

The background image shows a large, dimly lit industrial space, possibly a factory or warehouse. Several workers wearing high-visibility yellow safety vests are visible. One worker in the foreground is looking at a laptop. A yellow caution tape with black text is stretched across the lower part of the frame. The scene is characterized by large, rusted metal pillars and a high ceiling with exposed pipes and structural elements. Light streams in from windows on the right side, creating a dramatic, high-contrast atmosphere.

**SPRING 2024**

# **INTRO TO RUST LANG LIFETIMES**

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# 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 vs Generics and Traits

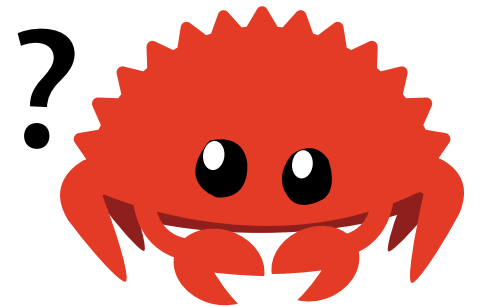
Lifetimes are similar to trait bounds.

- 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*.

```
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
```

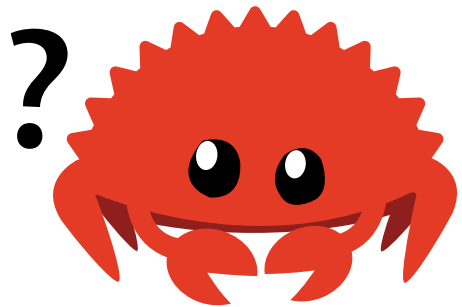
- The value that `r` refers to has gone out of scope before we could use it
- The scope of `r` is "larger" than the scope of `x`

# The Borrow Checker

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

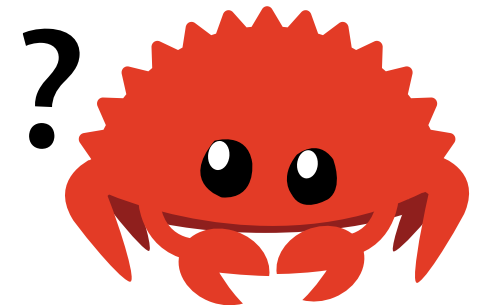
Here is the same code, but with a lifetime diagram:

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



# The Borrow Checker

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



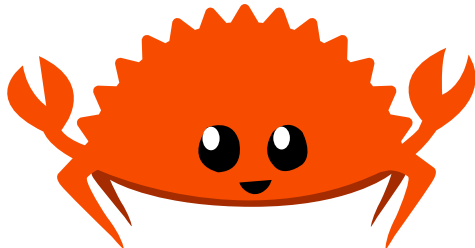
- The borrow checker will compare the "size" of the two lifetimes
  - `r` has a lifetime of `'a`
  - `r` refers to a variable with lifetime `'b`
  - Rejects because `'b` is shorter than `'a`



# Placating the Borrow Checker

We can fix this code by removing the scope.

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



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

# Generic Lifetimes

Let's try to write some string functions.

```
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
```

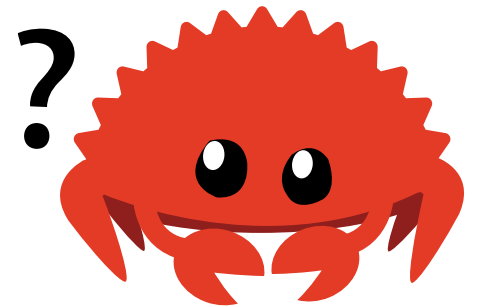
- Let's implement `longest` !

# longest

Here's a first attempt:

```
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:

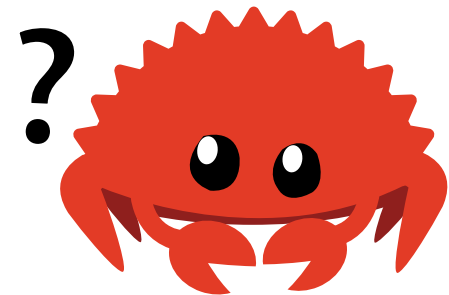
```
= help: this function's return type contains a borrowed value,  
but the signature does not say whether it is borrowed from `x` or `y`
```

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

# longest error

```
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 don't know the lifetimes of the input references either
- 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 (')
```

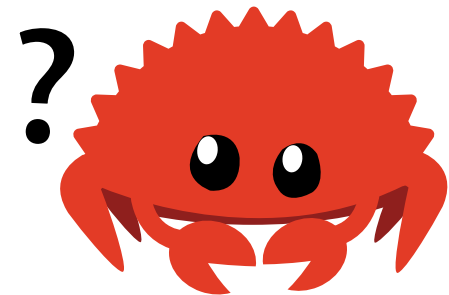
- Annotations do not change the how long references live, they only describe the relationship between lifetimes of references
- One annotation by itself has little meaning

# Longest Lifetimes

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

```
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?

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

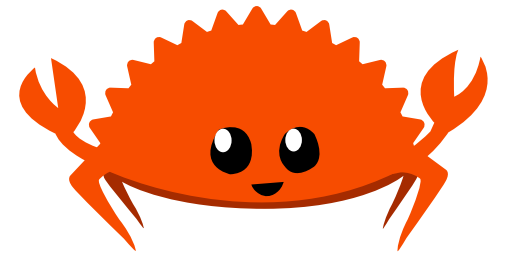
- We return either `x` or `y`, which each have their own lifetimes
- We want the returned reference to be valid as long as *both* input references `x` and `y` are valid
- So we want lifetimes of `x` and `y` to *outlive* the returned lifetime

# 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!
- *Remember that these lifetime annotations don't change the lifetimes of any values*



# Lifetime Annotations in Functions

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

```
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 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.

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

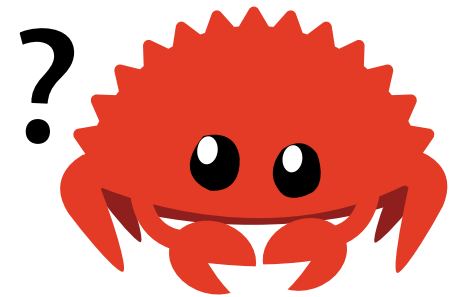
- `string1` is valid in the outer scope
- `string2` is valid in the inner scope
- `result` should only be valid in the smaller scope (by our lifetime annotations)
  - Since `println!` is in the smaller (inner) scope, this works!

# Borrow Checker Example 2

Let's reorder some things around.

```
fn main() {  
    let string1 = String::from("xyz");  
    let result;  
    {  
        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, and Rust gives us this error:

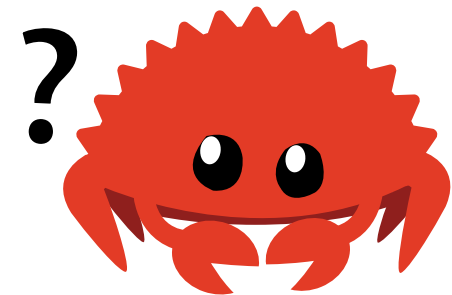
```
error[E0597]: `string2` does not live long enough
--> src/main.rs:6:44
   |
6  |         result = longest(string1.as_str(), string2.as_str());
   |                                                    ^^^^^^^^^^^^^^^^^^^^^
   |                                                    borrowed value does not live long enough
7  |     }
   |     - `string2` dropped here while still borrowed
8  |     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:

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





# Borrow Checker Example 3

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

- Even though we know (as a human) that the reference will be valid, the compiler does not know
- We even told the compiler that the returned lifetime would be the same as the smaller of the input lifetimes!

# 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.

```
fn dangling<'a>(x: &str, y: &str) -> &'a str {  
    let result = String::from("really long string");  
    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...

This is a version of a function we saw back in week 2:

```
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.

```
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`.

```
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:

```
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:

```
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.

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

fn main() {
    let novel = String::from("Call me Ishmael. Some years ago...");
    let first_sentence = novel.split('.').next().expect("Could not find a '.');
    let i = ImportantExcerpt {
        part: first_sentence,
    };
}
```



# Lifetimes in Structs

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

- 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.

```
impl<'a> ImportantExcerpt<'a> {  
    fn level(&self) -> i32 {  
        3  
    }  
}
```

# Lifetimes in Methods

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

```
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!

```
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.

```
#[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);
}

fn main() {
    let x = vec![9, 8, 0, 0, 8];
    let ref_x = Ref(&x);
    print_ref(&ref_x);
    // Prints to stdout: print_ref(t) is Ref([9, 8, 0, 0, 8])
}
```

# Lifetime-bounded Lifetimes

We can have lifetimes that are bounded by other lifetimes.

```
// 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!("{}", 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.

```
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 {  
  |           ++++++
```

- 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

```
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*.

```
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)
}

fn main() {
    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!

# The `'static` Bound

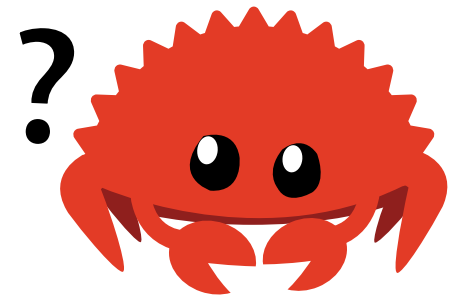
`'static` can also be used as a type bound. However..

- 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 chapter 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!

# Feedback

If you have 5 minutes, please fill out the [feedback form](#) (on Piazza).

- It will help us make this semester better for you
- It will also help make future offerings of this course better for others!
- Feedback is anonymous, so please be honest

# Homework 8

Homework 8 is a quiz on Gradescope!

- Think of homework 8 as a take-home midterm that only grades participation
- All 15 questions come from the experimental Brown Rust Book
  - They are doing active research in the best methods to teach Rust!
- *Please don't spend more than 1 hour on this*

## Next Lecture: **Box** and Trait Objects

- Thanks for coming!

