INTRO TO RUST LANG

SMART POINTERS AND UNSAFE

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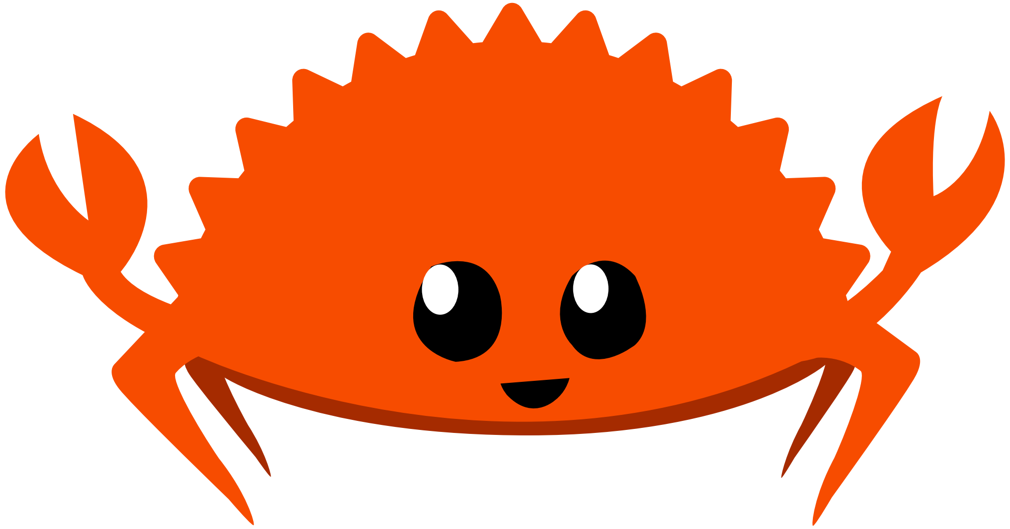
Week 10

🦀🦀🦀 We're in week 10! 🦀🦀🦀

Thank you all for sticking with us!



The Story So Far...

- We have covered all of the basic features of Rust, as well as many of the intermediate concepts
- If you are confident you understand the past 9 lectures, you can probably say you are proficient with Rust!
- Now for the *really* interesting stuff...

Finale

Here is the plan for the last ~3.5 lectures:

1. Smart Pointers and `unsafe`
2. Parallelism
3. Concurrency
4. Macros

Epilogue

As much as we'd love to dive deep into each of these topics in depth, we simply do not have time.

However...

- The goal of this course was never to feed you information
- The goal was to teach you the *core ideas* of Rust and how to think about it
- We hope that you will take the knowledge from this class and use it to explore more about this programming language *yourself*

Final Project

Here are the high-level details about the final project:

- We would like you to spend 6-8 hours developing a project of your choosing
    - *This means a good faith attempt at completing a project*
    - *This bound includes time spent planning and thinking!*
- Your project should incorporate 1 of the 4 advanced topics we will talk about
    - *We can make exceptions if you have a specific idea*
- *If you have less than 400 homework points, you will need to do this*
- More details to come later!

Smart Pointers

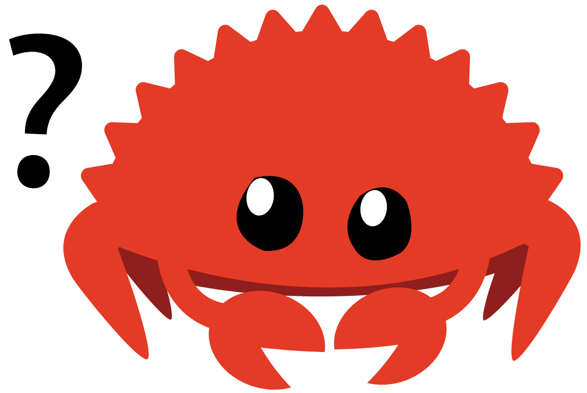
- `Rc<T>`
- `RefCell<T>`
- Interior Mutability
- Memory Leaks

Motivation for `Rc<T>`

Let's Make a List (again)

Let's say we wanted to make recursive-style list with `Box` like before

```
enum List {
  Cons(i32, Box<List>),
  Nil,
}

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

fn main() {
  let a = Cons(5, Box::new(Cons(10, Box::new(Nil))));
  let b = Cons(3, Box::new(a));
  let c = Cons(4, Box::new(a));
}
```



Cargo's Suggestion

```
   Compiling cons-list v0.1.0 (file:///projects/cons-list)
error[E0382]: use of moved value: `a`
  --> src/main.rs:11:30
   |
9  |     let a = Cons(5, Box::new(Cons(10, Box::new(Nil))));
   |         - move occurs because `a` has type `List`, which does not implement the `Copy` trait
10 |     let b = Cons(3, Box::new(a));
   |                              - value moved here
11 |     let c = Cons(4, Box::new(a));
   |                              ^ value used here after move
```

- `Cons` needs to **own** the data it holds (Recall: `Box`)
- Using `a` again when creating `c`, but `a` has been moved

References?

```
enum List<'a> {
    Cons(i32, &'a List<'a>),
    Nil,
}

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

fn main() {
  let nil = Nil;
  let a = Cons(10, &nil);
  let b = Cons(5, &a);
  let c = Cons(3, &a);
  let d = Cons(4, &a);
}
```

- While it can be done, it's a little messy
- Now we have to deal with lifetimes... gross

Introducing Rc<T>

```rust
enum List {
  Cons(i32, Rc<List>),
  Nil,
}

use crate::List::{Cons, Nil};
use std::rc::Rc;

fn main() {
  let a = Rc::new(Cons(5, Rc::new(Cons(10, Rc::new(Nil)))));
  let b = Cons(3, Rc::clone(&a));
  let c = Cons(4, Rc::clone(&a));
}
```

- Short for reference counter
- keeps track of the number of references to a value to determine dropping

When to use `Rc<T>`

- Allocate data on the heap for *multiple* parts of our program to *read*
  - Can’t determine at compile time which part will use the data last
- Only used for single threaded scenarios (We'll talk about `Arc<T>` next week)
- Use `Rc::new(T)` to create a new `Rc<T>`
  - `Rc::clone()` isn't a deep clone, it increments the ref counter

Cloning Demonstrated

```rust
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));
}
// Rc::strong_count(&a) is now 0, cleaned up and dropped
```

```
count after creating a = 1
count after creating b = 2
count after creating c = 3
count after c goes out of scope = 2
```

`Rc<T>` Recap

- Great for sharing **immutable** references without lifetimes
- Should be used when last variable to use the data is unknown
  - Otherwise, make that variable the owner and have everything borrow
- Provides almost no overhead
  - O(1) increment of counter
  - Potential allocation/de-allocation on heap

`RefCell<T>` and Interior Mutability

A safe abstraction over unsafe code™

First, `Cell<T>`

```rust
use std::cell::Cell;

let c1 = Cell::new(5i32);
c1.set(15i32);

let c2 = Cell::new(10i32);
c1.swap(&c2);

assert_eq!(10, c1.into_inner()); // consumes cell
assert_eq!(15, c2.get()); // returns copy of value
```

- Shareable, mutable container
- Move values in and out of cell
- Is used for `Copy` types
    - where copying or moving values isn't too resource intensive
- If an option, should always be used for low overhead

`RefCell<T>`

- Hold's sole ownership like `Box<T>`
- Allows borrow checker rules to be enforced at **runtime**
  - Interface with `.borrow()` or `borrow_mut()`
  - If borrowing rules are violated, `panic!`
- Typically used when Rust's conservative checking "gets in the way"
- It is **not** thread safe!
  - Use `Mutex<T>` instead

Interior Mutability

```
fn main() {
  let x = 5;
  let y = &mut x; // cannot borrow immutable x as mutable
}
```

- 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 wouldn't be able to mutate it
- This can be achieved with `RefCell<T>`

Interior Mutability with Mock Objects

```rust
pub trait Messenger {
    fn send(&self, msg: &str); // Note how this takes an &self NOT &mut self
}

pub struct LimitTracker<'a, T: Messenger> {
    messenger: &'a T,
    value: usize,
    max: usize,
}
```

- `LimitTracker` tracks a value against a maximum value and sends messages based on how close to the maximum value the current value is
- We want to mock a messenger for our limit tracker to keep track of messages for testing

Limit Tracker

```
impl<'a, T> LimitTracker<'a, T>
where
    T: Messenger,
{
    // --- snip ---
    pub fn set_value(&mut self, value: usize) {
        self.value = value;

        let percentage_of_max = self.value as f64 / self.max as f64;

        if percentage_of_max >= 1.0 {
            self.messenger.send("Error: You are over your quota!");
        } else if percentage_of_max >= 0.9 {
            self.messenger
                .send("Urgent warning: You've used up over 90% of your quota!");
        } else if percentage_of_max >= 0.75 {
            self.messenger
                .send("Warning: You've used up over 75% of your quota!");
        }
    }
}
```

Our Mock Messenger

```rust
struct MockMessenger {
  sent_messages: Vec<String>,
}

impl MockMessenger {
  fn new() -> MockMessenger {
    MockMessenger { sent_messages: vec![] }
  }
}

impl Messenger for MockMessenger {
  fn send(&self, message: &str) {
    self.sent_messages.push(String::from(message));
  }
}
```

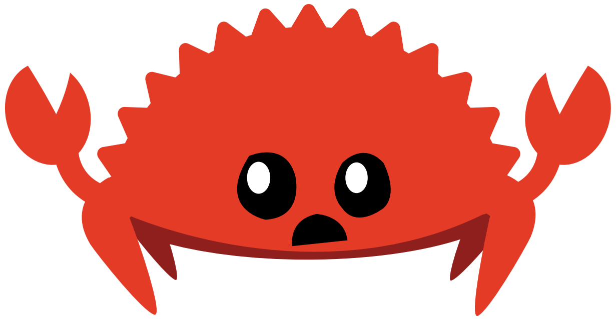
- This code won't compile! `self.sent_messages.push` requires `&mut self`

Let's Use Interior Mutability

```rust
use std::cell::RefCell;

struct MockMessenger {
  sent_messages: RefCell<Vec<String>>,
}

impl MockMessenger {
  fn new() -> MockMessenger {
    MockMessenger {
      sent_messages: RefCell::new(vec![]),
    }
  }
}

impl Messenger for MockMessenger {
  fn send(&self, message: &str) {
    self.sent_messages.borrow_mut().push(String::from(message));
  }
}
```

Managing Borrows

```
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));
  }
}
```



- We still use the `&` and `mut` syntax for `RefCell`
- `borrow` returns either a `Ref` or `RefMut` which implement `Deref`
    - This means coercion applies: treat them like normal references

What Makes Each Smart Pointer Unique

- `Rc<T>` - Enables multiple owners of the same data
- `Box<T>` - Allows immutable or mutable borrows that are checked at compile time
- `RefCell<T>` - Allows immutable/mutable borrows that are checked at runtime

Combining Smart Pointers: `Rc<RefCell<T>>`

```rust
#[derive(Debug)]
enum List {
  Cons(Rc<RefCell<i32>>, Rc<List>),
  Nil,
}
```

- Common type seen in Rust
- Enables multiple owners of mutable data (with runtime checks)
- Extremely powerful, but comes with some overhead

`Rc<RefCell<T>>` List

```rust
let value = Rc::new(RefCell::new(5));

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

let b = Cons(Rc::new(RefCell::new(3)), Rc::clone(&a));
let c = Cons(Rc::new(RefCell::new(4)), Rc::clone(&a));

*value.borrow_mut() += 10;

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

```
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))
```

Let's Try Another List

```rust
enum List {
  Cons(i32, RefCell<Rc<List>>),
  Nil,
}

impl List {
  fn tail(&self) -> Option<&RefCell<Rc<List>>> {
    match self {
      Cons(_, item) => Some(item),
      Nil => None,
    }
  }
}
```

- This implementation allows modifying the list structure instead of list values
- Now we have a function `tail` that gets the rest of our list

What Happens?

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

println!("a initial rc count = {}", Rc::strong_count(&a));
println!("a next item = {:?}", a.tail());

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

println!("a rc count after b creation = {}", Rc::strong_count(&a));
println!("b initial rc count = {}", Rc::strong_count(&b));
println!("b next item = {:?}", b.tail());

if let Some(link) = a.tail() {
  *link.borrow_mut() = Rc::clone(&b);
}

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

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

Answer

```
Exited with signal 6 (SIGABRT): abort program

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
a next item = Some(RefCell { value: Cons(10, RefCell { value: Cons(5, RefCell...
```

- We see that at the end we have a reference cycle!

Let's Look Closer

```
let a = Rc::new(Cons(5, RefCell::new(Rc::new(Nil))));
// a is Cons(5, Nil)

let b = Rc::new(Cons(10, RefCell::new(Rc::clone(&a))));
// b is Cons(10, a) = Cons(10, Cons(5, Nil))

if let Some(link) = a.tail() {
    // link is Nil (pointed to by a)
    *link.borrow_mut() = Rc::clone(&b);
    // link is now b = Cons(10, a)
}
// a = Cons(5, link) = Cons(5, b) = Cons(5, Cons(10, a))
// ^^^ reference cycle of a made!
```

- This can cause a memory leak!
  - `Rc` only frees when the `strong_count` is 0

Avoiding Reference Cycles

- We know `Rc::clone` increases the `strong_count`
- You can create a `Weak<T>` reference to a value with `Rc::downgrade`
  - This increases the `weak_count` and can be nonzero when the `Rc` is freed
- To ensure valid references, `Weak<T>` must be upgraded before any use
  - Returns an `Option<Rc<T>>`

`Weak<T>` Trees

```rust
use std::cell::RefCell;
use std::rc::{Rc, Weak};

#[derive(Debug)]
struct Node {
  value: i32,
  parent: RefCell<Weak<Node>>,
  children: RefCell<Vec<Rc<Node>>>,
}
```

Weak<T> Trees In Action

```rust
fn main() {
  let leaf = Rc::new(Node {
    value: 3,
    parent: RefCell::new(Weak::new()),
    children: RefCell::new(vec![]),
  });

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

  let branch = Rc::new(Node {
    value: 5,
    parent: RefCell::new(Weak::new()),
    children: RefCell::new(vec![Rc::clone(&leaf)]),
  });

  *leaf.parent.borrow_mut() = Rc::downgrade(&branch);

  println!("leaf parent = {:?}", leaf.parent.borrow().upgrade());
} // Tree is effectively dropped even with parent references!
```

Unsafe Rust

Into the Woods

So far, we've only seen code where memory safety is guaranteed at compile time.

- Rust has a second language hidden inside called *unsafe Rust*
- `unsafe` Rust does not enforce memory safety guarantees

Why `unsafe`?

- Static analysis is *conservative*
- By definition, it enforces *soundness* rather than *completeness*
- We need a way to tell the compiler: "Trust me, I know what I'm doing"
- Additionally, computer hardware is inherently unsafe

`unsafe` in 2024

- Rust's precise requirements for `unsafe` code are still being determined
- There's an entire book dedicated to `unsafe` Rust called the Rustonomicon

What is `unsafe`, really?

If you take anything away from today, it should be this:

Unsafe code is the mechanism Rust gives developers for taking advantage of invariants that, for whatever reason, the compiler cannot check.

- *Jon Gjengset, Rust for Rustaceans*

What `unsafe` is not

It's important to understand that `unsafe` is not a way to skirt the rules of Rust.

- Ownership
- Borrow Checking
- Lifetimes
- `unsafe` is a way to *enforce* these rules using reasoning beyond the compiler
- The onus is on *you* to ensure the code is **safe**

The `unsafe` Keyword

There are 2 ways to use the `unsafe` keyword in Rust. The first is marking a function as `unsafe`.

```rust
impl<T> SomeType<T> {
    pub unsafe fn decr(&self) {
        self.some_usize -= 1;
    }
}
```

- Here, the `unsafe` keyword serves as a warning to the caller
- There may be additional invariants that must be upheld before calling `decr`

The `unsafe` Keyword

The second way is marking an expression as `unsafe`

```
impl<T> SomeType<T> {
    pub fn as_ref(&self) -> &T {
        unsafe { &*self.ptr }
    }
}
```

The `unsafe` Contracts

```rust
impl<T> SomeType<T> {
    pub unsafe fn decr(&self) {
        self.some_usize -= 1;
    }

    pub fn as_ref(&self) -> &T {
        unsafe { &*self.ptr }
    }
}
```

- The first requires the caller to be careful
- The second assumes the caller *was* careful when invoking `decr`

The `unsafe` Contracts

Imagine is `SomeType<T>` was really `Rc<T>`:

```rust
impl<T> Rc<T> {
    pub unsafe fn decr(&self) {
        self.count -= 1;
    }

    pub fn as_ref(&self) -> &T {
        unsafe { &*self.ptr }
    }
}
```

- When `self.count` hits 0, `T` is dropped
- What if someone else constructed `&T` without incrementing `count`?
- As long as nobody corrupts the reference count, this code is safe

Unsafe Superpowers

So what can we do with `unsafe`?

With `unsafe`, we get 5 superpowers! We can:

1. Call an `unsafe` function or method
2. Access or modify a mutable static variable
3. Implement an `unsafe` trait
4. Access fields of `union`s

Unsafe Superpowers

1. Call an `unsafe` function or method
2. Access or modify a mutable static variable
3. Implement an `unsafe` trait
4. Access fields of `union`s

These 4 things aren't all that interesting, so why the big fuss?

THE UNSAFE SUPERPOWER

The **biggest** superpower of all is superpower 5!

- **Dereference a raw pointer**
- 🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀 🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀 🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀 `That's it` 🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀 🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀 🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀🦀
- *But honestly, it's enough to wreak all sorts of havoc*

Raw Pointers

Unsafe Rust has 2 types of Raw Pointers:

- `*const T` is an immutable raw pointer
- `*mut T` is a mutable raw pointer
- *Note that the asterisk* `*` *is part of the type name*
- *Immutable* here means that the pointer can't directly be reassigned after being dereferenced

Pointers vs References

Raw Pointers themselves are allowed to do some special things:

- They can ignore borrowing rules by have multiple immutable and mutable pointers to the same location
- They are not guaranteed to point to valid memory
- They don't implement any automatic cleanup
- They can be `NULL` 💀

Raw Pointers Example

Here's an example of creating raw pointers.

```rust
let mut num = 5;

let r1 = &num as *const i32;
let r2 = &mut num as *mut i32;
```

- We have both an immutable and mutable pointer pointing to the same place
- Notice how there is no `unsafe` keyword here
- We can *create* raw pointers safely, we just cannot *dereference* them

Raw Pointers Example

Here is another example of creating a raw pointer.

```rust
let address: usize = 0xDEADBEEF;
let r = address as *const i32;
```

- We construct a pointer to (likely) invalid memory
- Again, no `unsafe` keyword necessary here!

Raw Pointers and `unsafe`

Let's actually try and dereference these pointers.

```rust
let mut num = 5;

let r1 = &num as *const i32;
let r2 = &mut num as *mut i32;

unsafe {
    println!("r1 is: {}", *r1);
    println!("r2 is: {}", *r2);
}
```

- There's no undefined behavior here? Right?
- *Right?*
- 🦀 Right 🦀

Calling `unsafe` Functions

Calling `unsafe` functions is similar, we must call them in an `unsafe` block.

```rust
unsafe fn dangerous() {}

fn main() {
    unsafe {
        dangerous();
    }
}
```

- We would get an error if we called `dangerous` without the `unsafe` block!

Using `extern` Functions

Sometimes, we might need to interact with code from another language.

- Rust has the keyword `extern` that facilitates the use of a *Foreign Function Interface (FFI)*
- Since other languages will not have Rust's safety guarantees, we will have no idea if they are safe to call or not!

`extern "C"`

Let's see how we would set up integration with the `abs` function from the C standard library.

```rust
extern "C" {
    fn abs(input: i32) -> i32;
}

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

- The `"C"` defines the *Application Binary Interface (ABI)* that the external function uses
- We have no idea if `abs` is doing what it is supposed to be doing, so it is on us as the programmer to ensure safety

`extern "C"`

We can also use `extern` to allow other languages to call Rust code!

```rust
#[no_mangle]
pub extern "C" fn call_from_c() {
    println!("Just called a Rust function from C!");
}
```

- Note how the usage of `extern` does not require `unsafe`

Mutable Static Variables

We can mutate global static variables with `unsafe`.

```rust
static mut COUNTER: u32 = 0;

fn add_to_count(inc: u32) {
    unsafe {
        COUNTER += inc;
    }
}

fn main() {
    add_to_count(3);

    unsafe {
        println!("COUNTER: {}", COUNTER);
    }
}
```

Last 2 Superpowers

The last 2 superpowers are implementing an `unsafe` trait and accessing fields of a `union`.

- We may or may not cover `unsafe` traits next week
  - (specifically `Send` and `Sync`)
- `union`s are primarily used to interface with unions in C code

How to use `unsafe` code

- Just because a function contains `unsafe` code doesn't mean need to mark the entire function as `unsafe`
- Often, we want to write `unsafe` code that we *know* is actually safe
- A common abstraction is to wrap `unsafe` code in a safe function

`split_at_mut`

Let's take a look at `split_at_mut` from the standard library.

```rust
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]);
```

`split_at_mut`

```rust
fn split_at_mut(values: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]);
```

- Unfortunately, we cannot write this function using only safe Rust
- How would we attempt it?

`split_at_mut` Implementation

```rust
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..])
}
```

- What is the issue with this?
- Can you figure out what the compiler will tell us *just by looking at the function signature*?

`split_at_mut` Compiler Error

If we try to compile, we get this error:

```
$ cargo run
   Compiling unsafe-example v0.1.0 (file:///projects/unsafe-example)
error[E0499]: cannot borrow `*values` as mutable more than once at a time
 --> src/main.rs:6:31
  |
1 | fn split_at_mut(values: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]) {
  |                         - let's call the lifetime of this reference `'1`
...
6 |     (&mut values[..mid], &mut values[mid..])
  |     --------------------------^^^^^^--------
  |     |     |                   |
  |     |     |                   second mutable borrow occurs here
  |     |     first mutable borrow occurs here
  |     returning this value requires that `*values` is borrowed for `'1`

For more information about this error, try `rustc --explain E0499`.
error: could not compile `unsafe-example` due to previous error
```

`split_at_mut` Implementation

Let's try again with `unsafe`.

```
use std::slice;

fn split_at_mut(values: &mut [i32], mid: usize) -> (&mut [i32], &mut [i32]) {
    let len = values.len();
    let ptr = values.as_mut_ptr();

    assert!(mid <= len);

    unsafe {
        (
            slice::from_raw_parts_mut(ptr, mid),
            slice::from_raw_parts_mut(ptr.add(mid), len - mid),
        )
    }
}
```

`split_at_mut` Implementation

```rust
unsafe {
    (
        slice::from_raw_parts_mut(ptr, mid),
        slice::from_raw_parts_mut(ptr.add(mid), len - mid),
    )
}
```

- `from_raw_parts_mut` is `unsafe` because it takes a raw pointer and must trust it is valid
- Since the `ptr` came from a valid slice, we know it is valid!

`from_raw_parts_mut` Safety Contract

Here is the actual safety contract for `from_raw_parts_mut`:

```
/// # Safety
///
/// Behavior is undefined if any of the following conditions are violated:
///
/// * `data` must be [valid] for both reads and writes for `len * mem::size_of::<T>()` many bytes,
///   and it must be properly aligned. This means in particular:
///
///     * The entire memory range of this slice must be contained within a single allocated object!
///       Slices can never span across multiple allocated objects.
///     * `data` must be non-null and aligned even for zero-length slices. One
///       reason for this is that enum layout optimizations may rely on references
///       (including slices of any length) being aligned and non-null to distinguish
///       them from other data. You can obtain a pointer that is usable as `data`
///       for zero-length slices using [`NonNull::dangling()`].
///
/// * `data` must point to `len` consecutive properly initialized values of type `T`.
///
/// * The memory referenced by the returned slice must not be accessed through any other pointer
///   (not derived from the return value) for the duration of lifetime `'a`.
///   Both read and write accesses are forbidden.
///
/// * The total size `len * mem::size_of::<T>()` of the slice must be no larger than `isize::MAX`,
///   and adding that size to `data` must not "wrap around" the address space.
///   See the safety documentation of [`pointer::offset`].
```

`from_raw_parts_mut` Misuse

We could very easily misuse `from_raw_parts_mut` if we wanted to…

```rust
use std::slice;

let address: usize = 0xDEADBEEF;
let r = address as *mut i32;

let values: &[i32] = unsafe { slice::from_raw_parts_mut(r, 10000) };
```

- This might seem ridiculous, but when you always assume your code is safe…

With Great Power...

What could go wrong?

- Probably not much, *if* you're careful
- If you do get something wrong though...
- With `unsafe`, you hold great responsibility

Undefined Behavior

If you get something wrong, your program now has *undefined behavior*.

- It should go without saying that undefined behavior is bad
- The best scenario is you get a visible error:
  - Segfaults
  - Unexpected deadlocks
  - Garbled output
  - Panics that *don't* exit the program
- The worst case...

Undefined Behavior

The worst case scenario is that your program state is invisibly corrupted.

- Data races
- Transactions aren't atomic
- Backups are corrupted
- Security leaks
- Schrödinger’s Bug

Interacting with Safe Rust

Unsafe code is not defined.

- The compiler could eliminate the entire `unsafe` block if it wanted to
- It could also miscompile surrounding, safe code!
- In a lot of ways, `unsafe` Rust is far worse than C/C++ because it assumes *all* of Rust's safety guarantees

Safe `unsafe`: Valid References

You may recall that all references must be valid. A valid reference:

- must never dangle
- must always be aligned
- must always point to a valid value for their target type
- must either be immutably shared or mutably exclusive
- Plus more guarantees relating to lifetimes

Other Validity Requirements

Some primitive types have other guarantees:

- `bool` is 1 byte, but can only hold `0x00` or `0x01`
- `char` cannot hold a value above `char::MAX`
- Most Rust types cannot be constructed from uninitialized memory
- If Rust didn't enforce this, it wouldn't be able to make niche optimizations
  - `Option<&T>` is a good example
  - What if `Option<Option<bool>>` used `0x00` through `0x03`?
- It doesn't matter if Rust does make the optimization, all that matters is that it is *allowed* to whenever it wants

Even More Validity Requirements

Here are some even more requirements:

- Owned Pointer Types (like `Box` and `Vec`) are subject to optimizations assuming the pointer to memory is not shared or aliased anywhere
- You can never assume the layout of a type when casting
- All code must prepared to handle `panic!`s and *stack unwinding*
- Stack unwinding drops everything in the current scope, returns from that scope, drops everything in that scope, returns, etc…
- All variables are subject to something called the *Drop Check*, and if you drop something incorrectly, you might cause undefined behavior

Fighting with `unsafe`

That was a lot, right?

- Remember that it is very possible to write safe `unsafe` code
- A lot of the time, it isn't actually that difficult
- Being careful is half the battle
- Being absolutely sure you actually need `unsafe` is the other half

Working with `unsafe`

It is tempting to reason about unsafety *locally*.

- Consider whether the code in the `unsafe` block is safe in the context of both the rest of the codebase, and in the context of other people using your library
- Encapsulate the unsafety as best you can
- Read and write documentation!
- Use tools like `Miri` to verify your code!
- **Make sure to formally reason about your program**

Recap: `unsafe`

- With `unsafe`, we have great powers
- But we must accept the responsibility of leveraging those powers
- There are consequences to writing unsafe `unsafe` code
- `unsafe` is a way to *promise* to the compiler that the indicated code is safe

Next Lecture: Parallelism

- Thanks for coming!