you use to manage the heap. Different programs can use different ‘memory allocators’, which are libraries that manage this for you. Rust programs use `jemalloc`<sup>2</sup> for this purpose.

Anyway, back to our example. Since this memory is on the heap, it can stay alive longer than the function which allocates the box. In this case, however, it doesn’t.<sup>[^moving]</sup> When the function is over, we need to free the stack frame for `main()`. `Box<T>`, though, has a trick up its sleeve: `Drop` (section 5.21, page 180). The implementation of `Drop` for `Box` deallocates the memory that was allocated when it was created. Great! So when `x` goes away, it first frees the memory allocated on the heap:

Address	Name	Value
1	y	42
0	x	?????

sometimes called ‘moving out of the box’. More complex examples will be covered later.

And then the stack frame goes away, freeing all of our memory.

#### 4.1.4 Arguments and borrowing

We’ve got some basic examples with the stack and the heap going, but what about function arguments and borrowing? Here’s a small Rust program:

```
fn foo(i: &i32) {
    let z = 42;
```

<sup>2</sup><http://www.canonware.com/jemalloc/>



```

}

fn main() {
    let x = 5;
    let y = &x;

    foo(y);
}

```

When we enter `main()`, memory looks like this:

Address	Name	Value
1	y	0
0	x	5

`x` is a plain old 5, and `y` is a reference to `x`. So its value is the memory location that `x` lives at, which in this case is 0.

What about when we call `foo()`, passing `y` as an argument?

Address	Name	Value
3	z	42
2	i	0
1	y	0
0	x	5

Stack frames aren't just for local bindings, they're for arguments too. So in this case, we need to have both `i`, our argument, and `z`, our local variable binding. `i` is a copy of the argument, `y`. Since `y`'s value is 0, so is `i`'s.

This is one reason why borrowing a variable doesn't deallocate any memory: the value of a reference is just a pointer to a memory location. If we got rid of the underlying memory, things wouldn't work very well.

### 4.1.5 A complex example

Okay, let's go through this complex program step-by-step:

```

fn foo(x: &i32) {
    let y = 10;
    let z = &y;

    baz(z);
    bar(x, z);
}

```

```

fn bar(a: &i32, b: &i32) {
    let c = 5;
    let d = Box::new(5);
    let e = &d;

    baz(e);
}

fn baz(f: &i32) {
    let g = 100;
}

fn main() {
    let h = 3;
    let i = Box::new(20);
    let j = &h;

    foo(j);
}

```

First, we call `main()`:

Address	Name	Value
230		20
...	...	...
2	j	0
1	i	230
0	h	3

We allocate memory for `j`, `i`, and `h`. `i` is on the heap, and so has a value pointing there.

Next, at the end of `main()`, `foo()` gets called:

Address	Name	Value
230		20
...	...	...
5	z	4
4	y	10
3	x	0
2	j	0
1	i	230
0	h	3

Space gets allocated for `x`, `y`, and `z`. The argument `x` has the same value as `j`, since that's what we passed it in. It's a pointer to the `0` address, since `j` points at `h`.

Next, `foo()` calls `baz()`, passing `z`:

Address	Name	Value
230		20
...	...	...
7	g	100
6	f	4
5	z	4
4	y	10
3	x	0
2	j	0
1	i	230
0	h	3

We've allocated memory for `f` and `g`. `baz()` is very short, so when it's over, we get rid of its stack frame:

Address	Name	Value
230		20
...	...	...
5	z	4
4	y	10
3	x	0
2	j	0
1	i	230
0	h	3

Next, `foo()` calls `bar()` with `x` and `z`:

Address	Name	Value
230		20
(230) - 1		5
...	...	...
10	e	9
9	d	(230) - 1
8	c	5
7	b	4
6	a	0
5	z	4
4	y	10
3	x	0
2	j	0
1	i	230
0	h	3

We end up allocating another value on the heap, and so we have to subtract one from 230. It's easier to just write that than 1,073,741,823. In any case, we set up the variables as usual.

At the end of `bar()`, it calls `baz()`:

Address	Name	Value
230		20
(230) - 1		5
...	...	...
12	g	100
11	f	4
10	e	9
9	d	(230) - 1
8	c	5
7	b	4
6	a	0
5	z	4
4	y	10
3	x	0
2	j	0
1	i	230
0	h	3

With this, we're at our deepest point! Whew! Congrats for following along this far.

After `baz()` is over, we get rid of `f` and `g`:

Address	Name	Value
230		20
(230) - 1		5
...	...	...
10	e	9
9	d	(230) - 1
8	c	5
7	b	4
6	a	0
5	z	4
4	y	10
3	x	0
2	j	0
1	i	230
0	h	3

Next, we return from `bar()`. `d` in this case is a `Box<T>`, so it also frees what it points to: (230) - 1.

Address	Name	Value
230		20
...	...	...
5	z	4
4	y	10
3	x	0
2	j	0
1	i	230
0	h	3

And after that, `foo()` returns:

Address	Name	Value
230		20
...	...	...
2	j	0
1	i	230
0	h	3

And then, finally, `main()`, which cleans the rest up. When `i` is `Dropped`, it will clean up the last of the heap too.

#### 4.1.6 What do other languages do?

Most languages with a garbage collector heap-allocate by default. This means that every value is boxed. There are a number of reasons why this is done, but they're out of scope for this tutorial. There are some possible optimizations that don't make it true 100% of the time, too. Rather than relying on the stack and `Drop` to clean up memory, the garbage collector deals with the heap instead.

#### 4.1.7 Which to use?

So if the stack is faster and easier to manage, why do we need the heap? A big reason is that Stack-allocation alone means you only have LIFO semantics for reclaiming storage. Heap-allocation is strictly more general, allowing storage to be taken from and returned to the pool in arbitrary order, but at a complexity cost.

Generally, you should prefer stack allocation, and so, Rust stack-allocates by default. The LIFO model of the stack is simpler, at a fundamental level. This has two big impacts: runtime efficiency and semantic impact.

#### Runtime Efficiency.

Managing the memory for the stack is trivial: The machine just increments or decrements a single value, the so-called “stack pointer”. Managing memory for the heap is non-trivial: heap-

allocated memory is freed at arbitrary points, and each block of heap-allocated memory can be of arbitrary size, the memory manager must generally work much harder to identify memory for reuse.

If you'd like to dive into this topic in greater detail, this paper<sup>3</sup> is a great introduction.

### Semantic impact

Stack-allocation impacts the Rust language itself, and thus the developer's mental model. The LIFO semantics is what drives how the Rust language handles automatic memory management. Even the deallocation of a uniquely-owned heap-allocated box can be driven by the stack-based LIFO semantics, as discussed throughout this chapter. The flexibility (i.e. expressiveness) of non LIFO-semantics means that in general the compiler cannot automatically infer at compile-time where memory should be freed; it has to rely on dynamic protocols, potentially from outside the language itself, to drive deallocation (reference counting, as used by `Rc<T>` and `Arc<T>`, is one example of this).

When taken to the extreme, the increased expressive power of heap allocation comes at the cost of either significant runtime support (e.g. in the form of a garbage collector) or significant programmer effort (in the form of explicit memory management calls that require verification not provided by the Rust compiler).

## 4.2 Testing

Program testing can be a very effective way to show the presence of bugs, but it is hopelessly inadequate for showing their absence.

Edsger W. Dijkstra, "The Humble Programmer" (1972)

Let's talk about how to test Rust code. What we will not be talking about is the right way to test Rust code. There are many schools of thought regarding the right and wrong way to write tests. All of these approaches use the same basic tools, and so we'll show you the syntax for using them.

### 4.2.1 The `test` attribute

At its simplest, a test in Rust is a function that's annotated with the `test` attribute. Let's make a new project with Cargo called `adder`:

```
$ cargo new adder
$ cd adder
```

Cargo will automatically generate a simple test when you make a new project. Here's the contents of `src/lib.rs`:

---

<sup>3</sup><http://www.cs.northwestern.edu/~pdinda/icsclass/doc/dsa.pdf>

```
#[test]
fn it_works() {
}
```

Note the `#[test]`. This attribute indicates that this is a test function. It currently has no body. That's good enough to pass! We can run the tests with `cargo test`:

```
$ cargo test
   Compiling adder v0.0.1 (file:///home/you/projects/adder)
   Running target/adder-91b3e234d4ed382a

running 1 test
test it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

Cargo compiled and ran our tests. There are two sets of output here: one for the test we wrote, and another for documentation tests. We'll talk about those later. For now, see this line:

```
test it_works ... ok
```

Note the `it_works`. This comes from the name of our function:

```
fn it_works() {
```

We also get a summary line:

```
test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

So why does our do-nothing test pass? Any test which doesn't `panic!` passes, and any test that does `panic!` fails. Let's make our test fail:

```
#[test]
fn it_works() {
    assert!(false);
}
```

`assert!` is a macro provided by Rust which takes one argument: if the argument is `true`, nothing happens. If the argument is `false`, it `panic!`s. Let's run our tests again:

```
$ cargo test
  Compiling adder v0.0.1 (file:///home/you/projects/adder)
    Running target/adder-91b3e234d4ed382a

running 1 test
test it_works ... FAILED

failures:

---- it_works stdout ----
      thread 'it_works' panicked at 'assertion failed: false', /home/steve/tmp/adder/src/lib.rs:3

failures:
    it_works

test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured

thread '<main>' panicked at 'Some tests failed', /home/steve/src/rust/src/libtest/lib.rs:247
```

Rust indicates that our test failed:

```
test it_works ... FAILED
```

And that's reflected in the summary line:

```
test result: FAILED. 0 passed; 1 failed; 0 ignored; 0 measured
```

We also get a non-zero status code:

```
$ echo $?
101
```

This is useful if you want to integrate `cargo test` into other tooling.

We can invert our test's failure with another attribute: `should_panic`:

```
#[test]
#[should_panic]
fn it_works() {
    assert!(false);
}
```

This test will now succeed if we `panic!` and fail if we complete. Let's try it:



```
$ cargo test
  Compiling adder v0.0.1 (file:///home/you/projects/adder)
    Running target/adder-91b3e234d4ed382a

running 1 test
test it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

```
Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

Rust provides another macro, `assert_eq!`, that compares two arguments for equality:

```
#[test]
#[should_panic]
fn it_works() {
    assert_eq!("Hello", "world");
}
```

Does this test pass or fail? Because of the `should_panic` attribute, it passes:

```
$ cargo test
  Compiling adder v0.0.1 (file:///home/you/projects/adder)
    Running target/adder-91b3e234d4ed382a

running 1 test
test it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

`should_panic` tests can be fragile, as it's hard to guarantee that the test didn't fail for an unexpected reason. To help with this, an optional `expected` parameter can be added to the `should_panic` attribute. The test harness will make sure that the failure message contains the provided text. A safer version of the example above would be:

```
#[test]
#[should_panic(expected = "assertion failed")]
fn it_works() {
```

```
    assert_eq!("Hello", "world");  
}
```

That’s all there is to the basics! Let’s write one ‘real’ test:

```
pub fn add_two(a: i32) -> i32 {  
    a + 2  
}  
  
#[test]  
fn it_works() {  
    assert_eq!(4, add_two(2));  
}
```

This is a very common use of `assert_eq!`: call some function with some known arguments and compare it to the expected output.

### 4.2.2 The `tests` module

There is one way in which our existing example is not idiomatic: it’s missing the `tests` module. The idiomatic way of writing our example looks like this:

```
pub fn add_two(a: i32) -> i32 {  
    a + 2  
}  
  
#[cfg(test)]  
mod tests {  
    use super::add_two;  
  
    #[test]  
    fn it_works() {  
        assert_eq!(4, add_two(2));  
    }  
}
```

There’s a few changes here. The first is the introduction of a `mod tests` with a `cfg` attribute. The module allows us to group all of our tests together, and to also define helper functions if needed, that don’t become a part of the rest of our crate. The `cfg` attribute only compiles our test code if we’re currently trying to run the tests. This can save compile time, and also ensures that our tests are entirely left out of a normal build.

The second change is the `use` declaration. Because we’re in an inner module, we need to bring our test function into scope. This can be annoying if you have a large module, and so this is a common use of the `glob` feature. Let’s change our `src/lib.rs` to make use of it:

```
pub fn add_two(a: i32) -> i32 {
    a + 2
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_works() {
        assert_eq!(4, add_two(2));
    }
}
```

Note the different use line. Now we run our tests:

```
$ cargo test
  Updating registry `https://github.com/rust-lang/crates.io-index`
  Compiling adder v0.0.1 (file:///home/you/projects/adder)
  Running target/adder-91b3e234d4ed382a

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

It works!

The current convention is to use the `tests` module to hold your “unit-style” tests. Anything that just tests one small bit of functionality makes sense to go here. But what about “integration-style” tests instead? For that, we have the `tests` directory

### 4.2.3 The `tests` directory

To write an integration test, let’s make a `tests` directory, and put a `tests/lib.rs` file inside, with this as its contents:

```
extern crate adder;

#[test]
fn it_works() {
```

```
    assert_eq!(4, adder::add_two(2));
}
```

This looks similar to our previous tests, but slightly different. We now have an `extern crate adder` at the top. This is because the tests in the `tests` directory are an entirely separate crate, and so we need to import our library. This is also why `tests` is a suitable place to write integration-style tests: they use the library like any other consumer of it would.

Let's run them:

```
$ cargo test
  Compiling adder v0.0.1 (file:///home/you/projects/adder)
    Running target/adder-91b3e234d4ed382a

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

    Running target/lib-c18e7d3494509e74

running 1 test
test it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

   Doc-tests adder

running 0 tests

test result: ok. 0 passed; 0 failed; 0 ignored; 0 measured
```

Now we have three sections: our previous test is also run, as well as our new one.

That's all there is to the `tests` directory. The `tests` module isn't needed here, since the whole thing is focused on tests.

Let's finally check out that third section: documentation tests.

#### 4.2.4 Documentation tests

Nothing is better than documentation with examples. Nothing is worse than examples that don't actually work, because the code has changed since the documentation has been written. To this end, Rust supports automatically running examples in your documentation. Here's a fleshed-out `src/lib.rs` with examples:

```
///! The `adder` crate provides functions that add numbers to other numbers.
///!
```

```

/// # Examples
///
/// ```
/// assert_eq!(4, adder::add_two(2));
/// ```

/// This function adds two to its argument.
///
/// # Examples
///
/// ```
/// use adder::add_two;
///
/// assert_eq!(4, add_two(2));
/// ```
pub fn add_two(a: i32) -> i32 {
    a + 2
}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn it_works() {
        assert_eq!(4, add_two(2));
    }
}

```

Note the module-level documentation with `///` and the function-level documentation with `///`. Rust's documentation supports Markdown in comments, and so triple graves mark code blocks. It is conventional to include the `# Examples` section, exactly like that, with examples following.

Let's run the tests again:

```

$ cargo test
  Compiling adder v0.0.1 (file:///home/steve/tmp/adder)
    Running target/adder-91b3e234d4ed382a

running 1 test
test tests::it_works ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured

    Running target/lib-c18e7d3494509e74

running 1 test
test it_works ... ok

```

```
test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured
```

```
Doc-tests adder
```

```
running 2 tests
test add_two_0 ... ok
test _0 ... ok
```

```
test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured
```

Now we have all three kinds of tests running! Note the names of the documentation tests: the `_0` is generated for the module test, and `add_two_0` for the function test. These will auto increment with names like `add_two_1` as you add more examples.

## 4.3 Conditional Compilation

Rust has a special attribute, `#[cfg]`, which allows you to compile code based on a flag passed to the compiler. It has two forms:

```
#[cfg(foo)]
#[cfg(bar = "baz")]
```

They also have some helpers:

```
#[cfg(any(unix, windows))]
#[cfg(all(unix, target_pointer_width = "32"))]
#[cfg(not(foo))]
```

These can nest arbitrarily:

```
#[cfg(any(not(unix), all(target_os="macos", target_arch = "powerpc")))]
```

As for how to enable or disable these switches, if you're using Cargo, they get set in the `[features]` section<sup>4</sup> of your `Cargo.toml`:

```
[features]
# no features by default
default = []

# The "secure-password" feature depends on the bcrypt package.
secure-password = ["bcrypt"]
```

---

<sup>4</sup><http://doc.crates.io/manifest.html#the-features-section>

When you do this, Cargo passes along a flag to `rustc`:

```
--cfg feature="${feature_name}"
```

The sum of these `cfg` flags will determine which ones get activated, and therefore, which code gets compiled. Let's take this code:

```
#[cfg(feature = "foo")]
mod foo {
}
```

If we compile it with `cargo build --features "foo"`, it will send the `--cfg feature="foo"` flag to `rustc`, and the output will have the `mod foo` in it. If we compile it with a regular `cargo build`, no extra flags get passed on, and so, no `foo` module will exist.

### 4.3.1 `cfg_attr`

You can also set another attribute based on a `cfg` variable with `cfg_attr`:

```
#[cfg_attr(a, b)]
```

Will be the same as `#[b]` if `a` is set by `cfg` attribute, and nothing otherwise.

### 4.3.2 `cfg!`

The `cfg!` syntax extension (section 6.1, page 241) lets you use these kinds of flags elsewhere in your code, too:

```
if cfg!(target_os = "macos") || cfg!(target_os = "ios") {
    println!("Think Different!");
}
```

These will be replaced by a `true` or `false` at compile-time, depending on the configuration settings.

## 4.4 Documentation

Documentation is an important part of any software project, and it's first-class in Rust. Let's talk about the tooling Rust gives you to document your project.

### About `rustdoc`

The Rust distribution includes a tool, `rustdoc`, that generates documentation. `rustdoc` is also used by Cargo through `cargo doc`.

Documentation can be generated in two ways: from source code, and from standalone Markdown files.

## Documenting source code

The primary way of documenting a Rust project is through annotating the source code. You can use documentation comments for this purpose:

```
/// Constructs a new `Rc<T>`.
///
/// # Examples
///
/// ```
/// use std::rc::Rc;
///
/// let five = Rc::new(5);
/// ```
pub fn new(value: T) -> Rc<T> {
    // implementation goes here
}
```

This code generates documentation that looks like this<sup>5</sup>. I’ve left the implementation out, with a regular comment in its place. That’s the first thing to notice about this annotation: it uses `///`, instead of `//`. The triple slash indicates a documentation comment.

Documentation comments are written in Markdown.

Rust keeps track of these comments, and uses them when generating documentation. This is important when documenting things like enums:

```
/// The `Option` type. See [the module level documentation](../) for more.
enum Option<T> {
    /// No value
    None,
    /// Some value `T`
    Some(T),
}
```

The above works, but this does not:

```
/// The `Option` type. See [the module level documentation](../) for more.
enum Option<T> {
    None, /// No value
    Some(T), /// Some value `T`
}
```

You’ll get an error:

```
hello.rs:4:1: 4:2 error: expected ident, found `}`
hello.rs:4 }
      ^
```

<sup>5</sup><http://doc.rust-lang.org/nightly/std/rc/struct.Rc.html#method.new>



This unfortunate error<sup>6</sup> is correct: documentation comments apply to the thing after them, and there's no thing after that last comment.

**Writing documentation comments** Anyway, let's cover each part of this comment in detail:

```
/// Constructs a new `Rc<T>`.  
# fn foo() {}
```

The first line of a documentation comment should be a short summary of its functionality. One sentence. Just the basics. High level.

```
///  
/// Other details about constructing `Rc<T>`s, maybe describing complicated  
/// semantics, maybe additional options, all kinds of stuff.  
///  
# fn foo() {}
```

Our original example had just a summary line, but if we had more things to say, we could have added more explanation in a new paragraph.

### Special sections

```
/// # Examples  
# fn foo() {}
```

Next, are special sections. These are indicated with a header, `#`. There are three kinds of headers that are commonly used. They aren't special syntax, just convention, for now.

```
/// # Panics  
# fn foo() {}
```

Unrecoverable misuses of a function (i.e. programming errors) in Rust are usually indicated by panics, which kill the whole current thread at the very least. If your function has a non-trivial contract like this, that is detected/enforced by panics, documenting it is very important.

```
/// # Failures  
# fn foo() {}
```

If your function or method returns a `Result<T, E>`, then describing the conditions under which it returns `Err(E)` is a nice thing to do. This is slightly less important than `Panics`, because failure is encoded into the type system, but it's still a good thing to do.

```
/// # Safety  
# fn foo() {}
```

---

<sup>6</sup><https://github.com/rust-lang/rust/issues/22547>

If your function is `unsafe`, you should explain which invariants the caller is responsible for upholding.

```
/// # Examples
///
/// ```
/// use std::rc::Rc;
///
/// let five = Rc::new(5);
/// ```
# fn foo() {}
```

Third, **Examples**. Include one or more examples of using your function or method, and your users will love you for it. These examples go inside of code block annotations, which we'll talk about in a moment, and can have more than one section:

```
/// # Examples
///
/// Simple `&str` patterns:
///
/// ```
/// let v: Vec<&str> = "Mary had a little lamb".split(' ').collect();
/// assert_eq!(v, vec!["Mary", "had", "a", "little", "lamb"]);
/// ```
///
/// More complex patterns with a lambda:
///
/// ```
/// let v: Vec<&str> = "abcdef2ghi".split(|c: char| c.is_numeric()).collect();
/// assert_eq!(v, vec!["abc", "def", "ghi"]);
/// ```
# fn foo() {}
```

Let's discuss the details of these code blocks.

**Code block annotations** To write some Rust code in a comment, use the triple graves:

```
/// ```
/// println!("Hello, world");
/// ```
# fn foo() {}
```

If you want something that's not Rust code, you can add an annotation:

```
/// ```c
/// printf("Hello, world\n");
/// ```
# fn foo() {}
```

This will highlight according to whatever language you're showing off. If you're just showing plain text, choose `text`.

It's important to choose the correct annotation here, because `rustdoc` uses it in an interesting way: It can be used to actually test your examples, so that they don't get out of date. If you have some C code but `rustdoc` thinks it's Rust because you left off the annotation, `rustdoc` will complain when trying to generate the documentation.

### Documentation as tests

Let's discuss our sample example documentation:

```
/// ```
/// println!("Hello, world");
/// ```
# fn foo() {}
```

You'll notice that you don't need a `fn main()` or anything here. `rustdoc` will automatically add a `main()` wrapper around your code, and in the right place. For example:

```
/// ```
/// use std::rc::Rc;
///
/// let five = Rc::new(5);
/// ```
# fn foo() {}
```

This will end up testing:

```
fn main() {
    use std::rc::Rc;
    let five = Rc::new(5);
}
```

Here's the full algorithm `rustdoc` uses to postprocess examples:

1. Any leading `#![foo]` attributes are left intact as crate attributes.
2. Some common `allow` attributes are inserted, including `unused_variables`, `unused_`  
`assignments`, `unused_mut`, `unused_attributes`, and `dead_code`. Small examples often trigger these lints.
3. If the example does not contain `extern crate`, then `extern crate <mycrate>;` is inserted.
4. Finally, if the example does not contain `fn main`, the remainder of the text is wrapped in `fn main() { your_code }`

Sometimes, this isn't enough, though. For example, all of these code samples with `///` we've been talking about? The raw text:

```
/// Some documentation.  
# fn foo() {}
```

looks different than the output:

```
/// Some documentation.  
# fn foo() {}
```

Yes, that's right: you can add lines that start with `#`, and they will be hidden from the output, but will be used when compiling your code. You can use this to your advantage. In this case, documentation comments need to apply to some kind of function, so if I want to show you just a documentation comment, I need to add a little function definition below it. At the same time, it's just there to satisfy the compiler, so hiding it makes the example more clear. You can use this technique to explain longer examples in detail, while still preserving the testability of your documentation. For example, this code:

```
let x = 5;  
let y = 6;  
println!("{}", x + y);
```

Here's an explanation, rendered:

First, we set `x` to five:

```
let x = 5;  
# let y = 6;  
# println!("{}", x + y);
```

Next, we set `y` to six:

```
# let x = 5;  
let y = 6;  
# println!("{}", x + y);
```

Finally, we print the sum of `x` and `y`:

```
# let x = 5;  
# let y = 6;  
println!("{}", x + y);
```

Here's the same explanation, in raw text:

First, we set `x` to five:

```
let x = 5;  
# let y = 6;  
# println!("{}", x + y);
```

Next, we set `y` to six:

```
# let x = 5;
let y = 6;
# println!("{}", x + y);
```

Finally, we print the sum of `x` and `y`:

```
# let x = 5;
# let y = 6;
println!("{}", x + y);
```

By repeating all parts of the example, you can ensure that your example still compiles, while only showing the parts that are relevant to that part of your explanation.

**Documenting macros** Here’s an example of documenting a macro:

```
/// Panic with a given message unless an expression evaluates to true.
///
/// # Examples
///
/// ```
/// # #[macro_use] extern crate foo;
/// # fn main() {
///   panic_unless!(1 + 1 == 2, "Math is broken." );
/// # }
/// ```
///
/// ```should_panic
/// # #[macro_use] extern crate foo;
/// # fn main() {
///   panic_unless!(true == false, "I' m broken." );
/// # }
/// ```
#[macro_export]
macro_rules! panic_unless {
    ($condition:expr, $($rest:expr),+) => ({ if ! $condition { panic!($($rest),+); } });
}
# fn main() {}
```

You’ll note three things: we need to add our own `extern crate` line, so that we can add the `#[macro_use]` attribute. Second, we’ll need to add our own `main()` as well. Finally, a judicious use of `#` to comment out those two things, so they don’t show up in the output.

**Running documentation tests** To run the tests, either

```
$ rustdoc --test path/to/my/crate/root.rs
# or
$ cargo test
```

That’s right, `cargo test` tests embedded documentation too. However, `cargo test` will not test binary crates, only library ones. This is due to the way `rustdoc` works: it links against the library to be tested, but with a binary, there’s nothing to link to.

There are a few more annotations that are useful to help `rustdoc` do the right thing when testing your code:

```
/// ```ignore
/// fn foo() {
/// ```
# fn foo() {}
```

The `ignore` directive tells Rust to ignore your code. This is almost never what you want, as it’s the most generic. Instead, consider annotating it with `text` if it’s not code, or using `#s` to get a working example that only shows the part you care about.

```
/// ```should_panic
/// assert!(false);
/// ```
# fn foo() {}
```

`should_panic` tells `rustdoc` that the code should compile correctly, but not actually pass as a test.

```
/// ```no_run
/// loop {
///     println!("Hello, world");
/// }
/// ```
# fn foo() {}
```

The `no_run` attribute will compile your code, but not run it. This is important for examples such as “Here’s how to start up a network service,” which you would want to make sure compile, but might run in an infinite loop!

**Documenting modules** Rust has another kind of doc comment, `//!`. This comment doesn’t document the next item, but the enclosing item. In other words:

```
mod foo {
    //! This is documentation for the `foo` module.
    //!
    //! # Examples

    // ...
}
```

This is where you'll see `//!` used most often: for module documentation. If you have a module in `foo.rs`, you'll often open its code and see this:

```
//! A module for using `foo`s.
//!
//! The `foo` module contains a lot of useful functionality blah blah blah
```

**Documentation comment style** Check out RFC 505<sup>7</sup> for full conventions around the style and format of documentation.

### Other documentation

All of this behavior works in non-Rust source files too. Because comments are written in Markdown, they're often `.md` files.

When you write documentation in Markdown files, you don't need to prefix the documentation with comments. For example:

```
/// # Examples
///
/// ```
/// use std::rc::Rc;
///
/// let five = Rc::new(5);
/// ```
# fn foo() {}
```

is just

```
# Examples

use std::rc::Rc;

let five = Rc::new(5);
```

when it's in a Markdown file. There is one wrinkle though: Markdown files need to have a title like this:

```
% The title

This is the example documentation.
```

This `%` line needs to be the very first line of the file.

---

<sup>7</sup><https://github.com/rust-lang/rfcs/blob/master/text/0505-api-comment-conventions.md>

**doc attributes**

At a deeper level, documentation comments are sugar for documentation attributes:

```
/// this
# fn foo() {}

#[doc="this"]
# fn bar() {}
```

are the same, as are these:

```
//! this

#![doc="/// this"]
```

You won't often see this attribute used for writing documentation, but it can be useful when changing some options, or when writing a macro.

**Re-exports** `rustdoc` will show the documentation for a public re-export in both places:

```
extern crate foo;

pub use foo::bar;
```

This will create documentation for `bar` both inside the documentation for the crate `foo`, as well as the documentation for your crate. It will use the same documentation in both places.

This behavior can be suppressed with `no_inline`:

```
extern crate foo;

#[doc(no_inline)]
pub use foo::bar;
```

**Controlling HTML** You can control a few aspects of the HTML that `rustdoc` generates through the `#![doc]` version of the attribute:

```
#![doc(html_logo_url = "http://www.rust-lang.org/logos/rust-logo-128x128-blk-v2.png",
      html_favicon_url = "http://www.rust-lang.org/favicon.ico",
      html_root_url = "http://doc.rust-lang.org/");]
```

This sets a few different options, with a logo, favicon, and a root URL.



## Generation options

rustdoc also contains a few other options on the command line, for further customization:

- `--html-in-header FILE`: includes the contents of `FILE` at the end of the `<head>...</head>` section.
- `--html-before-content FILE`: includes the contents of `FILE` directly after `<body>`, before the rendered content (including the search bar).
- `--html-after-content FILE`: includes the contents of `FILE` after all the rendered content.

## Security note

The Markdown in documentation comments is placed without processing into the final webpage. Be careful with literal HTML:

```
/// <script>alert(document.cookie)</script>
```

## 4.5 Iterators

Let's talk about loops.

Remember Rust's `for` loop? Here's an example:

```
for x in 0..10 {  
    println!("{}", x);  
}
```

Now that you know more Rust, we can talk in detail about how this works. Ranges (the `0..10`) are 'iterators'. An iterator is something that we can call the `.next()` method on repeatedly, and it gives us a sequence of things.

Like this:

```
let mut range = 0..10;  
  
loop {  
    match range.next() {  
        Some(x) => {  
            println!("{}", x);  
        },  
        None => { break }  
    }  
}
```

We make a mutable binding to the range, which is our iterator. We then `loop`, with an inner `match`. This `match` is used on the result of `range.next()`, which gives us a reference to the next

value of the iterator. `next` returns an `Option<i32>`, in this case, which will be `Some(i32)` when we have a value and `None` once we run out. If we get `Some(i32)`, we print it out, and if we get `None`, we `break` out of the loop.

This code sample is basically the same as our `for` loop version. The `for` loop is just a handy way to write this `loop/match/break` construct.

`for` loops aren't the only thing that uses iterators, however. Writing your own iterator involves implementing the `Iterator` trait. While doing that is outside of the scope of this guide, Rust provides a number of useful iterators to accomplish various tasks. Before we talk about those, we should talk about a Rust anti-pattern. And that's using ranges like this.

Yes, we just talked about how ranges are cool. But ranges are also very primitive. For example, if you needed to iterate over the contents of a vector, you may be tempted to write this:

```
let nums = vec![1, 2, 3];

for i in 0..nums.len() {
    println!("{}", nums[i]);
}
```

This is strictly worse than using an actual iterator. You can iterate over vectors directly, so write this:

```
let nums = vec![1, 2, 3];

for num in &nums {
    println!("{}", num);
}
```

There are two reasons for this. First, this more directly expresses what we mean. We iterate through the entire vector, rather than iterating through indexes, and then indexing the vector. Second, this version is more efficient: the first version will have extra bounds checking because it used indexing, `nums[i]`. But since we yield a reference to each element of the vector in turn with the iterator, there's no bounds checking in the second example. This is very common with iterators: we can ignore unnecessary bounds checks, but still know that we're safe.

There's another detail here that's not 100% clear because of how `println!` works. `num` is actually of type `&i32`. That is, it's a reference to an `i32`, not an `i32` itself. `println!` handles the dereferencing for us, so we don't see it. This code works fine too:

```
let nums = vec![1, 2, 3];

for num in &nums {
    println!("{}", *num);
}
```

Now we're explicitly dereferencing `num`. Why does `&nums` give us references? Firstly, because we explicitly asked it to with `&`. Secondly, if it gave us the data itself, we would have to be its owner, which would involve making a copy of the data and giving us the copy. With references, we're

just borrowing a reference to the data, and so it's just passing a reference, without needing to do the move.

So, now that we've established that ranges are often not what you want, let's talk about what you do want instead.

There are three broad classes of things that are relevant here: iterators, *iterator adapters*, and *consumers*. Here's some definitions:

- *iterators* give you a sequence of values.
- *iterator adapters* operate on an iterator, producing a new iterator with a different output sequence.
- *consumers* operate on an iterator, producing some final set of values.

Let's talk about consumers first, since you've already seen an iterator, ranges.

### Consumers

A *consumer* operates on an iterator, returning some kind of value or values. The most common consumer is `collect()`. This code doesn't quite compile, but it shows the intention:

```
let one_to_one_hundred = (1..101).collect();
```

As you can see, we call `collect()` on our iterator. `collect()` takes as many values as the iterator will give it, and returns a collection of the results. So why won't this compile? Rust can't determine what type of things you want to collect, and so you need to let it know. Here's the version that does compile:

```
let one_to_one_hundred = (1..101).collect::

```

If you remember, the `::<>` syntax allows us to give a type hint, and so we tell it that we want a vector of integers. You don't always need to use the whole type, though. Using a `_` will let you provide a partial hint:

```
let one_to_one_hundred = (1..101).collect::

```

This says "Collect into a `Vec<T>`, please, but infer what the `T` is for me." `_` is sometimes called a "type placeholder" for this reason.

`collect()` is the most common consumer, but there are others too. `find()` is one:

```
let greater_than_forty_two = (0..100)
    .find(|x| *x > 42);

match greater_than_forty_two {
    Some(_) => println!("We got some numbers!"),
    None => println!("No numbers found :("),
}
```

`find` takes a closure, and works on a reference to each element of an iterator. This closure returns `true` if the element is the element we're looking for, and `false` otherwise. Because we might not find a matching element, `find` returns an `Option` rather than the element itself.

Another important consumer is `fold`. Here's what it looks like:

```
let sum = (1..4).fold(0, |sum, x| sum + x);
```

`fold()` is a consumer that looks like this: `fold(base, |accumulator, element| ...)`. It takes two arguments: the first is an element called the *base*. The second is a closure that itself takes two arguments: the first is called the *accumulator*, and the second is an *element*. Upon each iteration, the closure is called, and the result is the value of the accumulator on the next iteration. On the first iteration, the base is the value of the accumulator.

Okay, that's a bit confusing. Let's examine the values of all of these things in this iterator:

base	accumulator	element	closure result
0	0	1	1
0	1	2	3
0	3	3	6

We called `fold()` with these arguments:

```
.fold(0, |sum, x| sum + x);
```

So, `0` is our base, `sum` is our accumulator, and `x` is our element. On the first iteration, we set `sum` to `0`, and `x` is the first element of `nums`, `1`. We then add `sum` and `x`, which gives us `0 + 1 = 1`. On the second iteration, that value becomes our accumulator, `sum`, and the element is the second element of the array, `2`. `1 + 2 = 3`, and so that becomes the value of the accumulator for the last iteration. On that iteration, `x` is the last element, `3`, and `3 + 3 = 6`, which is our final result for our sum. `1 + 2 + 3 = 6`, and that's the result we got.

Whew. `fold` can be a bit strange the first few times you see it, but once it clicks, you can use it all over the place. Any time you have a list of things, and you want a single result, `fold` is appropriate.

Consumers are important due to one additional property of iterators we haven't talked about yet: laziness. Let's talk some more about iterators, and you'll see why consumers matter.

## Iterators

As we've said before, an iterator is something that we can call the `.next()` method on repeatedly, and it gives us a sequence of things. Because you need to call the method, this means that iterators can be *lazy* and not generate all of the values upfront. This code, for example, does not actually generate the numbers `1-100`, instead creating a value that merely represents the sequence:

```
let nums = 1..100;
```

Since we didn't do anything with the range, it didn't generate the sequence. Let's add the consumer:

```
let nums = (1..100).collect::<Vec<i32>>();
```

Now, `collect()` will require that the range gives it some numbers, and so it will do the work of generating the sequence.

Ranges are one of two basic iterators that you'll see. The other is `iter()`. `iter()` can turn a vector into a simple iterator that gives you each element in turn:

```
let nums = vec![1, 2, 3];

for num in nums.iter() {
    println!("{}", num);
}
```

These two basic iterators should serve you well. There are some more advanced iterators, including ones that are infinite.

That's enough about iterators. Iterator adapters are the last concept we need to talk about with regards to iterators. Let's get to it!

### Iterator adapters

*Iterator adapters* take an iterator and modify it somehow, producing a new iterator. The simplest one is called `map`:

```
(1..100).map(|x| x + 1);
```

`map` is called upon another iterator, and produces a new iterator where each element reference has the closure it's been given as an argument called on it. So this would give us the numbers from 2-100. Well, almost! If you compile the example, you'll get a warning:

```
warning: unused result which must be used: iterator adapters are lazy and
do nothing unless consumed, #[warn(unused_must_use)] on by default
(1..100).map(|x| x + 1);
^~~~~~
```

Laziness strikes again! That closure will never execute. This example doesn't print any numbers:

```
(1..100).map(|x| println!("{}", x));
```

If you are trying to execute a closure on an iterator for its side effects, just use `for` instead.

There are tons of interesting iterator adapters. `take(n)` will return an iterator over the next `n` elements of the original iterator. Note that this has no side effect on the original iterator. Let's try it out with our infinite iterator from before:

```
for i in (1..).step_by(5).take(5) {  
    println!("{}", i);  
}
```

This will print

```
1  
6  
11  
16  
21
```

`filter()` is an adapter that takes a closure as an argument. This closure returns `true` or `false`. The new iterator `filter()` produces only the elements that that closure returns `true` for:

```
for i in (1..100).filter(|&x| x % 2 == 0) {  
    println!("{}", i);  
}
```

This will print all of the even numbers between one and a hundred. (Note that because `filter` doesn't consume the elements that are being iterated over, it is passed a reference to each element, and thus the filter predicate uses the `&x` pattern to extract the integer itself.)

You can chain all three things together: start with an iterator, adapt it a few times, and then consume the result. Check it out:

```
(1..1000)  
    .filter(|&x| x % 2 == 0)  
    .filter(|&x| x % 3 == 0)  
    .take(5)  
    .collect::<Vec<i32>>();
```

This will give you a vector containing 6, 12, 18, 24, and 30.

This is just a small taste of what iterators, iterator adapters, and consumers can help you with. There are a number of really useful iterators, and you can write your own as well. Iterators provide a safe, efficient way to manipulate all kinds of lists. They're a little unusual at first, but if you play with them, you'll get hooked. For a full list of the different iterators and consumers, check out the iterator module documentation<sup>8</sup>.

## 4.6 Concurrency

Concurrency and parallelism are incredibly important topics in computer science, and are also a hot topic in industry today. Computers are gaining more and more cores, yet many programmers aren't prepared to fully utilize them.

---

<sup>8</sup><http://doc.rust-lang.org/std/iter/index.html>

Rust's memory safety features also apply to its concurrency story too. Even concurrent Rust programs must be memory safe, having no data races. Rust's type system is up to the task, and gives you powerful ways to reason about concurrent code at compile time.

Before we talk about the concurrency features that come with Rust, it's important to understand something: Rust is low-level enough that all of this is provided by the standard library, not by the language. This means that if you don't like some aspect of the way Rust handles concurrency, you can implement an alternative way of doing things. `mio`<sup>9</sup> is a real-world example of this principle in action.

### Background: Send and Sync

Concurrency is difficult to reason about. In Rust, we have a strong, static type system to help us reason about our code. As such, Rust gives us two traits to help us make sense of code that can possibly be concurrent.

**Send** The first trait we're going to talk about is `Send`<sup>10</sup>. When a type `T` implements `Send`, it indicates to the compiler that something of this type is able to have ownership transferred safely between threads.

This is important to enforce certain restrictions. For example, if we have a channel connecting two threads, we would want to be able to send some data down the channel and to the other thread. Therefore, we'd ensure that `Send` was implemented for that type.

In the opposite way, if we were wrapping a library with FFI that isn't threadsafe, we wouldn't want to implement `Send`, and so the compiler will help us enforce that it can't leave the current thread.

**Sync** The second of these traits is called `Sync`<sup>11</sup>. When a type `T` implements `Sync`, it indicates to the compiler that something of this type has no possibility of introducing memory unsafety when used from multiple threads concurrently.

For example, sharing immutable data with an atomic reference count is threadsafe. Rust provides a type like this, `Arc<T>`, and it implements `Sync`, so it is safe to share between threads.

These two traits allow you to use the type system to make strong guarantees about the properties of your code under concurrency. Before we demonstrate why, we need to learn how to create a concurrent Rust program in the first place!

### Threads

Rust's standard library provides a library for threads, which allow you to run Rust code in parallel. Here's a basic example of using `std::thread`:

```
use std::thread;
```

---

<sup>9</sup><https://github.com/carllerche/mio>

<sup>10</sup><http://doc.rust-lang.org/std/marker/trait.Send.html>

<sup>11</sup><http://doc.rust-lang.org/std/marker/trait.Sync.html>

```
fn main() {
    thread::spawn(|| {
        println!("Hello from a thread!");
    });
}
```

The `thread::spawn()` method accepts a closure, which is executed in a new thread. It returns a handle to the thread, that can be used to wait for the child thread to finish and extract its result:

```
use std::thread;

fn main() {
    let handle = thread::spawn(|| {
        "Hello from a thread!"
    });

    println!("{}", handle.join().unwrap());
}
```

Many languages have the ability to execute threads, but it's wildly unsafe. There are entire books about how to prevent errors that occur from shared mutable state. Rust helps out with its type system here as well, by preventing data races at compile time. Let's talk about how you actually share things between threads.

### Safe Shared Mutable State

Due to Rust's type system, we have a concept that sounds like a lie: "safe shared mutable state." Many programmers agree that shared mutable state is very, very bad.

Someone once said this:

Shared mutable state is the root of all evil. Most languages attempt to deal with this problem through the 'mutable' part, but Rust deals with it by solving the 'shared' part.

The same ownership system (section 5.8, page 135) that helps prevent using pointers incorrectly also helps rule out data races, one of the worst kinds of concurrency bugs.

As an example, here is a Rust program that would have a data race in many languages. It will not compile:

```
use std::thread;

fn main() {
    let mut data = vec![1u32, 2, 3];

    for i in 0..3 {
```



```

        thread::spawn(move || {
            data[i] += 1;
        });
    }

    thread::sleep_ms(50);
}

```

This gives us an error:

```

8:17 error: capture of moved value: `data`
      data[i] += 1;
      ^~~~

```

In this case, we know that our code *should* be safe, but Rust isn't sure. And it's actually not safe: if we had a reference to `data` in each thread, and the thread takes ownership of the reference, we have three owners! That's bad. We can fix this by using the `Arc<T>` type, which is an atomic reference counted pointer. The 'atomic' part means that it's safe to share across threads.

`Arc<T>` assumes one more property about its contents to ensure that it is safe to share across threads: it assumes its contents are `Sync`. But in our case, we want to be able to mutate the value. We need a type that can ensure only one person at a time can mutate what's inside. For that, we can use the `Mutex<T>` type. Here's the second version of our code. It still doesn't work, but for a different reason:

```

use std::thread;
use std::sync::Mutex;

fn main() {
    let mut data = Mutex::new(vec![1u32, 2, 3]);

    for i in 0..3 {
        let data = data.lock().unwrap();
        thread::spawn(move || {
            data[i] += 1;
        });
    }

    thread::sleep_ms(50);
}

```

Here's the error:

```

<anon>:9:9: 9:22 error: the trait `core::marker::Send` is not implemented for the type `std::sync::mutex::MutexGuard<'_, collections::vec::Vec<u32>>`
<anon>:11      thread::spawn(move || {
               ^~~~~~
<anon>:9:9: 9:22 note: `std::sync::mutex::MutexGuard<'_, collections::vec::Vec<u32>>` cannot be sent between threads safely
<anon>:11      thread::spawn(move || {
               ^~~~~~

```

You see, `Mutex`<sup>12</sup> has a `lock`<sup>13</sup> method which has this signature:

```
fn lock(&self) -> LockResult<MutexGuard<T>>
```

Because `Send` is not implemented for `MutexGuard<T>`, we can't transfer the guard across thread boundaries, which gives us our error.

We can use `Arc<T>` to fix this. Here's the working version:

```
use std::sync::{Arc, Mutex};
use std::thread;

fn main() {
    let data = Arc::new(Mutex::new(vec![1u32, 2, 3]));

    for i in 0..3 {
        let data = data.clone();
        thread::spawn(move || {
            let mut data = data.lock().unwrap();
            data[i] += 1;
        });
    }

    thread::sleep_ms(50);
}
```

We now call `clone()` on our `Arc`, which increases the internal count. This handle is then moved into the new thread. Let's examine the body of the thread more closely:

```
thread::spawn(move || {
    let mut data = data.lock().unwrap();
    data[i] += 1;
});
```

First, we call `lock()`, which acquires the mutex's lock. Because this may fail, it returns an `Result<T, E>`, and because this is just an example, we `unwrap()` it to get a reference to the data. Real code would have more robust error handling here. We're then free to mutate it, since we have the lock.

Lastly, while the threads are running, we wait on a short timer. But this is not ideal: we may have picked a reasonable amount of time to wait but it's more likely we'll either be waiting longer than necessary or not long enough, depending on just how much time the threads actually take to finish computing when the program runs.

A more precise alternative to the timer would be to use one of the mechanisms provided by the Rust standard library for synchronizing threads with each other. Let's talk about one of them: channels.

<sup>12</sup><http://doc.rust-lang.org/std/sync/struct.Mutex.html>

<sup>13</sup><http://doc.rust-lang.org/std/sync/struct.Mutex.html#method.lock>

## Channels

Here's a version of our code that uses channels for synchronization, rather than waiting for a specific time:

```
use std::sync::{Arc, Mutex};
use std::thread;
use std::sync::mpsc;

fn main() {
    let data = Arc::new(Mutex::new(0u32));

    let (tx, rx) = mpsc::channel();

    for _ in 0..10 {
        let (data, tx) = (data.clone(), tx.clone());

        thread::spawn(move || {
            let mut data = data.lock().unwrap();
            *data += 1;

            tx.send(());
        });
    }

    for _ in 0..10 {
        rx.recv();
    }
}
```

We use the `mpsc::channel()` method to construct a new channel. We just `send` a simple `()` down the channel, and then wait for ten of them to come back.

While this channel is just sending a generic signal, we can send any data that is `Send` over the channel!

```
use std::thread;
use std::sync::mpsc;

fn main() {
    let (tx, rx) = mpsc::channel();

    for _ in 0..10 {
        let tx = tx.clone();

        thread::spawn(move || {
            let answer = 42u32;

            tx.send(answer);
        });
    }
}
```

```

    });
}

rx.recv().ok().expect("Could not receive answer");
}

```

A `u32` is `Send` because we can make a copy. So we create a thread, ask it to calculate the answer, and then it `send()`s us the answer over the channel.

## Panics

A `panic!` will crash the currently executing thread. You can use Rust’s threads as a simple isolation mechanism:

```

use std::thread;

let result = thread::spawn(move || {
    panic!("oops!");
}).join();

assert!(result.is_err());

```

Our `Thread` gives us a `Result` back, which allows us to check if the thread has panicked or not.

## 4.7 Error Handling

The best-laid plans of mice and men  
Often go awry  
“Tae a Moose”, Robert Burns

Sometimes, things just go wrong. It’s important to have a plan for when the inevitable happens. Rust has rich support for handling errors that may (let’s be honest: will) occur in your programs.

There are two main kinds of errors that can occur in your programs: failures, and panics. Let’s talk about the difference between the two, and then discuss how to handle each. Then, we’ll discuss upgrading failures to panics.

### 4.7.1 Failure vs. Panic

Rust uses two terms to differentiate between two forms of error: failure, and panic. A *failure* is an error that can be recovered from in some way. A *panic* is an error that cannot be recovered from.

What do we mean by “recover”? Well, in most cases, the possibility of an error is expected. For example, consider the `parse` function:

```
"5".parse();
```

This method converts a string into another type. But because it's a string, you can't be sure that the conversion actually works. For example, what should this convert to?

```
"hello5world".parse();
```

This won't work. So we know that this function will only work properly for some inputs. It's expected behavior. We call this kind of error a *failure*.

On the other hand, sometimes, there are errors that are unexpected, or which we cannot recover from. A classic example is an `assert!`:

```
assert!(x == 5);
```

We use `assert!` to declare that something is true. If it's not true, something is very wrong. Wrong enough that we can't continue with things in the current state. Another example is using the `unreachable!()` macro:

```
enum Event {
    NewRelease,
}

fn probability(_: &Event) -> f64 {
    // real implementation would be more complex, of course
    0.95
}

fn descriptive_probability(event: Event) -> &'static str {
    match probability(&event) {
        1.00 => "certain",
        0.00 => "impossible",
        0.00 ... 0.25 => "very unlikely",
        0.25 ... 0.50 => "unlikely",
        0.50 ... 0.75 => "likely",
        0.75 ... 1.00 => "very likely",
    }
}

fn main() {
    std::io::println(descriptive_probability(NewRelease));
}
```

This will give us an error:

```
error: non-exhaustive patterns: `_` not covered [E0004]
```

While we know that we've covered all possible cases, Rust can't tell. It doesn't know that probability is between 0.0 and 1.0. So we add another case:

```
use Event::NewRelease;

enum Event {
    NewRelease,
}

fn probability(_: &Event) -> f64 {
    // real implementation would be more complex, of course
    0.95
}

fn descriptive_probability(event: Event) -> &'static str {
    match probability(&event) {
        1.00 => "certain",
        0.00 => "impossible",
        0.00 ... 0.25 => "very unlikely",
        0.25 ... 0.50 => "unlikely",
        0.50 ... 0.75 => "likely",
        0.75 ... 1.00 => "very likely",
        _ => unreachable!()
    }
}

fn main() {
    println!("{}", descriptive_probability(NewRelease));
}
```

We shouldn't ever hit the `_` case, so we use the `unreachable!()` macro to indicate this. `unreachable!()` gives a different kind of error than `Result`. Rust calls these sorts of errors *panics*.

### 4.7.2 Handling errors with `Option` and `Result`

The simplest way to indicate that a function may fail is to use the `Option<T>` type. For example, the `find` method on strings attempts to find a pattern in a string, and returns an `Option`:

```
let s = "foo";

assert_eq!(s.find('f'), Some(0));
assert_eq!(s.find('z'), None);
```

This is appropriate for the simplest of cases, but doesn't give us a lot of information in the failure case. What if we wanted to know *why* the function failed? For this, we can use the `Result<T, E>` type. It looks like this:

```
enum Result<T, E> {  
    Ok(T),  
    Err(E)  
}
```

This enum is provided by Rust itself, so you don't need to define it to use it in your code. The `Ok(T)` variant represents a success, and the `Err(E)` variant represents a failure. Returning a `Result` instead of an `Option` is recommended for all but the most trivial of situations.

Here's an example of using `Result`:

```
#[derive(Debug)]  
enum Version { Version1, Version2 }  
  
#[derive(Debug)]  
enum ParseError { InvalidHeaderLength, InvalidVersion }  
  
fn parse_version(header: &[u8]) -> Result<Version, ParseError> {  
    if header.len() < 1 {  
        return Err(ParseError::InvalidHeaderLength);  
    }  
    match header[0] {  
        1 => Ok(Version::Version1),  
        2 => Ok(Version::Version2),  
        _ => Err(ParseError::InvalidVersion)  
    }  
}  
  
let version = parse_version(&[1, 2, 3, 4]);  
match version {  
    Ok(v) => {  
        println!("working with version: {:?}", v);  
    }  
    Err(e) => {  
        println!("error parsing header: {:?}", e);  
    }  
}
```

This function makes use of an enum, `ParseError`, to enumerate the various errors that can occur.

The `Debug`<sup>14</sup> trait is what lets us print the enum value using the `{:?}` format operation.

### 4.7.3 Non-recoverable errors with `panic!`

In the case of an error that is unexpected and not recoverable, the `panic!` macro will induce a panic. This will crash the current thread, and give an error:

---

<sup>14</sup><http://doc.rust-lang.org/std/fmt/trait.Debug.html>

```
panic!("boom");
```

gives

```
thread '<main>' panicked at 'boom', hello.rs:2
```

when you run it.

Because these kinds of situations are relatively rare, use panics sparingly.

#### 4.7.4 Upgrading failures to panics

In certain circumstances, even though a function may fail, we may want to treat it as a panic instead. For example, `io::stdin().read_line(&mut buffer)` returns a `Result<usize>`, when there is an error reading the line. This allows us to handle and possibly recover from error.

If we don't want to handle this error, and would rather just abort the program, we can use the `unwrap()` method:

```
io::stdin().read_line(&mut buffer).unwrap();
```

`unwrap()` will panic! if the `Result` is `Err`. This basically says “Give me the value, and if something goes wrong, just crash.” This is less reliable than matching the error and attempting to recover, but is also significantly shorter. Sometimes, just crashing is appropriate.

There's another way of doing this that's a bit nicer than `unwrap()`:

```
let mut buffer = String::new();
let input = io::stdin().read_line(&mut buffer)
    .ok()
    .expect("Failed to read line");
```

`ok()` converts the `Result` into an `Option`, and `expect()` does the same thing as `unwrap()`, but takes a message. This message is passed along to the underlying panic!, providing a better error message if the code errors.

#### 4.7.5 Using try!

When writing code that calls many functions that return the `Result` type, the error handling can be tedious. The `try!` macro hides some of the boilerplate of propagating errors up the call stack.

It replaces this:

```
use std::fs::File;
use std::io;
use std::io::prelude::*;
```



```

struct Info {
    name: String,
    age: i32,
    rating: i32,
}

fn write_info(info: &Info) -> io::Result<()> {
    let mut file = File::create("my_best_friends.txt").unwrap();

    if let Err(e) = writeln!(&mut file, "name: {}", info.name) {
        return Err(e)
    }
    if let Err(e) = writeln!(&mut file, "age: {}", info.age) {
        return Err(e)
    }
    if let Err(e) = writeln!(&mut file, "rating: {}", info.rating) {
        return Err(e)
    }

    return Ok();
}

```

With this:

```

use std::fs::File;
use std::io;
use std::io::prelude::*;

struct Info {
    name: String,
    age: i32,
    rating: i32,
}

fn write_info(info: &Info) -> io::Result<()> {
    let mut file = try!(File::create("my_best_friends.txt"));

    try!(writeln!(&mut file, "name: {}", info.name));
    try!(writeln!(&mut file, "age: {}", info.age));
    try!(writeln!(&mut file, "rating: {}", info.rating));

    return Ok();
}

```

Wrapping an expression in `try!` will result in the unwrapped success (`Ok`) value, unless the result is `Err`, in which case `Err` is returned early from the enclosing function.

It's worth noting that you can only use `try!` from a function that returns a `Result`, which means that you cannot use `try!` inside of `main()`, because `main()` doesn't return anything.

`try!` makes use of `From<Error>`<sup>15</sup> to determine what to return in the error case.

## 4.8 FFI

### 4.8.1 Introduction

This guide will use the `snappy`<sup>16</sup> compression/decompression library as an introduction to writing bindings for foreign code. Rust is currently unable to call directly into a C++ library, but `snappy` includes a C interface (documented in `snappy-c.h`<sup>17</sup>).

The following is a minimal example of calling a foreign function which will compile if `snappy` is installed:

```
# #[feature(libc)]
extern crate libc;
use libc::size_t;

#[link(name = "snappy")]
extern {
    fn snappy_max_compressed_length(source_length: size_t) -> size_t;
}

fn main() {
    let x = unsafe { snappy_max_compressed_length(100) };
    println!("max compressed length of a 100 byte buffer: {}", x);
}
```

The `extern` block is a list of function signatures in a foreign library, in this case with the platform's C ABI. The `#[link(...)]` attribute is used to instruct the linker to link against the `snappy` library so the symbols are resolved.

Foreign functions are assumed to be unsafe so calls to them need to be wrapped with `unsafe {}` as a promise to the compiler that everything contained within truly is safe. C libraries often expose interfaces that aren't thread-safe, and almost any function that takes a pointer argument isn't valid for all possible inputs since the pointer could be dangling, and raw pointers fall outside of Rust's safe memory model.

When declaring the argument types to a foreign function, the Rust compiler can not check if the declaration is correct, so specifying it correctly is part of keeping the binding correct at runtime.

The `extern` block can be extended to cover the entire `snappy` API:

```
# #[feature(libc)]
extern crate libc;
use libc::{c_int, size_t};
```

<sup>15</sup><http://doc.rust-lang.org/std/convert/trait.From.html>

<sup>16</sup><https://github.com/google/snappy>

<sup>17</sup><https://github.com/google/snappy/blob/master/snappy-c.h>

```
#[link(name = "snappy")]
extern {
    fn snappy_compress(input: *const u8,
                       input_length: size_t,
                       compressed: *mut u8,
                       compressed_length: *mut size_t) -> c_int;
    fn snappy_uncompress(compressed: *const u8,
                        compressed_length: size_t,
                        uncompressed: *mut u8,
                        uncompressed_length: *mut size_t) -> c_int;
    fn snappy_max_compressed_length(source_length: size_t) -> size_t;
    fn snappy_uncompressed_length(compressed: *const u8,
                                compressed_length: size_t,
                                result: *mut size_t) -> c_int;
    fn snappy_validate_compressed_buffer(compressed: *const u8,
                                       compressed_length: size_t) -> c_int;
}
# fn main() {}
```

### 4.8.2 Creating a safe interface

The raw C API needs to be wrapped to provide memory safety and make use of higher-level concepts like vectors. A library can choose to expose only the safe, high-level interface and hide the unsafe internal details.

Wrapping the functions which expect buffers involves using the `slice::raw` module to manipulate Rust vectors as pointers to memory. Rust's vectors are guaranteed to be a contiguous block of memory. The length is number of elements currently contained, and the capacity is the total size in elements of the allocated memory. The length is less than or equal to the capacity.

```
# #![feature(libc)]
# extern crate libc;
# use libc::{c_int, size_t};
# unsafe fn snappy_validate_compressed_buffer(_: *const u8, _: size_t) -> c_int { 0 }
# fn main() {}
pub fn validate_compressed_buffer(src: &[u8]) -> bool {
    unsafe {
        snappy_validate_compressed_buffer(src.as_ptr(), src.len() as size_t) == 0
    }
}
```

The `validate_compressed_buffer` wrapper above makes use of an `unsafe` block, but it makes the guarantee that calling it is safe for all inputs by leaving off `unsafe` from the function signature.

The `snappy_compress` and `snappy_uncompress` functions are more complex, since a buffer has to be allocated to hold the output too.

The `snappy_max_compressed_length` function can be used to allocate a vector with the maximum required capacity to hold the compressed output. The vector can then be passed to the `snappy_compress` function as an output parameter. An output parameter is also passed to retrieve the true length after compression for setting the length.

```
# #![feature(libc)]
# extern crate libc;
# use libc::{size_t, c_int};
# unsafe fn snappy_compress(a: *const u8, b: size_t, c: *mut u8,
#                             d: *mut size_t) -> c_int { 0 }
# unsafe fn snappy_max_compressed_length(a: size_t) -> size_t { a }
# fn main() {}
pub fn compress(src: &[u8]) -> Vec<u8> {
    unsafe {
        let srclen = src.len() as size_t;
        let psrc = src.as_ptr();

        let mut dstlen = snappy_max_compressed_length(srclen);
        let mut dst = Vec::with_capacity(dstlen as usize);
        let pdst = dst.as_mut_ptr();

        snappy_compress(psrc, srclen, pdst, &mut dstlen);
        dst.set_len(dstlen as usize);
        dst
    }
}
```

Decompression is similar, because snappy stores the uncompressed size as part of the compression format and `snappy_uncompressed_length` will retrieve the exact buffer size required.

```
# #![feature(libc)]
# extern crate libc;
# use libc::{size_t, c_int};
# unsafe fn snappy_uncompress(compressed: *const u8,
#                             compressed_length: size_t,
#                             uncompressed: *mut u8,
#                             uncompressed_length: *mut size_t) -> c_int { 0 }
# unsafe fn snappy_uncompressed_length(compressed: *const u8,
#                                       compressed_length: size_t,
#                                       result: *mut size_t) -> c_int { 0 }
# fn main() {}
pub fn uncompress(src: &[u8]) -> Option<Vec<u8>> {
    unsafe {
        let srclen = src.len() as size_t;
        let psrc = src.as_ptr();

        let mut dstlen: size_t = 0;
        snappy_uncompressed_length(psrc, srclen, &mut dstlen);
    }
}
```

```

    let mut dst = Vec::with_capacity(dstlen as usize);
    let pdst = dst.as_mut_ptr();

    if snappy_uncompress(psrc, srclen, pdst, &mut dstlen) == 0 {
        dst.set_len(dstlen as usize);
        Some(dst)
    } else {
        None // SNAPPY_INVALID_INPUT
    }
}
}

```

For reference, the examples used here are also available as a library on GitHub<sup>18</sup>.

### 4.8.3 Destructors

Foreign libraries often hand off ownership of resources to the calling code. When this occurs, we must use Rust's destructors to provide safety and guarantee the release of these resources (especially in the case of panic).

For more about destructors, see the Drop trait<sup>19</sup>.

### 4.8.4 Callbacks from C code to Rust functions

Some external libraries require the usage of callbacks to report back their current state or intermediate data to the caller. It is possible to pass functions defined in Rust to an external library. The requirement for this is that the callback function is marked as `extern` with the correct calling convention to make it callable from C code.

The callback function can then be sent through a registration call to the C library and afterwards be invoked from there.

A basic example is:

Rust code:

```

extern fn callback(a: i32) {
    println!("I'm called from C with value {0}", a);
}

#[link(name = "extlib")]
extern {
    fn register_callback(cb: extern fn(i32)) -> i32;
    fn trigger_callback();
}

fn main() {

```

---

<sup>18</sup><https://github.com/thestinger/rust-snappy>

<sup>19</sup><http://doc.rust-lang.org/std/ops/trait.Drop.html>

```

    unsafe {
        register_callback(callback);
        trigger_callback(); // Triggers the callback
    }
}

```

C code:

```

typedef void (*rust_callback)(int32_t);
rust_callback cb;

int32_t register_callback(rust_callback callback) {
    cb = callback;
    return 1;
}

void trigger_callback() {
    cb(7); // Will call callback(7) in Rust
}

```

In this example Rust's `main()` will call `trigger_callback()` in C, which would, in turn, call back to `callback()` in Rust.

### Targeting callbacks to Rust objects

The former example showed how a global function can be called from C code. However it is often desired that the callback is targeted to a special Rust object. This could be the object that represents the wrapper for the respective C object.

This can be achieved by passing an unsafe pointer to the object down to the C library. The C library can then include the pointer to the Rust object in the notification. This will allow the callback to unsafely access the referenced Rust object.

Rust code:

```

#[repr(C)]
struct RustObject {
    a: i32,
    // other members
}

extern "C" fn callback(target: *mut RustObject, a: i32) {
    println!("I'm called from C with value {0}", a);
    unsafe {
        // Update the value in RustObject with the value received from the callback
        (*target).a = a;
    }
}

```

```

#[link(name = "extlib")]
extern {
    fn register_callback(target: *mut RustObject,
                        cb: extern fn(*mut RustObject, i32)) -> i32;
    fn trigger_callback();
}

fn main() {
    // Create the object that will be referenced in the callback
    let mut rust_object = Box::new(RustObject { a: 5 });

    unsafe {
        register_callback(&mut *rust_object, callback);
        trigger_callback();
    }
}

```

C code:

```

typedef void (*rust_callback)(void*, int32_t);
void* cb_target;
rust_callback cb;

int32_t register_callback(void* callback_target, rust_callback callback) {
    cb_target = callback_target;
    cb = callback;
    return 1;
}

void trigger_callback() {
    cb(cb_target, 7); // Will call callback(&rustObject, 7) in Rust
}

```

### Asynchronous callbacks

In the previously given examples the callbacks are invoked as a direct reaction to a function call to the external C library. The control over the current thread is switched from Rust to C to Rust for the execution of the callback, but in the end the callback is executed on the same thread that called the function which triggered the callback.

Things get more complicated when the external library spawns its own threads and invokes callbacks from there. In these cases access to Rust data structures inside the callbacks is especially unsafe and proper synchronization mechanisms must be used. Besides classical synchronization mechanisms like mutexes, one possibility in Rust is to use channels (in `std::comm`) to forward data from the C thread that invoked the callback into a Rust thread.

If an asynchronous callback targets a special object in the Rust address space it is also absolutely necessary that no more callbacks are performed by the C library after the respective Rust object

gets destroyed. This can be achieved by unregistering the callback in the object's destructor and designing the library in a way that guarantees that no callback will be performed after deregistration.

### 4.8.5 Linking

The `link` attribute on `extern` blocks provides the basic building block for instructing rustc how it will link to native libraries. There are two accepted forms of the `link` attribute today:

- `#[link(name = "foo")]`
- `#[link(name = "foo", kind = "bar")]`

In both of these cases, `foo` is the name of the native library that we're linking to, and in the second case `bar` is the type of native library that the compiler is linking to. There are currently three known types of native libraries:

- Dynamic - `#[link(name = "readline")]`
- Static - `#[link(name = "my_build_dependency", kind = "static")]`
- Frameworks - `#[link(name = "CoreFoundation", kind = "framework")]`

Note that frameworks are only available on OSX targets.

The different `kind` values are meant to differentiate how the native library participates in linkage. From a linkage perspective, the rust compiler creates two flavors of artifacts: partial (rlib/staticlib) and final (dylib/binary). Native dynamic libraries and frameworks are propagated to the final artifact boundary, while static libraries are not propagated at all.

A few examples of how this model can be used are:

- A native build dependency. Sometimes some C/C++ glue is needed when writing some rust code, but distribution of the C/C++ code in a library format is just a burden. In this case, the code will be archived into `libfoo.a` and then the rust crate would declare a dependency via `#[link(name = "foo", kind = "static")]`.

Regardless of the flavor of output for the crate, the native static library will be included in the output, meaning that distribution of the native static library is not necessary.

- A normal dynamic dependency. Common system libraries (like `readline`) are available on a large number of systems, and often a static copy of these libraries cannot be found. When this dependency is included in a rust crate, partial targets (like rlibs) will not link to the library, but when the rlib is included in a final target (like a binary), the native library will be linked in.

On OSX, frameworks behave with the same semantics as a dynamic library.



### 4.8.6 Unsafe blocks

Some operations, like dereferencing unsafe pointers or calling functions that have been marked unsafe are only allowed inside unsafe blocks. Unsafe blocks isolate unsafety and are a promise to the compiler that the unsafety does not leak out of the block.

Unsafe functions, on the other hand, advertise it to the world. An unsafe function is written like this:

```
unsafe fn kaboom(ptr: *const i32) -> i32 { *ptr }
```

This function can only be called from an `unsafe` block or another `unsafe` function.

### 4.8.7 Accessing foreign globals

Foreign APIs often export a global variable which could do something like track global state. In order to access these variables, you declare them in `extern` blocks with the `static` keyword:

```
# #[feature(libc)]
extern crate libc;

#[link(name = "readline")]
extern {
    static rl_readline_version: libc::c_int;
}

fn main() {
    println!("You have readline version {} installed.",
            rl_readline_version as i32);
}
```

Alternatively, you may need to alter global state provided by a foreign interface. To do this, statics can be declared with `mut` so we can mutate them.

```
# #[feature(libc)]
extern crate libc;

use std::ffi::CString;
use std::ptr;

#[link(name = "readline")]
extern {
    static mut rl_prompt: *const libc::c_char;
}

fn main() {
    let prompt = CString::new("[my-awesome-shell] $").unwrap();
```

```

    unsafe {
        rl_prompt = prompt.as_ptr();

        println!("{:?}", rl_prompt);

        rl_prompt = ptr::null();
    }
}

```

Note that all interaction with a `static mut` is unsafe, both reading and writing. Dealing with global mutable state requires a great deal of care.

### 4.8.8 Foreign calling conventions

Most foreign code exposes a C ABI, and Rust uses the platform's C calling convention by default when calling foreign functions. Some foreign functions, most notably the Windows API, use other calling conventions. Rust provides a way to tell the compiler which convention to use:

```

# #[feature(libc)]
extern crate libc;

#[cfg(all(target_os = "win32", target_arch = "x86"))]
#[link(name = "kernel32")]
#[allow(non_snake_case)]
extern "stdcall" {
    fn SetEnvironmentVariableA(n: *const u8, v: *const u8) -> libc::c_int;
}
# fn main() { }

```

This applies to the entire `extern` block. The list of supported ABI constraints are:

- `stdcall`
- `aapcs`
- `cdecl`
- `fastcall`
- `Rust`
- `rust-intrinsic`
- `system`
- `C`
- `win64`

Most of the abis in this list are self-explanatory, but the `system` abi may seem a little odd. This constraint selects whatever the appropriate ABI is for interoperating with the target's libraries. For example, on `win32` with a `x86` architecture, this means that the abi used would be `stdcall`. On `x86_64`, however, windows uses the C calling convention, so `C` would be used. This means that in our previous example, we could have used `extern "system" { ... }` to define a block for all windows systems, not just `x86` ones.

### 4.8.9 Interoperability with foreign code

Rust guarantees that the layout of a `struct` is compatible with the platform’s representation in C only if the `#[repr(C)]` attribute is applied to it. `#[repr(C, packed)]` can be used to lay out struct members without padding. `#[repr(C)]` can also be applied to an enum.

Rust’s owned boxes (`Box<T>`) use non-nullable pointers as handles which point to the contained object. However, they should not be manually created because they are managed by internal allocators. References can safely be assumed to be non-nullable pointers directly to the type. However, breaking the borrow checking or mutability rules is not guaranteed to be safe, so prefer using raw pointers (\*) if that’s needed because the compiler can’t make as many assumptions about them.

Vectors and strings share the same basic memory layout, and utilities are available in the `vec` and `str` modules for working with C APIs. However, strings are not terminated with `\0`. If you need a NUL-terminated string for interoperability with C, you should use the `CString` type in the `std::ffi` module.

The standard library includes type aliases and function definitions for the C standard library in the `libc` module, and Rust links against `libc` and `libm` by default.

#### 4.8.10 The “nullable pointer optimization”

Certain types are defined to not be `null`. This includes references (`&T`, `&mut T`), boxes (`Box<T>`), and function pointers (`extern "abi" fn()`). When interfacing with C, pointers that might be `null` are often used. As a special case, a generic enum that contains exactly two variants, one of which contains no data and the other containing a single field, is eligible for the “nullable pointer optimization”. When such an enum is instantiated with one of the non-nullable types, it is represented as a single pointer, and the non-data variant is represented as the `null` pointer. So `Option<extern "C" fn(c_int) -> c_int>` is how one represents a nullable function pointer using the C ABI.

#### 4.8.11 Calling Rust code from C

You may wish to compile Rust code in a way so that it can be called from C. This is fairly easy, but requires a few things:

```
#[no_mangle]
pub extern fn hello_rust() -> *const u8 {
    "Hello, world!\0".as_ptr()
}
# fn main() {}
```

The `extern` makes this function adhere to the C calling convention, as discussed above in “Foreign Calling Conventions”<sup>20</sup>. The `no_mangle` attribute turns off Rust’s name mangling, so that it is easier to link to.

---

<sup>20</sup>[ffi.html#foreign-calling-conventions](http://ffi.html#foreign-calling-conventions)

## 4.9 Borrow and AsRef

The `Borrow`<sup>21</sup> and `AsRef`<sup>22</sup> traits are very similar, but different. Here's a quick refresher on what these two traits mean.

### 4.9.1 Borrow

The `Borrow` trait is used when you're writing a datastructure, and you want to use either an owned or borrowed type as synonymous for some purpose.

For example, `HashMap`<sup>23</sup> has a `get` method<sup>24</sup> which uses `Borrow`:

```
fn get<Q: ?Sized>(&self, k: &Q) -> Option<&V>
    where K: Borrow<Q>,
           Q: Hash + Eq
```

This signature is pretty complicated. The `K` parameter is what we're interested in here. It refers to a parameter of the `HashMap` itself:

```
struct HashMap<K, V, S = RandomState> {
```

The `K` parameter is the type of *key* the `HashMap` uses. So, looking at the signature of `get()` again, we can use `get()` when the key implements `Borrow<Q>`. That way, we can make a `HashMap` which uses `String` keys, but use `&str`s when we're searching:

```
use std::collections::HashMap;

let mut map = HashMap::new();
map.insert("Foo".to_string(), 42);

assert_eq!(map.get("Foo"), Some(&42));
```

This is because the standard library has `impl Borrow<str> for String`.

For most types, when you want to take an owned or borrowed type, a `&T` is enough. But one area where `Borrow` is effective is when there's more than one kind of borrowed value. Slices are an area where this is especially true: you can have both an `&[T]` or a `&mut [T]`. If we wanted to accept both of these types, `Borrow` is up for it:

```
use std::borrow::Borrow;
use std::fmt::Display;

fn foo<T: Borrow<i32> + Display>(a: T) {
    println!("a is borrowed: {}", a);
```

<sup>21</sup><http://doc.rust-lang.org/std/borrow/trait.Borrow.html>

<sup>22</sup><http://doc.rust-lang.org/std/convert/trait.AsRef.html>

<sup>23</sup><http://doc.rust-lang.org/std/collections/struct.HashMap.html>

<sup>24</sup><http://doc.rust-lang.org/std/collections/struct.HashMap.html#method.get>

```
}

let mut i = 5;

foo(&i);
foo(&mut i);
```

This will print out `a is borrowed: 5` twice.

### 4.9.2 AsRef

The `AsRef` trait is a conversion trait. It's used for converting some value to a reference in generic code. Like this:

```
let s = "Hello".to_string();

fn foo<T: AsRef<str>>(s: T) {
    let slice = s.as_ref();
}
```

### 4.9.3 Which should I use?

We can see how they're kind of the same: they both deal with owned and borrowed versions of some type. However, they're a bit different.

Choose `Borrow` when you want to abstract over different kinds of borrowing, or when you're building a datastructure that treats owned and borrowed values in equivalent ways, such as hashing and comparison.

Choose `AsRef` when you want to convert something to a reference directly, and you're writing generic code.

## 4.10 Release Channels

The Rust project uses a concept called 'release channels' to manage releases. It's important to understand this process to choose which version of Rust your project should use.

### 4.10.1 Overview

There are three channels for Rust releases:

- Nightly
- Beta
- Stable

New nightly releases are created once a day. Every six weeks, the latest nightly release is promoted to ‘Beta’. At that point, it will only receive patches to fix serious errors. Six weeks later, the beta is promoted to ‘Stable’, and becomes the next release of `1.x`.

This process happens in parallel. So every six weeks, on the same day, nightly goes to beta, beta goes to stable. When `1.x` is released, at the same time, `1.(x + 1)-beta` is released, and the nightly becomes the first version of `1.(x + 2)-nightly`.

### 4.10.2 Choosing a version

Generally speaking, unless you have a specific reason, you should be using the stable release channel. These releases are intended for a general audience.

However, depending on your interest in Rust, you may choose to use nightly instead. The basic tradeoff is this: in the nightly channel, you can use unstable, new Rust features. However, unstable features are subject to change, and so any new nightly release may break your code. If you use the stable release, you cannot use experimental features, but the next release of Rust will not cause significant issues through breaking changes.

### 4.10.3 Helping the ecosystem through CI

What about beta? We encourage all Rust users who use the stable release channel to also test against the beta channel in their continuous integration systems. This will help alert the team in case there’s an accidental regression.

Additionally, testing against nightly can catch regressions even sooner, and so if you don’t mind a third build, we’d appreciate testing against all channels.

# 5

## Syntax and Semantics

This section breaks Rust down into small chunks, one for each concept.

If you'd like to learn Rust from the bottom up, reading this in order is a great way to do that.

These sections also form a reference for each concept, so if you're reading another tutorial and find something confusing, you can find it explained somewhere in here.

### 5.1 Variable Bindings

Virtually every non-‘Hello World’ Rust program uses *variable bindings*. They look like this:

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

Putting `fn main() {` in each example is a bit tedious, so we'll leave that out in the future. If you're following along, make sure to edit your `main()` function, rather than leaving it off. Otherwise, you'll get an error.

In many languages, this is called a *variable*, but Rust's variable bindings have a few tricks up their sleeves. For example the left-hand side of a `let` expression is a ‘pattern (section 5.15, page 159)’, not just a variable name. This means we can do things like:

```
let (x, y) = (1, 2);
```

After this expression is evaluated, `x` will be one, and `y` will be two. Patterns are really powerful, and have their own section (section 5.15, page 159) in the book. We don't need those features for now, so we'll just keep this in the back of our minds as we go forward.

Rust is a statically typed language, which means that we specify our types up front, and they're checked at compile time. So why does our first example compile? Well, Rust has this thing called

‘type inference’. If it can figure out what the type of something is, Rust doesn’t require you to actually type it out.

We can add the type if we want to, though. Types come after a colon (:):

```
let x: i32 = 5;
```

If I asked you to read this out loud to the rest of the class, you’d say “x is a binding with the type i32 and the value five.”

In this case we chose to represent x as a 32-bit signed integer. Rust has many different primitive integer types. They begin with i for signed integers and u for unsigned integers. The possible integer sizes are 8, 16, 32, and 64 bits.

In future examples, we may annotate the type in a comment. The examples will look like this:

```
fn main() {
    let x = 5; // x: i32
}
```

Note the similarities between this annotation and the syntax you use with `let`. Including these kinds of comments is not idiomatic Rust, but we’ll occasionally include them to help you understand what the types that Rust infers are.

By default, bindings are *immutable*. This code will not compile:

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

It will give you this error:

```
error: re-assignment of immutable variable `x`
    x = 10;
    ^~~~~~
```

If you want a binding to be mutable, you can use `mut`:

```
let mut x = 5; // mut x: i32
x = 10;
```

There is no single reason that bindings are immutable by default, but we can think about it through one of Rust’s primary focuses: safety. If you forget to say `mut`, the compiler will catch it, and let you know that you have mutated something you may not have intended to mutate. If bindings were mutable by default, the compiler would not be able to tell you this. If you *did* intend mutation, then the solution is quite easy: add `mut`.

There are other good reasons to avoid mutable state when possible, but they’re out of the scope of this guide. In general, you can often avoid explicit mutation, and so it is preferable in Rust. That said, sometimes, mutation is what you need, so it’s not verboten.



Let's get back to bindings. Rust variable bindings have one more aspect that differs from other languages: bindings are required to be initialized with a value before you're allowed to use them.

Let's try it out. Change your `src/main.rs` file to look like this:

```
fn main() {
    let x: i32;

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

You can use `cargo build` on the command line to build it. You'll get a warning, but it will still print "Hello, world!":

```
Compiling hello_world v0.0.1 (file:///home/you/projects/hello_world)
src/main.rs:2:9: 2:10 warning: unused variable: `x`, #[warn(unused_variable)]
on by default
src/main.rs:2      let x: i32;
                   ^
```

Rust warns us that we never use the variable binding, but since we never use it, no harm, no foul. Things change if we try to actually use this `x`, however. Let's do that. Change your program to look like this:

```
fn main() {
    let x: i32;

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

And try to build it. You'll get an error:

```
$ cargo build
Compiling hello_world v0.0.1 (file:///home/you/projects/hello_world)
src/main.rs:4:39: 4:40 error: use of possibly uninitialized variable: `x`
src/main.rs:4      println!("The value of x is: {}", x);
                   ^

note: in expansion of format_args!
<std macros>:2:23: 2:77 note: expansion site
<std macros>:1:1: 3:2 note: in expansion of println!
src/main.rs:4:5: 4:42 note: expansion site
error: aborting due to previous error
Could not compile `hello_world`.
```

Rust will not let us use a value that has not been initialized. Next, let's talk about this stuff we've added to `println!`.

If you include two curly braces (`{}`, some call them moustaches...) in your string to print, Rust will interpret this as a request to interpolate some sort of value. *String interpolation* is a computer

science term that means “stick in the middle of a string.” We add a comma, and then `x`, to indicate that we want `x` to be the value we’re interpolating. The comma is used to separate arguments we pass to functions and macros, if you’re passing more than one.

When you just use the curly braces, Rust will attempt to display the value in a meaningful way by checking out its type. If you want to specify the format in a more detailed manner, there are a wide number of options available<sup>1</sup>. For now, we’ll just stick to the default: integers aren’t very complicated to print.

## 5.2 Functions

Every Rust program has at least one function, the `main` function:

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

This is the simplest possible function declaration. As we mentioned before, `fn` says ‘this is a function’, followed by the name, some parentheses because this function takes no arguments, and then some curly braces to indicate the body. Here’s a function named `foo`:

```
fn foo() {  
}
```

So, what about taking arguments? Here’s a function that prints a number:

```
fn print_number(x: i32) {  
    println!("x is: {}", x);  
}
```

Here’s a complete program that uses `print_number`:

```
fn main() {  
    print_number(5);  
}  
  
fn print_number(x: i32) {  
    println!("x is: {}", x);  
}
```

As you can see, function arguments work very similar to `let` declarations: you add a type to the argument name, after a colon.

Here’s a complete program that adds two numbers together and prints them:

---

<sup>1</sup><http://doc.rust-lang.org/std/fmt/index.html>

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

fn print_sum(x: i32, y: i32) {
    println!("sum is: {}", x + y);
}
```

You separate arguments with a comma, both when you call the function, as well as when you declare it.

Unlike `let`, you *must* declare the types of function arguments. This does not work:

```
fn print_sum(x, y) {
    println!("sum is: {}", x + y);
}
```

You get this error:

```
expected one of `!`, `:`, or `@`, found ``
fn print_number(x, y) {
```

This is a deliberate design decision. While full-program inference is possible, languages which have it, like Haskell, often suggest that documenting your types explicitly is a best-practice. We agree that forcing functions to declare types while allowing for inference inside of function bodies is a wonderful sweet spot between full inference and no inference.

What about returning a value? Here's a function that adds one to an integer:

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

Rust functions return exactly one value, and you declare the type after an 'arrow', which is a dash (-) followed by a greater-than sign (>). The last line of a function determines what it returns. You'll note the lack of a semicolon here. If we added it in:

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

We would get an error:

```
error: not all control paths return a value
fn add_one(x: i32) -> i32 {
    x + 1;
}
```

help: consider removing this semicolon:

```
x + 1;
    ^
```

This reveals two interesting things about Rust: it is an expression-based language, and semicolons are different from semicolons in other ‘curly brace and semicolon’-based languages. These two things are related.

### Expressions vs. Statements

Rust is primarily an expression-based language. There are only two kinds of statements, and everything else is an expression.

So what’s the difference? Expressions return a value, and statements do not. That’s why we end up with ‘not all control paths return a value’ here: the statement `x + 1;` doesn’t return a value. There are two kinds of statements in Rust: ‘declaration statements’ and ‘expression statements’. Everything else is an expression. Let’s talk about declaration statements first.

In some languages, variable bindings can be written as expressions, not just statements. Like Ruby:

```
x = y = 5
```

In Rust, however, using `let` to introduce a binding is *not* an expression. The following will produce a compile-time error:

```
let x = (let y = 5); // expected identifier, found keyword `let`
```

The compiler is telling us here that it was expecting to see the beginning of an expression, and a `let` can only begin a statement, not an expression.

Note that assigning to an already-bound variable (e.g. `y = 5`) is still an expression, although its value is not particularly useful. Unlike other languages where an assignment evaluates to the assigned value (e.g. `5` in the previous example), in Rust the value of an assignment is an empty tuple `()`:

```
let mut y = 5;
```

```
let x = (y = 6); // x has the value `()`, not `6`
```

The second kind of statement in Rust is the *expression statement*. Its purpose is to turn any expression into a statement. In practical terms, Rust’s grammar expects statements to follow other statements. This means that you use semicolons to separate expressions from each other. This means that Rust looks a lot like most other languages that require you to use semicolons at the end of every line, and you will see semicolons at the end of almost every line of Rust code you see.

What is this exception that makes us say “almost”? You saw it already, in this code:

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

Our function claims to return an `i32`, but with a semicolon, it would return `()` instead. Rust realizes this probably isn't what we want, and suggests removing the semicolon in the error we saw before.

### Early returns

But what about early returns? Rust does have a keyword for that, `return`:

```
fn foo(x: i32) -> i32 {  
    return x;  
  
    // we never run this code!  
    x + 1  
}
```

Using a `return` as the last line of a function works, but is considered poor style:

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

The previous definition without `return` may look a bit strange if you haven't worked in an expression-based language before, but it becomes intuitive over time.

### Diverging functions

Rust has some special syntax for 'diverging functions', which are functions that do not return:

```
fn diverges() -> ! {  
    panic!("This function never returns!");  
}
```

`panic!` is a macro, similar to `println!()` that we've already seen. Unlike `println!()`, `panic!()` causes the current thread of execution to crash with the given message.

Because this function will cause a crash, it will never return, and so it has the type `'!'`, which is read 'diverges'. A diverging function can be used as any type:

```
# fn diverges() -> ! {  
#     panic!("This function never returns!");  
# }  
let x: i32 = diverges();  
let x: String = diverges();
```

## 5.3 Primitive Types

The Rust language has a number of types that are considered ‘primitive’. This means that they’re built-in to the language. Rust is structured in such a way that the standard library also provides a number of useful types built on top of these ones, as well, but these are the most primitive.

### 5.3.1 Booleans

Rust has a built in boolean type, named `bool`. It has two values, `true` and `false`:

```
let x = true;

let y: bool = false;
```

A common use of booleans is in `if` conditionals (section 5.5, page 131).

You can find more documentation for `bools` in the standard library documentation<sup>2</sup>.

### 5.3.2 char

The `char` type represents a single Unicode scalar value. You can create `chars` with a single tick: `('')`

```
let x = 'x';
let two_hearts = '❤️';
```

Unlike some other languages, this means that Rust’s `char` is not a single byte, but four.

You can find more documentation for `chars` in the standard library documentation<sup>3</sup>.

### 5.3.3 Numeric types

Rust has a variety of numeric types in a few categories: signed and unsigned, fixed and variable, floating-point and integer.

These types consist of two parts: the category, and the size. For example, `u16` is an unsigned type with sixteen bits of size. More bits lets you have bigger numbers.

If a number literal has nothing to cause its type to be inferred, it defaults:

```
let x = 42; // x has type i32

let y = 1.0; // y has type f64
```

Here’s a list of the different numeric types, with links to their documentation in the standard library:

---

<sup>2</sup><http://doc.rust-lang.org/std/primitive.bool.html>

<sup>3</sup><http://doc.rust-lang.org/std/primitive.char.html>

- `i8`<sup>4</sup>
- `i16`<sup>5</sup>
- `i32`<sup>6</sup>
- `i64`<sup>7</sup>
- `u8`<sup>8</sup>
- `u16`<sup>9</sup>
- `u32`<sup>10</sup>
- `u64`<sup>11</sup>
- `isize`<sup>12</sup>
- `usize`<sup>13</sup>
- `f32`<sup>14</sup>
- `f64`<sup>15</sup>

Let's go over them by category:

### Signed and Unsigned

Integer types come in two varieties: signed and unsigned. To understand the difference, let's consider a number with four bits of size. A signed, four-bit number would let you store numbers from `-8` to `+7`. Signed numbers use “two's complement representation”. An unsigned four bit number, since it does not need to store negatives, can store values from `0` to `+15`.

Unsigned types use a `u` for their category, and signed types use `i`. The `i` is for ‘integer’. So `u8` is an eight-bit unsigned number, and `i8` is an eight-bit signed number.

### Fixed size types

Fixed size types have a specific number of bits in their representation. Valid bit sizes are `8`, `16`, `32`, and `64`. So, `u32` is an unsigned, 32-bit integer, and `i64` is a signed, 64-bit integer.

### Variable sized types

Rust also provides types whose size depends on the size of a pointer of the underlying machine. These types have ‘size’ as the category, and come in signed and unsigned varieties. This makes for two types: `isize` and `usize`.

---

<sup>4</sup><http://doc.rust-lang.org/std/primitive.i8.html>

<sup>5</sup><http://doc.rust-lang.org/std/primitive.i16.html>

<sup>6</sup><http://doc.rust-lang.org/std/primitive.i32.html>

<sup>7</sup><http://doc.rust-lang.org/std/primitive.i64.html>

<sup>8</sup><http://doc.rust-lang.org/std/primitive.u8.html>

<sup>9</sup><http://doc.rust-lang.org/std/primitive.u16.html>

<sup>10</sup><http://doc.rust-lang.org/std/primitive.u32.html>

<sup>11</sup><http://doc.rust-lang.org/std/primitive.u64.html>

<sup>12</sup><http://doc.rust-lang.org/std/primitive.isize.html>

<sup>13</sup><http://doc.rust-lang.org/std/primitive.usize.html>

<sup>14</sup><http://doc.rust-lang.org/std/primitive.f32.html>

<sup>15</sup><http://doc.rust-lang.org/std/primitive.f64.html>

## Floating-point types

Rust also has two floating point types: `f32` and `f64`. These correspond to IEEE-754 single and double precision numbers.

### 5.3.4 Arrays

Like many programming languages, Rust has list types to represent a sequence of things. The most basic is the *array*, a fixed-size list of elements of the same type. By default, arrays are immutable.

```
let a = [1, 2, 3]; // a: [i32; 3]
let mut m = [1, 2, 3]; // m: [i32; 3]
```

Arrays have type `[T; N]`. We'll talk about this `T` notation in the generics section (section 5.19, page 171). The `N` is a compile-time constant, for the length of the array.

There's a shorthand for initializing each element of an array to the same value. In this example, each element of `a` will be initialized to `0`:

```
let a = [0; 20]; // a: [i32; 20]
```

You can get the number of elements in an array `a` with `a.len()`:

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

println!("a has {} elements", a.len());
```

You can access a particular element of an array with *subscript notation*:

```
let names = ["Graydon", "Brian", "Niko"]; // names: [&str; 3]

println!("The second name is: {}", names[1]);
```

Subscripts start at zero, like in most programming languages, so the first name is `names[0]` and the second name is `names[1]`. The above example prints `The second name is: Brian`. If you try to use a subscript that is not in the array, you will get an error: array access is bounds-checked at run-time. Such errant access is the source of many bugs in other systems programming languages.

You can find more documentation for arrays in the standard library documentation<sup>16</sup>.

### 5.3.5 Slices

A 'slice' is a reference to (or "view" into) another data structure. They are useful for allowing safe, efficient access to a portion of an array without copying. For example, you might want to reference just one line of a file read into memory. By nature, a slice is not created directly, but

---

<sup>16</sup><http://doc.rust-lang.org/std/primitive.array.html>



from an existing variable. Slices have a length, can be mutable or not, and in many ways behave like arrays:

```
let a = [0, 1, 2, 3, 4];
let middle = &a[1..4]; // A slice of a: just the elements 1, 2, and 3
let complete = &a[..]; // A slice containing all of the elements in a
```

Slices have type `&[T]`. We'll talk about that `T` when we cover generics (section 5.19, page 171).

You can find more documentation for slices in the standard library documentation<sup>17</sup>.

### 5.3.6 `str`

Rust's `str` type is the most primitive string type. As an unsized type (section 5.32, page 215), it's not very useful by itself, but becomes useful when placed behind a reference, like `&str` (section 5.18, page 169). As such, we'll just leave it at that.

You can find more documentation for `str` in the standard library documentation<sup>18</sup>.

### 5.3.7 Tuples

A tuple is an ordered list of fixed size. Like this:

```
let x = (1, "hello");
```

The parentheses and commas form this two-length tuple. Here's the same code, but with the type annotated:

```
let x: (i32, &str) = (1, "hello");
```

As you can see, the type of a tuple looks just like the tuple, but with each position having a type name rather than the value. Careful readers will also note that tuples are heterogeneous: we have an `i32` and a `&str` in this tuple. In systems programming languages, strings are a bit more complex than in other languages. For now, just read `&str` as a *string slice*, and we'll learn more soon.

You can assign one tuple into another, if they have the same contained types and arity<sup>19</sup>. Tuples have the same arity when they have the same length.

```
let mut x = (1, 2); // x: (i32, i32)
let y = (2, 3); // y: (i32, i32)

x = y;
```

You can access the fields in a tuple through a *destructuring let*. Here's an example:

<sup>17</sup><http://doc.rust-lang.org/std/primitive.slice.html>

<sup>18</sup><http://doc.rust-lang.org/std/primitive.str.html>

<sup>19</sup>[glossary.html#arity](http://doc.rust-lang.org/glossary.html#arity)

```
let (x, y, z) = (1, 2, 3);

println!("x is {}", x);
```

Remember before (section 5.1, page 119) when I said the left-hand side of a `let` statement was more powerful than just assigning a binding? Here we are. We can put a pattern on the left-hand side of the `let`, and if it matches up to the right-hand side, we can assign multiple bindings at once. In this case, `let` “destructures” or “breaks up” the tuple, and assigns the bits to three bindings.

This pattern is very powerful, and we’ll see it repeated more later.

You can disambiguate a single-element tuple from a value in parentheses with a comma:

```
(0,); // single-element tuple
(0); // zero in parentheses
```

### Tuple Indexing

You can also access fields of a tuple with indexing syntax:

```
let tuple = (1, 2, 3);

let x = tuple.0;
let y = tuple.1;
let z = tuple.2;

println!("x is {}", x);
```

Like array indexing, it starts at zero, but unlike array indexing, it uses a `.`, rather than `[]`s.

You can find more documentation for tuples in the standard library documentation<sup>20</sup>.

### 5.3.8 Functions

Functions also have a type! They look like this:

```
fn foo(x: i32) -> i32 { x }

let x: fn(i32) -> i32 = foo;
```

In this case, `x` is a ‘function pointer’ to a function that takes an `i32` and returns an `i32`.

---

<sup>20</sup><http://doc.rust-lang.org/std/primitive.tuple.html>

## 5.4 Comments

Now that we have some functions, it's a good idea to learn about comments. Comments are notes that you leave to other programmers to help explain things about your code. The compiler mostly ignores them.

Rust has two kinds of comments that you should care about: *line comments* and *doc comments*.

```
// Line comments are anything after '//' and extend to the end of the line.

let x = 5; // this is also a line comment.

// If you have a long explanation for something, you can put line comments next
// to each other. Put a space between the // and your comment so that it's
// more readable.
```

The other kind of comment is a doc comment. Doc comments use `///` instead of `//`, and support Markdown notation inside:

```
/// Adds one to the number given.
///
/// # Examples
///
/// ```
/// let five = 5;
///
/// assert_eq!(6, add_one(5));
/// ```
fn add_one(x: i32) -> i32 {
    x + 1
}
```

When writing doc comments, providing some examples of usage is very, very helpful. You'll notice we've used a new macro here: `assert_eq!`. This compares two values, and `panic!`s if they're not equal to each other. It's very helpful in documentation. There's another macro, `assert!`, which `panic!`s if the value passed to it is `false`.

You can use the `rustdoc` (section 4.4, page 79) tool to generate HTML documentation from these doc comments, and also to run the code examples as tests!

## 5.5 if

Rust's take on `if` is not particularly complex, but it's much more like the `if` you'll find in a dynamically typed language than in a more traditional systems language. So let's talk about it, to make sure you grasp the nuances.

`if` is a specific form of a more general concept, the 'branch'. The name comes from a branch in a tree: a decision point, where depending on a choice, multiple paths can be taken.

In the case of `if`, there is one choice that leads down two paths:

```
let x = 5;

if x == 5 {
    println!("x is five!");
}
```

If we changed the value of `x` to something else, this line would not print. More specifically, if the expression after the `if` evaluates to `true`, then the block is executed. If it's `false`, then it is not.

If you want something to happen in the `false` case, use an `else`:

```
let x = 5;

if x == 5 {
    println!("x is five!");
} else {
    println!("x is not five :(");
}
```

If there is more than one case, use an `else if`:

```
let x = 5;

if x == 5 {
    println!("x is five!");
} else if x == 6 {
    println!("x is six!");
} else {
    println!("x is not five or six :(");
}
```

This is all pretty standard. However, you can also do this:

```
let x = 5;

let y = if x == 5 {
    10
} else {
    15
}; // y: i32
```

Which we can (and probably should) write like this:

```
let x = 5;

let y = if x == 5 { 10 } else { 15 }; // y: i32
```

This works because `if` is an expression. The value of the expression is the value of the last expression in whichever branch was chosen. An `if` without an `else` always results in `()` as the value.

## 5.6 for loops

The `for` loop is used to loop a particular number of times. Rust's `for` loops work a bit differently than in other systems languages, however. Rust's `for` loop doesn't look like this "C-style" `for` loop:

```
for (x = 0; x < 10; x++) {  
    printf( "%d\n", x );  
}
```

Instead, it looks like this:

```
for x in 0..10 {  
    println!("{}", x); // x: i32  
}
```

In slightly more abstract terms,

```
for var in expression {  
    code  
}
```

The expression is an iterator (section 4.5, page 89). The iterator gives back a series of elements. Each element is one iteration of the loop. That value is then bound to the name `var`, which is valid for the loop body. Once the body is over, the next value is fetched from the iterator, and we loop another time. When there are no more values, the `for` loop is over.

In our example, `0..10` is an expression that takes a start and an end position, and gives an iterator over those values. The upper bound is exclusive, though, so our loop will print 0 through 9, not 10.

Rust does not have the "C-style" `for` loop on purpose. Manually controlling each element of the loop is complicated and error prone, even for experienced C developers.

## 5.7 while loops

Rust also has a `while` loop. It looks like this:

```
let mut x = 5; // mut x: i32  
let mut done = false; // mut done: bool
```

```
while !done {  
    x += x - 3;  
  
    println!("{}", x);  
  
    if x % 5 == 0 {  
        done = true;  
    }  
}
```

while loops are the correct choice when you're not sure how many times you need to loop.

If you need an infinite loop, you may be tempted to write this:

```
while true {
```

However, Rust has a dedicated keyword, `loop`, to handle this case:

```
loop {
```

Rust's control-flow analysis treats this construct differently than a `while true`, since we know that it will always loop. In general, the more information we can give to the compiler, the better it can do with safety and code generation, so you should always prefer `loop` when you plan to loop infinitely.

### Ending iteration early

Let's take a look at that `while` loop we had earlier:

```
let mut x = 5;  
let mut done = false;  
  
while !done {  
    x += x - 3;  
  
    println!("{}", x);  
  
    if x % 5 == 0 {  
        done = true;  
    }  
}
```

We had to keep a dedicated `mut` boolean variable binding, `done`, to know when we should exit out of the loop. Rust has two keywords to help us with modifying iteration: `break` and `continue`.

In this case, we can write the loop in a better way with `break`:

```
let mut x = 5;

loop {
    x += x - 3;

    println!("{}", x);

    if x % 5 == 0 { break; }
}
```

We now loop forever with `loop` and use `break` to break out early.

`continue` is similar, but instead of ending the loop, goes to the next iteration. This will only print the odd numbers:

```
for x in 0..10 {
    if x % 2 == 0 { continue; }

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

Both `continue` and `break` are valid in both `while` loops and `for` loops (section 5.6, page 133).

## 5.8 Ownership

This guide is one of three presenting Rust’s ownership system. This is one of Rust’s most unique and compelling features, with which Rust developers should become quite acquainted. Ownership is how Rust achieves its largest goal, memory safety. There are a few distinct concepts, each with its own chapter:

- ownership, which you’re reading now
- borrowing (section 5.9, page 138), and their associated feature ‘references’
- lifetimes (section 5.10, page 145), an advanced concept of borrowing

These three chapters are related, and in order. You’ll need all three to fully understand the ownership system.

### 5.8.1 Meta

Before we get to the details, two important notes about the ownership system.

Rust has a focus on safety and speed. It accomplishes these goals through many ‘zero-cost abstractions’, which means that in Rust, abstractions cost as little as possible in order to make them work. The ownership system is a prime example of a zero-cost abstraction. All of the analysis we’ll talk about in this guide is *done at compile time*. You do not pay any run-time cost for any of these features.

However, this system does have a certain cost: learning curve. Many new users to Rust experience something we like to call ‘fighting with the borrow checker’, where the Rust compiler refuses to compile a program that the author thinks is valid. This often happens because the programmer’s mental model of how ownership should work doesn’t match the actual rules that Rust implements. You probably will experience similar things at first. There is good news, however: more experienced Rust developers report that once they work with the rules of the ownership system for a period of time, they fight the borrow checker less and less.

With that in mind, let’s learn about ownership.

## 5.8.2 Ownership

Variable bindings (section 5.1, page 119) have a property in Rust: they ‘have ownership’ of what they’re bound to. This means that when a binding goes out of scope, the resource that they’re bound to are freed. For example:

```
fn foo() {
    let v = vec![1, 2, 3];
}
```

When `v` comes into scope, a new `Vec<T>`<sup>21</sup> is created. In this case, the vector also allocates space on the heap (section 4.1, page 59), for the three elements. When `v` goes out of scope at the end of `foo()`, Rust will clean up everything related to the vector, even the heap-allocated memory. This happens deterministically, at the end of the scope.

## 5.8.3 Move semantics

There’s some more subtlety here, though: Rust ensures that there is *exactly one* binding to any given resource. For example, if we have a vector, we can assign it to another binding:

```
let v = vec![1, 2, 3];

let v2 = v;
```

But, if we try to use `v` afterwards, we get an error:

```
let v = vec![1, 2, 3];

let v2 = v;

println!("v[0] is: {}", v[0]);
```

It looks like this:

```
error: use of moved value: `v`
println!("v[0] is: {}", v[0]);
                        ^
```

<sup>21</sup><http://doc.rust-lang.org/std/vec/struct.Vec.html>



A similar thing happens if we define a function which takes ownership, and try to use something after we've passed it as an argument:

```
fn take(v: Vec<i32>) {  
    // what happens here isn't important.  
}  
  
let v = vec![1, 2, 3];  
  
take(v);  
  
println!("v[0] is: {}", v[0]);
```

Same error: 'use of moved value'. When we transfer ownership to something else, we say that we've 'moved' the thing we refer to. You don't need some sort of special annotation here, it's the default thing that Rust does.

### The details

The reason that we cannot use a binding after we've moved it is subtle, but important. When we write code like this:

```
let v = vec![1, 2, 3];  
  
let v2 = v;
```

The first line allocates memory for the vector object, `v`, and for the data it contains. The vector object is stored on the stack (section 4.1, page 59) and contains a pointer to the content (`[1, 2, 3]`) stored on the heap (section 4.1, page 59). When we move `v` to `v2`, it creates a copy of that pointer, for `v2`. Which means that there would be two pointers to the content of the vector on the heap. It would violate Rust's safety guarantees by introducing a data race. Therefore, Rust forbids using `v` after we've done the move.

It's also important to note that optimizations may remove the actual copy of the bytes on the stack, depending on circumstances. So it may not be as inefficient as it initially seems.

### Copy types

We've established that when ownership is transferred to another binding, you cannot use the original binding. However, there's a trait (section 5.20, page 173) that changes this behavior, and it's called `Copy`. We haven't discussed traits yet, but for now, you can think of them as an annotation to a particular type that adds extra behavior. For example:

```
let v = 1;  
  
let v2 = v;  
  
println!("v is: {}", v);
```

In this case, `v` is an `i32`, which implements the `Copy` trait. This means that, just like a move, when we assign `v` to `v2`, a copy of the data is made. But, unlike a move, we can still use `v` afterward. This is because an `i32` has no pointers to data somewhere else, copying it is a full copy.

We will discuss how to make your own types `Copy` in the traits (section 5.20, page 173) section.

### 5.8.4 More than ownership

Of course, if we had to hand ownership back with every function we wrote:

```
fn foo(v: Vec<i32>) -> Vec<i32> {
    // do stuff with v

    // hand back ownership
    v
}
```

This would get very tedious. It gets worse the more things we want to take ownership of:

```
fn foo(v1: Vec<i32>, v2: Vec<i32>) -> (Vec<i32>, Vec<i32>, i32) {
    // do stuff with v1 and v2

    // hand back ownership, and the result of our function
    (v1, v2, 42)
}

let v1 = vec![1, 2, 3];
let v2 = vec![1, 2, 3];

let (v1, v2, answer) = foo(v1, v2);
```

Ugh! The return type, return line, and calling the function gets way more complicated.

Luckily, Rust offers a feature, borrowing, which helps us solve this problem. It's the topic of the next section!

## 5.9 References and Borrowing

This guide is one of three presenting Rust's ownership system. This is one of Rust's most unique and compelling features, with which Rust developers should become quite acquainted. Ownership is how Rust achieves its largest goal, memory safety. There are a few distinct concepts, each with its own chapter:

- ownership (section 5.8, page 135), the key concept
- borrowing, which you're reading now
- lifetimes (section 5.10, page 145), an advanced concept of borrowing

These three chapters are related, and in order. You'll need all three to fully understand the ownership system.

### 5.9.1 Meta

Before we get to the details, two important notes about the ownership system.

Rust has a focus on safety and speed. It accomplishes these goals through many 'zero-cost abstractions', which means that in Rust, abstractions cost as little as possible in order to make them work. The ownership system is a prime example of a zero cost abstraction. All of the analysis we'll talk about in this guide is *done at compile time*. You do not pay any run-time cost for any of these features.

However, this system does have a certain cost: learning curve. Many new users to Rust experience something we like to call 'fighting with the borrow checker', where the Rust compiler refuses to compile a program that the author thinks is valid. This often happens because the programmer's mental model of how ownership should work doesn't match the actual rules that Rust implements. You probably will experience similar things at first. There is good news, however: more experienced Rust developers report that once they work with the rules of the ownership system for a period of time, they fight the borrow checker less and less.

With that in mind, let's learn about borrowing.

### 5.9.2 Borrowing

At the end of the ownership (section 5.8, page 135) section, we had a nasty function that looked like this:

```
fn foo(v1: Vec<i32>, v2: Vec<i32>) -> (Vec<i32>, Vec<i32>, i32) {
    // do stuff with v1 and v2

    // hand back ownership, and the result of our function
    (v1, v2, 42)
}

let v1 = vec![1, 2, 3];
let v2 = vec![1, 2, 3];

let (v1, v2, answer) = foo(v1, v2);
```

This is not idiomatic Rust, however, as it doesn't take advantage of borrowing. Here's the first step:

```
fn foo(v1: &Vec<i32>, v2: &Vec<i32>) -> i32 {
    // do stuff with v1 and v2

    // return the answer
    42
}
```

```

}

let v1 = vec![1, 2, 3];
let v2 = vec![1, 2, 3];

let answer = foo(&v1, &v2);

// we can use v1 and v2 here!

```

Instead of taking `Vec<i32>`s as our arguments, we take a reference: `&Vec<i32>`. And instead of passing `v1` and `v2` directly, we pass `&v1` and `&v2`. We call the `&T` type a ‘reference’, and rather than owning the resource, it borrows ownership. A binding that borrows something does not deallocate the resource when it goes out of scope. This means that after the call to `foo()`, we can use our original bindings again.

References are immutable, just like bindings. This means that inside of `foo()`, the vectors can’t be changed at all:

```

fn foo(v: &Vec<i32>) {
    v.push(5);
}

let v = vec![];

foo(&v);

```

errors with:

```

error: cannot borrow immutable borrowed content `*v` as mutable
v.push(5);
^

```

Pushing a value mutates the vector, and so we aren’t allowed to do it.

### 5.9.3 &mut references

There’s a second kind of reference: `&mut T`. A ‘mutable reference’ allows you to mutate the resource you’re borrowing. For example:

```

let mut x = 5;
{
    let y = &mut x;
    *y += 1;
}
println!("{}", x);

```

This will print 6. We make `y` a mutable reference to `x`, then add one to the thing `y` points at. You'll notice that `x` had to be marked `mut` as well, if it wasn't, we couldn't take a mutable borrow to an immutable value.

Otherwise, `&mut` references are just like references. There *is* a large difference between the two, and how they interact, though. You can tell something is fishy in the above example, because we need that extra scope, with the `{` and `}`. If we remove them, we get an error:

```
error: cannot borrow `x` as immutable because it is also borrowed as mutable
    println!("{}", x);
      ^
note: previous borrow of `x` occurs here; the mutable borrow prevents
subsequent moves, borrows, or modification of `x` until the borrow ends
    let y = &mut x;
      ^
note: previous borrow ends here
fn main() {

}
^
```

As it turns out, there are rules.

#### 5.9.4 The Rules

Here's the rules about borrowing in Rust:

First, any borrow must last for a smaller scope than the owner. Second, you may have one or the other of these two kinds of borrows, but not both at the same time:

- 0 to N references (`&T`) to a resource.
- exactly one mutable reference (`&mut T`)

You may notice that this is very similar, though not exactly the same as, to the definition of a data race:

There is a 'data race' when two or more pointers access the same memory location at the same time, where at least one of them is writing, and the operations are not synchronized.

With references, you may have as many as you'd like, since none of them are writing. If you are writing, you need two or more pointers to the same memory, and you can only have one `&mut` at a time. This is how Rust prevents data races at compile time: we'll get errors if we break the rules.

With this in mind, let's consider our example again.

### Thinking in scopes

Here's the code:

```
let mut x = 5;
let y = &mut x;

*y += 1;

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

This code gives us this error:

```
error: cannot borrow `x` as immutable because it is also borrowed as mutable
    println!("{}", x);
                  ^
```

This is because we've violated the rules: we have a `&mut T` pointing to `x`, and so we aren't allowed to create any `&Ts`. One or the other. The note hints at how to think about this problem:

```
note: previous borrow ends here
fn main() {

}
^
```

In other words, the mutable borrow is held through the rest of our example. What we want is for the mutable borrow to end *before* we try to call `println!` and make an immutable borrow. In Rust, borrowing is tied to the scope that the borrow is valid for. And our scopes look like this:

```
let mut x = 5;

let y = &mut x;    // -+ &mut borrow of x starts here
                  // |
*y += 1;           // |
                  // |
println!("{}", x); // -+ - try to borrow x here
                  // -+ &mut borrow of x ends here
```

The scopes conflict: we can't make an `&x` while `y` is in scope.

So when we add the curly braces:

```
let mut x = 5;

{
    let y = &mut x; // -+ &mut borrow starts here
    *y += 1;       // |
}
```

```

}                                // -+ ... and ends here

println!("{}", x); // <- try to borrow x here

```

There's no problem. Our mutable borrow goes out of scope before we create an immutable one. But scope is the key to seeing how long a borrow lasts for.

### Issues borrowing prevents

Why have these restrictive rules? Well, as we noted, these rules prevent data races. What kinds of issues do data races cause? Here's a few.

**Iterator invalidation** One example is 'iterator invalidation', which happens when you try to mutate a collection that you're iterating over. Rust's borrow checker prevents this from happening:

```

let mut v = vec![1, 2, 3];

for i in &v {
    println!("{}", i);
}

```

This prints out one through three. As we iterate through the vectors, we're only given references to the elements. And `v` is itself borrowed as immutable, which means we can't change it while we're iterating:

```

let mut v = vec![1, 2, 3];

for i in &v {
    println!("{}", i);
    v.push(34);
}

```

Here's the error:

```

error: cannot borrow `v` as mutable because it is also borrowed as immutable
    v.push(34);
    ^

note: previous borrow of `v` occurs here; the immutable borrow prevents
subsequent moves or mutable borrows of `v` until the borrow ends
for i in &v {
    ^
note: previous borrow ends here
for i in &v {
    println!("{}", i);
    v.push(34);
}
^

```

We can't modify `v` because it's borrowed by the loop.

**use after free** References must live as long as the resource they refer to. Rust will check the scopes of your references to ensure that this is true.

If Rust didn't check that this property, we could accidentally use a reference which was invalid. For example:

```
let y: &i32;
{
    let x = 5;
    y = &x;
}

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

We get this error:

```
error: `x` does not live long enough
      y = &x;
        ^

note: reference must be valid for the block suffix following statement 0 at
2:16...
let y: &i32;
{
    let x = 5;
    y = &x;
}

note: ...but borrowed value is only valid for the block suffix following
statement 0 at 4:18
    let x = 5;
    y = &x;
}
```

In other words, `y` is only valid for the scope where `x` exists. As soon as `x` goes away, it becomes invalid to refer to it. As such, the error says that the borrow 'doesn't live long enough' because it's not valid for the right amount of time.

The same problem occurs when the reference is declared *before* the variable it refers to:

```
let y: &i32;
let x = 5;
y = &x;

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

We get this error:



error: `x` does not live long enough

```
y = &x;
    ^
```

note: reference must be valid for the block suffix following statement 0 at 2:16...

```
    let y: &i32;
    let x = 5;
    y = &x;

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

note: ...but borrowed value is only valid for the block suffix following statement 1 at 3:14

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

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

## 5.10 Lifetimes

This guide is one of three presenting Rust’s ownership system. This is one of Rust’s most unique and compelling features, with which Rust developers should become quite acquainted. Ownership is how Rust achieves its largest goal, memory safety. There are a few distinct concepts, each with its own chapter:

- ownership (section 5.8, page 135), the key concept
- borrowing (section 5.9, page 138), and their associated feature ‘references’
- lifetimes, which you’re reading now

These three chapters are related, and in order. You’ll need all three to fully understand the ownership system.

### 5.10.1 Meta

Before we get to the details, two important notes about the ownership system.

Rust has a focus on safety and speed. It accomplishes these goals through many ‘zero-cost abstractions’, which means that in Rust, abstractions cost as little as possible in order to make them work. The ownership system is a prime example of a zero-cost abstraction. All of the analysis we’ll talk about in this guide is *done at compile time*. You do not pay any run-time cost for any of these features.

However, this system does have a certain cost: learning curve. Many new users to Rust experience something we like to call ‘fighting with the borrow checker’, where the Rust compiler refuses to compile a program that the author thinks is valid. This often happens because the

programmer’s mental model of how ownership should work doesn’t match the actual rules that Rust implements. You probably will experience similar things at first. There is good news, however: more experienced Rust developers report that once they work with the rules of the ownership system for a period of time, they fight the borrow checker less and less.

With that in mind, let’s learn about lifetimes.

### 5.10.2 Lifetimes

Lending out a reference to a resource that someone else owns can be complicated. For example, imagine this set of operations:

- I acquire a handle to some kind of resource.
- I lend you a reference to the resource.
- I decide I’m done with the resource, and deallocate it, while you still have your reference.
- You decide to use the resource.

Uh oh! Your reference is pointing to an invalid resource. This is called a dangling pointer or ‘use after free’, when the resource is memory.

To fix this, we have to make sure that step four never happens after step three. The ownership system in Rust does this through a concept called lifetimes, which describe the scope that a reference is valid for.

When we have a function that takes a reference by argument, we can be implicit or explicit about the lifetime of the reference:

```
// implicit
fn foo(x: &i32) {
}

// explicit
fn bar<'a>(x: &'a i32) {
}
```

The `'a` reads ‘the lifetime `a`’. Technically, every reference has some lifetime associated with it, but the compiler lets you elide them in common cases. Before we get to that, though, let’s break the explicit example down:

```
fn bar<'a>(...)
```

This part declares our lifetimes. This says that `bar` has one lifetime, `'a`. If we had two reference parameters, it would look like this:

```
fn bar<'a, 'b>(...)
```

Then in our parameter list, we use the lifetimes we’ve named:

```
... (x: &'a i32)
```

If we wanted an `&mut` reference, we'd do this:

```
... (x: &'a mut i32)
```

If you compare `&mut i32` to `&'a mut i32`, they're the same, it's just that the lifetime `'a` has snuck in between the `&` and the `mut i32`. We read `&mut i32` as 'a mutable reference to an `i32`' and `&'a mut i32` as 'a mutable reference to an `i32` with the lifetime `'a`'.

You'll also need explicit lifetimes when working with `struct` (section 5.12, page 153)s:

```
struct Foo<'a> {
    x: &'a i32,
}

fn main() {
    let y = &5; // this is the same as `let _y = 5; let y = &_y;`
    let f = Foo { x: y };

    println!("{}", f.x);
}
```

As you can see, structs can also have lifetimes. In a similar way to functions,

```
struct Foo<'a> {
```

declares a lifetime, and

```
x: &'a i32,
```

uses it. So why do we need a lifetime here? We need to ensure that any reference to a `Foo` cannot outlive the reference to an `i32` it contains.

### Thinking in scopes

A way to think about lifetimes is to visualize the scope that a reference is valid for. For example:

```
fn main() {
    let y = &5;      // -+ y goes into scope
                    // |
    // stuff        // |
                    // |
                    // -+ y goes out of scope
}
```

Adding in our `Foo`:

```

struct Foo<'a> {
    x: &'a i32,
}

fn main() {
    let y = &5;           // -+ y goes into scope
    let f = Foo { x: y }; // -+ f goes into scope
    // stuff              // |
                          // |
                          // -+ f and y go out of scope
}

```

Our `f` lives within the scope of `y`, so everything works. What if it didn't? This code won't work:

```

struct Foo<'a> {
    x: &'a i32,
}

fn main() {
    let x;                // -+ x goes into scope
                          // |
    {                     // |
        let y = &5;        // ---+ y goes into scope
        let f = Foo { x: y }; // ---+ f goes into scope
        x = &f.x;         // | | error here
    }                     // ---+ f and y go out of scope
                          // |
    println!("{}", x);    // |
                          // -+ x goes out of scope
}

```

Whew! As you can see here, the scopes of `f` and `y` are smaller than the scope of `x`. But when we do `x = &f.x`, we make `x` a reference to something that's about to go out of scope.

Named lifetimes are a way of giving these scopes a name. Giving something a name is the first step towards being able to talk about it.

### 'static

The lifetime named `'static` is a special lifetime. It signals that something has the lifetime of the entire program. Most Rust programmers first come across `'static` when dealing with strings:

```

let x: &'static str = "Hello, world.";

```

String literals have the type `&'static str` because the reference is always alive: they are baked into the data segment of the final binary. Another example are globals:

```

static F00: i32 = 5;
let x: &'static i32 = &F00;

```

This adds an `i32` to the data segment of the binary, and `x` is a reference to it.

## Lifetime Elision

Rust supports powerful local type inference in function bodies, but it's forbidden in item signatures to allow reasoning about the types just based in the item signature alone. However, for ergonomic reasons a very restricted secondary inference algorithm called “lifetime elision” applies in function signatures. It infers only based on the signature components themselves and not based on the body of the function, only infers lifetime parameters, and does this with only three easily memorizable and unambiguous rules. This makes lifetime elision a shorthand for writing an item signature, while not hiding away the actual types involved as full local inference would if applied to it.

When talking about lifetime elision, we use the term *input lifetime* and *output lifetime*. An *input lifetime* is a lifetime associated with a parameter of a function, and an *output lifetime* is a lifetime associated with the return value of a function. For example, this function has an input lifetime:

```
fn foo<'a>(bar: &'a str)
```

This one has an output lifetime:

```
fn foo<'a>() -> &'a str
```

This one has a lifetime in both positions:

```
fn foo<'a>(bar: &'a str) -> &'a str
```

Here are the three rules:

- Each elided lifetime in a function's arguments becomes a distinct lifetime parameter.
- If there is exactly one input lifetime, elided or not, that lifetime is assigned to all elided lifetimes in the return values of that function.
- If there are multiple input lifetimes, but one of them is `&self` or `&mut self`, the lifetime of `self` is assigned to all elided output lifetimes.

Otherwise, it is an error to elide an output lifetime.

**Examples** Here are some examples of functions with elided lifetimes. We've paired each example of an elided lifetime with its expanded form.

```
fn print(s: &str); // elided
fn print<'a>(s: &'a str); // expanded

fn debug(lvl: u32, s: &str); // elided
fn debug<'a>(lvl: u32, s: &'a str); // expanded

// In the preceding example, `lvl` doesn't need a lifetime because it's not a
// reference (`&`). Only things relating to references (such as a `struct`
```

```
// which contains a reference) need lifetimes.

fn substr(s: &str, until: u32) -> &str; // elided
fn substr<'a>(s: &'a str, until: u32) -> &'a str; // expanded

fn get_str() -> &str; // ILLEGAL, no inputs

fn frob(s: &str, t: &str) -> &str; // ILLEGAL, two inputs
fn frob<'a, 'b>(s: &'a str, t: &'b str) -> &str; // Expanded: Output lifetime is unclear

fn get_mut(&mut self) -> &mut T; // elided
fn get_mut<'a>(&'a mut self) -> &'a mut T; // expanded

fn args<T: ToCStr>(&mut self, args: &[T]) -> &mut Command // elided
fn args<'a, 'b, T: ToCStr>(&'a mut self, args: &'b [T]) -> &'a mut Command // expanded

fn new(buf: &mut [u8]) -> BufWriter; // elided
fn new<'a>(buf: &'a mut [u8]) -> BufWriter<'a> // expanded
```

## 5.11 Mutability

Mutability, the ability to change something, works a bit differently in Rust than in other languages. The first aspect of mutability is its non-default status:

```
let x = 5;
x = 6; // error!
```

We can introduce mutability with the `mut` keyword:

```
let mut x = 5;

x = 6; // no problem!
```

This is a mutable variable binding (section 5.1, page 119). When a binding is mutable, it means you're allowed to change what the binding points to. So in the above example, it's not so much that the value at `x` is changing, but that the binding changed from one `i32` to another.

If you want to change what the binding points to, you'll need a mutable reference (section 5.9, page 138):

```
let mut x = 5;
let y = &mut x;
```

`y` is an immutable binding to a mutable reference, which means that you can't bind `y` to something else (`y = &mut z`), but you can mutate the thing that's bound to `y` (`*y = 5`). A subtle distinction.

Of course, if you need both:

```
let mut x = 5;  
let mut y = &mut x;
```

Now `y` can be bound to another value, and the value it's referencing can be changed.

It's important to note that `mut` is part of a pattern (section 5.15, page 159), so you can do things like this:

```
let (mut x, y) = (5, 6);  
  
fn foo(mut x: i32) {
```

### 5.11.1 Interior vs. Exterior Mutability

However, when we say something is 'immutable' in Rust, that doesn't mean that it's not able to be changed: We mean something has 'exterior mutability'. Consider, for example, `Arc<T>`<sup>22</sup>:

```
use std::sync::Arc;  
  
let x = Arc::new(5);  
let y = x.clone();
```

When we call `clone()`, the `Arc<T>` needs to update the reference count. Yet we've not used any `mut`s here, `x` is an immutable binding, and we didn't take `&mut 5` or anything. So what gives?

To understand this, we have to go back to the core of Rust's guiding philosophy, memory safety, and the mechanism by which Rust guarantees it, the ownership (section 5.8, page 135) system, and more specifically, borrowing<sup>23</sup>:

You may have one or the other of these two kinds of borrows, but not both at the same time:

- one or more references (`&T`) to a resource.
- exactly one mutable reference (`&mut T`)

So, that's the real definition of 'immutability': is this safe to have two pointers to? In `Arc<T>`'s case, yes: the mutation is entirely contained inside the structure itself. It's not user facing. For this reason, it hands out `&T` with `clone()`. If it handed out `&mut Ts`, though, that would be a problem.

Other types, like the ones in the `std::cell`<sup>24</sup> module, have the opposite: interior mutability. For example:

---

<sup>22</sup><http://doc.rust-lang.org/std/sync/struct.Arc.html>

<sup>23</sup>[borrowing.html#The-Rules](http://doc.rust-lang.org/std/borrowing.html#The-Rules)

<sup>24</sup><http://doc.rust-lang.org/std/cell/index.html>

```
use std::cell::RefCell;

let x = RefCell::new(42);

let y = x.borrow_mut();
```

RefCell hands out `&mut` references to what's inside of it with the `borrow_mut()` method. Isn't that dangerous? What if we do:

```
use std::cell::RefCell;

let x = RefCell::new(42);

let y = x.borrow_mut();
let z = x.borrow_mut();
```

This will in fact panic, at runtime. This is what `RefCell` does: it enforces Rust's borrowing rules at runtime, and `panic!`s if they're violated. This allows us to get around another aspect of Rust's mutability rules. Let's talk about it first.

### Field-level mutability

Mutability is a property of either a borrow (`&mut`) or a binding (`let mut`). This means that, for example, you cannot have a `struct` (section 5.12, page 153) with some fields mutable and some immutable:

```
struct Point {
    x: i32,
    mut y: i32, // nope
}
```

The mutability of a struct is in its binding:

```
struct Point {
    x: i32,
    y: i32,
}

let mut a = Point { x: 5, y: 6 };

a.x = 10;

let b = Point { x: 5, y: 6 };

b.x = 10; // error: cannot assign to immutable field `b.x`
```

However, by using `Cell<T>`, you can emulate field-level mutability:



```
use std::cell::Cell;

struct Point {
    x: i32,
    y: Cell<i32>,
}

let point = Point { x: 5, y: Cell::new(6) };

point.y.set(7);

println!("y: {:?}", point.y);
```

This will print `y: Cell { value: 7 }`. We've successfully updated `y`.

## 5.12 Structs

Structs are a way of creating more complex data types. For example, if we were doing calculations involving coordinates in 2D space, we would need both an `x` and a `y` value:

```
let origin_x = 0;
let origin_y = 0;
```

A struct lets us combine these two into a single, unified datatype:

```
struct Point {
    x: i32,
    y: i32,
}

fn main() {
    let origin = Point { x: 0, y: 0 }; // origin: Point

    println!("The origin is at ({}, {})", origin.x, origin.y);
}
```

There's a lot going on here, so let's break it down. We declare a `struct` with the `struct` keyword, and then with a name. By convention, `structs` begin with a capital letter and are camel cased: `PointInSpace`, not `Point_In_Space`.

We can create an instance of our struct via `let`, as usual, but we use a `key: value` style syntax to set each field. The order doesn't need to be the same as in the original declaration.

Finally, because fields have names, we can access the field through dot notation: `origin.x`.

The values in structs are immutable by default, like other bindings in Rust. Use `mut` to make them mutable:

```

struct Point {
    x: i32,
    y: i32,
}

fn main() {
    let mut point = Point { x: 0, y: 0 };

    point.x = 5;

    println!("The point is at ({} , {})", point.x, point.y);
}

```

This will print The point is at (5, 0).

Rust does not support field mutability at the language level, so you cannot write something like this:

```

struct Point {
    mut x: i32,
    y: i32,
}

```

Mutability is a property of the binding, not of the structure itself. If you're used to field-level mutability, this may seem strange at first, but it significantly simplifies things. It even lets you make things mutable for a short time only:

```

struct Point {
    x: i32,
    y: i32,
}

fn main() {
    let mut point = Point { x: 0, y: 0 };

    point.x = 5;

    let point = point; // this new binding can't change now

    point.y = 6; // this causes an error
}

```

### 5.12.1 Update syntax

A `struct` can include `..` to indicate that you want to use a copy of some other struct for some of the values. For example:

```
struct Point3d {
    x: i32,
    y: i32,
    z: i32,
}

let mut point = Point3d { x: 0, y: 0, z: 0 };
point = Point3d { y: 1, .. point };
```

This gives `point` a new `y`, but keeps the old `x` and `z` values. It doesn't have to be the same `struct` either, you can use this syntax when making new ones, and it will copy the values you don't specify:

```
let origin = Point3d { x: 0, y: 0, z: 0 };
let point = Point3d { z: 1, x: 2, .. origin };
```

### 5.12.2 Tuple structs

Rust has another data type that's like a hybrid between a tuple<sup>25</sup> and a struct, called a 'tuple struct'. Tuple structs have a name, but their fields don't:

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

These two will not be equal, even if they have the same values:

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

It is almost always better to use a struct than a tuple struct. We would write `Color` and `Point` like this instead:

```
struct Color {
    red: i32,
    blue: i32,
    green: i32,
}

struct Point {
    x: i32,
    y: i32,
    z: i32,
}
```

---

<sup>25</sup>[primitive-types.html#tuples](https://doc.rust-lang.org/std/primitive-types.html#tuples)

Now, we have actual names, rather than positions. Good names are important, and with a struct, we have actual names.

There *is* one case when a tuple struct is very useful, though, and that's a tuple struct with only one element. We call this the 'newtype' pattern, because it allows you to create a new type, distinct from that of its contained value and expressing its own semantic meaning:

```
struct Inches(i32);

let length = Inches(10);

let Inches(integer_length) = length;
println!("length is {} inches", integer_length);
```

As you can see here, you can extract the inner integer type through a destructuring `let`, just as with regular tuples. In this case, the `let Inches(integer_length)` assigns 10 to `integer_length`.

### 5.12.3 Unit-like structs

You can define a struct with no members at all:

```
struct Electron;
```

Such a struct is called 'unit-like' because it resembles the empty tuple, `()`, sometimes called 'unit'. Like a tuple struct, it defines a new type.

This is rarely useful on its own (although sometimes it can serve as a marker type), but in combination with other features, it can become useful. For instance, a library may ask you to create a structure that implements a certain trait (section 5.20, page 173) to handle events. If you don't have any data you need to store in the structure, you can just create a unit-like struct.

## 5.13 Enums

An `enum` in Rust is a type that represents data that could be one of several possible variants:

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

Each variant can optionally have data associated with it. The syntax for defining variants resembles the syntaxes used to define structs: you can have variants with no data (like unit-like structs), variants with named data, and variants with unnamed data (like tuple structs). Unlike separate struct definitions, however, an `enum` is a single type. A value of the enum can match any

of the variants. For this reason, an enum is sometimes called a ‘sum type’: the set of possible values of the enum is the sum of the sets of possible values for each variant.

We use the `::` syntax to use the name of each variant: they’re scoped by the name of the enum itself. This allows both of these to work:

```
let x: Message = Message::Move { x: 3, y: 4 };

enum BoardGameTurn {
    Move { squares: i32 },
    Pass,
}

let y: BoardGameTurn = BoardGameTurn::Move { squares: 1 };
```

Both variants are named `Move`, but since they’re scoped to the name of the enum, they can both be used without conflict.

A value of an enum type contains information about which variant it is, in addition to any data associated with that variant. This is sometimes referred to as a ‘tagged union’, since the data includes a ‘tag’ indicating what type it is. The compiler uses this information to enforce that you’re accessing the data in the enum safely. For instance, you can’t simply try to destructure a value as if it were one of the possible variants:

```
fn process_color_change(msg: Message) {
    let Message::ChangeColor(r, g, b) = msg; // compile-time error
}
```

Not supporting these operations may seem rather limiting, but it’s a limitation which we can overcome. There are two ways: by implementing equality ourselves, or by pattern matching variants with `match` (section 5.14, page 157) expressions, which you’ll learn in the next section. We don’t know enough about Rust to implement equality yet, but we’ll find out in the `traits` (section 5.20, page 173) section.

## 5.14 Match

Often, a simple `if` (section 5.5, page 131)/`else` isn’t enough, because you have more than two possible options. Also, conditions can get quite complex. Rust has a keyword, `match`, that allows you to replace complicated `if/else` groupings with something more powerful. Check it out:

```
let x = 5;

match x {
    1 => println!("one"),
    2 => println!("two"),
    3 => println!("three"),
    4 => println!("four"),
    5 => println!("five"),
```

```

    _ => println!("something else"),
}

```

`match` takes an expression and then branches based on its value. Each ‘arm’ of the branch is of the form `val => expression`. When the value matches, that arm’s expression will be evaluated. It’s called `match` because of the term ‘pattern matching’, which `match` is an implementation of. There’s an entire section on patterns (section 5.15, page 159) that covers all the patterns that are possible here.

So what’s the big advantage? Well, there are a few. First of all, `match` enforces ‘exhaustiveness checking’. Do you see that last arm, the one with the underscore (`_`)? If we remove that arm, Rust will give us an error:

```
error: non-exhaustive patterns: `_` not covered
```

In other words, Rust is trying to tell us we forgot a value. Because `x` is an integer, Rust knows that it can have a number of different values – for example, 6. Without the `_`, however, there is no arm that could match, and so Rust refuses to compile the code. `_` acts like a ‘catch-all arm’. If none of the other arms match, the arm with `_` will, and since we have this catch-all arm, we now have an arm for every possible value of `x`, and so our program will compile successfully.

`match` is also an expression, which means we can use it on the right-hand side of a `let` binding or directly where an expression is used:

```

let x = 5;

let number = match x {
    1 => "one",
    2 => "two",
    3 => "three",
    4 => "four",
    5 => "five",
    _ => "something else",
};

```

Sometimes it’s a nice way of converting something from one type to another.

### 5.14.1 Matching on enums

Another important use of the `match` keyword is to process the possible variants of an enum:

```

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

```

```
fn quit() { /* ... */ }
fn change_color(r: i32, g: i32, b: i32) { /* ... */ }
fn move_cursor(x: i32, y: i32) { /* ... */ }

fn process_message(msg: Message) {
    match msg {
        Message::Quit => quit(),
        Message::ChangeColor(r, g, b) => change_color(r, g, b),
        Message::Move { x: x, y: y } => move_cursor(x, y),
        Message::Write(s) => println!("{}", s),
    };
}
```

Again, the Rust compiler checks exhaustiveness, so it demands that you have a match arm for every variant of the enum. If you leave one off, it will give you a compile-time error unless you use `_`.

Unlike the previous uses of `match`, you can't use the normal `if` statement to do this. You can use the `if let` (section 5.22, page 182) statement, which can be seen as an abbreviated form of `match`.

## 5.15 Patterns

Patterns are quite common in Rust. We use them in variable bindings (section 5.1, page 119), match statements (section 5.14, page 157), and other places, too. Let's go on a whirlwind tour of all of the things patterns can do!

A quick refresher: you can match against literals directly, and `_` acts as an 'any' case:

```
let x = 1;

match x {
    1 => println!("one"),
    2 => println!("two"),
    3 => println!("three"),
    _ => println!("anything"),
}
```

This prints one.

### 5.15.1 Multiple patterns

You can match multiple patterns with `|`:

```
let x = 1;

match x {
```

```
1 | 2 => println!("one or two"),
3 => println!("three"),
_ => println!("anything"),
}
```

This prints one or two.

### 5.15.2 Ranges

You can match a range of values with ...:

```
let x = 1;

match x {
  1 ... 5 => println!("one through five"),
  _ => println!("anything"),
}
```

This prints one through five.

Ranges are mostly used with integers and chars:

```
let x = 'x';

match x {
  'a' ... 'j' => println!("early letter"),
  'k' ... 'z' => println!("late letter"),
  _ => println!("something else"),
}
```

This prints something else.

### 5.15.3 Bindings

You can bind values to names with @:

```
let x = 1;

match x {
  e @ 1 ... 5 => println!("got a range element {}", e),
  _ => println!("anything"),
}
```

This prints got a range element 1. This is useful when you want to do a complicated match of part of a data structure:



```
#[derive(Debug)]
struct Person {
    name: Option<String>,
}

let name = "Steve".to_string();
let mut x: Option<Person> = Some(Person { name: Some(name) });
match x {
    Some(Person { name: ref a @ Some(_), .. }) => println!("{:?}", a),
    _ => {}
}
```

This prints `Some("Steve")`: We've bound the inner name to `a`.

If you use `@` with `|`, you need to make sure the name is bound in each part of the pattern:

```
let x = 5;

match x {
    e @ 1 ... 5 | e @ 8 ... 10 => println!("got a range element {}", e),
    _ => println!("anything"),
}
```

#### 5.15.4 Ignoring variants

If you're matching on an enum which has variants, you can use `..` to ignore the value and type in the variant:

```
enum OptionalInt {
    Value(i32),
    Missing,
}

let x = OptionalInt::Value(5);

match x {
    OptionalInt::Value(..) => println!("Got an int!"),
    OptionalInt::Missing => println!("No such luck."),
}
```

This prints `Got an int!`.

#### 5.15.5 Guards

You can introduce 'match guards' with `if`:

```
enum OptionalInt {
    Value(i32),
    Missing,
}

let x = OptionalInt::Value(5);

match x {
    OptionalInt::Value(i) if i > 5 => println!("Got an int bigger than five!"),
    OptionalInt::Value(..) => println!("Got an int!"),
    OptionalInt::Missing => println!("No such luck."),
}
```

This prints Got an int!.

### 5.15.6 ref and ref mut

If you want to get a reference (section 5.9, page 138), use the `ref` keyword:

```
let x = 5;

match x {
    ref r => println!("Got a reference to {}", r),
}
```

This prints Got a reference to 5.

Here, the `r` inside the `match` has the type `&i32`. In other words, the `ref` keyword *creates* a reference, for use in the pattern. If you need a mutable reference, `ref mut` will work in the same way:

```
let mut x = 5;

match x {
    ref mut mr => println!("Got a mutable reference to {}", mr),
}
```

### 5.15.7 Destructuring

If you have a compound data type, like a `struct` (section 5.12, page 153), you can destructure it inside of a pattern:

```
struct Point {
    x: i32,
    y: i32,
}
```

```
let origin = Point { x: 0, y: 0 };

match origin {
  Point { x: x, y: y } => println!("{}", x, y),
}
```

If we only care about some of the values, we don't have to give them all names:

```
struct Point {
  x: i32,
  y: i32,
}

let origin = Point { x: 0, y: 0 };

match origin {
  Point { x: x, .. } => println!("x is {}", x),
}
```

This prints `x is 0`.

You can do this kind of match on any member, not just the first:

```
struct Point {
  x: i32,
  y: i32,
}

let origin = Point { x: 0, y: 0 };

match origin {
  Point { y: y, .. } => println!("y is {}", y),
}
```

This prints `y is 0`.

This ‘destructuring’ behavior works on any compound data type, like tuples<sup>26</sup> or enums (section 5.13, page 156).

### 5.15.8 Mix and Match

Whew! That's a lot of different ways to match things, and they can all be mixed and matched, depending on what you're doing:

```
match x {
  Foo { x: Some(ref name), y: None } => ...
}
```

Patterns are very powerful. Make good use of them.

---

<sup>26</sup>[primitive-types.html#tuples](http://primitive-types.html#tuples)

## 5.16 Method Syntax

Functions are great, but if you want to call a bunch of them on some data, it can be awkward. Consider this code:

```
baz(bar(foo));
```

We would read this left-to right, and so we see ‘baz bar foo’. But this isn’t the order that the functions would get called in, that’s inside-out: ‘foo bar baz’. Wouldn’t it be nice if we could do this instead?

```
foo.bar().baz();
```

Luckily, as you may have guessed with the leading question, you can! Rust provides the ability to use this ‘method call syntax’ via the `impl` keyword.

### 5.16.1 Method calls

Here’s how it works:

```
struct Circle {  
    x: f64,  
    y: f64,  
    radius: f64,  
}  
  
impl Circle {  
    fn area(&self) -> f64 {  
        std::f64::consts::PI * (self.radius * self.radius)  
    }  
}  
  
fn main() {  
    let c = Circle { x: 0.0, y: 0.0, radius: 2.0 };  
    println!("{}", c.area());  
}
```

This will print 12.566371.

We’ve made a struct that represents a circle. We then write an `impl` block, and inside it, define a method, `area`.

Methods take a special first parameter, of which there are three variants: `self`, `&self`, and `&mut self`. You can think of this first parameter as being the `foo` in `foo.bar()`. The three variants correspond to the three kinds of things `foo` could be: `self` if it’s just a value on the stack, `&self` if it’s a reference, and `&mut self` if it’s a mutable reference. Because we took the `&self` parameter to `area`, we can use it just like any other parameter. Because we know it’s a `Circle`, we can access the `radius` just like we would with any other struct.

We should default to using `&self`, as you should prefer borrowing over taking ownership, as well as taking immutable references over mutable ones. Here's an example of all three variants:

```
struct Circle {
    x: f64,
    y: f64,
    radius: f64,
}

impl Circle {
    fn reference(&self) {
        println!("taking self by reference!");
    }

    fn mutable_reference(&mut self) {
        println!("taking self by mutable reference!");
    }

    fn takes_ownership(self) {
        println!("taking ownership of self!");
    }
}
```

### 5.16.2 Chaining method calls

So, now we know how to call a method, such as `foo.bar()`. But what about our original example, `foo.bar().baz()`? This is called 'method chaining', and we can do it by returning `self`.

```
struct Circle {
    x: f64,
    y: f64,
    radius: f64,
}

impl Circle {
    fn area(&self) -> f64 {
        std::f64::consts::PI * (self.radius * self.radius)
    }

    fn grow(&self, increment: f64) -> Circle {
        Circle { x: self.x, y: self.y, radius: self.radius + increment }
    }
}

fn main() {
    let c = Circle { x: 0.0, y: 0.0, radius: 2.0 };
    println!("{}", c.area());
}
```

```

    let d = c.grow(2.0).area();
    println!("{}", d);
}

```

Check the return type:

```

# struct Circle;
# impl Circle {
    fn grow(&self) -> Circle {
# Circle } }

```

We just say we’re returning a `Circle`. With this method, we can grow a new circle to any arbitrary size.

### 5.16.3 Associated functions

You can also define associated functions that do not take a `self` parameter. Here’s a pattern that’s very common in Rust code:

```

struct Circle {
    x: f64,
    y: f64,
    radius: f64,
}

impl Circle {
    fn new(x: f64, y: f64, radius: f64) -> Circle {
        Circle {
            x: x,
            y: y,
            radius: radius,
        }
    }
}

fn main() {
    let c = Circle::new(0.0, 0.0, 2.0);
}

```

This ‘associated function’ builds a new `Circle` for us. Note that associated functions are called with the `Struct::function()` syntax, rather than the `ref.method()` syntax. Some other languages call associated functions ‘static methods’.

### 5.16.4 Builder Pattern

Let’s say that we want our users to be able to create `Circles`, but we will allow them to only set the properties they care about. Otherwise, the `x` and `y` attributes will be `0.0`, and the `radius`

will be 1.0. Rust doesn't have method overloading, named arguments, or variable arguments. We employ the builder pattern instead. It looks like this:

```
struct Circle {
    x: f64,
    y: f64,
    radius: f64,
}

impl Circle {
    fn area(&self) -> f64 {
        std::f64::consts::PI * (self.radius * self.radius)
    }
}

struct CircleBuilder {
    x: f64,
    y: f64,
    radius: f64,
}

impl CircleBuilder {
    fn new() -> CircleBuilder {
        CircleBuilder { x: 0.0, y: 0.0, radius: 1.0, }
    }

    fn x(&mut self, coordinate: f64) -> &mut CircleBuilder {
        self.x = coordinate;
        self
    }

    fn y(&mut self, coordinate: f64) -> &mut CircleBuilder {
        self.y = coordinate;
        self
    }

    fn radius(&mut self, radius: f64) -> &mut CircleBuilder {
        self.radius = radius;
        self
    }

    fn finalize(&self) -> Circle {
        Circle { x: self.x, y: self.y, radius: self.radius }
    }
}

fn main() {
    let c = CircleBuilder::new()
        .x(1.0)
```

```

        .y(2.0)
        .radius(2.0)
        .finalize();

println!("area: {}", c.area());
println!("x: {}", c.x);
println!("y: {}", c.y);
}

```

What we've done here is make another struct, `CircleBuilder`. We've defined our builder methods on it. We've also defined our `area()` method on `Circle`. We also made one more method on `CircleBuilder`: `finalize()`. This method creates our final `Circle` from the builder. Now, we've used the type system to enforce our concerns: we can use the methods on `CircleBuilder` to constrain making `Circles` in any way we choose.

## 5.17 Vectors

A 'vector' is a dynamic or 'growable' array, implemented as the standard library type `Vec<T>`<sup>27</sup>. The `T` means that we can have vectors of any type (see the chapter on generics (section 5.19, page 171) for more). Vectors always allocate their data on the heap. You can create them with the `vec!` macro:

```
let v = vec![1, 2, 3, 4, 5]; // v: Vec<i32>
```

(Notice that unlike the `println!` macro we've used in the past, we use square brackets `[]` with `vec!` macro. Rust allows you to use either in either situation, this is just convention.)

There's an alternate form of `vec!` for repeating an initial value:

```
let v = vec![0; 10]; // ten zeroes
```

### Accessing elements

To get the value at a particular index in the vector, we use `[]`s:

```
let v = vec![1, 2, 3, 4, 5];

println!("The third element of v is {}", v[2]);
```

The indices count from 0, so the third element is `v[2]`.

### Iterating

Once you have a vector, you can iterate through its elements with `for`. There are three versions:

<sup>27</sup><http://doc.rust-lang.org/std/vec/index.html>



```
let mut v = vec![1, 2, 3, 4, 5];

for i in &v {
    println!("A reference to {}", i);
}

for i in &mut v {
    println!("A mutable reference to {}", i);
}

for i in v {
    println!("Take ownership of the vector and its element {}", i);
}
```

Vectors have many more useful methods, which you can read about in their API documentation<sup>28</sup>.

## 5.18 Strings

Strings are an important concept for any programmer to master. Rust's string handling system is a bit different from other languages, due to its systems focus. Any time you have a data structure of variable size, things can get tricky, and strings are a re-sizable data structure. That being said, Rust's strings also work differently than in some other systems languages, such as C.

Let's dig into the details. A 'string' is a sequence of Unicode scalar values encoded as a stream of UTF-8 bytes. All strings are guaranteed to be a valid encoding of UTF-8 sequences. Additionally, unlike some systems languages, strings are not null-terminated and can contain null bytes.

Rust has two main types of strings: `&str` and `String`. Let's talk about `&str` first. These are called 'string slices'. String literals are of the type `&'static str`:

```
let string = "Hello there."; // string: &'static str
```

This string is statically allocated, meaning that it's saved inside our compiled program, and exists for the entire duration it runs. The `string` binding is a reference to this statically allocated string. String slices have a fixed size, and cannot be mutated.

A `String`, on the other hand, is a heap-allocated string. This string is growable, and is also guaranteed to be UTF-8. Strings are commonly created by converting from a string slice using the `to_string` method.

```
let mut s = "Hello".to_string(); // mut s: String
println!("{}", s);

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

Strings will coerce into `&str` with an `&`:

<sup>28</sup><http://doc.rust-lang.org/std/vec/index.html>

```
fn takes_slice(slice: &str) {
    println!("Got: {}", slice);
}

fn main() {
    let s = "Hello".to_string();
    takes_slice(&s);
}
```

Viewing a `String` as a `&str` is cheap, but converting the `&str` to a `String` involves allocating memory. No reason to do that unless you have to!

## Indexing

Because strings are valid UTF-8, strings do not support indexing:

```
let s = "hello";

println!("The first letter of s is {}", s[0]); // ERROR!!!
```

Usually, access to a vector with `[]` is very fast. But, because each character in a UTF-8 encoded string can be multiple bytes, you have to walk over the string to find the `n` letter of a string. This is a significantly more expensive operation, and we don't want to be misleading. Furthermore, 'letter' isn't something defined in Unicode, exactly. We can choose to look at a string as individual bytes, or as codepoints:

```
let hachiko = " 忠犬ハチ公";

for b in hachiko.as_bytes() {
    print!("{}", b);
}

println!("");

for c in hachiko.chars() {
    print!("{}", c);
}

println!("");
```

This prints:

```
229, 191, 160, 231, 138, 172, 227, 131, 143, 227, 131, 129, 229, 133, 172,
忠, 犬, ハ, チ, 公,
```

As you can see, there are more bytes than chars.

You can get something similar to an index like this:

```
let dog = hachiko.chars().nth(1); // kinda like hachiko[1]
```

This emphasizes that we have to go through the whole list of `chars`.

### Concatenation

If you have a `String`, you can concatenate a `&str` to the end of it:

```
let hello = "Hello ".to_string();
let world = "world!";

let hello_world = hello + world;
```

But if you have two `Strings`, you need an `&`:

```
let hello = "Hello ".to_string();
let world = "world!".to_string();

let hello_world = hello + &world;
```

This is because `&String` can automatically coerce to a `&str`. This is a feature called ‘`Deref` coercions’ (section 5.34, page 217).

## 5.19 Generics

Sometimes, when writing a function or data type, we may want it to work for multiple types of arguments. Luckily, Rust has a feature that gives us a better way: generics. Generics are called ‘parametric polymorphism’ in type theory, which means that they are types or functions that have multiple forms (‘poly’ is multiple, ‘morph’ is form) over a given parameter (‘parametric’).

Anyway, enough with type theory, let’s check out some generic code. Rust’s standard library provides a type, `Option<T>`, that’s generic:

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

The `<T>` part, which you’ve seen a few times before, indicates that this is a generic data type. Inside the declaration of our enum, wherever we see a `T`, we substitute that type for the same type used in the generic. Here’s an example of using `Option<T>`, with some extra type annotations:

```
let x: Option<i32> = Some(5);
```

In the type declaration, we say `Option<i32>`. Note how similar this looks to `Option<T>`. So, in this particular `Option`, `T` has the value of `i32`. On the right-hand side of the binding, we do make a `Some(T)`, where `T` is `5`. Since that’s an `i32`, the two sides match, and Rust is happy. If they didn’t match, we’d get an error:

```
let x: Option<f64> = Some(5);
// error: mismatched types: expected `core::option::Option<f64>`,
// found `core::option::Option<_>` (expected f64 but found integral variable)
```

That doesn’t mean we can’t make `Option<T>`s that hold an `f64`! They just have to match up:

```
let x: Option<i32> = Some(5);
let y: Option<f64> = Some(5.0f64);
```

This is just fine. One definition, multiple uses.

Generics don’t have to only be generic over one type. Consider another type from Rust’s standard library that’s similar, `Result<T, E>`:

```
enum Result<T, E> {
    Ok(T),
    Err(E),
}
```

This type is generic over *two* types: `T` and `E`. By the way, the capital letters can be any letter you’d like. We could define `Result<T, E>` as:

```
enum Result<A, Z> {
    Ok(A),
    Err(Z),
}
```

if we wanted to. Convention says that the first generic parameter should be `T`, for ‘type’, and that we use `E` for ‘error’. Rust doesn’t care, however.

The `Result<T, E>` type is intended to be used to return the result of a computation, and to have the ability to return an error if it didn’t work out.

## Generic functions

We can write functions that take generic types with a similar syntax:

```
fn takes_anything<T>(x: T) {
    // do something with x
}
```

The syntax has two parts: the `<T>` says “this function is generic over one type, `T`”, and the `x: T` says “`x` has the type `T`.”

Multiple arguments can have the same generic type:

```
fn takes_two_of_the_same_things<T>(x: T, y: T) {
    // ...
}
```

We could write a version that takes multiple types:

```
fn takes_two_things<T, U>(x: T, y: U) {
    // ...
}
```

Generic functions are most useful with ‘trait bounds’, which we’ll cover in the section on traits (section 5.20, page 173).

### Generic structs

You can store a generic type in a `struct` as well:

```
struct Point<T> {
    x: T,
    y: T,
}

let int_origin = Point { x: 0, y: 0 };
let float_origin = Point { x: 0.0, y: 0.0 };
```

Similarly to functions, the `<T>` is where we declare the generic parameters, and we then use `x: T` in the type declaration, too.

## 5.20 Traits

Do you remember the `impl` keyword, used to call a function with method syntax (section 5.16, page 164)?

```
struct Circle {
    x: f64,
    y: f64,
    radius: f64,
}

impl Circle {
    fn area(&self) -> f64 {
        std::f64::consts::PI * (self.radius * self.radius)
    }
}
```

Traits are similar, except that we define a trait with just the method signature, then implement the trait for that struct. Like this:

```
struct Circle {
    x: f64,
    y: f64,
    radius: f64,
}

trait HasArea {
    fn area(&self) -> f64;
}

impl HasArea for Circle {
    fn area(&self) -> f64 {
        std::f64::consts::PI * (self.radius * self.radius)
    }
}
```

As you can see, the `trait` block looks very similar to the `impl` block, but we don't define a body, just a type signature. When we `impl` a trait, we use `impl Trait for Item`, rather than just `impl Item`.

We can use traits to constrain our generics. Consider this function, which does not compile, and gives us a similar error:

```
fn print_area<T>(shape: T) {
    println!("This shape has an area of {}", shape.area());
}
```

Rust complains:

```
error: type `T` does not implement any method in scope named `area`
```

Because `T` can be any type, we can't be sure that it implements the `area` method. But we can add a 'trait constraint' to our generic `T`, ensuring that it does:

```
fn print_area<T: HasArea>(shape: T) {
    println!("This shape has an area of {}", shape.area());
}
```

The syntax `<T: HasArea>` means any type that implements the `HasArea` trait. Because traits define function type signatures, we can be sure that any type which implements `HasArea` will have an `.area()` method.

Here's an extended example of how this works:

```
trait HasArea {
    fn area(&self) -> f64;
}

struct Circle {
    x: f64,
    y: f64,
    radius: f64,
}

impl HasArea for Circle {
    fn area(&self) -> f64 {
        std::f64::consts::PI * (self.radius * self.radius)
    }
}

struct Square {
    x: f64,
    y: f64,
    side: f64,
}

impl HasArea for Square {
    fn area(&self) -> f64 {
        self.side * self.side
    }
}

fn print_area<T: HasArea>(shape: T) {
    println!("This shape has an area of {}", shape.area());
}

fn main() {
    let c = Circle {
        x: 0.0f64,
        y: 0.0f64,
        radius: 1.0f64,
    };

    let s = Square {
        x: 0.0f64,
        y: 0.0f64,
        side: 1.0f64,
    };

    print_area(c);
    print_area(s);
}
```

This program outputs:

```
This shape has an area of 3.141593
This shape has an area of 1
```

As you can see, `print_area` is now generic, but also ensures that we have passed in the correct types. If we pass in an incorrect type:

```
print_area(5);
```

We get a compile-time error:

```
error: failed to find an implementation of trait main::HasArea for int
```

So far, we've only added trait implementations to structs, but you can implement a trait for any type. So technically, we *could* implement `HasArea` for `i32`:

```
trait HasArea {
    fn area(&self) -> f64;
}

impl HasArea for i32 {
    fn area(&self) -> f64 {
        println!("this is silly");

        *self as f64
    }
}

5.area();
```

It is considered poor style to implement methods on such primitive types, even though it is possible.

This may seem like the Wild West, but there are two other restrictions around implementing traits that prevent this from getting out of hand. The first is that if the trait isn't defined in your scope, it doesn't apply. Here's an example: the standard library provides a `Write`<sup>29</sup> trait which adds extra functionality to `Files`, for doing file I/O. By default, a `File` won't have its methods:

```
let mut f = std::fs::File::open("foo.txt").ok().expect("Couldn't open foo.txt");
let result = f.write("whatever".as_bytes());
```

Here's the error:

```
error: type `std::fs::File` does not implement any method in scope named `write`
```

```
let result = f.write(b"whatever");
                ^~~~~~
```

<sup>29</sup><http://doc.rust-lang.org/std/io/trait.Write.html>



We need to use the `Write` trait first:

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

let mut f = std::fs::File::open("foo.txt").ok().expect("Couldn't open foo.txt");
let result = f.write("whatever".as_bytes());
```

This will compile without error.

This means that even if someone does something bad like add methods to `int`, it won't affect you, unless you use that trait.

There's one more restriction on implementing traits. Either the trait or the type you're writing the `impl` for must be defined by you. So, we could implement the `HasArea` type for `i32`, because `HasArea` is in our code. But if we tried to implement `Float`, a trait provided by Rust, for `i32`, we could not, because neither the trait nor the type are in our code.

One last thing about traits: generic functions with a trait bound use 'monomorphization' (mono: one, morph: form), so they are statically dispatched. What's that mean? Check out the chapter on trait objects (section 5.23, page 183) for more details.

### 5.20.1 Multiple trait bounds

You've seen that you can bound a generic type parameter with a trait:

```
fn foo<T: Clone>(x: T) {
    x.clone();
}
```

If you need more than one bound, you can use `+`:

```
use std::fmt::Debug;

fn foo<T: Clone + Debug>(x: T) {
    x.clone();
    println!("{:?}", x);
}
```

`T` now needs to be both `Clone` as well as `Debug`.

### 5.20.2 Where clause

Writing functions with only a few generic types and a small number of trait bounds isn't too bad, but as the number increases, the syntax gets increasingly awkward:

```
use std::fmt::Debug;

fn foo<T: Clone, K: Clone + Debug>(x: T, y: K) {
```

```

    x.clone();
    y.clone();
    println!("{:?}", y);
}

```

The name of the function is on the far left, and the parameter list is on the far right. The bounds are getting in the way.

Rust has a solution, and it's called a 'where clause':

```

use std::fmt::Debug;

fn foo<T: Clone, K: Clone + Debug>(x: T, y: K) {
    x.clone();
    y.clone();
    println!("{:?}", y);
}

fn bar<T, K>(x: T, y: K) where T: Clone, K: Clone + Debug {
    x.clone();
    y.clone();
    println!("{:?}", y);
}

fn main() {
    foo("Hello", "world");
    bar("Hello", "workd");
}

```

`foo()` uses the syntax we showed earlier, and `bar()` uses a `where` clause. All you need to do is leave off the bounds when defining your type parameters, and then add `where` after the parameter list. For longer lists, whitespace can be added:

```

use std::fmt::Debug;

fn bar<T, K>(x: T, y: K)
    where T: Clone,
           K: Clone + Debug {

    x.clone();
    y.clone();
    println!("{:?}", y);
}

```

This flexibility can add clarity in complex situations.

`where` is also more powerful than the simpler syntax. For example:

```

trait ConvertTo<Output> {
    fn convert(&self) -> Output;
}

impl ConvertTo<i64> for i32 {
    fn convert(&self) -> i64 { *self as i64 }
}

// can be called with T == i32
fn normal<T: ConvertTo<i64>>(x: &T) -> i64 {
    x.convert()
}

// can be called with T == i64
fn inverse<T>() -> T
    // this is using ConvertTo as if it were "ConvertFrom<i32>"
    where i32: ConvertTo<T> {
    li32.convert()
}

```

This shows off the additional feature of `where` clauses: they allow bounds where the left-hand side is an arbitrary type (`i32` in this case), not just a plain type parameter (like `T`).

### Default methods

There's one last feature of traits we should cover: default methods. It's easiest just to show an example:

```

trait Foo {
    fn bar(&self);

    fn baz(&self) { println!("We called baz."); }
}

```

Implementors of the `Foo` trait need to implement `bar()`, but they don't need to implement `baz()`. They'll get this default behavior. They can override the default if they so choose:

```

struct UseDefault;

impl Foo for UseDefault {
    fn bar(&self) { println!("We called bar."); }
}

struct OverrideDefault;

impl Foo for OverrideDefault {
    fn bar(&self) { println!("We called bar."); }
}

```

```

    fn baz(&self) { println!("Override baz!"); }
}

let default = UseDefault;
default.baz(); // prints "We called baz."

let over = OverrideDefault;
over.baz(); // prints "Override baz!"

```

### 5.20.3 Inheritance

Sometimes, implementing a trait requires implementing another trait:

```

trait Foo {
    fn foo(&self);
}

trait FooBar : Foo {
    fn foobar(&self);
}

```

Implementors of `FooBar` must also implement `Foo`, like this:

```

struct Baz;

impl Foo for Baz {
    fn foo(&self) { println!("foo"); }
}

impl FooBar for Baz {
    fn foobar(&self) { println!("foobar"); }
}

```

If we forget to implement `Foo`, Rust will tell us:

```
error: the trait `main::Foo` is not implemented for the type `main::Baz` [E0277]
```

## 5.21 Drop

Now that we've discussed traits, let's talk about a particular trait provided by the Rust standard library, `Drop`<sup>30</sup>. The `Drop` trait provides a way to run some code when a value goes out of scope. For example:

---

<sup>30</sup><http://doc.rust-lang.org/std/ops/trait.Drop.html>

```

struct HasDrop;

impl Drop for HasDrop {
    fn drop(&mut self) {
        println!("Dropping!");
    }
}

fn main() {
    let x = HasDrop;

    // do stuff

} // x goes out of scope here

```

When `x` goes out of scope at the end of `main()`, the code for `Drop` will run. `Drop` has one method, which is also called `drop()`. It takes a mutable reference to `self`.

That's it! The mechanics of `Drop` are very simple, but there are some subtleties. For example, values are dropped in the opposite order they are declared. Here's another example:

```

struct Firework {
    strength: i32,
}

impl Drop for Firework {
    fn drop(&mut self) {
        println!("BOOM times {}", self.strength);
    }
}

fn main() {
    let firecracker = Firework { strength: 1 };
    let tnt = Firework { strength: 100 };
}

```

This will output:

```

BOOM times 100!!!
BOOM times 1!!!

```

The TNT goes off before the firecracker does, because it was declared afterwards. Last in, first out.

So what is `Drop` good for? Generally, `Drop` is used to clean up any resources associated with a `struct`. For example, the `Arc<T>` type<sup>31</sup> is a reference-counted type. When `Drop` is called, it will decrement the reference count, and if the total number of references is zero, will clean up the underlying value.

---

<sup>31</sup><http://doc.rust-lang.org/std/sync/struct.Arc.html>

## 5.22 if let

`if let` allows you to combine `if` and `let` together to reduce the overhead of certain kinds of pattern matches.

For example, let's say we have some sort of `Option<T>`. We want to call a function on it if it's `Some<T>`, but do nothing if it's `None`. That looks like this:

```
match option {
    Some(x) => { foo(x) },
    None => {},
}
```

We don't have to use `match` here, for example, we could use `if`:

```
if option.is_some() {
    let x = option.unwrap();
    foo(x);
}
```

Neither of these options is particularly appealing. We can use `if let` to do the same thing in a nicer way:

```
if let Some(x) = option {
    foo(x);
}
```

If a pattern (section 5.15, page 159) matches successfully, it binds any appropriate parts of the value to the identifiers in the pattern, then evaluates the expression. If the pattern doesn't match, nothing happens.

If you'd rather do something else when the pattern does not match, you can use `else`:

```
if let Some(x) = option {
    foo(x);
} else {
    bar();
}
```

### while let

In a similar fashion, `while let` can be used when you want to conditionally loop as long as a value matches a certain pattern. It turns code like this:

```
loop {
    match option {
        Some(x) => println!("{}", x),
        _ => break,
    }
}
```

Into code like this:

```
while let Some(x) = option {  
    println!("{}", x);  
}
```

## 5.23 Trait Objects

When code involves polymorphism, there needs to be a mechanism to determine which specific version is actually run. This is called ‘dispatch’. There are two major forms of dispatch: static dispatch and dynamic dispatch. While Rust favors static dispatch, it also supports dynamic dispatch through a mechanism called ‘trait objects’.

### Background

For the rest of this chapter, we’ll need a trait and some implementations. Let’s make a simple one, `Foo`. It has one method that is expected to return a `String`.

```
trait Foo {  
    fn method(&self) -> String;  
}
```

We’ll also implement this trait for `u8` and `String`:

```
impl Foo for u8 {  
    fn method(&self) -> String { format!("u8: {}", *self) }  
}  
  
impl Foo for String {  
    fn method(&self) -> String { format!("string: {}", *self) }  
}
```

### Static dispatch

We can use this trait to perform static dispatch with trait bounds:

```
fn do_something<T: Foo>(x: T) {  
    x.method();  
}  
  
fn main() {  
    let x = 5u8;  
    let y = "Hello".to_string();  
  
    do_something(x);  
    do_something(y);  
}
```

Rust uses ‘monomorphization’ to perform static dispatch here. This means that Rust will create a special version of `do_something()` for both `u8` and `String`, and then replace the call sites with calls to these specialized functions. In other words, Rust generates something like this:

```
fn do_something_u8(x: u8) {
    x.method();
}

fn do_something_string(x: String) {
    x.method();
}

fn main() {
    let x = 5u8;
    let y = "Hello".to_string();

    do_something_u8(x);
    do_something_string(y);
}
```

This has a great upside: static dispatch allows function calls to be inlined because the callee is known at compile time, and inlining is the key to good optimization. Static dispatch is fast, but it comes at a tradeoff: ‘code bloat’, due to many copies of the same function existing in the binary, one for each type.

Furthermore, compilers aren’t perfect and may “optimize” code to become slower. For example, functions inlined too eagerly will bloat the instruction cache (cache rules everything around us). This is part of the reason that `#[inline]` and `#[inline(always)]` should be used carefully, and one reason why using a dynamic dispatch is sometimes more efficient.

However, the common case is that it is more efficient to use static dispatch, and one can always have a thin statically-dispatched wrapper function that does a dynamic dispatch, but not vice versa, meaning static calls are more flexible. The standard library tries to be statically dispatched where possible for this reason.

## Dynamic dispatch

Rust provides dynamic dispatch through a feature called ‘trait objects’. Trait objects, like `&Foo` or `Box<Foo>`, are normal values that store a value of *any* type that implements the given trait, where the precise type can only be known at runtime.

A trait object can be obtained from a pointer to a concrete type that implements the trait by *casting* it (e.g. `&x as &Foo`) or *coercing* it (e.g. using `&x` as an argument to a function that takes `&Foo`).

These trait object coercions and casts also work for pointers like `&mut T` to `&mut Foo` and `Box<T>` to `Box<Foo>`, but that’s all at the moment. Coercions and casts are identical.

This operation can be seen as ‘erasing’ the compiler’s knowledge about the specific type of the pointer, and hence trait objects are sometimes referred to as ‘type erasure’.



Coming back to the example above, we can use the same trait to perform dynamic dispatch with trait objects by casting:

```
fn do_something(x: &Foo) {
    x.method();
}

fn main() {
    let x = 5u8;
    do_something(&x as &Foo);
}
```

or by coercing:

```
fn do_something(x: &Foo) {
    x.method();
}

fn main() {
    let x = "Hello".to_string();
    do_something(&x);
}
```

A function that takes a trait object is not specialized to each of the types that implements `Foo`: only one copy is generated, often (but not always) resulting in less code bloat. However, this comes at the cost of requiring slower virtual function calls, and effectively inhibiting any chance of inlining and related optimizations from occurring.

**Why pointers?** Rust does not put things behind a pointer by default, unlike many managed languages, so types can have different sizes. Knowing the size of the value at compile time is important for things like passing it as an argument to a function, moving it about on the stack and allocating (and deallocating) space on the heap to store it.

For `Foo`, we would need to have a value that could be at least either a `String` (24 bytes) or a `u8` (1 byte), as well as any other type for which dependent crates may implement `Foo` (any number of bytes at all). There's no way to guarantee that this last point can work if the values are stored without a pointer, because those other types can be arbitrarily large.

Putting the value behind a pointer means the size of the value is not relevant when we are tossing a trait object around, only the size of the pointer itself.

**Representation** The methods of the trait can be called on a trait object via a special record of function pointers traditionally called a 'vtable' (created and managed by the compiler).

Trait objects are both simple and complicated: their core representation and layout is quite straight-forward, but there are some curly error messages and surprising behaviors to discover.

Let's start simple, with the runtime representation of a trait object. The `std::raw` module contains structs with layouts that are the same as the complicated built-in types, including trait objects<sup>32</sup>:

```
pub struct TraitObject {
    pub data: *mut (),
    pub vtable: *mut (),
}
```

That is, a trait object like `&Foo` consists of a 'data' pointer and a 'vtable' pointer.

The data pointer addresses the data (of some unknown type `T`) that the trait object is storing, and the vtable pointer points to the vtable ('virtual method table') corresponding to the implementation of `Foo` for `T`.

A vtable is essentially a struct of function pointers, pointing to the concrete piece of machine code for each method in the implementation. A method call like `trait_object.method()` will retrieve the correct pointer out of the vtable and then do a dynamic call of it. For example:

```
struct FooVtable {
    destructor: fn(*mut ()),
    size: usize,
    align: usize,
    method: fn(*const ()) -> String,
}

// u8:

fn call_method_on_u8(x: *const ()) -> String {
    // the compiler guarantees that this function is only called
    // with `x` pointing to a u8
    let byte: &u8 = unsafe { &*(x as *const u8) };

    byte.method()
}

static Foo_for_u8_vtable: FooVtable = FooVtable {
    destructor: /* compiler magic */,
    size: 1,
    align: 1,

    // cast to a function pointer
    method: call_method_on_u8 as fn(*const ()) -> String,
};

// String:
```

<sup>32</sup><http://doc.rust-lang.org/std/raw/struct.TraitObject.html>

```
fn call_method_on_String(x: *const ()) -> String {
    // the compiler guarantees that this function is only called
    // with `x` pointing to a String
    let string: &String = unsafe { &*(x as *const String) };

    string.method()
}

static Foo_for_String_vtable: FooVtable = FooVtable {
    destructor: /* compiler magic */,
    // values for a 64-bit computer, halve them for 32-bit ones
    size: 24,
    align: 8,

    method: call_method_on_String as fn(*const ()) -> String,
};
```

The `destructor` field in each vtable points to a function that will clean up any resources of the vtable's type, for `u8` it is trivial, but for `String` it will free the memory. This is necessary for owning trait objects like `Box<Foo>`, which need to clean-up both the `Box` allocation as well as the internal type when they go out of scope. The `size` and `align` fields store the size of the erased type, and its alignment requirements; these are essentially unused at the moment since the information is embedded in the destructor, but will be used in the future, as trait objects are progressively made more flexible.

Suppose we've got some values that implement `Foo`, then the explicit form of construction and use of `Foo` trait objects might look a bit like (ignoring the type mismatches: they're all just pointers anyway):

```
let a: String = "foo".to_string();
let x: u8 = 1;

// let b: &Foo = &a;
let b = TraitObject {
    // store the data
    data: &a,
    // store the methods
    vtable: &Foo_for_String_vtable
};

// let y: &Foo = x;
let y = TraitObject {
    // store the data
    data: &x,
    // store the methods
    vtable: &Foo_for_u8_vtable
};

// b.method();
```

```
(b.vtable.method)(b.data);

// y.method();
(y.vtable.method)(y.data);
```

If `b` or `y` were owning trait objects (`Box<Foo>`), there would be a `(b.vtable.destructor)(b.data)` (respectively `y`) call when they went out of scope.

## 5.24 Closures

Rust not only has named functions, but anonymous functions as well. Anonymous functions that have an associated environment are called ‘closures’, because they close over an environment. Rust has a really great implementation of them, as we’ll see.

### 5.24.1 Syntax

Closures look like this:

```
let plus_one = |x: i32| x + 1;

assert_eq!(2, plus_one(1));
```

We create a binding, `plus_one`, and assign it to a closure. The closure’s arguments go between the pipes (`|`), and the body is an expression, in this case, `x + 1`. Remember that `{ }` is an expression, so we can have multi-line closures too:

```
let plus_two = |x| {
    let mut result: i32 = x;

    result += 1;
    result += 1;

    result
};

assert_eq!(4, plus_two(2));
```

You’ll notice a few things about closures that are a bit different than regular functions defined with `fn`. The first of which is that we did not need to annotate the types of arguments the closure takes or the values it returns. We can:

```
let plus_one = |x: i32| -> i32 { x + 1 };

assert_eq!(2, plus_one(1));
```

But we don't have to. Why is this? Basically, it was chosen for ergonomic reasons. While specifying the full type for named functions is helpful with things like documentation and type inference, the types of closures are rarely documented since they're anonymous, and they don't cause the kinds of error-at-a-distance that inferring named function types can.

The second is that the syntax is similar, but a bit different. I've added spaces here to make them look a little closer:

```
fn plus_one_v1 (x: i32) -> i32 { x + 1 }
let plus_one_v2 = |x: i32| -> i32 { x + 1 };
let plus_one_v3 = |x: i32|      x + 1 ;
```

Small differences, but they're similar in ways.

### 5.24.2 Closures and their environment

Closures are called such because they 'close over their environment'. It looks like this:

```
let num = 5;
let plus_num = |x: i32| x + num;

assert_eq!(10, plus_num(5));
```

This closure, `plus_num`, refers to a `let` binding in its scope: `num`. More specifically, it borrows the binding. If we do something that would conflict with that binding, we get an error. Like this one:

```
let mut num = 5;
let plus_num = |x: i32| x + num;

let y = &mut num;
```

Which errors with:

```
error: cannot borrow `num` as mutable because it is also borrowed as immutable
    let y = &mut num;
              ^~~

note: previous borrow of `num` occurs here due to use in closure; the immutable
      borrow prevents subsequent moves or mutable borrows of `num` until the borrow
      ends
    let plus_num = |x| x + num;
                  ^~~~~~

note: previous borrow ends here
fn main() {
    let mut num = 5;
    let plus_num = |x| x + num;
```

```

    let y = &mut num;
}
^

```

A verbose yet helpful error message! As it says, we can't take a mutable borrow on `num` because the closure is already borrowing it. If we let the closure go out of scope, we can:

```

let mut num = 5;
{
    let plus_num = |x: i32| x + num;

} // plus_num goes out of scope, borrow of num ends

let y = &mut num;

```

If your closure requires it, however, Rust will take ownership and move the environment instead:

```

let nums = vec![1, 2, 3];

let takes_nums = || nums;

println!("{:?}", nums);

```

This gives us:

```

note: `nums` moved into closure environment here because it has type
      `[closure(() -> collections::vec::Vec<i32>)]`, which is non-copyable
let takes_nums = || nums;
                  ^~~~~~

```

`Vec<T>` has ownership over its contents, and therefore, when we refer to it in our closure, we have to take ownership of `nums`. It's the same as if we'd passed `nums` to a function that took ownership of it.

### move closures

We can force our closure to take ownership of its environment with the `move` keyword:

```

let num = 5;

let owns_num = move |x: i32| x + num;

```

Now, even though the keyword is `move`, the variables follow normal move semantics. In this case, 5 implements `Copy`, and so `owns_num` takes ownership of a copy of `num`. So what's the difference?

```
let mut num = 5;

{
    let mut add_num = |x: i32| num += x;

    add_num(5);
}

assert_eq!(10, num);
```

So in this case, our closure took a mutable reference to `num`, and then when we called `add_num`, it mutated the underlying value, as we'd expect. We also needed to declare `add_num` as `mut` too, because we're mutating its environment.

If we change to a `move` closure, it's different:

```
let mut num = 5;

{
    let mut add_num = move |x: i32| num += x;

    add_num(5);
}

assert_eq!(5, num);
```

We only get 5. Rather than taking a mutable borrow out on our `num`, we took ownership of a copy.

Another way to think about `move` closures: they give a closure its own stack frame. Without `move`, a closure may be tied to the stack frame that created it, while a `move` closure is self-contained. This means that you cannot generally return a non-`move` closure from a function, for example.

But before we talk about taking and returning closures, we should talk some more about the way that closures are implemented. As a systems language, Rust gives you tons of control over what your code does, and closures are no different.

### 5.24.3 Closure implementation

Rust's implementation of closures is a bit different than other languages. They are effectively syntax sugar for traits. You'll want to make sure to have read the traits chapter (section 5.20, page 173) before this one, as well as the chapter on trait objects (section 5.23, page 183).

Got all that? Good.

The key to understanding how closures work under the hood is something a bit strange: Using `()` to call a function, like `foo()`, is an overloadable operator. From this, everything else clicks into place. In Rust, we use the trait system to overload operators. Calling functions is no different. We have three separate traits to overload with:

```

pub trait Fn<Args> : FnMut<Args> {
    extern "rust-call" fn call(&self, args: Args) -> Self::Output;
}

pub trait FnMut<Args> : FnOnce<Args> {
    extern "rust-call" fn call_mut(&mut self, args: Args) -> Self::Output;
}

pub trait FnOnce<Args> {
    type Output;

    extern "rust-call" fn call_once(self, args: Args) -> Self::Output;
}

```

You'll notice a few differences between these traits, but a big one is `self`: `Fn` takes `&self`, `FnMut` takes `&mut self`, and `FnOnce` takes `self`. This covers all three kinds of `self` via the usual method call syntax. But we've split them up into three traits, rather than having a single one. This gives us a large amount of control over what kind of closures we can take.

The `|| {}` syntax for closures is sugar for these three traits. Rust will generate a struct for the environment, `impl` the appropriate trait, and then use it.

#### 5.24.4 Taking closures as arguments

Now that we know that closures are traits, we already know how to accept and return closures: just like any other trait!

This also means that we can choose static vs dynamic dispatch as well. First, let's write a function which takes something callable, calls it, and returns the result:

```

fn call_with_one<F>(some_closure: F) -> i32
    where F : Fn(i32) -> i32 {

    some_closure(1)
}

let answer = call_with_one(|x| x + 2);

assert_eq!(3, answer);

```

We pass our closure, `|x| x + 2`, to `call_with_one`. It just does what it suggests: it calls the closure, giving it `1` as an argument.

Let's examine the signature of `call_with_one` in more depth:

```

fn call_with_one<F>(some_closure: F) -> i32

```

We take one parameter, and it has the type `F`. We also return a `i32`. This part isn't interesting. The next part is:



```
where F : Fn(i32) -> i32 {
```

Because `Fn` is a trait, we can bound our generic with it. In this case, our closure takes a `i32` as an argument and returns an `i32`, and so the generic bound we use is `Fn(i32) -> i32`.

There's one other key point here: because we're bounding a generic with a trait, this will get monomorphized, and therefore, we'll be doing static dispatch into the closure. That's pretty neat. In many languages, closures are inherently heap allocated, and will always involve dynamic dispatch. In Rust, we can stack allocate our closure environment, and statically dispatch the call. This happens quite often with iterators and their adapters, which often take closures as arguments.

Of course, if we want dynamic dispatch, we can get that too. A trait object handles this case, as usual:

```
fn call_with_one(some_closure: &Fn(i32) -> i32) -> i32 {
    some_closure(1)
}

let answer = call_with_one(&|x| x + 2);

assert_eq!(3, answer);
```

Now we take a trait object, a `&Fn`. And we have to make a reference to our closure when we pass it to `call_with_one`, so we use `&|`.

### 5.24.5 Returning closures

It's very common for functional-style code to return closures in various situations. If you try to return a closure, you may run into an error. At first, it may seem strange, but we'll figure it out. Here's how you'd probably try to return a closure from a function:

```
fn factory() -> (Fn(i32) -> Vec<i32>) {
    let vec = vec![1, 2, 3];

    |n| vec.push(n)
}

let f = factory();

let answer = f(4);
assert_eq!(vec![1, 2, 3, 4], answer);
```

This gives us these long, related errors:

```
error: the trait `core::marker::Sized` is not implemented for the type
`core::ops::Fn(i32) -> collections::vec::Vec<i32>` [E0277]
```

```
f = factory();
^
```

```
note: `core::ops::Fn(i32) -> collections::vec::Vec<i32>` does not have a
constant size known at compile-time
```

```
f = factory();
^
```

```
error: the trait `core::marker::Sized` is not implemented for the type
`core::ops::Fn(i32) -> collections::vec::Vec<i32>` [E0277]
```

```
factory() -> (Fn(i32) -> Vec<i32>) {
    ^~~~~~
```

```
note: `core::ops::Fn(i32) -> collections::vec::Vec<i32>` does not have a constant size known at compile
factory() -> (Fn(i32) -> Vec<i32>) {
    ^~~~~~
```

In order to return something from a function, Rust needs to know what size the return type is. But since `Fn` is a trait, it could be various things of various sizes: many different types can implement `Fn`. An easy way to give something a size is to take a reference to it, as references have a known size. So we'd write this:

```
fn factory() -> &(Fn(i32) -> Vec<i32>) {
    let vec = vec![1, 2, 3];

    |n| vec.push(n)
}

let f = factory();

let answer = f(4);
assert_eq!(vec![1, 2, 3, 4], answer);
```

But we get another error:

```
error: missing lifetime specifier [E0106]
```

```
fn factory() -> &(Fn(i32) -> i32) {
    ^~~~~~
```

Right. Because we have a reference, we need to give it a lifetime. But our `factory()` function takes no arguments, so elision doesn't kick in here. What lifetime can we choose? `'static`:

```
fn factory() -> &'static (Fn(i32) -> i32) {
    let num = 5;

    |x| x + num
}

let f = factory();

let answer = f(1);
assert_eq!(6, answer);
```

But we get another error:

```
error: mismatched types:
  expected `&'static core::ops::Fn(i32) -> i32`,
  found `[closure <anon>:7:9: 7:20]`
(expected &-ptr,
  found closure) [E0308]
    |x| x + num
    ^~~~~~
```

This error is letting us know that we don't have a `&'static Fn(i32) -> i32`, we have a `[closure <anon>:7:9: 7:20]`. Wait, what?

Because each closure generates its own environment `struct` and implementation of `Fn` and friends, these types are anonymous. They exist just solely for this closure. So Rust shows them as `closure <anon>`, rather than some autogenerated name.

But why doesn't our closure implement `&'static Fn`? Well, as we discussed before, closures borrow their environment. And in this case, our environment is based on a stack-allocated `5`, the `num` variable binding. So the borrow has a lifetime of the stack frame. So if we returned this closure, the function call would be over, the stack frame would go away, and our closure is capturing an environment of garbage memory!

So what to do? This *almost* works:

```
fn factory() -> Box<Fn(i32) -> i32> {
    let num = 5;

    Box::new(|x| x + num)
}
let f = factory();

let answer = f(1);
assert_eq!(6, answer);
```

We use a trait object, by `Boxing` up the `Fn`. There's just one last problem:

```
error: `num` does not live long enough
Box::new(|x| x + num)
    ^~~~~~
```

We still have a reference to the parent stack frame. With one last fix, we can make this work:

```
fn factory() -> Box<Fn(i32) -> i32> {
    let num = 5;

    Box::new(move |x| x + num)
}
let f = factory();
```

```
let answer = f(1);
assert_eq!(6, answer);
```

By making the inner closure a `move Fn`, we create a new stack frame for our closure. By `Boxing` it up, we've given it a known size, and allowing it to escape our stack frame.

## 5.25 Universal Function Call Syntax

Sometimes, functions can have the same names. Consider this code:

```
trait Foo {
    fn f(&self);
}

trait Bar {
    fn f(&self);
}

struct Baz;

impl Foo for Baz {
    fn f(&self) { println!("Baz' s impl of Foo"); }
}

impl Bar for Baz {
    fn f(&self) { println!("Baz' s impl of Bar"); }
}

let b = Baz;
```

If we were to try to call `b.f()`, we'd get an error:

```
error: multiple applicable methods in scope [E0034]
b.f();
  ^~~
note: candidate #1 is defined in an impl of the trait `main::Foo` for the type
`main::Baz`
    fn f(&self) { println!("Baz' s impl of Foo"); }
    ^~~~~~
note: candidate #2 is defined in an impl of the trait `main::Bar` for the type
`main::Baz`
    fn f(&self) { println!("Baz' s impl of Bar"); }
    ^~~~~~
```

We need a way to disambiguate which method we need. This feature is called ‘universal function call syntax’, and it looks like this:

```
Foo::f(&b);
Bar::f(&b);
```

Let's break it down.

```
Foo::
Bar::
```

These halves of the invocation are the types of the two traits: **Foo** and **Bar**. This is what ends up actually doing the disambiguation between the two: Rust calls the one from the trait name you use.

```
f(&b)
```

When we call a method like `b.f()` using method syntax (section 5.16, page 164), Rust will automatically borrow `b` if `f()` takes `&self`. In this case, Rust will not, and so we need to pass an explicit `&b`.

### 5.25.1 Angle-bracket Form

The form of UFCS we just talked about:

```
Trait::method(args);
```

Is a short-hand. There's an expanded form of this that's needed in some situations:

```
<Type as Trait>::method(args);
```

The `<>::` syntax is a means of providing a type hint. The type goes inside the `<>`s. In this case, the type is `Type as Trait`, indicating that we want `Trait`'s version of `method` to be called here. The `as Trait` part is optional if it's not ambiguous. Same with the angle brackets, hence the shorter form.

Here's an example of using the longer form.

```
trait Foo {
    fn clone(&self);
}

#[derive(Clone)]
struct Bar;

impl Foo for Bar {
    fn clone(&self) {
        println!("Making a clone of Bar");

        <Bar as Clone>::clone(self);
    }
}
```

This will call the `Clone` trait's `clone()` method, rather than `Foo`'s.

## 5.26 Crates and Modules

When a project starts getting large, it's considered good software engineering practice to split it up into a bunch of smaller pieces, and then fit them together. It's also important to have a well-defined interface, so that some of your functionality is private, and some is public. To facilitate these kinds of things, Rust has a module system.

### 5.26.1 Basic terminology: Crates and Modules

Rust has two distinct terms that relate to the module system: 'crate' and 'module'. A crate is synonymous with a 'library' or 'package' in other languages. Hence "Cargo" as the name of Rust's package management tool: you ship your crates to others with Cargo. Crates can produce an executable or a library, depending on the project.

Each crate has an implicit *root module* that contains the code for that crate. You can then define a tree of sub-modules under that root module. Modules allow you to partition your code within the crate itself.

As an example, let's make a *phrases* crate, which will give us various phrases in different languages. To keep things simple, we'll stick to 'greetings' and 'farewells' as two kinds of phrases, and use English and Japanese (日本語) as two languages for those phrases to be in. We'll use this module layout:

```

                                     +-----+
                                     +---| greetings |
                                     | +-----+
                                     |
                               +-----+ |
                               +---| english |---+
                               | +-----+ | +-----+
                               | +-----+ | +---| farewells |
+-----+ | +-----+
| phrases |---+
+-----+ | +-----+
          | +-----+
          | +---| greetings |
          | +-----+ | +-----+
+---| japanese |--+
          +-----+ |
          | +-----+
          +---| farewells |
          +-----+

```

In this example, `phrases` is the name of our crate. All of the rest are modules. You can see that they form a tree, branching out from the crate *root*, which is the root of the tree: `phrases` itself.

Now that we have a plan, let's define these modules in code. To start, generate a new crate with Cargo:

```
$ cargo new phrases
$ cd phrases
```

If you remember, this generates a simple project for us:

```
$ tree .
.
├── Cargo.toml
└── src
    └── lib.rs
```

1 directory, 2 files

`src/lib.rs` is our crate root, corresponding to the `phrases` in our diagram above.

### 5.26.2 Defining Modules

To define each of our modules, we use the `mod` keyword. Let's make our `src/lib.rs` look like this:

```
mod english {
    mod greetings {
    }

    mod farewells {
    }
}

mod japanese {
    mod greetings {
    }

    mod farewells {
    }
}
```

After the `mod` keyword, you give the name of the module. Module names follow the conventions for other Rust identifiers: `lower_snake_case`. The contents of each module are within curly braces (`{}`).

Within a given `mod`, you can declare sub-mods. We can refer to sub-modules with double-colon (`::`) notation: our four nested modules are `english::greetings`, `english::farewells`, `japanese::greetings`, and `japanese::farewells`. Because these sub-modules are namespaced under their parent module, the names don't conflict: `english::greetings` and `japanese::greetings` are distinct, even though their names are both `greetings`.

Because this crate does not have a `main()` function, and is called `lib.rs`, Cargo will build this crate as a library:

```
$ cargo build
   Compiling phrases v0.0.1 (file:///home/you/projects/phrases)
$ ls target/debug
build  deps  examples  libphrases-a7448e02a0468eaa.rlib  native
```

`libphrase-hash.rlib` is the compiled crate. Before we see how to use this crate from another crate, let's break it up into multiple files.

### 5.26.3 Multiple file crates

If each crate were just one file, these files would get very large. It's often easier to split up crates into multiple files, and Rust supports this in two ways.

Instead of declaring a module like this:

```
mod english {
    // contents of our module go here
}
```

We can instead declare our module like this:

```
mod english;
```

If we do that, Rust will expect to find either a `english.rs` file, or a `english/mod.rs` file with the contents of our module.

Note that in these files, you don't need to re-declare the module: that's already been done with the initial `mod` declaration.

Using these two techniques, we can break up our crate into two directories and seven files:

```
$ tree .
.
├── Cargo.lock
├── Cargo.toml
├── src
│   ├── english
│   │   ├── farewells.rs
│   │   ├── greetings.rs
│   │   └── mod.rs
│   ├── japanese
│   │   ├── farewells.rs
│   │   ├── greetings.rs
│   │   └── mod.rs
│   └── lib.rs
└── target
    ├── debug
    │   ├── build
    │   └── deps
```



```
|— examples
|— libphrases-a7448e02a0468eaa.rlib
|— native
```

`src/lib.rs` is our crate root, and looks like this:

```
mod english;
mod japanese;
```

These two declarations tell Rust to look for either `src/english.rs` and `src/japanese.rs`, or `src/english/mod.rs` and `src/japanese/mod.rs`, depending on our preference. In this case, because our modules have sub-modules, we've chosen the second. Both `src/english/mod.rs` and `src/japanese/mod.rs` look like this:

```
mod greetings;
mod farewells;
```

Again, these declarations tell Rust to look for either `src/english/greetings.rs` and `src/japanese/greetings.rs` or `src/english/farewells/mod.rs` and `src/japanese/farewells/mod.rs`. Because these sub-modules don't have their own sub-modules, we've chosen to make them `src/english/greetings.rs` and `src/japanese/farewells.rs`. Whew!

The contents of `src/english/greetings.rs` and `src/japanese/farewells.rs` are both empty at the moment. Let's add some functions.

Put this in `src/english/greetings.rs`:

```
fn hello() -> String {
    "Hello!".to_string()
}
```

Put this in `src/english/farewells.rs`:

```
fn goodbye() -> String {
    "Goodbye.".to_string()
}
```

Put this in `src/japanese/greetings.rs`:

```
fn hello() -> String {
    " こんにちは".to_string()
}
```

Of course, you can copy and paste this from this web page, or just type something else. It's not important that you actually put 'konnichiwa' to learn about the module system.

Put this in `src/japanese/farewells.rs`:

```
fn goodbye() -> String {
    " さようなら".to_string()
}
```

(This is ‘Sayōnara’, if you’re curious.)

Now that we have some functionality in our crate, let’s try to use it from another crate.

#### 5.26.4 Importing External Crates

We have a library crate. Let’s make an executable crate that imports and uses our library.

Make a `src/main.rs` and put this in it (it won’t quite compile yet):

```
extern crate phrases;

fn main() {
    println!("Hello in English: {}", phrases::english::greetings::hello());
    println!("Goodbye in English: {}", phrases::english::farewells::goodbye());

    println!("Hello in Japanese: {}", phrases::japanese::greetings::hello());
    println!("Goodbye in Japanese: {}", phrases::japanese::farewells::goodbye());
}
```

The `extern crate` declaration tells Rust that we need to compile and link to the `phrases` crate. We can then use `phrases`’ modules in this one. As we mentioned earlier, you can use double colons to refer to sub-modules and the functions inside of them.

Also, Cargo assumes that `src/main.rs` is the crate root of a binary crate, rather than a library crate. Our package now has two crates: `src/lib.rs` and `src/main.rs`. This pattern is quite common for executable crates: most functionality is in a library crate, and the executable crate uses that library. This way, other programs can also use the library crate, and it’s also a nice separation of concerns.

This doesn’t quite work yet, though. We get four errors that look similar to this:

```
$ cargo build
   Compiling phrases v0.0.1 (file:///home/you/projects/phrases)
src/main.rs:4:38: 4:72 error: function `hello` is private
src/main.rs:4      println!("Hello in English: {}", phrases::english::greetings::hello());
                                                    ^~~~~~

note: in expansion of format_args!
<std macros>:2:25: 2:58 note: expansion site
<std macros>:1:1: 2:62 note: in expansion of println!
<std macros>:3:1: 3:54 note: expansion site
<std macros>:1:1: 3:58 note: in expansion of println!
phrases/src/main.rs:4:5: 4:76 note: expansion site
```

By default, everything is private in Rust. Let’s talk about this in some more depth.

### 5.26.5 Exporting a Public Interface

Rust allows you to precisely control which aspects of your interface are public, and so private is the default. To make things public, you use the `pub` keyword. Let's focus on the `english` module first, so let's reduce our `src/main.rs` to just this:

```
extern crate phrases;

fn main() {
    println!("Hello in English: {}", phrases::english::greetings::hello());
    println!("Goodbye in English: {}", phrases::english::farewells::goodbye());
}
```

In our `src/lib.rs`, let's add `pub` to the `english` module declaration:

```
pub mod english;
mod japanese;
```

And in our `src/english/mod.rs`, let's make both `pub`:

```
pub mod greetings;
pub mod farewells;
```

In our `src/english/greetings.rs`, let's add `pub` to our `fn` declaration:

```
pub fn hello() -> String {
    "Hello!".to_string()
}
```

And also in `src/english/farewells.rs`:

```
pub fn goodbye() -> String {
    "Goodbye.".to_string()
}
```

Now, our crate compiles, albeit with warnings about not using the `japanese` functions:

```
$ cargo run
   Compiling phrases v0.0.1 (file:///home/you/projects/phrases)
src/japanese/greetings.rs:1:1: 3:2 warning: function is never used: `hello`, #[warn(dead_code)] on by default
src/japanese/greetings.rs:1 fn hello() -> String {
src/japanese/greetings.rs:2     "こんにちは".to_string()
src/japanese/greetings.rs:3 }
src/japanese/farewells.rs:1:1: 3:2 warning: function is never used: `goodbye`, #[warn(dead_code)] on by default
src/japanese/farewells.rs:1 fn goodbye() -> String {
src/japanese/farewells.rs:2     "さようなら".to_string()
src/japanese/farewells.rs:3 }
    Running `target/debug/phrases`
Hello in English: Hello!
Goodbye in English: Goodbye.
```

Now that our functions are public, we can use them. Great! However, typing out `phrases::english::greetings::hello()` is very long and repetitive. Rust has another keyword for importing names into the current scope, so that you can refer to them with shorter names. Let's talk about `use`.

### 5.26.6 Importing Modules with `use`

Rust has a `use` keyword, which allows us to import names into our local scope. Let's change our `src/main.rs` to look like this:

```
extern crate phrases;

use phrases::english::greetings;
use phrases::english::farewells;

fn main() {
    println!("Hello in English: {}", greetings::hello());
    println!("Goodbye in English: {}", farewells::goodbye());
}
```

The two `use` lines import each module into the local scope, so we can refer to the functions by a much shorter name. By convention, when importing functions, it's considered best practice to import the module, rather than the function directly. In other words, you *can* do this:

```
extern crate phrases;

use phrases::english::greetings::hello;
use phrases::english::farewells::goodbye;

fn main() {
    println!("Hello in English: {}", hello());
    println!("Goodbye in English: {}", goodbye());
}
```

But it is not idiomatic. This is significantly more likely to introduce a naming conflict. In our short program, it's not a big deal, but as it grows, it becomes a problem. If we have conflicting names, Rust will give a compilation error. For example, if we made the `japanese` functions public, and tried to do this:

```
extern crate phrases;

use phrases::english::greetings::hello;
use phrases::japanese::greetings::hello;

fn main() {
    println!("Hello in English: {}", hello());
    println!("Hello in Japanese: {}", hello());
}
```

Rust will give us a compile-time error:

```
Compiling phrases v0.0.1 (file:///home/you/projects/phrases)
src/main.rs:4:5: 4:40 error: a value named `hello` has already been imported in this module [E0252]
src/main.rs:4 use phrases::japanese::greetings::hello;
                ^~~~~~
error: aborting due to previous error
Could not compile `phrases`.
```

If we're importing multiple names from the same module, we don't have to type it out twice. Instead of this:

```
use phrases::english::greetings;
use phrases::english::farewells;
```

We can use this shortcut:

```
use phrases::english::{greetings, farewells};
```

### Re-exporting with `pub use`

You don't just use `use` to shorten identifiers. You can also use it inside of your crate to re-export a function inside another module. This allows you to present an external interface that may not directly map to your internal code organization.

Let's look at an example. Modify your `src/main.rs` to read like this:

```
extern crate phrases;

use phrases::english::{greetings, farewells};
use phrases::japanese;

fn main() {
    println!("Hello in English: {}", greetings::hello());
    println!("Goodbye in English: {}", farewells::goodbye());

    println!("Hello in Japanese: {}", japanese::hello());
    println!("Goodbye in Japanese: {}", japanese::goodbye());
}
```

Then, modify your `src/lib.rs` to make the `japanese` mod public:

```
pub mod english;
pub mod japanese;
```

Next, make the two functions public, first in `src/japanese/greetings.rs`:

```
pub fn hello() -> String {
    " こんにちは".to_string()
}
```

And then in `src/japanese/farewells.rs`:

```
pub fn goodbye() -> String {
    " さようなら".to_string()
}
```

Finally, modify your `src/japanese/mod.rs` to read like this:

```
pub use self::greetings::hello;
pub use self::farewells::goodbye;

mod greetings;
mod farewells;
```

The `pub use` declaration brings the function into scope at this part of our module hierarchy. Because we've `pub used` this inside of our `japanese` module, we now have a `phrases::japanese::hello()` function and a `phrases::japanese::goodbye()` function, even though the code for them lives in `phrases::japanese::greetings::hello()` and `phrases::japanese::farewells::goodbye()`. Our internal organization doesn't define our external interface.

Here we have a `pub use` for each function we want to bring into the `japanese` scope. We could alternatively use the wildcard syntax to include everything from `greetings` into the current scope: `pub use self::greetings::*`.

What about the `self`? Well, by default, `use` declarations are absolute paths, starting from your crate root. `self` makes that path relative to your current place in the hierarchy instead. There's one more special form of `use`: you can use `super::` to reach one level up the tree from your current location. Some people like to think of `self` as `.` and `super` as `..`, from many shells' display for the current directory and the parent directory.

Outside of `use`, paths are relative: `foo::bar()` refers to a function inside of `foo` relative to where we are. If that's prefixed with `::`, as in `::foo::bar()`, it refers to a different `foo`, an absolute path from your crate root.

Also, note that we `pub used` before we declared our `mods`. Rust requires that `use` declarations go first.

This will build and run:

```
$ cargo run
   Compiling phrases v0.0.1 (file:///home/you/projects/phrases)
   Running `target/debug/phrases`
Hello in English: Hello!
Goodbye in English: Goodbye.
Hello in Japanese: こんにちは
Goodbye in Japanese: さようなら
```

## 5.27 const and static

Rust has a way of defining constants with the `const` keyword:

```
const N: i32 = 5;
```

Unlike `let` (section 5.1, page 119) bindings, you must annotate the type of a `const`.

Constants live for the entire lifetime of a program. More specifically, constants in Rust have no fixed address in memory. This is because they're effectively inlined to each place that they're used. References to the same constant are not necessarily guaranteed to refer to the same memory address for this reason.

### 5.27.1 static

Rust provides a 'global variable' sort of facility in static items. They're similar to constants, but static items aren't inlined upon use. This means that there is only one instance for each value, and it's at a fixed location in memory.

Here's an example:

```
static N: i32 = 5;
```

Unlike `let` (section 5.1, page 119) bindings, you must annotate the type of a `static`.

Statics live for the entire lifetime of a program, and therefore any reference stored in a constant has a 'static lifetime' (section 5.10, page 145):

```
static NAME: &'static str = "Steve";
```

### Mutability

You can introduce mutability with the `mut` keyword:

```
static mut N: i32 = 5;
```

Because this is mutable, one thread could be updating `N` while another is reading it, causing memory unsafety. As such both accessing and mutating a `static mut` is `unsafe` (section 5.37, page 235), and so must be done in an `unsafe` block:

```
unsafe {  
    N += 1;  
  
    println!("N: {}", N);  
}
```

Furthermore, any type stored in a `static` must be `Sync`.

### 5.27.2 Initializing

Both `const` and `static` have requirements for giving them a value. They may only be given a value that's a constant expression. In other words, you cannot use the result of a function call or anything similarly complex or at runtime.

### 5.27.3 Which construct should I use?

Almost always, if you can choose between the two, choose `const`. It's pretty rare that you actually want a memory location associated with your constant, and using a `const` allows for optimizations like constant propagation not only in your crate but downstream crates.

A `const` can be thought of as a `#define` in C: it has metadata overhead but it has no runtime overhead. "Should I use a `#define` or a `static` in C," is largely the same question as whether you should use a `const` or a `static` in Rust.

## 5.28 Attributes

Declarations can be annotated with 'attributes' in Rust. They look like this:

```
#[test]
```

or like this:

```
#![test]
```

The difference between the two is the `!`, which changes what the attribute applies to:

```
#[foo]
struct Foo;

mod bar {
    #![bar]
}
```

The `#[foo]` attribute applies to the next item, which is the `struct` declaration. The `#![bar]` attribute applies to the item enclosing it, which is the `mod` declaration. Otherwise, they're the same. Both change the meaning of the item they're attached to somehow.

For example, consider a function like this:

```
#[test]
fn check() {
    assert_eq!(2, 1 + 1);
}
```



It is marked with `#[test]`. This means it's special: when you run tests (section 4.2, page 70), this function will execute. When you compile as usual, it won't even be included. This function is now a test function.

Attributes may also have additional data:

```
#[inline(always)]
fn super_fast_fn() {
```

Or even keys and values:

```
#[cfg(target_os = "macos")]
mod macos_only {
```

Rust attributes are used for a number of different things. There is a full list of attributes in the reference<sup>33</sup>. Currently, you are not allowed to create your own attributes, the Rust compiler defines them.

## 5.29 type aliases

The `type` keyword lets you declare an alias of another type:

```
type Name = String;
```

You can then use this type as if it were a real type:

```
type Name = String;

let x: Name = "Hello".to_string();
```

Note, however, that this is an *alias*, not a new type entirely. In other words, because Rust is strongly typed, you'd expect a comparison between two different types to fail:

```
let x: i32 = 5;
let y: i64 = 5;

if x == y {
    // ...
}
```

this gives

```
error: mismatched types:
  expected `i32`,
```

---

<sup>33</sup><http://doc.rust-lang.org/reference.html#attributes>

```

    found `i64`
(expected i32,
    found i64) [E0308]
    if x == y {
        ^

```

But, if we had an alias:

```

type Num = i32;

let x: i32 = 5;
let y: Num = 5;

if x == y {
    // ...
}

```

This compiles without error. Values of a `Num` type are the same as a value of type `i32`, in every way.

You can also use type aliases with generics:

```

use std::result;

enum ConcreteError {
    Foo,
    Bar,
}

type Result<T> = result::Result<T, ConcreteError>;

```

This creates a specialized version of the `Result` type, which always has a `ConcreteError` for the `E` part of `Result<T, E>`. This is commonly used in the standard library to create custom errors for each subsection. For example, `io::Result`<sup>34</sup>.

## 5.30 Casting between types

Rust, with its focus on safety, provides two different ways of casting different types between each other. The first, `as`, is for safe casts. In contrast, `transmute` allows for arbitrary casting, and is one of the most dangerous features of Rust!

### 5.30.1 `as`

The `as` keyword does basic casting:

---

<sup>34</sup><http://doc.rust-lang.org/std/io/type.Result.html>

```
let x: i32 = 5;

let y = x as i64;
```

It only allows certain kinds of casting, however:

```
let a = [0u8, 0u8, 0u8, 0u8];

let b = a as u32; // four eights makes 32
```

This errors with:

```
error: non-scalar cast: `[u8; 4]` as `u32`
let b = a as u32; // four eights makes 32
      ^~~~~~
```

It's a 'non-scalar cast' because we have multiple values here: the four elements of the array. These kinds of casts are very dangerous, because they make assumptions about the way that multiple underlying structures are implemented. For this, we need something more dangerous.

### 5.30.2 transmute

The `transmute` function is provided by a compiler intrinsic (section 6.4, page 251), and what it does is very simple, but very scary. It tells Rust to treat a value of one type as though it were another type. It does this regardless of the typechecking system, and just completely trusts you.

In our previous example, we know that an array of four `u8`s represents a `u32` properly, and so we want to do the cast. Using `transmute` instead of `as`, Rust lets us:

```
use std::mem;

unsafe {
    let a = [0u8, 0u8, 0u8, 0u8];

    let b = mem::transmute::<[u8; 4], u32>(a);
}
```

We have to wrap the operation in an `unsafe` block for this to compile successfully. Technically, only the `mem::transmute` call itself needs to be in the block, but it's nice in this case to enclose everything related, so you know where to look. In this case, the details about `a` are also important, and so they're in the block. You'll see code in either style, sometimes the context is too far away, and wrapping all of the code in `unsafe` isn't a great idea.

While `transmute` does very little checking, it will at least make sure that the types are the same size. This errors:

```
use std::mem;

unsafe {
    let a = [0u8, 0u8, 0u8, 0u8];

    let b = mem::transmute::<[u8; 4], u64>(a);
}
```

with:

```
error: transmute called on types with different sizes: [u8; 4] (32 bits) to u64
(64 bits)
```

Other than that, you're on your own!

## 5.31 Associated Types

Associated types are a powerful part of Rust's type system. They're related to the idea of a 'type family', in other words, grouping multiple types together. That description is a bit abstract, so let's dive right into an example. If you want to write a `Graph` trait, you have two types to be generic over: the node type and the edge type. So you might write a trait, `Graph<N, E>`, that looks like this:

```
trait Graph<N, E> {
    fn has_edge(&self, &N, &N) -> bool;
    fn edges(&self, &N) -> Vec<E>;
    // etc
}
```

While this sort of works, it ends up being awkward. For example, any function that wants to take a `Graph` as a parameter now *also* needs to be generic over the `Node` and `Edge` types too:

```
fn distance<N, E, G: Graph<N, E>>(graph: &G, start: &N, end: &N) -> u32 { ... }
```

Our distance calculation works regardless of our `Edge` type, so the `E` stuff in this signature is just a distraction.

What we really want to say is that a certain `Edge` and `Node` type come together to form each kind of `Graph`. We can do that with associated types:

```
trait Graph {
    type N;
    type E;

    fn has_edge(&self, &Self::N, &Self::N) -> bool;
    fn edges(&self, &Self::N) -> Vec<Self::E>;
    // etc
}
```

Now, our clients can be abstract over a given Graph:

```
fn distance<G: Graph>(graph: &G, start: &G::N, end: &G::N) -> uint { ... }
```

No need to deal with the Edge type here!

Let's go over all this in more detail.

### Defining associated types

Let's build that Graph trait. Here's the definition:

```
trait Graph {
    type N;
    type E;

    fn has_edge(&self, &Self::N, &Self::N) -> bool;
    fn edges(&self, &Self::N) -> Vec<Self::E>;
}
```

Simple enough. Associated types use the `type` keyword, and go inside the body of the trait, with the functions.

These `type` declarations can have all the same thing as functions do. For example, if we wanted our `N` type to implement `Display`, so we can print the nodes out, we could do this:

```
use std::fmt;

trait Graph {
    type N: fmt::Display;
    type E;

    fn has_edge(&self, &Self::N, &Self::N) -> bool;
    fn edges(&self, &Self::N) -> Vec<Self::E>;
}
```

### Implementing associated types

Just like any trait, traits that use associated types use the `impl` keyword to provide implementations. Here's a simple implementation of Graph:

```
struct Node;

struct Edge;

struct MyGraph;

impl Graph for MyGraph {
```

```

type N = Node;
type E = Edge;

fn has_edge(&self, n1: &Node, n2: &Node) -> bool {
    true
}

fn edges(&self, n: &Node) -> Vec<Edge> {
    Vec::new()
}
}

```

This silly implementation always returns `true` and an empty `Vec<Edge>`, but it gives you an idea of how to implement this kind of thing. We first need three structs, one for the graph, one for the node, and one for the edge. If it made more sense to use a different type, that would work as well, we're just going to use structs for all three here.

Next is the `impl` line, which is just like implementing any other trait.

From here, we use `=` to define our associated types. The name the trait uses goes on the left of the `=`, and the concrete type we're implementing this for goes on the right. Finally, we use the concrete types in our function declarations.

### Trait objects with associated types

There's one more bit of syntax we should talk about: trait objects. If you try to create a trait object from an associated type, like this:

```

let graph = MyGraph;
let obj = Box::new(graph) as Box<Graph>;

```

You'll get two errors:

```

error: the value of the associated type `E` (from the trait `main::Graph`) must
be specified [E0191]
let obj = Box::new(graph) as Box<Graph>;
    ^~~~~~
24:44 error: the value of the associated type `N` (from the trait
`main::Graph`) must be specified [E0191]
let obj = Box::new(graph) as Box<Graph>;
    ^~~~~~

```

We can't create a trait object like this, because we don't know the associated types. Instead, we can write this:

```

let graph = MyGraph;
let obj = Box::new(graph) as Box<Graph<N=Node, E=Edge>>;

```

The `N=Node` syntax allows us to provide a concrete type, `Node`, for the `N` type parameter. Same with `E=Edge`. If we didn't provide this constraint, we couldn't be sure which `impl` to match this trait object to.

## 5.32 Unsized Types

Most types have a particular size, in bytes, that is knowable at compile time. For example, an `i32` is thirty-two bits big, or four bytes. However, there are some types which are useful to express, but do not have a defined size. These are called 'unsized' or 'dynamically sized' types. One example is `[T]`. This type represents a certain number of `T` in sequence. But we don't know how many there are, so the size is not known.

Rust understands a few of these types, but they have some restrictions. There are three:

1. We can only manipulate an instance of an unsized type via a pointer. An `&[T]` works just fine, but a `[T]` does not.
2. Variables and arguments cannot have dynamically sized types.
3. Only the last field in a `struct` may have a dynamically sized type; the other fields must not. Enum variants must not have dynamically sized types as data.

So why bother? Well, because `[T]` can only be used behind a pointer, if we didn't have language support for unsized types, it would be impossible to write this:

```
impl Foo for str {
```

or

```
impl<T> Foo for [T] {
```

Instead, you would have to write:

```
impl Foo for &str {
```

Meaning, this implementation would only work for references (section 5.9, page 138), and not other types of pointers. With the `impl for str`, all pointers, including (at some point, there are some bugs to fix first) user-defined custom smart pointers, can use this `impl`.

### 5.32.1 ?Sized

If you want to write a function that accepts a dynamically sized type, you can use the special bound, `?Sized`:

```
struct Foo<T: ?Sized> {
    f: T,
}
```

This `?`, read as "T may be `Sized`", means that this bound is special: it lets us match more kinds, not less. It's almost like every `T` implicitly has `T: Sized`, and the `?` undoes this default.

### 5.33 Operators and Overloading

Rust allows for a limited form of operator overloading. There are certain operators that are able to be overloaded. To support a particular operator between types, there's a specific trait that you can implement, which then overloads the operator.

For example, the `+` operator can be overloaded with the `Add` trait:

```
use std::ops::Add;

#[derive(Debug)]
struct Point {
    x: i32,
    y: i32,
}

impl Add for Point {
    type Output = Point;

    fn add(self, other: Point) -> Point {
        Point { x: self.x + other.x, y: self.y + other.y }
    }
}

fn main() {
    let p1 = Point { x: 1, y: 0 };
    let p2 = Point { x: 2, y: 3 };

    let p3 = p1 + p2;

    println!("{:?}", p3);
}
```

In `main`, we can use `+` on our two `Points`, since we've implemented `Add<Output=Point>` for `Point`.

There are a number of operators that can be overloaded this way, and all of their associated traits live in the `std::ops`<sup>35</sup> module. Check out its documentation for the full list.

Implementing these traits follows a pattern. Let's look at `Add`<sup>36</sup> in more detail:

```
pub trait Add<RHS = Self> {
    type Output;

    fn add(self, rhs: RHS) -> Self::Output;
}
```

There's three types in total involved here: the type you `impl Add` for, `RHS`, which defaults to `Self`, and `Output`. For an expression `let z = x + y`, `x` is the `Self` type, `y` is the `RHS`, and `z` is the `Self::Output` type.

<sup>35</sup><http://doc.rust-lang.org/std/ops/index.html>

<sup>36</sup><http://doc.rust-lang.org/std/ops/trait.Add.html>



```
impl Add<i32> for Point {
    type Output = f64;

    fn add(self, rhs: i32) -> f64 {
        // add an i32 to a Point and get an f64
    }
}
```

will let you do this:

```
let p: Point = // ...
let x: f64 = p + 2i32;
```

## 5.34 Deref coercions

The standard library provides a special trait, `Deref`<sup>37</sup>. It's normally used to overload `*`, the dereference operator:

```
use std::ops::Deref;

struct DerefExample<T> {
    value: T,
}

impl<T> Deref for DerefExample<T> {
    type Target = T;

    fn deref(&self) -> &T {
        &self.value
    }
}

fn main() {
    let x = DerefExample { value: 'a' };
    assert_eq!('a', *x);
}
```

This is useful for writing custom pointer types. However, there's a language feature related to `Deref`: 'deref coercions'. Here's the rule: If you have a type `U`, and it implements `Deref<Target=T>`, values of `&U` will automatically coerce to a `&T`. Here's an example:

```
fn foo(s: &str) {
    // borrow a string for a second
}
```

<sup>37</sup><http://doc.rust-lang.org/std/ops/trait.Deref.html>

```
// String implements Deref<Target=str>
let owned = "Hello".to_string();

// therefore, this works:
foo(&owned);
```

Using an ampersand in front of a value takes a reference to it. So `owned` is a `String`, `&owned` is an `&String`, and since `impl Deref<Target=str>` for `String`, `&String` will deref to `&str`, which `foo()` takes.

That's it. This rule is one of the only places in which Rust does an automatic conversion for you, but it adds a lot of flexibility. For example, the `Rc<T>` type implements `Deref<Target=T>`, so this works:

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

fn foo(s: &str) {
    // borrow a string for a second
}

// String implements Deref<Target=str>
let owned = "Hello".to_string();
let counted = Rc::new(owned);

// therefore, this works:
foo(&counted);
```

All we've done is wrap our `String` in an `Rc<T>`. But we can now pass the `Rc<String>` around anywhere we'd have a `String`. The signature of `foo` didn't change, but works just as well with either type. This example has two conversions: `Rc<String>` to `String` and then `String` to `&str`. Rust will do this as many times as possible until the types match.

Another very common implementation provided by the standard library is:

```
fn foo(s: &[i32]) {
    // borrow a slice for a second
}

// Vec<T> implements Deref<Target=[T]>
let owned = vec![1, 2, 3];

foo(&owned);
```

Vectors can `Deref` to a slice.

### Deref and method calls

`Deref` will also kick in when calling a method. In other words, these are the same two things in Rust:



### 5.35.1 Defining a macro

You may have seen the `vec!` macro, used to initialize a vector (section 5.17, page 168) with any number of elements.

```
let x: Vec<u32> = vec![1, 2, 3];
```

This can't be an ordinary function, because it takes any number of arguments. But we can imagine it as syntactic shorthand for

```
let x: Vec<u32> = {
  let mut temp_vec = Vec::new();
  temp_vec.push(1);
  temp_vec.push(2);
  temp_vec.push(3);
  temp_vec
};
```

We can implement this shorthand, using a macro: <sup>38</sup>

```
macro_rules! vec {
  ( $( $x:expr ),* ) => {
    {
      let mut temp_vec = Vec::new();
      $(
        temp_vec.push($x);
      )*
      temp_vec
    }
  };
}
```

Whoa, that's a lot of new syntax! Let's break it down.

```
macro_rules! vec { ... }
```

This says we're defining a macro named `vec`, much as `fn vec` would define a function named `vec`. In prose, we informally write a macro's name with an exclamation point, e.g. `vec!`. The exclamation point is part of the invocation syntax and serves to distinguish a macro from an ordinary function.

#### Matching

The macro is defined through a series of rules, which are pattern-matching cases. Above, we had

---

<sup>38</sup>The actual definition of `vec!` in `libcollections` differs from the one presented here, for reasons of efficiency and reusability.

```
( $( $x:expr ),* ) => { ... };
```

This is like a `match` expression arm, but the matching happens on Rust syntax trees, at compile time. The semicolon is optional on the last (here, only) case. The “pattern” on the left-hand side of `=>` is known as a ‘matcher’. These have their own little grammar<sup>39</sup> within the language.

The matcher `$x:expr` will match any Rust expression, binding that syntax tree to the ‘metavariable’ `$x`. The identifier `expr` is a ‘fragment specifier’; the full possibilities are enumerated later in this chapter. Surrounding the matcher with `$(...),*` will match zero or more expressions, separated by commas.

Aside from the special matcher syntax, any Rust tokens that appear in a matcher must match exactly. For example,

```
macro_rules! foo {
    (x => $e:expr) => (println!("mode X: {}", $e));
    (y => $e:expr) => (println!("mode Y: {}", $e));
}

fn main() {
    foo!(y => 3);
}
```

will print

```
mode Y: 3
```

With

```
foo!(z => 3);
```

we get the compiler error

```
error: no rules expected the token `z`
```

## Expansion

The right-hand side of a macro rule is ordinary Rust syntax, for the most part. But we can splice in bits of syntax captured by the matcher. From the original example:

```
$(
    temp_vec.push($x);
)*
```

---

<sup>39</sup><http://doc.rust-lang.org/reference.html#macros>

Each matched expression `$x` will produce a single `push` statement in the macro expansion. The repetition in the expansion proceeds in “lockstep” with repetition in the matcher (more on this in a moment).

Because `$x` was already declared as matching an expression, we don’t repeat `:expr` on the right-hand side. Also, we don’t include a separating comma as part of the repetition operator. Instead, we have a terminating semicolon within the repeated block.

Another detail: the `vec!` macro has *two* pairs of braces on the right-hand side. They are often combined like so:

```
macro_rules! foo {
  () => {{
    ...
  }}
}
```

The outer braces are part of the syntax of `macro_rules!`. In fact, you can use `()` or `[]` instead. They simply delimit the right-hand side as a whole.

The inner braces are part of the expanded syntax. Remember, the `vec!` macro is used in an expression context. To write an expression with multiple statements, including `let`-bindings, we use a block. If your macro expands to a single expression, you don’t need this extra layer of braces.

Note that we never *declared* that the macro produces an expression. In fact, this is not determined until we use the macro as an expression. With care, you can write a macro whose expansion works in several contexts. For example, shorthand for a data type could be valid as either an expression or a pattern.

## Repetition

The repetition operator follows two principal rules:

1. `$(...)*` walks through one “layer” of repetitions, for all of the `$names` it contains, in lockstep, and
2. each `$name` must be under at least as many `$(...)*`s as it was matched against. If it is under more, it’ll be duplicated, as appropriate.

This baroque macro illustrates the duplication of variables from outer repetition levels.

```
macro_rules! o_0 {
  (
    $(
      $x:expr; [ $( $y:expr ),* ]
    );*
  ) => {
    &[ $( $( $x + $y ),* ),* ]
  }
}
```

```

}

fn main() {
    let a: &[i32]
        = o_0!(10; [1, 2, 3];
              20; [4, 5, 6]);

    assert_eq!(a, [11, 12, 13, 24, 25, 26]);
}

```

That’s most of the matcher syntax. These examples use `$(...)*`, which is a “zero or more” match. Alternatively you can write `$(...)+` for a “one or more” match. Both forms optionally include a separator, which can be any token except `+` or `*`.

This system is based on “Macro-by-Example<sup>40</sup>” ([PDF link](#)).

### 5.35.2 Hygiene

Some languages implement macros using simple text substitution, which leads to various problems. For example, this C program prints 13 instead of the expected 25.

```

#define FIVE_TIMES(x) 5 * x

int main() {
    printf("%d\n", FIVE_TIMES(2 + 3));
    return 0;
}

```

After expansion we have `5 * 2 + 3`, and multiplication has greater precedence than addition. If you’ve used C macros a lot, you probably know the standard idioms for avoiding this problem, as well as five or six others. In Rust, we don’t have to worry about it.

```

macro_rules! five_times {
    ($x:expr) => (5 * $x);
}

fn main() {
    assert_eq!(25, five_times!(2 + 3));
}

```

The metavariable `$x` is parsed as a single expression node, and keeps its place in the syntax tree even after substitution.

Another common problem in macro systems is ‘variable capture’. Here’s a C macro, using a GNU C extension<sup>41</sup> to emulate Rust’s expression blocks.

<sup>40</sup><http://www.cs.indiana.edu/ftp/techreports/TR206.pdf>

<sup>41</sup><https://gcc.gnu.org/onlinedocs/gcc/Statement-Exprs.html>

```
#define LOG(msg) ({ \
    int state = get_log_state(); \
    if (state > 0) { \
        printf("log(%d): %s\n", state, msg); \
    } \
})
```

Here's a simple use case that goes terribly wrong:

```
const char *state = "reticulating splines";
LOG(state)
```

This expands to

```
const char *state = "reticulating splines";
int state = get_log_state();
if (state > 0) {
    printf("log(%d): %s\n", state, state);
}
```

The second variable named `state` shadows the first one. This is a problem because the print statement should refer to both of them.

The equivalent Rust macro has the desired behavior.

```
macro_rules! log {
    ($msg:expr) => {{
        let state: i32 = get_log_state();
        if state > 0 {
            println!("log({}): {}", state, $msg);
        }
    }};
}

fn main() {
    let state: &str = "reticulating splines";
    log!(state);
}
```

This works because Rust has a hygienic macro system<sup>42</sup>. Each macro expansion happens in a distinct ‘syntax context’, and each variable is tagged with the syntax context where it was introduced. It’s as though the variable `state` inside `main` is painted a different “color” from the variable `state` inside the macro, and therefore they don’t conflict.

This also restricts the ability of macros to introduce new bindings at the invocation site. Code such as the following will not work:

---

<sup>42</sup>[http://en.wikipedia.org/wiki/Hygienic\\_macro](http://en.wikipedia.org/wiki/Hygienic_macro)



```
macro_rules! foo {
    () => (let x = 3);
}

fn main() {
    foo!();
    println!("{}", x);
}
```

Instead you need to pass the variable name into the invocation, so it's tagged with the right syntax context.

```
macro_rules! foo {
    ($v:ident) => (let $v = 3);
}

fn main() {
    foo!(x);
    println!("{}", x);
}
```

This holds for `let` bindings and loop labels, but not for items<sup>43</sup>. So the following code does compile:

```
macro_rules! foo {
    () => (fn x() { });
}

fn main() {
    foo!();
    x();
}
```

### 5.35.3 Recursive macros

A macro's expansion can include more macro invocations, including invocations of the very same macro being expanded. These recursive macros are useful for processing tree-structured input, as illustrated by this (simplistic) HTML shorthand:

```
macro_rules! write_html {
    ($w:expr, ) => (());

    ($w:expr, $e:tt) => (write!($w, "{}", $e));

    ($w:expr, $tag:ident [ $($inner:tt)* ] $($rest:tt)*) => {{
```

<sup>43</sup><http://doc.rust-lang.org/reference.html#items>

```

        write!($w, "<{}>", stringify!($tag));
        write_html!($w, $($inner)*);
        write!($w, "</{}>", stringify!($tag));
        write_html!($w, $($rest)*);
    });
}

fn main() {
    use std::fmt::Write;
    let mut out = String::new();

    write_html!(&mut out,
        html[
            head[title["Macros guide"]]
            body[h1["Macros are the best!"]]
        ]
    );

    assert_eq!(out,
        "<html><head><title>Macros guide</title></head>\n
        <body><h1>Macros are the best!</h1></body></html>");
}

```

### 5.35.4 Debugging macro code

To see the results of expanding macros, run `rustc --pretty expanded`. The output represents a whole crate, so you can also feed it back in to `rustc`, which will sometimes produce better error messages than the original compilation. Note that the `--pretty expanded` output may have a different meaning if multiple variables of the same name (but different syntax contexts) are in play in the same scope. In this case `--pretty expanded,hygiene` will tell you about the syntax contexts.

`rustc` provides two syntax extensions that help with macro debugging. For now, they are unstable and require feature gates.

- `log_syntax!(...)` will print its arguments to standard output, at compile time, and “expand” to nothing.
- `trace_macros!(true)` will enable a compiler message every time a macro is expanded. Use `trace_macros!(false)` later in expansion to turn it off.

### 5.35.5 Syntactic requirements

Even when Rust code contains un-expanded macros, it can be parsed as a full syntax tree<sup>44</sup>. This property can be very useful for editors and other tools that process code. It also has a few consequences for the design of Rust’s macro system.

<sup>44</sup>[glossary.html#abstract-syntax-tree](https://glossary.html5e.org/abstract-syntax-tree)

One consequence is that Rust must determine, when it parses a macro invocation, whether the macro stands in for

- zero or more items,
- zero or more methods,
- an expression,
- a statement, or
- a pattern.

A macro invocation within a block could stand for some items, or for an expression / statement. Rust uses a simple rule to resolve this ambiguity. A macro invocation that stands for items must be either

- delimited by curly braces, e.g. `foo! { ... }`, or
- terminated by a semicolon, e.g. `foo!(...);`

Another consequence of pre-expansion parsing is that the macro invocation must consist of valid Rust tokens. Furthermore, parentheses, brackets, and braces must be balanced within a macro invocation. For example, `foo!()` is forbidden. This allows Rust to know where the macro invocation ends.

More formally, the macro invocation body must be a sequence of ‘token trees’. A token tree is defined recursively as either

- a sequence of token trees surrounded by matching `()`, `[]`, or `{}`, or
- any other single token.

Within a matcher, each metavariable has a ‘fragment specifier’, identifying which syntactic form it matches.

- **ident**: an identifier. Examples: `x`; `foo`.
- **path**: a qualified name. Example: `T::SpecialA`.
- **expr**: an expression. Examples: `2 + 2`; `if true then { 1 } else { 2 }`; `f(42)`.
- **ty**: a type. Examples: `i32`; `Vec<(char, String)>`; `&T`.
- **pat**: a pattern. Examples: `Some(t)`; `(17, 'a')`; `_`.
- **stmt**: a single statement. Example: `let x = 3`.
- **block**: a brace-delimited sequence of statements. Example: `{ log(error, "hi"); return 12; }`.
- **item**: an item<sup>45</sup>. Examples: `fn foo() { }`; `struct Bar;`.
- **meta**: a “meta item”, as found in attributes. Example: `cfg(target_os = "windows")`.
- **tt**: a single token tree.

There are additional rules regarding the next token after a metavariable:

- **expr** variables must be followed by one of: `=>` , `,` `;`

---

<sup>45</sup><http://doc.rust-lang.org/reference.html#items>

- `ty` and `path` variables must be followed by one of: `=>` , `:` `=` `>` `as`
- `pat` variables must be followed by one of: `=>` , `=`
- Other variables may be followed by any token.

These rules provide some flexibility for Rust's syntax to evolve without breaking existing macros.

The macro system does not deal with parse ambiguity at all. For example, the grammar `$(t:ty)* $e:expr` will always fail to parse, because the parser would be forced to choose between parsing `$t` and parsing `$e`. Changing the invocation syntax to put a distinctive token in front can solve the problem. In this case, you can write `$(T t:ty)* E $e:exp`.

### 5.35.6 Scoping and macro import/export

Macros are expanded at an early stage in compilation, before name resolution. One downside is that scoping works differently for macros, compared to other constructs in the language.

Definition and expansion of macros both happen in a single depth-first, lexical-order traversal of a crate's source. So a macro defined at module scope is visible to any subsequent code in the same module, which includes the body of any subsequent child `mod` items.

A macro defined within the body of a single `fn`, or anywhere else not at module scope, is visible only within that item.

If a module has the `macro_use` attribute, its macros are also visible in its parent module after the child's `mod` item. If the parent also has `macro_use` then the macros will be visible in the grandparent after the parent's `mod` item, and so forth.

The `macro_use` attribute can also appear on `extern crate`. In this context it controls which macros are loaded from the external crate, e.g.

```
#[macro_use(foo, bar)]
extern crate baz;
```

If the attribute is given simply as `#[macro_use]`, all macros are loaded. If there is no `#[macro_use]` attribute then no macros are loaded. Only macros defined with the `#[macro_export]` attribute may be loaded.

To load a crate's macros without linking it into the output, use `#[no_link]` as well.

An example:

```
macro_rules! m1 { () => (() ) }

// visible here: m1

mod foo {
    // visible here: m1

    #[macro_export]
    macro_rules! m2 { () => (() ) }
```

```

    // visible here: m1, m2
}

// visible here: m1

macro_rules! m3 { () => (() ) }

// visible here: m1, m3

#[macro_use]
mod bar {
    // visible here: m1, m3

    macro_rules! m4 { () => (() ) }

    // visible here: m1, m3, m4
}

// visible here: m1, m3, m4

```

When this library is loaded with `#[macro_use] extern crate`, only `m2` will be imported. The Rust Reference has a listing of macro-related attributes<sup>46</sup>.

### 5.35.7 The variable `$crate`

A further difficulty occurs when a macro is used in multiple crates. Say that `mylib` defines

```

pub fn increment(x: u32) -> u32 {
    x + 1
}

#[macro_export]
macro_rules! inc_a {
    ($x:expr) => ( ::increment($x) )
}

#[macro_export]
macro_rules! inc_b {
    ($x:expr) => ( ::mylib::increment($x) )
}

```

`inc_a` only works within `mylib`, while `inc_b` only works outside the library. Furthermore, `inc_b` will break if the user imports `mylib` under another name.

Rust does not (yet) have a hygiene system for crate references, but it does provide a simple workaround for this problem. Within a macro imported from a crate named `foo`, the special

<sup>46</sup><http://doc.rust-lang.org/reference.html#macro-related-attributes>

macro variable `$crate` will expand to `::foo`. By contrast, when a macro is defined and then used in the same crate, `$crate` will expand to nothing. This means we can write

```
#[macro_export]
macro_rules! inc {
    ($x:expr) => ( $crate::increment($x) )
}
```

to define a single macro that works both inside and outside our library. The function name will expand to either `::increment` or `::mylib::increment`.

To keep this system simple and correct, `#[macro_use] extern crate ...` may only appear at the root of your crate, not inside `mod`. This ensures that `$crate` is a single identifier.

### 5.35.8 The deep end

The introductory chapter mentioned recursive macros, but it did not give the full story. Recursive macros are useful for another reason: Each recursive invocation gives you another opportunity to pattern-match the macro's arguments.

As an extreme example, it is possible, though hardly advisable, to implement the Bitwise Cyclic Tag<sup>47</sup> automaton within Rust's macro system.

```
macro_rules! bct {
    // cmd 0: d ... => ...
    (0, $($ps:tt),* ; $_d:tt)
    => (bct!($($ps),*, 0 ; ));
    (0, $($ps:tt),* ; $_d:tt, $($ds:tt),*)
    => (bct!($($ps),*, 0 ; $($ds),*));

    // cmd 1p: 1 ... => 1 ... p
    (1, $p:tt, $($ps:tt),* ; 1)
    => (bct!($($ps),*, 1, $p ; 1, $p));
    (1, $p:tt, $($ps:tt),* ; 1, $($ds:tt),*)
    => (bct!($($ps),*, 1, $p ; 1, $($ds),*, $p));

    // cmd 1p: 0 ... => 0 ...
    (1, $p:tt, $($ps:tt),* ; $($ds:tt),*)
    => (bct!($($ps),*, 1, $p ; $($ds),*));

    // halt on empty data string
    ( $($ps:tt),* ; )
    => (());
}
```

Exercise: use macros to reduce duplication in the above definition of the `bct!` macro.

<sup>47</sup>[http://esolangs.org/wiki/Bitwise\\_Cyclic\\_Tag](http://esolangs.org/wiki/Bitwise_Cyclic_Tag)

### 5.35.9 Common macros

Here are some common macros you'll see in Rust code.

#### **panic!**

This macro causes the current thread to panic. You can give it a message to panic with:

```
panic!("oh no!");
```

#### **vec!**

The `vec!` macro is used throughout the book, so you've probably seen it already. It creates `Vec<T>`s with ease:

```
let v = vec![1, 2, 3, 4, 5];
```

It also lets you make vectors with repeating values. For example, a hundred zeroes:

```
let v = vec![0; 100];
```

#### **assert! and assert\_eq!**

These two macros are used in tests. `assert!` takes a boolean, and `assert_eq!` takes two values and compares them. Truth passes, success `panic!`s. Like this:

```
// A-ok!  
assert!(true);  
assert_eq!(5, 3 + 2);  
  
// nope :(  
assert!(5 < 3);  
assert_eq!(5, 3);
```

#### **try!**

`try!` is used for error handling. It takes something that can return a `Result<T, E>`, and gives `T` if it's a `Ok<T>`, and returns with the `Err(E)` if it's that. Like this:

```
use std::fs::File;  
  
fn foo() -> std::io::Result<()> {  
    let f = try!(File::create("foo.txt"));
```

```
Ok(())
}
```

This is cleaner than doing this:

```
use std::fs::File;

fn foo() -> std::io::Result<()> {
    let f = File::create("foo.txt");

    let f = match f {
        Ok(t) => t,
        Err(e) => return Err(e),
    };

    Ok(())
}
```

### unreachable!

This macro is used when you think some code should never execute:

```
if false {
    unreachable!();
}
```

Sometimes, the compiler may make you have a different branch that you know will never, ever run. In these cases, use this macro, so that if you end up wrong, you'll get a **panic!** about it.

```
let x: Option<i32> = None;

match x {
    Some(_) => unreachable!(),
    None => println!("I know x is None!"),
}
```

### unimplemented!

The `unimplemented!` macro can be used when you're trying to get your functions to typecheck, and don't want to worry about writing out the body of the function. One example of this situation is implementing a trait with multiple required methods, where you want to tackle one at a time. Define the others as `unimplemented!` until you're ready to write them.



### 5.35.10 Procedural macros

If Rust’s macro system can’t do what you need, you may want to write a compiler plugin (section 6.1, page 241) instead. Compared to `macro_rules!` macros, this is significantly more work, the interfaces are much less stable, and bugs can be much harder to track down. In exchange you get the flexibility of running arbitrary Rust code within the compiler. Syntax extension plugins are sometimes called ‘procedural macros’ for this reason.

## 5.36 Raw Pointers

Rust has a number of different smart pointer types in its standard library, but there are two types that are extra-special. Much of Rust’s safety comes from compile-time checks, but raw pointers don’t have such guarantees, and are unsafe (section 5.37, page 235) to use.

`*const T` and `*mut T` are called ‘raw pointers’ in Rust. Sometimes, when writing certain kinds of libraries, you’ll need to get around Rust’s safety guarantees for some reason. In this case, you can use raw pointers to implement your library, while exposing a safe interface for your users. For example, `*` pointers are allowed to alias, allowing them to be used to write shared-ownership types, and even thread-safe shared memory types (the `Rc<T>` and `Arc<T>` types are both implemented entirely in Rust).

Here are some things to remember about raw pointers that are different than other pointer types. They:

- are not guaranteed to point to valid memory and are not even guaranteed to be non-null (unlike both `Box` and `&`);
- do not have any automatic clean-up, unlike `Box`, and so require manual resource management;
- are plain-old-data, that is, they don’t move ownership, again unlike `Box`, hence the Rust compiler cannot protect against bugs like use-after-free;
- lack any form of lifetimes, unlike `&`, and so the compiler cannot reason about dangling pointers; and
- have no guarantees about aliasing or mutability other than mutation not being allowed directly through a `*const T`.

### 5.36.1 Basics

Creating a raw pointer is perfectly safe:

```
let x = 5;
let raw = &x as *const i32;

let mut y = 10;
let raw_mut = &mut y as *mut i32;
```

However, dereferencing one is not. This won’t work:

```
let x = 5;
let raw = &x as *const i32;

println!("raw points at {}", *raw);
```

It gives this error:

```
error: dereference of unsafe pointer requires unsafe function or block [E0133]
    println!("raw points at{}", *raw);
                                ^~~~
```

When you dereference a raw pointer, you're taking responsibility that it's not pointing somewhere that would be incorrect. As such, you need `unsafe`:

```
let x = 5;
let raw = &x as *const i32;

let points_at = unsafe { *raw };

println!("raw points at {}", points_at);
```

For more operations on raw pointers, see their API documentation<sup>48</sup>.

### 5.36.2 FFI

Raw pointers are useful for FFI: Rust's `*const T` and `*mut T` are similar to C's `const T*` and `T*`, respectfully. For more about this use, consult the FFI chapter (section 4.8, page 106).

### 5.36.3 References and raw pointers

At runtime, a raw pointer `*` and a reference pointing to the same piece of data have an identical representation. In fact, an `&T` reference will implicitly coerce to an `*const T` raw pointer in safe code and similarly for the `mut` variants (both coercions can be performed explicitly with, respectively, `value as *const T` and `value as *mut T`).

Going the opposite direction, from `*const` to a reference `&`, is not safe. A `&T` is always valid, and so, at a minimum, the raw pointer `*const T` has to point to a valid instance of type `T`. Furthermore, the resulting pointer must satisfy the aliasing and mutability laws of references. The compiler assumes these properties are true for any references, no matter how they are created, and so any conversion from raw pointers is asserting that they hold. The programmer *must* guarantee this.

The recommended method for the conversion is

<sup>48</sup><http://doc.rust-lang.org/std/primitive.pointer.html>

```

let i: u32 = 1;

// explicit cast
let p_imm: *const u32 = &i as *const u32;
let mut m: u32 = 2;

// implicit coercion
let p_mut: *mut u32 = &mut m;

unsafe {
    let ref_imm: &u32 = &*p_imm;
    let ref_mut: &mut u32 = &mut *p_mut;
}

```

The `&*x` dereferencing style is preferred to using a `transmute`. The latter is far more powerful than necessary, and the more restricted operation is harder to use incorrectly; for example, it requires that `x` is a pointer (unlike `transmute`).

## 5.37 unsafe

Rust’s main draw is its powerful static guarantees about behavior. But safety checks are conservative by nature: there are some programs that are actually safe, but the compiler is not able to verify this is true. To write these kinds of programs, we need to tell the compiler to relax its restrictions a bit. For this, Rust has a keyword, `unsafe`. Code using `unsafe` has less restrictions than normal code does.

Let’s go over the syntax, and then we’ll talk semantics. `unsafe` is used in two contexts. The first one is to mark a function as unsafe:

```

unsafe fn danger_will_robinson() {
    // scary stuff
}

```

All functions called from FFI (section 4.8, page 106) must be marked as `unsafe`, for example. The second use of `unsafe` is an unsafe block:

```

unsafe {
    // scary stuff
}

```

It’s important to be able to explicitly delineate code that may have bugs that cause big problems. If a Rust program segfaults, you can be sure it’s somewhere in the sections marked `unsafe`.

### 5.37.1 What does ‘safe’ mean?

Safe, in the context of Rust, means “doesn’t do anything unsafe.” Easy!

Okay, let’s try again: what is not safe to do? Here’s a list:

- Data races
- Dereferencing a null/dangling raw pointer
- Reads of `undef`<sup>49</sup> (uninitialized) memory
- Breaking the pointer aliasing rules<sup>50</sup> with raw pointers.
- `&mut T` and `&T` follow LLVM’s scoped noalias<sup>51</sup> model, except if the `&T` contains an `UnsafeCell<U>`. Unsafe code must not violate these aliasing guarantees.
- Mutating an immutable value/reference without `UnsafeCell<U>`
- Invoking undefined behavior via compiler intrinsics:
- Indexing outside of the bounds of an object with `std::ptr::offset` (offset intrinsic), with the exception of one byte past the end which is permitted.
- Using `std::ptr::copy_nonoverlapping_memory` (`memcpy32/memcpy64` intrinsics) on overlapping buffers
- Invalid values in primitive types, even in private fields/locals:
- Null/dangling references or boxes
- A value other than `false` (0) or `true` (1) in a `bool`
- A discriminant in an `enum` not included in its type definition
- A value in a `char` which is a surrogate or above `char::MAX`
- Non-UTF-8 byte sequences in a `str`
- Unwinding into Rust from foreign code or unwinding from Rust into foreign code.

Whew! That’s a bunch of stuff. It’s also important to notice all kinds of behaviors that are certainly bad, but are expressly *not* unsafe:

- Deadlocks
- Reading data from private fields
- Leaks due to reference count cycles
- Exiting without calling destructors
- Sending signals
- Accessing/modifying the file system
- Integer overflow

Rust cannot prevent all kinds of software problems. Buggy code can and will be written in Rust. These things aren’t great, but they don’t qualify as `unsafe` specifically.

### 5.37.2 Unsafe Superpowers

In both unsafe functions and unsafe blocks, Rust will let you do three things that you normally can not do. Just three. Here they are:

1. Access or update a static mutable variable<sup>52</sup>.
2. Dereference a raw pointer.

<sup>49</sup><http://llvm.org/docs/LangRef.html#undefined-values>

<sup>50</sup><http://llvm.org/docs/LangRef.html#pointer-aliasing-rules>

<sup>51</sup><http://llvm.org/docs/LangRef.html#noalias>

<sup>52</sup>[const-and-static.html#static](http://llvm.org/docs/LangRef.html#static)

3. Call unsafe functions. This is the most powerful ability.

That's it. It's important that `unsafe` does not, for example, 'turn off the borrow checker'. Adding `unsafe` to some random Rust code doesn't change its semantics, it won't just start accepting anything.

But it will let you write things that *do* break some of the rules. Let's go over these three abilities in order.

#### Access or update a `static mut`

Rust has a feature called '`static mut`' which allows for mutable global state. Doing so can cause a data race, and as such is inherently not safe. For more details, see the `static`<sup>53</sup> section of the book.

#### Dereference a raw pointer

Raw pointers let you do arbitrary pointer arithmetic, and can cause a number of different memory safety and security issues. In some senses, the ability to dereference an arbitrary pointer is one of the most dangerous things you can do. For more on raw pointers, see their section of the book (section 5.36, page 233).

#### Call unsafe functions

This last ability works with both aspects of `unsafe`: you can only call functions marked `unsafe` from inside an `unsafe` block.

This ability is powerful and varied. Rust exposes some compiler intrinsics (section 6.4, page 251) as unsafe functions, and some unsafe functions bypass safety checks, trading safety for speed.

I'll repeat again: even though you *can* do arbitrary things in `unsafe` blocks and functions doesn't mean you should. The compiler will act as though you're upholding its invariants, so be careful!

---

<sup>53</sup>[const-and-static.html#static](#)



# 6

## Nightly Rust

Rust provides three distribution channels for Rust: nightly, beta, and stable. Unstable features are only available on nightly Rust. For more details on this process, see ‘Stability as a deliverable’<sup>1</sup>.

To install nightly Rust, you can use `rustup.sh`:

```
$ curl -s https://static.rust-lang.org/rustup.sh | sh -s -- --channel=nightly
```

If you’re concerned about the potential insecurity<sup>2</sup> of using `curl | sh`, please keep reading and see our disclaimer below. And feel free to use a two-step version of the installation and examine our installation script:

```
$ curl -f -L https://static.rust-lang.org/rustup.sh -O
$ sh rustup.sh --channel=nightly
```

If you’re on Windows, please download either the 32-bit installer<sup>3</sup> or the 64-bit installer<sup>4</sup> and run it.

### Uninstalling

If you decide you don’t want Rust anymore, we’ll be a bit sad, but that’s okay. Not every programming language is great for everyone. Just run the uninstall script:

```
$ sudo /usr/local/lib/rustlib/uninstall.sh
```

---

<sup>1</sup><http://blog.rust-lang.org/2014/10/30/Stability.html>

<sup>2</sup><http://curlpipesh.tumblr.com>

<sup>3</sup><https://static.rust-lang.org/dist/rust-1.0.0-beta-i686-pc-windows-gnu.msi>

<sup>4</sup>[https://static.rust-lang.org/dist/rust-1.0.0-beta-x86\\_64-pc-windows-gnu.msi](https://static.rust-lang.org/dist/rust-1.0.0-beta-x86_64-pc-windows-gnu.msi)

If you used the Windows installer, just re-run the `.msi` and it will give you an uninstall option.

Some people, and somewhat rightfully so, get very upset when we tell you to `curl | sh`. Basically, when you do this, you are trusting that the good people who maintain Rust aren't going to hack your computer and do bad things. That's a good instinct! If you're one of those people, please check out the documentation on building Rust from Source<sup>5</sup>, or the official binary downloads<sup>6</sup>.

Oh, we should also mention the officially supported platforms:

- Windows (7, 8, Server 2008 R2)
- Linux (2.6.18 or later, various distributions), x86 and x86-64
- OSX 10.7 (Lion) or greater, x86 and x86-64

We extensively test Rust on these platforms, and a few others, too, like Android. But these are the ones most likely to work, as they have the most testing.

Finally, a comment about Windows. Rust considers Windows to be a first-class platform upon release, but if we're honest, the Windows experience isn't as integrated as the Linux/OS X experience is. We're working on it! If anything does not work, it is a bug. Please let us know if that happens. Each and every commit is tested against Windows just like any other platform.

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

```
$ rustc --version
```

You should see the version number, commit hash, commit date and build date:

```
rustc 1.0.0-nightly (f11f3e7ba 2015-01-04) (built 2015-01-06)
```

If you did, Rust has been installed successfully! Congrats!

This installer also installs a copy of the documentation locally, so you can read it offline. On UNIX systems, `/usr/local/share/doc/rust` is the location. On Windows, it's in a `share/doc` directory, inside wherever you installed Rust to.

If not, there are a number of places where you can get help. The easiest is the `#rust` IRC channel on `irc.mozilla.org`<sup>7</sup>, which you can access through Mibbit<sup>8</sup>. Click that link, and you'll be chatting with other Rustaceans (a silly nickname we call ourselves), and we can help you out. Other great resources include the user's forum<sup>9</sup>, and Stack Overflow<sup>10</sup>.

---

<sup>5</sup><https://github.com/rust-lang/rust#building-from-source>

<sup>6</sup><http://www.rust-lang.org/install.html>

<sup>7</sup><irc://irc.mozilla.org/#rust>

<sup>8</sup><http://chat.mibbit.com/?server=irc.mozilla.org&channel=%23rust>

<sup>9</sup><http://users.rust-lang.org/>

<sup>10</sup><http://stackoverflow.com/questions/tagged/rust>



## 6.1 Compiler Plugins

### 6.1.1 Introduction

`rustc` can load compiler plugins, which are user-provided libraries that extend the compiler's behavior with new syntax extensions, lint checks, etc.

A plugin is a dynamic library crate with a designated *registrar* function that registers extensions with `rustc`. Other crates can load these extensions using the crate attribute `#![plugin(...)]`. See the `rustc::plugin`<sup>11</sup> documentation for more about the mechanics of defining and loading a plugin.

If present, arguments passed as `#![plugin(foo(... args ...))]` are not interpreted by `rustc` itself. They are provided to the plugin through the `Registry`'s `args` method<sup>12</sup>.

In the vast majority of cases, a plugin should *only* be used through `#![plugin]` and not through an `extern crate` item. Linking a plugin would pull in all of `libsyntax` and `librustc` as dependencies of your crate. This is generally unwanted unless you are building another plugin. The `plugin_as_library` lint checks these guidelines.

The usual practice is to put compiler plugins in their own crate, separate from any `macro_rules!` macros or ordinary Rust code meant to be used by consumers of a library.

### 6.1.2 Syntax extensions

Plugins can extend Rust's syntax in various ways. One kind of syntax extension is the procedural macro. These are invoked the same way as ordinary macros (section 5.35, page 219), but the expansion is performed by arbitrary Rust code that manipulates syntax trees<sup>13</sup> at compile time.

Let's write a plugin `roman_numerals.rs`<sup>14</sup> that implements Roman numeral integer literals.

```
#![crate_type="dylib"]
#![feature(plugin_registrar, rustc_private)]

extern crate syntax;
extern crate rustc;

use syntax::codemap::Span;
use syntax::parse::token;
use syntax::ast::{TokenTree, TtToken};
use syntax::ext::base::{ExtCtxt, MacResult, DummyResult, MacEager};
use syntax::ext::build::AstBuilder; // trait for expr_use
use rustc::plugin::Registry;

fn expand_rn(cx: &mut ExtCtxt, sp: Span, args: &[TokenTree])
    -> Box<MacResult + 'static> {
```

<sup>11</sup><http://doc.rust-lang.org/rustc/plugin/index.html>

<sup>12</sup><http://doc.rust-lang.org/rustc/plugin/registry/struct.Registry.html#method.args>

<sup>13</sup><http://doc.rust-lang.org/syntax/ast/index.html>

<sup>14</sup>[https://github.com/rust-lang/rust/tree/master/src/test/auxiliary/roman\\_numerals.rs](https://github.com/rust-lang/rust/tree/master/src/test/auxiliary/roman_numerals.rs)

```

static NUMERALS: &'static [(&'static str, u32)] = &[
    ("M", 1000), ("CM", 900), ("D", 500), ("CD", 400),
    ("C", 100), ("XC", 90), ("L", 50), ("XL", 40),
    ("X", 10), ("IX", 9), ("V", 5), ("IV", 4),
    ("I", 1)];

let text = match args {
    [TtToken(_, token::Ident(s, _))] => token::get_ident(s).to_string(),
    _ => {
        cx.span_err(sp, "argument should be a single identifier");
        return DummyResult::any(sp);
    }
};

let mut text = &*text;
let mut total = 0;
while !text.is_empty() {
    match NUMERALS.iter().find(|&(rn, _)| text.starts_with(rn)) {
        Some(&(rn, val)) => {
            total += val;
            text = &text[rn.len()..];
        }
        None => {
            cx.span_err(sp, "invalid Roman numeral");
            return DummyResult::any(sp);
        }
    }
}

MacEager::expr(cx.expr_u32(sp, total))
}

#[plugin_registrar]
pub fn plugin_registrar(reg: &mut Registry) {
    reg.register_macro("rn", expand_rn);
}

```

Then we can use `rn!()` like any other macro:

```

#![feature(plugin)]
#![plugin(roman_numerals)]

fn main() {
    assert_eq!(rn!(MMXV), 2015);
}

```

The advantages over a simple `fn(&str) -> u32` are:

- The (arbitrarily complex) conversion is done at compile time.
- Input validation is also performed at compile time.
- It can be extended to allow use in patterns, which effectively gives a way to define new literal syntax for any data type.

In addition to procedural macros, you can define new `derive`<sup>15</sup>-like attributes and other kinds of extensions. See `Registry::register_syntax_extension`<sup>16</sup> and the `SyntaxExtension` enum<sup>17</sup>. For a more involved macro example, see `regex_macros`<sup>18</sup>.

## Tips and tricks

Some of the macro debugging tips<sup>19</sup> are applicable.

You can use `syntax::parse`<sup>20</sup> to turn token trees into higher-level syntax elements like expressions:

```
fn expand_foo(cx: &mut ExtCtxt, sp: Span, args: &[TokenTree])
    -> Box<MacResult+'static> {

    let mut parser = cx.new_parser_from_tts(args);

    let expr: P<Expr> = parser.parse_expr();
```

Looking through `libsyntax` parser code<sup>21</sup> will give you a feel for how the parsing infrastructure works.

Keep the `Spans`<sup>22</sup> of everything you parse, for better error reporting. You can wrap `Spanned`<sup>23</sup> around your custom data structures.

Calling `ExtCtxt::span_fatal`<sup>24</sup> will immediately abort compilation. It's better to instead call `ExtCtxt::span_err`<sup>25</sup> and return `DummyResult`<sup>26</sup>, so that the compiler can continue and find further errors.

To print syntax fragments for debugging, you can use `span_note`<sup>27</sup> together with `syntax::print::pprust::*_to_string`<sup>28</sup>.

The example above produced an integer literal using `AstBuilder::expr_usize`<sup>29</sup>. As an alternative to the `AstBuilder` trait, `libsyntax` provides a set of quasiquote macros<sup>30</sup>. They are undocumented

<sup>15</sup><http://doc.rust-lang.org/reference.html#derive>

<sup>16</sup>[http://doc.rust-lang.org/rustc/plugin/registry/struct.Registry.html#method.register\\_syntax\\_extension](http://doc.rust-lang.org/rustc/plugin/registry/struct.Registry.html#method.register_syntax_extension)

<sup>17</sup><http://doc.rust-lang.org/syntax/ext/base/enum.SyntaxExtension.html>

<sup>18</sup>[https://github.com/rust-lang/regex/blob/master/regex\\_macros/src/lib.rs](https://github.com/rust-lang/regex/blob/master/regex_macros/src/lib.rs)

<sup>19</sup>[macros.html#debugging-macro-code](http://doc.rust-lang.org/macros.html#debugging-macro-code)

<sup>20</sup><http://doc.rust-lang.org/syntax/parse/index.html>

<sup>21</sup><https://github.com/rust-lang/rust/blob/master/src/libsyntax/parse/parser.rs>

<sup>22</sup><http://doc.rust-lang.org/syntax/codemap/struct.Span.html>

<sup>23</sup><http://doc.rust-lang.org/syntax/codemap/struct.Spanned.html>

<sup>24</sup>[http://doc.rust-lang.org/syntax/ext/base/struct.ExtCtxt.html#method.span\\_fatal](http://doc.rust-lang.org/syntax/ext/base/struct.ExtCtxt.html#method.span_fatal)

<sup>25</sup>[http://doc.rust-lang.org/syntax/ext/base/struct.ExtCtxt.html#method.span\\_err](http://doc.rust-lang.org/syntax/ext/base/struct.ExtCtxt.html#method.span_err)

<sup>26</sup><http://doc.rust-lang.org/syntax/ext/base/struct.DummyResult.html>

<sup>27</sup>[http://doc.rust-lang.org/syntax/ext/base/struct.ExtCtxt.html#method.span\\_note](http://doc.rust-lang.org/syntax/ext/base/struct.ExtCtxt.html#method.span_note)

<sup>28</sup><http://doc.rust-lang.org/syntax/print/pprust/index.html#functions>

<sup>29</sup>[http://doc.rust-lang.org/syntax/ext/build/trait.AstBuilder.html#tymethod.expr\\_usize](http://doc.rust-lang.org/syntax/ext/build/trait.AstBuilder.html#tymethod.expr_usize)

<sup>30</sup><http://doc.rust-lang.org/syntax/ext/quote/index.html>

and very rough around the edges. However, the implementation may be a good starting point for an improved quasiquote as an ordinary plugin library.

### 6.1.3 Lint plugins

Plugins can extend Rust's lint infrastructure<sup>31</sup> with additional checks for code style, safety, etc. You can see `src/test/auxiliary/lint_plugin_test.rs`<sup>32</sup> for a full example, the core of which is reproduced here:

```
declare_lint!(TEST_LINT, Warn,
            "Warn about items named 'lintme'");

struct Pass;

impl LintPass for Pass {
    fn get_lints(&self) -> LintArray {
        lint_array!(TEST_LINT)
    }

    fn check_item(&mut self, cx: &Context, it: &ast::Item) {
        let name = token::get_ident(it.ident);
        if name.get() == "lintme" {
            cx.span_lint(TEST_LINT, it.span, "item is named 'lintme'");
        }
    }
}

#[plugin_registrar]
pub fn plugin_registrar(reg: &mut Registry) {
    reg.register_lint_pass(box Pass as LintPassObject);
}
```

Then code like

```
#![plugin(lint_plugin_test)]

fn lintme() { }
```

will produce a compiler warning:

```
foo.rs:4:1: 4:16 warning: item is named 'lintme', #[warn(test_lint)] on by default
foo.rs:4 fn lintme() { }
```

^~~~~~

The components of a lint plugin are:

<sup>31</sup><http://doc.rust-lang.org/reference.html#lint-check-attributes>

<sup>32</sup>[https://github.com/rust-lang/rust/blob/master/src/test/auxiliary/lint\\_plugin\\_test.rs](https://github.com/rust-lang/rust/blob/master/src/test/auxiliary/lint_plugin_test.rs)

- one or more `declare_lint!` invocations, which define static `Lint`<sup>33</sup> structs;
- a struct holding any state needed by the lint pass (here, none);
- a `LintPass`<sup>34</sup> implementation defining how to check each syntax element. A single `LintPass` may call `span_lint` for several different `Lints`, but should register them all through the `get_lints` method.

Lint passes are syntax traversals, but they run at a late stage of compilation where type information is available. `rustc`'s built-in lints<sup>35</sup> mostly use the same infrastructure as lint plugins, and provide examples of how to access type information.

Lints defined by plugins are controlled by the usual attributes and compiler flags<sup>36</sup>, e.g. `#[allow(test_lint)]` or `-A test-lint`. These identifiers are derived from the first argument to `declare_lint!`, with appropriate case and punctuation conversion.

You can run `rustc -W help foo.rs` to see a list of lints known to `rustc`, including those provided by plugins loaded by `foo.rs`.

## 6.2 Inline Assembly

For extremely low-level manipulations and performance reasons, one might wish to control the CPU directly. Rust supports using inline assembly to do this via the `asm!` macro. The syntax roughly matches that of GCC & Clang:

```
asm!(assembly template
    : output operands
    : input operands
    : clobbers
    : options
    );
```

Any use of `asm` is feature gated (requires `#![feature(asm)]` on the crate to allow) and of course requires an `unsafe` block.

**Note:** the examples here are given in x86/x86-64 assembly, but all platforms are supported.

### Assembly template

The `assembly template` is the only required parameter and must be a literal string (i.e. `"`)

<sup>33</sup><http://doc.rust-lang.org/rustc/lint/struct.Lint.html>

<sup>34</sup><http://doc.rust-lang.org/rustc/lint/trait.LintPass.html>

<sup>35</sup><https://github.com/rust-lang/rust/blob/master/src/librustc/lint/builtin.rs>

<sup>36</sup><http://doc.rust-lang.org/reference.html#lint-check-attributes>

```

#![feature(asm)]

#[cfg(any(target_arch = "x86", target_arch = "x86_64"))]
fn foo() {
    unsafe {
        asm!("NOP");
    }
}

// other platforms
#[cfg(not(any(target_arch = "x86", target_arch = "x86_64")))]
fn foo() { /* ... */ }

fn main() {
    // ...
    foo();
    // ...
}

```

(The `feature(asm)` and `#[cfg]`s are omitted from now on.)

Output operands, input operands, clobbers and options are all optional but you must add the right number of `:` if you skip them:

```

# #![feature(asm)]
# #[cfg(any(target_arch = "x86", target_arch = "x86_64"))]
# fn main() { unsafe {
asm!("xor %eax, %eax"
    :
    :
    : "{eax}"
);
# } }

```

Whitespace also doesn't matter:

```

# #![feature(asm)]
# #[cfg(any(target_arch = "x86", target_arch = "x86_64"))]
# fn main() { unsafe {
asm!("xor %eax, %eax" ::: "{eax}");
# } }

```

## Operands

Input and output operands follow the same format: `: "constraints1"(expr1), "constraints2"(expr2), ...`. Output operand expressions must be mutable lvalues, or not yet assigned:

```

# #![feature(asm)]
# #[cfg(any(target_arch = "x86", target_arch = "x86_64"))]
fn add(a: i32, b: i32) -> i32 {
    let c: i32;
    unsafe {
        asm!("add $2, $0"
            : "=r"(c)
            : "0"(a), "r"(b)
            );
    }
    c
}
# #[cfg(not(any(target_arch = "x86", target_arch = "x86_64")))]
# fn add(a: i32, b: i32) -> i32 { a + b }

fn main() {
    assert_eq!(add(3, 14159), 14162)
}

```

If you would like to use real operands in this position, however, you are required to put curly braces {} around the register that you want, and you are required to put the specific size of the operand. This is useful for very low level programming, where which register you use is important:

```

# #![feature(asm)]
# #[cfg(any(target_arch = "x86", target_arch = "x86_64"))]
# unsafe fn read_byte_in(port: u16) -> u8 {
    let result: u8;
    asm!("in %dx, %al" : "{al}"(result) : "{dx}"(port));
    result
# }

```

## Clobbers

Some instructions modify registers which might otherwise have held different values so we use the clobbers list to indicate to the compiler not to assume any values loaded into those registers will stay valid.

```

# #![feature(asm)]
# #[cfg(any(target_arch = "x86", target_arch = "x86_64"))]
# fn main() { unsafe {
    // Put the value 0x200 in eax
    asm!("mov $0x200, %eax" : /* no outputs */ : /* no inputs */ : "{eax}");
# } }

```

Input and output registers need not be listed since that information is already communicated by the given constraints. Otherwise, any other registers used either implicitly or explicitly should be listed.

If the assembly changes the condition code register `cc` should be specified as one of the clobbers. Similarly, if the assembly modifies memory, `memory` should also be specified.

## Options

The last section, `options` is specific to Rust. The format is comma separated literal strings (i.e. `:"foo", "bar", "baz"`). It's used to specify some extra info about the inline assembly:

Current valid options are:

1. *volatile* - specifying this is analogous to `__asm__ __volatile__ (...)` in gcc/clang.
2. *alignstack* - certain instructions expect the stack to be aligned a certain way (i.e. SSE) and specifying this indicates to the compiler to insert its usual stack alignment code
3. *intel* - use intel syntax instead of the default AT&T.

```
# #![feature(asm)]
# #[cfg(any(target_arch = "x86", target_arch = "x86_64"))]
# fn main() {
  let result: i32;
  unsafe {
    asm!("mov eax, 2" : "{eax}"(result) : : : "intel")
  }
  println!("eax is currently {}", result);
# }
```

## 6.3 No stdlib

By default, `std` is linked to every Rust crate. In some contexts, this is undesirable, and can be avoided with the `#![no_std]` attribute attached to the crate.

```
// a minimal library
#![crate_type="lib"]
#![feature(no_std)]
#![no_std]
# // fn main() {} tricked you, rustdoc!
```

Obviously there's more to life than just libraries: one can use `#![no_std]` with an executable, controlling the entry point is possible in two ways: the `#[start]` attribute, or overriding the default shim for the C `main` function with your own.

The function marked `#[start]` is passed the command line parameters in the same format as C:

```
#![feature(lang_items, start, no_std, libc)]
#![no_std]

// Pull in the system libc library for what crt0.o likely requires
```



```
extern crate libc;

// Entry point for this program
#[start]
fn start(_argc: isize, _argv: *const *const u8) -> isize {
    0
}

// These functions and traits are used by the compiler, but not
// for a bare-bones hello world. These are normally
// provided by libstd.
#[lang = "stack_exhausted"] extern fn stack_exhausted() {}
#[lang = "eh_personality"] extern fn eh_personality() {}
#[lang = "panic_fmt"] fn panic_fmt() -> ! { loop {} }
# // fn main() {} tricked you, rustdoc!
```

To override the compiler-inserted `main` shim, one has to disable it with `#![no_main]` and then create the appropriate symbol with the correct ABI and the correct name, which requires overriding the compiler's name mangling too:

```
#![feature(no_std)]
#![no_std]
#![no_main]
#![feature(lang_items, start)]

extern crate libc;

#[no_mangle] // ensure that this symbol is called `main` in the output
pub extern fn main(argc: i32, argv: *const *const u8) -> i32 {
    0
}

#[lang = "stack_exhausted"] extern fn stack_exhausted() {}
#[lang = "eh_personality"] extern fn eh_personality() {}
#[lang = "panic_fmt"] fn panic_fmt() -> ! { loop {} }
# // fn main() {} tricked you, rustdoc!
```

The compiler currently makes a few assumptions about symbols which are available in the executable to call. Normally these functions are provided by the standard library, but without it you must define your own.

The first of these three functions, `stack_exhausted`, is invoked whenever stack overflow is detected. This function has a number of restrictions about how it can be called and what it must do, but if the stack limit register is not being maintained then a thread always has an “infinite stack” and this function shouldn't get triggered.

The second of these three functions, `eh_personality`, is used by the failure mechanisms of the compiler. This is often mapped to GCC's personality function (see the `libstd` implementation<sup>37</sup>

---

<sup>37</sup><http://doc.rust-lang.org/std/rt/unwind/index.html>

for more information), but crates which do not trigger a panic can be assured that this function is never called. The final function, `panic_fmt`, is also used by the failure mechanisms of the compiler.

### Using `libcore`

**Note:** the core library’s structure is unstable, and it is recommended to use the standard library instead wherever possible.

With the above techniques, we’ve got a bare-metal executable running some Rust code. There is a good deal of functionality provided by the standard library, however, that is necessary to be productive in Rust. If the standard library is not sufficient, then `libcore`<sup>38</sup> is designed to be used instead.

The core library has very few dependencies and is much more portable than the standard library itself. Additionally, the core library has most of the necessary functionality for writing idiomatic and effective Rust code.

As an example, here is a program that will calculate the dot product of two vectors provided from C, using idiomatic Rust practices.

```
#![feature(lang_items, start, no_std, core, libc)]
#![no_std]

# extern crate libc;
extern crate core;

use core::prelude::*;

use core::mem;

#[no_mangle]
pub extern fn dot_product(a: *const u32, a_len: u32,
                          b: *const u32, b_len: u32) -> u32 {
    use core::raw::Slice;

    // Convert the provided arrays into Rust slices.
    // The core::raw module guarantees that the Slice
    // structure has the same memory layout as a &[T]
    // slice.
    //
    // This is an unsafe operation because the compiler
    // cannot tell the pointers are valid.
    let (a_slice, b_slice): (&[u32], &[u32]) = unsafe {
        mem::transmute((
            Slice { data: a, len: a_len as usize },
            Slice { data: b, len: b_len as usize },
        ))
    }
}
```

---

<sup>38</sup><http://doc.rust-lang.org/core/index.html>

```

    ))
};

// Iterate over the slices, collecting the result
let mut ret = 0;
for (i, j) in a_slice.iter().zip(b_slice.iter()) {
    ret += (*i) * (*j);
}
return ret;
}

#[lang = "panic_fmt"]
extern fn panic_fmt(args: &core::fmt::Arguments,
                    file: &str,
                    line: u32) -> ! {
    loop {}
}

#[lang = "stack_exhausted"] extern fn stack_exhausted() {}
#[lang = "eh_personality"] extern fn eh_personality() {}
# #[start] fn start(argc: isize, argv: *const *const u8) -> isize { 0 }
# fn main() {}

```

Note that there is one extra lang item here which differs from the examples above, `panic_fmt`. This must be defined by consumers of libcore because the core library declares panics, but it does not define it. The `panic_fmt` lang item is this crate's definition of panic, and it must be guaranteed to never return.

As can be seen in this example, the core library is intended to provide the power of Rust in all circumstances, regardless of platform requirements. Further libraries, such as `liballoc`, add functionality to libcore which make other platform-specific assumptions, but continue to be more portable than the standard library itself.

## 6.4 Intrinsics

**Note:** intrinsics will forever have an unstable interface, it is recommended to use the stable interfaces of libcore rather than intrinsics directly.

These are imported as if they were FFI functions, with the special `rust-intrinsic` ABI. For example, if one was in a freestanding context, but wished to be able to `transmute` between types, and perform efficient pointer arithmetic, one would import those functions via a declaration like

```

# #![feature(intrinsics)]
# fn main() {}

extern "rust-intrinsic" {
    fn transmute<T, U>(x: T) -> U;

```

```
fn offset<T>(dst: *const T, offset: isize) -> *const T;
}
```

As with any other FFI functions, these are always `unsafe` to call.

## 6.5 Lang items

**Note:** lang items are often provided by crates in the Rust distribution, and lang items themselves have an unstable interface. It is recommended to use officially distributed crates instead of defining your own lang items.

The `rustc` compiler has certain pluggable operations, that is, functionality that isn't hard-coded into the language, but is implemented in libraries, with a special marker to tell the compiler it exists. The marker is the attribute `#[lang = "..."]` and there are various different values of ..., i.e. various different 'lang items'.

For example, `Box` pointers require two lang items, one for allocation and one for deallocation. A freestanding program that uses the `Box` sugar for dynamic allocations via `malloc` and `free`:

```
#![feature(lang_items, box_syntax, start, no_std, libc)]
#![no_std]

extern crate libc;

extern {
    fn abort() -> !;
}

#[lang = "owned_box"]
pub struct Box<T>(*mut T);

#[lang = "exchange_malloc"]
unsafe fn allocate(size: usize, _align: usize) -> *mut u8 {
    let p = libc::malloc(size as libc::size_t) as *mut u8;

    // malloc failed
    if p as usize == 0 {
        abort();
    }

    p
}

#[lang = "exchange_free"]
unsafe fn deallocate(ptr: *mut u8, _size: usize, _align: usize) {
    libc::free(ptr as *mut libc::c_void)
}
```

```
#[start]
fn main(argc: isize, argv: *const *const u8) -> isize {
    let x = box 1;

    0
}

#[lang = "stack_exhausted"] extern fn stack_exhausted() {}
#[lang = "eh_personality"] extern fn eh_personality() {}
#[lang = "panic_fmt"] fn panic_fmt() -> ! { loop {} }
```

Note the use of `abort`: the `exchange_malloc` lang item is assumed to return a valid pointer, and so needs to do the check internally.

Other features provided by lang items include:

- overloadable operators via traits: the traits corresponding to the `==`, `<`, dereferencing `(*)` and `+` (etc.) operators are all marked with lang items; those specific four are `eq`, `ord`, `deref`, and `add` respectively.
- stack unwinding and general failure; the `eh_personality`, `fail` and `fail_bounds_checks` lang items.
- the traits in `std::marker` used to indicate types of various kinds; lang items `send`, `sync` and `copy`.
- the marker types and variance indicators found in `std::marker`; lang items `covariant_type`, `contravariant_lifetime`, etc.

Lang items are loaded lazily by the compiler; e.g. if one never uses `Box` then there is no need to define functions for `exchange_malloc` and `exchange_free`. `rustc` will emit an error when an item is needed but not found in the current crate or any that it depends on.

## 6.6 Link args

There is one other way to tell `rustc` how to customize linking, and that is via the `link_args` attribute. This attribute is applied to `extern` blocks and specifies raw flags which need to get passed to the linker when producing an artifact. An example usage would be:

```
#![feature(link_args)]

#[link_args = "-foo -bar -baz"]
extern {}

# fn main() {}
```

Note that this feature is currently hidden behind the `feature(link_args)` gate because this is not a sanctioned way of performing linking. Right now `rustc` shells out to the system linker, so it makes sense to provide extra command line arguments, but this will not always be the case.

In the future `rustc` may use LLVM directly to link native libraries in which case `link_args` will have no meaning.

It is highly recommended to *not* use this attribute, and rather use the more formal `#[link(...)]` attribute on `extern` blocks instead.

## 6.7 Benchmark Tests

Rust supports benchmark tests, which can test the performance of your code. Let's make our `src/lib.rs` look like this (comments elided):

```
#![feature(test)]

extern crate test;

pub fn add_two(a: i32) -> i32 {
    a + 2
}

#[cfg(test)]
mod tests {
    use super::*;
    use test::Bencher;

    #[test]
    fn it_works() {
        assert_eq!(4, add_two(2));
    }

    #[bench]
    fn bench_add_two(b: &mut Bencher) {
        b.iter(|| add_two(2));
    }
}
```

Note the `test` feature gate, which enables this unstable feature.

We've imported the `test` crate, which contains our benchmarking support. We have a new function as well, with the `bench` attribute. Unlike regular tests, which take no arguments, benchmark tests take a `&mut Bencher`. This `Bencher` provides an `iter` method, which takes a closure. This closure contains the code we'd like to benchmark.

We can run benchmark tests with `cargo bench`:

```
$ cargo bench
  Compiling adder v0.0.1 (file:///home/steve/tmp/adder)
    Running target/release/adder-91b3e234d4ed382a

running 2 tests
```

```
test tests::it_works ... ignored
test tests::bench_add_two ... bench:          1 ns/iter (+/- 0)

test result: ok. 0 passed; 0 failed; 1 ignored; 1 measured
```

Our non-benchmark test was ignored. You may have noticed that `cargo bench` takes a bit longer than `cargo test`. This is because Rust runs our benchmark a number of times, and then takes the average. Because we’re doing so little work in this example, we have a `1 ns/iter (+/- 0)`, but this would show the variance if there was one.

Advice on writing benchmarks:

- Move setup code outside the `iter` loop; only put the part you want to measure inside
- Make the code do “the same thing” on each iteration; do not accumulate or change state
- Make the outer function idempotent too; the benchmark runner is likely to run it many times
- Make the inner `iter` loop short and fast so benchmark runs are fast and the calibrator can adjust the run-length at fine resolution
- Make the code in the `iter` loop do something simple, to assist in pinpointing performance improvements (or regressions)

### Gotcha: optimizations

There’s another tricky part to writing benchmarks: benchmarks compiled with optimizations activated can be dramatically changed by the optimizer so that the benchmark is no longer benchmarking what one expects. For example, the compiler might recognize that some calculation has no external effects and remove it entirely.

```
#![feature(test)]

extern crate test;
use test::Bencher;

#[bench]
fn bench_xor_1000_ints(b: &mut Bencher) {
    b.iter(|| {
        (0..1000).fold(0, |old, new| old ^ new);
    });
}
```

gives the following results

```
running 1 test
test bench_xor_1000_ints ... bench:          0 ns/iter (+/- 0)

test result: ok. 0 passed; 0 failed; 0 ignored; 1 measured
```

The benchmarking runner offers two ways to avoid this. Either, the closure that the `iter` method receives can return an arbitrary value which forces the optimizer to consider the result used and ensures it cannot remove the computation entirely. This could be done for the example above by adjusting the `b.iter` call to

```
b.iter(|| {
    // note lack of `;` (could also use an explicit `return`).
    (0..1000).fold(0, |old, new| old ^ new)
});
```

Or, the other option is to call the generic `test::black_box` function, which is an opaque “black box” to the optimizer and so forces it to consider any argument as used.

```
#![feature(test)]

extern crate test;

b.iter(|| {
    let n = test::black_box(1000);

    (0..n).fold(0, |a, b| a ^ b)
})
```

Neither of these read or modify the value, and are very cheap for small values. Larger values can be passed indirectly to reduce overhead (e.g. `black_box(&huge_struct)`).

Performing either of the above changes gives the following benchmarking results

```
running 1 test
test bench_xor_1000_ints ... bench:      131 ns/iter (+/- 3)

test result: ok. 0 passed; 0 failed; 0 ignored; 1 measured
```

However, the optimizer can still modify a testcase in an undesirable manner even when using either of the above.

## 6.8 Box Syntax and Patterns

Currently the only stable way to create a `Box` is via the `Box::new` method. Also it is not possible in stable Rust to destructure a `Box` in a match pattern. The unstable `box` keyword can be used to both create and destructure a `Box`. An example usage would be:

```
#![feature(box_syntax, box_patterns)]

fn main() {
    let b = Some(box 5);
    match b {
```



```

    Some(box n) if n < 0 => {
        println!("Box contains negative number {}", n);
    },
    Some(box n) if n >= 0 => {
        println!("Box contains non-negative number {}", n);
    },
    None => {
        println!("No box");
    },
    _ => unreachable!()
}
}

```

Note that these features are currently hidden behind the `box_syntax` (box creation) and `box_patterns` (destructuring and pattern matching) gates because the syntax may still change in the future.

### 6.8.1 Returning Pointers

In many languages with pointers, you'd return a pointer from a function so as to avoid copying a large data structure. For example:

```

struct BigStruct {
    one: i32,
    two: i32,
    // etc
    one_hundred: i32,
}

fn foo(x: Box<BigStruct>) -> Box<BigStruct> {
    Box::new(*x)
}

fn main() {
    let x = Box::new(BigStruct {
        one: 1,
        two: 2,
        one_hundred: 100,
    });

    let y = foo(x);
}

```

The idea is that by passing around a box, you're only copying a pointer, rather than the hundred ints that make up the `BigStruct`.

This is an antipattern in Rust. Instead, write this:

```

#![feature(box_syntax)]

struct BigStruct {
    one: i32,
    two: i32,
    // etc
    one_hundred: i32,
}

fn foo(x: Box<BigStruct>) -> BigStruct {
    *x
}

fn main() {
    let x = Box::new(BigStruct {
        one: 1,
        two: 2,
        one_hundred: 100,
    });

    let y: Box<BigStruct> = box foo(x);
}

```

This gives you flexibility without sacrificing performance.

You may think that this gives us terrible performance: return a value and then immediately box it up ?! Isn't this pattern the worst of both worlds? Rust is smarter than that. There is no copy in this code. `main` allocates enough room for the `box`, passes a pointer to that memory into `foo` as `x`, and then `foo` writes the value straight into the `Box<T>`.

This is important enough that it bears repeating: pointers are not for optimizing returning values from your code. Allow the caller to choose how they want to use your output.

## 6.9 Slice Patterns

If you want to match against a slice or array, you can use `&` with the `slice_patterns` feature:

```

#![feature(slice_patterns)]

fn main() {
    let v = vec!["match_this", "1"];

    match &v[..] {
        ["match_this", second] => println!("The second element is {}", second),
        _ => {},
    }
}

```

The `advanced_slice_patterns` gate lets you use `..` to indicate any number of elements inside a pattern matching a slice. This wildcard can only be used once for a given array. If there's an identifier before the `..`, the result of the slice will be bound to that name. For example:

```
#![feature(advanced_slice_patterns, slice_patterns)]

fn is_symmetric(list: &[u32]) -> bool {
    match list {
        [] | [_] => true,
        [x, inside.., y] if x == y => is_symmetric(inside),
        _ => false
    }
}

fn main() {
    let sym = &[0, 1, 4, 2, 4, 1, 0];
    assert!(is_symmetric(sym));

    let not_sym = &[0, 1, 7, 2, 4, 1, 0];
    assert!(!is_symmetric(not_sym));
}
```

## 6.10 Associated Constants

With the `associated_consts` feature, you can define constants like this:

```
#![feature(associated_consts)]

trait Foo {
    const ID: i32;
}

impl Foo for i32 {
    const ID: i32 = 1;
}

fn main() {
    assert_eq!(1, i32::ID);
}
```

Any implementor of `Foo` will have to define `ID`. Without the definition:

```
#![feature(associated_consts)]

trait Foo {
    const ID: i32;
}
```

```
impl Foo for i32 {
}
```

gives

```
error: not all trait items implemented, missing: `ID` [E0046]
    impl Foo for i32 {
    }
```

A default value can be implemented as well:

```
#![feature(associated_consts)]

trait Foo {
    const ID: i32 = 1;
}

impl Foo for i32 {
}

impl Foo for i64 {
    const ID: i32 = 5;
}

fn main() {
    assert_eq!(1, i32::ID);
    assert_eq!(5, i64::ID);
}
```

As you can see, when implementing `Foo`, you can leave it unimplemented, as with `i32`. It will then use the default value. But, as in `i64`, we can also add our own definition.

Associated constants don't have to be associated with a trait. An `impl` block for a `struct` works fine too:

```
#![feature(associated_consts)]

struct Foo;

impl Foo {
    pub const F00: u32 = 3;
}
```

# 7

## Glossary

Not every Rustacean has a background in systems programming, nor in computer science, so we've added explanations of terms that might be unfamiliar.

**Arity** Arity refers to the number of arguments a function or operation takes.

```
let x = (2, 3);  
let y = (4, 6);  
let z = (8, 2, 6);
```

In the example above x and y have arity 2. z has arity 3.

**Abstract Syntax Tree** When a compiler is compiling your program, it does a number of different things. One of the things that it does is turn the text of your program into an 'abstract syntax tree', or 'AST'. This tree is a representation of the structure of your program. For example,  $2 + 3$  can be turned into a tree:

```
  +  
 / \  
2  3
```

And  $2 + (3 * 4)$  would look like this:

```
  +  
 / \  
2  *  
   / \  
  3  4
```



# 8

## Academic Research

An incomplete list of papers that have had some influence in Rust.

Recommended for inspiration and a better understanding of Rust's background.

### Type system

- Region based memory management in Cyclone<sup>1</sup>
- Safe manual memory management in Cyclone<sup>2</sup>
- Typeclasses: making ad-hoc polymorphism less ad hoc<sup>3</sup>
- Macros that work together<sup>4</sup>
- Traits: composable units of behavior<sup>5</sup>
- Alias burying<sup>6</sup> - We tried something similar and abandoned it.
- External uniqueness is unique enough<sup>7</sup>
- Uniqueness and Reference Immutability for Safe Parallelism<sup>8</sup>
- Region Based Memory Management<sup>9</sup>

### Concurrency

- Singularity: rethinking the software stack<sup>10</sup>

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<sup>1</sup><http://209.68.42.137/ucsd-pages/Courses/cse227.w03/handouts/cyclone-regions.pdf>

<sup>2</sup><http://www.cs.umd.edu/projects/PL/cyclone/scp.pdf>

<sup>3</sup><http://www.ps.uni-sb.de/courses/typen-ws99/class.ps.gz>

<sup>4</sup><http://www.cs.utah.edu/plt/publications/jfp12-draft-fcdf.pdf>

<sup>5</sup><http://scg.unibe.ch/archive/papers/Scha03aTraits.pdf>

<sup>6</sup><http://www.cs.uwm.edu/faculty/boyland/papers/unique-preprint.ps>

<sup>7</sup><http://www.computingscience.nl/research/techreps/repo/CS-2002/2002-048.pdf>

<sup>8</sup><https://research.microsoft.com/pubs/170528/msr-tr-2012-79.pdf>

<sup>9</sup><http://www.cs.ucla.edu/~palsberg/tba/papers/tofte-talpin-iandc97.pdf>

<sup>10</sup>[https://research.microsoft.com/pubs/69431/osr2007\\_rethinkingsoftwarestack.pdf](https://research.microsoft.com/pubs/69431/osr2007_rethinkingsoftwarestack.pdf)

- Language support for fast and reliable message passing in singularity OS<sup>11</sup>
- Scheduling multithreaded computations by work stealing<sup>12</sup>
- Thread scheduling for multiprogramming multiprocessors<sup>13</sup>
- The data locality of work stealing<sup>14</sup>
- Dynamic circular work stealing deque<sup>15</sup> - The Chase/Lev deque
- Work-first and help-first scheduling policies for async-finish task parallelism<sup>16</sup> - More general than fully-strict work stealing
- A Java fork/join calamity<sup>17</sup> - critique of Java's fork/join library, particularly its application of work stealing to non-strict computation
- Scheduling techniques for concurrent systems<sup>18</sup>
- Contention aware scheduling<sup>19</sup>
- Balanced work stealing for time-sharing multicores<sup>20</sup>
- Three layer cake<sup>21</sup>
- Non-blocking steal-half work queues<sup>22</sup>
- Reagents: expressing and composing fine-grained concurrency<sup>23</sup>
- Algorithms for scalable synchronization of shared-memory multiprocessors<sup>24</sup>

### Others

- Crash-only software<sup>25</sup>
- Composing High-Performance Memory Allocators<sup>26</sup>
- Reconsidering Custom Memory Allocation<sup>27</sup>

### Papers *about* Rust

- GPU programming in Rust<sup>28</sup>
- Parallel closures: a new twist on an old idea<sup>29</sup> - not exactly about rust, but by nmatsakis

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<sup>11</sup><https://research.microsoft.com/pubs/67482/singsharp.pdf>

<sup>12</sup><http://supertech.csail.mit.edu/papers/steal.pdf>

<sup>13</sup><http://www.eecis.udel.edu/%7Ecavazos/cisc879-spring2008/papers/arora98thread.pdf>

<sup>14</sup>[http://www.aladdin.cs.cmu.edu/papers/pdfs/y2000/locality\\_spaa00.pdf](http://www.aladdin.cs.cmu.edu/papers/pdfs/y2000/locality_spaa00.pdf)

<sup>15</sup><http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.170.1097&rep=rep1&type=pdf>

<sup>16</sup><http://www.cs.rice.edu/%7Eyguo/pubs/PID824943.pdf>

<sup>17</sup><http://www.coopsoft.com/ar/CalamityArticle.html>

<sup>18</sup><http://www.ece.rutgers.edu/%7Eparashar/Classes/ece572-papers/05/ps-ousterhout.pdf>

<sup>19</sup><http://www.blagodurov.net/files/a8-blagodurov.pdf>

<sup>20</sup><http://www.cse.ohio-state.edu/hpcs/WWW/HTML/publications/papers/TR-12-1.pdf>

<sup>21</sup>[http://www.upcrc.illinois.edu/workshops/paraplop10/papers/paraplop10\\_submission\\_8.pdf](http://www.upcrc.illinois.edu/workshops/paraplop10/papers/paraplop10_submission_8.pdf)

<sup>22</sup><http://www.cs.bgu.ac.il/%7Ehendlerd/papers/p280-hendler.pdf>

<sup>23</sup><http://www.mpi-sws.org/~turon/reagents.pdf>

<sup>24</sup>[https://www.cs.rochester.edu/u/scott/papers/1991\\_TOCS\\_synch.pdf](https://www.cs.rochester.edu/u/scott/papers/1991_TOCS_synch.pdf)

<sup>25</sup>[https://www.usenix.org/legacy/events/hotos03/tech/full\\_papers/candea/candea.pdf](https://www.usenix.org/legacy/events/hotos03/tech/full_papers/candea/candea.pdf)

<sup>26</sup><http://people.cs.umass.edu/~emery/pubs/berger-pldi2001.pdf>

<sup>27</sup><http://people.cs.umass.edu/~emery/pubs/berger-oopsla2002.pdf>

<sup>28</sup><http://www.cs.indiana.edu/~eholk/papers/hips2013.pdf>

<sup>29</sup><https://www.usenix.org/conference/hotpar12/parallel-closures-new-twist-old-idea>