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Smart Pointers

A pointer is a general concept for a variable that contains an address in memory. This address refers to, or “points at,” some other data. The most common kind of pointer in Rust is a reference, which you learned about in Chapter 4. References are indicated by the & symbol and borrow the value they point to. They don’t have any special capabilities other than referring to data, and have no overhead.

Smart pointers, on the other hand, are data structures that act like a pointer but also have additional metadata and capabilities. The concept of smart pointers isn’t unique to Rust: smart pointers originated in C++ and exist in other languages as well. Rust has a variety of smart pointers defined in the standard library that provide functionality beyond that provided by references. To explore the general concept, we’ll look at a couple of different examples of smart pointers, including a reference counting smart pointer type. This pointer enables you to allow data to have multiple owners by keeping track of the number of owners and, when no owners remain, cleaning up the data.

Rust, with its concept of ownership and borrowing, has an additional difference between references and smart pointers: while references only borrow data, in many cases, smart pointers own the data they point to.

Though we didn’t call them as such at the time, we’ve already encountered a few smart pointers in this book, including String and Vec<T> in Chapter 8. Both these types count as smart pointers because they own some memory and allow you to manipulate it. They also have metadata and extra capabilities or guarantees. String, for example, stores its capacity as metadata and has the extra ability to ensure its data will always be valid UTF-8.

Smart pointers are usually implemented using structs. Unlike an ordinary struct, smart pointers implement the Deref and Drop traits. The Deref trait allows an instance of the smart pointer struct to behave like a reference so you can write your code to work with either references or smart pointers. The Drop trait allows you to customize the code that’s run when an instance of the smart pointer goes out of scope. In this chapter, we’ll discuss both traits and demonstrate why they’re important to smart pointers.

Given that the smart pointer pattern is a general design pattern used frequently in Rust, this chapter won’t cover every existing smart pointer. Many libraries have their own smart pointers, and you can even write your own. We’ll cover the most common smart pointers in the standard library:

* Box<T> for allocating values on the heap
* Rc<T>, a reference counting type that enables multiple ownership
* Ref<T> and RefMut<T>, accessed through RefCell<T>, a type that enforces the borrowing rules at runtime instead of compile time

In addition, we’ll cover the interior mutability pattern where an immutable type exposes an API for mutating an interior value. We’ll also discuss reference cycles: how they can leak memory and how to prevent them.

Let’s dive in!

Using Box<T> to Point to Data on the Heap

The most straightforward smart pointer is a box, whose type is written Box<T>. Boxes allow you to store data on the heap rather than the stack. What remains on the stack is the pointer to the heap data. Refer to Chapter 4 to review the difference between the stack and the heap.

Boxes don’t have performance overhead, other than storing their data on the heap instead of on the stack. But they don’t have many extra capabilities either. You’ll use them most often in these situations:

* When you have a type whose size can’t be known at compile time and you want to use a value of that type in a context that requires an exact size
* When you have a large amount of data and you want to transfer ownership but ensure the data won’t be copied when you do so
* When you want to own a value and you care only that it’s a type that implements a particular trait rather than being of a specific type

We’ll demonstrate the first situation in the “Enabling Recursive Types with Boxes” section. In the second case, transferring ownership of a large amount of data can take a long time because the data is copied around on the stack. To improve performance in this situation, we can store the large amount of data on the heap in a box. Then, only the small amount of pointer data is copied around on the stack, while the data it references stays in one place on the heap. The third case is known as a trait object, and Chapter 17 devotes an entire section, “Using Trait Objects That Allow for Values of Different Types,” just to that topic. So what you learn here you’ll apply again in Chapter 17!

Using a Box<T> to Store Data on the Heap

Before we discuss the heap storage use case for Box<T>, we’ll cover the syntax and how to interact with values stored within a Box<T>.

Listing 15-1 shows how to use a box to store an i32 value on the heap:

src/main.rs

fn main() {

let b = Box::new(5);

println!("b = {}", b);

}

Storing an i32 value on the heap using a box

We define the variable b to have the value of a Box that points to the value 5, which is allocated on the heap. This program will print b = 5; in this case, we can access the data in the box similar to how we would if this data were on the stack. Just like any owned value, when a box goes out of scope, as b does at the end of main, it will be deallocated. The deallocation happens both for the box (stored on the stack) and the data it points to (stored on the heap).

Putting a single value on the heap isn’t very useful, so you won’t use boxes by themselves in this way very often. Having values like a single i32 on the stack, where they’re stored by default, is more appropriate in the majority of situations. Let’s look at a case where boxes allow us to define types that we wouldn’t be allowed to if we didn’t have boxes.

Enabling Recursive Types with Boxes

A value of recursive type can have another value of the same type as part of itself. Recursive types pose an issue because at compile time Rust needs to know how much space a type takes up. However, the nesting of values of recursive types could theoretically continue infinitely, so Rust can’t know how much space the value needs. Because boxes have a known size, we can enable recursive types by inserting a box in the recursive type definition.

As an example of a recursive type, let’s explore the cons list. This is a data type commonly found in functional programming languages. The cons list type we’ll define is straightforward except for the recursion; therefore, the concepts in the example we’ll work with will be useful any time you get into more complex situations involving recursive types.

More Information About the Cons List

A cons list is a data structure that comes from the Lisp programming language and its dialects and is made up of nested pairs, and is the Lisp version of a linked list. Its name comes from the cons function (short for “construct function”) in Lisp that constructs a new pair from its two arguments. By calling cons on a pair consisting of a value and another pair, we can construct cons lists made up of recursive pairs.

For example, here’s a pseudocode representation of a cons list containing the list 1, 2, 3 with each pair in parentheses:

(1, (2, (3, Nil)))

Each item in a cons list contains two elements: the value of the current item and the next item. The last item in the list contains only a value called Nil without a next item. A cons list is produced by recursively calling the cons function. The canonical name to denote the base case of the recursion is Nil. Note that this is not the same as the “null” or “nil” concept in Chapter 6, which is an invalid or absent value.

The cons list isn’t a commonly used data structure in Rust. Most of the time when you have a list of items in Rust, Vec<T> is a better choice to use. Other, more complex recursive data types are useful in various situations, but by starting with the cons list in this chapter, we can explore how boxes let us define a recursive data type without much distraction.

Listing 15-2 contains an enum definition for a cons list. Note that this code won’t compile yet because the List type doesn’t have a known size, which we’ll demonstrate.

src/main.rs

enum List {

Cons(i32, List),

Nil,

}

The first attempt at defining an enum to represent a cons list data structure of i32 values

Note We’re implementing a cons list that holds only i32 values for the purposes of this example. We could have implemented it using generics, as we discussed in Chapter 10, to define a cons list type that could store values of any type.

Using the List type to store the list 1, 2, 3 would look like the code in Listing 15-3:

src/main.rs

use crate::List::{Cons, Nil};

fn main() {

let list = Cons(1, Cons(2, Cons(3, Nil)));

}

Using the List enum to store the list 1, 2, 3

The first Cons value holds 1 and another List value. This List value is another Cons value that holds 2 and another List value. This List value is one more Cons value that holds 3 and a List value, which is finally Nil, the non-recursive variant that signals the end of the list.

If we try to compile the code in Listing 15-3, we get the error shown in Listing 15-4:

error[E0072]: recursive type `List` has infinite size

--> src/main.rs:1:1

|

1 | enum List {

| ^^^^^^^^^ recursive type has infinite size

2 | Cons(i32, List),

| ---- recursive without indirection

|

help: insert some indirection (e.g., a `Box`, `Rc`, or `&`) to make `List` representable

The error we get when attempting to define a recursive enum

The error shows this type “has infinite size.” The reason is that we’ve defined List with a variant that is recursive: it holds another value of itself directly. As a result, Rust can’t figure out how much space it needs to store a List value. Let’s break down why we get this error. First, we’ll look at how Rust decides how much space it needs to store a value of a non-recursive type.

Computing the Size of a Non-Recursive Type

Recall the Message enum we defined in Listing 6-2 when we discussed enum definitions in Chapter 6:

enum Message {

Quit,

Move { x: i32, y: i32 },

Write(String),

ChangeColor(i32, i32, i32),

}

To determine how much space to allocate for a Message value, Rust goes through each of the variants to see which variant needs the most space. Rust sees that Message::Quit doesn’t need any space, Message::Move needs enough space to store two i32 values, and so forth. Because only one variant will be used, the most space a Message value will need is the space it would take to store the largest of its variants.

Contrast this with what happens when Rust tries to determine how much space a recursive type like the List enum in Listing 15-2 needs. The compiler starts by looking at the Cons variant, which holds a value of type i32 and a value of type List. Therefore, Cons needs an amount of space equal to the size of an i32 plus the size of a List. To figure out how much memory the List type needs, the compiler looks at the variants, starting with the Cons variant. The Cons variant holds a value of type i32 and a value of type List, and this process continues infinitely, as shown in Figure 15-1.

[f15001.eps]

* + - * 1. An infinite List consisting of infinite Cons variants

Using Box<T> to Get a Recursive Type with a Known Size

Because Rust can’t figure out how much space to allocate for recursively defined types, the compiler gives an error with this helpful suggestion:

help: insert some indirection (e.g., a `Box`, `Rc`, or `&`) to make `List` representable

In this suggestion, “indirection” means that instead of storing a value directly, we should change the data structure to store the value indirectly by storing a pointer to the value instead.

Because a Box<T> is a pointer, Rust always knows how much space a Box<T> needs: a pointer’s size doesn’t change based on the amount of data it’s pointing to. This means we can put a Box<T> inside the Cons variant instead of another List value directly. The Box<T> will point to the next List value that will be on the heap rather than inside the Cons variant. Conceptually, we still have a list, created with lists holding other lists, but this implementation is now more like placing the items next to one another rather than inside one another.

We can change the definition of the List enum in Listing 15-2 and the usage of the List in Listing 15-3 to the code in Listing 15-5, which will compile:

src/main.rs

enum List {

Cons(i32, Box<List>),

Nil,

}

use crate::List::{Cons, Nil};

fn main() {

let list = Cons(1, Box::new(Cons(2, Box::new(Cons(3, Box::new(Nil))))));

}

Definition of List that uses Box<T> in order to have a known size

The Cons variant needs the size of an i32 plus the space to store the box’s pointer data. The Nil variant stores no values, so it needs less space than the Cons variant. We now know that any List value will take up the size of an i32 plus the size of a box’s pointer data. By using a box, we’ve broken the infinite, recursive chain, so the compiler can figure out the size it needs to store a List value. Figure 15-2 shows what the Cons variant looks like now.

[f15002.eps]

* + - * 1. A List that is not infinitely sized because Cons holds a Box

Boxes provide only the indirection and heap allocation; they don’t have any other special capabilities, like those we’ll see with the other smart pointer types. They also don’t have the performance overhead that these special capabilities incur, so they can be useful in cases like the cons list where the indirection is the only feature we need. We’ll look at more use cases for boxes in Chapter 17, too.

The Box<T> type is a smart pointer because it implements the Deref trait, which allows Box<T> values to be treated like references. When a Box<T> value goes out of scope, the heap data that the box is pointing to is cleaned up as well because of the Drop trait implementation. These two traits will be even more important to the functionality provided by the other smart pointer types we’ll discuss in the rest of this chapter. Let’s explore these two traits in more detail.

Treating Smart Pointers Like Regular References with Deref

Implementing the Deref trait allows you to customize the behavior of the dereference operator \* (not to be confused with the multiplication or glob operator). By implementing Deref in such a way that a smart pointer can be treated like a regular reference, you can write code that operates on references and use that code with smart pointers too.

Let’s first look at how the dereference operator works with regular references. Then we’ll try to define a custom type that behaves like Box<T>, and see why the dereference operator doesn’t work like a reference on our newly defined type. We’ll explore how implementing the Deref trait makes it possible for smart pointers to work in ways similar to references. Then we’ll look at Rust’s deref coercion feature and how it lets us work with either references or smart pointers.

Note: there’s one big difference between the MyBox<T> type we’re about to build and the real Box<T>: our version will not store its data on the heap. We are focusing this example on Deref, so where the data is actually stored is less important than the pointer-like behavior.

Following the Pointer to the Value

A regular reference is a type of pointer, and one way to think of a pointer is as an arrow to a value stored somewhere else. In Listing 15-6, we create a reference to an i32 value and then use the dereference operator to follow the reference to the value:

src/main.rs

fn main() {

1 let x = 5;

2 let y = &x;

3 assert\_eq!(5, x);

4 assert\_eq!(5, \*y);

}

Using the dereference operator to follow a reference to an i32 value

The variable x holds an i32 value 5 1. We set y equal to a reference to x 2. We can assert that x is equal to 5 3. However, if we want to make an assertion about the value in y, we have to use \*y to follow the reference to the value it’s pointing to (hence dereference) so the compiler can compare the actual value 4. Once we dereference y, we have access to the integer value y is pointing to that we can compare with 5.

If we tried to write assert\_eq!(5, y); instead, we would get this compilation error:

error[E0277]: can't compare `{integer}` with `&{integer}`

--> src/main.rs:6:5

|

6 | assert\_eq!(5, y);

| ^^^^^^^^^^^^^^^^ no implementation for `{integer} == &{integer}`

|

= help: the trait `PartialEq<&{integer}>` is not implemented for `{integer}`

Comparing a number and a reference to a number isn’t allowed because they’re different types. We must use the dereference operator to follow the reference to the value it’s pointing to.

Using Box<T> Like a Reference

We can rewrite the code in Listing 15-6 to use a Box<T> instead of a reference; the dereference operator used on the Box<T> in Listing 15-7 functions in the same way as the dereference operator used on the reference in Listing 15-6:

src/main.rs

fn main() {

let x = 5;

1 let y = Box::new(x);

assert\_eq!(5, x);

2 assert\_eq!(5, \*y);

}

Using the dereference operator on a Box<i32>

The main difference between Listing 15-7 and Listing 15-6 is that here we set y to be an instance of a box pointing to a copied value of x rather than a reference pointing to the value of x 1. In the last assertion 2, we can use the dereference operator to follow the box’s pointer in the same way that we did when y was a reference. Next, we’ll explore what is special about Box<T> that enables us to use the dereference operator by defining our own box type.

Defining Our Own Smart Pointer

Let’s build a smart pointer similar to the Box<T> type provided by the standard library to experience how smart pointers behave differently from references by default. Then we’ll look at how to add the ability to use the dereference operator.

The Box<T> type is ultimately defined as a tuple struct with one element, so Listing 15-8 defines a MyBox<T> type in the same way. We’ll also define a new function to match the new function defined on Box<T>.

src/main.rs

1 struct MyBox<T>(T);

impl<T> MyBox<T> {

2 fn new(x: T) -> MyBox<T> {

3 MyBox(x)

}

}

Defining a MyBox<T> type

We define a struct named MyBox and declare a generic parameter T 1, because we want our type to hold values of any type. The MyBox type is a tuple struct with one element of type T. The MyBox::new function takes one parameter of type T 2 and returns a MyBox instance that holds the value passed in 3.

Let’s try adding the main function in Listing 15-7 to Listing 15-8 and changing it to use the MyBox<T> type we’ve defined instead of Box<T>. The code in Listing 15-9 won’t compile because Rust doesn’t know how to dereference MyBox.

src/main.rs

fn main() {

let x = 5;

let y = MyBox::new(x);

assert\_eq!(5, x);

assert\_eq!(5, \*y);

}

Attempting to use MyBox<T> in the same way we used references and Box<T>

Here’s the resulting compilation error:

error[E0614]: type `MyBox<{integer}>` cannot be dereferenced

--> src/main.rs:14:19

|

14 | assert\_eq!(5, \*y);

| ^^

Our MyBox<T> type can’t be dereferenced because we haven’t implemented that ability on our type. To enable dereferencing with the \* operator, we implement the Deref trait.

Implementing the Deref Trait

As discussed in the “Implementing a Trait on a Type” section of Chapter 10, to implement a trait, we need to provide implementations for the trait’s required methods. The Deref trait, provided by the standard library, requires us to implement one method named deref that borrows self and returns a reference to the inner data. Listing 15-10 contains an implementation of Deref to add to the definition of MyBox:

src/main.rs

use std::ops::Deref;

impl<T> Deref for MyBox<T> {

1 type Target = T;

fn deref(&self) -> &Self::Target {

2 &self.0

}

}

Implementing Deref on MyBox<T>

The type Target = T; syntax 1 defines an associated type for the Deref trait to use. Associated types are a slightly different way of declaring a generic parameter, but you don’t need to worry about them for now; we’ll cover them in more detail in Chapter 19.

We fill in the body of the deref method with &self.0 so deref returns a reference to the value we want to access with the \* operator 2; recall from the “Using Tuple Structs without Named Fields to Create Different Types” section of Chapter 5 that .0 accesses the first value in a tuple struct. The main function in Listing 15-9 that calls \* on the MyBox<T> value now compiles, and the assertions pass!

Without the Deref trait, the compiler can only dereference & references. The deref method gives the compiler the ability to take a value of any type that implements Deref and call the deref method to get a & reference that it knows how to dereference.

When we entered \*y in Listing 15-9, behind the scenes Rust actually ran this code:

\*(y.deref())

Rust substitutes the \* operator with a call to the deref method and then a plain dereference so we don’t have to think about whether or not we need to call the deref method. This Rust feature lets us write code that functions identically whether we have a regular reference or a type that implements Deref.

The reason the deref method returns a reference to a value, and that the plain dereference outside the parentheses in \*(y.deref()) is still necessary, is to do with the ownership system. If the deref method returned the value directly instead of a reference to the value, the value would be moved out of self. We don’t want to take ownership of the inner value inside MyBox<T> in this case or in most cases where we use the dereference operator.

Note that the \* operator is replaced with a call to the deref method and then a call to the \* operator just once, each time we use a \* in our code. Because the substitution of the \* operator does not recurse infinitely, we end up with data of type i32, which matches the 5 in assert\_eq! in Listing 15-9.

Implicit Deref Coercions with Functions and Methods

Deref coercion converts a reference to a type that implements the Deref trait into a reference to another type. For example, deref coercion can convert &String to &str because String implements the Deref trait such that it returns &str. Deref coercion is a convenience Rust performs on arguments to functions and methods, and works only on types that implement the Deref trait. It happens automatically when we pass a reference to a particular type’s value as an argument to a function or method that doesn’t match the parameter type in the function or method definition. A sequence of calls to the deref method converts the type we provided into the type the parameter needs.

Deref coercion was added to Rust so that programmers writing function and method calls don’t need to add as many explicit references and dereferences with & and \*. The deref coercion feature also lets us write more code that can work for either references or smart pointers.

To see deref coercion in action, let’s use the MyBox<T> type we defined in Listing 15-8 as well as the implementation of Deref that we added in Listing 15-10. Listing 15-11 shows the definition of a function that has a string slice parameter:

src/main.rs

fn hello(name: &str) {

println!("Hello, {name}!");

}

A hello function that has the parameter name of type &str

We can call the hello function with a string slice as an argument, such as hello("Rust"); for example. Deref coercion makes it possible to call hello with a reference to a value of type MyBox<String>, as shown in Listing 15-12:

src/main.rs

fn main() {

let m = MyBox::new(String::from("Rust"));

hello(&m);

}

Calling hello with a reference to a MyBox<String> value, which works because of deref coercion

Here we’re calling the hello function with the argument &m, which is a reference to a MyBox<String> value. Because we implemented the Deref trait on MyBox<T> in Listing 15-10, Rust can turn &MyBox<String> into &String by calling deref. The standard library provides an implementation of Deref on String that returns a string slice, and this is in the API documentation for Deref. Rust calls deref again to turn the &String into &str, which matches the hello function’s definition.

If Rust didn’t implement deref coercion, we would have to write the code in Listing 15-13 instead of the code in Listing 15-12 to call hello with a value of type &MyBox<String>.

src/main.rs

fn main() {

let m = MyBox::new(String::from("Rust"));

hello(&(\*m)[..]);

}

The code we would have to write if Rust didn’t have deref coercion

The (\*m) dereferences the MyBox<String> into a String. Then the & and [..] take a string slice of the String that is equal to the whole string to match the signature of hello. This code without deref coercions is harder to read, write, and understand with all of these symbols involved. Deref coercion allows Rust to handle these conversions for us automatically.

When the Deref trait is defined for the types involved, Rust will analyze the types and use Deref::deref as many times as necessary to get a reference to match the parameter’s type. The number of times that Deref::deref needs to be inserted is resolved at compile time, so there is no runtime penalty for taking advantage of deref coercion!

How Deref Coercion Interacts with Mutability

Similar to how you use the Deref trait to override the \* operator on immutable references, you can use the DerefMut trait to override the \* operator on mutable references.

Rust does deref coercion when it finds types and trait implementations in three cases:

* From &T to &U when T: Deref<Target=U>
* From &mut T to &mut U when T: DerefMut<Target=U>
* From &mut T to &U when T: Deref<Target=U>

The first two cases are the same as each other except that the second implements mutability. The first case states that if you have a &T, and T implements Deref to some type U, you can get a &U transparently. The second case states that the same deref coercion happens for mutable references.

The third case is trickier: Rust will also coerce a mutable reference to an immutable one. But the reverse is not possible: immutable references will never coerce to mutable references. Because of the borrowing rules, if you have a mutable reference, that mutable reference must be the only reference to that data (otherwise, the program wouldn’t compile). Converting one mutable reference to one immutable reference will never break the borrowing rules. Converting an immutable reference to a mutable reference would require that the initial immutable reference is the only immutable reference to that data, but the borrowing rules don’t guarantee that. Therefore, Rust can’t make the assumption that converting an immutable reference to a mutable reference is possible.

Running Code on Cleanup with the Drop Trait

The second trait important to the smart pointer pattern is Drop, which lets you customize what happens when a value is about to go out of scope. You can provide an implementation for the Drop trait on any type, and that code can be used to release resources like files or network connections.

We’re introducing Drop in the context of smart pointers because the functionality of the Drop trait is almost always used when implementing a smart pointer. For example, when a Box<T> is dropped it will deallocate the space on the heap that the box points to.

In some languages, for some types, the programmer must call code to free memory or resources every time they finish using an instance of those types. Examples include file handles, sockets, or locks. If they forget, the system might become overloaded and crash. In Rust, you can specify that a particular bit of code be run whenever a value goes out of scope, and the compiler will insert this code automatically. As a result, you don’t need to be careful about placing cleanup code everywhere in a program that an instance of a particular type is finished with—you still won’t leak resources!

You specify the code to run when a value goes out of scope by implementing the Drop trait. The Drop trait requires you to implement one method named drop that takes a mutable reference to self. To see when Rust calls drop, let’s implement drop with println! statements for now.

Listing 15-14 shows a CustomSmartPointer struct whose only custom functionality is that it will print Dropping CustomSmartPointer! when the instance goes out of scope, to show when Rust runs the drop function.

src/main.rs

struct CustomSmartPointer {

data: String,

}

1 impl Drop for CustomSmartPointer {

fn drop(&mut self) {

2 println!("Dropping CustomSmartPointer with data `{}`!", self.data);

}

}

fn main() {

3 let c = CustomSmartPointer {

data: String::from("my stuff"),

};

4 let d = CustomSmartPointer {

data: String::from("other stuff"),

};

5 println!("CustomSmartPointers created.");

6 }

A CustomSmartPointer struct that implements the Drop trait where we would put our cleanup code

The Drop trait is included in the prelude, so we don’t need to bring it into scope. We implement the Drop trait on CustomSmartPointer 1 and provide an implementation for the drop method that calls println! 2. The body of the drop function is where you would place any logic that you wanted to run when an instance of your type goes out of scope. We’re printing some text here to demonstrate visually when Rust will call drop.

In main, we create two instances of CustomSmartPointer 34 and then print CustomSmartPointers created 5. At the end of main 6, our instances of CustomSmartPointer will go out of scope, and Rust will call the code we put in the drop method 2, printing our final message. Note that we didn’t need to call the drop method explicitly.

When we run this program, we’ll see the following output:

CustomSmartPointers created.

Dropping CustomSmartPointer with data `other stuff`!

Dropping CustomSmartPointer with data `my stuff`!

Rust automatically called drop for us when our instances went out of scope, calling the code we specified. Variables are dropped in the reverse order of their creation, so d was dropped before c. This example’s purpose is to give you a visual guide to how the drop method works; usually you would specify the cleanup code that your type needs to run rather than a print message.

Unfortunately, it’s not straightforward to disable the automatic drop functionality. Disabling drop isn’t usually necessary; the whole point of the Drop trait is that it’s taken care of automatically. Occasionally, however, you might want to clean up a value early. One example is when using smart pointers that manage locks: you might want to force the drop method that releases the lock so that other code in the same scope can acquire the lock. Rust doesn’t let you call the Drop trait’s drop method manually; instead you have to call the std::mem::drop function provided by the standard library if you want to force a value to be dropped before the end of its scope.

If we try to call the Drop trait’s drop method manually by modifying the main function from Listing 15-14, as shown in Listing 15-15, we’ll get a compiler error:

src/main.rs

fn main() {

let c = CustomSmartPointer {

data: String::from("some data"),

};

println!("CustomSmartPointer created.");

c.drop();

println!(

"CustomSmartPointer dropped before the end of main."

);

}

Attempting to call the drop method from the Drop trait manually to clean up early

When we try to compile this code, we’ll get this error:

error[E0040]: explicit use of destructor method

--> src/main.rs:16:7

|

16 | c.drop();

| --^^^^--

| | |

| | explicit destructor calls not allowed

This error message states that we’re not allowed to explicitly call drop. The error message uses the term destructor, which is the general programming term for a function that cleans up an instance. A destructor is analogous to a constructor, which creates an instance. The drop function in Rust is one particular destructor.

Rust doesn’t let us call drop explicitly because Rust would still automatically call drop on the value at the end of main. This would cause a double free error because Rust would be trying to clean up the same value twice.

We can’t disable the automatic insertion of drop when a value goes out of scope, and we can’t call the drop method explicitly. So, if we need to force a value to be cleaned up early, we use the std::mem::drop function.

The std::mem::drop function is different from the drop method in the Drop trait. We call it by passing as an argument the value we want to force drop. The function is in the prelude, so we can modify main in Listing 15-15 to call the drop function, as shown in Listing 15-16:

src/main.rs

fn main() {

let c = CustomSmartPointer {

data: String::from("some data"),

};

println!("CustomSmartPointer created.");

drop(c);

println!(

"CustomSmartPointer dropped before the end of main."

);

}

Calling std::mem::drop to explicitly drop a value before it goes out of scope

Running this code will print the following:

CustomSmartPointer created.

Dropping CustomSmartPointer with data `some data`!

CustomSmartPointer dropped before the end of main.

The text Dropping CustomSmartPointer with data `some data`! is printed between the CustomSmartPointer created. and CustomSmartPointer dropped before the end of main. text, showing that the drop method code is called to drop c at that point.

You can use code specified in a Drop trait implementation in many ways to make cleanup convenient and safe: for instance, you could use it to create your own memory allocator! With the Drop trait and Rust’s ownership system, you don’t have to remember to clean up because Rust does it automatically.

You also don’t have to worry about problems resulting from accidentally cleaning up values still in use: the ownership system that makes sure references are always valid also ensures that drop gets called only once when the value is no longer being used.

Now that we’ve examined Box<T> and some of the characteristics of smart pointers, let’s look at a few other smart pointers defined in the standard library.

Rc<T>, the Reference Counted Smart Pointer

In the majority of cases, ownership is clear: you know exactly which variable owns a given value. However, there are cases when a single value might have multiple owners. For example, in graph data structures, multiple edges might point to the same node, and that node is conceptually owned by all of the edges that point to it. A node shouldn’t be cleaned up unless it doesn’t have any edges pointing to it and so has no owners.

You have to enable multiple ownership explicitly by using the Rust type Rc<T>, which is an abbreviation for reference counting. The Rc<T> type keeps track of the number of references to a value to determine whether or not the value is still in use. If there are zero references to a value, the value can be cleaned up without any references becoming invalid.

Imagine Rc<T> as a TV in a family room. When one person enters to watch TV, they turn it on. Others can come into the room and watch the TV. When the last person leaves the room, they turn off the TV because it’s no longer being used. If someone turns off the TV while others are still watching it, there would be uproar from the remaining TV watchers!

We use the Rc<T> type when we want to allocate some data on the heap for multiple parts of our program to read and we can’t determine at compile time which part will finish using the data last. If we knew which part would finish last, we could just make that part the data’s owner, and the normal ownership rules enforced at compile time would take effect.

Note that Rc<T> is only for use in single-threaded scenarios. When we discuss concurrency in Chapter 16, we’ll cover how to do reference counting in multithreaded programs.

Using Rc<T> to Share Data

Let’s return to our cons list example in Listing 15-5. Recall that we defined it using Box<T>. This time, we’ll create two lists that both share ownership of a third list. Conceptually, this looks similar to Figure 15-3:

[f15003.eps]

* + - * 1. Two lists, b and c, sharing ownership of a third list, a

We’ll create list a that contains 5 and then 10. Then we’ll make two more lists: b that starts with 3 and c that starts with 4. Both b and c lists will then continue on to the first a list containing 5 and 10. In other words, both lists will share the first list containing 5 and 10.

Trying to implement this scenario using our definition of List with Box<T> won’t work, as shown in Listing 15-17:

src/main.rs

enum List {

Cons(i32, Box<List>),

Nil,

}

use crate::List::{Cons, Nil};

fn main() {

let a = Cons(5, Box::new(Cons(10, Box::new(Nil))));

1 let b = Cons(3, Box::new(a));

2 let c = Cons(4, Box::new(a));

}

Demonstrating we’re not allowed to have two lists using Box<T> that try to share ownership of a third list

When we compile this code, we get this error:

error[E0382]: use of moved value: `a`

--> src/main.rs:11:30

|

9 | let a = Cons(5, Box::new(Cons(10, Box::new(Nil))));

| - move occurs because `a` has type `List`, which does not implement the `Copy` trait

10 | let b = Cons(3, Box::new(a));

| - value moved here

11 | let c = Cons(4, Box::new(a));

| ^ value used here after move

The Cons variants own the data they hold, so when we create the b list 1, a is moved into b and b owns a. Then, when we try to use a again when creating c 2, we’re not allowed to because a has been moved.

We could change the definition of Cons to hold references instead, but then we would have to specify lifetime parameters. By specifying lifetime parameters, we would be specifying that every element in the list will live at least as long as the entire list. This is the case for the elements and lists in Listing 15-17, but not in every scenario.

Instead, we’ll change our definition of List to use Rc<T> in place of Box<T>, as shown in Listing 15-18. Each Cons variant will now hold a value and an Rc<T> pointing to a List. When we create b, instead of taking ownership of a, we’ll clone the Rc<List> that a is holding, thereby increasing the number of references from one to two and letting a and b share ownership of the data in that Rc<List>. We’ll also clone a when creating c, increasing the number of references from two to three. Every time we call Rc::clone, the reference count to the data within the Rc<List> will increase, and the data won’t be cleaned up unless there are zero references to it.

src/main.rs

enum List {

Cons(i32, Rc<List>),

Nil,

}

use crate::List::{Cons, Nil};

1 use std::rc::Rc;

fn main() {

2 let a = Rc::new(Cons(5, Rc::new(Cons(10, Rc::new(Nil)))));

3 let b = Cons(3, Rc::clone(&a));

4 let c = Cons(4, Rc::clone(&a));

}

A definition of List that uses Rc<T>

We need to add a use statement to bring Rc<T> into scope 1 because it’s not in the prelude. In main, we create the list holding 5 and 10 and store it in a new Rc<List> in a 2. Then when we create b 3 and c 4, we call the Rc::clone function and pass a reference to the Rc<List> in a as an argument.

We could have called a.clone() rather than Rc::clone(&a), but Rust’s convention is to use Rc::clone in this case. The implementation of Rc::clone doesn’t make a deep copy of all the data like most types’ implementations of clone do. The call to Rc::clone only increments the reference count, which doesn’t take much time. Deep copies of data can take a lot of time. By using Rc::clone for reference counting, we can visually distinguish between the deep-copy kinds of clones and the kinds of clones that increase the reference count. When looking for performance problems in the code, we only need to consider the deep-copy clones and can disregard calls to Rc::clone.

Cloning an Rc<T> Increases the Reference Count

Let’s change our working example in Listing 15-18 so we can see the reference counts changing as we create and drop references to the Rc<List> in a.

In Listing 15-19, we’ll change main so it has an inner scope around list c; then we can see how the reference count changes when c goes out of scope.

src/main.rs

fn main() {

let a = Rc::new(Cons(5, Rc::new(Cons(10, Rc::new(Nil)))));

println!(

"count after creating a = {}",

Rc::strong\_count(&a)

);

let b = Cons(3, Rc::clone(&a));

println!(

"count after creating b = {}",

Rc::strong\_count(&a)

);

{

let c = Cons(4, Rc::clone(&a));

println!(

"count after creating c = {}",

Rc::strong\_count(&a)

);

}

println!(

"count after c goes out of scope = {}",

Rc::strong\_count(&a)

);

}

Printing the reference count

At each point in the program where the reference count changes, we print the reference count, which we get by calling the Rc::strong\_count function. This function is named strong\_count rather than count because the Rc<T> type also has a weak\_count; we’ll see what weak\_count is used for in the “Preventing Reference Cycles: Turning an Rc<T> into a Weak<T>” section.

This code prints the following:

count after creating a = 1

count after creating b = 2

count after creating c = 3

count after c goes out of scope = 2

We can see that the Rc<List> in a has an initial reference count of 1; then each time we call clone, the count goes up by 1. When c goes out of scope, the count goes down by 1. We don’t have to call a function to decrease the reference count like we have to call Rc::clone to increase the reference count: the implementation of the Drop trait decreases the reference count automatically when an Rc<T> value goes out of scope.

What we can’t see in this example is that when b and then a go out of scope at the end of main, the count is then 0, and the Rc<List> is cleaned up completely. Using Rc<T> allows a single value to have multiple owners, and the count ensures that the value remains valid as long as any of the owners still exist.

Via immutable references, Rc<T> allows you to share data between multiple parts of your program for reading only. If Rc<T> allowed you to have multiple mutable references too, you might violate one of the borrowing rules discussed in Chapter 4: multiple mutable borrows to the same place can cause data races and inconsistencies. But being able to mutate data is very useful! In the next section, we’ll discuss the interior mutability pattern and the RefCell<T> type that you can use in conjunction with an Rc<T> to work with this immutability restriction.

RefCell<T> and the Interior Mutability Pattern

Interior mutability is a design pattern in Rust that allows you to mutate data even when there are immutable references to that data; normally, this action is disallowed by the borrowing rules. To mutate data, the pattern uses unsafe code inside a data structure to bend Rust’s usual rules that govern mutation and borrowing. Unsafe code indicates to the compiler that we’re checking the rules manually instead of relying on the compiler to check them for us; we will discuss unsafe code more in Chapter 19.

We can use types that use the interior mutability pattern only when we can ensure that the borrowing rules will be followed at runtime, even though the compiler can’t guarantee that. The unsafe code involved is then wrapped in a safe API, and the outer type is still immutable.

Let’s explore this concept by looking at the RefCell<T> type that follows the interior mutability pattern.

Enforcing Borrowing Rules at Runtime with RefCell<T>

Unlike Rc<T>, the RefCell<T> type represents single ownership over the data it holds. So, what makes RefCell<T> different from a type like Box<T>? Recall the borrowing rules you learned in Chapter 4:

* At any given time, you can have either (but not both) one mutable reference or any number of immutable references.
* References must always be valid.

With references and Box<T>, the borrowing rules’ invariants are enforced at compile time. With RefCell<T>, these invariants are enforced at runtime. With references, if you break these rules, you’ll get a compiler error. With RefCell<T>, if you break these rules, your program will panic and exit.

The advantages of checking the borrowing rules at compile time are that errors will be caught sooner in the development process, and there is no impact on runtime performance because all the analysis is completed beforehand. For those reasons, checking the borrowing rules at compile time is the best choice in the majority of cases, which is why this is Rust’s default.

The advantage of checking the borrowing rules at runtime instead is that certain memory-safe scenarios are then allowed, where they would’ve been disallowed by the compile-time checks. Static analysis, like the Rust compiler, is inherently conservative. Some properties of code are impossible to detect by analyzing the code: the most famous example is the Halting Problem, which is beyond the scope of this book but is an interesting topic to research.

Because some analysis is impossible, if the Rust compiler can’t be sure the code complies with the ownership rules, it might reject a correct program; in this way, it’s conservative. If Rust accepted an incorrect program, users wouldn’t be able to trust in the guarantees Rust makes. However, if Rust rejects a correct program, the programmer will be inconvenienced, but nothing catastrophic can occur. The RefCell<T> type is useful when you’re sure your code follows the borrowing rules but the compiler is unable to understand and guarantee that.

Similar to Rc<T>, RefCell<T> is only for use in single-threaded scenarios and will give you a compile-time error if you try using it in a multithreaded context. We’ll talk about how to get the functionality of RefCell<T> in a multithreaded program in Chapter 16.

Here is a recap of the reasons to choose Box<T>, Rc<T>, or RefCell<T>:

* Rc<T> enables multiple owners of the same data; Box<T> and RefCell<T> have single owners.
* Box<T> allows immutable or mutable borrows checked at compile time; Rc<T> allows only immutable borrows checked at compile time; RefCell<T> allows immutable or mutable borrows checked at runtime.
* Because RefCell<T> allows mutable borrows checked at runtime, you can mutate the value inside the RefCell<T> even when the RefCell<T> is immutable.

Mutating the value inside an immutable value is the interior mutability pattern. Let’s look at a situation in which interior mutability is useful and examine how it’s possible.

Interior Mutability: A Mutable Borrow to an Immutable Value

A consequence of the borrowing rules is that when you have an immutable value, you can’t borrow it mutably. For example, this code won’t compile:

fn main() {

let x = 5;

let y = &mut x;

}

If you tried to compile this code, you’d get the following error:

error[E0596]: cannot borrow `x` as mutable, as it is not declared

as mutable

--> src/main.rs:3:13

|

2 | let x = 5;

| - help: consider changing this to be mutable: `mut x`

3 | let y = &mut x;

| ^^^^^^ cannot borrow as mutable

However, there are situations in which it would be useful for a value to mutate itself in its methods but appear immutable to other code. Code outside the value’s methods would not be able to mutate the value. Using RefCell<T> is one way to get the ability to have interior mutability, but RefCell<T> doesn’t get around the borrowing rules completely: the borrow checker in the compiler allows this interior mutability, and the borrowing rules are checked at runtime instead. If you violate the rules, you’ll get a panic! instead of a compiler error.

Let’s work through a practical example where we can use RefCell<T> to mutate an immutable value and see why that is useful.

A Use Case for Interior Mutability: Mock Objects

Sometimes during testing a programmer will use a type in place of another type, in order to observe particular behavior and assert it’s implemented correctly. This placeholder type is called a test double. Think of it in the sense of a “stunt double” in filmmaking, where a person steps in and substitutes for an actor to do a particular tricky scene. Test doubles stand in for other types when we’re running tests. Mock objects are specific types of test doubles that record what happens during a test so you can assert that the correct actions took place.

Rust doesn’t have objects in the same sense as other languages have objects, and Rust doesn’t have mock object functionality built into the standard library as some other languages do. However, you can definitely create a struct that will serve the same purposes as a mock object.

Here’s the scenario we’ll test: we’ll create a library that tracks a value against a maximum value and sends messages based on how close to the maximum value the current value is. This library could be used to keep track of a user’s quota for the number of API calls they’re allowed to make, for example.

Our library will only provide the functionality of tracking how close to the maximum a value is and what the messages should be at what times. Applications that use our library will be expected to provide the mechanism for sending the messages: the application could put a message in the application, send an email, send a text message, or something else. The library doesn’t need to know that detail. All it needs is something that implements a trait we’ll provide called Messenger. Listing 15-20 shows the library code:

src/lib.rs

pub trait Messenger {

fn send(&self, msg: &str); 1

}

pub struct LimitTracker<'a, T: Messenger> {

messenger: &'a T,

value: usize,

max: usize,

}

impl<'a, T> LimitTracker<'a, T>

where

T: Messenger,

{

pub fn new(messenger: &'a T, max: usize) -> LimitTracker<'a, T> {

LimitTracker {

messenger,

value: 0,

max,

}

}

pub fn set\_value(&mut self, value: usize) { 2

self.value = value;

let percentage\_of\_max = self.value as f64 / self.max as f64;

if percentage\_of\_max >= 1.0 {

self.messenger.send("Error: You are over your quota!");

} else if percentage\_of\_max >= 0.9 {

self.messenger

.send(

"Urgent warning: You've used up over 90% of your quota!"

);

} else if percentage\_of\_max >= 0.75 {

self.messenger

.send("Warning: You've used up over 75% of your quota!");

}

}

}

A library to keep track of how close a value is to a maximum value and warn when the value is at certain levels

One important part of this code is that the Messenger trait has one method called send that takes an immutable reference to self and the text of the message 1. This trait is the interface our mock object needs to implement so that the mock can be used in the same way a real object is. The other important part is that we want to test the behavior of the set\_value method on the LimitTracker 2. We can change what we pass in for the value parameter, but set\_value doesn’t return anything for us to make assertions on. We want to be able to say that if we create a LimitTracker with something that implements the Messenger trait and a particular value for max, when we pass different numbers for value, the messenger is told to send the appropriate messages.

We need a mock object that, instead of sending an email or text message when we call send, will only keep track of the messages it’s told to send. We can create a new instance of the mock object, create a LimitTracker that uses the mock object, call the set\_value method on LimitTracker, and then check that the mock object has the messages we expect. Listing 15-21 shows an attempt to implement a mock object to do just that, but the borrow checker won’t allow it:

src/lib.rs

#[cfg(test)]

mod tests {

use super::\*;

1 struct MockMessenger {

2 sent\_messages: Vec<String>,

}

impl MockMessenger {

3 fn new() -> MockMessenger {

MockMessenger {

sent\_messages: vec![],

}

}

}

4 impl Messenger for MockMessenger {

fn send(&self, message: &str) {

5 self.sent\_messages.push(String::from(message));

}

}

#[test]

6 fn it\_sends\_an\_over\_75\_percent\_warning\_message() {

let mock\_messenger = MockMessenger::new();

let mut limit\_tracker = LimitTracker::new(

&mock\_messenger,

100

);

limit\_tracker.set\_value(80);

assert\_eq!(mock\_messenger.sent\_messages.len(), 1);

}

}

An attempt to implement a MockMessenger that isn’t allowed by the borrow checker

This test code defines a MockMessenger struct 1 that has a sent\_messages field with a Vec of String values 2 to keep track of the messages it’s told to send. We also define an associated function new 3 to make it convenient to create new MockMessenger values that start with an empty list of messages. We then implement the Messenger trait for MockMessenger 4 so we can give a MockMessenger to a LimitTracker. In the definition of the send method 5, we take the message passed in as a parameter and store it in the MockMessenger list of sent\_messages.

In the test, we’re testing what happens when the LimitTracker is told to set value to something that is more than 75 percent of the max value 6. First, we create a new MockMessenger, which will start with an empty list of messages. Then we create a new LimitTracker and give it a reference to the new MockMessenger and a max value of 100. We call the set\_value method on the LimitTracker with a value of 80, which is more than 75 percent of 100. Then we assert that the list of messages that the MockMessenger is keeping track of should now have one message in it.

However, there’s one problem with this test, as shown here:

error[E0596]: cannot borrow `self.sent\_messages` as mutable, as it is behind a `&` reference

--> src/lib.rs:58:13

|

2 | fn send(&self, msg: &str);

| ----- help: consider changing that to be a mutable reference: `&mut self`

...

58 | self.sent\_messages.push(String::from(message));

| ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ `self` is a `&` reference, so the data it refers to cannot be borrowed as mutable

We can’t modify the MockMessenger to keep track of the messages, because the send method takes an immutable reference to self. We also can’t take the suggestion from the error text to use &mut self instead, because then the signature of send wouldn’t match the signature in the Messenger trait definition (feel free to try and see what error message you get).

This is a situation in which interior mutability can help! We’ll store the sent\_messages within a RefCell<T>, and then the send method will be able to modify sent\_messages to store the messages we’ve seen. Listing 15-22 shows what that looks like:

src/lib.rs

#[cfg(test)]

mod tests {

use super::\*;

use std::cell::RefCell;

struct MockMessenger {

sent\_messages: RefCell<Vec<String>>,1

}

impl MockMessenger {

fn new() -> MockMessenger {

MockMessenger {

sent\_messages: RefCell::new(vec![]),2

}

}

}

impl Messenger for MockMessenger {

fn send(&self, message: &str) {

self.sent\_messages.borrow\_mut().push(String::from(message));3

}

}

#[test]

fn it\_sends\_an\_over\_75\_percent\_warning\_message() {

--snip--

assert\_eq!(mock\_messenger.sent\_messages.borrow().len(), 1);4

}

}

Using RefCell<T> to mutate an inner value while the outer value is considered immutable

The sent\_messages field is now of type RefCell<Vec<String>> 1 instead of Vec<String>. In the new function, we create a new RefCell<Vec<String>> instance around the empty vector 2.

For the implementation of the send method, the first parameter is still an immutable borrow of self, which matches the trait definition. We call borrow\_mut on the RefCell<Vec<String>> in self.sent\_messages 3 to get a mutable reference to the value inside the RefCell<Vec<String>>, which is the vector. Then we can call push on the mutable reference to the vector to keep track of the messages sent during the test.

The last change we have to make is in the assertion: to see how many items are in the inner vector, we call borrow on the RefCell<Vec<String>> to get an immutable reference to the vector 4.

Now that you’ve seen how to use RefCell<T>, let’s dig into how it works!

Keeping Track of Borrows at Runtime with RefCell<T>

When creating immutable and mutable references, we use the & and &mut syntax, respectively. With RefCell<T>, we use the borrow and borrow\_mut methods, which are part of the safe API that belongs to RefCell<T>. The borrow method returns the smart pointer type Ref<T>, and borrow\_mut returns the smart pointer type RefMut<T>. Both types implement Deref, so we can treat them like regular references.

The RefCell<T> keeps track of how many Ref<T> and RefMut<T> smart pointers are currently active. Every time we call borrow, the RefCell<T> increases its count of how many immutable borrows are active. When a Ref<T> value goes out of scope, the count of immutable borrows goes down by one. Just like the compile-time borrowing rules, RefCell<T> lets us have many immutable borrows or one mutable borrow at any point in time.

If we try to violate these rules, rather than getting a compiler error as we would with references, the implementation of RefCell<T> will panic at runtime. Listing 15-23 shows a modification of the implementation of send in Listing 15-22. We’re deliberately trying to create two mutable borrows active for the same scope to illustrate that RefCell<T> prevents us from doing this at runtime.

src/lib.rs

impl Messenger for MockMessenger {

fn send(&self, message: &str) {

let mut one\_borrow = self.sent\_messages.borrow\_mut();

let mut two\_borrow = self.sent\_messages.borrow\_mut();

one\_borrow.push(String::from(message));

two\_borrow.push(String::from(message));

}

}

Creating two mutable references in the same scope to see that RefCell<T> will panic

We create a variable one\_borrow for the RefMut<T> smart pointer returned from borrow\_mut. Then we create another mutable borrow in the same way in the variable two\_borrow. This makes two mutable references in the same scope, which isn’t allowed. When we run the tests for our library, the code in Listing 15-23 will compile without any errors, but the test will fail:

---- tests::it\_sends\_an\_over\_75\_percent\_warning\_message stdout ----

thread 'main' panicked at 'already borrowed: BorrowMutError', src/lib.rs:60:53

note: run with `RUST\_BACKTRACE=1` environment variable to display a backtrace

Notice that the code panicked with the message already borrowed: BorrowMutError. This is how RefCell<T> handles violations of the borrowing rules at runtime.

Choosing to catch borrowing errors at runtime rather than compile time, as we’ve done here, means you’d potentially be finding mistakes in your code later in the development process: possibly not until your code was deployed to production. Also, your code would incur a small runtime performance penalty as a result of keeping track of the borrows at runtime rather than compile time. However, using RefCell<T> makes it possible to write a mock object that can modify itself to keep track of the messages it has seen while you’re using it in a context where only immutable values are allowed. You can use RefCell<T> despite its trade-offs to get more functionality than regular references provide.

Allowing Multiple Owners of Mutable Data with Rc<T> and RefCell<T>

A common way to use RefCell<T> is in combination with Rc<T>. Recall that Rc<T> lets you have multiple owners of some data, but it only gives immutable access to that data. If you have an Rc<T> that holds a RefCell<T>, you can get a value that can have multiple owners and that you can mutate!

For example, recall the cons list example in Listing 15-18 where we used Rc<T> to allow multiple lists to share ownership of another list. Because Rc<T> holds only immutable values, we can’t change any of the values in the list once we’ve created them. Let’s add in RefCell<T> to gain the ability to change the values in the lists. Listing 15-24 shows that by using a RefCell<T> in the Cons definition, we can modify the value stored in all the lists:

src/main.rs

#[derive(Debug)]

enum List {

Cons(Rc<RefCell<i32>>, Rc<List>),

Nil,

}

use crate::List::{Cons, Nil};

use std::cell::RefCell;

use std::rc::Rc;

fn main() {

1 let value = Rc::new(RefCell::new(5));

2 let a = Rc::new(Cons(Rc::clone(&value), Rc::new(Nil)));

let b = Cons(Rc::new(RefCell::new(3)), Rc::clone(&a));

let c = Cons(Rc::new(RefCell::new(4)), Rc::clone(&a));

3 \*value.borrow\_mut() += 10;

println!("a after = {:?}", a);

println!("b after = {:?}", b);

println!("c after = {:?}", c);

}

Using Rc<RefCell<i32>> to create a List that we can mutate

We create a value that is an instance of Rc<RefCell<i32>> and store it in a variable named value 1 so we can access it directly later. Then we create a List in a with a Cons variant that holds value 2. We need to clone value so both a and value have ownership of the inner 5 value rather than transferring ownership from value to a or having a borrow from value.

We wrap the list a in an Rc<T> so when we create lists b and c, they can both refer to a, which is what we did in Listing 15-18.

After we’ve created the lists in a, b, and c, we want to add 10 to the value in value 3. We do this by calling borrow\_mut on value, which uses the automatic dereferencing feature we discussed in Chapter 5 (see the section “Where’s the -> Operator?”) to dereference the Rc<T> to the inner RefCell<T> value. The borrow\_mut method returns a RefMut<T> smart pointer, and we use the dereference operator on it and change the inner value.

When we print a, b, and c, we can see that they all have the modified value of 15 rather than 5:

a after = Cons(RefCell { value: 15 }, Nil)

b after = Cons(RefCell { value: 3 }, Cons(RefCell { value: 15 }, Nil))

c after = Cons(RefCell { value: 4 }, Cons(RefCell { value: 15 }, Nil))

This technique is pretty neat! By using RefCell<T>, we have an outwardly immutable List value. But we can use the methods on RefCell<T> that provide access to its interior mutability so we can modify our data when we need to. The runtime checks of the borrowing rules protect us from data races, and it’s sometimes worth trading a bit of speed for this flexibility in our data structures. Note that RefCell<T> does not work for multithreaded code! Mutex<T> is the thread-safe version of RefCell<T> and we’ll discuss Mutex<T> in Chapter 16.

Reference Cycles Can Leak Memory

Rust’s memory safety guarantees make it difficult, but not impossible, to accidentally create memory that is never cleaned up (known as a memory leak). Preventing memory leaks entirely is not one of Rust’s guarantees, meaning memory leaks are memory safe in Rust. We can see that Rust allows memory leaks by using Rc<T> and RefCell<T>: it’s possible to create references where items refer to each other in a cycle. This creates memory leaks because the reference count of each item in the cycle will never reach 0, and the values will never be dropped.

Creating a Reference Cycle

Let’s look at how a reference cycle might happen and how to prevent it, starting with the definition of the List enum and a tail method in Listing 15-25:

src/main.rs

use crate::List::{Cons, Nil};

use std::cell::RefCell;

use std::rc::Rc;

#[derive(Debug)]

enum List {

1 Cons(i32, RefCell<Rc<List>>),

Nil,

}

impl List {

2 fn tail(&self) -> Option<&RefCell<Rc<List>>> {

match self {

Cons(\_, item) => Some(item),

Nil => None,

}

}

}

A cons list definition that holds a RefCell<T> so we can modify what a Cons variant is referring to.

We’re using another variation of the List definition from Listing 15-5. The second element in the Cons variant is now RefCell<Rc<List>> 1, meaning that instead of having the ability to modify the i32 value as we did in Listing 15-24, we want to modify the List value a Cons variant is pointing to. We’re also adding a tail method 2 to make it convenient for us to access the second item if we have a Cons variant.

In Listing 15-26, we’re adding a main function that uses the definitions in Listing 15-25. This code creates a list in a and a list in b that points to the list in a. Then it modifies the list in a to point to b, creating a reference cycle. There are println! statements along the way to show what the reference counts are at various points in this process.

src/main.rs

fn main() {

1 let a = Rc::new(Cons(5, RefCell::new(Rc::new(Nil))));

println!("a initial rc count = {}", Rc::strong\_count(&a));

println!("a next item = {:?}", a.tail());

2 let b = Rc::new(Cons(10, RefCell::new(Rc::clone(&a))));

println!("a rc count after b creation = {}", Rc::strong\_count(&a));

println!("b initial rc count = {}", Rc::strong\_count(&b));

println!("b next item = {:?}", b.tail());

3 if let Some(link) = a.tail() {

4 \*link.borrow\_mut() = Rc::clone(&b);

}

println!("b rc count after changing a = {}", Rc::strong\_count(&b));

println!("a rc count after changing a = {}", Rc::strong\_count(&a));

// Uncomment the next line to see that we have a cycle;

// it will overflow the stack

// println!("a next item = {:?}", a.tail());

}

Creating a reference cycle of two List values pointing to each other.

We create an Rc<List> instance holding a List value in the variable a with an initial list of 5, Nil 1. We then create an Rc<List> instance holding another List value in the variable b that contains the value 10 and points to the list in a 2.

We modify a so it points to b instead of Nil, creating a cycle. We do that by using the tail method to get a reference to the RefCell<Rc<List>> in a, which we put in the variable link 3. Then we use the borrow\_mut method on the RefCell<Rc<List>> to change the value inside from an Rc<List> that holds a Nil value to the Rc<List> in b 4.

When we run this code, keeping the last println! commented out for the moment, we’ll get this output:

a initial rc count = 1

a next item = Some(RefCell { value: Nil })

a rc count after b creation = 2

b initial rc count = 1

b next item = Some(RefCell { value: Cons(5, RefCell { value: Nil }) })

b rc count after changing a = 2

a rc count after changing a = 2

The reference count of the Rc<List> instances in both a and b are 2 after we change the list in a to point to b. At the end of main, Rust drops the variable b, which decreases the reference count of the b Rc<List> instance from 2 to 1. The memory that Rc<List> has on the heap won’t be dropped at this point, because its reference count is 1, not 0. Then Rust drops a, which decreases the reference count of the a Rc<List> instance from 2 to 1 as well. This instance’s memory can’t be dropped either, because the other Rc<List> instance still refers to it. The memory allocated to the list will remain uncollected forever. To visualize this reference cycle, we’ve created a diagram in Figure 15-4.

[f15004.eps]

* + - * 1. A reference cycle of lists a and b pointing to each other

If you uncomment the last println! and run the program, Rust will try to print this cycle with a pointing to b pointing to a and so forth until it overflows the stack.

Compared to a real-world program, the consequences creating a reference cycle in this example aren’t very dire: right after we create the reference cycle, the program ends. However, if a more complex program allocated lots of memory in a cycle and held onto it for a long time, the program would use more memory than it needed and might overwhelm the system, causing it to run out of available memory.

Creating reference cycles is not easily done, but it’s not impossible either. If you have RefCell<T> values that contain Rc<T> values or similar nested combinations of types with interior mutability and reference counting, you must ensure that you don’t create cycles; you can’t rely on Rust to catch them. Creating a reference cycle would be a logic bug in your program that you should use automated tests, code reviews, and other software development practices to minimize.

Another solution for avoiding reference cycles is reorganizing your data structures so that some references express ownership and some references don’t. As a result, you can have cycles made up of some ownership relationships and some non-ownership relationships, and only the ownership relationships affect whether or not a value can be dropped. In Listing 15-25, we always want Cons variants to own their list, so reorganizing the data structure isn’t possible. Let’s look at an example using graphs made up of parent nodes and child nodes to see when non-ownership relationships are an appropriate way to prevent reference cycles.

Preventing Reference Cycles Using Weak<T>

So far, we’ve demonstrated that calling Rc::clone increases the strong\_count of an Rc<T> instance, and an Rc<T> instance is only cleaned up if its strong\_count is 0. You can also create a weak reference to the value within an Rc<T> instance by calling Rc::downgrade and passing a reference to the Rc<T>. Strong references are how you can share ownership of an Rc<T> instance. Weak references don’t express an ownership relationship, and their count doesn’t affect when an Rc<T> instance is cleaned up. They won’t cause a reference cycle because any cycle involving some weak references will be broken once the strong reference count of values involved is 0.

When you call Rc::downgrade, you get a smart pointer of type Weak<T>. Instead of increasing the strong\_count in the Rc<T> instance by 1, calling Rc::downgrade increases the weak\_count by 1. The Rc<T> type uses weak\_count to keep track of how many Weak<T> references exist, similar to strong\_count. The difference is the weak\_count doesn’t need to be 0 for the Rc<T> instance to be cleaned up.

Because the value that Weak<T> references might have been dropped, to do anything with the value that a Weak<T> is pointing to, you must make sure the value still exists. Do this by calling the upgrade method on a Weak<T> instance, which will return an Option<Rc<T>>. You’ll get a result of Some if the Rc<T> value has not been dropped yet and a result of None if the Rc<T> value has been dropped. Because upgrade returns an Option<Rc<T>>, Rust will ensure that the Some case and the None case are handled, and there won’t be an invalid pointer.

As an example, rather than using a list whose items know only about the next item, we’ll create a tree whose items know about their children items and their parent items.

Creating a Tree Data Structure: a Node with Child Nodes

To start, we’ll build a tree with nodes that know about their child nodes. We’ll create a struct named Node that holds its own i32 value as well as references to its children Node values:

src/main.rs

use std::cell::RefCell;

use std::rc::Rc;

#[derive(Debug)]

struct Node {

value: i32,

children: RefCell<Vec<Rc<Node>>>,

}

We want a Node to own its children, and we want to share that ownership with variables so we can access each Node in the tree directly. To do this, we define the Vec<T> items to be values of type Rc<Node>. We also want to modify which nodes are children of another node, so we have a RefCell<T> in children around the Vec<Rc<Node>>.

Next, we’ll use our struct definition and create one Node instance named leaf with the value 3 and no children, and another instance named branch with the value 5 and leaf as one of its children, as shown in Listing 15-27:

src/main.rs

fn main() {

let leaf = Rc::new(Node {

value: 3,

children: RefCell::new(vec![]),

});

let branch = Rc::new(Node {

value: 5,

children: RefCell::new(vec![Rc::clone(&leaf)]),

});

}

Creating a leaf node with no children and a branch node with leaf as one of its children

We clone the Rc<Node> in leaf and store that in branch, meaning the Node in leaf now has two owners: leaf and branch. We can get from branch to leaf through branch.children, but there’s no way to get from leaf to branch. The reason is that leaf has no reference to branch and doesn’t know they’re related. We want leaf to know that branch is its parent. We’ll do that next.

Adding a Reference from a Child to Its Parent

To make the child node aware of its parent, we need to add a parent field to our Node struct definition. The trouble is in deciding what the type of parent should be. We know it can’t contain an Rc<T>, because that would create a reference cycle with leaf.parent pointing to branch and branch.children pointing to leaf, which would cause their strong\_count values to never be 0.

Thinking about the relationships another way, a parent node should own its children: if a parent node is dropped, its child nodes should be dropped as well. However, a child should not own its parent: if we drop a child node, the parent should still exist. This is a case for weak references!

So instead of Rc<T>, we’ll make the type of parent use Weak<T>, specifically a RefCell<Weak<Node>>. Now our Node struct definition looks like this:

src/main.rs

use std::cell::RefCell;

use std::rc::{Rc, Weak};

#[derive(Debug)]

struct Node {

value: i32,

parent: RefCell<Weak<Node>>,

children: RefCell<Vec<Rc<Node>>>,

}

A node will be able to refer to its parent node but doesn’t own its parent. In Listing 15-28, we update main to use this new definition so the leaf node will have a way to refer to its parent, branch:

src/main.rs

fn main() {

let leaf = Rc::new(Node {

value: 3,

1 parent: RefCell::new(Weak::new()),

children: RefCell::new(vec![]),

});

2 println!("leaf parent = {:?}", leaf.parent.borrow().upgrade());

let branch = Rc::new(Node {

value: 5,

3 parent: RefCell::new(Weak::new()),

children: RefCell::new(vec![Rc::clone(&leaf)]),

});

4 \*leaf.parent.borrow\_mut() = Rc::downgrade(&branch);

5 println!("leaf parent = {:?}", leaf.parent.borrow().upgrade());

}

A leaf node with a weak reference to its parent node branch

Creating the leaf node looks similar to Listing 15-27 with the exception of the parent field: leaf starts out without a parent, so we create a new, empty Weak<Node> reference instance 1.

At this point, when we try to get a reference to the parent of leaf by using the upgrade method, we get a None value. We see this in the output from the first println! statement 2:

leaf parent = None

When we create the branch node, it will also have a new Weak<Node> reference in the parent field 3, because branch doesn’t have a parent node. We still have leaf as one of the children of branch. Once we have the Node instance in branch, we can modify leaf to give it a Weak<Node> reference to its parent 4. We use the borrow\_mut method on the RefCell<Weak<Node>> in the parent field of leaf, and then we use the Rc::downgrade function to create a Weak<Node> reference to branch from the Rc<Node> in branch.

When we print the parent of leaf again 5, this time we’ll get a Some variant holding branch: now leaf can access its parent! When we print leaf, we also avoid the cycle that eventually ended in a stack overflow like we had in Listing 15-26; the Weak<Node> references are printed as (Weak):

leaf parent = Some(Node { value: 5, parent: RefCell { value: (Weak) },

children: RefCell { value: [Node { value: 3, parent: RefCell { value: (Weak) },

children: RefCell { value: [] } }] } })

The lack of infinite output indicates that this code didn’t create a reference cycle. We can also tell this by looking at the values we get from calling Rc::strong\_count and Rc::weak\_count.

Visualizing Changes to strong\_count and weak\_count

Let’s look at how the strong\_count and weak\_count values of the Rc<Node> instances change by creating a new inner scope and moving the creation of branch into that scope. By doing so, we can see what happens when branch is created and then dropped when it goes out of scope. The modifications are shown in Listing 15-29:

src/main.rs

fn main() {

let leaf = Rc::new(Node {

value: 3,

parent: RefCell::new(Weak::new()),

children: RefCell::new(vec![]),

});

1 println!(

"leaf strong = {}, weak = {}",

Rc::strong\_count(&leaf),

Rc::weak\_count(&leaf),

);

{

2 let branch = Rc::new(Node {

value: 5,

parent: RefCell::new(Weak::new()),

children: RefCell::new(vec![Rc::clone(&leaf)]),

});

\*leaf.parent.borrow\_mut() = Rc::downgrade(&branch);

3 println!(

"branch strong = {}, weak = {}",

Rc::strong\_count(&branch),

Rc::weak\_count(&branch),

);

4 println!(

"leaf strong = {}, weak = {}",

Rc::strong\_count(&leaf),

Rc::weak\_count(&leaf),

);

5 }

6 println!(

"leaf parent = {:?}",

leaf.parent.borrow().upgrade()

);

7 println!(

"leaf strong = {}, weak = {}",

Rc::strong\_count(&leaf),

Rc::weak\_count(&leaf),

);

}

Creating branch in an inner scope and examining strong and weak reference counts

After leaf is created, its Rc<Node> has a strong count of 1 and a weak count of 0 1. In the inner scope 2, we create branch and associate it with leaf, at which point when we print the counts 3, the Rc<Node> in branch will have a strong count of 1 and a weak count of 1 (for leaf.parent pointing to branch with a Weak<Node>). When we print the counts in leaf 4, we’ll see it will have a strong count of 2, because branch now has a clone of the Rc<Node> of leaf stored in branch.children, but will still have a weak count of 0.

When the inner scope ends 5, branch goes out of scope and the strong count of the Rc<Node> decreases to 0, so its Node is dropped. The weak count of 1 from leaf.parent has no bearing on whether or not Node is dropped, so we don’t get any memory leaks!

If we try to access the parent of leaf after the end of the scope, we’ll get None again 6. At the end of the program 7, the Rc<Node> in leaf has a strong count of 1 and a weak count of 0, because the variable leaf is now the only reference to the Rc<Node> again.

All of the logic that manages the counts and value dropping is built into Rc<T> and Weak<T> and their implementations of the Drop trait. By specifying that the relationship from a child to its parent should be a Weak<T> reference in the definition of Node, you’re able to have parent nodes point to child nodes and vice versa without creating a reference cycle and memory leaks.

Summary

This chapter covered how to use smart pointers to make different guarantees and trade-offs from those Rust makes by default with regular references. The Box<T> type has a known size and points to data allocated on the heap. The Rc<T> type keeps track of the number of references to data on the heap so that data can have multiple owners. The RefCell<T> type with its interior mutability gives us a type that we can use when we need an immutable type but need to change an inner value of that type; it also enforces the borrowing rules at runtime instead of at compile time.

Also discussed were the Deref and Drop traits, which enable a lot of the functionality of smart pointers. We explored reference cycles that can cause memory leaks and how to prevent them using Weak<T>.

If this chapter has piqued your interest and you want to implement your own smart pointers, check out “The Rustonomicon” at [https://doc.rust-lang.org/stable/nomicon](https://doc.rust-lang.org/stable/nomicon/) for more useful information.

Next, we’ll talk about concurrency in Rust. You’ll even learn about a few new smart pointers.