Lifetimes, Function Types & More Ownership

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Outline

Why Do We Need Lifetimes?

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- Some subsection of the duration we can use the owning variable
- Construct of Rust's borrow checker, not checked at runtime!

Lifetimes Roughly Correspond To Scope

```
// Error: x isn't in scope
let x_ref1 = &x;

let x = String::from("hello");

let x_ref2 = &x;
take_ownership(x);

// Error: x was moved
let x_ref3 = &x;
```

Returning An Invalid Reference

```
fn make_string() -> &String {
    let s = String::from("hello");
    &s
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- Compiler knows lifetime of `make_string` will end once it returns, so reference won't be valid
- (but first we'd run into an issue about what lifetime the returned reference would have)

Fixing The Example: Use Moves

Just don't return a reference! Move semantics already avoid copying things on the heap when not necessary

```
fn make_string() -> String {
    String::from("hello")
}
```

Denoting Lifetimes

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&'a mut Ty
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- Not super common to need to denote explicitly, but sometimes necessary for:
  - Structs/Enums with references inside them
  - Functions taking in those structs/enums
  - Other, more funky functions

Explicit Lifetimes In Structs

```
struct Vertex<'a> {
    edges: Vec<&'a Edge<'a>>,
}
struct Edge<'a> {
    info: EdgeInfo,
    vertex: &'a Vertex<'a>,
}
```

Explicit Lifetimes In Function Signatures

```
fn bfs<'a>(
start_vertex: &'a Vertex<'a>,
max_depth: usize,
) -> Vec<&'a Vertex<'a>> {
    ...
}
```

Returning An Invalid Reference Revisited

```
fn make_string<'a>() -> &'a String {
    let s = String::from("hello");
    &s
}
```

The same underlying issue as before, made more obvious by the lifetime annotation.

Rules For Lifetimes In Function Signatures

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- any reference *must* have an annotated lifetime
- any reference being returned *must* have the same lifetime as an input, or be `'static`

```
fn f1<'a, 'b>(x: &'a i32, y: &'b i32) -> &'a i32 {
    // what goes here?
}
```

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- any reference *must* have an annotated lifetime
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fn f1<'a, 'b>(x: &'a i32, y: &'b i32) -> &'a i32 {
    // what goes here?
}
```

```
fn f2<'a, 'b>(x: &'a i32) -> &'b i32 {
    // what goes here?
}
```

Lifetime Elison

Certain patterns in Rust are very common:

```
// One input lifetime, return value is reference
fn f3<'a>(x: &'a i32) -> &'a i32 { ... }
// Multiple input lifetimes, return value is not reference
fn f4<'a, 'b, 'c>(x: &'a i32, y: &'b i32, z: &'c i32) -> i32 { ... }
```

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Certain patterns in Rust are very common:

```
// One input lifetime, return value is reference
fn f3<'a>(x: &'a i32) -> &'a i32 { ... }
// Multiple input lifetimes, return value is not reference
fn f4<'a, 'b, 'c>(x: &'a i32, y: &'b i32, z: &'c i32) -> i32 { ... }
```

So if it falls into one of these patterns, you don't have to explicitly write them!

```
fn g3(x: &i32) -> &i32 { ... }
fn g4(x: &i32, y: &i32, z: &i32) -> i32 { ... }
```

Lifetime Elison Example

```
fn make_string(allocator: &mut Vec<String>) -> &String {
    allocator.push(String::from("hello"));
    &allocator[allocator.len() - 1]
}
```

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fn make_string(allocator: &mut Vec<String>) -> &String {
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- Input and Output lifetimes elided to be the same

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}
```

- Input and Output lifetimes elided to be the same
- Valid reference returned via reference to original data

Sidenote: Loop Labels

```
'outer: for y in 0..5 {
    'inner: for x in 0..5 {
        if arr1[y][x] { break 'outer; }
        if arr2[x][y] { break 'inner; }
    }
}
```

Loop labels are not lifetimes—same syntax as lifetimes, and same sort of scope idea, but you can't actually make references with these names and have it make sense

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- "A bag of things that go together"
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  - Types, Traits
  - Constants, Static members,
  - Other modules!
- Defines a namespace

Modules Within a File

```
fn f() { ... }
mod foo {
    fn f() { ... }
}
```

Directory Structure *Is* Module Structure

```
src/
├── lib.rs
└── bar/
    ├── mod.rs (bar)
    ├── baz.rs (bar::baz)
    └── qux.rs (bar::qux)
```

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Alternatively,

```
src/
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├── bar.rs (bar)
└── bar/
    ├── baz.rs (bar::baz)
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```

Declaring File Modules

```
// In src/lib.rs:
mod bar;
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```
// In src/lib.rs:
mod bar;
```

```
// In the `bar` module:
mod baz;
mod qux;
```

Visibility

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We need to explicitly declare items as public using the `pub` keyword:

```
pub struct Foo {
    x: usize,
    pub y: usize,
}
pub enum Bar {
    Bar1,
    Bar2,
}
pub fn calculate(f: Foo) -> Bar { ... }

pub mod baz;
mod qux;
```

Using Modules

```
mod foo {
    fn f() { ... }
}
fn main() {
    foo::f();
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mod foo {
    fn f() { ... }
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Alternatively,

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use foo::f;
fn main() {
    f();
}
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Using Multiple Things At Once

```
use bar::{g, baz::h};
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use bar::{g, baz::h};
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```
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```

Useful for re-exports, collecting all useful includes into one “prelude”:

```
pub use crate::{
    bar::{g, baz::h},
    qux::*,
};
```

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- Every value has a type
- Functions are values! (sorry 15-122 stans)
- Allows us to pass in functions as arguments to other functions, which many other good languages do in some capacity

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Value of the function pointer type is either:

- A “function item” (named function in the code), or
- A closure that doesn’t capture (which is effectively the same)

Example: Using A Function Pointer

```
fn double(n: i32) -> i32 { 2 * n }
fn giveme_fnptr(f: fn(i32) -> i32) -> i32 {
    f(42)
}
fn test_fnptr() {
    assert_eq!(giveme_fnptr(double), 84);
}
```

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Closure Syntax

From https://doc.rust-lang.org/book/ch13-01-closures.html

```
fn  add_one_v1   (x: i32) -> i32 { x + 1 }
let add_one_v2 = |x: i32| -> i32 { x + 1 };
let add_one_v3 = |x|             { x + 1 };
let add_one_v4 = |x|               x + 1  ;
```

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let z = 5;
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```

This can't be done with functions! Will fail to compile:

```
fn f(x: i32) -> bool { z == x }
```

Consuming State With Closures

Sometimes, we *do* want to move a value into a closure:

```
let message = String::from("hello");
thread::spawn(move || {
    println!("{}", message);
});
```

Consuming State With Closures

Sometimes, we *do* want to move a value into a closure:

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let message = String::from("hello");
thread::spawn(move || {
    println!("{}", message);
});
```

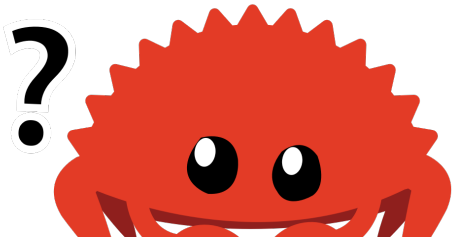
`move` keyword: anything that would be captured by reference is now captured by value (moved)

Things Closures Can't Be

- Recursive
- Generic
- In most cases, function pointers
  - If a closure doesn't capture anything from its environment, it can be coerced to a function pointer:

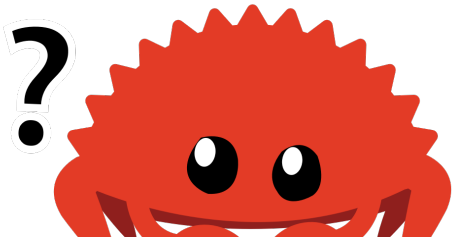
```
let x: fn(i32, i32) -> i32 = |x, y| x + y;
```

Type Of A Closure



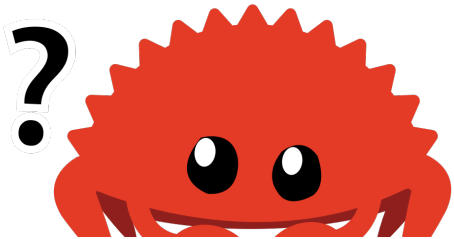
Type Of A Closure

- You can't write down their type!



Type Of A Closure

- You can't write down their type!
- Wait, so how can we take them as arguments??



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- More about this next lecture

`Fn` Trait

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- Can be called by shared reference
- Closure must:
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  - Not move any captured state out
- All (safe) function pointers also implement `Fn`

Example: Using `Fn`

```
fn giveme_fn1(f: impl Fn(i32) -> i32) -> i32 {
    f(42)
}
// Or, verbosely:
fn giveme_fn2<T: Fn(i32) -> i32>(f: T) -> i32 {
    f(42)
}
// Or, even more verbosely:
fn giveme_fn3<T>(f: T) -> i32
    where T: Fn(i32) -> i32
{
    f(42)
}
```

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FnMut Trait

```
let mut state = 0;
let fnmut_closure = |x| {
    state += x;
    state
};
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- Can be called by mutable reference
- Closure must not move any captured state out

Example: Using FnMut

```
fn giveme_fnmut(mut f: impl FnMut(i32) -> i32) -> i32 {
    let x = f(42);
    f(x)
}
assert_eq!(giveme_fnmut(fnmut_closure), 84);
```

Example: Using FnMut

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fn giveme_fnmut(mut f: impl FnMut(i32) -> i32) -> i32 {
    let x = f(42);
    f(x)
}
assert_eq!(giveme_fnmut(fnmut_closure), 84);
```

`FnOnce` Trait

```
let state = Box::new(42);
let fnonce_closure = move |x| {
    let y = x + *state;
    drop(state);
    y
};
```

`FnOnce` Trait

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let state = Box::new(42);
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```
let state = Box::new(42);
let fnonce_closure = move |x| {
    let y = x + *state;
    drop(state);
    y
};
```

- Can be called by taking ownership of the closure
- All closures implement this

Example: Using FnOnce

```
fn giveme_fnonce(f: impl FnOnce(i32) -> i32) -> i32 {
    let x = f(42);
    // let y = f(9 * 6); // Does not compile
    x
}
```

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  - `FnOnce`: "This can only be called 0 or 1 times because it may drop local state when called."

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  - `FnMut`: "This may modify local state, but doesn't result in any local state being dropped when called"
  - `FnOnce`: "This can only be called 0 or 1 times because it may drop local state when called."
- Anything higher on the list can be used as anything lower on the list

Next Time

- Polymorphism
- Traits & trait bounds
- Trait objects & dynamic dispatch

Homework: Sudoku Solver Using CPS

Tarball: https://rust-stuco.github.io/handouts/sudoku-handout.tgz
Handout PDF: https://rust-stuco.github.io/handouts/sudoku-writeup.pdf