Intro to Rust Lang

Lifetimes

Today: Lifetimes

We've used the term "lifetime" a few times before, and today we're going to explore what exactly it means.

- What is `'a` lifetime?
- How to think about lifetimes
- Other perspectives...

Lifetimes

Lifetimes are all about references, and **nothing** else.

- Informal definition:
  Lifetimes provide a way for Rust to validate pointers at compile time
- Formal definition:
  Lifetimes are named regions of code that a reference must be valid for
- Remember that references are just pointers with constraints!

Lifetimes and References vs Traits and Generics

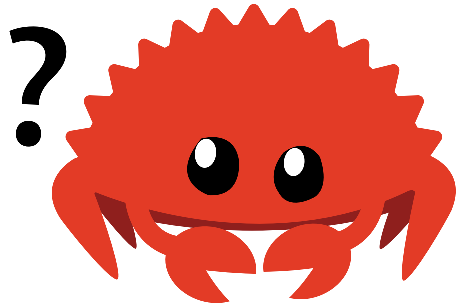
Lifetimes are similar to trait bounds on generic types.

- Traits ensure that a generic type has the behavior we want
- Lifetimes ensure that references are valid for as long as we need them to be

Validating References

The main goal of lifetimes is to prevent *dangling references*.

```rust
fn main() {
    let r;

    {
        let x = 5;
        r = &x;
    }

    println!("r: {}", r);
}
```



- What is the issue with this code?

Validating References

```
error[E0597]: `x` does not live long enough
 --> src/main.rs:6:13
  |
6 |         r = &x;
  |             ^^ borrowed value does not live long enough
7 |     }
  |     - `x` dropped here while still borrowed
8 |
9 |     println!("r: {}", r);
  |                       - borrow later used here
```

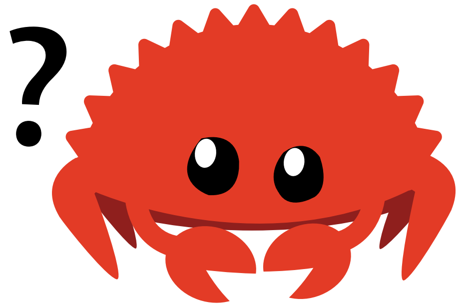
- The value that `r` refers to has gone out of scope before we could use it
- The scope of `r` is "larger" than the scope of `x`

The Borrow Checker

The Rust compiler's borrow checker will compare scopes to determine whether all borrows are valid.

Here is the same code, but with a lifetime diagram:

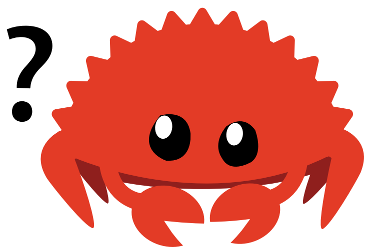
```rust
fn main() {
    let r;                // ---------+-- 'a
                          //          |
    {                     //          |
        let x = 5;        // -+-- 'b  |
        r = &x;           //  |       |
    }                     // -+       |
                          //          |
    println!("r: {}", r); //          |
}                         // ---------+
```



The Borrow Checker

The borrow checker will compare the "size" of the two lifetimes

```
fn main() {
    let r;                // ---------+-- 'a
    {                     //          |
        let x = 5;        // -+-- 'b  |
        r = &x;           //  |       |
    }                     // -+       |
    println!("r: {}", r); //          |
}                         // ---------+
```

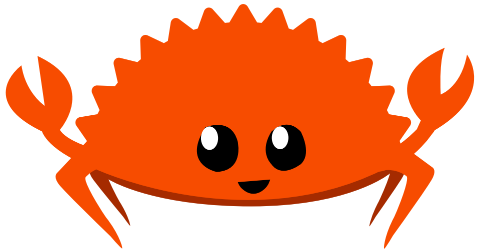


- `r` has a lifetime of `'a`
- `r` refers to a variable with lifetime `'b`
- Rejects because `'b` is shorter than `'a`

Placating the Borrow Checker

We can fix this code by removing the scope.

```rust
fn main() {
    let r;                // --+-- 'a
                          //   |
    let x = 5;            // ----------+- 'b
    r = &x;               //   |       |
                          //   |       |
    println!("r: {}", r); //   |       |
                          // --+       |
}                         // ----------+
```



- `x` now "outlives" `r`, so `r` can reference `x`

Generic Lifetimes

Let's try to write some string functions.

```rust
fn main() {
    let string1 = String::from("abcd");
    let string2 = "xyz";

    let result = longest(string1.as_str(), string2);
    println!("The longest string is {}", result);
}
```

We want this output:

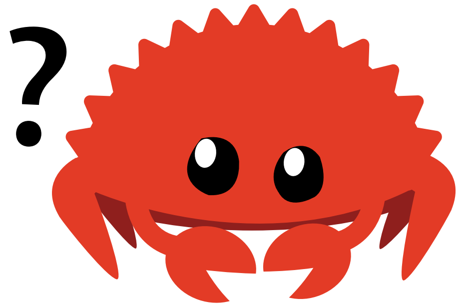
```
The longest string is abcd
```

- Let's implement `longest`!

`longest`

Here is a first attempt:

```rust
fn longest(x: &str, y: &str) -> &str {
    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```



- *We don't want to take ownership, so we take `&str` inputs*

`longest` Error

Unfortunately, our attempt will not compile:

```
error[E0106]: missing lifetime specifier
 --> src/main.rs:9:33
  |
9 | fn longest(x: &str, y: &str) -> &str {
  |               ----     ----     ^ expected named lifetime parameter
  |
  = help: this function's return type contains a borrowed value,
    but the signature does not say whether it is borrowed from `x` or `y`
help: consider introducing a named lifetime parameter
  |
9 | fn longest<'a>(x: &'a str, y: &'a str) -> &'a str {
  |           ++++     ++          ++          ++
```

`longest` Error

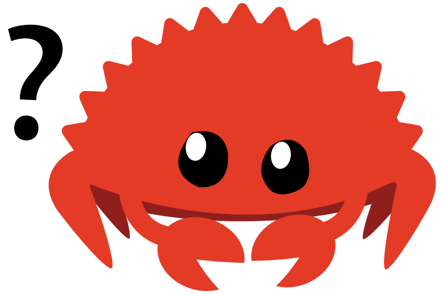
The help text from the compiler error reveals some useful information:

```
  = help: this function's return type contains a borrowed value,
    but the signature does not say whether it is borrowed from `x` or `y`
```

- Rust can't figure out if the reference returned refers to `x` or `y`
- In fact, neither do we!

`longest` Error

```rust
fn longest(x: &str, y: &str) -> &str {
    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```



- We don't know which execution path this code will take
- We also don't know the lifetimes of the input references
- Thus we cannot determine the lifetime we return!
- We will need to *annotate* these references

Lifetime Annotation Syntax

We can annotate lifetimes with generic parameters that start with a `'`, like `'a`.

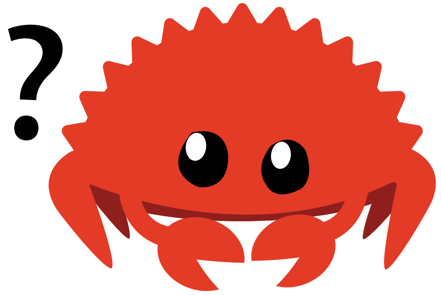
```
&i32            // a reference
&'a i32         // a reference with an explicit annotated lifetime
&'a mut i32     // a mutable reference with an explicit lifetime

&'hello usize // annotations can be any word or character,
&'world bool  // as long as it starts with a tick (')
```

- Annotations do not change how long references live, they only describe the *relationship* between lifetimes of references
  - Think of `'a` as a lower bound for the lifetime of the reference
  - `x: 'a i32` means `x` lives at least as long as some lifetime `'a`
  - Borrow checker identifies if references share a lower bound

`longest` Lifetimes

Let's return back to our `longest` function.

```rust
fn longest(x: &str, y: &str) -> &str {
    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```



- What do we want the function signature to express?
- What should the relationship be between the lifetimes of the references?

`longest` Lifetimes

What exactly are we returning?

```rust
if x.len() > y.len() {
    x
} else {
    y
}
```

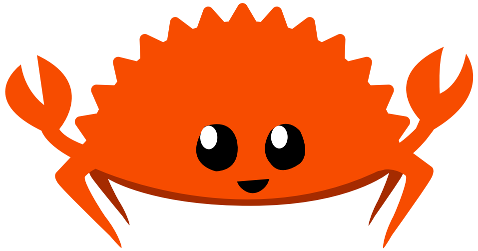
- We return either `x` or `y`, which each have their own lifetimes
- We want the returned reference to be valid as long as *both* input references `x` and `y` are valid
- So we want lifetimes of `x` and `y` to *outlive* the returned lifetime

`longest` Lifetimes

Since lifetimes are a kind of generic parameter, we must declare them like normal generic type parameters.

```
fn longest<'a>(x: &'a str, y: &'a str) -> &'a str {
    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```

- This will compile now!
- *Note that these lifetime annotations don't **change** any lifetimes, they just **restrict***



Lifetime Annotations in Functions

We can extrapolate a lot from a function's signature, even without the body.

```rust
fn longest<'a>(x: &'a str, y: &'a str) -> &'a str;
```

- This function takes two string slices (`x` and `y`) that live at least as long as the lifetime `'a`
- The string slice returned (the longer of `x` or `y`) will also live at least as long as `'a`

Lifetime Annotations in Functions

```
fn longest<'a>(x: &'a str, y: &'a str) -> &'a str;
```

- When calling `longest`, the lifetime that is substituted for `'a` is the intersection of the lifetimes of `x` and `y`
- In practice, this means the lifetime returned by `longest` is the same as the **smaller** of the two input lifetimes

Borrow Checker Example 1

Let's look at some examples where the borrow checker is and isn't happy.

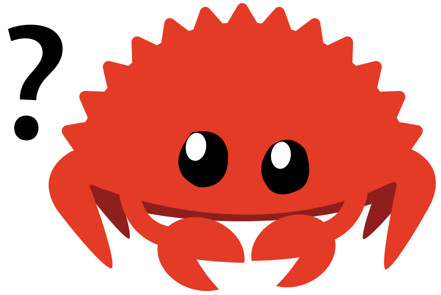
```rust
let string1 = String::from("long string is long");

{
    let string2 = String::from("xyz");

    let result = longest(string1.as_str(), string2.as_str());
    println!("The longest string is {}", result);
}
```

- `string1` is valid in the outer scope, `string2` is valid in the inner scope
- `result` should only be valid in the smaller scope (by our lifetime annotations)
  - Since `println!` is in the smaller (inner) scope, this works!

Borrow Checker Example 2

Let's reorder some things around.

```rust
let result;
let string1 = String::from("xyz");

{
    let string2 = String::from("long string is long");
    result = longest(string1.as_str(), string2.as_str());
}

println!("The longest string is {}", result);
```



- `result` should only be valid in the smaller (inner) scope, but we try to reference it in the outer scope

Borrow Checker Example 2

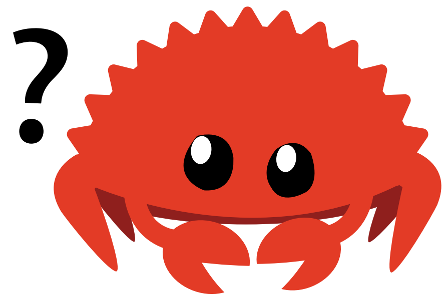
Sure enough, this does not compile! Rust gives us this error:

```
error[E0597]: `string2` does not live long enough
  --> src/main.rs:7:44
   |
6  |         let string2 = String::from("long string is long");
   |             ------- binding `string2` declared here
7  |         result = longest(string1.as_str(), string2.as_str());
   |                                            ^^^^^^^ borrowed value does
                                                       not live long enough
8  |     }
   |     - `string2` dropped here while still borrowed
9  |
10 |     println!("The longest string is {}", result);
   |                                          ------ borrow later used here
```

Borrow Checker Example 3

What if we knew (as the programmer) that `string1` is always longer than `string2`?

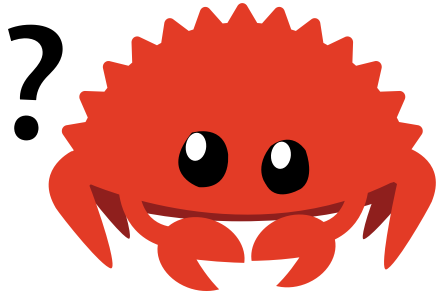
Let's switch the strings around:



```rust
let result;
let string1 = String::from("long string is long"); // Longer!

{
    let string2 = String::from("xyz"); // Shorter!
    result = longest(string1.as_str(), string2.as_str());
}

println!("The longest string is {}", result);
```

Borrow Checker Example 3

```rust
let result;
let string1 = String::from("long string is long"); // Longer!

{
    let string2 = String::from("xyz"); // Shorter!
    result = longest(string1.as_str(), string2.as_str());
}

println!("The longest string is {}", result);
```



- Even though we know (as humans) that the reference will be valid, the compiler does not know

Avoiding Lifetime Annotations

Suppose we wanted to always return the first input, `x`.

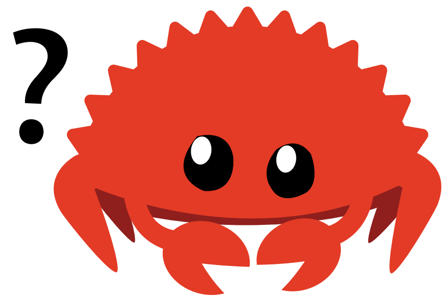
```
fn first<'a>(x: &'a str, y: &str) -> &'a str {
    x
}
```

- We don't need to annotate `y` with `'a`, because the return value doesn't care about `y`'s lifetime

Lifetimes of Return Values

The lifetime of a return value *must* match the lifetime of one of the inputs.

```rust
fn dangling<'a>(x: &str, y: &str) -> &'a str {
    let result = String::from("really long string");
    // What lifetime would we give this `&str`?
    result.as_str()
}
```



- If it didn't depend on an input, then it would *always* be a dangling reference!

Lifetime Elision

All references must have a lifetime. But we've seen many references without lifetime annotations…

```rust
fn first_word(s: &str) -> &str {
    let bytes = s.as_bytes();

    for (i, &item) in bytes.iter().enumerate() {
        if item == b' ' {
            return &s[0..i];
        }
    }

    &s[..]
}
```

- There are no lifetime annotations here!

Story Time

Long ago, in the dark ages of the 2010s, every reference needed an explicit lifetime.

```
fn first_word<'a>(s: &'a str) -> &'a str {
```

- Before Rust 1.0, every single `&` needed an explicit `'something` annotation
- This became incredibly repetitive, and so the Rust team programmed the borrow checker to infer lifetime annotation patterns of certain situations
- These patterns are called the *lifetime elision rules*

Lifetime Elision

- Lifetime elision does not provide full inference, it will only infer when it is absolutely sure it is correct
- Lifetimes on function or method arguments are called **input lifetimes**, and lifetimes on return values are called **output lifetimes**
- There are only 3 lifetime elision rules, the first for input lifetimes, the last two for output lifetimes

Lifetime Elision Rule 1

The first rule is that the compiler will assign a different lifetime parameter for each input lifetime.

```rust
fn foo(x: &i32);
fn foo<'a>(x: &'a i32);

fn bar(x: &i32, y: &i32);
fn bar<'a, 'b>(x: &'a i32, y: &'b i32);
```

Lifetime Elision Rule 2

The second rule is that if there is only 1 input lifetime parameter, then it is assigned to all output lifetimes.

```
fn foo(x: &i32) -> &i32;
fn foo<'a>(x: &'a i32) -> &'a i32;

fn bar(arr: &[i32]) -> (&i32, &i32);
fn bar<'a>(arr: &'a [i32]) -> (&'a i32, &'a i32);
```

Lifetime Elision Rule 3

If there are multiple input lifetime parameters, but the first parameter is `&self` or `&mut self`, the lifetime of `&self` is assigned to all output lifetimes.

- This only applies to methods
- Makes writing methods much nicer!
- *Examples to come later...*

Lifetime Elision Example 1

Let's pretend we are the compiler, and let's attempt to apply the lifetime elision rules to `first_word`.

```rust
fn first_word(s: &str) -> &str;
```

Lifetime Elision Example 1

We apply the first rule, which specifies that each parameter gets its own lifetime.

```
fn first_word<'a>(s: &'a str) -> &str;
```

Lifetime Elision Example 1

The second rule specifies that the lifetime of the single input parameter gets assigned to all output lifetimes, so the signature becomes this:

```rust
fn first_word<'a>(s: &'a str) -> &'a str;
```

- Since all references have lifetime annotations, we're done!

Lifetime Elision Example 2

So why didn't elision work with `longest`? Let's trace it out!

We start with this signature without annotations:

```rust
fn longest(x: &str, y: &str) -> &str;
```

Lifetime Elision Example 2

Let's apply the first rule and get annotations for all inputs.

```
fn longest<'a, 'b>(x: &'a str, y: &'b str) -> &str;
```

- What now?

Lifetime Elision Example 2

```
fn longest<'a, 'b>(x: &'a str, y: &'b str) -> &str;
```

- The second rule doesn't apply here, because there is more than 1 input lifetime (`'a` and `'b`)
- Since Rust cannot figure out what to do, it gives a compiler error to the programmer so they can write the annotations themselves

Lifetimes in Structs

So far, all of the `struct`s we've looked at have held *owned* type fields.

If we want a `struct` to hold a reference, we need to annotate them.

```rust
struct ImportantExcerpt<'a> {
    part: &'a str,
    importance: i32,
}

let novel = String::from("Call me Ishmael. Some years ago...");
let first_sentence: &str = novel.split('.').next().expect("No periods");

let important = ImportantExcerpt {
    part: first_sentence,
    importance: 42,
};
```

Lifetimes in Structs

```rust
struct ImportantExcerpt<'a> {
    part: &'a str,
    importance: i32,
}
```

- As with generic data types, we declare the name of the generic lifetime parameter inside angle brackets
- This annotation means an instance of `ImportantExcerpt` can’t outlive the reference it holds in its `part` field

Lifetimes in `impl` Blocks

Similarly, we need to annotate `impl` blocks with lifetime parameters.

```rust
impl<'a> ImportantExcerpt<'a> {
    fn importance(&self) -> i32 {
        self.importance
    }
}
```

Lifetimes in Methods

Here is an example where the third elision rule is applied:

```rust
impl<'a> ImportantExcerpt<'a> {
    fn announce_and_return_part(&self, announcement: &str) -> &str {
        println!("Attention please: {}", announcement);
        self.part
    }
}
```

- The first rule gives both `&self` and `announcement` their own lifetimes
- The third rule gives the return lifetime the lifetime of `&self`

Putting it all together...

Let’s briefly look at the syntax of specifying generic type parameters, trait bounds, and lifetimes all in one function!

```rust
fn longest_with_an_announcement<'a, T>(x: &'a str, y: &'a str, ann: T) -> &'a str
where
    T: Display,
{
    println!("Announcement! {}", ann);

    if x.len() > y.len() {
        x
    } else {
        y
    }
}
```

Lifetime Bounds

Lifetimes can be bounds, just like traits.

```rust
#[derive(Debug)]
struct Ref<'a, T: 'a>(&'a T);
```

- `Ref` contains a reference, with a lifetime of `'a`, to a generic type `T`
- `T` is bounded such that any references *in* `T` must live at least as long as `'a`
- Additionally, the lifetime of `Ref` may not exceed `'a`

Lifetime Bounds

Here is a similar example, but with a function instead of a `struct`.

```
fn print_ref<'a, T>(t: &'a T)
where
    T: Debug + 'a,
{
    println!("print_ref(t) is {:?}", t);
}
```

- `T` must implement `Debug`, and all references *in* `T` must outlive `'a`
- Additionally, `'a` must outlive this function call

Lifetime Bounds

Putting the `Ref` and `print_ref` together:

```
#[derive(Debug)]
struct Ref<'a, T: 'a>(&'a T);

fn print_ref<'a, T>(t: &'a T) where T: Debug + 'a {
    println!("print_ref(t) is {:?}", t);
}

let x = vec![9, 8, 0, 0, 8];
let ref_x = Ref(&x);
print_ref(&ref_x);
```

```
print_ref(t) is Ref([9, 8, 0, 0, 8])
```

Lifetime-bounded Lifetimes

We can have lifetimes that are bounded by other lifetimes.

```rust
// Takes in a `&'a i32` and return a `&'b i32` as a result of coercion
fn choose_first<'a: 'b, 'b>(first: &'a i32, _: &'b i32) -> &'b i32 {
    first
}

fn main() {
    let first = 2; // Longer lifetime
    {
        let second = 3; // Shorter lifetime
        println!("{} is the first", choose_first(&first, &second));
    }
}
```

- `'a: 'b` reads as "lifetime `'a` outlives `'b`"

The `'static` Lifetime

There is a special lifetime called `'static`.

```
let s: &'static str = "I have a static lifetime";
```

- `'static` implies that the reference will live until the end of the program (it is valid until the program stops running)
- Here, `s` is stored in the program binary, so it will always be valid!

`'static` Error Messages

You may see suggestions to use the `'static` lifetime in error messages.

```rust
fn foo() -> &i32 {
    let x = 5;
    &x
}
```

```
help: consider using the `'static` lifetime, but this is uncommon unless you're
      returning a borrowed value from a `const` or a `static`
  |
2 | fn foo() -> &'static i32 {
  |              +++++++
```

`'static` Error Messages

```
help: consider using the `'static` lifetime, but this is uncommon unless you're
      returning a borrowed value from a `const` or a `static`
  |
2 | fn foo() -> &'static i32 {
  |              ++++++++
```

- Before making a change, think about if your reference will *really* live until the end of the program
- You may actually be trying to create a dangling reference!

`'static` vs `static`

There are two common ways to make a variable with a `'static` lifetime.

1. Make a string literal with has type `&'static str`
2. Make a constant with the `static` declaration

`'static` vs `static` Example

```rust
static NUM: i32 = 42;
static NUM_REF: &'static i32 = &NUM;

fn main() {
    let msg: &'static str = "Hello World";
    println!("{msg} {NUM_REF}!");
}
```

```
Hello World 42!
```

`'static` Memory Leaks

There is a third way: we can create `'static` values by *leaking memory*.

```rust
fn random_vec() -> &'static [usize; 100] {
    let mut rng = rand::thread_rng();
    let mut boxed = Box::new([0; 100]);
    boxed.try_fill(&mut rng).unwrap();
    Box::leak(boxed)
}

let first: &'static [usize; 100] = random_vec();
let second: &'static [usize; 100] = random_vec();
assert_ne!(first, second)
```

- This allows us to *dynamically* create a `'static` reference
- *Note that leaking memory is NOT undefined behavior!*

The `'static` Bound

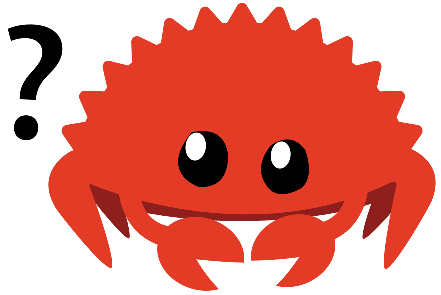
`'static` can also be used as a type bound. However...

- There is a subtle difference between the `'static` lifetime and the `'static` bound
- The `'static` bound means that the type does not contain any non-static references
- This means that all owned data implicitly has a `'static` bound, since owned data holds no references

'static Bound Example

Here's an example of using a `'static` bound.

```
fn print_it(input: impl Debug + 'static) {
    println!("'static value passed in is: {:?}", input);
}

fn main() {
    // `i` is owned and contains no references,
    // thus it has a 'static bound.
    let i = 5;
    print_it(i);

    // Oops, `&i` only has the lifetime defined by
    // the scope of main, so it's not 'static.
    print_it(&i);
}
```



`'static` Bound Example

We get a compiler error:

```
error[E0597]: `i` does not live long enough
  --> src/lib.rs:15:15
   |
15 |     print_it(&i);
   |     ---------^^--
   |     |        |
   |     |        borrowed value does not live long enough
   |     argument requires that `i` is borrowed for `'static`
16 | }
   | - `i` dropped here while still borrowed
```

Review

- Rust has lifetimes to prevent dangling references
- The borrow checker will ensure that lifetimes are always valid
- Rust will allow you elide lifetime annotations in some situations

Further Reading

- You can find some more examples here: Rust By Example
- If you want to go *really* in depth, read the Rustonomicon chapters on lifetimes

Another Perspective

What is 'a lifetime?

- This is a great video made by `leddoo` that explains another way to think about lifetimes!
- Instead of lifetimes as regions of code or scopes, what if we thought about lifetimes as regions of memory?
- Let's watch it together!

Watch Party

What is 'a lifetime?

What is `'a` lifetime?

Some quick points:

- Thinking about lifetimes as regions of code can be confusing
- Instead, think about lifetimes as regions of valid memory
- Both interpretations are valid!

Homework 9

- In this homework, you will be following a live-coding stream on YouTube:
  - Crust of Rust: Lifetime Annotations
- Jon Gjengset is a well-known educator in the Rust community
  - *He is also the inspiration for a lot of content in the second half of this course!*
- The livestream is 1.5 hours, but the writeup shows sections you can skip
  - We would recommend watching the livestream and *then* writing code!
- This homework is more about getting the tests to compile
  - *You'll only need to write about 20-30 lines of code!*

Next Lecture: Smart Pointers and Trait Objects

Thanks for coming!

Slides created by:

Connor Tsui, Benjamin Owad, David Rudo, Jessica Ruan, Fiona Fisher, Terrance Chen