Lecture 7

Smart Pointers and Trait Objects

From PLQ: # What Fn type should my function take?

more accepting ↑

FnOnce: implemented by all functions

FnMut: implemented by functions that don't move data out of their environment

Fn: implemented by functions that don't mutate or move data from their environment

FnOnce: can be called once

FnMut: can be called infinitely, as long as you have a mutable reference

Fn: can be called infinitely

more useful ↓

Writing a function that takes another function? Take the highest `Fn…` trait you can that still suits your needs

Quiz from last time

```
struct Foo<'a> {
    bar: &'a i32
}

fn baz<'a, 'b>(f: &'a Foo<'b>) -> &’??? i32
{ /* omitted */ }


fn baz<'a, 'b>(f: &'a &'b i32) -> &’??? i32
{ /* omitted */ }
```

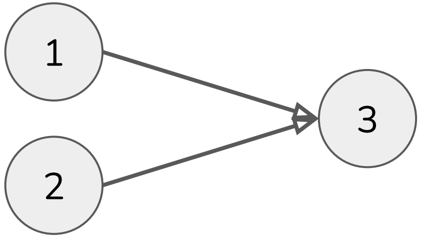
Will this compile? No!

Two separate lifetimes in the input

- can’t infer output lifetime without ambiguity

Smart Pointers

Back to lists




```rust
struct List<T> {
  value: T,
  next: Option<Box<List<T>>>,
}

impl<T> List<T> {
  fn new(value: T) -> Self {
    List { value, next: None }
  }
}
```

```rust
fn main() {
  let mut list1 = List::new(1);
  let mut list2 = List::new(2);
  let node = Box::new(List::new(3));

  list1.next = Some(node);
  list2.next = Some(node);
}
```

```
error[E0382]: use of moved value: `node`
 --> list.rs:17:21
16 |   list1.next = Some(node);
   |                     ---- value moved here
17 |   list2.next = Some(node);
   |                     ^^^^ value used here after move
```

Why `as_mut()`?

```
pub fn as_mut<T>(&mut Option<T>) -> Option<&mut T>

pub fn as_ref<T>(&Option<T>) -> Option<&T>


let mut x: Option<u32> = Some(5);
let as_mut_ref: &mut Option<u32> = &mut x;

as_mut_ref.unwrap() = 7; // bad!

*as_mut_ref.as_mut().unwrap() = 7; // good!
```

type: `u32` (not assignable)

type: `&mut u32` (assignable)

Recall: why ownership?

1. Each value in Rust has an *owner*.
2. There can only be one owner at a time.
3. When the owner goes out of scope, the value will be dropped.

One owner -> statically determine when values can be destructed (when their owner is no longer accessible)

Is multiple ownership a sin?

Yes—why?

- How to tell when values should be destructed?

track at run-time instead of compile-time

No—why?

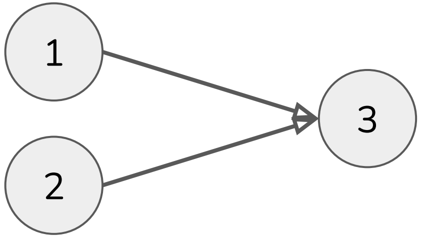
- Sometimes real programs need shared ownership

Multiple ownership via reference counting

Reasoning about shared ownership statically is impossible -> record ownership data at runtime

- When a clone is made, increment `refcount`
- When an owner goes out of scope, decrement `refcount`
- When `refcount` is 0, deallocate

Rc: reference counted pointer



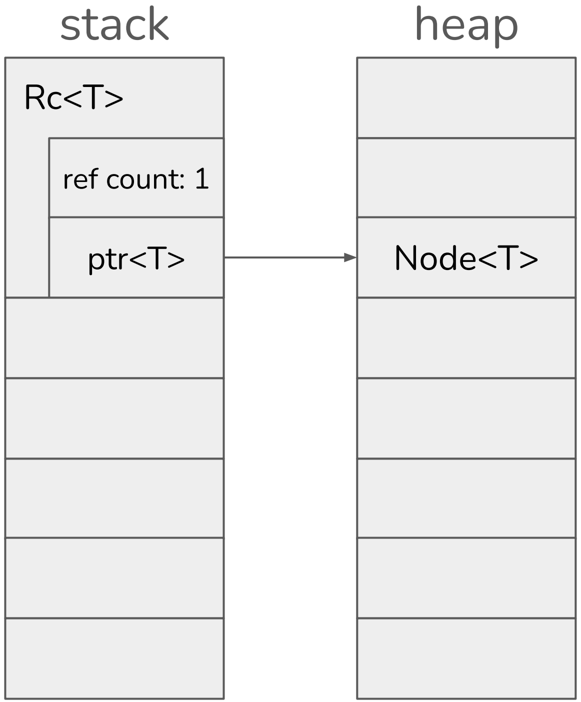

```
use std::rc::Rc;

struct List<T> {
  value: T,
  next: Option<Rc<List<T>>>,
}
impl<T> List<T> {
  fn new(value: T) -> Self {
    List { value, next: None }
  }
}
```

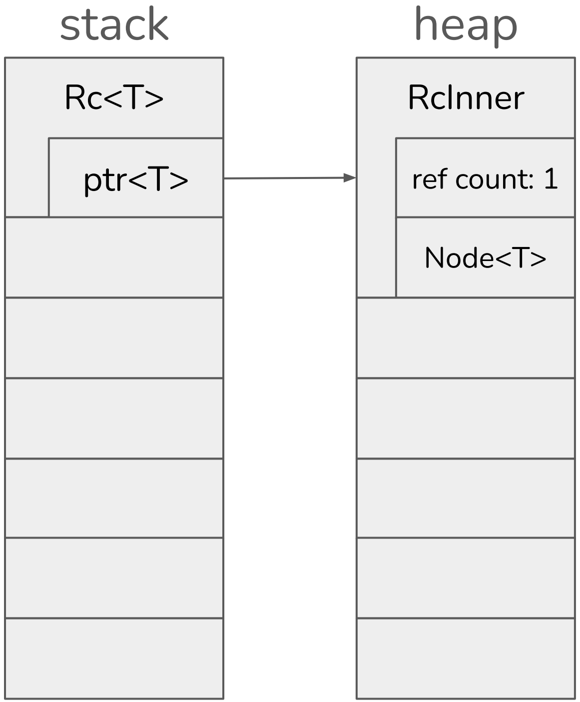
```
fn main() {
  let mut list1 = List::new(1);
  let mut list2 = List::new(2);
  let node = Rc::new(List::new(3));

  list1.next = Some(Rc::clone(&node));
  list2.next = Some(Rc::clone(&node));
}
```

three owners of `Node(3)`

> Rc allows shared ownership by figuring out when to run destructor at run-time

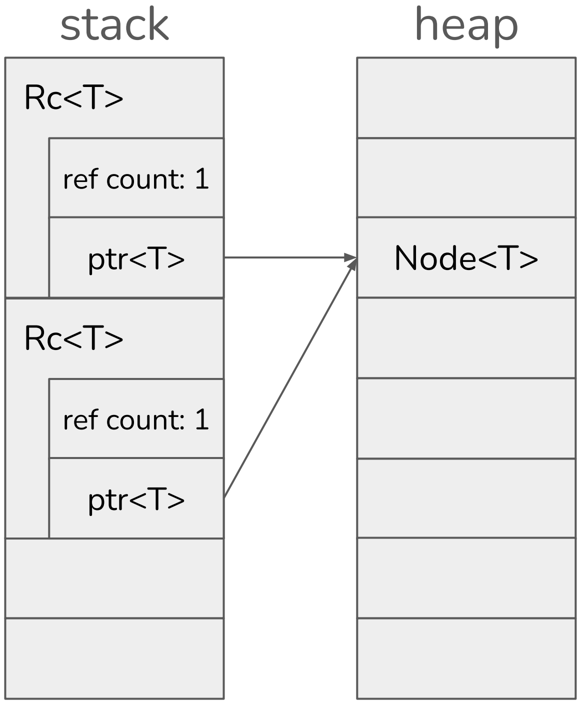
How to implement Rc?

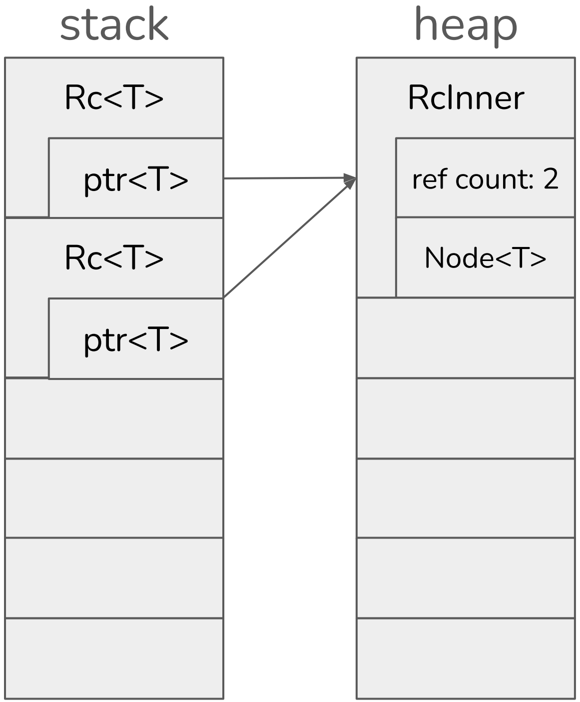




A or B?

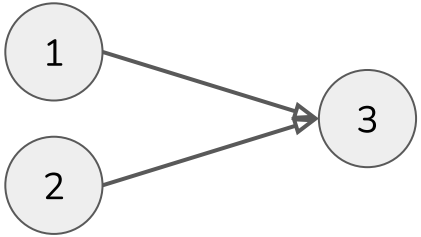
How to implement Rc?





A or B?

Rc: reference counted pointer




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

struct List<T> {
  value: T,
  next: Option<Rc<List<T>>>,
}
impl<T> List<T> {
  fn new(value: T) -> Self {
    List { value, next: None }
  }
}
```

```rust
fn main() {
  let mut list1 = List::new(1);
  let mut list2 = List::new(2);
  let node = Rc::new(List::new(3));

  list1.next = Some(Rc::clone(&node));
  list2.next = Some(Rc::clone(&node));
}
```

But, `next` isn't a field on `Rc`?

Types that are like pointers implement the `Deref` trait so that they can be treated like the inner type

auto-deref:

`&mut Rc<List<i32>>`

⇩

`&mut List<i32>`

https://doc.rust-lang.org/std/ops/trait.Deref.html

Using Rc as Garbage Collection

Don't want to think about ownership? Just wrap everything in Rc

- Don't actually do this, but it works in theory

Rc summary

Some data structures require shared ownership

- Reuse data instead of cloning
- graphs, linked lists, DAGs

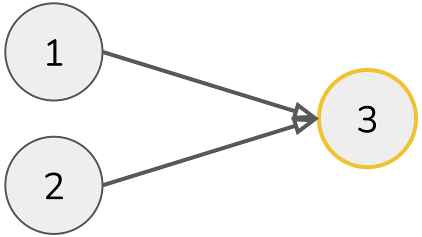
Reasoning about shared ownership statically is impossible -> record ownership data at runtime

- When a clone is made, increment `refcount`
- When an owner goes out of scope, decrement `refcount`
- When `refcount` is 0, deallocate

`Rc` is a primitive form of garbage collection

- e.g. in Python, every value is reference counted

Shared ownership woes

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use std::rc::Rc;

struct List<T> {
  value: T,
  next: Option<Rc<List<T>>>,
}
impl<T> List<T> {
  fn new(value: T) -> Self {
    List { value, next: None }
  }
}
```

```rust
fn main() {
  let mut list1 = List::new(1);
  let mut list2 = List::new(2);
  let node = Rc::new(List::new(3));

  list1.next = Some(Rc::clone(&node));
  list2.next = Some(Rc::clone(&node));
  node.value = 5;
}
```

```
error[E0594]: cannot assign to data in an `Rc`
 --> refcell.rs:22:3
   |
22 |   node.value = 5;
   |   ^^^^^^^^^^^^^^ cannot assign
   |
```

Shared ownership ≠ shared mutability

Since Rced values can have multiple owners, never safe to give out mutable references to inner type T!

How to mutate shared values without violating Rust's safety guarantees? (no dangling references)

```
fn main() {
    let mut v1: Rc<Vec<i32>> = Rc::new(vec![1]);
    let mut v2: Rc<Vec<i32>> = Rc::copy(&v1);

    let v1_mut: &mut Vec<i32> = &mut *v1;
    let v2_mut: &mut Vec<i32> = &mut *v2);
    let first: &mut i32  = &mut v2_mut[0];
    v1_mut.pop();

    println!("{:?}", first); // dangling!
}
```

Shared ownership ≠ shared mutability

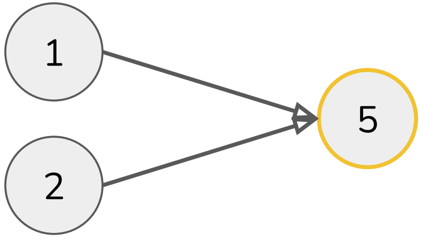
Since Rced values can have multiple owners, never safe to give out mutable references to inner type T!

How to mutate shared values without violating Rust's safety guarantees? (no dangling references)

```
fn main() {
    let mut v1: Rc<Vec<i32>> = Rc::new(vec![1]);
    let mut v2: Rc<Vec<i32>> = Rc::copy(&v1);

    v1_mut.pop();

    println!("{:?}", first); // dangling!
}
```

Rc: shared ownership -> dynamically track owners
??: shared mutation -> dynamically track mutators

List Attempt #3




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

struct List<T> {
  value: T,
  next: Option<Rc<RefCell<List<T>>>>,
}
impl<T> List<T> {
  fn new(value: T) -> Self {
    List { value, next: None }
  }
}
```

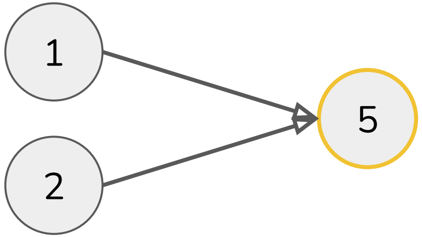
```rust
fn main() {
  let mut list1 = List::new(1);
  let mut list2 = List::new(2);
  let node =
Rc::new(RefCell::new(List::new(3)));

  list1.next = Some(Rc::clone(&node));
  list2.next = Some(Rc::clone(&node));
  node.borrow_mut().value = 5;
}
```

✅

`RefCell`: count mutable/immutable references at run-time

- create new refs with `borrow`/`borrow_mut`
- panics if more than one `mut` OR `mut` and non-`mut` at same time

List Attempt #3




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

struct List<T> {
  value: T,
  next: Option<Rc<RefCell<List<T>>>>,
}
impl<T> List<T> {
  fn new(value: T) -> Self {
    List { value, next: None }
  }
}
```

```rust
fn main() {
  let mut list1 = List::new(1);
  let mut list2 = List::new(2);
  let node =
Rc::new(RefCell::new(List::new(3)));

  list1.next = Some(Rc::clone(&node));
  list2.next = Some(Rc::clone(&node));
  let ref1 = node.borrow_mut();
```

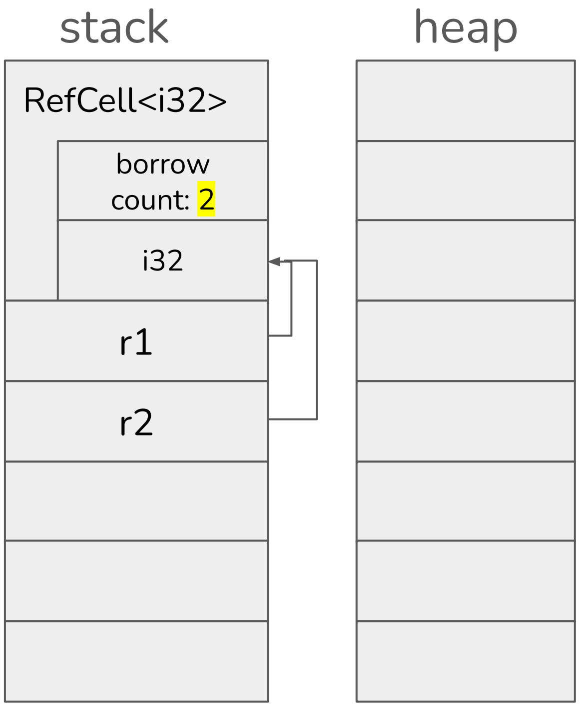
`RefCell`: count mutable/immutable references at run-time

- create new refs with `borrow`/`borrow_mut`
- panics if more than one `mut` OR `mut` and non-`mut` at same time

compiles✅… panics 😔

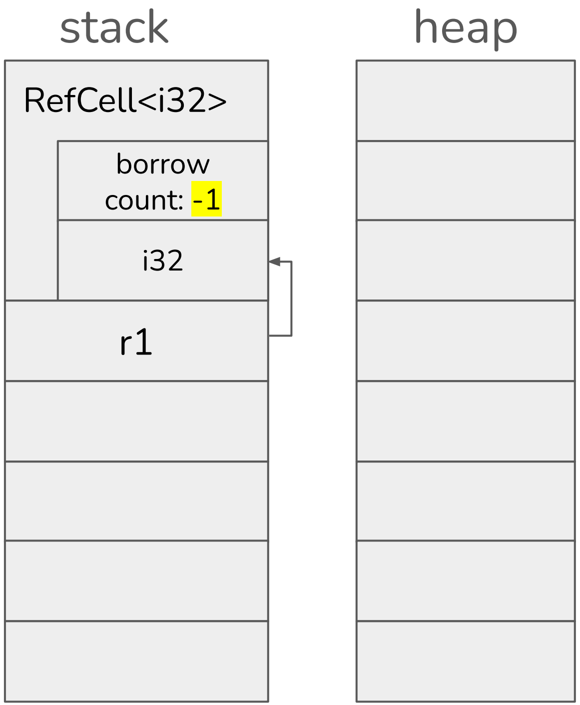
RefCell is not a reference/pointer!

```
use std::cell::RefCell;
fn main() {
    let v = RefCell::new(1);
    let r1 = v.borrow();
    let r2 = v.borrow();
}
```



RefCell is not a reference/pointer!

```
use std::cell::RefCell;
fn main() {
    let v = RefCell::new(1);
    let r1 = v.borrow_mut();
}
```



`RefCell` recapped

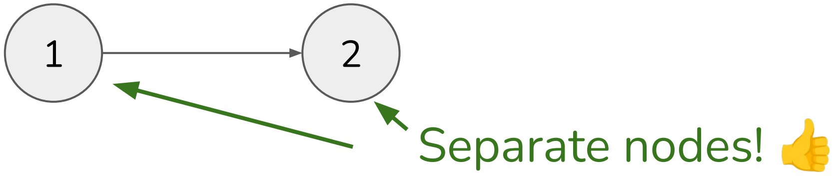
Sometimes the compiler can't statically verify that you follow the reference rules

- Offload reference checking to run-time

The Rule of References:

- **At any given time, you can have either one mutable reference or any number of immutable references.**
- References must always be valid.

Another RefCell example




```
struct List<T> {
  pub value: T,
  pub next: Option<Box<List<T>>>,
}

impl<T> List<T> {
  fn first(&mut self) -> &mut T { todo!() }
  fn last(&mut self)  -> &mut T { todo!() }
  fn ends(&mut self)  -> (&mut T, &mut T) {
    (self.first(), self.last())
  }
}
```

```
error[E0499]: cannot borrow `*self` as mutable more than once at a time
 --> partition_bad.rs:22:20
   |
21 |   fn ends(&mut self)  -> (&mut T, &mut T) {
22 |     (self.first(), self.last())
   |      ^^^^           ^^^^
   |      |              |
   |      |              second mutable borrow occurs here
   |      first mutable borrow occurs here
```

A quick aside on computability

Halting problem:

"Writing a program that decides whether a turing machine halts on a given input is impossible"

Rice's theorem:

"Statically deciding any non-trivial property of a program is impossible"

Things you can't decide just by looking at a program

- Does this program leak memory?
- Does this program have a use-after-free bug?
- Does this function always produce the same output as another function?
- Does this program have a race condition?

Rust and decidability

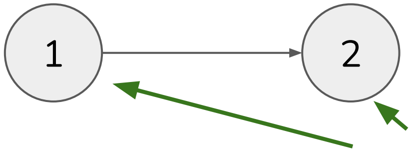
Programs Rust would like to disallow for you at compile time

- Multiple mutable references at the same time
- Reference pointing to invalid memory
- etc.

Pick One:

Unsound	**Incomplete**
• All valid programs are allowed👍 • Some invalid programs are allowed🚨	• Some valid programs aren’t allowed🚨 • All invalid programs aren’t allowed.👍

Another RefCell example



Separate nodes! 👍

Incomplete

- Some valid programs aren't allowed 🚨
- All invalid programs aren't allowed. 👍

```rust
  fn first(&mut self) -> &mut T { todo!() }
  fn last(&mut self)  -> &mut T { todo!() }
  fn ends(&mut self)  -> (&mut T, &mut T) {
    (self.first(), self.last())
  }
}
```

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error[E0499]: cannot borrow `*self` as mutable more than once at a time
 --> partition_bad.rs:22:20
   |
21 |    fn ends(&mut self)  -> (&mut T, &mut T) {
22 |      (self.first(), self.last())
   |       ^^^^          ^^^^
   |       |             |
   |       |             second mutable borrow occurs here
   |       first mutable borrow occurs here
```

A quick aside on computability

Halting problem:

"Writing a program that decides whether a turing machine halts on a given input is impossible"

↓

Rice's theorem:

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Things you can't decide just by looking at a program

- Does this program leak memory?
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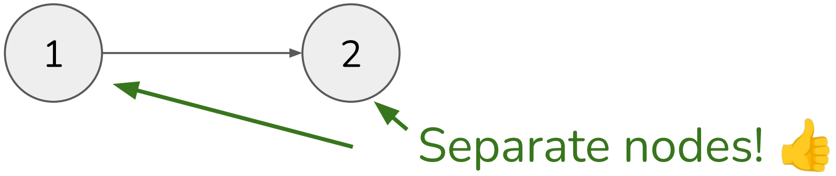
- Does this function always produce the same output as another function?
- Does this program have a race condition?

What about deciding dynamically (at run time)?

Another RefCell example




```rust
struct List<T> {
  pub value: T,
  pub next: Option<Box<List<T>>>,
}

impl<T> List<T> {
  fn first(&mut self) -> &mut T { todo!() }
  fn last(&mut self)  -> &mut T { todo!() }
  fn ends(&mut self)  -> (&mut T, &mut T) {
    (self.first(), self.last())
  }
}
```

```rust
use std::cell::RefCell;
use std::cell::RefMut;
struct List<T> {
  pub value: T,
  pub next: Option<Rc<RefCell<List<T>>>>,
}
impl<T> List<T> {
  fn first(&self) -> RefMut<T> { todo!() }
  fn last(&self) -> RefMut<T> { todo!() }
  fn ends(&self) -> (RefMut<T>, RefMut<T>) {
    (self.first(), self.last())
  }
}
```

✅

`&T`/`&mut T` -> checked by compiler

`Ref<T>`/`RefMut<T>` checked dynamically by `RefCell`

`RefCell`/`Rc` takeaways

When needing multiple ownership, often use
`Rc<RefCell<T>>`

It's not that the compiler isn't smart enough to validate your program, it's that **it's impossible to validate your program**

Inherited mutability vs. interior mutability

```
struct Person {
   name: String
}
```

```
fn clear_name(p: &mut Person) {
   p.name = name;
}
```

Inherited mutability: can't mutate the fields unless you have a `&mut` reference

```
fn clear_name(p: &RefCell<Person>) {
   p.borrow_mut().name = name;
}
```

Interior mutability: allows mutating even with a immutable reference (safety is checked by some other mechanism)

Trait Objects

New generic syntax:

Exactly the same

```rust
fn foo<T: Debug>(value: T) { todo!() }
```

```rust
fn foo(value: impl Debug) { todo!() }
```

Recall: No cost to use traits

```rust
trait Draw {
   fn draw(&self) -> String
}

struct Circle {
   radius: i32
}
impl Draw for Circle {
   fn draw(&self) -> String { todo!() }
}

struct Rect {
   size: (i32, i32),
}
impl Draw for Rect {
   fn draw(&self) -> String { todo!() }
}
```

```rust
fn show(shape: impl Draw) {
   println!("{}", shape.draw());
}

pub fn main() {
   show(Circle { radius: 1 });
   show(Rect { size: (1, 1) });
}
```

```
crate::show<Circle>:
        sub     rsp, 152
        mov     dword ptr [rsp + 12], edi
        ...

crate::show<Rect>:
        sub     rsp, 152
        mov     dword ptr [rsp + 12], edi
        ...
```

https://godbolt.org/z/n151dnK5q

Returning generics

```
fn make_drawable(is_circle: bool) -> impl Draw {
  if is_circle {
    Circle { radius: 1 }
  } else {
    Rect { size: (1, 1) }
  }
}
```

```
error[E0308]: `if` and `else` have incompatible types
 --> draw.rs:36:5
   |
33 | /   if is circle {
34 | |     Circle { radius: 1 }
   | |     -------------------- expected because of this
35 | |   } else {
36 | |     Rect { size: (1, 1) }
   | |     ^^^^^^^^^^^^^^^^^^^^^ expected `Circle`, found `Rect`
37 | |   }
   | |___- `if` and `else` have incompatible types
```

Returning generics

```rust
fn make_drawable() -> impl Draw {
  if rand::thread_rng().gen() {
    Circle { radius: 1 }
  } else {
    Rect { size: (1, 1) }
  }
}
```

Impossible to know whether `Circle` or `Rect` will be returned

```rust
pub fn main() {
 let s = make_drawable();
 println!("{}", std::mem::size_of_val(&s)); ???
}
```

```
error[E0308]: `if` and `else` have incompatible types
 --> draw.rs:36:5
   |
33 | /    if rand::thread rng().gen() {
34 | |      Circle { radius: 1 }
   | |      -------------------- expected because of this
35 | |    } else {
36 | |      Rect { size: (1, 1) }
   | |      ^^^^^^^^^^^^^^^^^^^^^ expected `Circle`, found `Rect`
37 | |    }
   | |___- `if` and `else` have incompatible types
```

Quick Quiz

```
fn foo<T: Draw>(_v: T) -> T {
    Circle { radius: 1 }
}
```

Is this program valid?

Quick Quiz

```
fn foo<T: Draw>(_v: T) -> T {
    Circle { radius: 1 }
}
```

Is this program valid?

No! Could be instantiated with `T=Rect` and then returning a `Circle` is improper

Trait Objects

```
fn make_drawable() -> impl Draw {
  if rand::thread_rng().gen() {
    Circle { radius: 1 }
  } else {
    Rect { size: (1, 1) }
  }
}
```

Generics have no run-time cost because we can resolve them at compile-time, but what if we can't?

Trait Objects

```
fn make_drawable() -> Box<dyn Draw> {
  if rand::thread_rng().gen() {
    Box::new(Circle { radius: 1 })
  } else {
    Box::new(Rect { size: (1, 1) })
  }
}
```

What type is in the box?

- don’t know, all we know is we can call `draw` on it

```
fn foo() {
  let s: Box<dyn Draw> = make_drawable();
  s.draw();
}
```

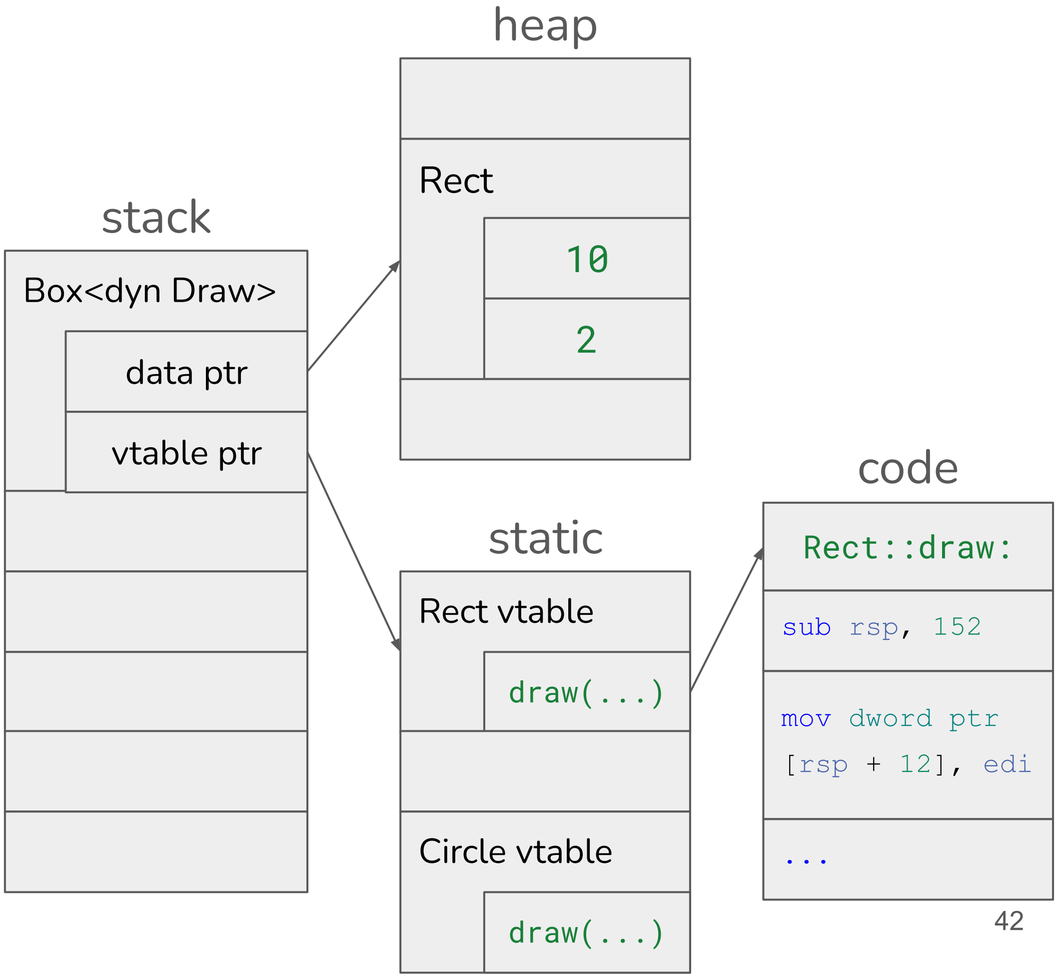
Working with trait objects

Unknown size: always behind a reference of some sort

- `Box<dyn Draw>`
- `&dyn Draw`
- `&mut dyn Draw`
- …

Trait object layout

```
pub fn main() {
  let rect = Rect { size: (1, 1) };
  let trait_obj: Box<dyn Draw> =
    Box::new(sq);
}
```



Cost of using trait objects

Normal function call

```
call    b15b6ba806fc18e4
```

Call of static address

- Can be inlined by compiler
- No branch misprediction

Trait object function call

load

```
mov     rax, qword ptr [rax + 24]
lea     rdi, [rsp + 16]
call    rax
```

Call of dynamic address

- Can’t be inlined by compiler
- Possible branch misprediction

https://godbolt.org/z/f8Gh7Tss7

Another example

```
fn show_all(v: Vec<&dyn Draw>) {
    for item in v {
        println!("{}", item.draw());
    }
}

fn main() {
 show_all(vec![
    Box::new(Circle { radius: 1 }),
    Box::new(Rect { size: (1, 1) })]);
}
```

`Vec` that has "different types" in it! (normally not allowed)

Allows implementing patterns from object oriented programming

Today's theme: offloading checks to run-time

Check at compile-time: no run-time performance penalty

- single ownership
- `&` and `&mut` references
- generics with `<T>`

Check at run-time: more flexibility

- multiple ownership with `Rc`
- `Ref` and `RefMut` references from `RefCell`
- generics with `dyn T`