Advanced Features

By now, you’ve learned the most commonly used parts of the Rust programming language. Before we do one more project, in Chapter 21, we’ll look at a few aspects of the language you might run into every once in a while but may not use every day. You can use this chapter as a reference for when you encounter any unknowns. The features covered here are useful in very specific situations. Although you might not reach for them often, we want to make sure you have a grasp of all the features Rust has to offer.

In this chapter, we’ll cover:

* Unsafe Rust: How to opt out of some of Rust’s guarantees and take responsibility for manually upholding those guarantees
* Advanced traits: Associated types, default type parameters, fully qualified syntax, supertraits, and the newtype pattern in relation to traits
* Advanced types: More about the newtype pattern, type aliases, the never type, and dynamically sized types
* Advanced functions and closures: Function pointers and returning closures
* Macros: Ways to define code that defines more code at compile time

It’s a panoply of Rust features with something for everyone! Let’s dive in!

Unsafe Rust

All the code we’ve discussed so far has had Rust’s memory safety guarantees enforced at compile time. However, Rust has a second language hidden inside it that doesn’t enforce these memory safety guarantees: It’s called unsafe Rust and works just like regular Rust but gives us extra superpowers.

Unsafe Rust exists because, by nature, static analysis is conservative. When the compiler tries to determine whether or not code upholds the guarantees, it’s better for it to reject some valid programs than to accept some invalid programs. Although the code might be okay, if the Rust compiler doesn’t have enough information to be confident, it will reject the code. In these cases, you can use unsafe code to tell the compiler, “Trust me, I know what I’m doing.” Be warned, however, that you use unsafe Rust at your own risk: If you use unsafe code incorrectly, problems can occur due to memory unsafety, such as null pointer dereferencing.

Another reason Rust has an unsafe alter ego is that the underlying computer hardware is inherently unsafe. If Rust didn’t let you do unsafe operations, you couldn’t do certain tasks. Rust needs to allow you to do low-level systems programming, such as directly interacting with the operating system or even writing your own operating system. Working with low-level systems programming is one of the goals of the language. Let’s explore what we can do with unsafe Rust and how to do it.

Performing Unsafe Superpowers

To switch to unsafe Rust, use the unsafe keyword and then start a new block that holds the unsafe code. You can take five actions in unsafe Rust that you can’t in safe Rust, which we call unsafe superpowers. Those superpowers include the ability to:

1. Dereference a raw pointer.
2. Call an unsafe function or method.
3. Access or modify a mutable static variable.
4. Implement an unsafe trait.
5. Access fields of unions.

It’s important to understand that unsafe doesn’t turn off the borrow checker or disable any of Rust’s other safety checks: If you use a reference in unsafe code, it will still be checked. The unsafe keyword only gives you access to these five features that are then not checked by the compiler for memory safety. You’ll still get some degree of safety inside an unsafe block.

In addition, unsafe does not mean the code inside the block is necessarily dangerous or that it will definitely have memory safety problems: The intent is that as the programmer, you’ll ensure that the code inside an unsafe block will access memory in a valid way.

People are fallible and mistakes will happen, but by requiring these five unsafe operations to be inside blocks annotated with unsafe, you’ll know that any errors related to memory safety must be within an unsafe block. Keep unsafe blocks small; you’ll be thankful later when you investigate memory bugs.

To isolate unsafe code as much as possible, it’s best to enclose such code within a safe abstraction and provide a safe API, which we’ll discuss later in the chapter when we examine unsafe functions and methods. Parts of the standard library are implemented as safe abstractions over unsafe code that has been audited. Wrapping unsafe code in a safe abstraction prevents uses of unsafe from leaking out into all the places that you or your users might want to use the functionality implemented with unsafe code, because using a safe abstraction is safe.

Let’s look at each of the five unsafe superpowers in turn. We’ll also look at some abstractions that provide a safe interface to unsafe code.

Dereferencing a Raw Pointer

In “Dangling References” on page XX, we mentioned that the compiler ensures that references are always valid. Unsafe Rust has two new types called raw pointers that are similar to references. As with references, raw pointers can be immutable or mutable and are written as \*const T and \*mut T, respectively. The asterisk isn’t the dereference operator; it’s part of the type name. In the context of raw pointers, immutable means that the pointer can’t be directly assigned to after being dereferenced.

Different from references and smart pointers, raw pointers:

* Are allowed to ignore the borrowing rules by having both immutable and mutable pointers or multiple mutable pointers to the same location
* Aren’t guaranteed to point to valid memory
* Are allowed to be null
* Don’t implement any automatic cleanup

By opting out of having Rust enforce these guarantees, you can give up guaranteed safety in exchange for greater performance or the ability to interface with another language or hardware where Rust’s guarantees don’t apply.

Listing 20-1 shows how to create an immutable and a mutable raw pointer.

let mut num = 5;

let r1 = &raw const num;

let r2 = &raw mut num;

Creating raw pointers with the raw borrow operators

Notice that we don’t include the unsafe keyword in this code. We can create raw pointers in safe code; we just can’t dereference raw pointers outside an unsafe block, as you’ll see in a bit.

We’ve created raw pointers by using the raw borrow operators: &raw const num creates a \*const i32 immutable raw pointer, and &raw mut num creates a \*mut i32 mutable raw pointer. Because we created them directly from a local variable, we know these particular raw pointers are valid, but we can’t make that assumption about just any raw pointer.

To demonstrate this, next we’ll create a raw pointer whose validity we can’t be so certain of, using the keyword as to cast a value instead of using the raw borrow operator. Listing 20-2 shows how to create a raw pointer to an arbitrary location in memory. Trying to use arbitrary memory is undefined: There might be data at that address or there might not, the compiler might optimize the code so that there is no memory access, or the program might terminate with a segmentation fault. Usually, there is no good reason to write code like this, especially in cases where you can use a raw borrow operator instead, but it is possible.

let address = 0x012345usize;

let r = address as \*const i32;

Creating a raw pointer to an arbitrary memory address

Recall that we can create raw pointers in safe code, but we can’t dereference raw pointers and read the data being pointed to. In Listing 20-3, we use the dereference operator \* on a raw pointer that requires an unsafe block.

let mut num = 5;

let r1 = &raw const num;

let r2 = &raw mut num;

unsafe {

println!("r1 is: {}", \*r1);

println!("r2 is: {}", \*r2);

}

Dereferencing raw pointers within an unsafe block

Creating a pointer does no harm; it’s only when we try to access the value that it points at that we might end up dealing with an invalid value.

Note also that in Listings 20-1 and 20-3, we created \*const i32 and \*mut i32 raw pointers that both pointed to the same memory location, where num is stored. If we instead tried to create an immutable and a mutable reference to num, the code would not have compiled because Rust’s ownership rules don’t allow a mutable reference at the same time as any immutable references. With raw pointers, we can create a mutable pointer and an immutable pointer to the same location and change data through the mutable pointer, potentially creating a data race. Be careful!

With all of these dangers, why would you ever use raw pointers? One major use case is when interfacing with C code, as you’ll see in the next section. Another case is when building up safe abstractions that the borrow checker doesn’t understand. We’ll introduce unsafe functions and then look at an example of a safe abstraction that uses unsafe code.

Calling an Unsafe Function or Method

The second type of operation you can perform in an unsafe block is calling unsafe functions. Unsafe functions and methods look exactly like regular functions and methods, but they have an extra unsafe before the rest of the definition. The unsafe keyword in this context indicates the function has requirements we need to uphold when we call this function, because Rust can’t guarantee we’ve met these requirements. By calling an unsafe function within an unsafe block, we’re saying that we’ve read this function’s documentation and we take responsibility for upholding the function’s contracts.

Here is an unsafe function named dangerous that doesn’t do anything in its body:

unsafe fn dangerous() {}

unsafe {

dangerous();

}

We must call the dangerous function within a separate unsafe block. If we try to call dangerous without the unsafe block, we’ll get an error:

error[E0133]: call to unsafe function `dangerous` is unsafe and

requires unsafe block

--> src/main.rs:4:5

|

4 | dangerous();

| ^^^^^^^^^^^ call to unsafe function

|

= note: consult the function's documentation for information on

how to avoid undefined behavior

With the unsafe block, we’re asserting to Rust that we’ve read the function’s documentation, we understand how to use it properly, and we’ve verified that we’re fulfilling the contract of the function.

To perform unsafe operations in the body of an unsafe function, you still need to use an unsafe block, just as within a regular function, and the compiler will warn you if you forget. This helps us keep unsafe blocks as small as possible, as unsafe operations may not be needed across the whole function body.

Creating a Safe Abstraction over Unsafe Code

Just because a function contains unsafe code doesn’t mean we need to mark the entire function as unsafe. In fact, wrapping unsafe code in a safe function is a common abstraction. As an example, let’s study the split\_at\_mut function from the standard library, which requires some unsafe code. We’ll explore how we might implement it. This safe method is defined on mutable slices: It takes one slice and makes it two by splitting the slice at the index given as an argument. Listing 20-4 shows how to use split\_at\_mut.

let mut v = vec![1, 2, 3, 4, 5, 6];

let r = &mut v[..];

let (a, b) = r.split\_at\_mut(3);

assert\_eq!(a, &mut [1, 2, 3]);

assert\_eq!(b, &mut [4, 5, 6]);

Using the safe split\_at\_mut function

We can’t implement this function using only safe Rust. An attempt might look something like Listing 20-5, which won’t compile. For simplicity, we’ll implement split\_at\_mut as a function rather than a method and only for slices of i32 values rather than for a generic type T.

fn split\_at\_mut(values: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]) {

let len = values.len();

assert!(mid <= len);

(&mut values[..mid], &mut values[mid..])

}

An attempted implementation of split\_at\_mut using only safe Rust

This function first gets the total length of the slice. Then, it asserts that the index given as a parameter is within the slice by checking whether it’s less than or equal to the length. The assertion means that if we pass an index that is greater than the length to split the slice at, the function will panic before it attempts to use that index.

Then, we return two mutable slices in a tuple: one from the start of the original slice to the mid index and another from mid to the end of the slice.

When we try to compile the code in Listing 20-5, we’ll get an error:

error[E0499]: cannot borrow `\*values` as mutable more than once at a time

--> src/main.rs:6:31

|

1 | fn split\_at\_mut(values: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]) {

| - let's call the lifetime of this reference `'1`

...

6 | (&mut values[..mid], &mut values[mid..])

| --------------------------^^^^^^--------

| | | |

| | | second mutable borrow occurs here

| | first mutable borrow occurs here

| returning this value requires that `\*values` is borrowed for `'1`

Rust’s borrow checker can’t understand that we’re borrowing different parts of the slice; it only knows that we’re borrowing from the same slice twice. Borrowing different parts of a slice is fundamentally okay because the two slices aren’t overlapping, but Rust isn’t smart enough to know this. When we know code is okay, but Rust doesn’t, it’s time to reach for unsafe code.

Listing 20-6 shows how to use an unsafe block, a raw pointer, and some calls to unsafe functions to make the implementation of split\_at\_mut work.

use std::slice;

fn split\_at\_mut(

values: &mut [i32],

mid: usize,

) -> (&mut [i32], &mut [i32]) {

1 let len = values.len();

2 let ptr = values.as\_mut\_ptr();

3 assert!(mid <= len);

4 unsafe {

(

5 slice::from\_raw\_parts\_mut(ptr, mid),

6 slice::from\_raw\_parts\_mut(ptr.add(mid), len - mid),

)

}

}

Using unsafe code in the implementation of the split\_at\_mut function

Recall from “The Slice Type” on page XX that a slice is a pointer to some data and the length of the slice. We use the len method to get the length of a slice 1 and the as\_mut\_ptr method to access the raw pointer of a slice 2. In this case, because we have a mutable slice to i32 values, as\_mut\_ptr returns a raw pointer with the type \*mut i32, which we’ve stored in the variable ptr.

We keep the assertion that the mid index is within the slice 3. Then, we get to the unsafe code 4: The slice::from\_raw\_parts\_mut function takes a raw pointer and a length, and it creates a slice. We use this function to create a slice that starts from ptr and is mid items long 5. Then, we call the add method on ptr with mid as an argument to get a raw pointer that starts at mid, and we create a slice using that pointer and the remaining number of items after mid as the length 6.

The function slice::from\_raw\_parts\_mut is unsafe because it takes a raw pointer and must trust that this pointer is valid. The add method on raw pointers is also unsafe because it must trust that the offset location is also a valid pointer. Therefore, we had to put an unsafe block around our calls to slice::from\_raw\_parts\_mut and add so that we could call them. By looking at the code and by adding the assertion that mid must be less than or equal to len, we can tell that all the raw pointers used within the unsafe block will be valid pointers to data within the slice. This is an acceptable and appropriate use of unsafe.

Note that we don’t need to mark the resultant split\_at\_mut function as unsafe, and we can call this function from safe Rust. We’ve created a safe abstraction to the unsafe code with an implementation of the function that uses unsafe code in a safe way, because it creates only valid pointers from the data this function has access to.

In contrast, the use of slice::from\_raw\_parts\_mut in Listing 20-7 would likely crash when the slice is used. This code takes an arbitrary memory location and creates a slice 10,000 items long.

use std::slice;

let address = 0x01234usize;

let r = address as \*mut i32;

let values: &[i32] = unsafe { slice::from\_raw\_parts\_mut(r, 10000) };

Creating a slice from an arbitrary memory location

We don’t own the memory at this arbitrary location, and there is no guarantee that the slice this code creates contains valid i32 values. Attempting to use values as though it’s a valid slice results in undefined behavior.

Using extern Functions to Call External Code

Sometimes your Rust code might need to interact with code written in another language. For this, Rust has the keyword extern that facilitates the creation and use of a Foreign Function Interface (FFI), which is a way for a programming language to define functions and enable a different (foreign) programming language to call those functions.

Listing 20-8 demonstrates how to set up an integration with the abs function from the C standard library. Functions declared within extern blocks are generally unsafe to call from Rust code, so extern blocks must also be marked unsafe. The reason is that other languages don’t enforce Rust’s rules and guarantees, and Rust can’t check them, so responsibility falls on the programmer to ensure safety.

src/main.rs

unsafe extern "C" {

fn abs(input: i32) -> i32;

}

fn main() {

unsafe {

println!("Absolute value of -3 according to C: {}", abs(-3));

}

}

Declaring and calling an extern function defined in another language

Within the unsafe extern "C" block, we list the names and signatures of external functions from another language we want to call. The "C" part defines which application binary interface (ABI) the external function uses: The ABI defines how to call the function at the assembly level. The "C" ABI is the most common and follows the C programming language’s ABI. Information about all the ABIs Rust supports is available in the Rust Reference at https://doc.rust-lang.org/reference/items/external-blocks.html#abi.

Every item declared within an unsafe extern block is implicitly unsafe. However, some FFI functions are safe to call. For example, the abs function from C’s standard library does not have any memory safety considerations, and we know it can be called with any i32. In cases like this, we can use the safe keyword to say that this specific function is safe to call even though it is in an unsafe extern block. Once we make that change, calling it no longer requires an unsafe block, as shown in Listing 20-9.

src/main.rs

unsafe extern "C" {

safe fn abs(input: i32) -> i32;

}

fn main() {

println!("Absolute value of -3 according to C: {}", abs(-3));

}

Explicitly marking a function as safe within an unsafe extern block and calling it safely

Marking a function as safe does not inherently make it safe! Instead, it is like a promise you are making to Rust that it is safe. It is still your responsibility to make sure that promise is kept!

Calling Rust Functions from Other Languages

We can also use extern to create an interface that allows other languages to call Rust functions. Instead of creating a whole extern block, we add the extern keyword and specify the ABI to use just before the fn keyword for the relevant function. We also need to add an #[unsafe(no\_mangle)] annotation to tell the Rust compiler not to mangle the name of this function. Mangling is when a compiler changes the name we’ve given a function to a different name that contains more information for other parts of the compilation process to consume but is less human readable. Every programming language compiler mangles names slightly differently, so for a Rust function to be nameable by other languages, we must disable the Rust compiler’s name mangling. This is unsafe because there might be name collisions across libraries without the built-in mangling, so it is our responsibility to make sure the name we choose is safe to export without mangling.

In the following example, we make the call\_from\_c function accessible from C code, after it’s compiled to a shared library and linked from C:

#[unsafe(no\_mangle)]

pub extern "C" fn call\_from\_c() {

println!("Just called a Rust function from C!");

}

This usage of extern requires unsafe only in the attribute, not on the extern block.

Accessing or Modifying a Mutable Static Variable

In this book, we’ve not yet talked about global variables, which Rust does support but which can be problematic with Rust’s ownership rules. If two threads are accessing the same mutable global variable, it can cause a data race.

In Rust, global variables are called static variables. Listing 20-10 shows an example declaration and use of a static variable with a string slice as a value.

src/main.rs

static HELLO\_WORLD: &str = "Hello, world!";

fn main() {

println!("value is: {HELLO\_WORLD}");

}

Defining and using an immutable static variable

Static variables are similar to constants, which we discussed in “Declaring Constants” on page XX. The names of static variables are in SCREAMING\_SNAKE\_CASE by convention. Static variables can only store references with the 'static lifetime, which means the Rust compiler can figure out the lifetime and we aren’t required to annotate it explicitly. Accessing an immutable static variable is safe.

A subtle difference between constants and immutable static variables is that values in a static variable have a fixed address in memory. Using the value will always access the same data. Constants, on the other hand, are allowed to duplicate their data whenever they’re used. Another difference is that static variables can be mutable. Accessing and modifying mutable static variables is unsafe. Listing 20-11 shows how to declare, access, and modify a mutable static variable named COUNTER.

src/main.rs

static mut COUNTER: u32 = 0;

/// SAFETY: Calling this from more than a single thread at a time is undefined

/// behavior, so you \*must\* guarantee you only call it from a single thread at

/// a time.

unsafe fn add\_to\_count(inc: u32) {

unsafe {

COUNTER += inc;

}

}

fn main() {

unsafe {

// SAFETY: This is only called from a single thread in `main`.

add\_to\_count(3);

println!("COUNTER: {}", \*(&raw const COUNTER));

}

}

Reading from or writing to a mutable static variable is unsafe.

As with regular variables, we specify mutability using the mut keyword. Any code that reads or writes from COUNTER must be within an unsafe block. The code in Listing 20-11 compiles and prints COUNTER: 3 as we would expect because it’s single threaded. Having multiple threads access COUNTER would likely result in data races, so it is undefined behavior. Therefore, we need to mark the entire function as unsafe and document the safety limitation so that anyone calling the function knows what they are and are not allowed to do safely.

Whenever we write an unsafe function, it is idiomatic to write a comment starting with SAFETY and explaining what the caller needs to do to call the function safely. Likewise, whenever we perform an unsafe operation, it is idiomatic to write a comment starting with SAFETY to explain how the safety rules are upheld.

Additionally, the compiler will deny by default any attempt to create references to a mutable static variable through a compiler lint. You must either explicitly opt out of that lint’s protections by adding an #[allow(static\_mut\_refs)] annotation or access the mutable static variable via a raw pointer created with one of the raw borrow operators. That includes cases where the reference is created invisibly, as when it is used in the println! in this code listing. Requiring references to static mutable variables to be created via raw pointers helps make the safety requirements for using them more obvious.

With mutable data that is globally accessible, it’s difficult to ensure that there are no data races, which is why Rust considers mutable static variables to be unsafe. Where possible, it’s preferable to use the concurrency techniques and thread-safe smart pointers we discussed in Chapter 16 so that the compiler checks that data access from different threads is done safely.

Implementing an Unsafe Trait

We can use unsafe to implement an unsafe trait. A trait is unsafe when at least one of its methods has some invariant that the compiler can’t verify. We declare that a trait is unsafe by adding the unsafe keyword before trait and marking the implementation of the trait as unsafe too, as shown in Listing 20-12.

unsafe trait Foo {

// methods go here

}

unsafe impl Foo for i32 {

// method implementations go here

}

Defining and implementing an unsafe trait

By using unsafe impl, we’re promising that we’ll uphold the invariants that the compiler can’t verify.

As an example, recall the Send and Sync marker traits we discussed in “Extensible Concurrency with Send and Sync” on page XX: The compiler implements these traits automatically if our types are composed entirely of other types that implement Send and Sync. If we implement a type that contains a type that does not implement Send or Sync, such as raw pointers, and we want to mark that type as Send or Sync, we must use unsafe. Rust can’t verify that our type upholds the guarantees that it can be safely sent across threads or accessed from multiple threads; therefore, we need to do those checks manually and indicate as such with unsafe.

Accessing Fields of a Union

The final action that works only with unsafe is accessing fields of a union. A union is similar to a struct, but only one declared field is used in a particular instance at one time. Unions are primarily used to interface with unions in C code. Accessing union fields is unsafe because Rust can’t guarantee the type of the data currently being stored in the union instance. You can learn more about unions in the Rust Reference at https://doc.rust-lang.org/reference/items/unions.html.

Using Miri to Check Unsafe Code

When writing unsafe code, you might want to check that what you have written actually is safe and correct. One of the best ways to do that is to use Miri, an official Rust tool for detecting undefined behavior. Whereas the borrow checker is a static tool that works at compile time, Miri is a dynamic tool that works at runtime. It checks your code by running your program, or its test suite, and detecting when you violate the rules it understands about how Rust should work.

Using Miri requires a nightly build of Rust. You can install both a nightly version of Rust and the Miri tool by typing rustup +nightly component add miri. This does not change what version of Rust your project uses; it only adds the tool to your system so that you can use it when you want to. You can run Miri on a project by typing cargo +nightly miri run or cargo +nightly miri test.

For an example of how helpful this can be, consider what happens when we run it against Listing 20-7.

$ cargo +nightly miri run

Compiling unsafe-example v0.1.0 (file:///projects/unsafe-example)

Finished `dev` profile [unoptimized + debuginfo] target(s) in 0.01s

Running `file:///home/.rustup/toolchains/nightly/bin/cargo-miri

runner target/miri/debug/unsafe-example`

warning: integer-to-pointer cast

--> src/main.rs:6:13

|

6 | let r = address as \*mut i32;

| ^^^^^^^^^^^^^^^^^^^ integer-to-pointer cast

|

= help: this program is using integer-to-pointer casts or (equivalently)

`ptr::with\_exposed\_provenance`, which means that Miri might miss pointer bugs in this program

= help: see https://doc.rust-lang.org/nightly/std/ptr/fn.with\_exposed\_provenance.html

for more details on that operation

= help: to ensure that Miri does not miss bugs in your program, use Strict Provenance APIs

(https://doc.rust-lang.org/nightly/std/ptr/index.html#strict-provenance,

https://crates.io/crates/sptr) instead

= help: you can then set `MIRIFLAGS=-Zmiri-strict-provenance` to ensure you are not relying

on `with\_exposed\_provenance` semantics

= help: alternatively, `MIRIFLAGS=-Zmiri-permissive-provenance` disables this warning

= note: BACKTRACE:

= note: inside `main` at src/main.rs:6:13: 6:32

error: Undefined Behavior: pointer not dereferenceable: pointer must be dereferenceable

for 40000 bytes, but got 0x1234[noalloc] which is a dangling pointer (it has no provenance)

--> src/main.rs:8:35

|

8 | let values: &[i32] = unsafe { slice::from\_raw\_parts\_mut(r, 10000) };

| ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ Undefined Behavior

occurred here

|

= help: this indicates a bug in the program: it performed an invalid operation, and caused

Undefined Behavior

= help: see https://doc.rust-lang.org/nightly/reference/behavior-considered-undefined.html

for further information

= note: BACKTRACE:

= note: inside `main` at src/main.rs:8:35: 8:70

note: some details are omitted, run with `MIRIFLAGS=-Zmiri-backtrace=full`

for a verbose backtrace

error: aborting due to 1 previous error; 1 warning emitted

Miri correctly warns us that we’re casting an integer to a pointer, which might be a problem, but Miri can’t determine whether a problem exists because it doesn’t know how the pointer originated. Then, Miri returns an error where Listing 20-7 has undefined behavior because we have a dangling pointer. Thanks to Miri, we now know there is a risk of undefined behavior, and we can think about how to make the code safe. In some cases, Miri can even make recommendations about how to fix errors.

Miri doesn’t catch everything you might get wrong when writing unsafe code. Miri is a dynamic analysis tool, so it only catches problems with code that actually gets run. That means you will need to use it in conjunction with good testing techniques to increase your confidence about the unsafe code you have written. Miri also does not cover every possible way your code can be unsound.

Put another way: If Miri does catch a problem, you know there’s a bug, but just because Miri doesn’t catch a bug doesn’t mean there isn’t a problem. It can catch a lot, though. Try running it on the other examples of unsafe code in this chapter and see what it says!

You can learn more about Miri at https://github.com/rust-lang/miri.

Using Unsafe Code Correctly

Using unsafe to use one of the five superpowers just discussed isn’t wrong or even frowned upon, but it is trickier to get unsafe code correct because the compiler can’t help uphold memory safety. When you have a reason to use unsafe code, you can do so, and having the explicit unsafe annotation makes it easier to track down the source of problems when they occur. Whenever you write unsafe code, you can use Miri to help you be more confident that the code you have written upholds Rust’s rules.

For a much deeper exploration of how to work effectively with unsafe Rust, read Rust’s official guide for unsafe, The Rustonomicon, at https://doc.rust-lang.org/nomicon.

Advanced Traits

We first covered traits in “Defining Shared Behavior with Traits” on page XX, but we didn’t discuss the more advanced details. Now that you know more about Rust, we can get into the nitty-gritty.

Defining Traits with Associated Types

Associated types connect a type placeholder with a trait such that the trait method definitions can use these placeholder types in their signatures. The implementor of a trait will specify the concrete type to be used instead of the placeholder type for the particular implementation. That way, we can define a trait that uses some types without needing to know exactly what those types are until the trait is implemented.

We’ve described most of the advanced features in this chapter as being rarely needed. Associated types are somewhere in the middle: They’re used more rarely than features explained in the rest of the book but more commonly than many of the other features discussed in this chapter.

One example of a trait with an associated type is the Iterator trait that the standard library provides. The associated type is named Item and stands in for the type of the values the type implementing the Iterator trait is iterating over. The definition of the Iterator trait is as shown in Listing 20-13.

pub trait Iterator {

type Item;

fn next(&mut self) -> Option<Self::Item>;

}

The definition of the Iterator trait that has an associated type Item

The type Item is a placeholder, and the next method’s definition shows that it will return values of type Option<Self::Item>. Implementors of the Iterator trait will specify the concrete type for Item, and the next method will return an Option containing a value of that concrete type.

Associated types might seem like a similar concept to generics, in that the latter allow us to define a function without specifying what types it can handle. To examine the difference between the two concepts, we’ll look at an implementation of the Iterator trait on a type named Counter that specifies the Item type is u32:

src/lib.rs

impl Iterator for Counter {

type Item = u32;

fn next(&mut self) -> Option<Self::Item> {

--snip--

This syntax seems comparable to that of generics. So, why not just define the Iterator trait with generics, as shown in Listing 20-14?

pub trait Iterator<T> {

fn next(&mut self) -> Option<T>;

}

A hypothetical definition of the Iterator trait using generics

The difference is that when using generics, as in Listing 20-14, we must annotate the types in each implementation; because we can also implement Iterator<String> for Counter or any other type, we could have multiple implementations of Iterator for Counter. In other words, when a trait has a generic parameter, it can be implemented for a type multiple times, changing the concrete types of the generic type parameters each time. When we use the next method on Counter, we would have to provide type annotations to indicate which implementation of Iterator we want to use.

With associated types, we don’t need to annotate types, because we can’t implement a trait on a type multiple times. In Listing 20-13 with the definition that uses associated types, we can choose what the type of Item will be only once because there can be only one impl Iterator for Counter. We don’t have to specify that we want an iterator of u32 values everywhere we call next on Counter.

Associated types also become part of the trait’s contract: Implementors of the trait must provide a type to stand in for the associated type placeholder. Associated types often have a name that describes how the type will be used, and documenting the associated type in the API documentation is a good practice.

Using Default Generic Parameters and Operator Overloading

When we use generic type parameters, we can specify a default concrete type for the generic type. This eliminates the need for implementors of the trait to specify a concrete type if the default type works. You specify a default type when declaring a generic type with the <PlaceholderType=ConcreteType> syntax.

A great example of a situation where this technique is useful is with operator overloading, in which you customize the behavior of an operator (such as +) in particular situations.

Rust doesn’t allow you to create your own operators or overload arbitrary operators. But you can overload the operations and corresponding traits listed in std::ops by implementing the traits associated with the operator. For example, in Listing 20-15, we overload the + operator to add two Point instances together. We do this by implementing the Add trait on a Point struct.

src/main.rs

use std::ops::Add;

#[derive(Debug, Copy, Clone, PartialEq)]

struct Point {

x: i32,

y: i32,

}

impl Add for Point {

type Output = Point;

fn add(self, other: Point) -> Point {

Point {

x: self.x + other.x,

y: self.y + other.y,

}

}

}

fn main() {

assert\_eq!(

Point { x: 1, y: 0 } + Point { x: 2, y: 3 },

Point { x: 3, y: 3 }

);

}

Implementing the Add trait to overload the + operator for Point instances

The add method adds the x values of two Point instances and the y values of two Point instances to create a new Point. The Add trait has an associated type named Output that determines the type returned from the add method.

The default generic type in this code is within the Add trait. Here is its definition:

trait Add<Rhs=Self> {

type Output;

fn add(self, rhs: Rhs) -> Self::Output;

}

This code should look generally familiar: a trait with one method and an associated type. The new part is Rhs=Self: This syntax is called default type parameters. The Rhs generic type parameter (short for “right-hand side”) defines the type of the rhs parameter in the add method. If we don’t specify a concrete type for Rhs when we implement the Add trait, the type of Rhs will default to Self, which will be the type we’re implementing Add on.

When we implemented Add for Point, we used the default for Rhs because we wanted to add two Point instances. Let’s look at an example of implementing the Add trait where we want to customize the Rhs type rather than using the default.

We have two structs, Millimeters and Meters, holding values in different units. This thin wrapping of an existing type in another struct is known as the newtype pattern, which we describe in more detail in “Implementing External Traits with the Newtype Pattern” on page XX. We want to add values in millimeters to values in meters and have the implementation of Add do the conversion correctly. We can implement Add for Millimeters with Meters as the Rhs, as shown in Listing 20-16.

src/lib.rs

use std::ops::Add;

struct Millimeters(u32);

struct Meters(u32);

impl Add<Meters> for Millimeters {

type Output = Millimeters;

fn add(self, other: Meters) -> Millimeters {

Millimeters(self.0 + (other.0 \* 1000))

}

}

Implementing the Add trait on Millimeters to add Millimeters and Meters

To add Millimeters and Meters, we specify impl Add<Meters> to set the value of the Rhs type parameter instead of using the default of Self.

You’ll use default type parameters in two main ways:

1. To extend a type without breaking existing code
2. To allow customization in specific cases most users won’t need

The standard library’s Add trait is an example of the second purpose: Usually, you’ll add two like types, but the Add trait provides the ability to customize beyond that. Using a default type parameter in the Add trait definition means you don’t have to specify the extra parameter most of the time. In other words, a bit of implementation boilerplate isn’t needed, making it easier to use the trait.

The first purpose is similar to the second but in reverse: If you want to add a type parameter to an existing trait, you can give it a default to allow extension of the functionality of the trait without breaking the existing implementation code.

Disambiguating Between Identically Named Methods

Nothing in Rust prevents a trait from having a method with the same name as another trait’s method, nor does Rust prevent you from implementing both traits on one type. It’s also possible to implement a method directly on the type with the same name as methods from traits.

When calling methods with the same name, you’ll need to tell Rust which one you want to use. Consider the code in Listing 20-17 where we’ve defined two traits, Pilot and Wizard, that both have a method called fly. We then implement both traits on a type Human that already has a method named fly implemented on it. Each fly method does something different.

src/main.rs

trait Pilot {

fn fly(&self);

}

trait Wizard {

fn fly(&self);

}

struct Human;

impl Pilot for Human {

fn fly(&self) {

println!("This is your captain speaking.");

}

}

impl Wizard for Human {

fn fly(&self) {

println!("Up!");

}

}

impl Human {

fn fly(&self) {

println!("\*waving arms furiously\*");

}

}

Two traits are defined to have a fly method and are implemented on the Human type, and a fly method is implemented on Human directly.

When we call fly on an instance of Human, the compiler defaults to calling the method that is directly implemented on the type, as shown in Listing 20-18.

src/main.rs

fn main() {

let person = Human;

person.fly();

}

Calling fly on an instance of Human

Running this code will print \*waving arms furiously\*, showing that Rust called the fly method implemented on Human directly.

To call the fly methods from either the Pilot trait or the Wizard trait, we need to use more explicit syntax to specify which fly method we mean. Listing 20-19 demonstrates this syntax.

src/main.rs

fn main() {

let person = Human;

Pilot::fly(&person);

Wizard::fly(&person);

person.fly();

}

Specifying which trait’s fly method we want to call

Specifying the trait name before the method name clarifies to Rust which implementation of fly we want to call. We could also write Human::fly(&person), which is equivalent to the person.fly() that we used in Listing 20-19, but this is a bit longer to write if we don’t need to disambiguate.

Running this code prints the following:

This is your captain speaking.

Up!

\*waving arms furiously\*

Because the fly method takes a self parameter, if we had two types that both implement one trait, Rust could figure out which implementation of a trait to use based on the type of self.

However, associated functions that are not methods don’t have a self parameter. When there are multiple types or traits that define non-method functions with the same function name, Rust doesn’t always know which type you mean unless you use fully qualified syntax. For example, in Listing 20-20, we create a trait for an animal shelter that wants to name all baby dogs Spot. We make an Animal trait with an associated non-method function baby\_name. The Animal trait is implemented for the struct Dog, on which we also provide an associated non-method function baby\_name directly.

src/main.rs

trait Animal {

fn baby\_name() -> String;

}

struct Dog;

impl Dog {

fn baby\_name() -> String {

String::from("Spot")

}

}

impl Animal for Dog {

fn baby\_name() -> String {

String::from("puppy")

}

}

fn main() {

println!("A baby dog is called a {}", Dog::baby\_name());

}

A trait with an associated function and a type with an associated function of the same name that also implements the trait

We implement the code for naming all puppies Spot in the baby\_name associated function that is defined on Dog. The Dog type also implements the trait Animal, which describes characteristics that all animals have. Baby dogs are called puppies, and that is expressed in the implementation of the Animal trait on Dog in the baby\_name function associated with the Animal trait.

In main, we call the Dog::baby\_name function, which calls the associated function defined on Dog directly. This code prints the following:

A baby dog is called a Spot

This output isn’t what we wanted. We want to call the baby\_name function that is part of the Animal trait that we implemented on Dog so that the code prints A baby dog is called a puppy. The technique of specifying the trait name that we used in Listing 20-19 doesn’t help here; if we change main to the code in Listing 20-21, we’ll get a compilation error.

src/main.rs

fn main() {

println!("A baby dog is called a {}", Animal::baby\_name());

}

Attempting to call the baby\_name function from the Animal trait, but Rust doesn’t know which implementation to use

Because Animal::baby\_name doesn’t have a self parameter, and there could be other types that implement the Animal trait, Rust can’t figure out which implementation of Animal::baby\_name we want. We’ll get this compiler error:

error[E0790]: cannot call associated function on trait without specifying

the corresponding `impl` type

--> src/main.rs:20:43

|

2 | fn baby\_name() -> String;

| ------------------------- `Animal::baby\_name` defined here

...

20 | println!("A baby dog is called a {}", Animal::baby\_name());

| ^^^^^^^^^^^^^^^^^^^ cannot call

associated function of trait

|

help: use the fully-qualified path to the only available implementation

|

20 | println!("A baby dog is called a {}", <Dog as Animal>::baby\_name());

| +++++++ +

To disambiguate and tell Rust that we want to use the implementation of Animal for Dog as opposed to the implementation of Animal for some other type, we need to use fully qualified syntax. Listing 20-22 demonstrates how to use fully qualified syntax.

src/main.rs

fn main() {

println!("A baby dog is called a {}", <Dog as Animal>::baby\_name());

}

Using fully qualified syntax to specify that we want to call the baby\_name function from the Animal trait as implemented on Dog

We’re providing Rust with a type annotation within the angle brackets, which indicates we want to call the baby\_name method from the Animal trait as implemented on Dog by saying that we want to treat the Dog type as an Animal for this function call. This code will now print what we want:

A baby dog is called a puppy

In general, fully qualified syntax is defined as follows:

<Type as Trait>::function(receiver\_if\_method, next\_arg, ...);

For associated functions that aren’t methods, there would not be a receiver: There would only be the list of other arguments. You could use fully qualified syntax everywhere that you call functions or methods. However, you’re allowed to omit any part of this syntax that Rust can figure out from other information in the program. You only need to use this more verbose syntax in cases where there are multiple implementations that use the same name and Rust needs help to identify which implementation you want to call.

Using Supertraits

Sometimes you might write a trait definition that depends on another trait: For a type to implement the first trait, you want to require that type to also implement the second trait. You would do this so that your trait definition can make use of the associated items of the second trait. The trait your trait definition is relying on is called a supertrait of your trait.

For example, let’s say we want to make an OutlinePrint trait with an outline\_print method that will print a given value formatted so that it’s framed in asterisks. That is, given a Point struct that implements the standard library trait Display to result in (x, y), when we call outline\_print on a Point instance that has 1 for x and 3 for y, it should print the following:

\*\*\*\*\*\*\*\*\*\*

\* \*

\* (1, 3) \*

\* \*

\*\*\*\*\*\*\*\*\*\*

In the implementation of the outline\_print method, we want to use the Display trait’s functionality. Therefore, we need to specify that the OutlinePrint trait will work only for types that also implement Display and provide the functionality that OutlinePrint needs. We can do that in the trait definition by specifying OutlinePrint: Display. This technique is similar to adding a trait bound to the trait. Listing 20-23 shows an implementation of the OutlinePrint trait.

src/main.rs

use std::fmt;

trait OutlinePrint: fmt::Display {

fn outline\_print(&self) {

let output = self.to\_string();

let len = output.len();

println!("{}", "\*".repeat(len + 4));

println!("\*{}\*", " ".repeat(len + 2));

println!("\* {output} \*");

println!("\*{}\*", " ".repeat(len + 2));

println!("{}", "\*".repeat(len + 4));

}

}

Implementing the OutlinePrint trait that requires the functionality from Display

Because we’ve specified that OutlinePrint requires the Display trait, we can use the to\_string function that is automatically implemented for any type that implements Display. If we tried to use to\_string without adding a colon and specifying the Display trait after the trait name, we’d get an error saying that no method named to\_string was found for the type &Self in the current scope.

Let’s see what happens when we try to implement OutlinePrint on a type that doesn’t implement Display, such as the Point struct:

src/main.rs

struct Point {

x: i32,

y: i32,

}

impl OutlinePrint for Point {}

We get an error saying that Display is required but not implemented:

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

--> src/main.rs:20:23

|

20 | impl OutlinePrint for Point {}

| ^^^^^ `Point` cannot be formatted with the default formatter

|

= help: the trait `std::fmt::Display` is not implemented for `Point`

= note: in format strings you may be able to use `{:?}` (or {:#?} for pretty-print) instead

note: required by a bound in `OutlinePrint`

--> src/main.rs:3:21

|

3 | trait OutlinePrint: fmt::Display {

| ^^^^^^^^^^^^ required by this bound in `OutlinePrint`

To fix this, we implement Display on Point and satisfy the constraint that OutlinePrint requires, like so:

src/main.rs

use std::fmt;

impl fmt::Display for Point {

fn fmt(&self, f: &mut fmt::Formatter) -> fmt::Result {

write!(f, "({}, {})", self.x, self.y)

}

}

Then, implementing the OutlinePrint trait on Point will compile successfully, and we can call outline\_print on a Point instance to display it within an outline of asterisks.

Implementing External Traits with the Newtype Pattern

In “Implementing a Trait on a Type” on page XX, we mentioned the orphan rule that states we’re only allowed to implement a trait on a type if either the trait or the type, or both, are local to our crate. It’s possible to get around this restriction using the newtype pattern, which involves creating a new type in a tuple struct. (We covered tuple structs in “Creating Different Types with Tuple Structs” on page XX.) The tuple struct will have one field and be a thin wrapper around the type for which we want to implement a trait. Then, the wrapper type is local to our crate, and we can implement the trait on the wrapper. Newtype is a term that originates from the Haskell programming language. There is no runtime performance penalty for using this pattern, and the wrapper type is elided at compile time.

As an example, let’s say we want to implement Display on Vec<T>, which the orphan rule prevents us from doing directly because the Display trait and the Vec<T> type are defined outside our crate. We can make a Wrapper struct that holds an instance of Vec<T>; then, we can implement Display on Wrapper and use the Vec<T> value, as shown in Listing 20-24.

src/main.rs

use std::fmt;

struct Wrapper(Vec<String>);

impl fmt::Display for Wrapper {

fn fmt(&self, f: &mut fmt::Formatter) -> fmt::Result {

write!(f, "[{}]", self.0.join(", "))

}

}

fn main() {

let w = Wrapper(vec![String::from("hello"), String::from("world")]);

println!("w = {w}");

}

Creating a Wrapper type around Vec<String> to implement Display

The implementation of Display uses self.0 to access the inner Vec<T> because Wrapper is a tuple struct and Vec<T> is the item at index 0 in the tuple. Then, we can use the functionality of the Display trait on Wrapper.

The downside of using this technique is that Wrapper is a new type, so it doesn’t have the methods of the value it’s holding. We would have to implement all the methods of Vec<T> directly on Wrapper such that the methods delegate to self.0, which would allow us to treat Wrapper exactly like a Vec<T>. If we wanted the new type to have every method the inner type has, implementing the Deref trait on the Wrapper to return the inner type would be a solution (we discussed implementing the Deref trait in “Treating Smart Pointers Like Regular References” on page XX). If we didn’t want the Wrapper type to have all the methods of the inner type—for example, to restrict the Wrapper type’s behavior—we would have to implement just the methods we do want manually.

This newtype pattern is also useful even when traits are not involved. Let’s switch focus and look at some advanced ways to interact with Rust’s type system.

Advanced Types

The Rust type system has some features that we’ve so far mentioned but haven’t yet discussed. We’ll start by discussing newtypes in general as we examine why they are useful as types. Then, we’ll move on to type aliases, a feature similar to newtypes but with slightly different semantics. We’ll also discuss the ! type and dynamically sized types.

Type Safety and Abstraction with the Newtype Pattern

This section assumes you’ve read the earlier section “Implementing External Traits with the Newtype Pattern” on page XX. The newtype pattern is also useful for tasks beyond those we’ve discussed so far, including statically enforcing that values are never confused and indicating the units of a value. You saw an example of using newtypes to indicate units in Listing 20-16: Recall that the Millimeters and Meters structs wrapped u32 values in a newtype. If we wrote a function with a parameter of type Millimeters, we wouldn’t be able to compile a program that accidentally tried to call that function with a value of type Meters or a plain u32.

We can also use the newtype pattern to abstract away some implementation details of a type: The new type can expose a public API that is different from the API of the private inner type.

Newtypes can also hide internal implementation. For example, we could provide a People type to wrap a HashMap<i32, String> that stores a person’s ID associated with their name. Code using People would only interact with the public API we provide, such as a method to add a name string to the People collection; that code wouldn’t need to know that we assign an i32 ID to names internally. The newtype pattern is a lightweight way to achieve encapsulation to hide implementation details, which we discussed in “Encapsulation That Hides Implementation Details” on page XX.

Type Synonyms and Type Aliases

Rust provides the ability to declare a type alias to give an existing type another name. For this we use the type keyword. For example, we can create the alias Kilometers to i32 like so:

type Kilometers = i32;

Now the alias Kilometers is a synonym for i32; unlike the Millimeters and Meters types we created in Listing 20-16, Kilometers is not a separate, new type. Values that have the type Kilometers will be treated the same as values of type i32:

type Kilometers = i32;

let x: i32 = 5;

let y: Kilometers = 5;

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

Because Kilometers and i32 are the same type, we can add values of both types and can pass Kilometers values to functions that take i32 parameters. However, using this method, we don’t get the type-checking benefits that we get from the newtype pattern discussed earlier. In other words, if we mix up Kilometers and i32 values somewhere, the compiler will not give us an error.

The main use case for type synonyms is to reduce repetition. For example, we might have a lengthy type like this:

Box<dyn Fn() + Send + 'static>

Writing this lengthy type in function signatures and as type annotations all over the code can be tiresome and error-prone. Imagine having a project full of code like that in Listing 20-25.

let f: Box<dyn Fn() + Send + 'static> = Box::new(|| {

println!("hi");

});

fn takes\_long\_type(f: Box<dyn Fn() + Send + 'static>) {

--snip--

}

fn returns\_long\_type() -> Box<dyn Fn() + Send + 'static> {

--snip--

}

Using a long type in many places

A type alias makes this code more manageable by reducing the repetition. In Listing 20-26, we’ve introduced an alias named Thunk for the verbose type and can replace all uses of the type with the shorter alias Thunk.

type Thunk = Box<dyn Fn() + Send + 'static>;

let f: Thunk = Box::new(|| println!("hi"));

fn takes\_long\_type(f: Thunk) {

--snip--

}

fn returns\_long\_type() -> Thunk {

--snip--

}

Introducing a type alias, Thunk, to reduce repetition

This code is much easier to read and write! Choosing a meaningful name for a type alias can help communicate your intent as well (thunk is a word for code to be evaluated at a later time, so it’s an appropriate name for a closure that gets stored).

Type aliases are also commonly used with the Result<T, E> type for reducing repetition. Consider the std::io module in the standard library. I/O operations often return a Result<T, E> to handle situations when operations fail to work. This library has a std::io::Error struct that represents all possible I/O errors. Many of the functions in std::io will be returning Result<T, E> where the E is std::io::Error, such as these functions in the Write trait:

use std::fmt;

use std::io::Error;

pub trait Write {

fn write(&mut self, buf: &[u8]) -> Result<usize, Error>;

fn flush(&mut self) -> Result<(), Error>;

fn write\_all(&mut self, buf: &[u8]) -> Result<(), Error>;

fn write\_fmt(&mut self, fmt: fmt::Arguments) -> Result<(), Error>;

}

The Result<..., Error> is repeated a lot. As such, std::io has this type alias declaration:

type Result<T> = std::result::Result<T, std::io::Error>;

Because this declaration is in the std::io module, we can use the fully qualified alias std::io::Result<T>; that is, a Result<T, E> with the E filled in as std::io::Error. The Write trait function signatures end up looking like this:

pub trait Write {

fn write(&mut self, buf: &[u8]) -> Result<usize>;

fn flush(&mut self) -> Result<()>;

fn write\_all(&mut self, buf: &[u8]) -> Result<()>;

fn write\_fmt(&mut self, fmt: fmt::Arguments) -> Result<()>;

}

The type alias helps in two ways: It makes code easier to write and it gives us a consistent interface across all of std::io. Because it’s an alias, it’s just another Result<T, E>, which means we can use any methods that work on Result<T, E> with it, as well as special syntax like the ? operator.

The Never Type That Never Returns

Rust has a special type named ! that’s known in type theory lingo as the empty type because it has no values. We prefer to call it the never type because it stands in the place of the return type when a function will never return. Here is an example:

fn bar() -> ! {

--snip--

}

This code is read as “the function bar returns never.” Functions that return never are called diverging functions. We can’t create values of the type !, so bar can never possibly return.

But what use is a type you can never create values for? Recall the code from Listing 2-5, part of the number-guessing game; we’ve reproduced a bit of it here in Listing 20-27.

let guess: u32 = match guess.trim().parse() {

Ok(num) => num,

Err(\_) => continue,

};

A match with an arm that ends in continue

At the time, we skipped over some details in this code. In “The match Control Flow Construct” on page XX, we discussed that match arms must all return the same type. So, for example, the following code doesn’t work:

let guess = match guess.trim().parse() {

Ok(\_) => 5,

Err(\_) => "hello",

};

The type of guess in this code would have to be an integer and a string, and Rust requires that guess have only one type. So, what does continue return? How were we allowed to return a u32 from one arm and have another arm that ends with continue in Listing 20-27?

As you might have guessed, continue has a ! value. That is, when Rust computes the type of guess, it looks at both match arms, the former with a value of u32 and the latter with a ! value. Because ! can never have a value, Rust decides that the type of guess is u32.

The formal way of describing this behavior is that expressions of type ! can be coerced into any other type. We’re allowed to end this match arm with continue because continue doesn’t return a value; instead, it moves control back to the top of the loop, so in the Err case, we never assign a value to guess.

The never type is useful with the panic! macro as well. Recall the unwrap function that we call on Option<T> values to produce a value or panic with this definition:

impl<T> Option<T> {

pub fn unwrap(self) -> T {

match self {

Some(val) => val,

None => panic!(

"called `Option::unwrap()` on a `None` value"

),

}

}

}

In this code, the same thing happens as in the match in Listing 20-27: Rust sees that val has the type T and panic! has the type !, so the result of the overall match expression is T. This code works because panic! doesn’t produce a value; it ends the program. In the None case, we won’t be returning a value from unwrap, so this code is valid.

One final expression that has the type ! is a loop:

print!("forever ");

loop {

print!("and ever ");

}

Here, the loop never ends, so ! is the value of the expression. However, this wouldn’t be true if we included a break, because the loop would terminate when it got to the break.

Dynamically Sized Types and the Sized Trait

Rust needs to know certain details about its types, such as how much space to allocate for a value of a particular type. This leaves one corner of its type system a little confusing at first: the concept of dynamically sized types. Sometimes referred to as DSTs or unsized types, these types let us write code using values whose size we can know only at runtime.

Let’s dig into the details of a dynamically sized type called str, which we’ve been using throughout the book. That’s right, not &str, but str on its own, is a DST. In many cases, such as when storing text entered by a user, we can’t know how long the string is until runtime. That means we can’t create a variable of type str, nor can we take an argument of type str. Consider the following code, which does not work:

let s1: str = "Hello there!";

let s2: str = "How's it going?";

Rust needs to know how much memory to allocate for any value of a particular type, and all values of a type must use the same amount of memory. If Rust allowed us to write this code, these two str values would need to take up the same amount of space. But they have different lengths: s1 needs 12 bytes of storage and s2 needs 15. This is why it’s not possible to create a variable holding a dynamically sized type.

So, what do we do? In this case, you already know the answer: We make the type of s1 and s2 string slice (&str) rather than str. Recall from “String Slices” on page XX that the slice data structure only stores the starting position and the length of the slice. So, although &T is a single value that stores the memory address of where the T is located, a string slice is two values: the address of the str and its length. As such, we can know the size of a string slice value at compile time: It’s twice the length of a usize. That is, we always know the size of a string slice, no matter how long the string it refers to is. In general, this is the way in which dynamically sized types are used in Rust: They have an extra bit of metadata that stores the size of the dynamic information. The golden rule of dynamically sized types is that we must always put values of dynamically sized types behind a pointer of some kind.

We can combine str with all kinds of pointers: for example, Box<str> or Rc<str>. In fact, you’ve seen this before but with a different dynamically sized type: traits. Every trait is a dynamically sized type we can refer to by using the name of the trait. In “Using Trait Objects to Abstract over Shared Behavior” on page XX, we mentioned that to use traits as trait objects, we must put them behind a pointer, such as &dyn Trait or Box<dyn Trait> (Rc<dyn Trait> would work too).

To work with DSTs, Rust provides the Sized trait to determine whether or not a type’s size is known at compile time. This trait is automatically implemented for everything whose size is known at compile time. In addition, Rust implicitly adds a bound on Sized to every generic function. That is, a generic function definition like this:

fn generic<T>(t: T) {

--snip--

}

is actually treated as though we had written this:

fn generic<T: Sized>(t: T) {

--snip--

}

By default, generic functions will work only on types that have a known size at compile time. However, you can use the following special syntax to relax this restriction:

fn generic<T: ?Sized>(t: &T) {

--snip--

}

A trait bound on ?Sized means “T may or may not be Sized,” and this notation overrides the default that generic types must have a known size at compile time. The ?Trait syntax with this meaning is only available for Sized, not any other traits.

Also note that we switched the type of the t parameter from T to &T. Because the type might not be Sized, we need to use it behind some kind of pointer. In this case, we’ve chosen a reference.

Next, we’ll talk about functions and closures!

Advanced Functions and Closures

This section explores some advanced features related to functions and closures, including function pointers and returning closures.

Function Pointers

We’ve talked about how to pass closures to functions; you can also pass regular functions to functions! This technique is useful when you want to pass a function you’ve already defined rather than defining a new closure. Functions coerce to the type fn (with a lowercase f), not to be confused with the Fn closure trait. The fn type is called a function pointer. Passing functions with function pointers will allow you to use functions as arguments to other functions.

The syntax for specifying that a parameter is a function pointer is similar to that of closures, as shown in Listing 20-28, where we’ve defined a function add\_one that adds 1 to its parameter. The function do\_twice takes two parameters: a function pointer to any function that takes an i32 parameter and returns an i32, and one i32 value. The do\_twice function calls the function f twice, passing it the arg value, then adds the two function call results together. The main function calls do\_twice with the arguments add\_one and 5.

src/main.rs

fn add\_one(x: i32) -> i32 {

x + 1

}

fn do\_twice(f: fn(i32) -> i32, arg: i32) -> i32 {

f(arg) + f(arg)

}

fn main() {

let answer = do\_twice(add\_one, 5);

println!("The answer is: {answer}");

}

Using the fn type to accept a function pointer as an argument

This code prints The answer is: 12. We specify that the parameter f in do\_twice is an fn that takes one parameter of type i32 and returns an i32. We can then call f in the body of do\_twice. In main, we can pass the function name add\_one as the first argument to do\_twice.

Unlike closures, fn is a type rather than a trait, so we specify fn as the parameter type directly rather than declaring a generic type parameter with one of the Fn traits as a trait bound.

Function pointers implement all three of the closure traits (Fn, FnMut, and FnOnce), meaning you can always pass a function pointer as an argument for a function that expects a closure. It’s best to write functions using a generic type and one of the closure traits so that your functions can accept either functions or closures.

That said, one example of where you would want to only accept fn and not closures is when interfacing with external code that doesn’t have closures: C functions can accept functions as arguments, but C doesn’t have closures.

As an example of where you could use either a closure defined inline or a named function, let’s look at a use of the map method provided by the Iterator trait in the standard library. To use the map method to turn a vector of numbers into a vector of strings, we could use a closure, as in Listing 20-29.

let list\_of\_numbers = vec![1, 2, 3];

let list\_of\_strings: Vec<String> =

list\_of\_numbers.iter().map(|i| i.to\_string()).collect();

Using a closure with the map method to convert numbers to strings

Or we could name a function as the argument to map instead of the closure. Listing 20-30 shows what this would look like.

let list\_of\_numbers = vec![1, 2, 3];

let list\_of\_strings: Vec<String> =

list\_of\_numbers.iter().map(ToString::to\_string).collect();

Using the String::to\_string function with the map method to convert numbers to strings

Note that we must use the fully qualified syntax that we talked about in “Advanced Traits” on page XX because there are multiple functions available named to\_string.

Here, we’re using the to\_string function defined in the ToString trait, which the standard library has implemented for any type that implements Display.

Recall from “Enum Values” on page XX that the name of each enum variant that we define also becomes an initializer function. We can use these initializer functions as function pointers that implement the closure traits, which means we can specify the initializer functions as arguments for methods that take closures, as seen in Listing 20-31.

enum Status {

Value(u32),

Stop,

}

let list\_of\_statuses: Vec<Status> =

(0u32..20).map(Status::Value).collect();

Using an enum initializer with the map method to create a Status instance from numbers

Here, we create Status::Value instances using each u32 value in the range that map is called on by using the initializer function of Status::Value. Some people prefer this style and some people prefer to use closures. They compile to the same code, so use whichever style is clearer to you.

Returning Closures

Closures are represented by traits, which means you can’t return closures directly. In most cases where you might want to return a trait, you can instead use the concrete type that implements the trait as the return value of the function. However, you can’t usually do that with closures because they don’t have a concrete type that is returnable; you’re not allowed to use the function pointer fn as a return type if the closure captures any values from its scope, for example.

Instead, you will normally use the impl Trait syntax we learned about in Chapter 10. You can return any function type, using Fn, FnOnce, and FnMut. For example, the code in Listing 20-32 will compile just fine.

fn returns\_closure() -> impl Fn(i32) -> i32 {

|x| x + 1

}

Returning a closure from a function using the impl Trait syntax

However, as we noted in “Inferring and Annotating Closure Types” on page XX, each closure is also its own distinct type. If you need to work with multiple functions that have the same signature but different implementations, you will need to use a trait object for them. Consider what happens if you write code like that shown in Listing 20-33.

fn main() {

let handlers = vec![

returns\_closure(),

returns\_initialized\_closure(123),

];

for handler in handlers {

let output = handler(5);

println!("{output}");

}

}

fn returns\_closure() -> impl Fn(i32) -> i32 {

|x| x + 1

}

fn returns\_initialized\_closure(init: i32) -> impl Fn(i32) -> i32 {

move |x| x + init

}

Creating a Vec<T> of closures defined by functions that return impl Fn types

Here we have two functions, returns\_closure and returns\_initialized\_closure, which both return impl Fn(i32) -> i32. Notice that the closures that they return are different, even though they implement the same type. If we try to compile this, Rust lets us know that it won’t work:

error[E0308]: mismatched types

--> src/main.rs:4:9

|

4 | returns\_initialized\_closure(123),

| ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ expected opaque type, found

a different opaque type

...

13 | fn returns\_closure() -> impl Fn(i32) -> i32 {

| ------------------- the expected opaque type

...

17 | fn returns\_initialized\_closure(init: i32) -> impl Fn(i32) -> i32 {

| ------------------- the found opaque type

|

= note: expected opaque type `impl Fn(i32) -> i32` (opaque type at <src/main.rs:13:25>)

found opaque type `impl Fn(i32) -> i32` (opaque type at <src/main.rs:17:46>)

= note: distinct uses of `impl Trait` result in different opaque types

The error message tells us that whenever we return an impl Trait, Rust creates a unique opaque type, a type where we cannot see into the details of what Rust constructs for us, nor can we guess the type Rust will generate to write ourselves. So, even though these functions return closures that implement the same trait, Fn(i32) -> i32, the opaque types Rust generates for each are distinct. (This is similar to how Rust produces different concrete types for distinct async blocks even when they have the same output type, as we saw in “The Pin Type and the Unpin Trait” on page XX.) We have seen a solution to this problem a few times now: We can use a trait object, as in Listing 20-34.

fn returns\_closure() -> Box<dyn Fn(i32) -> i32> {

Box::new(|x| x + 1)

}

fn returns\_initialized\_closure(init: i32) -> Box<dyn Fn(i32) -> i32> {

Box::new(move |x| x + init)

}

Creating a Vec<T> of closures defined by functions that return Box<dyn Fn> so that they have the same type

This code will compile just fine. For more about trait objects, refer to “Using Trait Objects to Abstract over Shared Behavior” on page XX.

Next, let’s look at macros!

Macros

We’ve used macros like println! throughout this book, but we haven’t fully explored what a macro is and how it works. The term macro refers to a family of features in Rust—declarative macros with macro\_rules! and three kinds of procedural macros:

* Custom #[derive] macros that specify code added with the derive attribute used on structs and enums
* Attribute-like macros that define custom attributes usable on any item
* Function-like macros that look like function calls but operate on the tokens specified as their argument

We’ll talk about each of these in turn, but first, let’s look at why we even need macros when we already have functions.

The Difference Between Macros and Functions

Fundamentally, macros are a way of writing code that writes other code, which is known as metaprogramming. In Appendix C, we discuss the derive attribute, which generates an implementation of various traits for you. We’ve also used the println! and vec! macros throughout the book. All of these macros expand to produce more code than the code you’ve written manually.

Metaprogramming is useful for reducing the amount of code you have to write and maintain, which is also one of the roles of functions. However, macros have some additional powers that functions don’t have.

A function signature must declare the number and type of parameters the function has. Macros, on the other hand, can take a variable number of parameters: We can call println!("hello") with one argument or println! ("hello {}", name) with two arguments. Also, macros are expanded before the compiler interprets the meaning of the code, so a macro can, for example, implement a trait on a given type. A function can’t, because it gets called at runtime and a trait needs to be implemented at compile time.

The downside to implementing a macro instead of a function is that macro definitions are more complex than function definitions because you’re writing Rust code that writes Rust code. Due to this indirection, macro definitions are generally more difficult to read, understand, and maintain than function definitions.

Another important difference between macros and functions is that you must define macros or bring them into scope before you call them in a file, as opposed to functions you can define anywhere and call anywhere.

Declarative Macros for General Metaprogramming

The most widely used form of macros in Rust is the declarative macro. These are also sometimes referred to as “macros by example,” “macro\_rules! macros,” or just plain “macros.” At their core, declarative macros allow you to write something similar to a Rust match expression. As discussed in Chapter 6, match expressions are control structures that take an expression, compare the resultant value of the expression to patterns, and then run the code associated with the matching pattern. Macros also compare a value to patterns that are associated with particular code: In this situation, the value is the literal Rust source code passed to the macro; the patterns are compared with the structure of that source code; and the code associated with each pattern, when matched, replaces the code passed to the macro. This all happens during compilation.

To define a macro, you use the macro\_rules! construct. Let’s explore how to use macro\_rules! by looking at how the vec! macro is defined. Chapter 8 covered how we can use the vec! macro to create a new vector with particular values. For example, the following macro creates a new vector containing three integers:

let v: Vec<u32> = vec![1, 2, 3];

We could also use the vec! macro to make a vector of two integers or a vector of five string slices. We wouldn’t be able to use a function to do the same because we wouldn’t know the number or type of values up front.

Listing 20-35 shows a slightly simplified definition of the vec! macro.

src/lib.rs

1 #[macro\_export]

2 macro\_rules! vec {

3 ( $( $x:expr ),\* ) => {

{

let mut temp\_vec = Vec::new();

4 $(

5 temp\_vec.push($x); 6

)\*

7 temp\_vec

}

};

}

A simplified version of the vec! macro definition

Note The actual definition of the vec! macro in the standard library includes code to pre-allocate the correct amount of memory up front. That code is an optimization that we don’t include here, to make the example simpler.

The #[macro\_export] annotation 1 indicates that this macro should be made available whenever the crate in which the macro is defined is brought into scope. Without this annotation, the macro can’t be brought into scope.

We then start the macro definition with macro\_rules! and the name of the macro we’re defining without the exclamation mark 2. The name, in this case vec, is followed by curly brackets denoting the body of the macro definition.

The structure in the vec! body is similar to the structure of a match expression. Here we have one arm with the pattern ( $( $x:expr ),\* ), followed by => and the block of code associated with this pattern 3. If the pattern matches, the associated block of code will be emitted. Given that this is the only pattern in this macro, there is only one valid way to match; any other pattern will result in an error. More complex macros will have more than one arm.

Valid pattern syntax in macro definitions is different from the pattern syntax covered in Chapter 19 because macro patterns are matched against Rust code structure rather than values. Let’s walk through what the pattern pieces in Listing 20-29 mean; for the full macro pattern syntax, see the Rust Reference at https://doc.rust-lang.org/reference/macros-by-example.html.

First, we use a set of parentheses to encompass the whole pattern. We use a dollar sign ($) to declare a variable in the macro system that will contain the Rust code matching the pattern. The dollar sign makes it clear this is a macro variable as opposed to a regular Rust variable. Next comes a set of parentheses that captures values that match the pattern within the parentheses for use in the replacement code. Within $() is $x:expr, which matches any Rust expression and gives the expression the name $x.

The comma following $() indicates that a literal comma separator character must appear between each instance of the code that matches the code in $(). The \* specifies that the pattern matches zero or more of whatever precedes the \*.

When we call this macro with vec![1, 2, 3];, the $x pattern matches three times with the three expressions 1, 2, and 3.

Now let’s look at the pattern in the body of the code associated with this arm: temp\_vec.push() 5 within $()\* 4 7 is generated for each part that matches $() in the pattern zero or more times depending on how many times the pattern matches. The $x 6 is replaced with each expression matched. When we call this macro with vec![1, 2, 3];, the code generated that replaces this macro call will be the following:

{

let mut temp\_vec = Vec::new();

temp\_vec.push(1);

temp\_vec.push(2);

temp\_vec.push(3);

temp\_vec

}

We’ve defined a macro that can take any number of arguments of any type and can generate code to create a vector containing the specified elements.

To learn more about how to write macros, consult the online documentation or other resources, such as “The Little Book of Rust Macros” at https://veykril.github.io/tlborm started by Daniel Keep and continued by Lukas Wirth.

Procedural Macros for Generating Code from Attributes

The second form of macros is the procedural macro, which acts more like a function (and is a type of procedure). Procedural macros accept some code as an input, operate on that code, and produce some code as an output rather than matching against patterns and replacing the code with other code as declarative macros do. The three kinds of procedural macros are custom derive, attribute-like, and function-like, and all work in a similar fashion.

When creating procedural macros, the definitions must reside in their own crate with a special crate type. This is for complex technical reasons that we hope to eliminate in the future. In Listing 20-36, we show how to define a procedural macro, where some\_attribute is a placeholder for using a specific macro variety.

src/lib.rs

use proc\_macro::TokenStream;

#[some\_attribute]

pub fn some\_name(input: TokenStream) -> TokenStream {

}

An example of defining a procedural macro

The function that defines a procedural macro takes a TokenStream as an input and produces a TokenStream as an output. The TokenStream type is defined by the proc\_macro crate that is included with Rust and represents a sequence of tokens. This is the core of the macro: The source code that the macro is operating on makes up the input TokenStream, and the code the macro produces is the output TokenStream. The function also has an attribute attached to it that specifies which kind of procedural macro we’re creating. We can have multiple kinds of procedural macros in the same crate.

Let’s look at the different kinds of procedural macros. We’ll start with a custom derive macro and then explain the small dissimilarities that make the other forms different.

Custom derive Macros

Let’s create a crate named hello\_macro that defines a trait named HelloMacro with one associated function named hello\_macro. Rather than making our users implement the HelloMacro trait for each of their types, we’ll provide a procedural macro so that users can annotate their type with #[derive(HelloMacro)] to get a default implementation of the hello\_macro function. The default implementation will print Hello, Macro! My name is TypeName! where TypeName is the name of the type on which this trait has been defined. In other words, we’ll write a crate that enables another programmer to write code like Listing 20-37 using our crate.

src/main.rs

use hello\_macro::HelloMacro;

use hello\_macro\_derive::HelloMacro;

#[derive(HelloMacro)]

struct Pancakes;

fn main() {

Pancakes::hello\_macro();

}

The code a user of our crate will be able to write when using our procedural macro

This code will print Hello, Macro! My name is Pancakes! when we’re done. The first step is to make a new library crate, like this:

$ cargo new hello\_macro --lib

Next, in Listing 20-38, we’ll define the HelloMacro trait and its associated function.

src/lib.rs

pub trait HelloMacro {

fn hello\_macro();

}

A simple trait that we will use with the derive macro

We have a trait and its function. At this point, our crate user could implement the trait to achieve the desired functionality, as in Listing 20-39.

use hello\_macro::HelloMacro;

struct Pancakes;

impl HelloMacro for Pancakes {

fn hello\_macro() {

println!("Hello, Macro! My name is Pancakes!");

}

}

fn main() {

Pancakes::hello\_macro();

}

How it would look if users wrote a manual implementation of the HelloMacro trait

However, they would need to write the implementation block for each type they wanted to use with hello\_macro; we want to spare them from having to do this work.

Additionally, we can’t yet provide the hello\_macro function with default implementation that will print the name of the type the trait is implemented on: Rust doesn’t have reflection capabilities, so it can’t look up the type’s name at runtime. We need a macro to generate code at compile time.

The next step is to define the procedural macro. At the time of this writing, procedural macros need to be in their own crate. Eventually, this restriction might be lifted. The convention for structuring crates and macro crates is as follows: For a crate named foo, a custom derive procedural macro crate is called foo\_derive. Let’s start a new crate called hello\_macro\_derive inside our hello\_macro project:

$ cargo new hello\_macro\_derive --lib

Our two crates are tightly related, so we create the procedural macro crate within the directory of our hello\_macro crate. If we change the trait definition in hello\_macro, we’ll have to change the implementation of the procedural macro in hello\_macro\_derive as well. The two crates will need to be published separately, and programmers using these crates will need to add both as dependencies and bring them both into scope. We could instead have the hello\_macro crate use hello\_macro\_derive as a dependency and re-export the procedural macro code. However, the way we’ve structured the project makes it possible for programmers to use hello\_macro even if they don’t want the derive functionality.

We need to declare the hello\_macro\_derive crate as a procedural macro crate. We’ll also need functionality from the syn and quote crates, as you’ll see in a moment, so we need to add them as dependencies. Add the following to the Cargo.toml file for hello\_macro\_derive:

hello\_macro\_derive/Cargo.toml

[lib]

proc-macro = true

[dependencies]

syn = "2.0"

quote = "1.0"

To start defining the procedural macro, place the code in Listing 20-40 into your src/lib.rs file for the hello\_macro\_derive crate. Note that this code won’t compile until we add a definition for the impl\_hello\_macro function.

hello\_macro\_derive/src/lib.rs

use proc\_macro::TokenStream;

use quote::quote;

#[proc\_macro\_derive(HelloMacro)]

pub fn hello\_macro\_derive(input: TokenStream) -> TokenStream {

// Construct a representation of Rust code as a syntax tree

// that we can manipulate.

let ast = syn::parse(input).unwrap();

// Build the trait implementation.

impl\_hello\_macro(&ast)

}

Code that most procedural macro crates will require in order to process Rust code

Notice that we’ve split the code into the hello\_macro\_derive function, which is responsible for parsing the TokenStream, and the impl\_hello\_macro function, which is responsible for transforming the syntax tree: This makes writing a procedural macro more convenient. The code in the outer function (hello\_macro\_derive in this case) will be the same for almost every procedural macro crate you see or create. The code you specify in the body of the inner function (impl\_hello\_macro in this case) will be different depending on your procedural macro’s purpose.

We’ve introduced three new crates: proc\_macro, syn (available from [*https://crates.io/crates/syn*](https://crates.io/crates/syn)), and quote (available from [*https://crates.io/crates/quote*](https://crates.io/crates/quote)). The proc\_macro crate comes with Rust, so we didn’t need to add that to the dependencies in Cargo.toml. The proc\_macro crate is the compiler’s API that allows us to read and manipulate Rust code from our code.

The syn crate parses Rust code from a string into a data structure that we can perform operations on. The quote crate turns syn data structures back into Rust code. These crates make it much simpler to parse any sort of Rust code we might want to handle: Writing a full parser for Rust code is no simple task.

The hello\_macro\_derive function will be called when a user of our library specifies #[derive(HelloMacro)] on a type. This is possible because we’ve annotated the hello\_macro\_derive function here with proc\_macro\_derive and specified the name HelloMacro, which matches our trait name; this is the convention most procedural macros follow.

The hello\_macro\_derive function first converts the input from a TokenStream to a data structure that we can then interpret and perform operations on. This is where syn comes into play. The parse function in syn takes a TokenStream and returns a DeriveInput struct representing the parsed Rust code. Listing 20-41 shows the relevant parts of the DeriveInput struct we get from parsing the struct Pancakes; string.

DeriveInput {

--snip--

ident: Ident {

ident: "Pancakes",

span: #0 bytes(95..103)

},

data: Struct(

DataStruct {

struct\_token: Struct,

fields: Unit,

semi\_token: Some(

Semi

)

}

)

}

The DeriveInput instance we get when parsing the code that has the macro’s attribute in Listing 20-37

The fields of this struct show that the Rust code we’ve parsed is a unit struct with the ident (identifier, meaning the name) of Pancakes. There are more fields on this struct for describing all sorts of Rust code; check the syn documentation for DeriveInput at https://docs.rs/syn/2.0/syn/struct.DeriveInput.html for more information.

Soon we’ll define the impl\_hello\_macro function, which is where we’ll build the new Rust code we want to include. But before we do, note that the output for our derive macro is also a TokenStream. The returned TokenStream is added to the code that our crate users write, so when they compile their crate, they’ll get the extra functionality that we provide in the modified TokenStream.

You might have noticed that we’re calling unwrap to cause the hello\_macro\_derive function to panic if the call to the syn::parse function fails here. It’s necessary for our procedural macro to panic on errors because proc\_macro\_derive functions must return TokenStream rather than Result to conform to the procedural macro API. We’ve simplified this example by using unwrap; in production code, you should provide more specific error messages about what went wrong by using panic! or expect.

Now that we have the code to turn the annotated Rust code from a TokenStream into a DeriveInput instance, let’s generate the code that implements the HelloMacro trait on the annotated type, as shown in Listing 20-42.

hello\_macro\_derive/src/lib.rs

fn impl\_hello\_macro(ast: &syn::DeriveInput) -> TokenStream {

let name = &ast.ident;

let generated = quote! {

impl HelloMacro for #name {

fn hello\_macro() {

println!(

"Hello, Macro! My name is {}!",

stringify!(#name)

);

}

}

};

generated.into()

}

Implementing the HelloMacro trait using the parsed Rust code

We get an Ident struct instance containing the name (identifier) of the annotated type using ast.ident. The struct in Listing 20-41 shows that when we run the impl\_hello\_macro function on the code in Listing 20-37, the ident we get will have the ident field with a value of "Pancakes". Thus, the name variable in Listing 20-42 will contain an Ident struct instance that, when printed, will be the string "Pancakes", the name of the struct in Listing 20-37.

The quote! macro lets us define the Rust code that we want to return. The compiler expects something different from the direct result of the quote! macro’s execution, so we need to convert it to a TokenStream. We do this by calling the into method, which consumes this intermediate representation and returns a value of the required TokenStream type.

The quote! macro also provides some very cool templating mechanics: We can enter #name, and quote! will replace it with the value in the variable name. You can even do some repetition similar to the way regular macros work. Check out the quote crate’s docs at https://docs.rs/quote for a thorough introduction.

We want our procedural macro to generate an implementation of our HelloMacro trait for the type the user annotated, which we can get by using #name. The trait implementation has the one function hello\_macro, whose body contains the functionality we want to provide: printing Hello, Macro! My name is and then the name of the annotated type.

The stringify! macro used here is built into Rust. It takes a Rust expression, such as 1 + 2, and at compile time turns the expression into a string literal, such as "1 + 2". This is different from format! or println!, which are macros that evaluate the expression and then turn the result into a String. There is a possibility that the #name input might be an expression to print literally, so we use stringify!. Using stringify! also saves an allocation by converting #name to a string literal at compile time.

At this point, cargo build should complete successfully in both hello\_macro and hello\_macro\_derive. Let’s hook up these crates to the code in Listing 20-37 to see the procedural macro in action! Create a new binary project in your projects directory using cargo new pancakes. We need to add hello\_macro and hello\_macro\_derive as dependencies in the pancakes crate’s Cargo.toml. If you’re publishing your versions of hello\_macro and hello\_macro\_derive to [*https://crates.io*](https://crates.io/), they would be regular dependencies; if not, you can specify them as path dependencies as follows:

[dependencies]

hello\_macro = { path = "../hello\_macro" }

hello\_macro\_derive = { path = "../hello\_macro/hello\_macro\_derive" }

Put the code in Listing 20-37 into src/main.rs, and run cargo run: It should print Hello, Macro! My name is Pancakes!. The implementation of the HelloMacro trait from the procedural macro was included without the pancakes crate needing to implement it; the #[derive(HelloMacro)] added the trait implementation.

Next, let’s explore how the other kinds of procedural macros differ from custom derive macros.

Attribute-Like Macros

Attribute-like macros are similar to custom derive macros, but instead of generating code for the derive attribute, they allow you to create new attributes. They’re also more flexible: derive only works for structs and enums; attributes can be applied to other items as well, such as functions. Here’s an example of using an attribute-like macro. Say you have an attribute named route that annotates functions when using a web application framework:

#[route(GET, "/")]

fn index() {

This #[route] attribute would be defined by the framework as a procedural macro. The signature of the macro definition function would look like this:

#[proc\_macro\_attribute]

pub fn route(attr: TokenStream, item: TokenStream) -> TokenStream {

Here, we have two parameters of type TokenStream. The first is for the contents of the attribute: the GET, "/" part. The second is the body of the item the attribute is attached to: in this case, fn index() {} and the rest of the function’s body.

Other than that, attribute-like macros work the same way as custom derive macros: You create a crate with the proc-macro crate type and implement a function that generates the code you want!

Function-Like Macros

Function-like macros define macros that look like function calls. Similarly to macro\_rules! macros, they’re more flexible than functions; for example, they can take an unknown number of arguments. However, macro\_rules! macros can only be defined using the match-like syntax we discussed in “Declarative Macros for General Metaprogramming” on page XX. Function-like macros take a TokenStream parameter, and their definition manipulates that TokenStream using Rust code as the other two types of procedural macros do. An example of a function-like macro is an sql! macro that might be called like so:

let sql = sql!(SELECT \* FROM posts WHERE id=1);

This macro would parse the SQL statement inside it and check that it’s syntactically correct, which is much more complex processing than a macro\_rules! macro can do. The sql! macro would be defined like this:

#[proc\_macro]

pub fn sql(input: TokenStream) -> TokenStream {

This definition is similar to the custom derive macro’s signature: We receive the tokens that are inside the parentheses and return the code we wanted to generate.

Summary

Whew! Now you have some Rust features in your toolbox that you likely won’t use often, but you’ll know they’re available in very particular circumstances. We’ve introduced several complex topics so that when you encounter them in error message suggestions or in other people’s code, you’ll be able to recognize these concepts and syntax. Use this chapter as a reference to guide you to solutions.

Next, we’ll put everything we’ve discussed throughout the book into practice and do one more project!