Intro to Rust Lang

Closures and Iterators

Today: Closures and Iterators

- Closures
- Iterators
- Crate Highlights

Closures

What Is A Closure?

Closures are anonymous functions that can capture values from the scope in which they're defined.

- Known as lambdas in "lesser languages" 😉
- You can save closures in variables or pass them as arguments to other functions

Closure Syntax

```rust
let annotated_closure = |num: i32| -> i32 {
    num
};
```

- This should feel very similar to functions we've seen...
- Like normal variables, Rust can derive closure type annotations from context!

Closures Simplified

```
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  ;

let _ = add_one_v3(3);
let _ = add_one_v4(4);
```

- `v1` is the equivalent function
- We can remove type parameters in `v3`
    - This is similar to eliding the type parameter in `let v = Vec::new()`
- For `v4`, we can remove the `{}` since the body is only one line

How about this?

```
let example_closure = |x| x;

let s = example_closure(String::from("hello"));
let n = example_closure(5);
```

- How would we describe the type of `example_closure`?

Closure Types

```rust
let example_closure = |x| x;
let s = example_closure(String::from("hello"));
let n = example_closure(5);
```

```
error[E0308]: mismatched types
 --> src/main.rs:5:29
  |
5 |     let n = example_closure(5);
  |             --------------- ^- help: try using a conversion method: `.to_string()`
  |             |               |
  |             |               expected struct `String`, found integer
  |             arguments to this function are incorrect
note: closure parameter defined here
 --> src/main.rs:2:28
  |
2 |     let example_closure = |x| x;
  |                            ^
```

Closure Types

```
let example_closure = |x| x;

let s = example_closure(String::from("hello"));
let n = example_closure(5);
```

- The first time we called `example_closure` with a `String`
- Rust inferred the type of `example_closure` to be `String -> String`
- Those types are now bound to the closure
  - `example_closure(5)` will not type check

Capturing References

Closures can capture values from their environment in three ways:

- Borrowing immutably
- Borrowing mutably
- Taking ownership
    - ***Moving*** the value into the closure

Immutable Borrowing in Closures

```rust
let list = vec![1, 2, 3];
println!("Before defining closure: {:?}", list);

let only_borrows = || { println!("From closure: {:?}", list); };

println!("Before calling closure: {:?}", list);
only_borrows(); // Prints "From closure: [1, 2, 3]"
println!("After calling closure: {:?}", list);
```

```
Before defining closure: [1, 2, 3]
Before calling closure: [1, 2, 3]
From closure: [1, 2, 3]
After calling closure: [1, 2, 3]
```

Immutable Borrowing in Closures

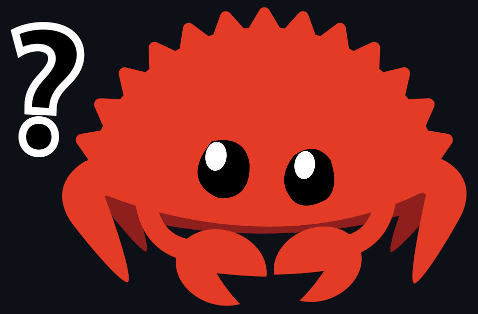
```rust
let list = vec![1, 2, 3];
println!("Before defining closure: {:?}", list);

let only_borrows = || { println!("From closure: {:?}", list); };

println!("Before calling closure: {:?}", list);
only_borrows(); // Prints "From closure: [1, 2, 3]"
println!("After calling closure: {:?}", list);
```

- Note how once a closure is defined, it's invoked in the same manner as a function
- Because we can have many immutable borrows, Rust allows us to to print, even with the closure holding a reference

Mutable Borrowing in Closures

What happens if we mutate captured variables from inside the closure?

```
let mut list = vec![1, 2, 3];
println!("Before defining closure: {:?}", list);

let borrows_mutably = || { list.push(7); };

borrows_mutably();
println!("After calling closure: {:?}", list);
```



- This seems like it should work...

Mutable Borrowing in Closures

```
error[E0596]: cannot borrow `borrows_mutably` as mutable, as it is not declared as mutable
 --> src/main.rs:7:5
  |
5 |     let borrows_mutably = || { list.push(7); };
  |                                ---- calling `borrows_mutably` requires mutable
  |                                     binding due to mutable borrow of `list`
6 |
7 |     borrows_mutably();
  |     ^^^^^^^^^^^^^^^ cannot borrow as mutable
```

- A closure mutating its captured state is *equivalent* to mutating *itself*
  - Calling `borrows_mutably` mutates the closure's internal state
    - We'll discuss in the next section...

Mutable Borrowing in Closures

```
help: consider changing this to be mutable
  |
5 |     let mut borrows_mutably = || { list.push(7); };
  |         +++
```

- As always, the compiler tells us how to fix our mistake!

Mutable Borrowing in Closures

```rust
let mut list = vec![1, 2, 3];
println!("Before defining closure: {:?}", list);

let mut borrows_mutably = || { list.push(7); };

borrows_mutably();
println!("After calling closure: {:?}", list);
```

```
Before defining closure: [1, 2, 3]
After calling closure: [1, 2, 3, 7]
```

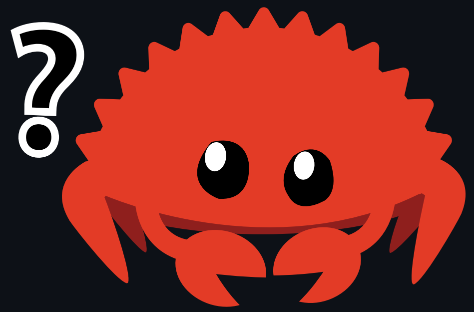
Closure Borrowing Rules

```rust
let mut list = vec![1, 2, 3];

let mut borrows_mutably = || { list.push(7); };

// println!("Before calling closure: {:?}", list); <-- Compiler error!
borrows_mutably();
println!("After calling closure: {:?}", list);
```

- Note how we can't have a `println!` before invoking `borrows_mutably`
- Rust only considers the **invocation** a borrow, not the definition
  - Closures are lazy in this sense

Giving Closures Ownership

```rust
let mystery = {
    let x = rand::random::<u32>();
    |y: u32| -> u32 { x + y }
};

println!("Mystery value is {}", mystery(5));
```



Giving Closures Ownership

```
error[E0373]: closure may outlive the current block, but it borrows `x`,
 which is owned by the current block
 --> src/main.rs:6:9
  |
6 |         |y: u32| -> u32 { x + y }
  |         ^^^^^^^^^^^^^^^   - `x` is borrowed here
  |         |
  |         may outlive borrowed value `x`
  |
  |
4 |     let mystery = {
  |         ^^^^^^^
help: to force the closure to take ownership of `x`, use the `move` keyword
  |
6 |         move |y: u32| -> u32 { x + y }
  |
```

Giving Closures Ownership

```rust
let mystery = {
    let x = rand::random::<u32>();
    move |y: u32| -> u32 { x + y }
//  ^^^^ Add the `move` keyword!
};

println!("Mystery value is {}", mystery(5));
```

- We can `move` values into closures instead of capturing references (borrowing)
  - Note that you can't selectively `move` parameters, it's all or nothing
- `move` semantics with closures are important for thread safety!

Threads Sneak Peek

Let's briefly explore spawning a new thread with a closure.

```rust
fn main() {
    let list = vec![1, 2, 3];
    println!("Before defining closure: {:?}", list);

    std::thread::spawn(move || println!("From thread: {:?}", list))
        .join()
        .unwrap();
}
```

Case for `move`: Thread Safety

```
fn main() {
    let list = vec![1, 2, 3];
    println!("Before defining closure: {:?}", list);

    std::thread::spawn(move || println!("From thread: {:?}", list))
        .join()
        .unwrap();
}
```

- Why do we `move` instead of borrow?
  - Child thread's `println!` only needs a reference to `list`...
- Parent might drop `list` before the child thread runs
  - Use after free in child thread! ☠️

Handling Captured Values

- A closure body can do any of the following to a value:
  - Move a captured value out of the closure
  - Mutate a captured value
  - Neither of the above
- It could also have captured nothing to begin with!
- The properties a closure has determines the function *trait* it implements

The `Fn` traits

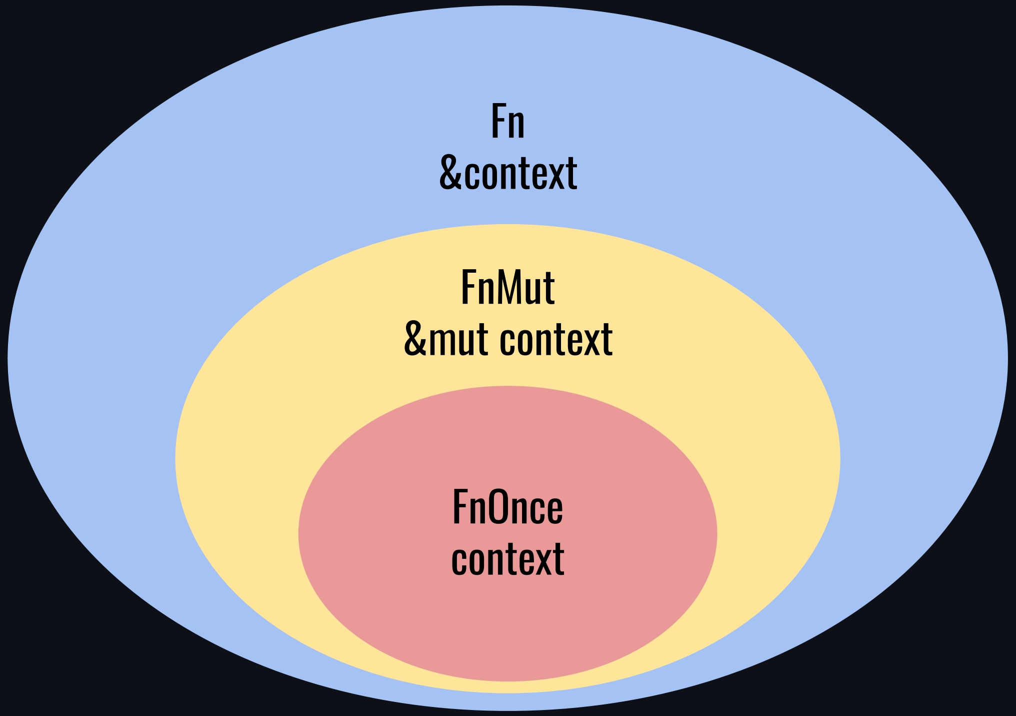
The `Fn` traits

What do you mean, function ***trait***???

- Rust has 3 special traits that define the *kind* of closure we want to use
- The 3 traits are:
  - `FnOnce`
  - `FnMut`
  - `Fn`
- Rust auto-implements these for closures and functions

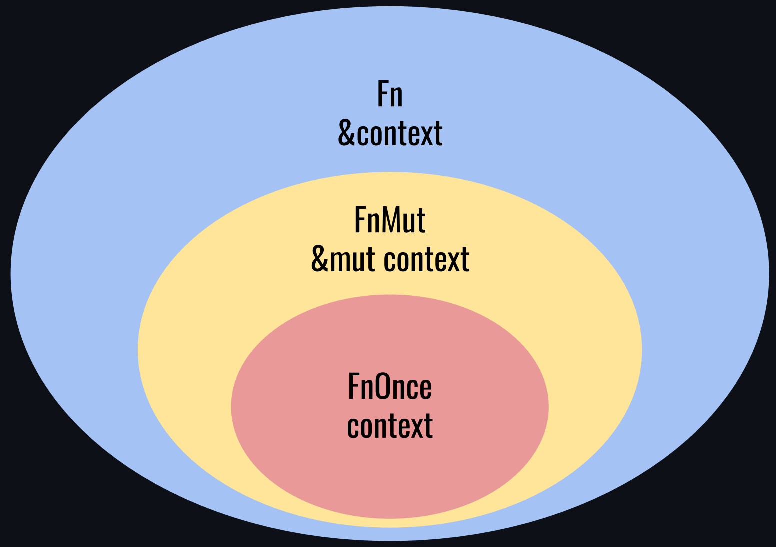
The `Fn` Traits: Visualized

- `FnMut` is also `FnOnce`
- `Fn` is also `FnMut` *and* `FnOnce`



The `Fn` traits

- `FnOnce`: Closures that can be called once
- `FnMut`: Closures that can mutate the captured values
- `Fn`: Everything else!



The `Fn` traits

- `FnOnce`: Closures that can be called once
  - All closures and functions implement this, since all closures can be called *at least* once
  - However, closures that are exclusively `FnOnce` can *only* be called once
    - e.g. A closure that moves captured values out of its body
- `FnMut`: Closures that can mutate the captured values
  - Can be called more than once
- `Fn`: Everything else!
  - Don't move values out, don't mutate, don't capture anything

`FnOnce`

A closure that moves captured values **out** of its body will *only* implement `FnOnce`, and not `FnMut` or `Fn`:

```rust
let my_str = String::from("x");

// Returns `my_str`, moving it out of the closure
let consume_and_return = move || my_str;
```

- Why can this closure only be called once?
  - It takes ownership of `my_str`, then gives ownership back to the caller
  - `my_str` is no longer accessible to our closure after it's called!
- `move` keyword specifies that the closure takes ownership when it's created, *not* when it's called

`unwrap_or_else`

All closures implement `FnOnce`, since all closures can be called once.

- This does not mean they can *only* be called once!
- One example is the `unwrap_or_else` method on `Result`

`unwrap_or_else`

`unwrap_or_else` processes the `Result<T, E>` of a function.

```
let count = |s: &str| s.len();

assert_eq!(Ok(2).unwrap_or_else(count), 2);
assert_eq!(Err("foobar").unwrap_or_else(count), 6);
```

- If successful, it unwraps the value from `Ok(T)` into `T`
- Otherwise, it takes `E` as input to the closure

`unwrap_or_else`

Let's look at the definition of the `unwrap_or_else` method on `Result<T>`.

```
impl<T, E> Result<T, E> {
    pub fn unwrap_or_else<F>(self, f: F) -> T
    where
        F: FnOnce(E) -> T
    {
        match self {
            Some(x) => x,
            None => f(e),
        }
    }
}
```

`unwrap_or_else`

First let's observe the function definition.

```
pub fn unwrap_or_else<F>(self, f: F) -> T
where
    F: FnOnce(E) -> T
// <-- snip -->
```

- This method is generic over `F`
- `F` is the type of the closure we provide when calling `unwrap_or_else`
- `F` must be able to be called once, take no arguments, and return a `T` for `Option<T>`

`unwrap_or_else`

Now let's observe the function body.

```
{
    match self {
        Some(x) => x,
        None => f(e),
    }
}
```

- If the `Option` is `Some`, then extract the inner value
- Otherwise, call `f` once and return the value
- Note that `f` is not *required* to only be `FnOnce` here
    - It is valid for `f` to be `FnMut` or `Fn`

`FnMut`

`FnMut` applies to closures that might mutate the captured values.

```
let mut x: usize = 1;
let mut add_two_to_x = || x += 2;
add_two_to_x();
```

- Use cases: Stateful operations on some shared resource
    - Imagine `x` were a score on a scoreboard
- Note that this will not compile without the second `mut`
    - `mut` signals that we are mutating our closure's environment

FnMut

Another simple example:

```rust
let mut base = String::from("");
let mut build_string = |addition| base.push_str(addition);

build_string("Ferris is ");
build_string("happy!");

println!("{}", base);
```

```
Ferris is happy!
```

`FnMut`

We can pass an `FnMut` closure as an argument to a function.

```
fn do_twice<F>(mut func: F)
where
    F: FnMut(),
{
    func();
    func();
}
```

- Would `do_twice` accept a closure that's exclusively `FnOnce`?
  - No, because we call our closure twice
- How about an `Fn` closure?
  - Yes!

`Fn`

The `Fn` trait is a superset of `FnOnce` and `FnMut`.

- `Fn` applies to closures that:
  - Don't move captured values out of their body
  - Don't mutate captured values
  - Don't capture anything from their environment
- Can be called more than once without mutating the environment
- Use cases:
  - Stateless operations without side effects
    - Logging, pretty printing
    - Predicates* for sorting, searching, filtering

`Fn`

`Fn` applies to closures that don't capture anything from their environment:

```
let double = |x| x * 2; // captures nothing

assert!(double(2) == 4);
```

`Fn`

`Fn` also applies to closures that don't mutate captured variables:

```
let mascot = String::from("Ferris");
let is_mascot = |guess| guess == mascot; // `mascot` immutably borrowed

assert!(is_mascot("Ferris"));     // true
assert!(!is_mascot("Ferrari"));   // false
```

`Fn`

The `Fn` usually represents pure functions, which means it makes sense to pass them as inputs to other functions!

```rust
fn reduce<F, T>(reducer: F, data: &[T]) -> Option<T>
where
    F: Fn(T, T) -> T,
{
    // <-- snip -->
}
```

- We can specify the arguments and return types for `Fn`
- Functions are values!

`fn` vs. `Fn`

Rust also has function pointers, denoted `fn` (instead of `Fn`).

```
fn add_one(x: i32) -> i32 {
    x + 1
}

fn do_twice(f: fn(i32) -> i32, arg: i32) -> i32 {
    f(arg) + f(arg)
}

fn main() {
    let answer = do_twice(add_one, 5);
}
```

- `fn` is a **type*** that implements all 3 closure traits `Fn`, `FnMut`, and `FnOnce`

Recap: Closure Traits

- `Fn`, `FnMut`, `FnOnce` describe different groups of closures
  - You don't `impl` them, they apply to a closure automatically if appropriate
  - A single closure can implement one or multiple of these traits
- `FnOnce` - call at least once, environment may be consumed
- `FnMut` - call multiple times, environment may change
- `Fn` - call multiple times, environment doesn't change

Iterators

- Sorry functional haters... it's show time!

What is an Iterator?

- Iterators allow you to perform some task on a sequence of elements
- Iterators manage iterating over each item and determining termination
- Rust iterators are *lazy*
  - This means we don't pay a cost until we consume the iterator

The `Iterator` Trait

All iterators must implement the `Iterator` trait:

```rust
pub trait Iterator {
    type Item;

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

    // methods with default implementations elided
}
```

- Keep generating `Some(item)`
- When the `Iterator` is finished, `None` is returned

`type Item`

What's going on with the `type Item`?

```rust
pub trait Iterator {
    type Item;

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

    // <-- methods with default implementations elided -->
}
```

- This is an *associated type*
- To define `Iterator` you must define the `Item` you're iterating over
- *Different from generic types!*
    - There can only be one way to iterate over something

Custom Iterator Example

Let's say we want to implement an iterator that generates the Fibonacci sequence.

```rust
struct Fibonacci {
    curr: u32,
    next: u32,
}
```

- First need to declare the `struct` that can implement `Iterator`
- We need to store two numbers to compute the next element

Fibonacci Example

```rust
impl Iterator for Fibonacci {
    type Item = u32;

    fn next(&mut self) -> Option<Self::Item> {
        let current = self.curr;

        self.curr = self.next;
        self.next = current + self.next;

        // No endpoint to a Fibonacci sequence - `Some` is always returned.
        Some(current)
    }
}
```

- Notice `Self::Item` is aliased to `u32`

Iterating Explicitly

```rust
let v1 = vec![1, 2, 3];

let mut v1_iter = v1.iter();

assert_eq!(v1_iter.next(), Some(&1));
assert_eq!(v1_iter.next(), Some(&2));
assert_eq!(v1_iter.next(), Some(&3));
assert_eq!(v1_iter.next(), None);
```

- Here we see how the `next` method is used
- Notice how `v1_iter` is mutable
  - When we call `next()` we've **consumed** that iterator element
  - The iterator's internal state has changed
  - Note that `iter()` provides immutable borrows to `v1`'s elements

`Vec` Iterators

```
let v1 = vec![1, 2, 3];

for val in v1.iter() {
    println!("Got: {}", val);
}

for val in &v1 {
    println!("Got: {}", val);
}
```

- These do the same thing!
  - Note that this is *not* syntax sugar
- We saw this code before in lecture 4
  - Except now we explicitly create the iterator that Rust did for us

Syntactic Sugar: `for` loops

```rust
let v1 = vec![1, 2, 3];

for val in v1.iter() {
    println!("Got: {}", val);
}

let mut v1_iter = v1.iter();
while let Some(val) = v1_iter.next() {
    println!("Got: {}", val);
}
```

- The `for` loop *is* syntax sugar

Iterators and Mutable Borrows

We can use the `iter_mut()` on `Vec` to get an iterator over mutable references.

```
let mut vec = vec![1, 2, 3]; // Note that we need `vec` to be mutable
let mut mutable_iter = vec.iter_mut();

while let Some(val) = mutable_iter.next() {
    *val += 1;
}

println!("{:?}", vec);
```

```
[2, 3, 4]
```

- Before we saw that `v1.iter()` gave us an iterator over `&i32`
- Now, we see that `v1.iter_mut()` gives us an iterator over `&mut i32`

More Mutable Iteration

```
let mut vec = vec![1, 2, 3];

let mut mutable_iter = vec.iter_mut();
while let Some(val) = mutable_iter.next() {
    *val += 1;
}

for val in vec.iter_mut() {
    *val += 1;
}

for val in &mut vec {
    *val += 1;
}
```

- All of these do the same thing!

Iterators and Ownership

If we want an iterator to iterate over *owned* values, we usually use `into_iter()`.

```
let mut vec = vec![1, 2, 3];

let owned_iter = vec.into_iter(); // vec is *consumed*
for val in owned_iter {
    println!("I own {}", val);
}

// owned_iter has been consumed
```

- To make an iterator that owns its values we have `into_iter()`
- `into_iter()` is the sole method on the `IntoIterator` trait
- This is what the `for` loops are actually consuming

Consuming Iterators

The standard library has many functions for using iterators.

```
let v1 = vec![1, 2, 3];

let v1_iter = v1.iter();

let total: i32 = v1_iter.sum(); // `.sum()` consumes `v1_iter`

assert_eq!(total, 6);
```

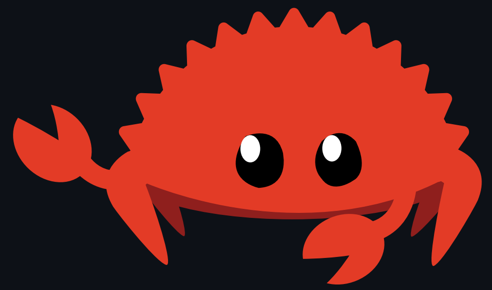
- Most of these functions *consume* iterators

Other consuming functions

- `fn sum(self)`
- `fn max(self)`
- `fn count(self)`
- `fn map(self, f: F)`
- `fn filter(self, predicate: P)`
- `fn fold(self, init: B, f: F)`
- `fn collect(self)`
  - Coming soon…
- Many, many more!

Producing Iterators

```rust
let v1: Vec<i32> = vec![1, 2, 3];

v1.iter().map(|x| x + 1);
```



- This code seems fine...

Producing Iterators

```
warning: unused `Map` that must be used
 --> src/main.rs:4:5
  |
4 |     v1.iter().map(|x| x + 1);
  |     ^^^^^^^^^^^^^^^^^^^^^^^^
  |
  = note: iterators are lazy and do nothing unless consumed
  = note: `#[warn(unused_must_use)]` on by default
```

- Zero-cost abstractions at work
- Rust won't make us pay for our iterator until we use it
    - It will compile and warn us of unused data

Producing Iterators

```
let v2: Vec<i32> = (1..4).map(|x| x + 1).collect();

println!("{:?}", v2);
```

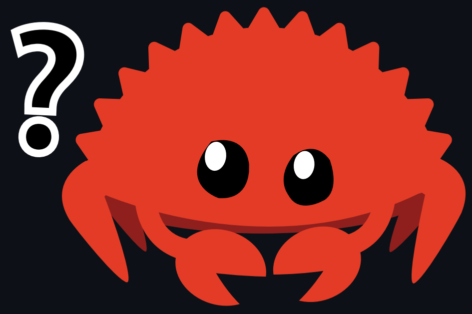
```
[2, 3, 4]
```

- We use `collect()` to tell Rust we're done modifying our iterator and want to convert our changes to a `Vec`
- `collect` is a super common method on iterators
  - If you don't use `collect`, no computation is performed
  - `collect` is the method that executes all of the desired operations!

Filter

```rust
fn filter_by(list: Vec<i32>, val: i32) -> Vec<i32> {
    list.into_iter().filter(|x| x == val).collect()
}
```

```
--> src/main.rs:2:35
  |
2 |     list.into_iter().filter(|x| x == val).collect()
  |                                   ^^ no implementation for `&i32 == i32`
  |
```



- Some iterator functions take a reference instead of ownership
- *Note how our filter closure captures the input* `val` *for our filtering needs!*

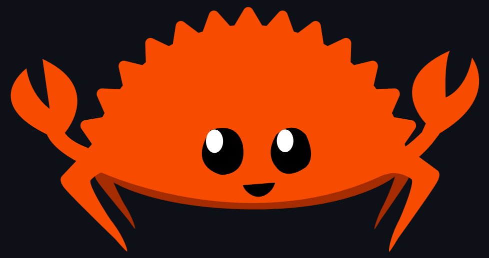
Filter

```
list.into_iter().filter(|&x| x == val).collect()
```

or

```
list.into_iter().filter(|x| *x == val).collect()
```

- We either explicitly match on the reference or dereference



Chaining It Together

```
let iter = (0..100).map(|x| x*x).skip(1).filter(|y| y % 3 == 0);

for x in iter.take(5) {
    print!("{}, ", x);
}
```

- You can read this as:
    - Print first 5 square numbers
    - Skipping 0
    - Only divisible by 3
- *Note that `filter` doesn't need a dereference for `%`*

Chaining It Together

```rust
let iter = (0..100).map(|x| x*x).skip(1).filter(|y| y % 3 == 0);
println!("{:?}", iter);

for x in iter.take(5) {
    print!("{}, ", x);
}
```

```
Filter { iter: Skip { iter: Map { iter: 0..100 }, n: 1 } }
9, 36, 81, 144, 225,
```

- Notice how `iter` is just a bunch of metadata
  - Lazy iterators on display!

Iterator Recap

- Iterators is an extremely powerful structure in Rust
- View the `std` library for more info on `Iterator` methods
- Rules regarding closures and ownership still apply
- Iterators are *lazy*
  - Remember to use `.collect()`!

Crate Highlights

`rand`

The standard library includes many things... but a random number generator isn't one of them*.

Here's an example of using the `rand` crate:

```
use rand::prelude::*;

let mut rng = rand::thread_rng();
let y: f64 = rng.gen(); // generates a float between 0 and 1

let mut nums: Vec<i32> = (1..100).collect();
nums.shuffle(&mut rng);
```

`rand`

```rust
use rand::prelude::*;

let mut rng = rand::thread_rng();
let y: f64 = rng.gen(); // generates a float between 0 and 1

let mut nums: Vec<i32> = (1..100).collect();
nums.shuffle(&mut rng);
```

- `rand` is the de facto crate for:
  - Generating random numbers
  - Creating probabilistic distributions
  - Providing randomness related algorithms (like vector shuffling)

`clap`

Often, we want our binary to take in command line arguments. A very popular argument parser used in Rust programs is `clap`.

```rust
use clap::Parser;

#[derive(Parser, Debug)]
#[command(version, about, long_about = None)]
struct Args {
    #[arg(short, long)]
    name: String, // Name of the person to greet

    #[arg(short, long, default_value_t = 1)]
    count: u8, // Number of times to greet
}
```

- Makes use of Rust's macro system to generate boilerplate code for us!

`clap`

Here's how you would use a `clap` struct called `Args`:

```rust
use clap::Parser;

// <-- snip -->
struct Args {
    // <-- snip -->
}

fn main() {
    let args = Args::parse(); // get-opt could never
    for _ in 0..args.count {
        println!("Hello {}!", args.name)
    }
}
```

`clap`

If we run the binary called `demo`:

```
$ demo --help
A simple to use, efficient, and full-featured Command Line Argument Parser

Usage: demo[EXE] [OPTIONS] --name <NAME>

Options:
  -n, --name <NAME>    Name of the person to greet
  -c, --count <COUNT>  Number of times to greet [default: 1]
  -h, --help           Print help
  -V, --version        Print version

$ demo --name Me
Hello Me!
```

- Note that `clap` is not the only 3rd-party crate option!

`anyhow`

Have code that can throw multiple error types that you wish was one? Use this!

```rust
use anyhow::Result;

fn get_cluster_info() -> Result<ClusterMap> {
    let config = std::fs::read_to_string("cluster.json")?;
    let map: ClusterMap = serde_json::from_str(&config)?;
    Ok(map)
}
```

- Both lines return different error types, but `anyhow` allows us to return both!
- Makes errors more dynamic and ergonomic

`anyhow`

Another example:

```rust
it.detach().context("Failed to detach the important thing")?;

let content = std::fs::read(path)
    .with_context(|| format!("Failed to read from {}", path))?;
```

Other `anyhow` features include:

- Downcasting to the original error types
- Attaching custom context / error messages
- More expressive custom errors

Error Handling Libraries

In addition to `anyhow`, there is also `thiserror` and `snafu`.

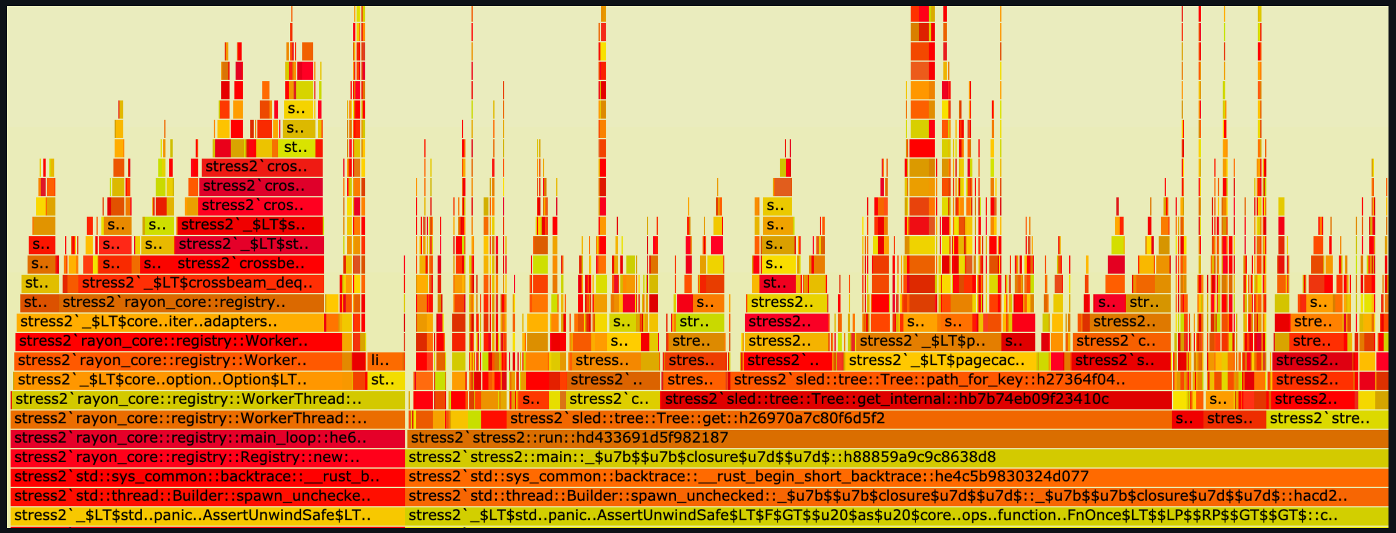
- `anyhow`: Use in binaries where you don't care what kind of error has occurred
- `thiserror`: Use in libraries where you *do* care what exactly happened
- `snafu`: Newer crate, combines the functionality of both!

`flamegraph`

Rust powered flamegraph generator with Cargo support!

With a bit of setup, you can generate this with `cargo flamegraph`.

- Can support non-Rust projects too
- Relies on `perf` or `dtrace`



Next Lecture: Ownership Revisited

Thanks for coming!

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