C/CPS 506

Comparative Programming Languages

Prof. Alex Ufkes

Topic 11: Ownership & Lifetime in Rust

Ryerson University

Notice!

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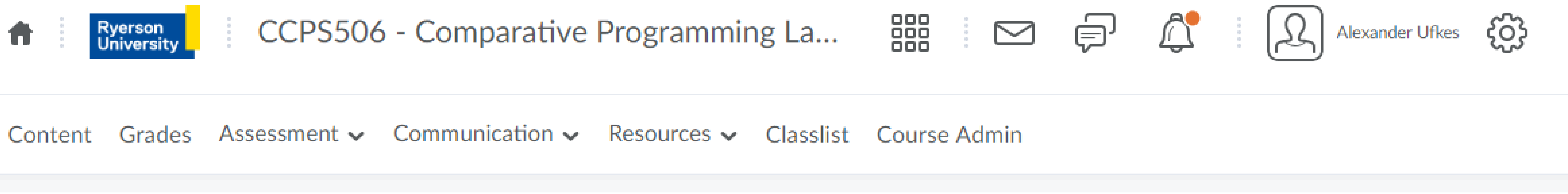
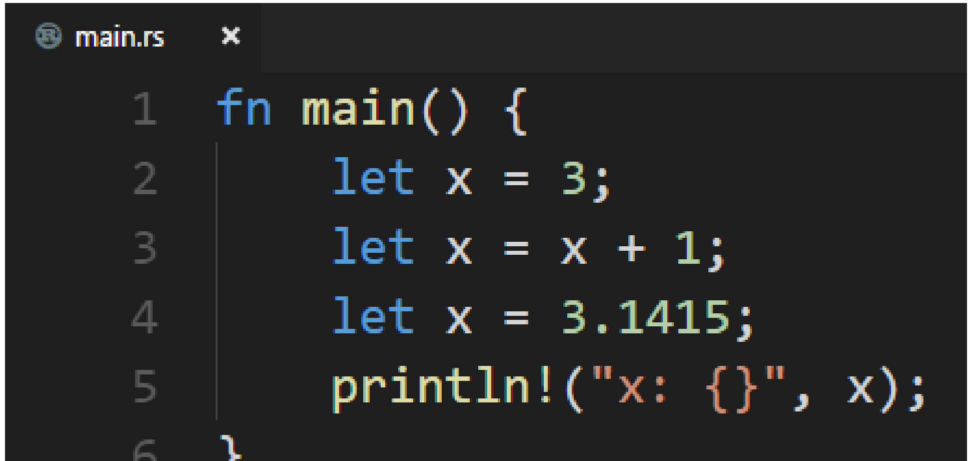
Course Administration (CCPS)



- Getting closer! Two more lectures.
- Don’t forget about the assignments!

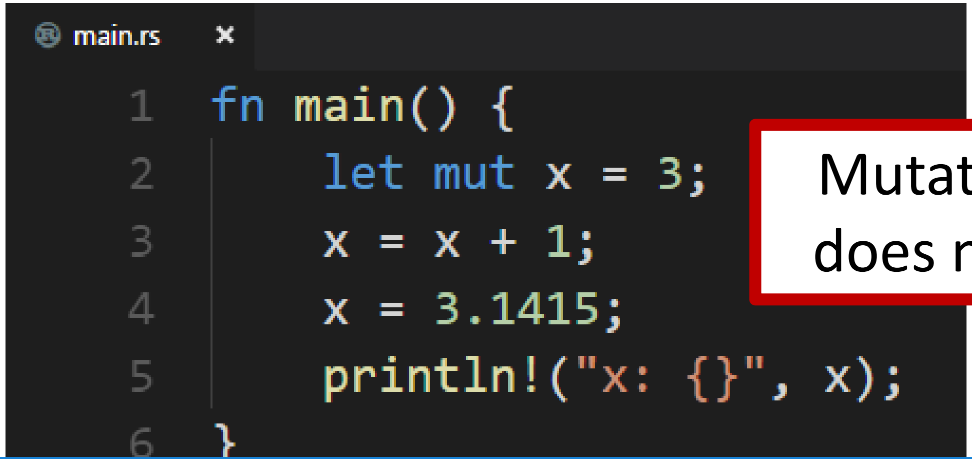
Previously

Shadowing **–VS–** Mutating



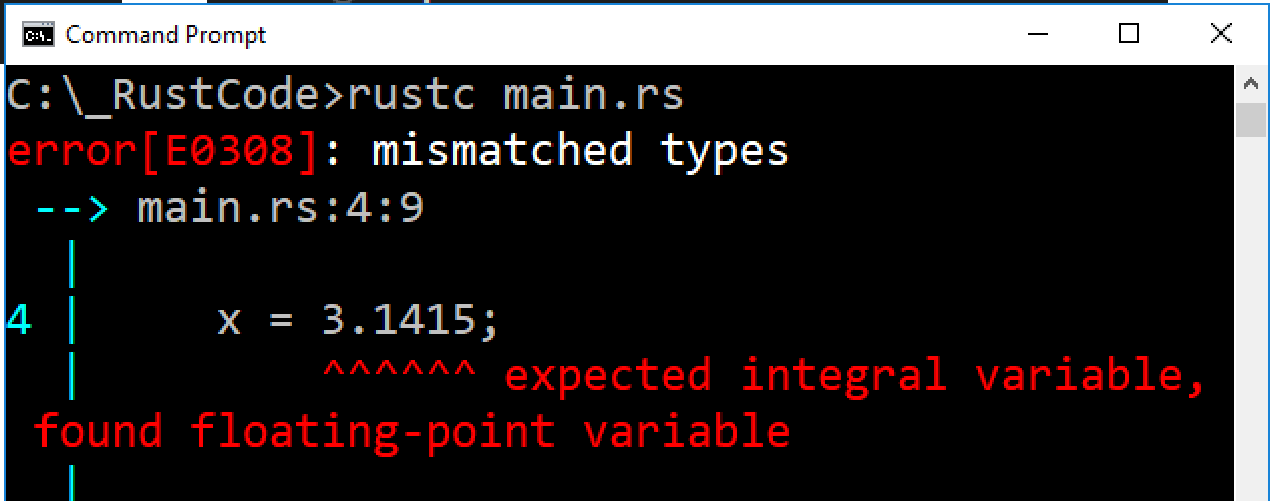
```rust
fn main() {
    let x = 3;
    let x = x + 1;
    let x = 3.1415;
    println!("x: {}", x);
}
```

Shadowing allows us to change type



```rust
fn main() {
    let mut x = 3;
    x = x + 1;
    x = 3.1415;
    println!("x: {}", x);
}
```

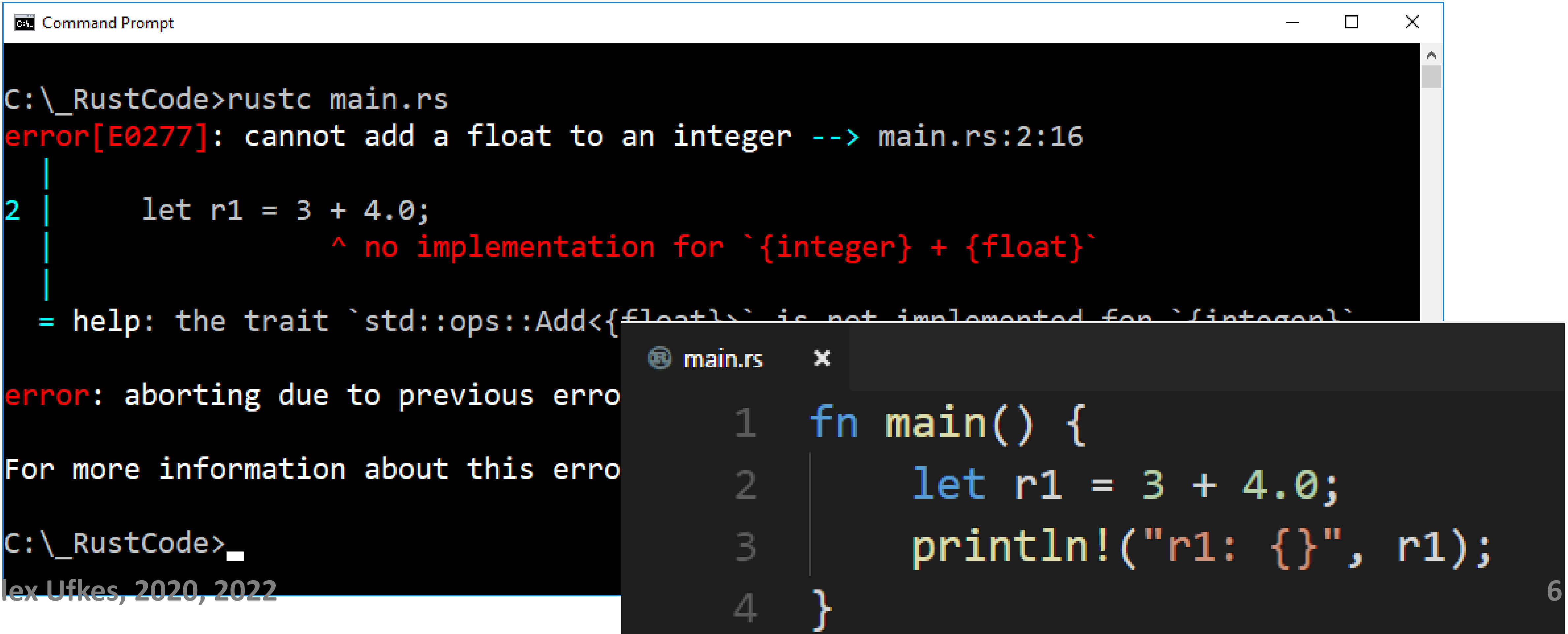
Mutating does not!



```
C:\_RustCode>rustc main.rs
error[E0308]: mismatched types
 --> main.rs:4:9
  |
4 |     x = 3.1415;
  |         ^^^^^^ expected integral variable,
 found floating-point variable
  |
```

Previously

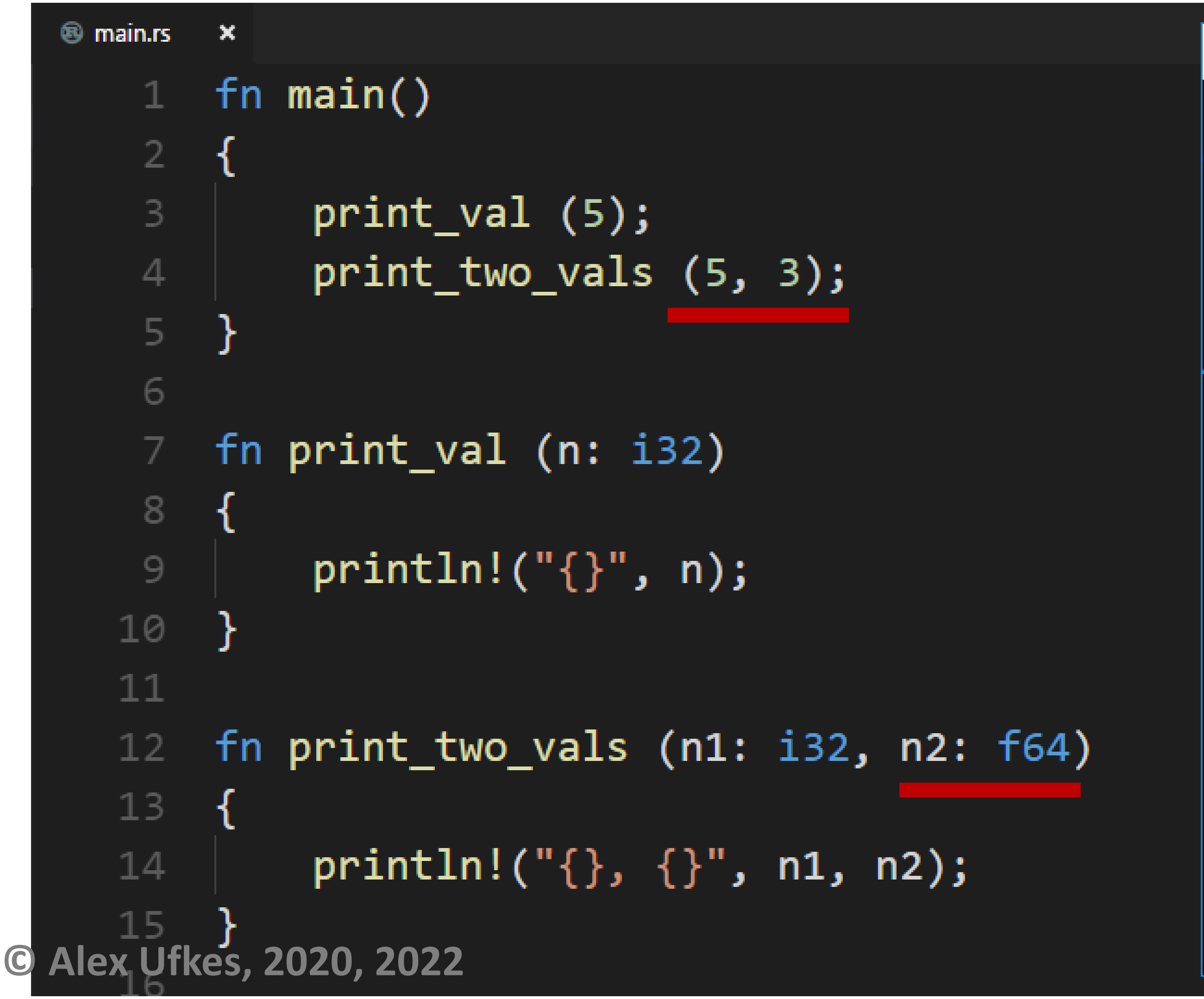
Rust is **VERY** strongly typed:



```
C:\_RustCode>rustc main.rs
error[E0277]: cannot add a float to an integer --> main.rs:2:16
  |
2 |     let r1 = 3 + 4.0;
  |                ^ no implementation for `{integer} + {float}`
  |
  = help: the trait `std::ops::Add<{float}>` is not implemented for `{integer}`

error: aborting due to previous erro

For more information about this erro

C:\_RustCode>_
```

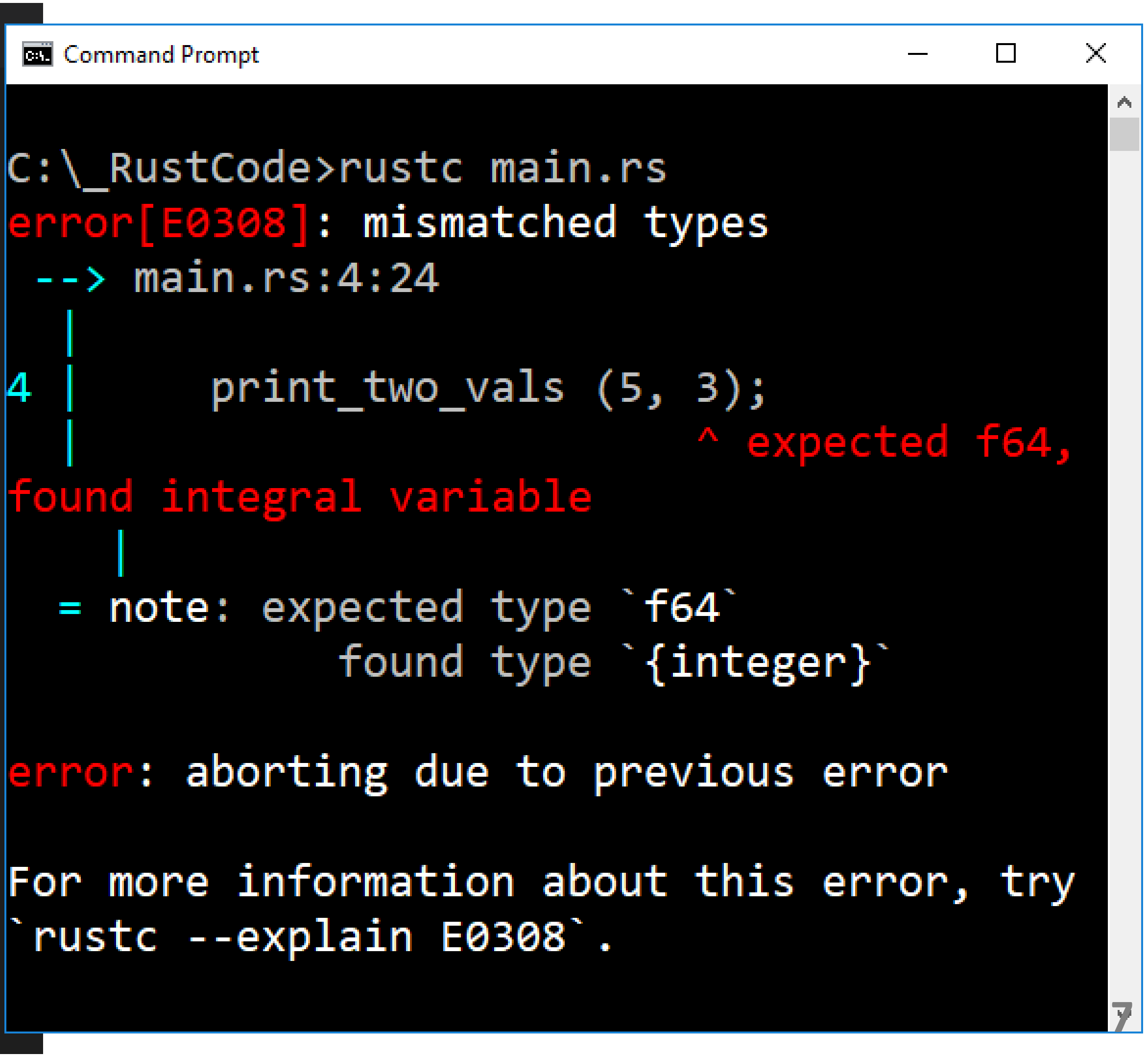
```rust
fn main() {
    let r1 = 3 + 4.0;
    println!("r1: {}", r1);
}
```

Previously



main.rs

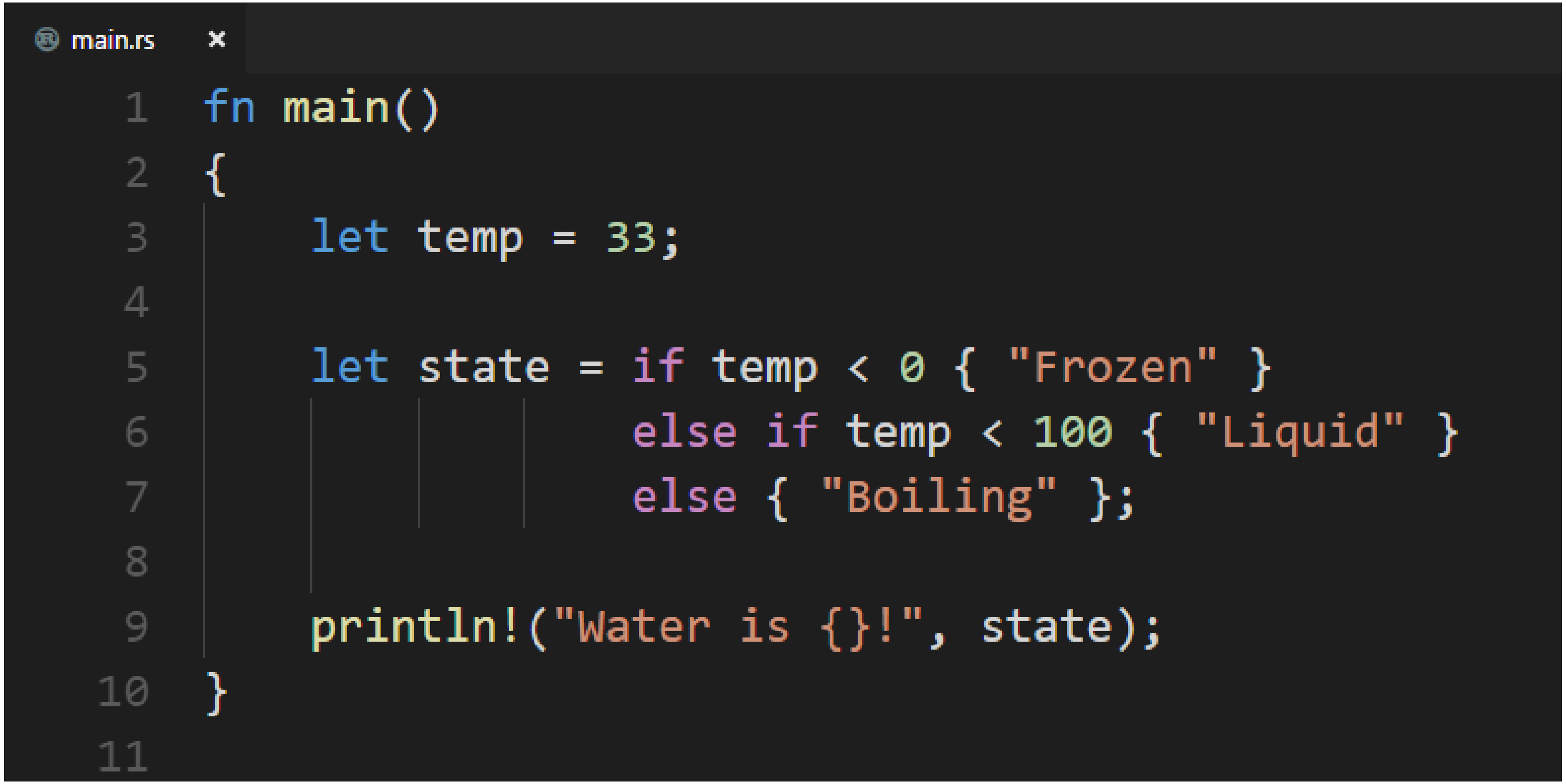
```rust
fn main()
{
    print_val (5);
    print_two_vals (5, 3);
}

fn print_val (n: i32)
{
    println!("{}", n);
}

fn print_two_vals (n1: i32, n2: f64)
{
    println!("{}, {}", n1, n2);
}
```



Command Prompt

```
C:\_RustCode>rustc main.rs
error[E0308]: mismatched types
 --> main.rs:4:24
  |
4 |     print_two_vals (5, 3);
  |                        ^ expected f64,
found integral variable
    |
  = note: expected type `f64`
             found type `{integer}`

error: aborting due to previous error

For more information about this error, try
`rustc --explain E0308`.
```

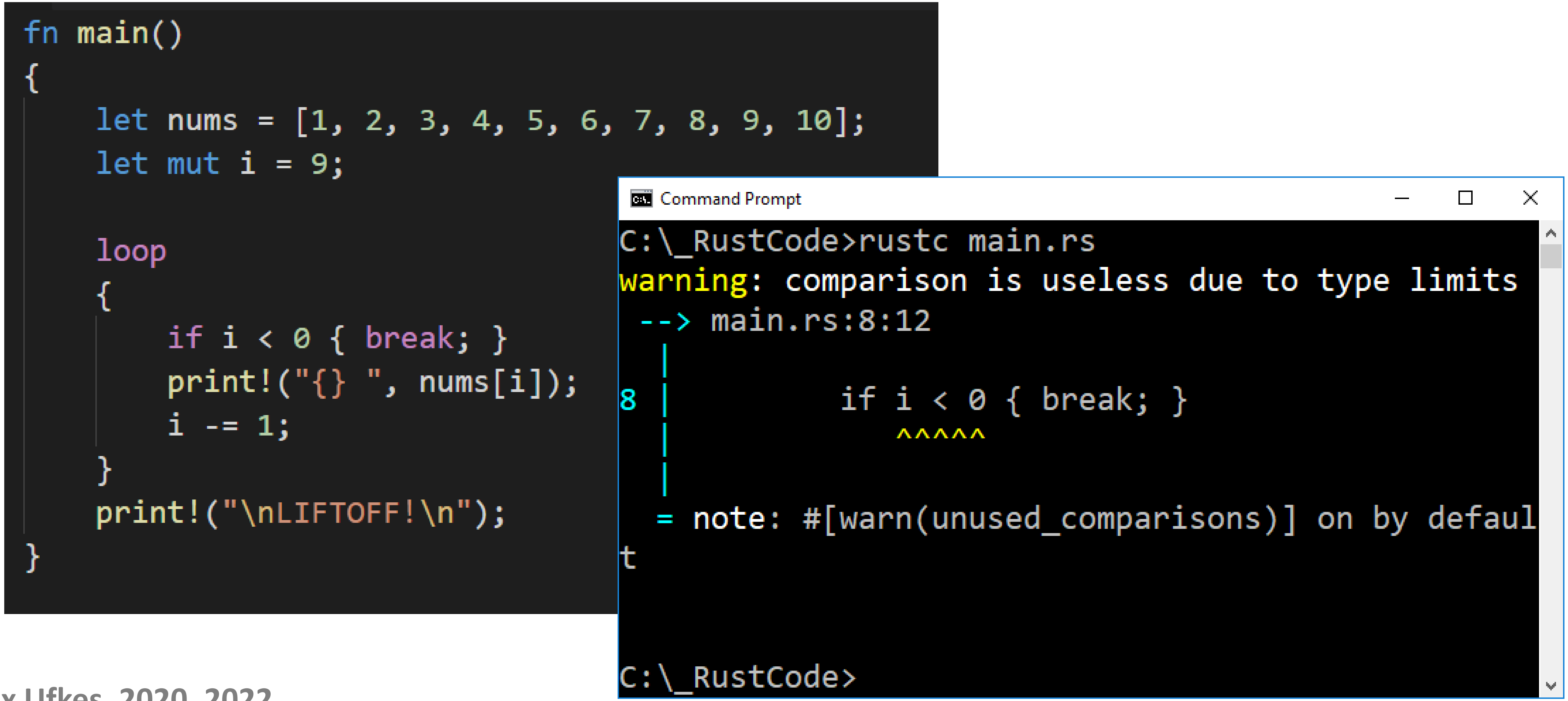
Previously



main.rs

```rust
fn main()
{
    let temp = 33;

    let state = if temp < 0 { "Frozen" }
                else if temp < 100 { "Liquid" }
                else { "Boiling" };

    println!("Water is {}!", state);
}

```

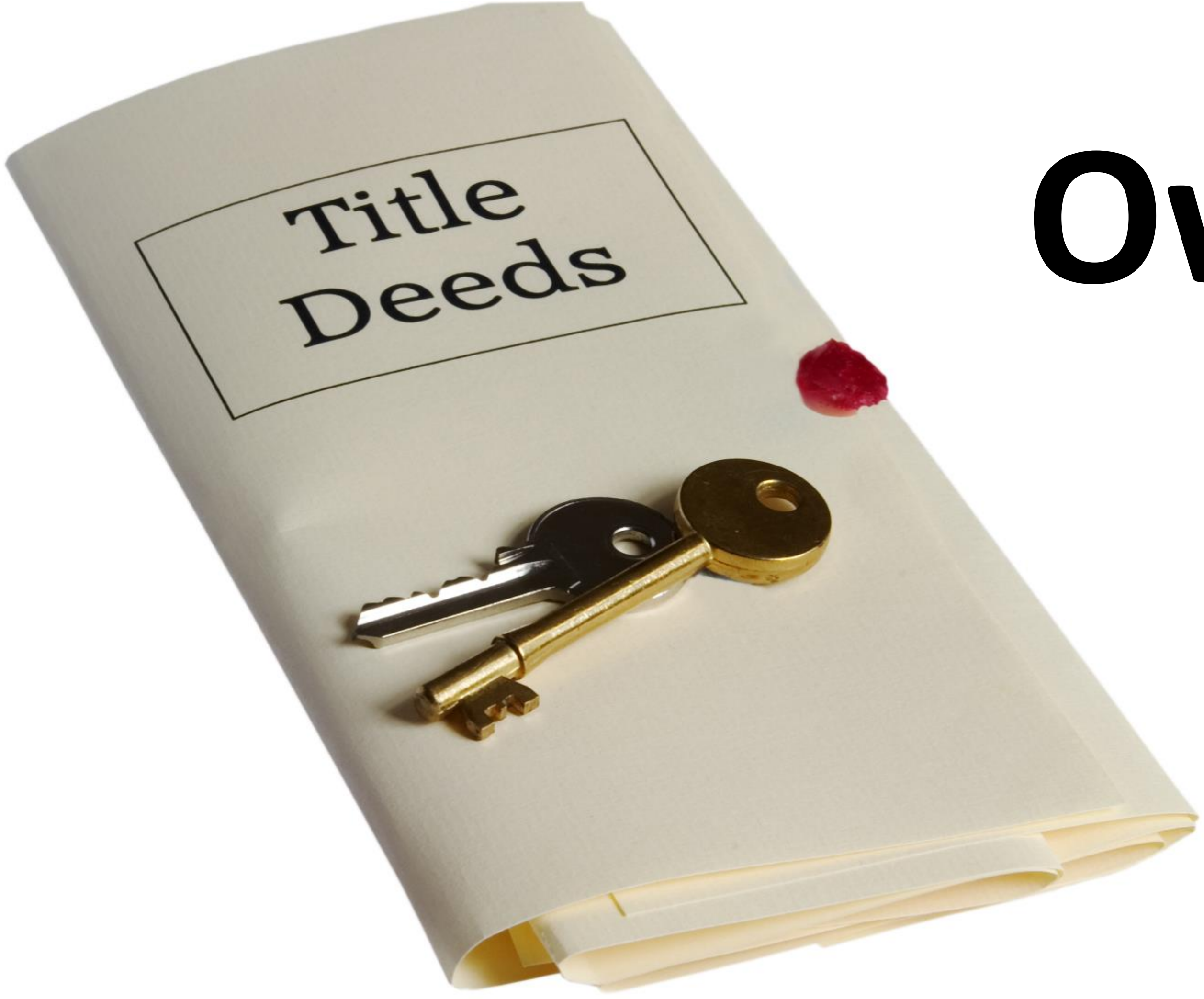
Previously



```rust
fn main()
{
    let nums = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10];
    let mut i = 9;

    loop
    {
        if i < 0 { break; }
        print!("{} ", nums[i]);
        i -= 1;
    }
    print!("\nLIFTOFF!\n");
}
```

```
C:\_RustCode>rustc main.rs
warning: comparison is useless due to type limits
 --> main.rs:8:12
  |
8 |         if i < 0 { break; }
  |            ^^^^^
  |
  = note: #[warn(unused_comparisons)] on by defaul
t


C:\_RustCode>
```

Moving on….



Ownership

Ownership

Arguably Rust's most unique feature:

- In C, the programmer is responsible for allocating and freeing heap memory. Memory leaks common!
- In Java, Smalltalk, Python, Elixir, Haskell, garbage collector periodically looks for unused memory and frees it.
- Rust takes a third approach: A system of ownership with rules checked at compile time.
    - Thus, the program is not slowed at run-time

Reminder: Stack VS Heap

Stack:
- Last in, first out
- Push/pop stack frames is fast
- Data has known, fixed size.

Heap:
- Less organized
- Slower access, follow pointers
- Data size can be unknown

- If we dynamically allocate memory in C/C++, the pointer goes on the stack, the memory itself is in the heap.
- Heap memory is allocated by the OS at the request of the program.
- Stack memory (some fixed amount) managed by the program, no need to involve the OS.

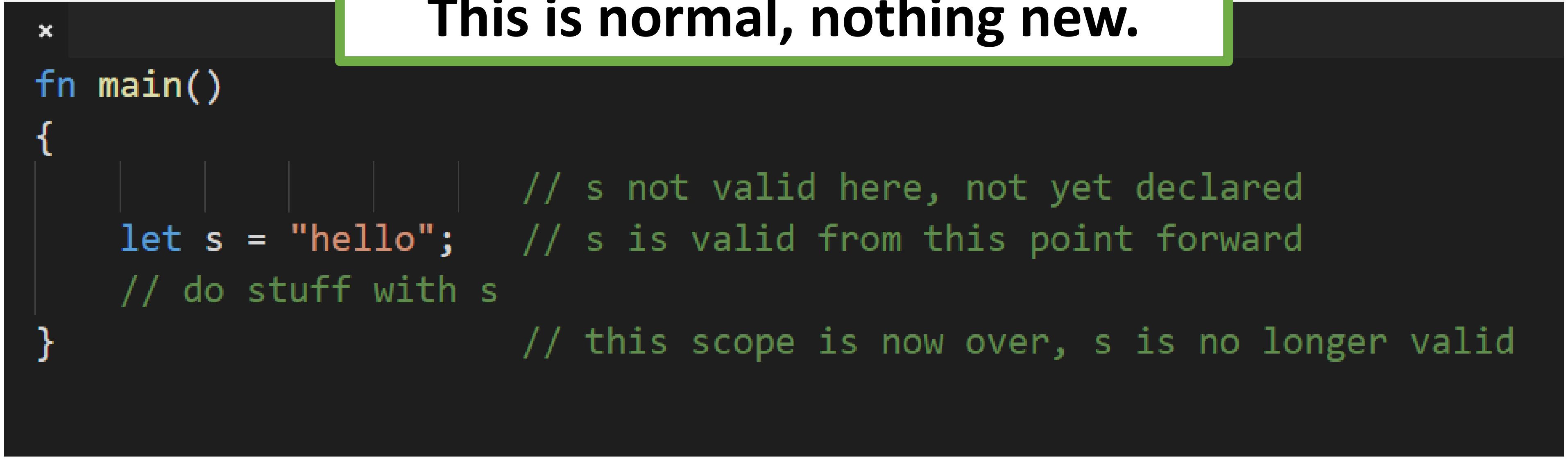
Ownership

Three rules:

1. Each value in Rust has a variable that’s called its ***owner***.
2. There can only be one owner at a time.
3. When the owner goes out of scope, the value is dropped.

Scope in Rust

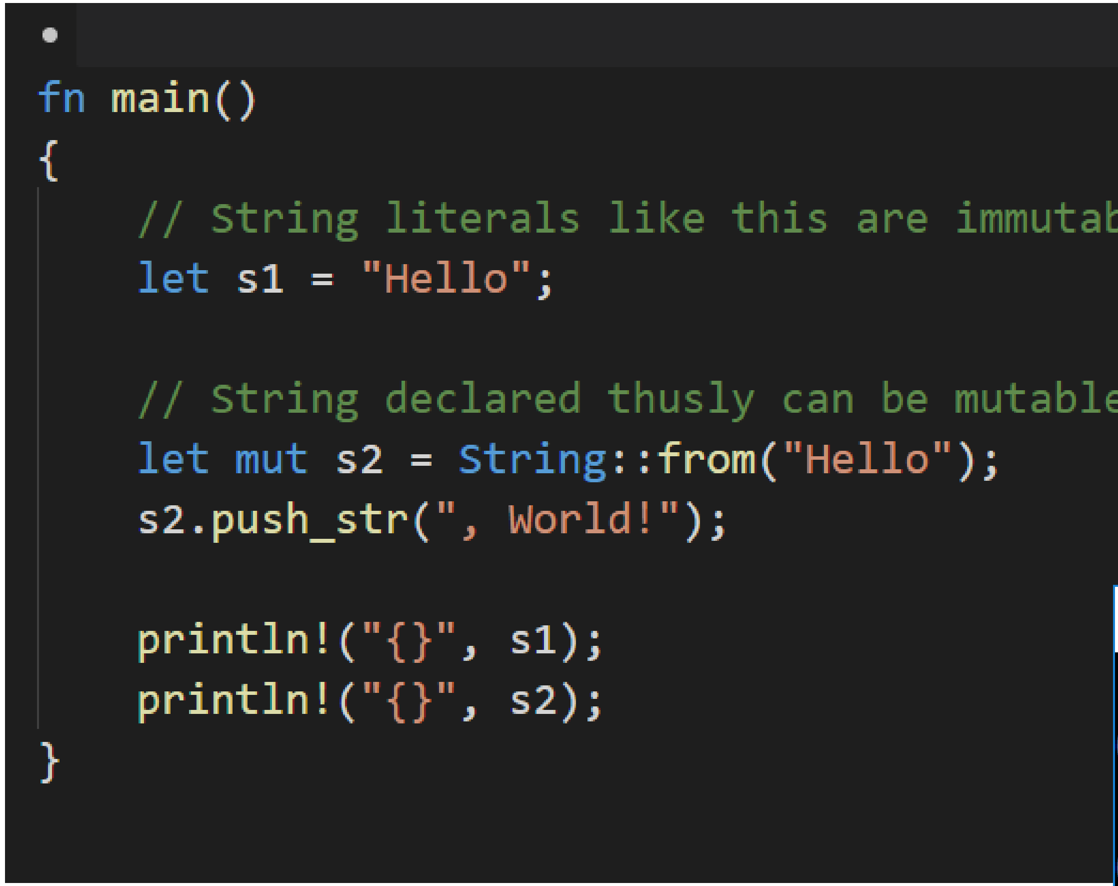
This is normal, nothing new.



```
fn main()
{
                       // s not valid here, not yet declared
    let s = "hello";   // s is valid from this point forward
    // do stuff with s
}                      // this scope is now over, s is no longer valid
```

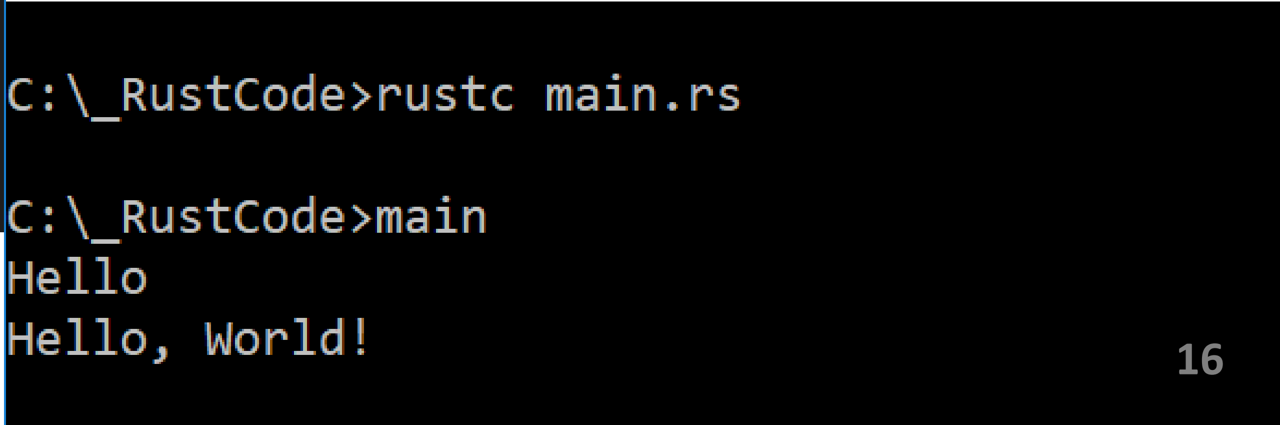
- Primitives stored on the stack behave as per usual.
- How does Rust clean up data stored on the heap?
- Consider Strings – A complex type stored on the heap.

Strings



```rust
fn main()
{
    // String literals like this are immutable!
    let s1 = "Hello";

    // String declared thusly can be mutable:
    let mut s2 = String::from("Hello");
    s2.push_str(", World!");

    println!("{}", s1);
    println!("{}", s2);
}
```

- String literals are different from regular strings.
- Their size is fixed, encoded directly into the executable.
- Strings not defined as a literal might have unknown size
- They are stored on the heap.

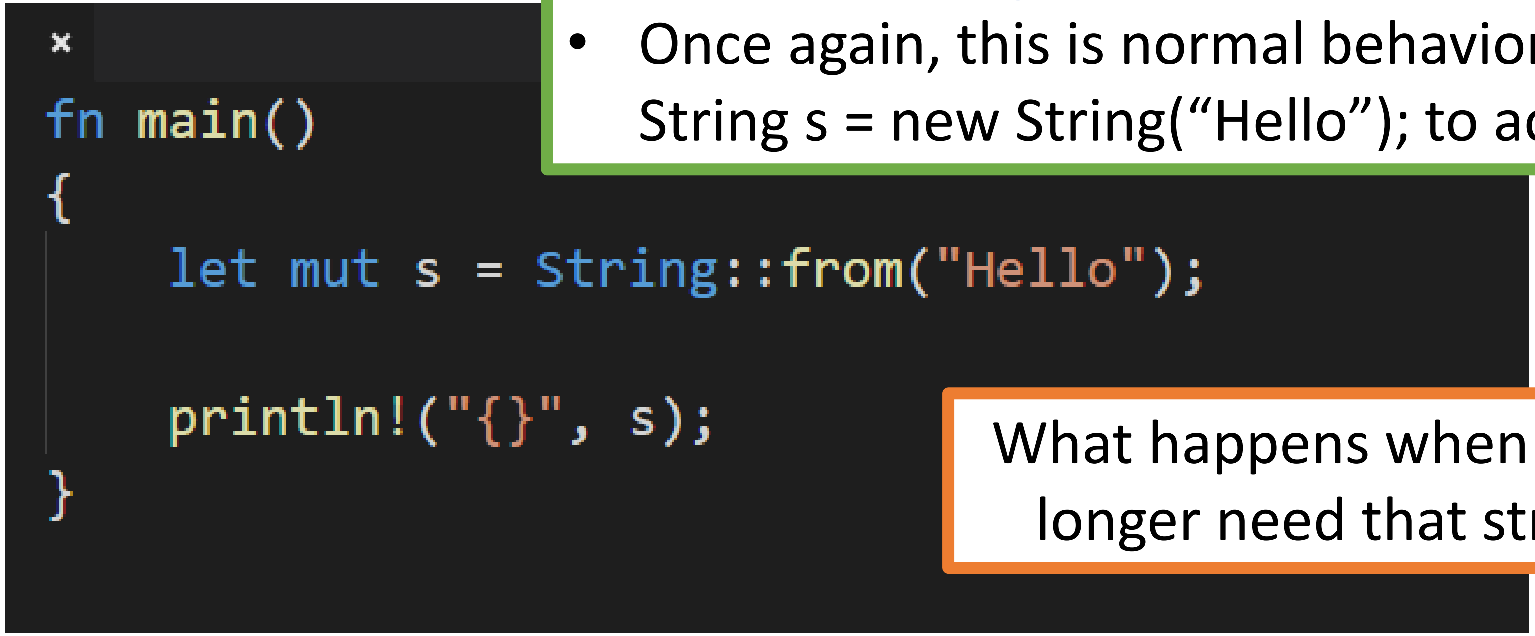


```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
Hello
Hello, World!
```

Heap Strings

- Memory for string requested at run time.
- Memory must be returned to the OS when we're done with the string.

- Calling `String::from` makes a memory request.
- Once again, this is normal behavior. In Java we would say: String s = new String("Hello"); to accomplish the same.



```
fn main()
{
    let mut s = String::from("Hello");

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

What happens when we no longer need that string?

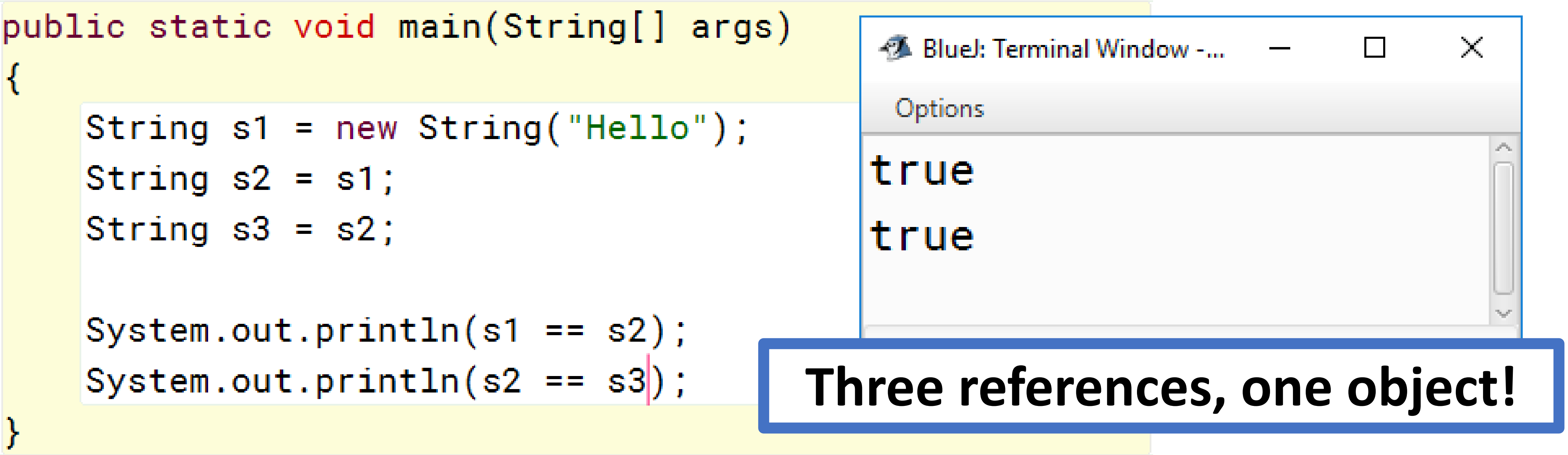
What happens when we no longer need that string?

- Without garbage collection, we must identify when memory is no longer being used and free it explicitly.
- This has historically been a difficult programming problem.
- Too early, variables still in scope become invalid. Too late, waste memory. Do it twice by accident? Also a problem.
- We need to pair one **`allocate()`** to one **`free()`**.

In Rust, memory is automatically returned when the variable that ***owns*** it leaves scope.

In Rust, memory is automatically returned
when the variable that owns it leaves scope.

What about having multiple references to a single object?
Freeing after one leaves scope could invalidates the others.



```java
public static void main(String[] args)
{
    String s1 = new String("Hello");
    String s2 = s1;
    String s3 = s2;

    System.out.println(s1 == s2);
    System.out.println(s2 == s3);
}
```

```
true
true
```

Three references, one object!

But Remember!

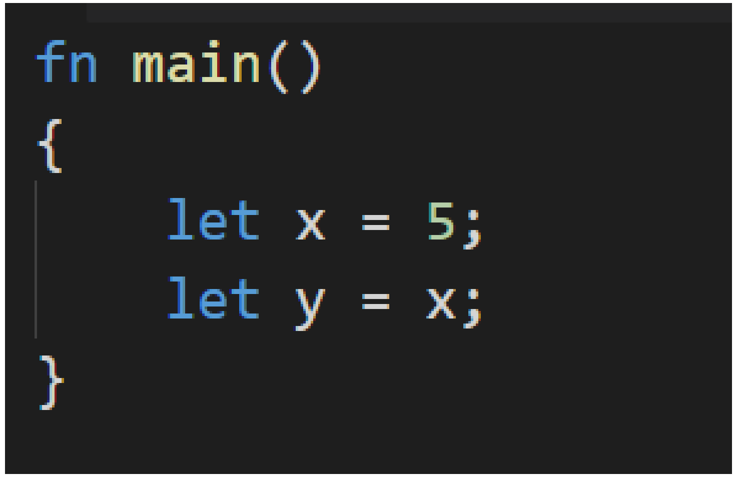
Ownership - Three Rules:

1. Each value in Rust has a variable that’s called its *owner*.
2. There can only be one owner at a time.
3. When the owner goes out of scope, the value is dropped.

There can only be one!

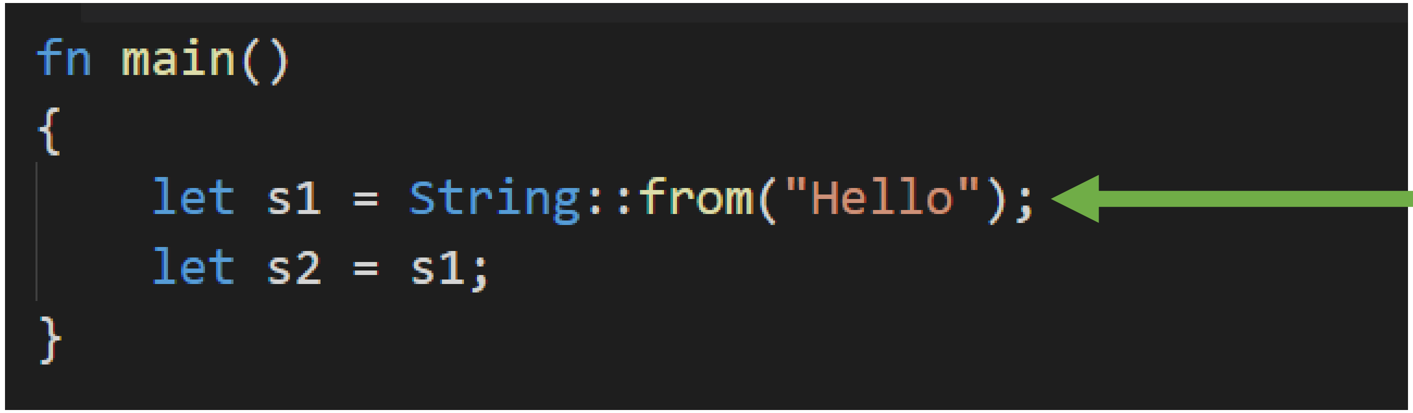
In Rust, memory is automatically returned when the variable that owns it leaves scope.

- When a variable goes out of scope, Rust calls a special function automatically called **`drop()`**
- This function is called at the closing **}**
- What happens if we have multiple variables interacting with the same data?

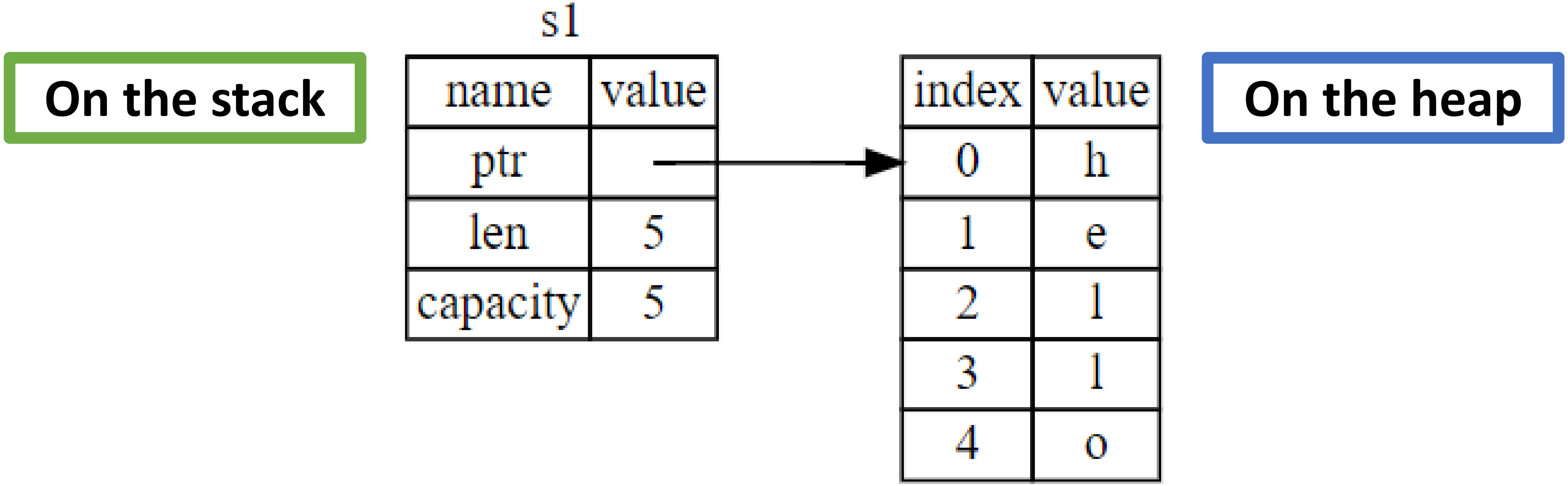


```
fn main()
{
    let x = 5;
    let y = x;
}
```

- With primitives, we get two separate variables stored in memory (stack)
- **x** and **y** are separate – changing one does not affect the other
- This is typical, and efficient

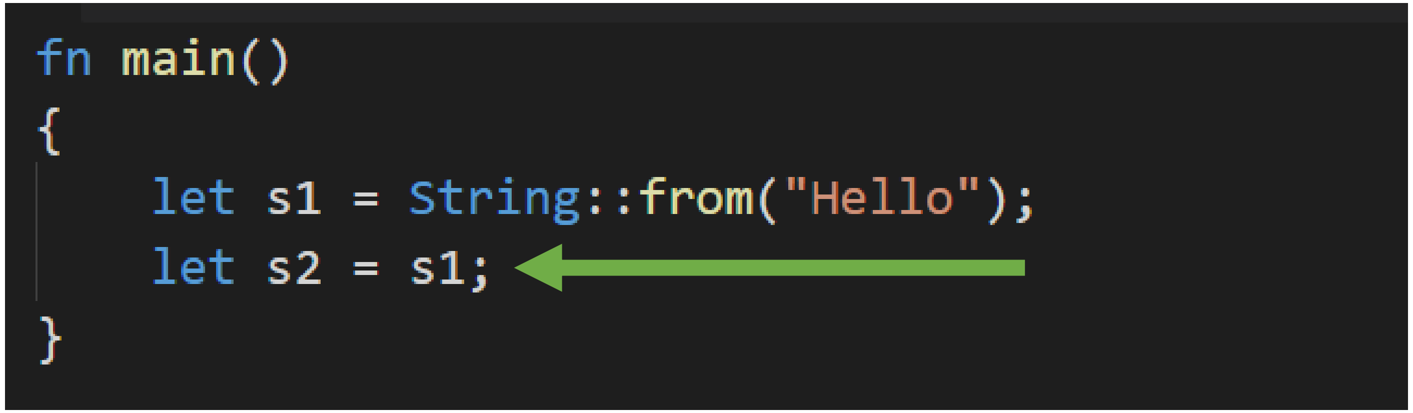


```
fn main()
{
    let s1 = String::from("Hello");
    let s2 = s1;
}
```

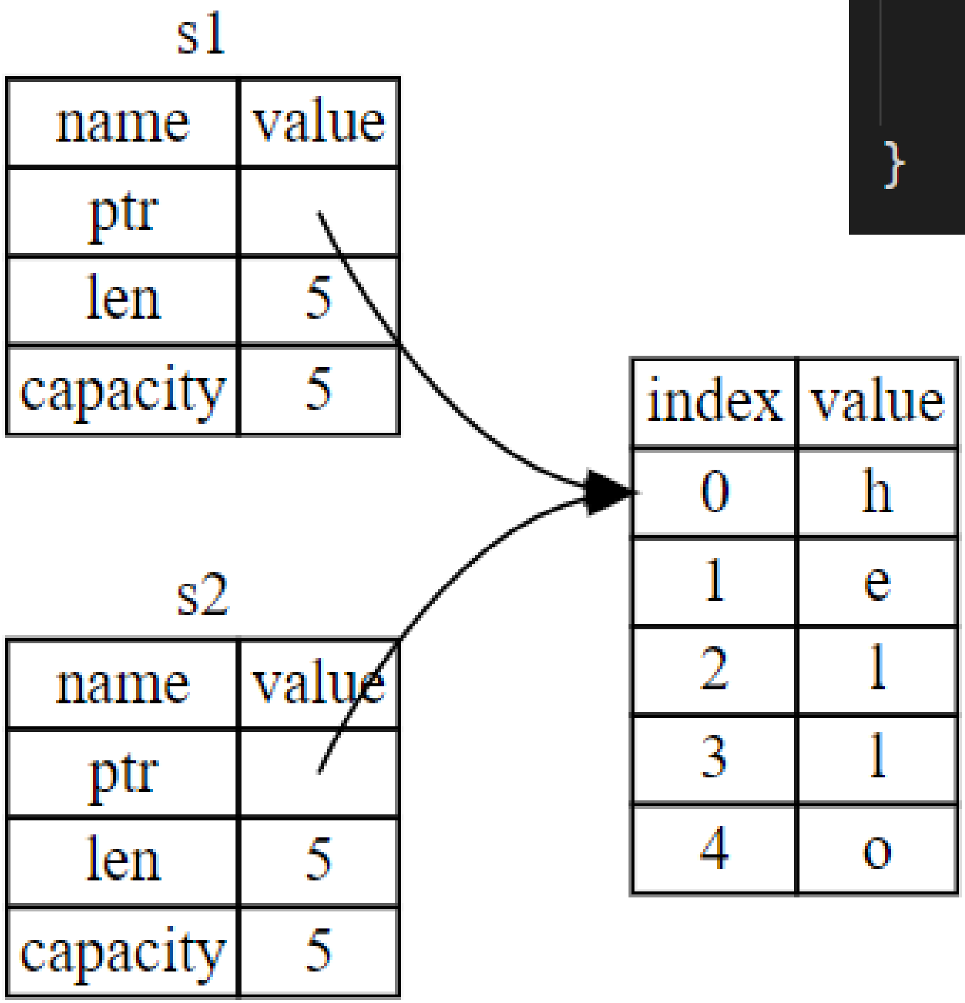


name	value
ptr	
len	5
capacity	5

index	value
0	h
1	e
2	l
3	l
4	o



```
fn main()
{
    let s1 = String::from("Hello");
    let s2 = s1;
}
```



s1

name	value
ptr	
len	5
capacity	5

s2

name	value
ptr	
len	5
capacity	5

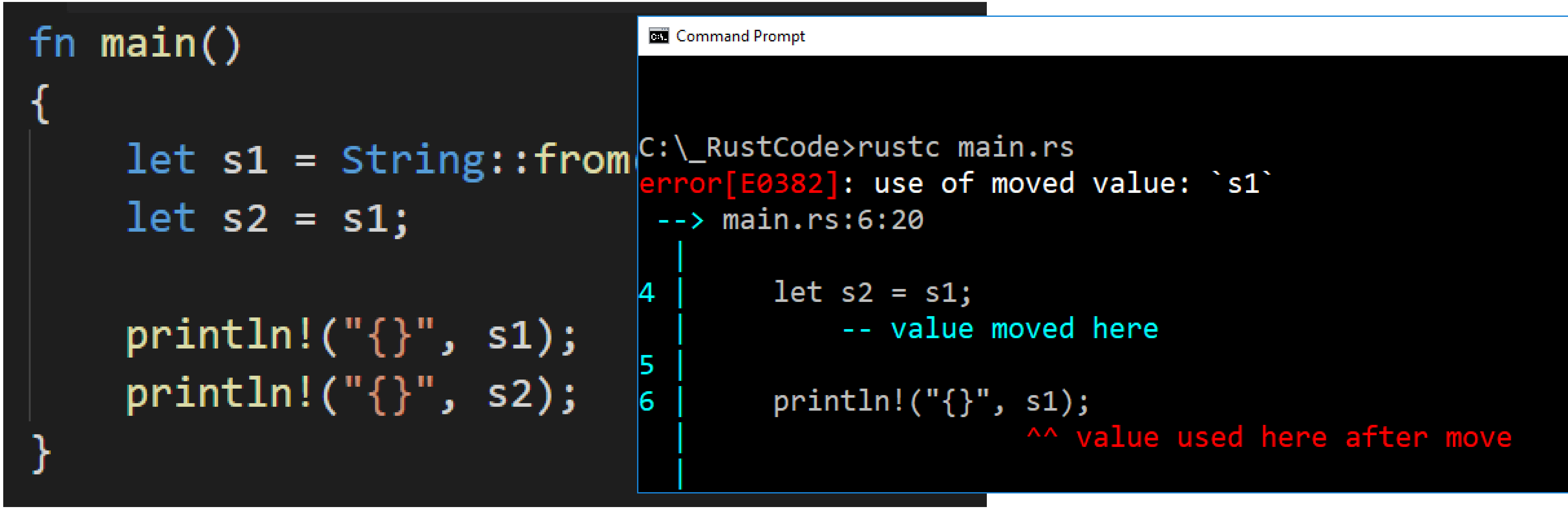
index	value
0	h
1	e
2	l
3	l
4	o

- Stack data copied; heap data is not.
- Copying heap data is more expensive.
- This is typical in most imperative languages.
- We can still potentially free data twice
- We can still potentially invalidate other references

1. Each value in Rust has a variable that’s called its *owner*.

2. There can only be one owner at a time.

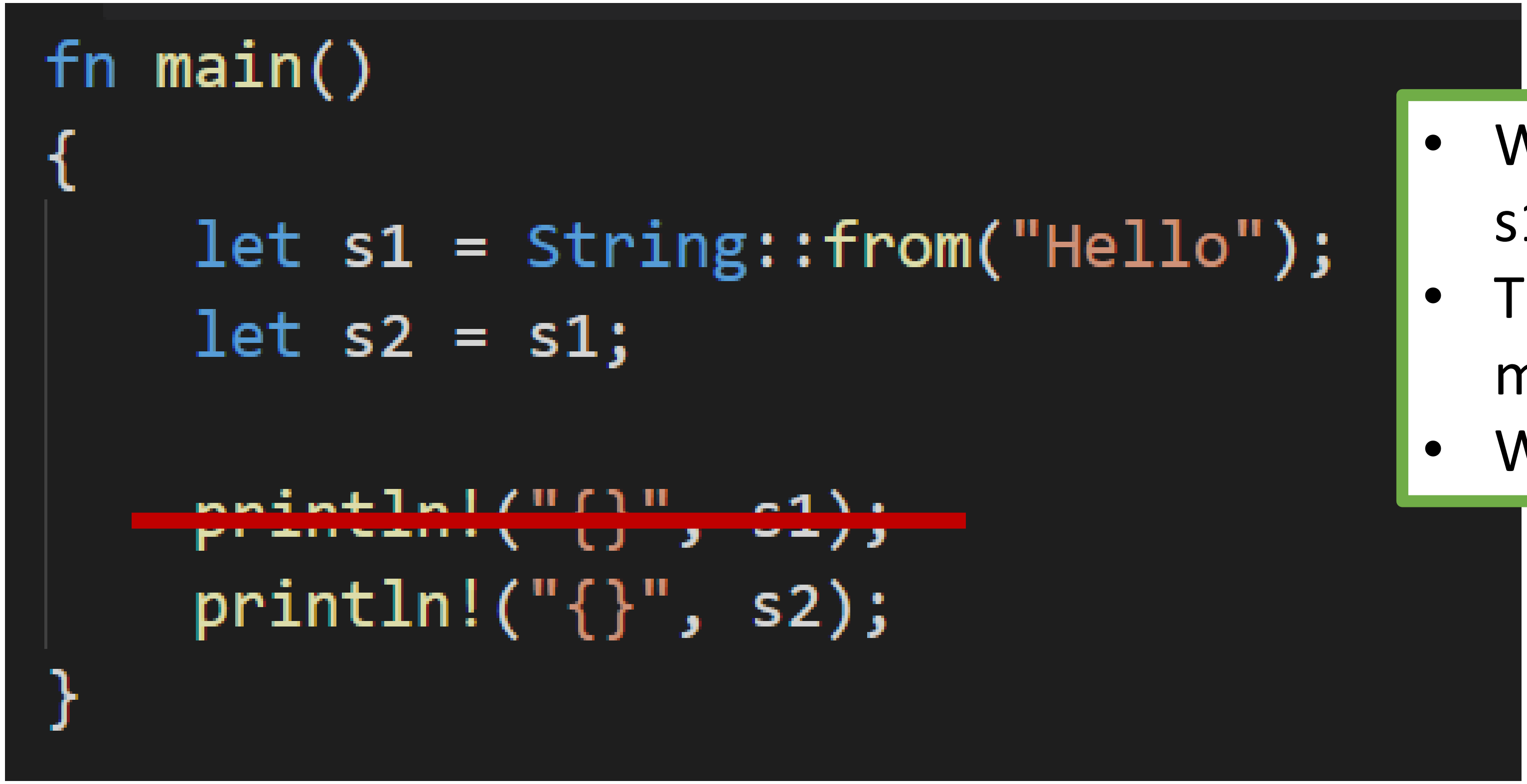
3. When the owner goes out of scope, the value is dropped.



```
fn main()
{
    let s1 = String::from
    let s2 = s1;

    println!("{}", s1);
    println!("{}", s2);
}
```

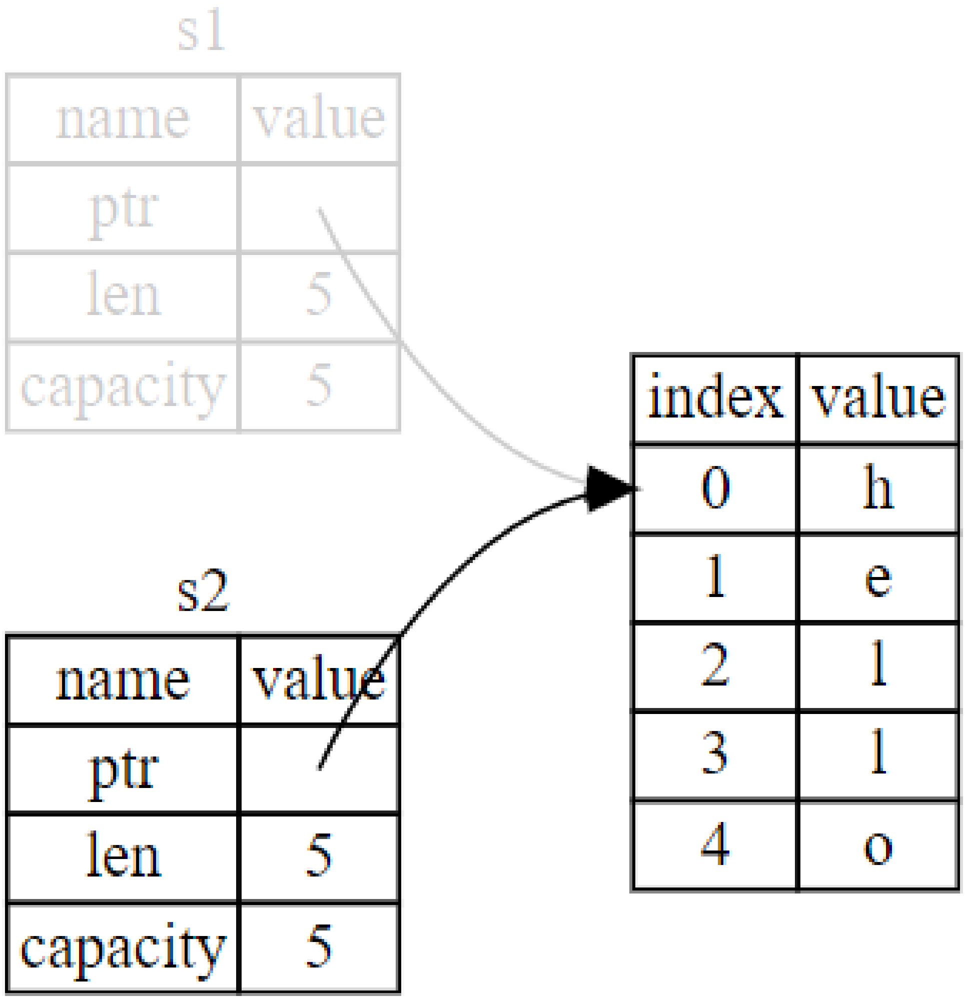
```
C:\_RustCode>rustc main.rs
error[E0382]: use of moved value: `s1`
 --> main.rs:6:20
  |
4 |     let s2 = s1;
  |         -- value moved here
5 |
6 |     println!("{}", s1);
  |                    ^^ value used here after move
  |
```

1. Each value in Rust has a variable that's called its *owner*.
2. **There can only be one owner at a time.**
3. When the owner goes out of scope, the value is dropped.



```
fn main()
{
    let s1 = String::from("Hello");
    let s2 = s1;

    ~~println!("{}", s1);~~
    println!("{}", s2);
}
```

- When we say `let s2=s1`, s1 becomes invalid.
- Thus, when it leaves scope, memory is not freed.
- We can no longer use s1!



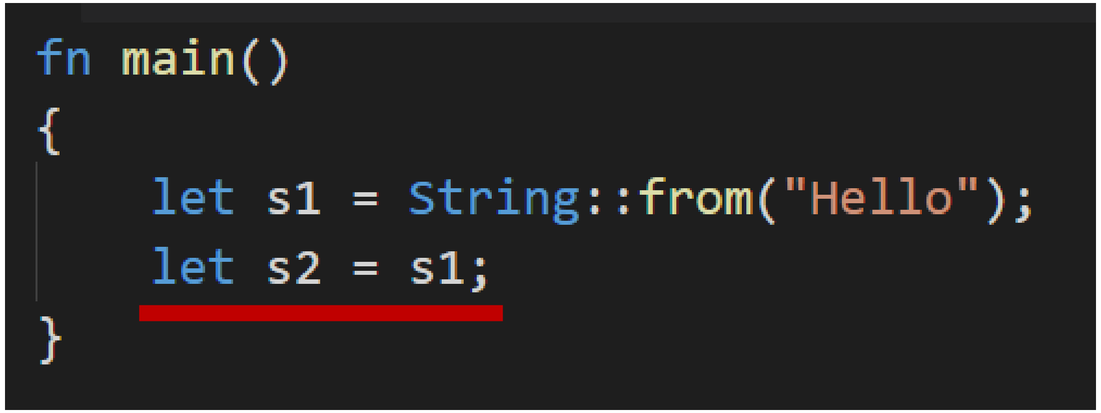
s1

name	value
ptr	
len	5
capacity	5

s2

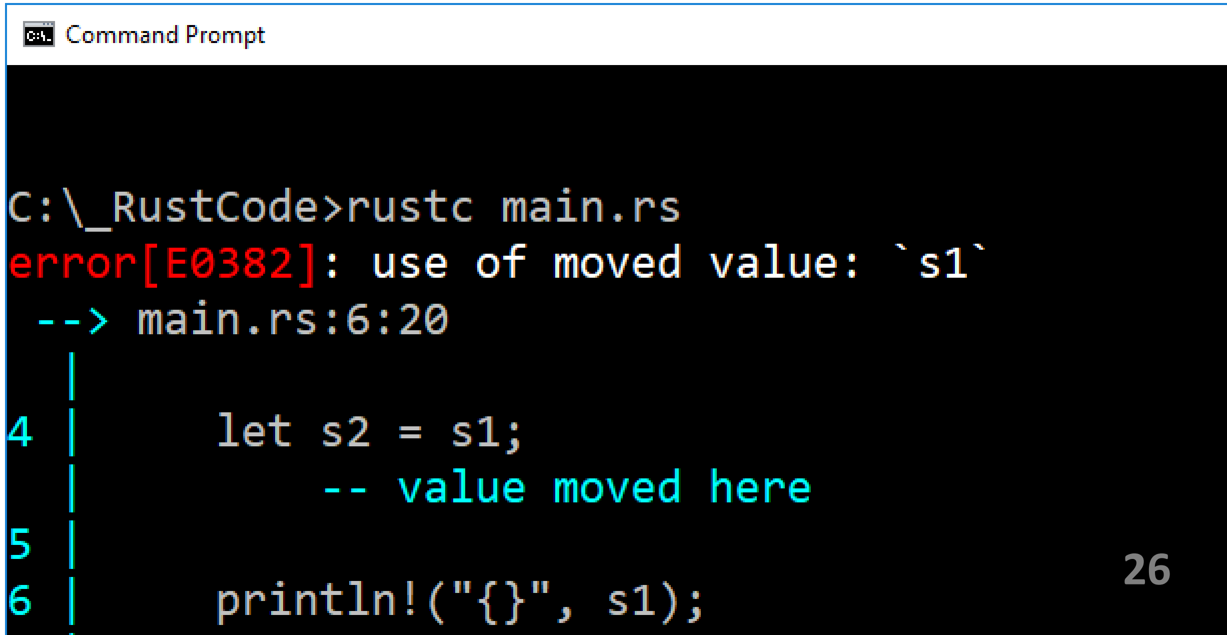
name	value
ptr	
len	5
capacity	5

index	value
0	h
1	e
2	l
3	l
4	o



```rust
fn main()
{
    let s1 = String::from("Hello");
    let s2 = s1;
}
```

In Rust, we say s1 gets *moved* to s2



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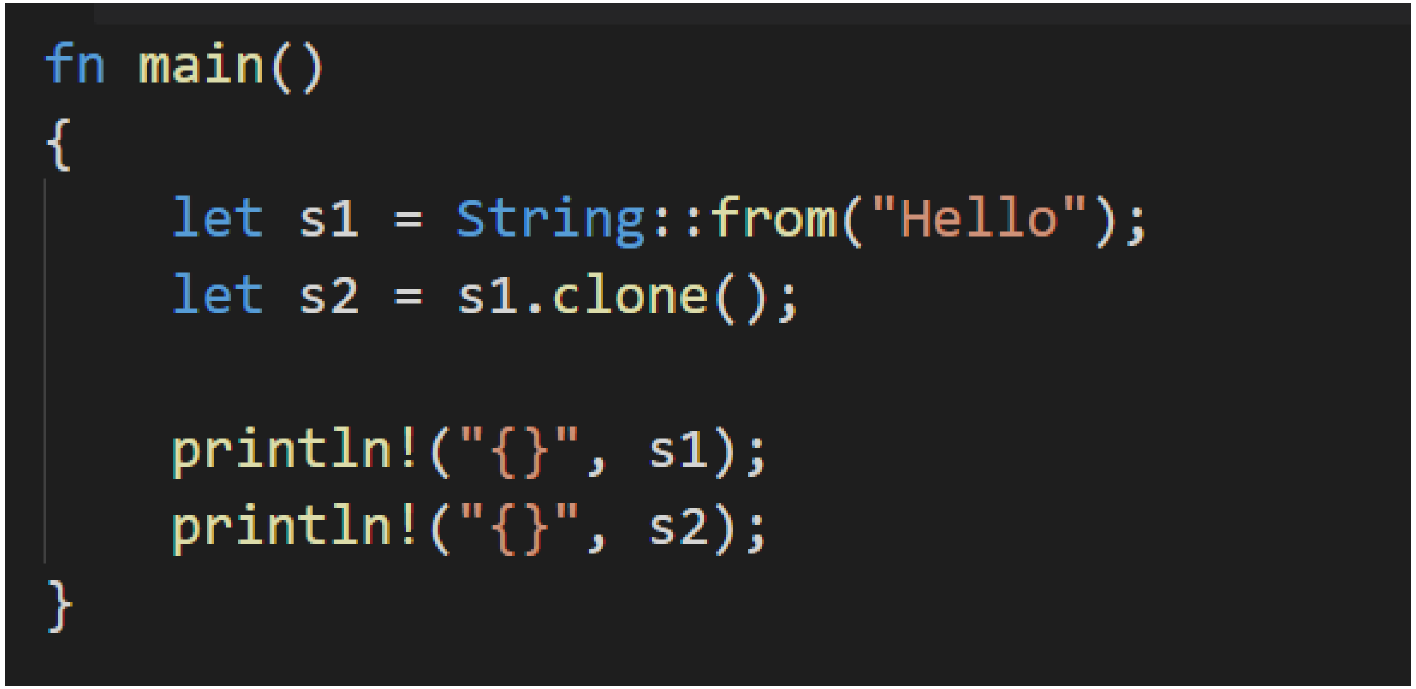
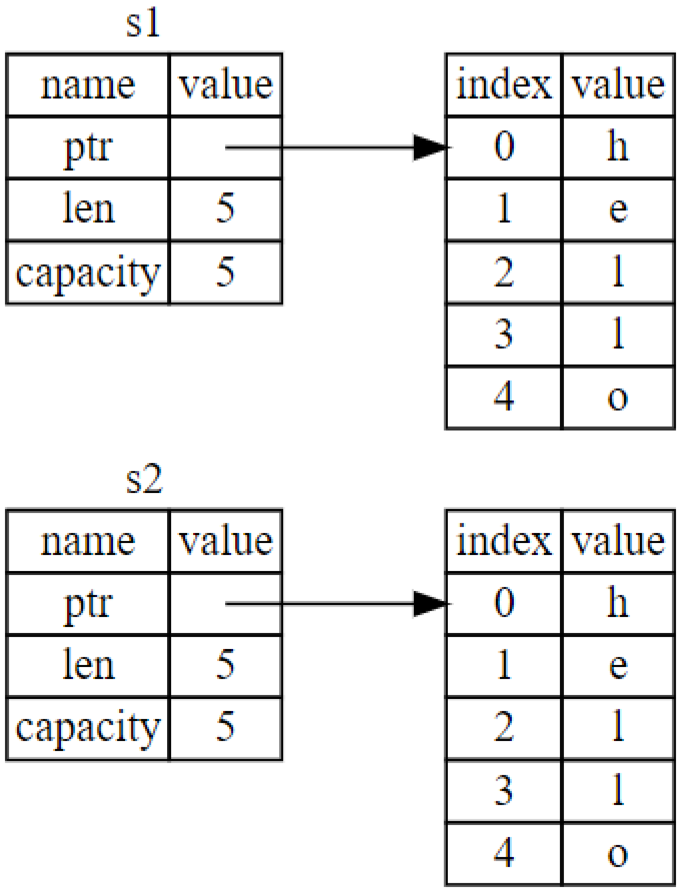
error[E0382]: use of moved value: `s1`
 --> main.rs:6:20
  |
4 |     let s2 = s1;
  |         -- value moved here
5 |
6 |     println!("{}", s1);
```

clone()

Like most languages, Rust can clone:



```rust
fn main()
{
    let s1 = String::from("Hello");
    let s2 = s1.clone();

    println!("{}", s1);
    println!("{}", s2);
}
```



s1

name	value
ptr	
len	5
capacity	5

index	value
0	h
1	e
2	l
3	l
4	o

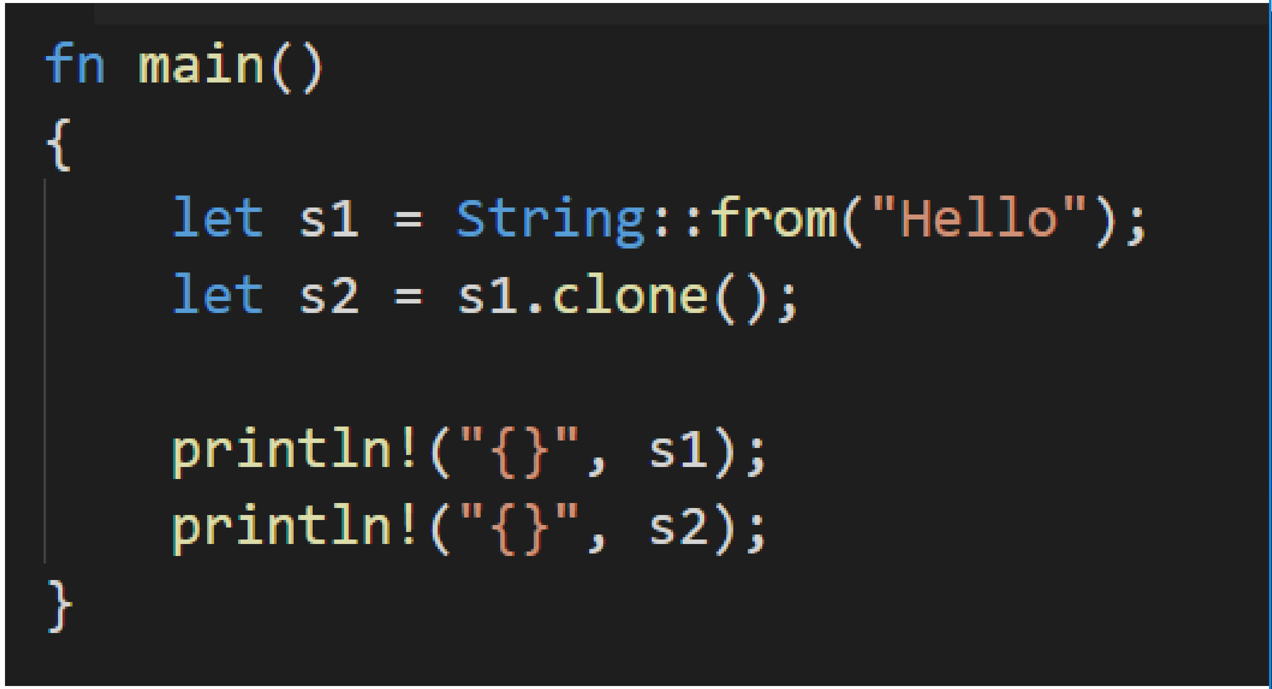
s2

name	value
ptr	
len	5
capacity	5

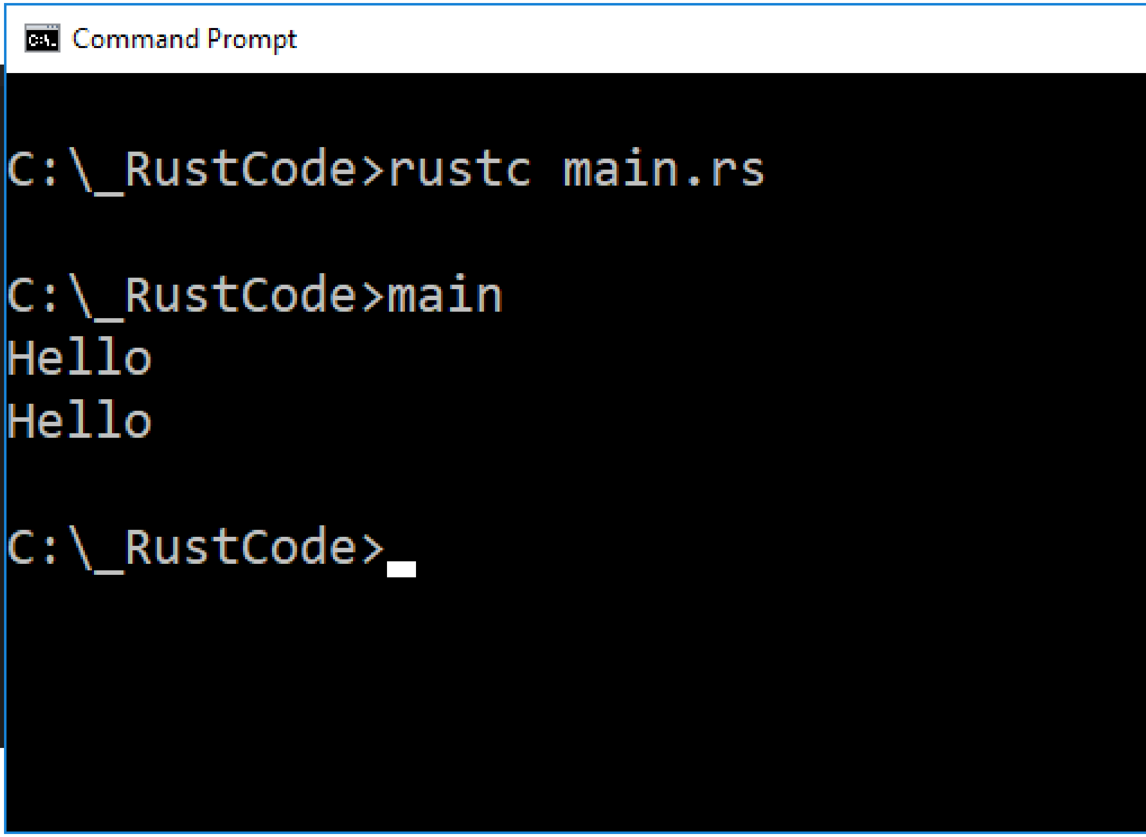
index	value
0	h
1	e
2	l
3	l
4	o

clone()

Like most languages, Rust can clone:



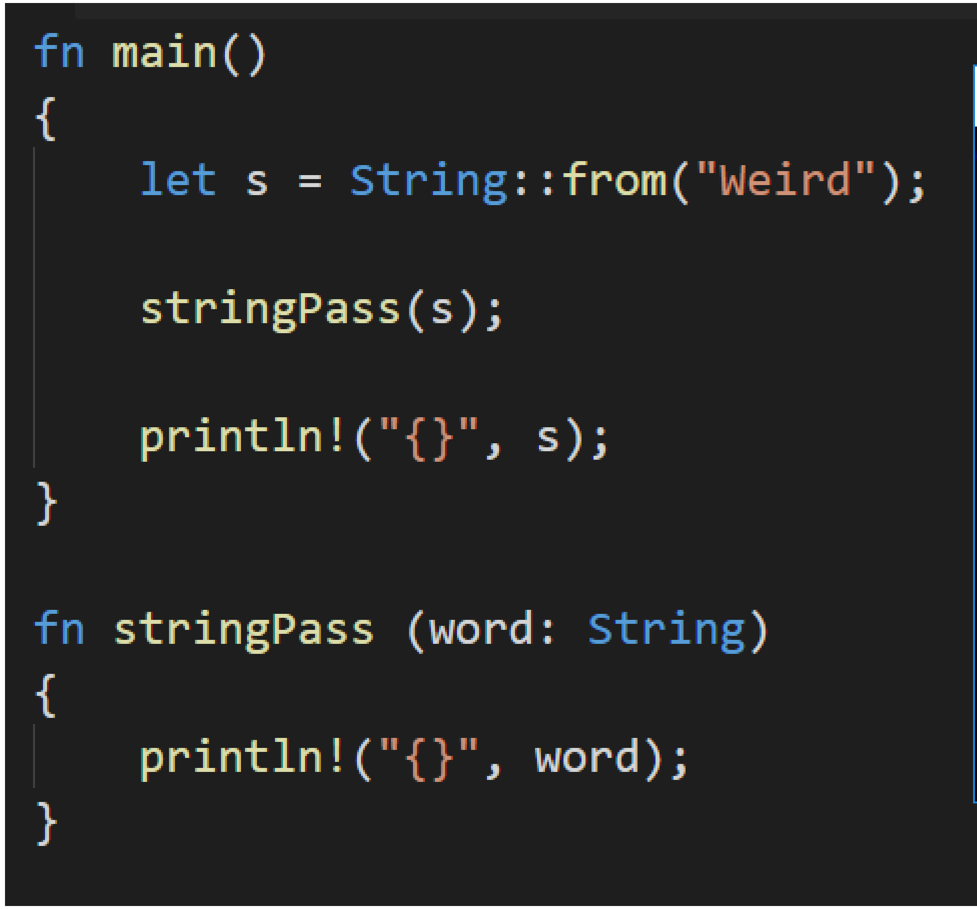
```rust
fn main()
{
    let s1 = String::from("Hello");
    let s2 = s1.clone();

    println!("{}", s1);
    println!("{}", s2);
}
```



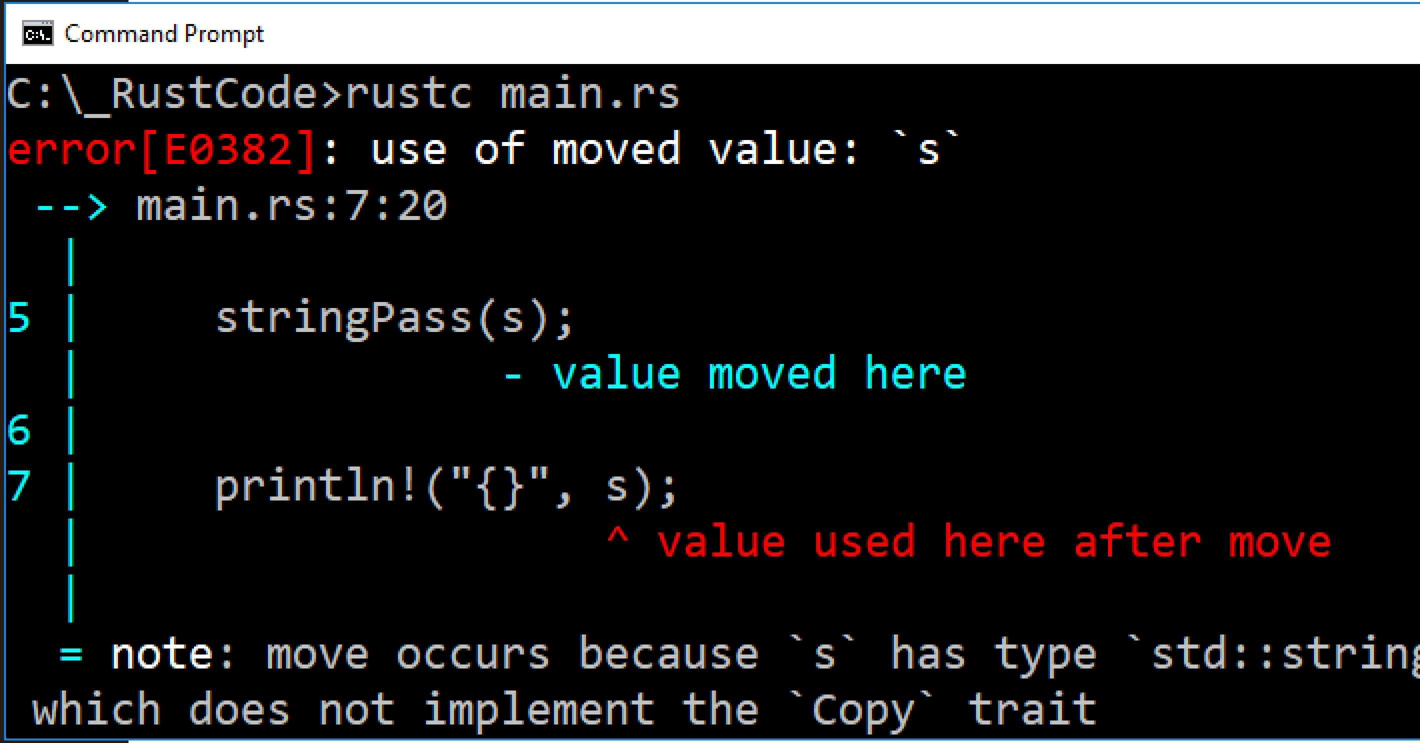
```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
Hello
Hello

C:\_RustCode>_
```

Ownership and Functions

Passing an argument moves or copies, just like assignment:



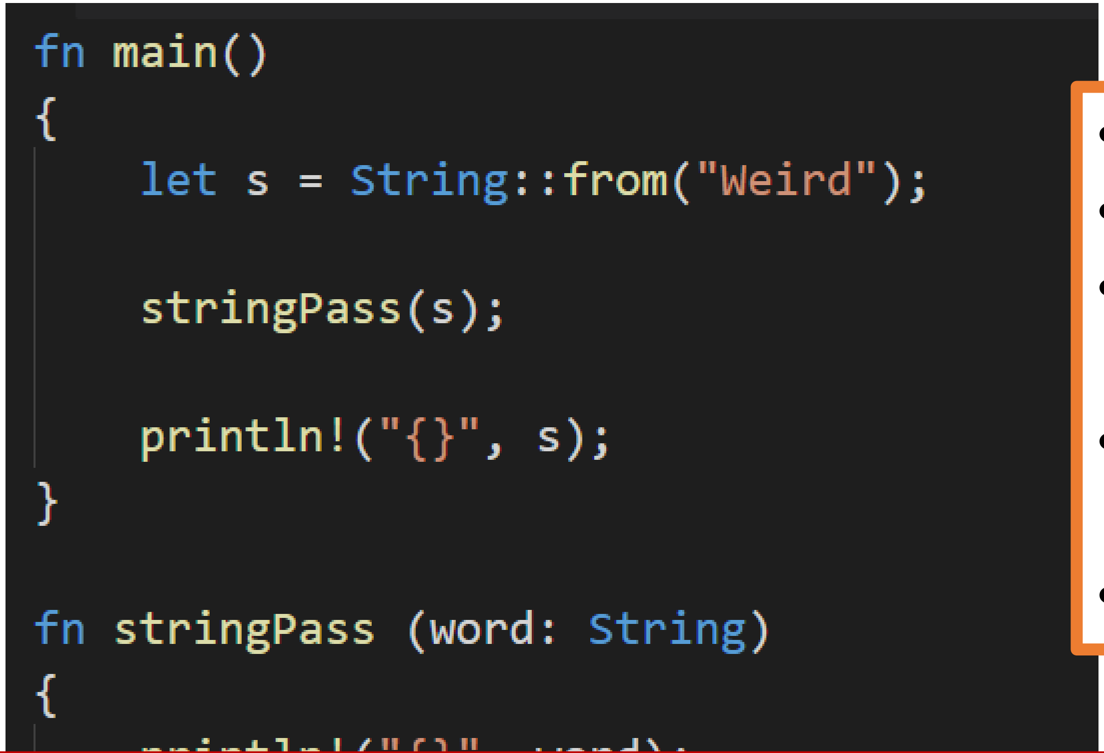
```
fn main()
{
    let s = String::from("Weird");

    stringPass(s);

    println!("{}", s);
}

fn stringPass (word: String)
{
    println!("{}", word);
}
```



```
C:\_RustCode>rustc main.rs
error[E0382]: use of moved value: `s`
 --> main.rs:7:20
  |
5 |     stringPass(s);
  |                - value moved here
6 |
7 |     println!("{}", s);
  |                    ^ value used here after move
  |
  = note: move occurs because `s` has type `std::string
 which does not implement the `Copy` trait
```

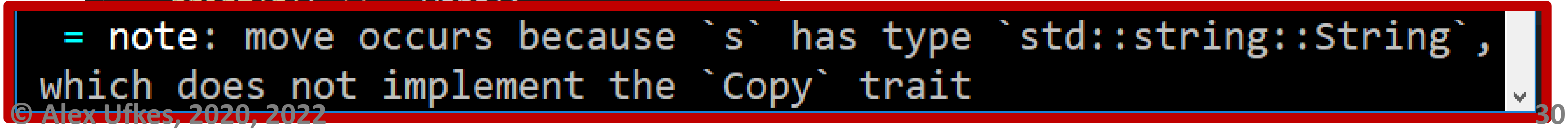
Ownership and Functions

Passing an argument moves or copies, just like assignment:



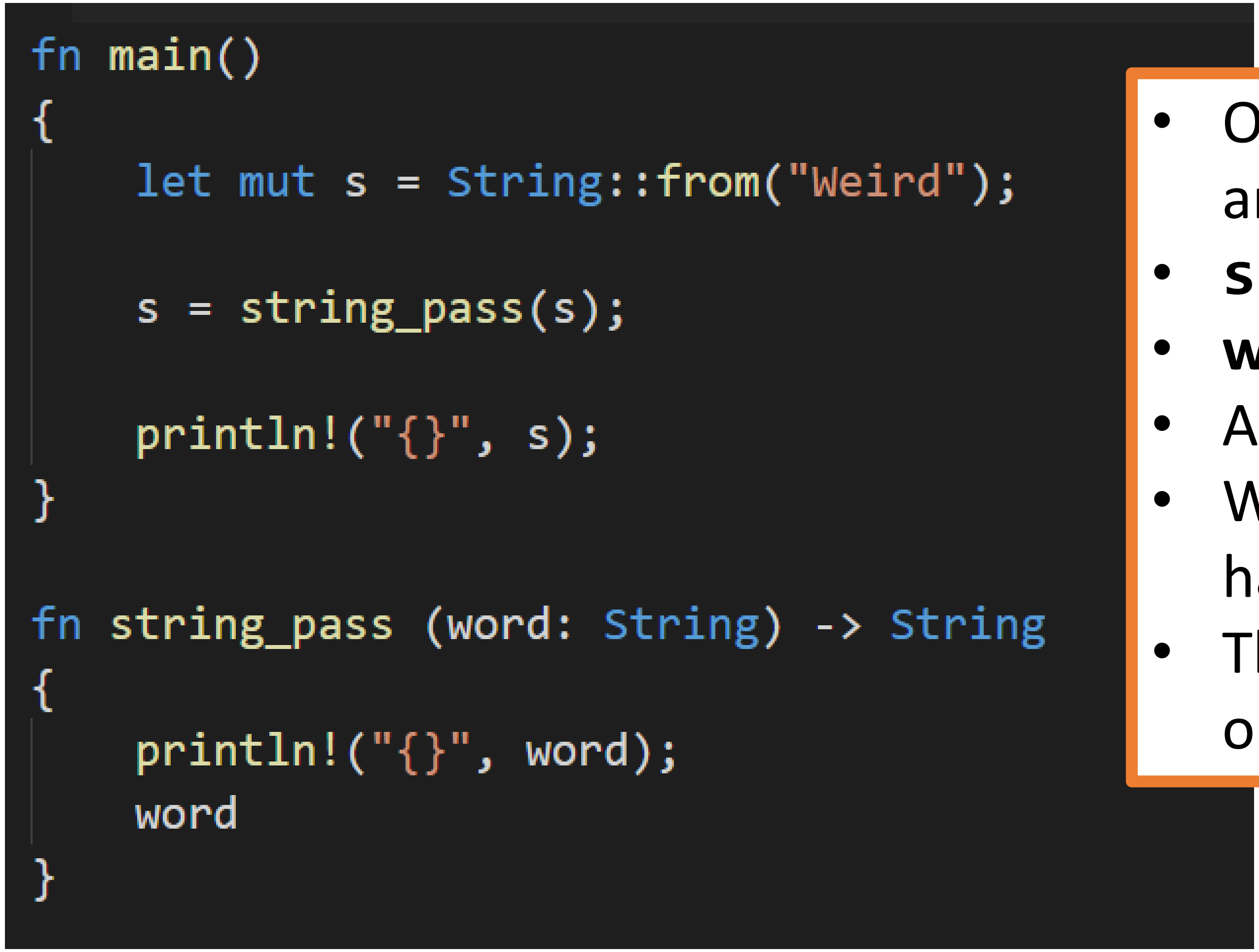
```
fn main()
{
    let s = String::from("Weird");

    stringPass(s);

    println!("{}", s);
}

fn stringPass (word: String)
{
    println!("{}", word);
```

- Ownership moved from **s** to **word**!
- **s** is now invalid!
- This is very different from any other language we're used to.
- This doesn't happen with primitives because they will simply be copied.
- We get a hint:



```
  = note: move occurs because `s` has type `std::string::String`,
which does not implement the `Copy` trait
```

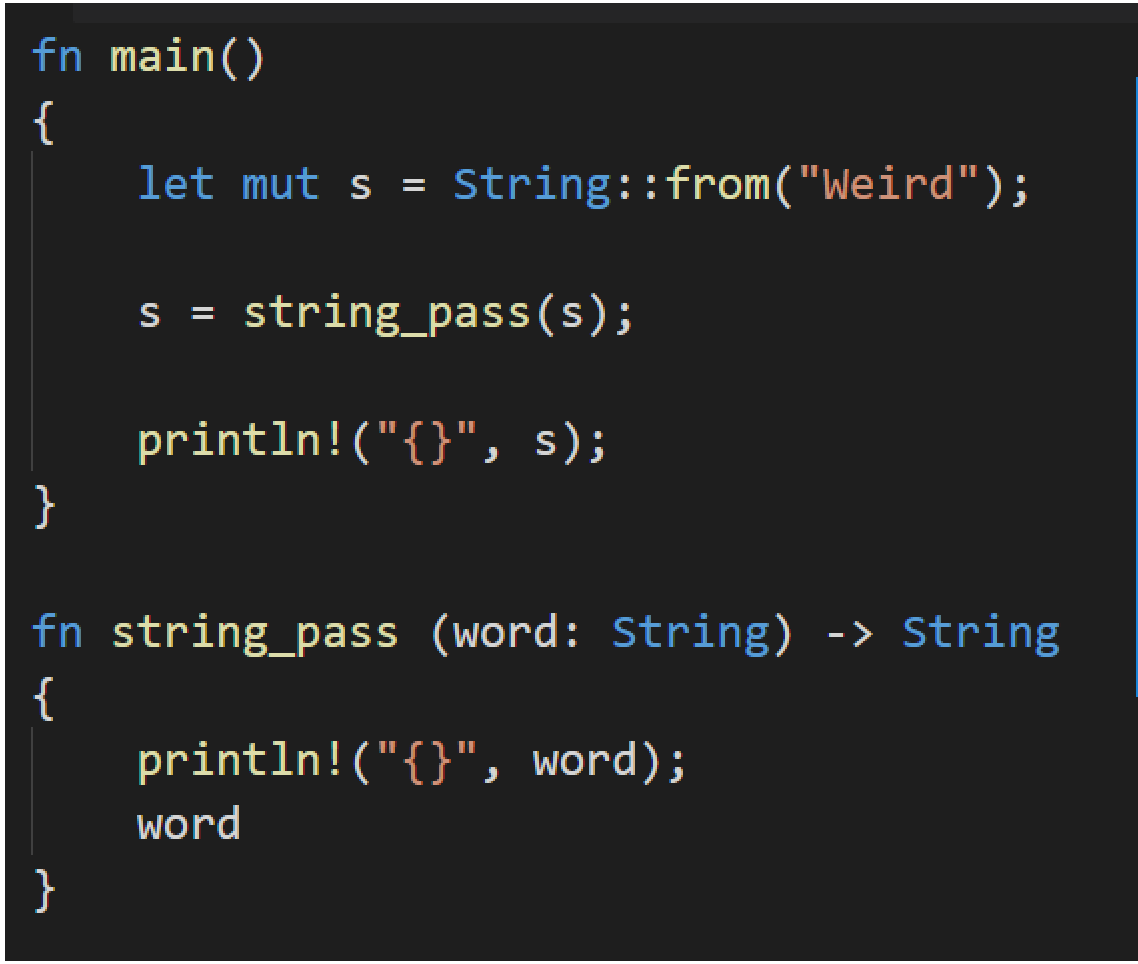
Returning Ownership



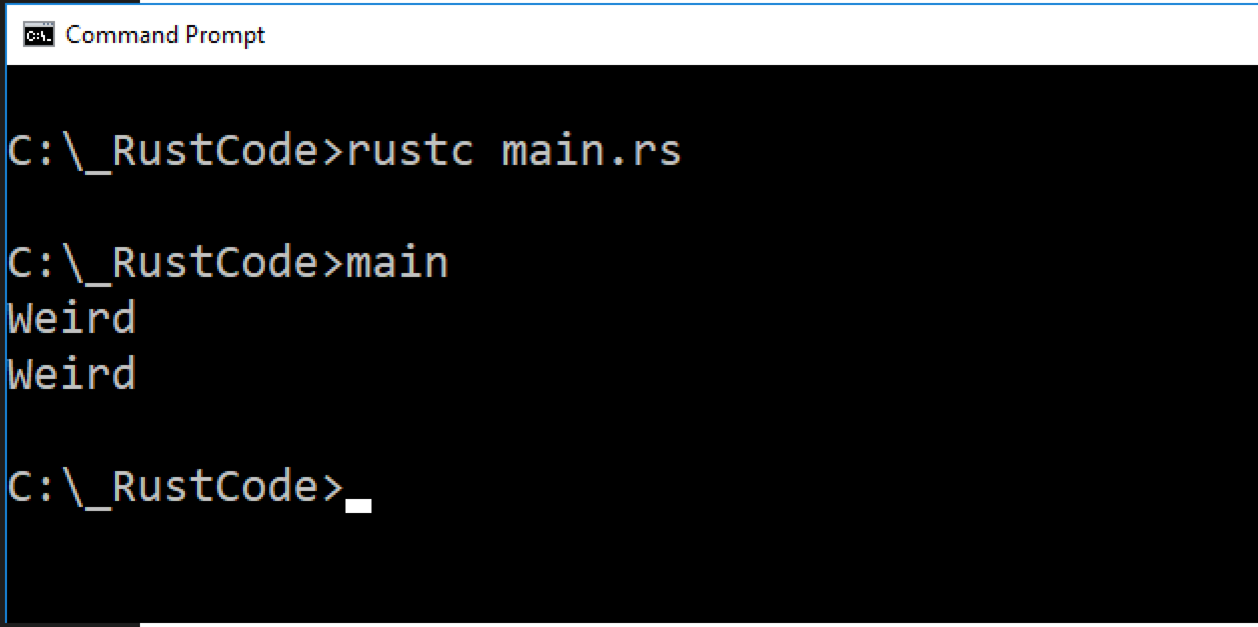
```
fn main()
{
    let mut s = String::from("Weird");

    s = string_pass(s);

    println!("{}", s);
}

fn string_pass (word: String) -> String
{
    println!("{}", word);
    word
}
```

- Ownership moved from **s** to **word** and back to **s**
- **s** is invalid when we move to **word**
- **word** is invalid when moved to **s**
- Allowed because **s** is mutable.
- When string_pass reaches }, **word** has already been moved to **s**
- Thus **word** is invalid and the string on the heap isn't freed.

Returning Ownership



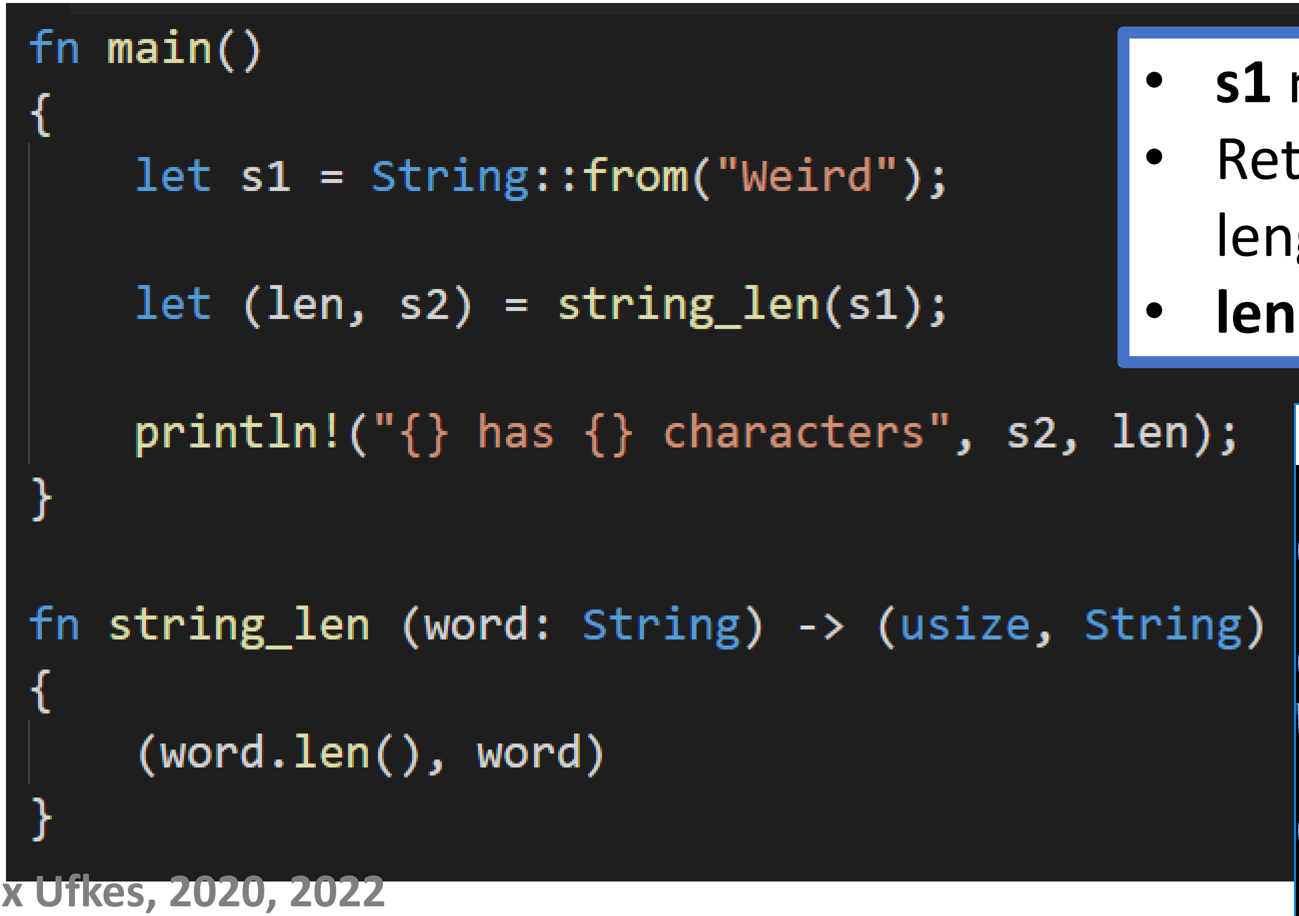
```rust
fn main()
{
    let mut s = String::from("Weird");

    s = string_pass(s);

    println!("{}", s);
}

fn string_pass (word: String) -> String
{
    println!("{}", word);
    word
}
```



```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
Weird
Weird

C:\_RustCode>_
```

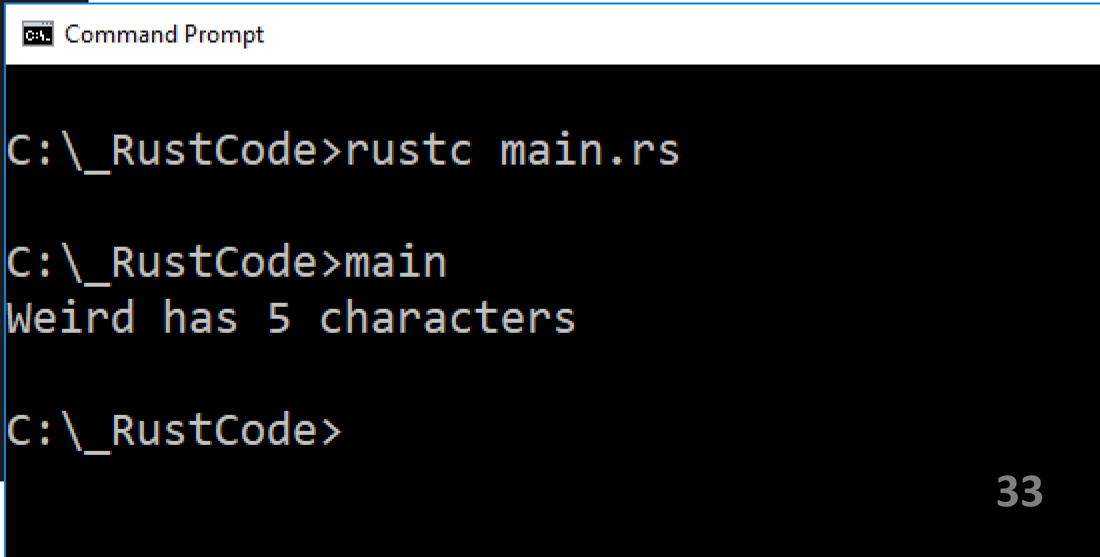
Returning Ownership

Limiting. Forced to use return value for ownership.



```
fn main()
{
    let s1 = String::from("Weird");

    let (len, s2) = string_len(s1);

    println!("{} has {} characters", s2, len);
}

fn string_len (word: String) -> (usize, String)
{
    (word.len(), word)
}
```

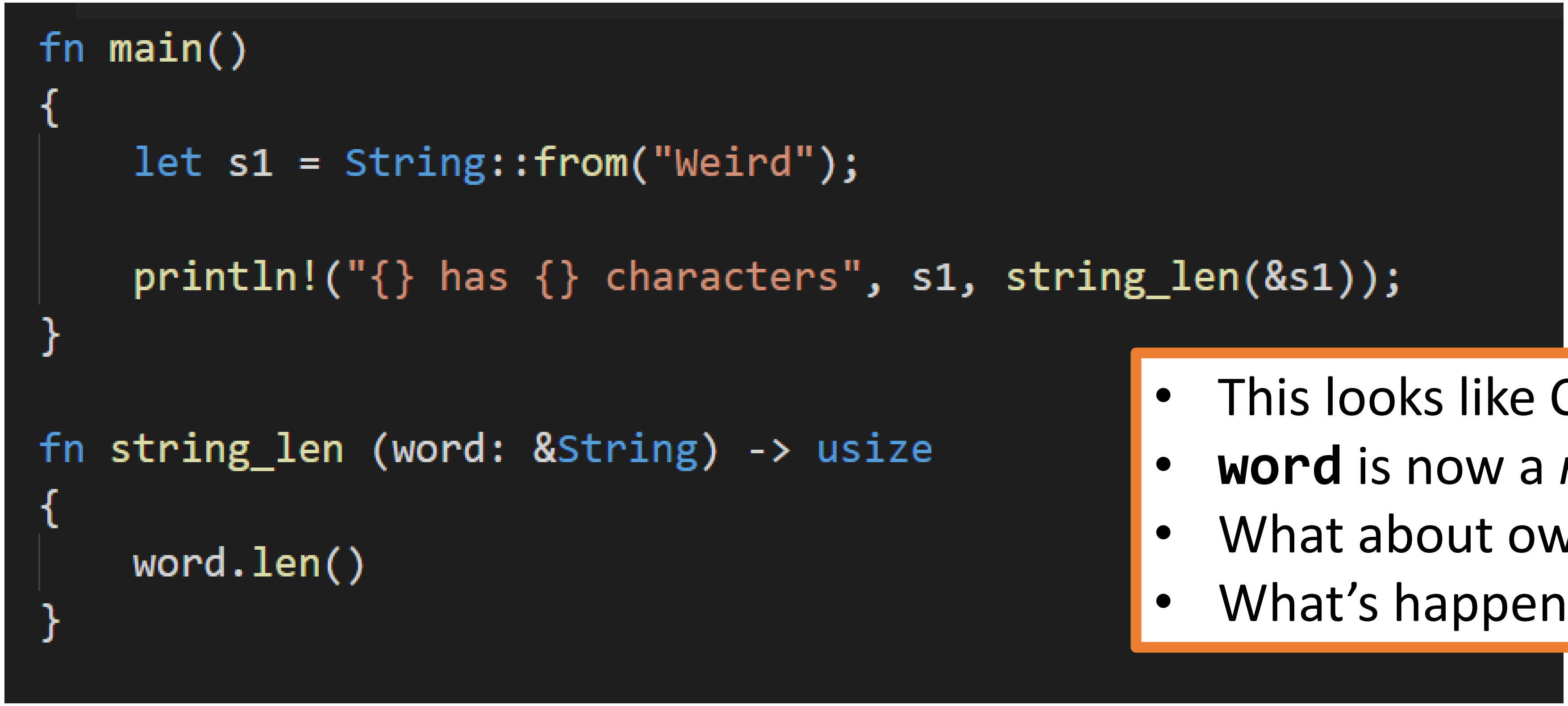
- **s1** moves to **word**, **word** moves to **s2**
- Return a tuple consisting of the length of word, and word itself.
- **len()** function returns length of array.



```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
Weird has 5 characters

C:\_RustCode>
```

Ownership: Moving VS *Borrowing*

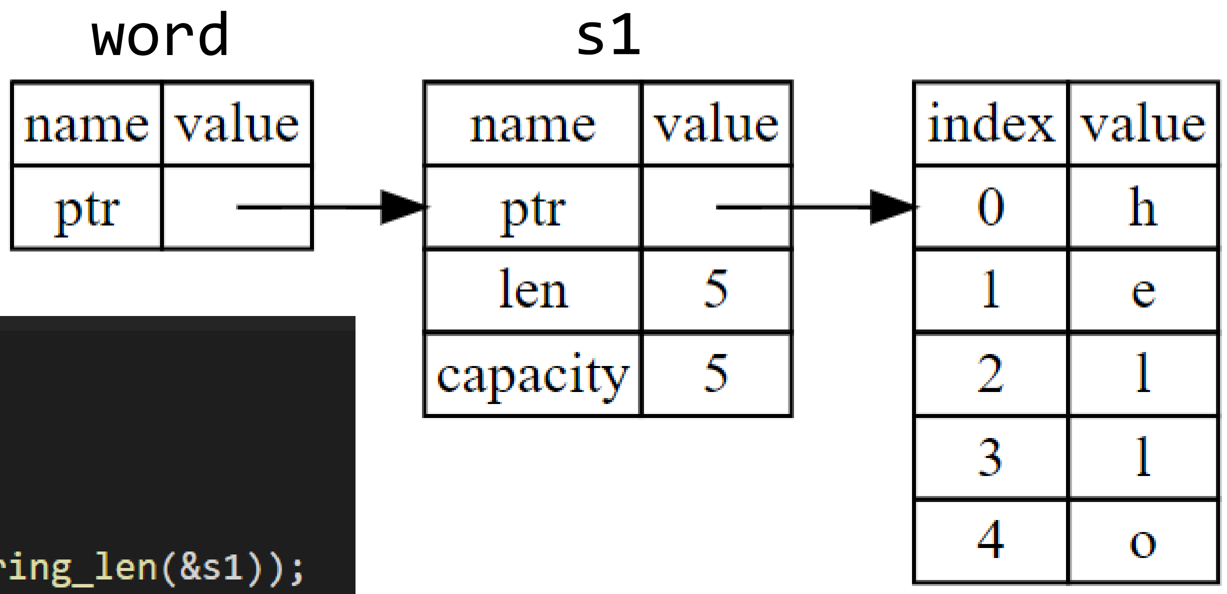
Instead of returning a tuple, pass a reference:



```
fn main()
{
    let s1 = String::from("Weird");

    println!("{} has {} characters", s1, string_len(&s1));
}

fn string_len (word: &String) -> usize
{
    word.len()
}
```

- This looks like C++
- **`word`** is now a *reference* to **`s1`**
- What about ownership?
- What's happening in memory?

Ownership: Moving VS ***Borrowing***



word

name	value
ptr	

s1

name	value
ptr	
len	5
capacity	5

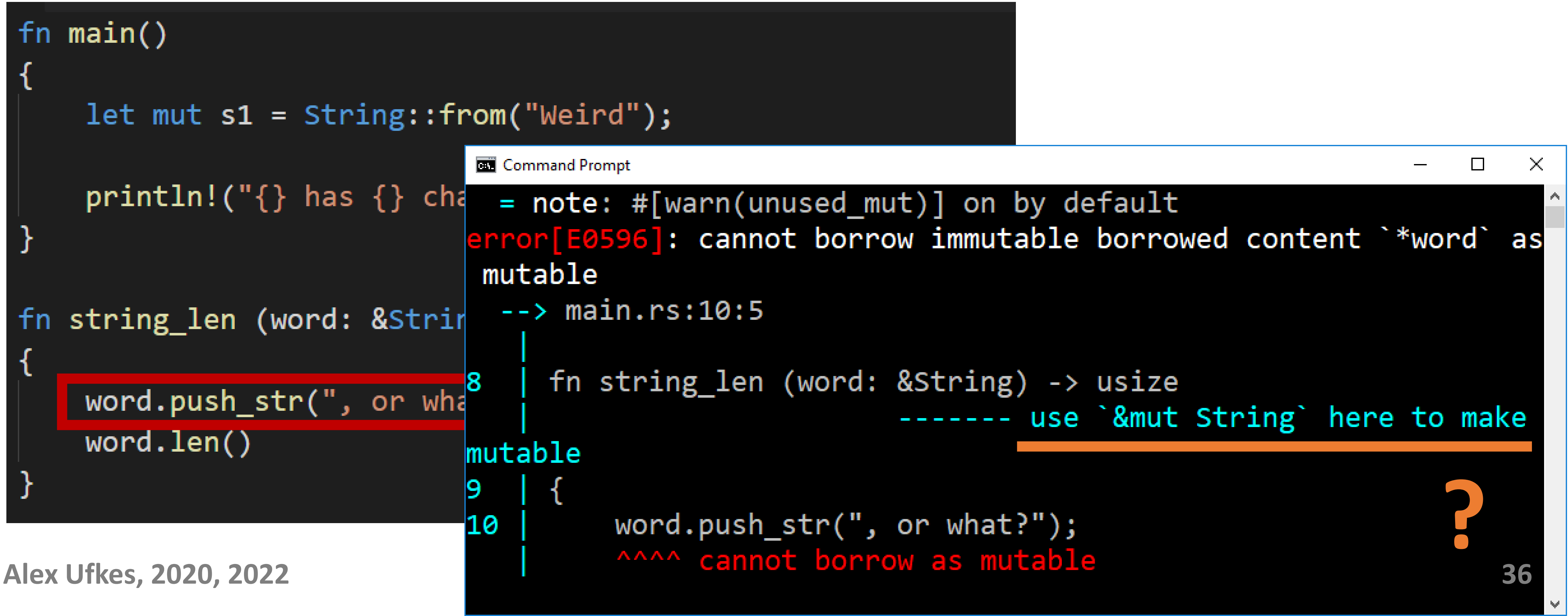
index	value
0	h
1	e
2	l
3	l
4	o

```
fn main()
{
    let s1 = String::from("Weird");

    println!("{} has {} characters", s1, string_len(&s1));
}

fn string_len (word: &String) -> usize
{
    word.len()
}
```

- word is a reference to s1, it does NOT point to the string in the heap.
- word has no ownership over s1.
- We call this ***borrowing***.

Ownership: Moving VS *Borrowing*

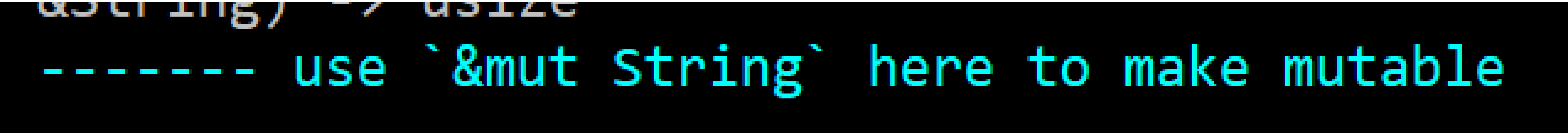
Unlike C++, we can’t modify something we’re borrowing:



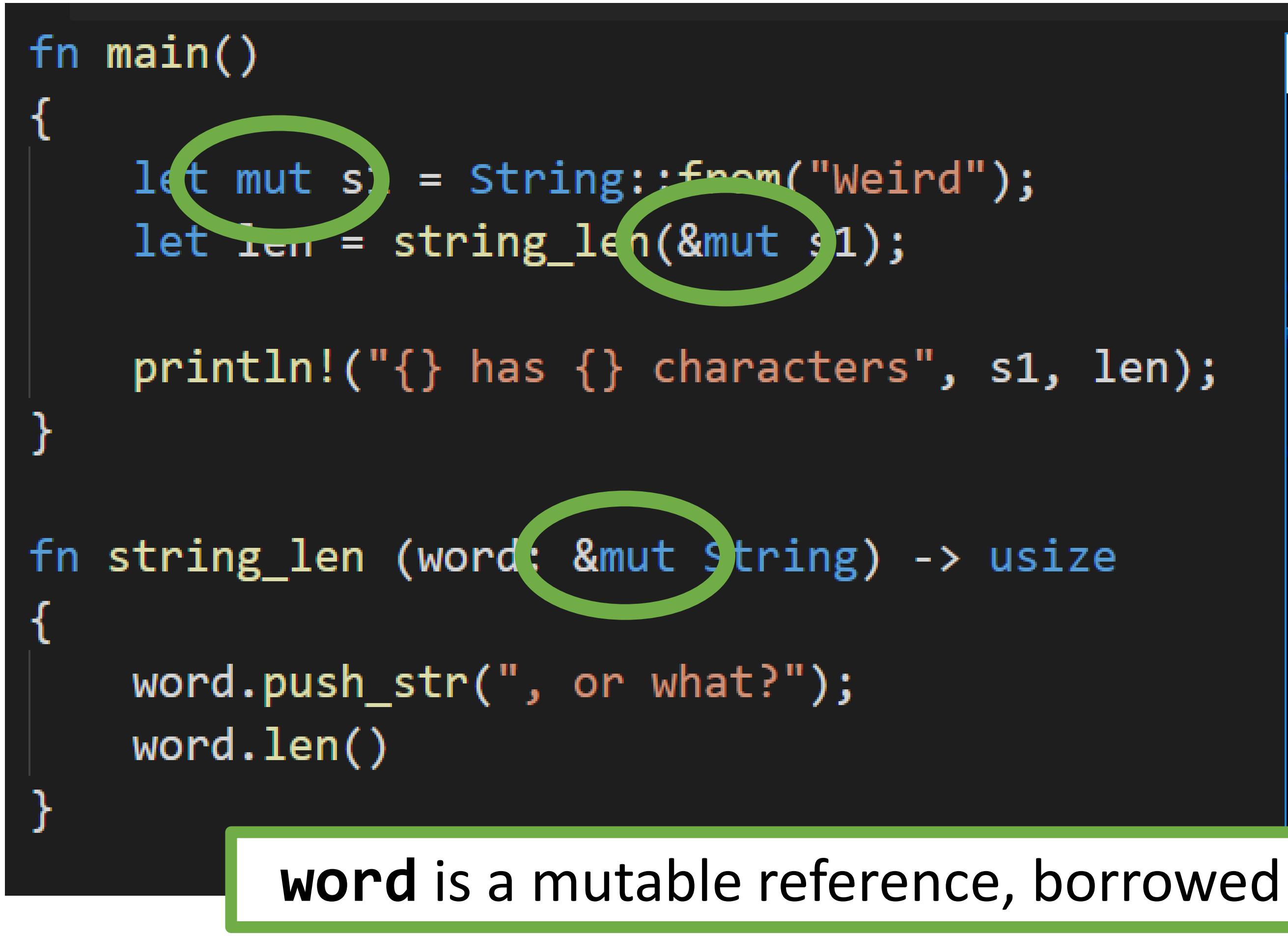
```
fn main()
{
    let mut s1 = String::from("Weird");

    println!("{} has {} cha
}

fn string_len (word: &Strin
{
    word.push_str(", or wha
    word.len()
}
```

```
  = note: #[warn(unused_mut)] on by default
error[E0596]: cannot borrow immutable borrowed content `*word` as
 mutable
  --> main.rs:10:5
   |
8  | fn string_len (word: &String) -> usize
   |                      ------- use `&mut String` here to make
mutable
9  | {
10 |     word.push_str(", or what?");
   |     ^^^^ cannot borrow as mutable
```

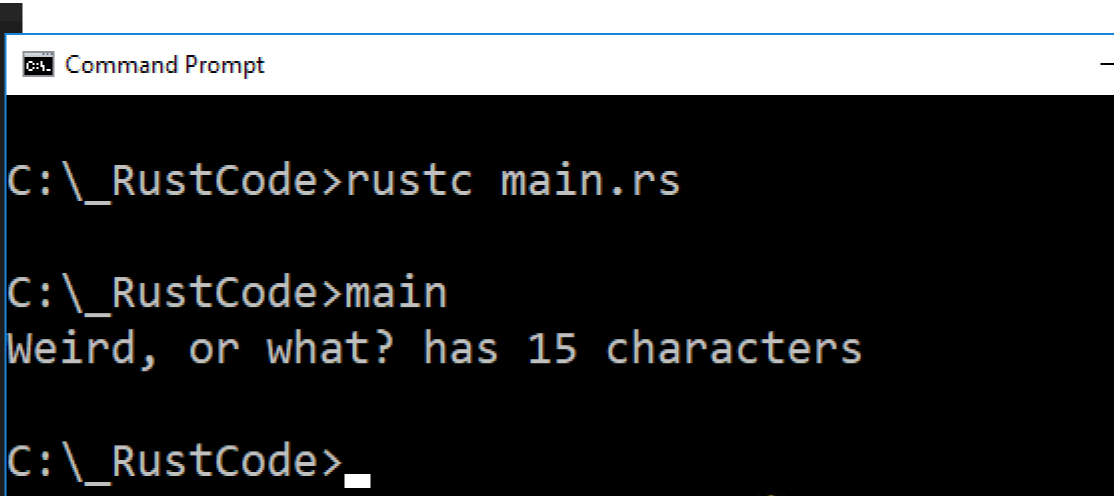
?



```
&String) -> usize
------- use `&mut String` here to make mutable
```



```
fn main()
{
    let mut s1 = String::from("Weird");
    let len = string_len(&mut s1);

    println!("{} has {} characters", s1, len);
}

fn string_len (word: &mut String) -> usize
{
    word.push_str(", or what?");
    word.len()
}
```

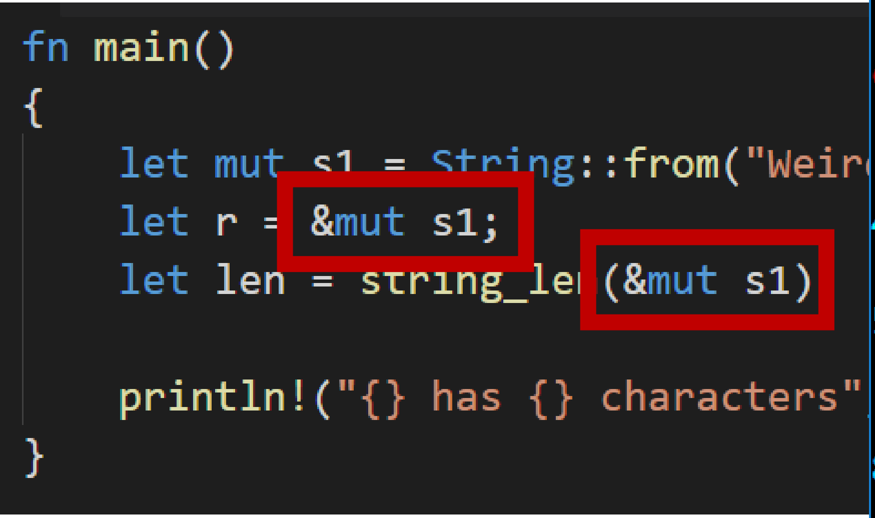


```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
Weird, or what? has 15 characters

C:\_RustCode>_
```

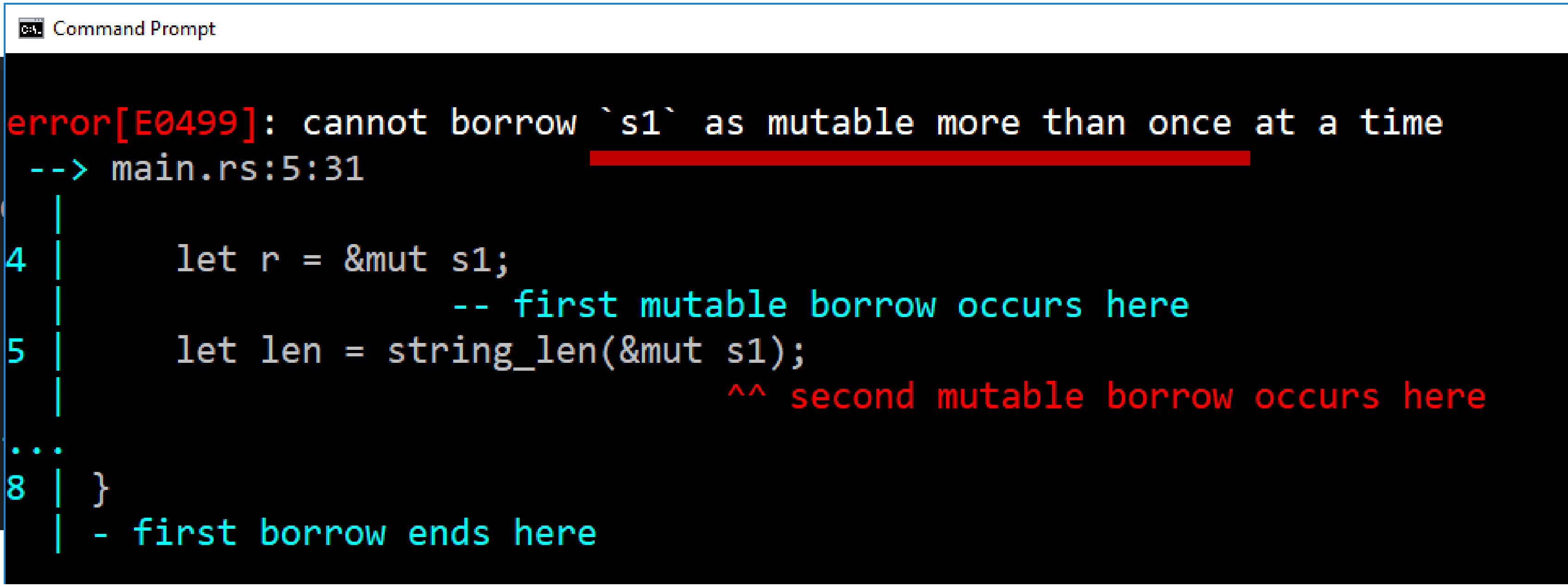
word is a mutable reference, borrowed from **s1**

Borrowing Rules

Can only have one mutable borrow at a time:



```
fn main()
{
    let mut s1 = String::from("Weir
    let r = &mut s1;
    let len = string_len(&mut s1)

    println!("{} has {} characters"
}
```

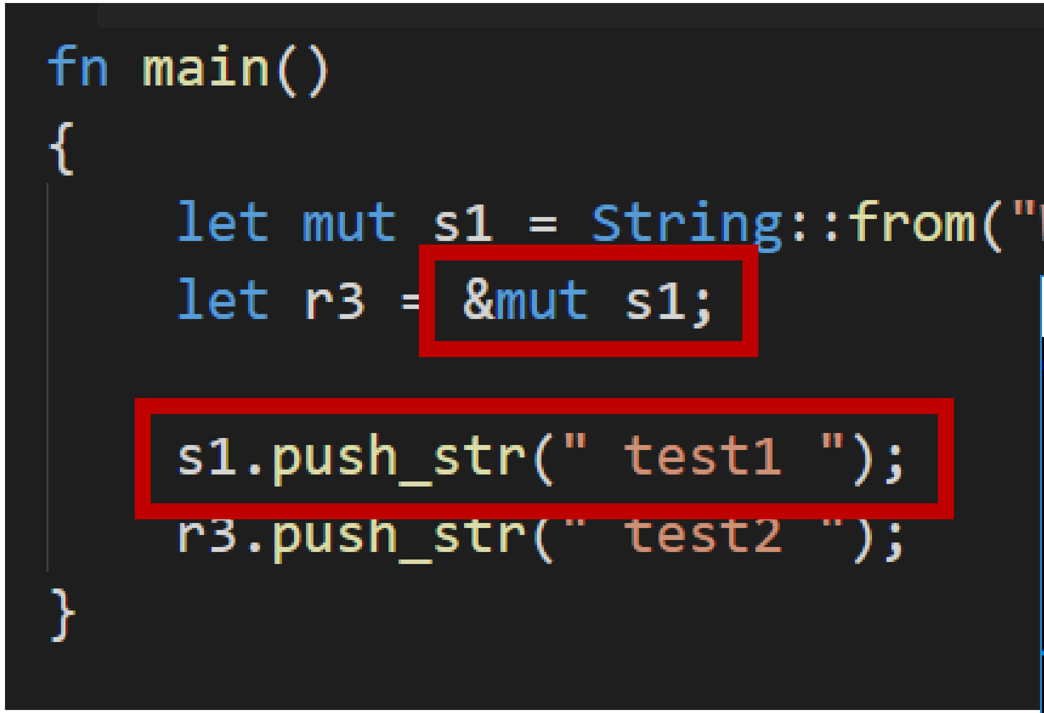


```
error[E0499]: cannot borrow `s1` as mutable more than once at a time
 --> main.rs:5:31
  |
4 |     let r = &mut s1;
  |             -- first mutable borrow occurs here
5 |     let len = string_len(&mut s1);
  |                               ^^ second mutable borrow occurs here
...
8 | }
  | - first borrow ends here
```

When the first mutable borrow goes out of scope, we can borrow again

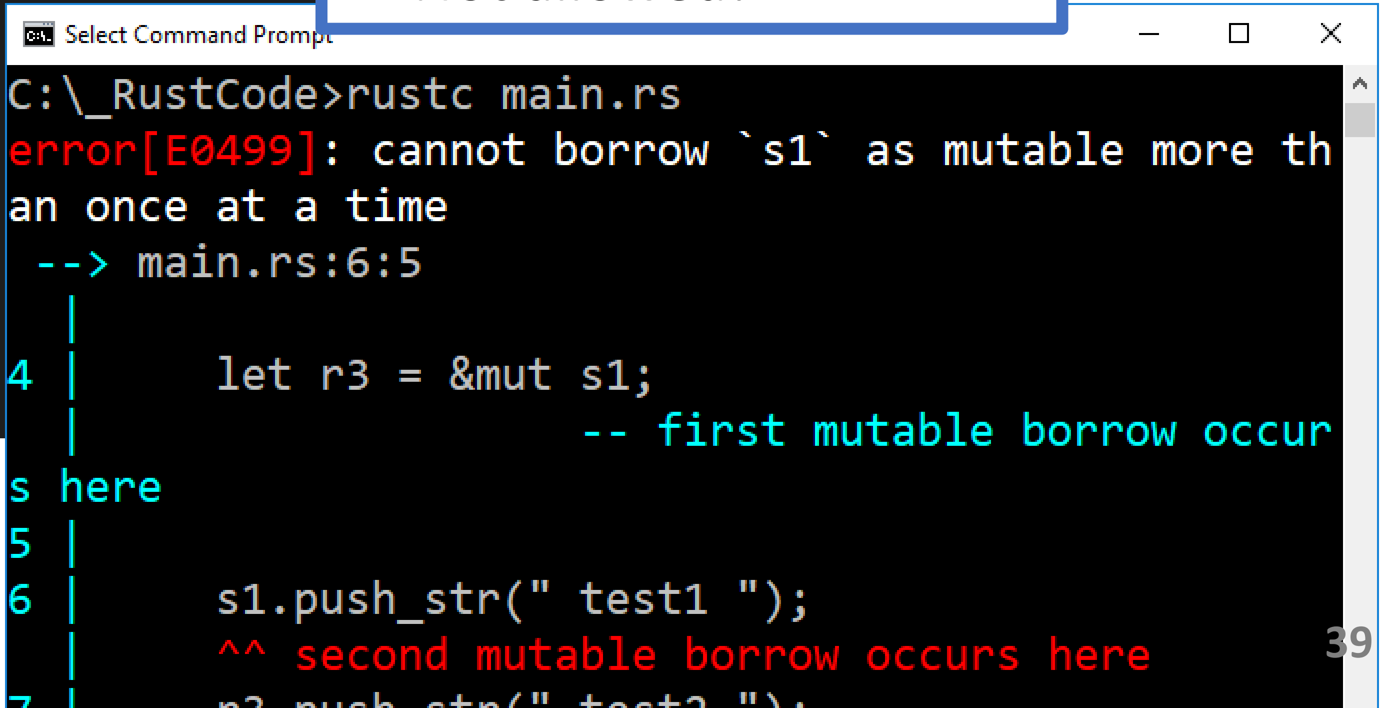
Borrowing Rules

Can only have one mutable borrow at a time:



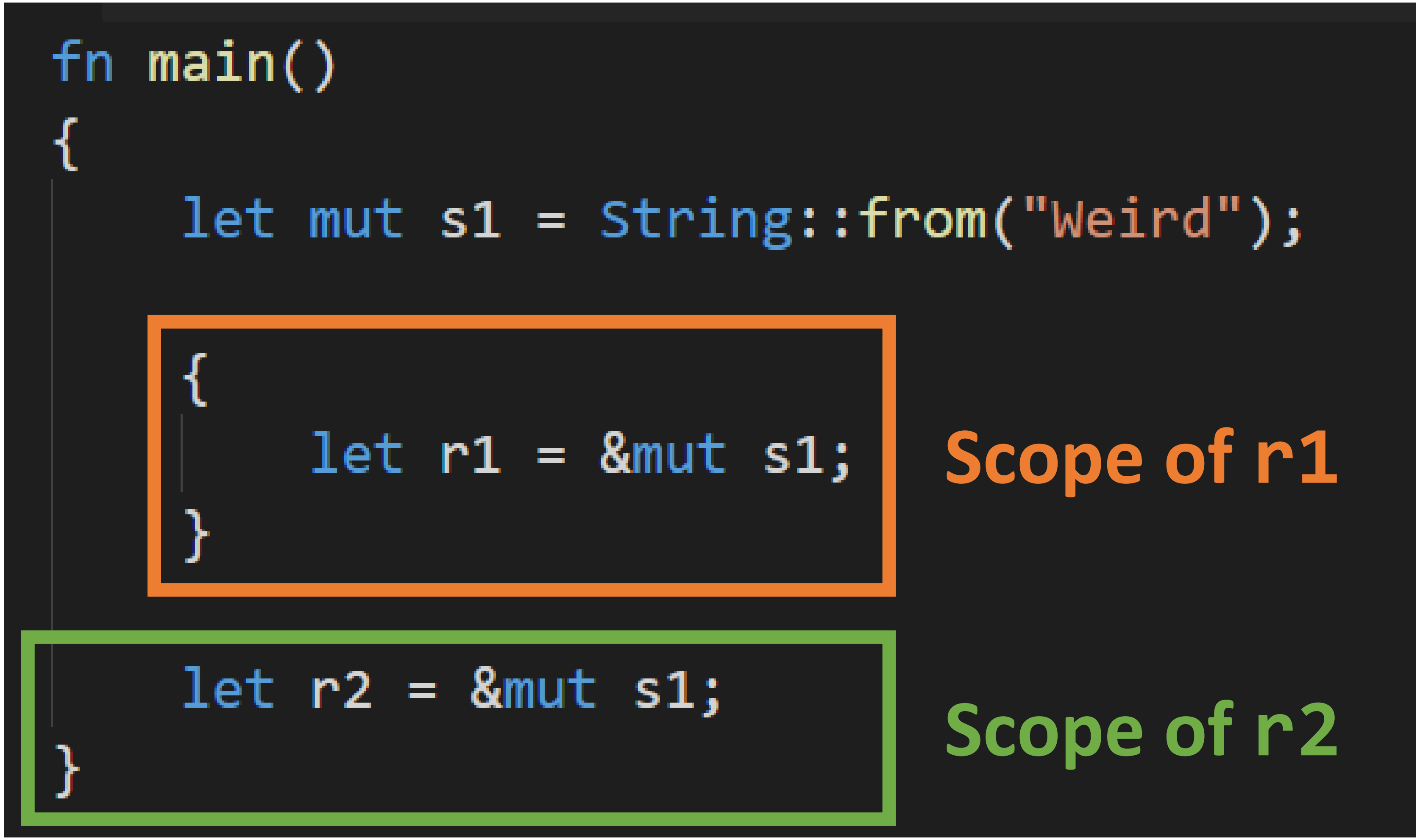
```
fn main()
{
    let mut s1 = String::from("Weird");
    let r3 = &mut s1;

    s1.push_str(" test1 ");
    r3.push_str(" test2 ");
}
```

- push_str must make mutable borrow of s1
- Not allowed!



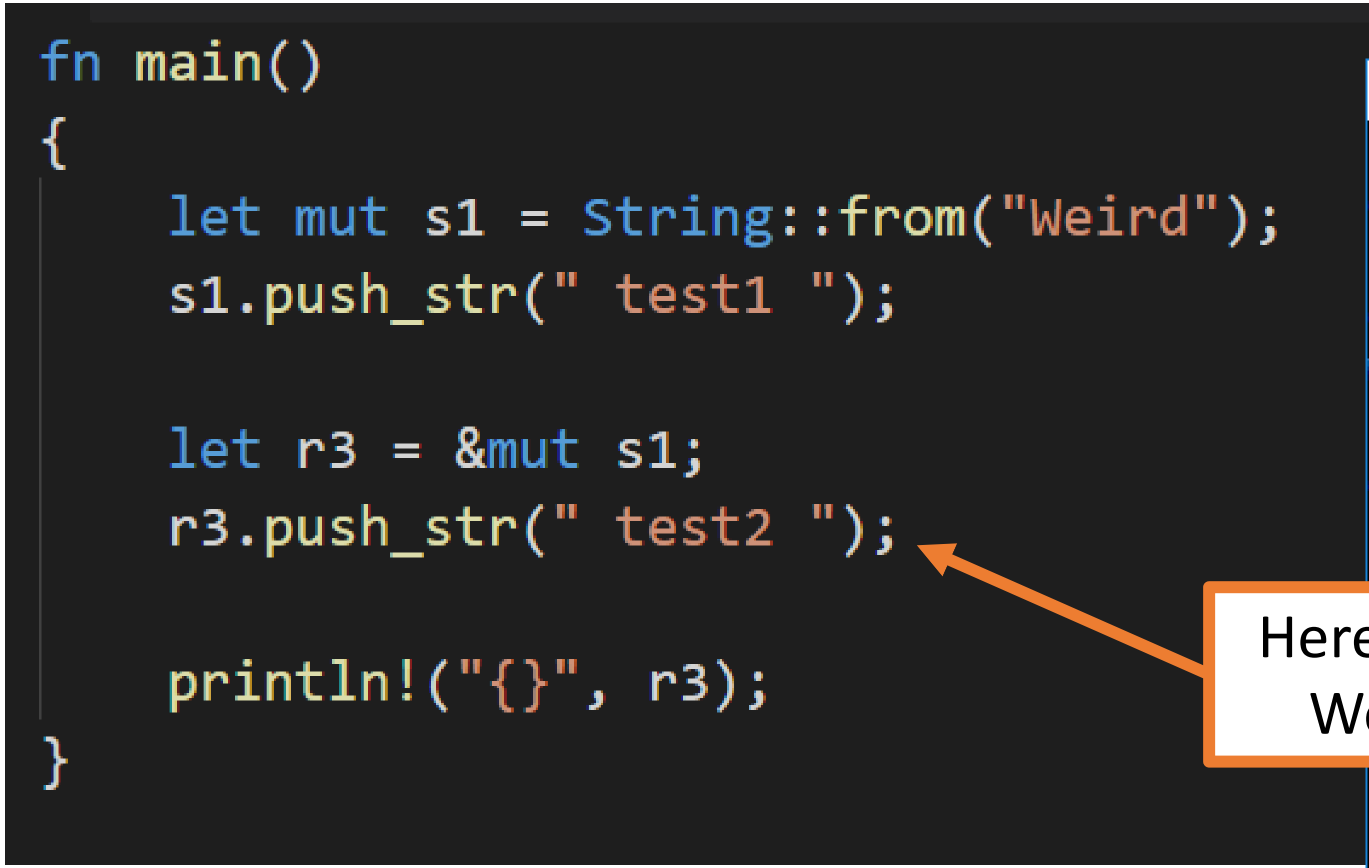
```
C:\_RustCode>rustc main.rs
error[E0499]: cannot borrow `s1` as mutable more th
an once at a time
 --> main.rs:6:5
  |
4 |     let r3 = &mut s1;
  |              -- first mutable borrow occur
s here
5 |
6 |     s1.push_str(" test1 ");
  |     ^^ second mutable borrow occurs here
7 |     r3.push_str(" test2 ");
```

When the first mutable borrow goes out of scope, we can borrow again



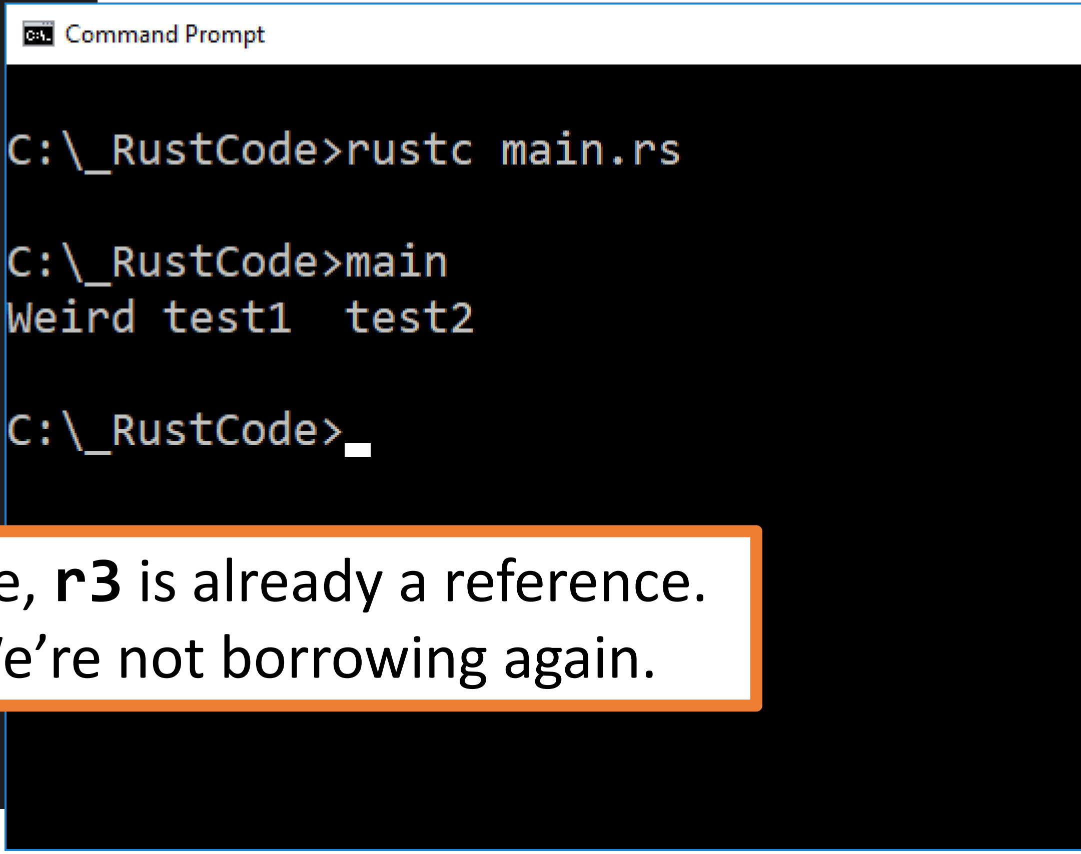
```
fn main()
{
    let mut s1 = String::from("Weird");

    {
        let r1 = &mut s1;
    }

    let r2 = &mut s1;
}
```

When the first mutable borrow goes out of scope, we can borrow again



```
fn main()
{
    let mut s1 = String::from("Weird");
    s1.push_str(" test1 ");

    let r3 = &mut s1;
    r3.push_str(" test2 ");

    println!("{}", r3);
}
```

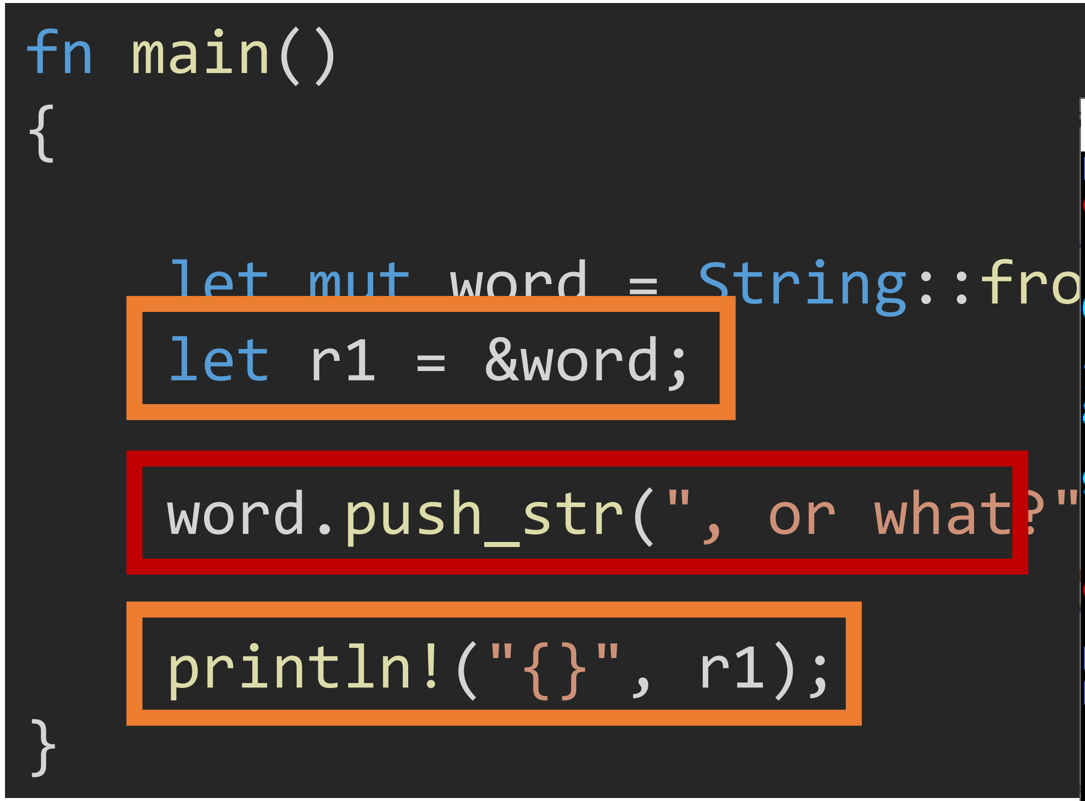
Here, **r3** is already a reference. We're not borrowing again.



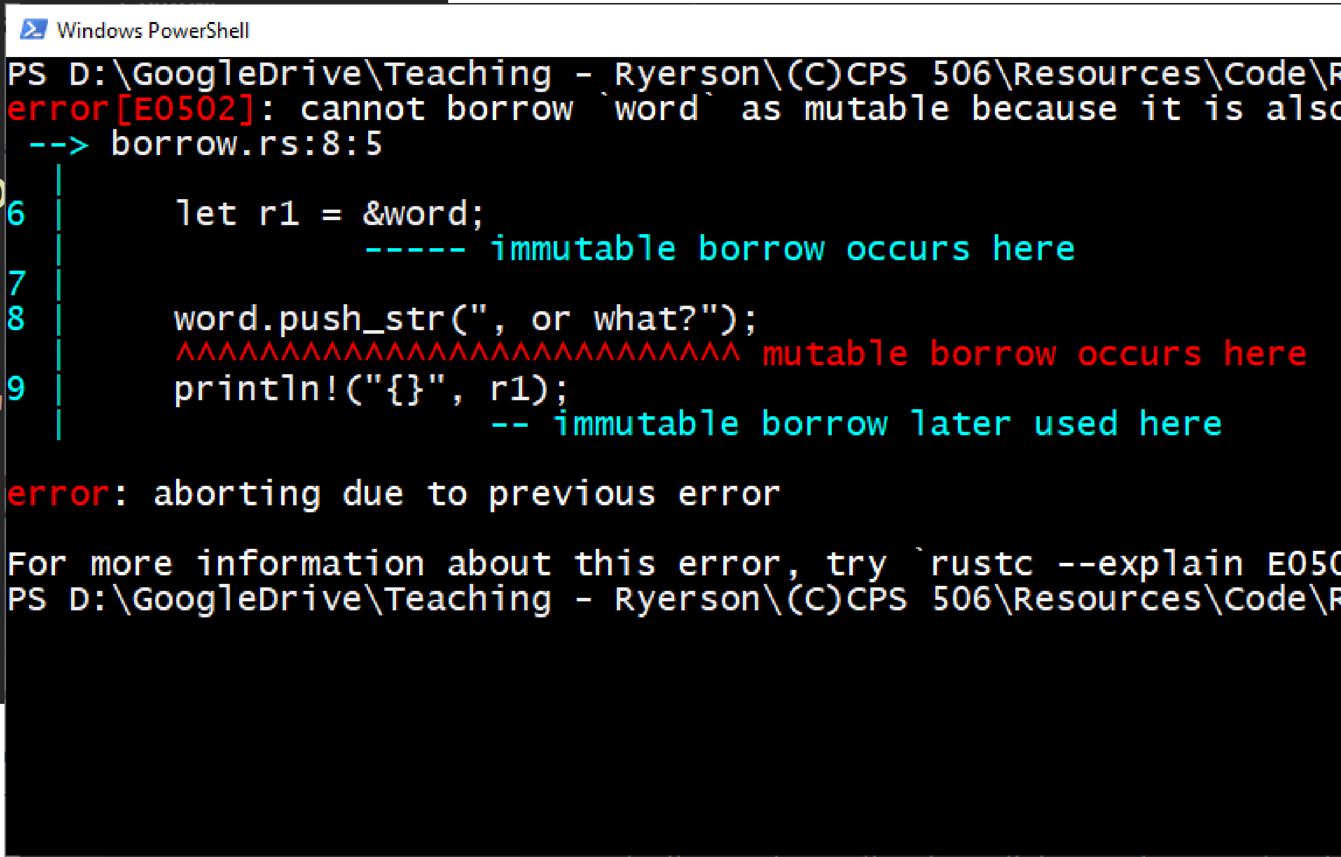
```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
Weird test1  test2

C:\_RustCode>_
```

Borrowing Rules

Using an immutably borrowed value prevents mutable borrow:



```
fn main()
{

    let mut word = String::fro
    let r1 = &word;

    word.push_str(", or what?"

    println!("{}", r1);
}
```



```
PS D:\GoogleDrive\Teaching - Ryerson\(C)CPS 506\Resources\Code\R
error[E0502]: cannot borrow `word` as mutable because it is also
 --> borrow.rs:8:5
  |
6 |     let r1 = &word;
  |              ----- immutable borrow occurs here
7 |
8 |     word.push_str(", or what?");
  |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^ mutable borrow occurs here
9 |     println!("{}", r1);
  |                    -- immutable borrow later used here

error: aborting due to previous error

For more information about this error, try `rustc --explain E050
PS D:\GoogleDrive\Teaching - Ryerson\(C)CPS 506\Resources\Code\R
```

Borrowing Rules: In Short

In any given scope, only ONE of the following can be true:

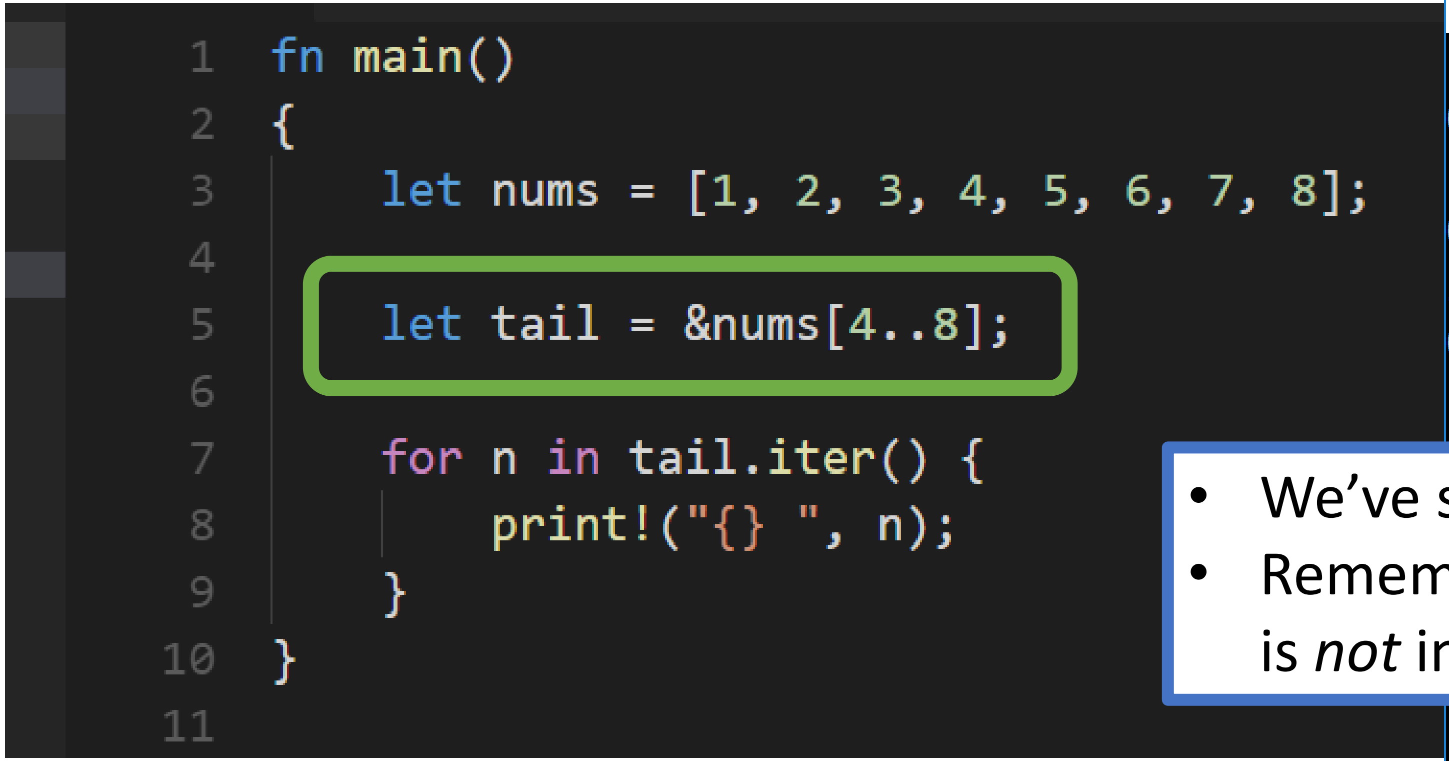
1. We can have a single mutable borrow
2. We can have any number of immutable borrows

These restrictions keep mutation under control

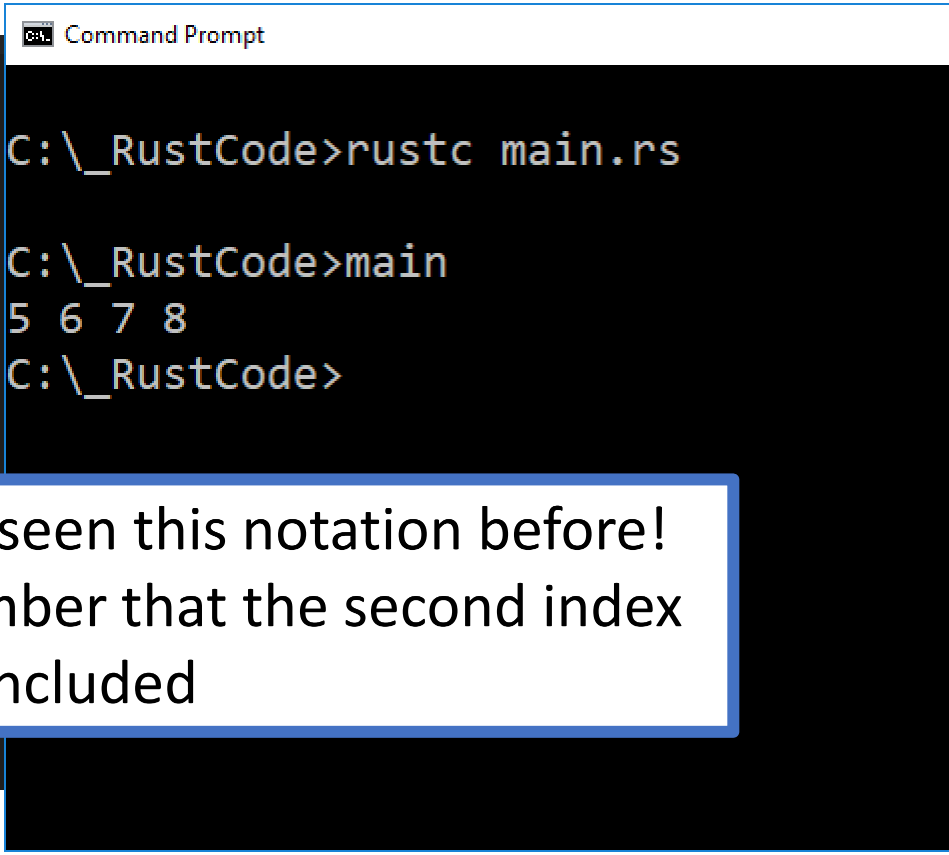
Slices

Slices

Reference to a subset of an array



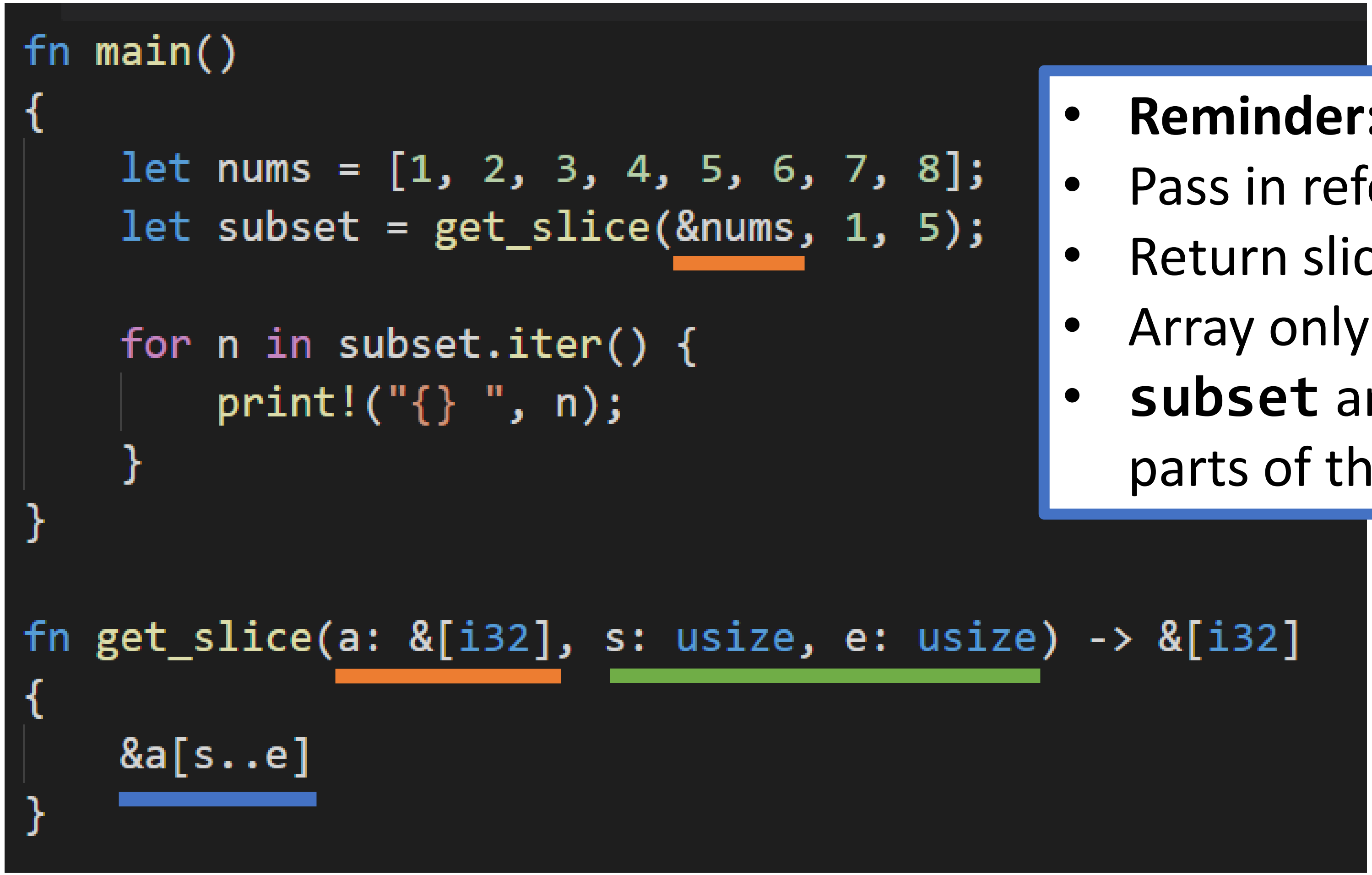
```
fn main()
{
    let nums = [1, 2, 3, 4, 5, 6, 7, 8];

    let tail = &nums[4..8];

    for n in tail.iter() {
        print!("{} ", n);
    }
}
```



```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
5 6 7 8
C:\_RustCode>
```

- We’ve seen this notation before!
- Remember that the second index is *not* included

Slices, Arguments, Functions

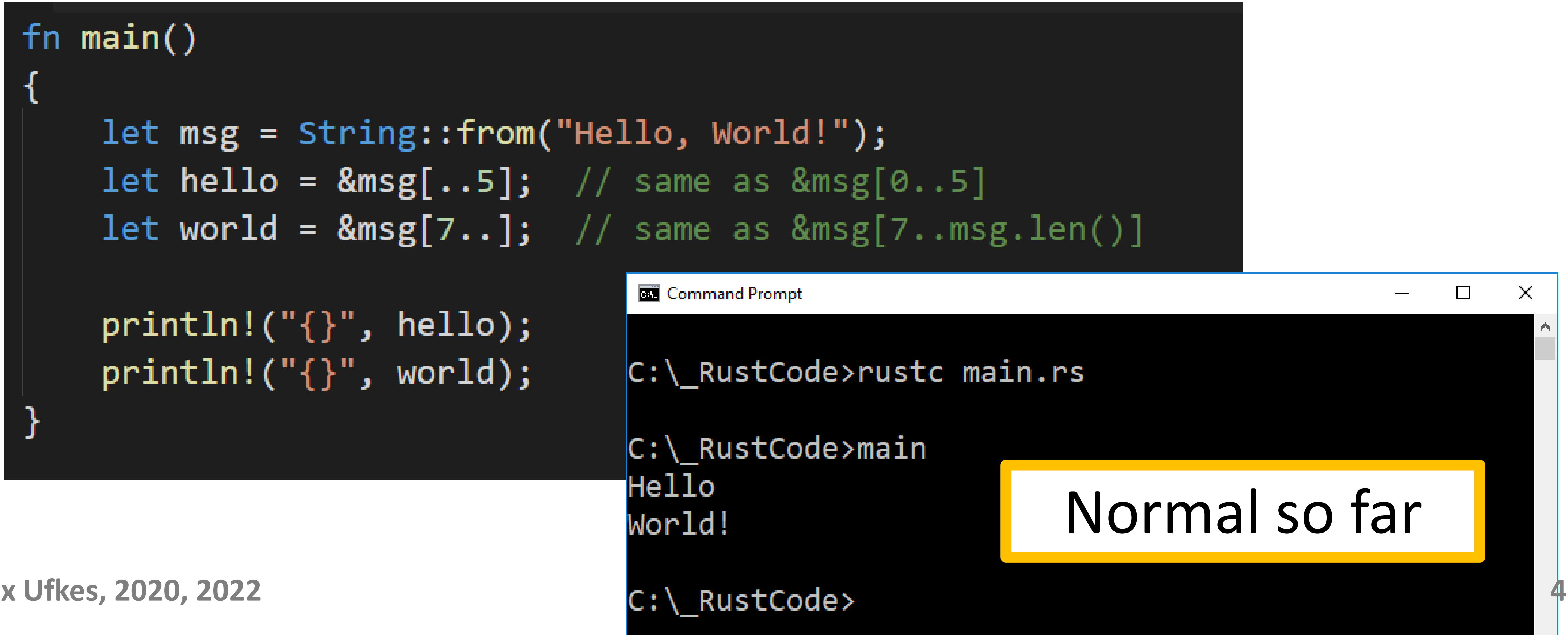


```
fn main()
{
    let nums = [1, 2, 3, 4, 5, 6, 7, 8];
    let subset = get_slice(&nums, 1, 5);

    for n in subset.iter() {
        print!("{} ", n);
    }
}

fn get_slice(a: &[i32], s: usize, e: usize) -> &[i32]
{
    &a[s..e]
}
```

- **Reminder:** indexes must be **usize**
- Pass in reference to array
- Return slice (reference to subarray)
- Array only exists once in memory
- **subset** and **nums** point to different parts of the same memory.

String Slices

… are a little bit different.

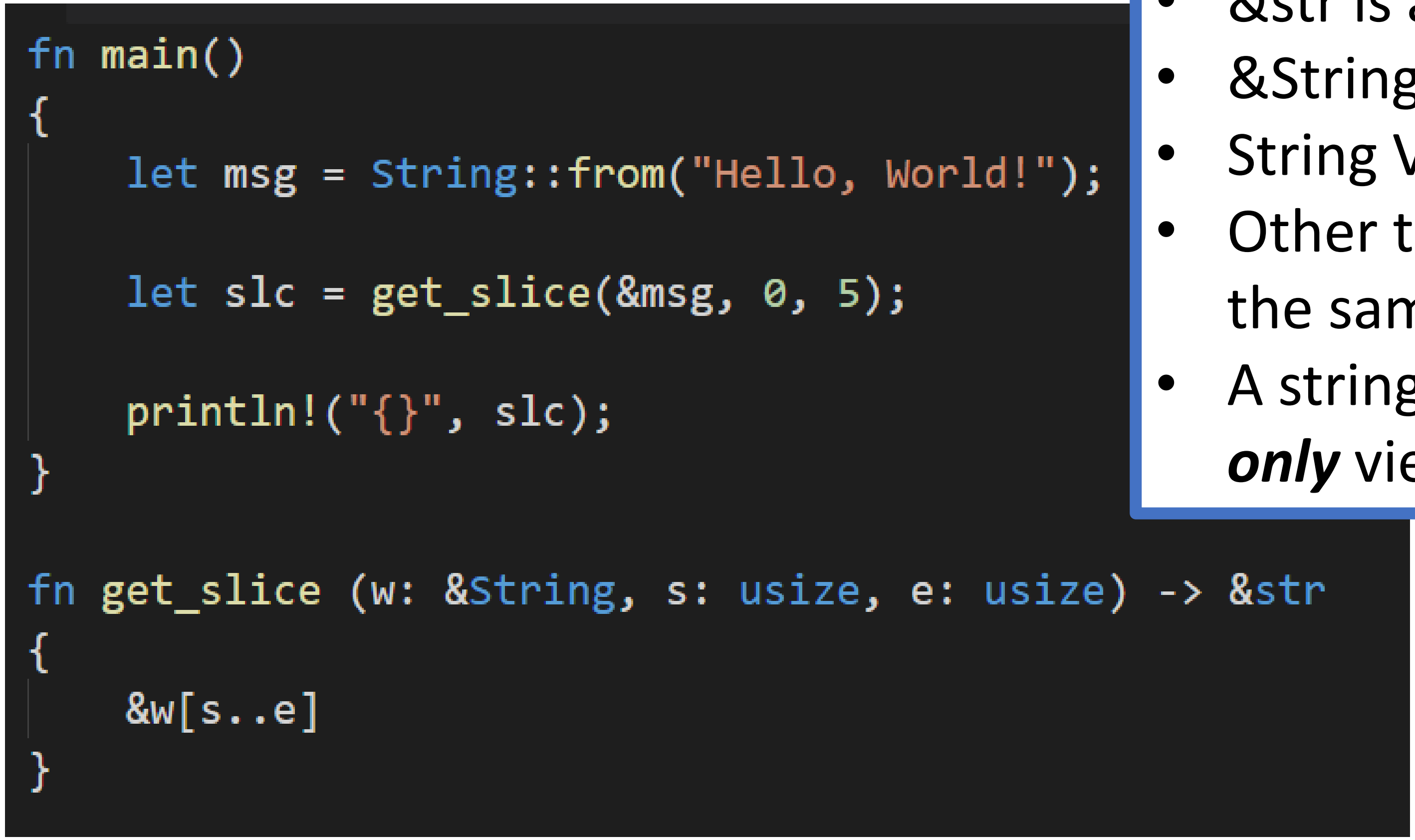


```
fn main()
{
    let msg = String::from("Hello, World!");
    let hello = &msg[..5];  // same as &msg[0..5]
    let world = &msg[7..];  // same as &msg[7..msg.len()]

    println!("{}", hello);
    println!("{}", world);
}
```

```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
Hello
World!

C:\_RustCode>
```

Normal so far

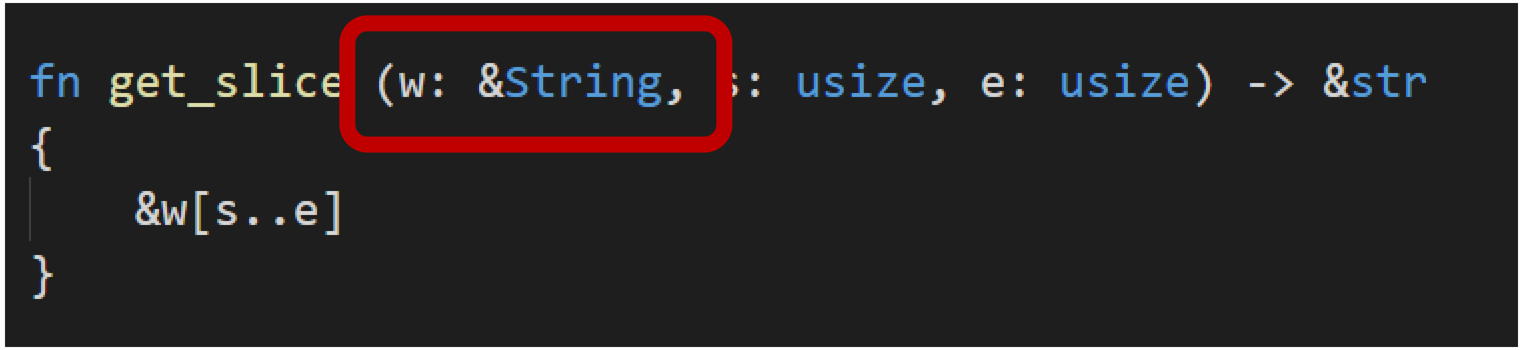
String Slice Type



```
fn main()
{
    let msg = String::from("Hello, World!");

    let slc = get_slice(&msg, 0, 5);

    println!("{}", slc);
}

fn get_slice (w: &String, s: usize, e: usize) -> &str
{
    &w[s..e]
}
```

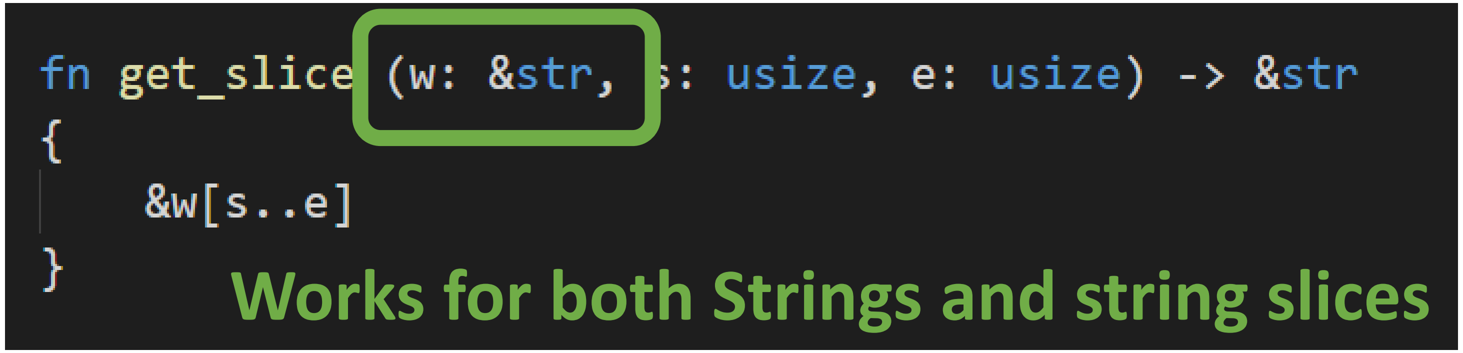
- &str is a reference to a string slice
- &String is a reference to a String
- String VS string slice: different types
- Other than that, the function works the same as with numeric arrays.
- A string slice is effectively a ***read-only*** view of a String.

String Slice Type



```
fn get_slice (w: &String, s: usize, e: usize) -> &str
{
    &w[s..e]
}
```

Better to do this:



```
fn get_slice (w: &str, s: usize, e: usize) -> &str
{
    &w[s..e]
}
```

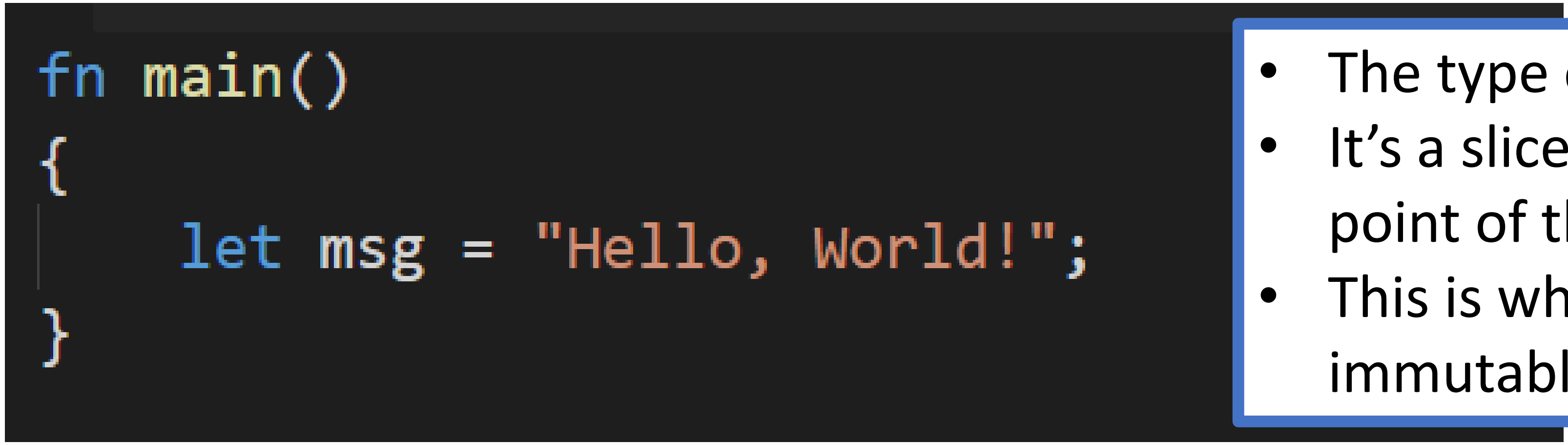
Works for both Strings and string slices

String Literals

Recall:

- String literals are different from regular strings.
- Their size is fixed, ***encoded directly into the executable***.
- They are immutable.

In fact, string literals are ***slices***:



```
fn main()
{
    let msg = "Hello, World!";
}
```

- The type of **`msg`** is **`&str`**
- It's a slice pointing to a specific point of the binary file.
- This is why string literals are immutable!

Lifetime

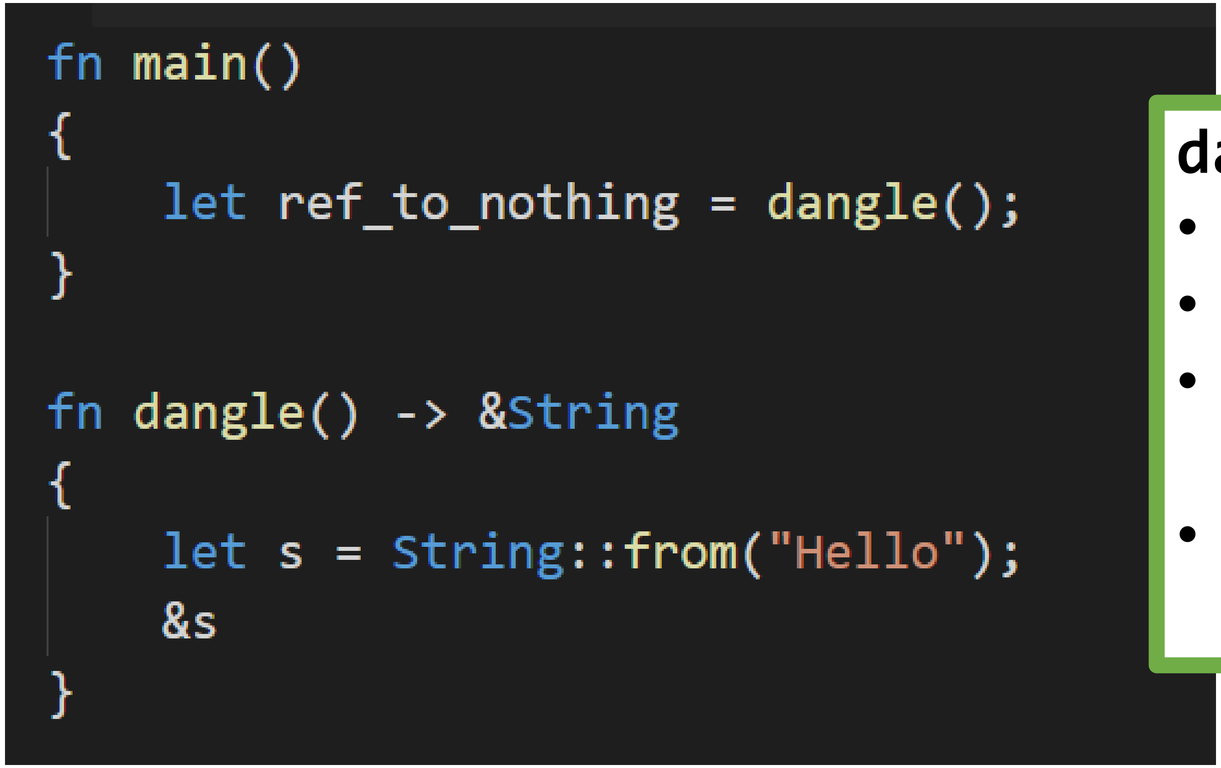
Rust Features

***Memory Safety*:**

- *Rust is designed to be memory safe*
- *Null or dangling pointers are not permitted.*

Dangling References

Rust prevents them:



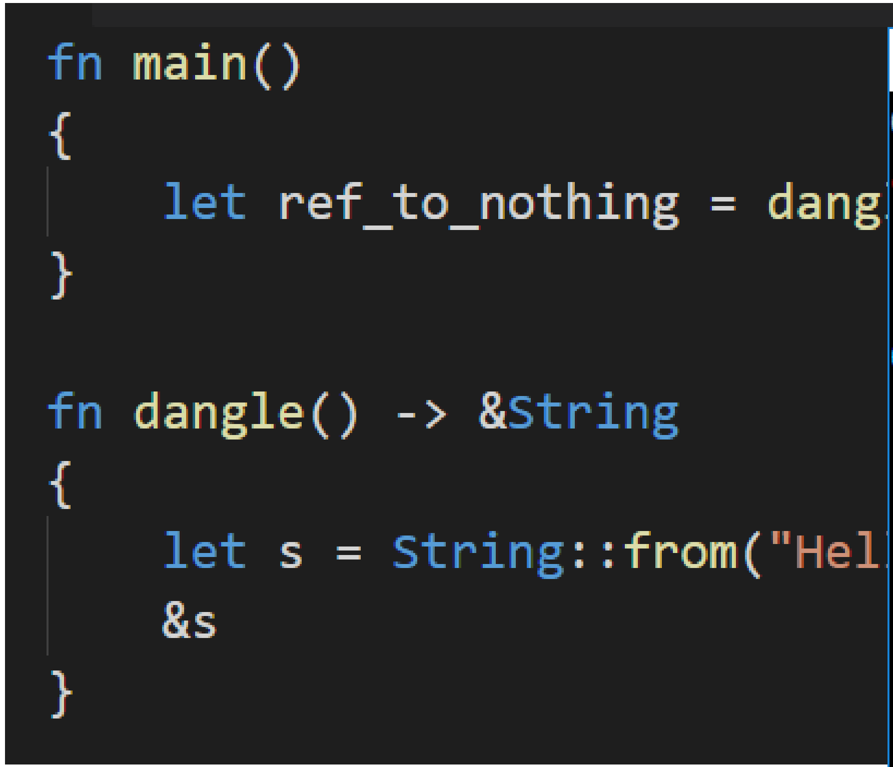
```
fn main()
{
    let ref_to_nothing = dangle();
}

fn dangle() -> &String
{
    let s = String::from("Hello");
    &s
}
```

dangle()

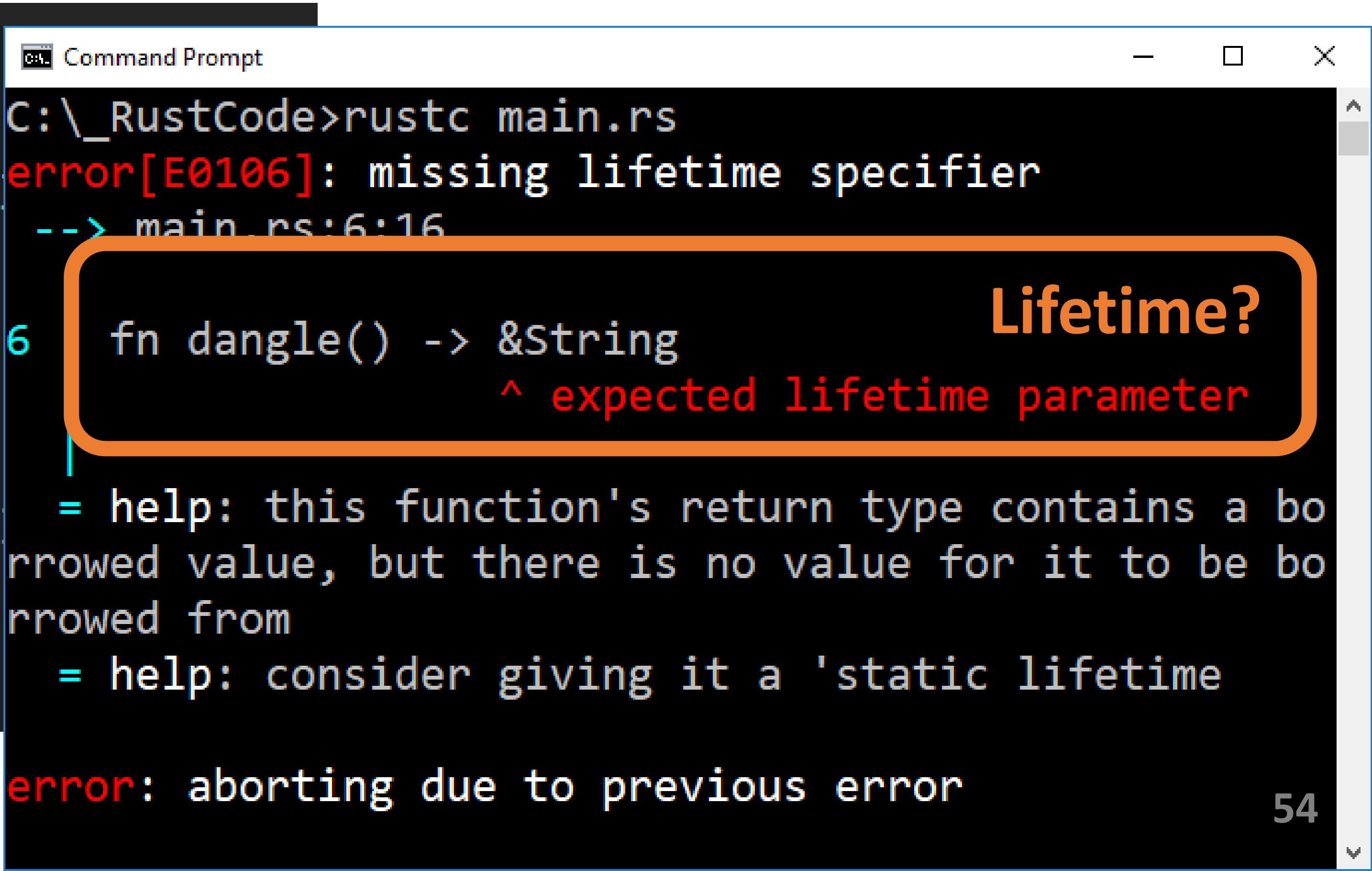
- Create String s
- Return a reference to it
- s goes out of scope when dangle function ends.
- What happens to the reference that was returned?

Dangling References

Rust prevents them:



```
fn main()
{
    let ref_to_nothing = dang
}

fn dangle() -> &String
{
    let s = String::from("Hel
    &s
}
```



```
C:\_RustCode>rustc main.rs
error[E0106]: missing lifetime specifier
 --> main.rs:6:16

6    fn dangle() -> &String
                    ^ expected lifetime parameter

  = help: this function's return type contains a bo
rrowed value, but there is no value for it to be bo
rrowed from
  = help: consider giving it a 'static lifetime

error: aborting due to previous error
```

Lifetime?

Lifetime is a very distinct feature of Rust:

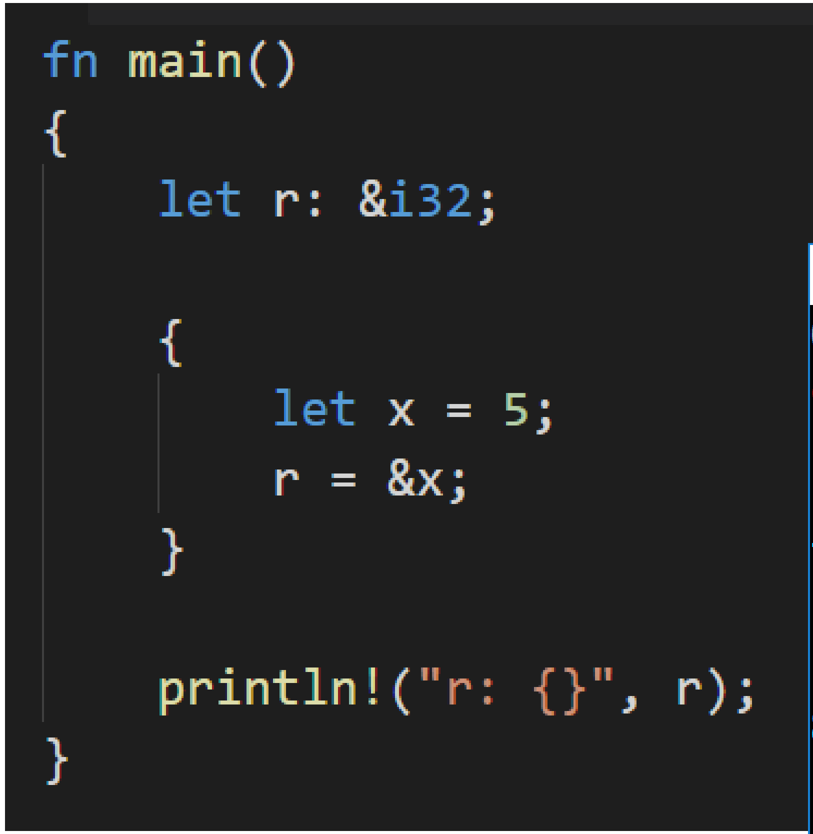
Every reference in Rust has *lifetime*

The lifetime of a reference is the scope for which that reference is valid.

Lifetimes are often implicit and inferred, but can be defined explicitly

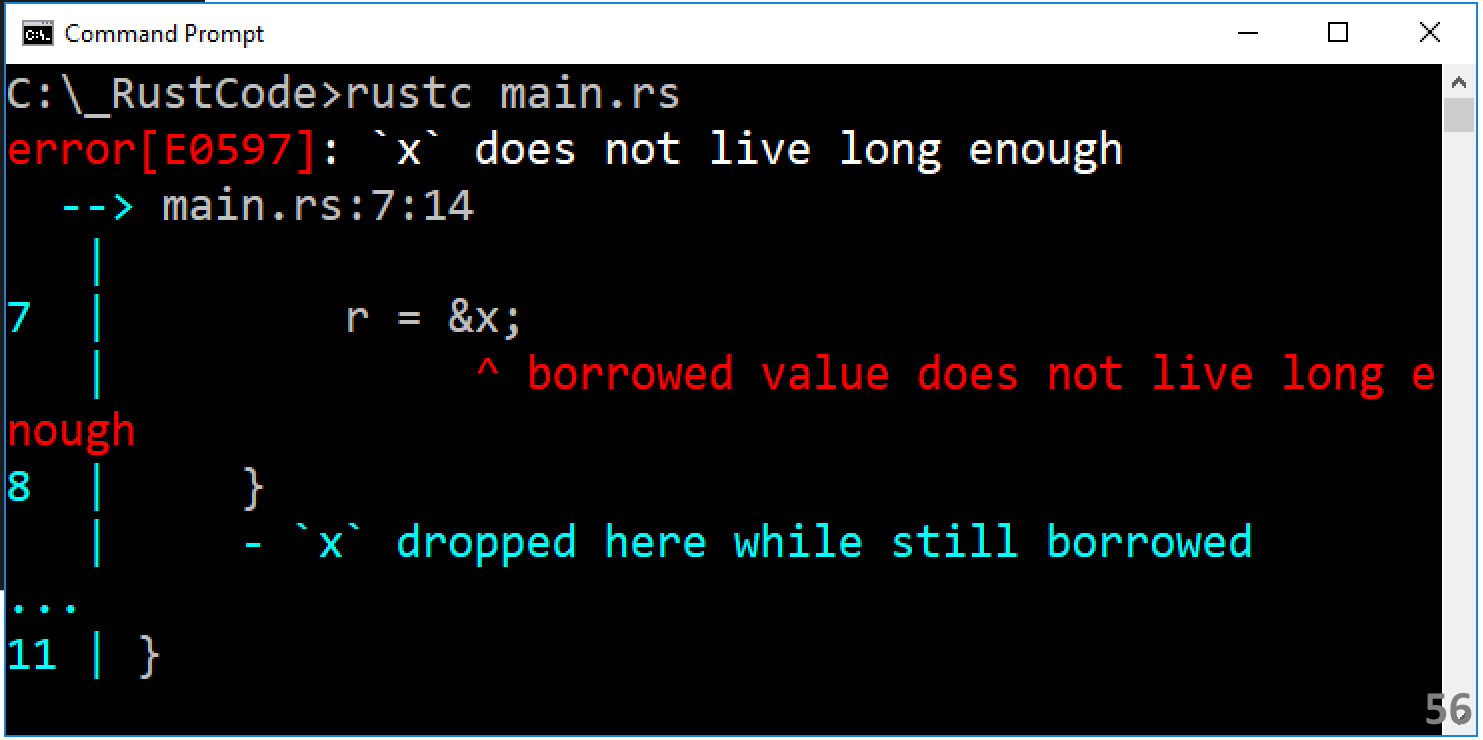
Just like variable types!

Example



```rust
fn main()
{
    let r: &i32;

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

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

- **r** is a reference to **x**
- **x** goes out of scope while **r** is still referring to it!



```
C:\_RustCode>rustc main.rs
error[E0597]: `x` does not live long enough
  --> main.rs:7:14
   |
7  |         r = &x;
   |              ^ borrowed value does not live long e
nough
8  |     }
   |     - `x` dropped here while still borrowed
...
11 | }
```

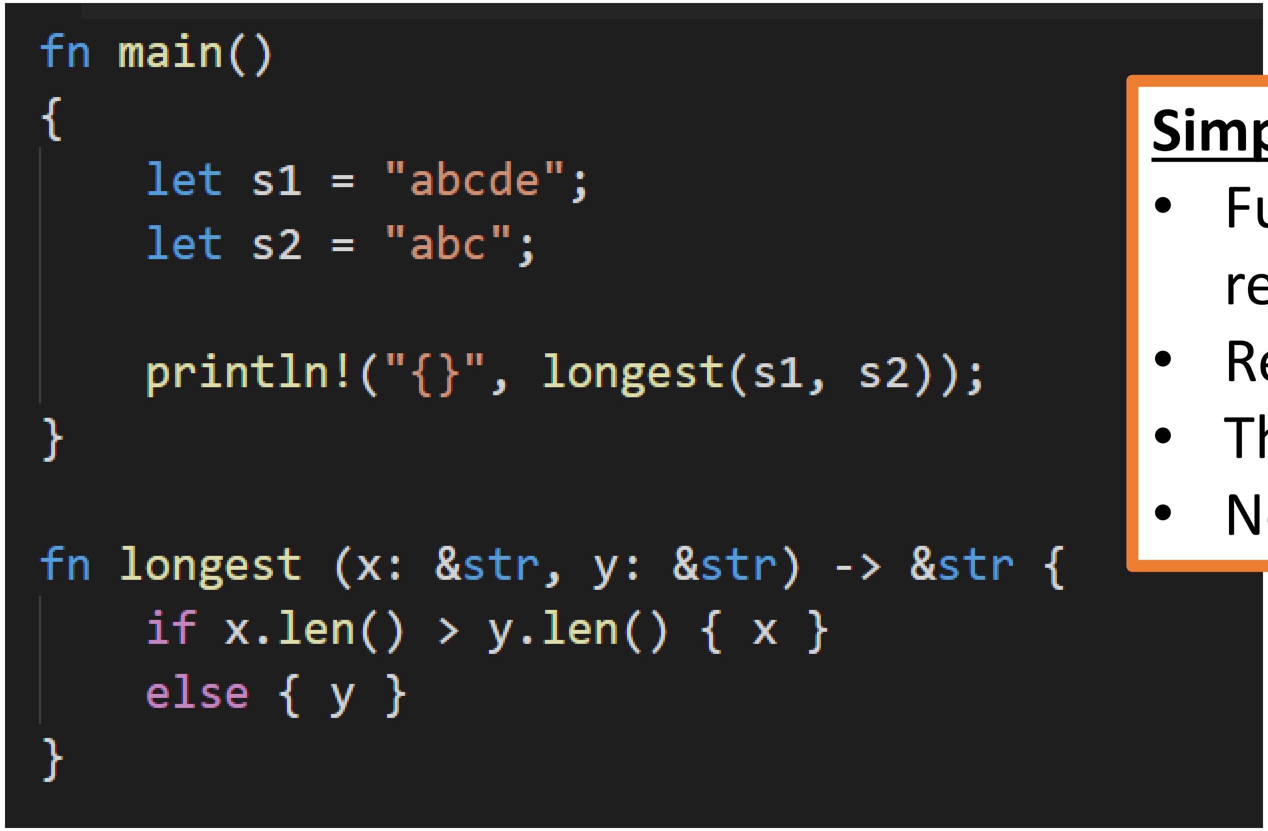
The Borrow Checker

- The Rust compiler has a “Borrow Checker” that compares scope to determine if borrows are valid
- If one variable borrows another, the variable being borrowed must have a lifetime at least as long as the variable doing the borrowing.

What happens if the borrow checker gets confused?

Generic Lifetimes

Consider:



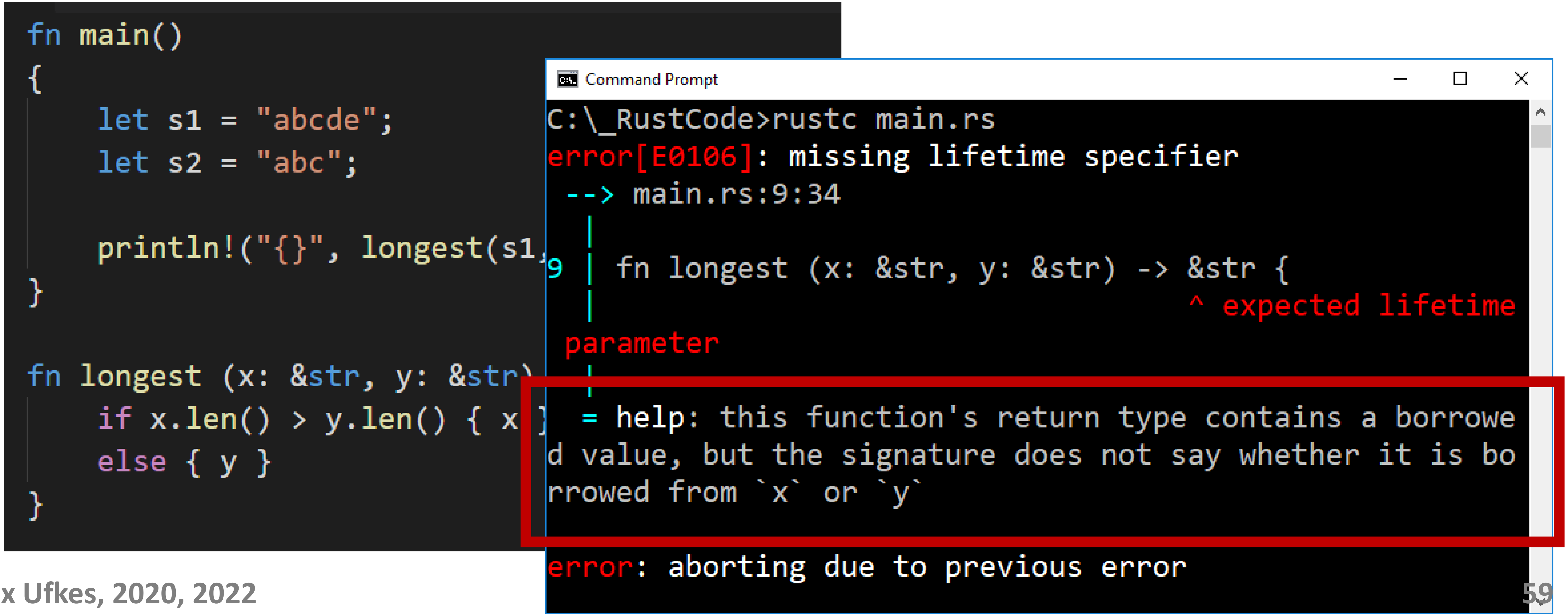
```
fn main()
{
    let s1 = "abcde";
    let s2 = "abc";

    println!("{}", longest(s1, s2));
}

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

Simple program:

- Function accepts two string slices, returns the slice that is longer.
- Recall that slices are just references
- There’s no ownership changing here
- No moves

Generic Lifetimes

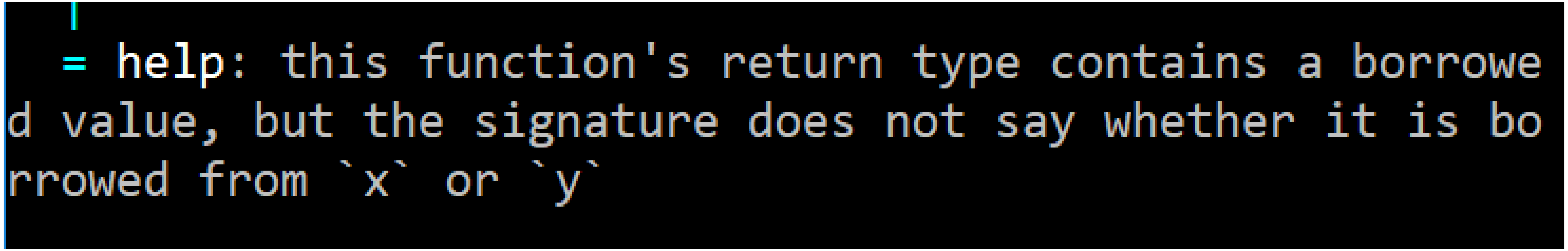
Consider:



```
fn main()
{
    let s1 = "abcde";
    let s2 = "abc";

    println!("{}", longest(s1,
}

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

```
C:\_RustCode>rustc main.rs
error[E0106]: missing lifetime specifier
 --> main.rs:9:34
  |
9 | fn longest (x: &str, y: &str) -> &str {
  |                                  ^ expected lifetime
 parameter
  |
  = help: this function's return type contains a borrowe
d value, but the signature does not say whether it is bo
rrowed from `x` or `y`

error: aborting due to previous error
```

Generic Lifetimes

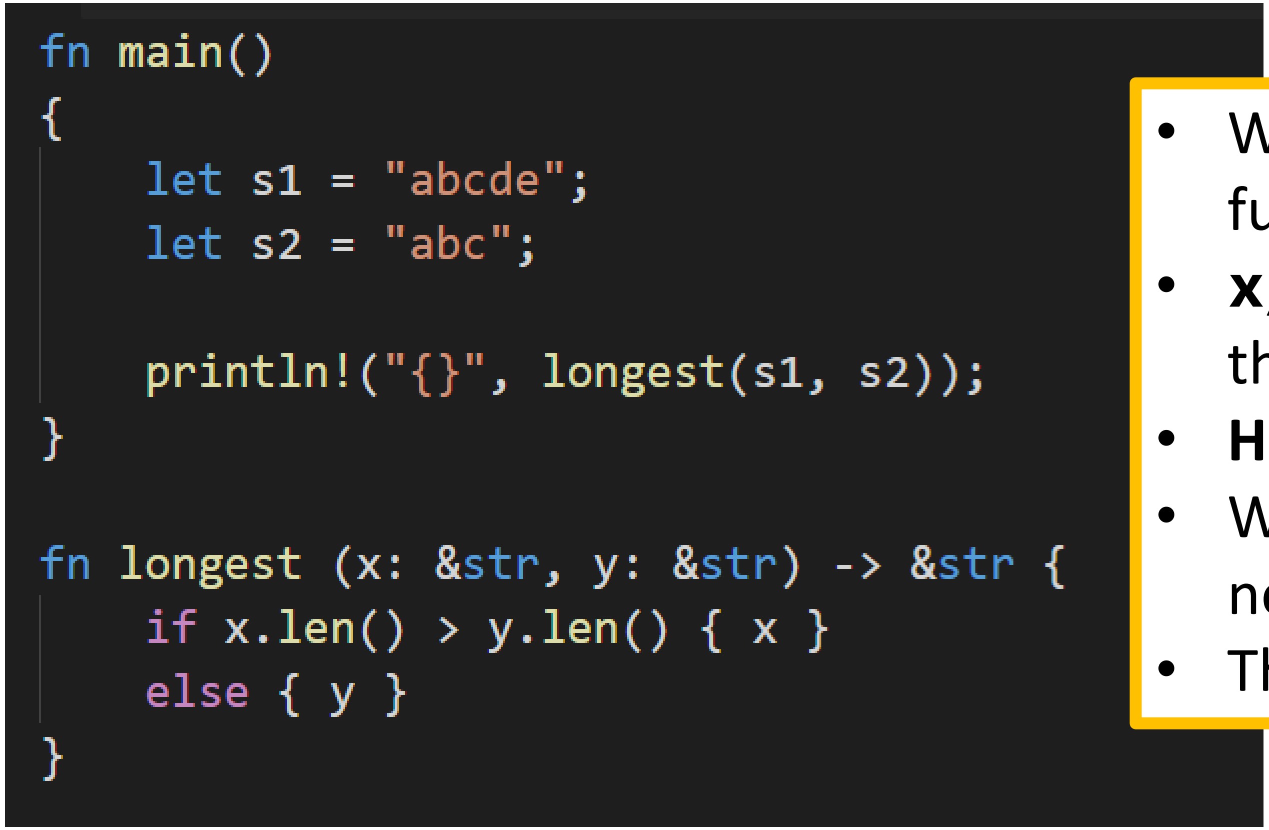


```
  |
  = help: this function's return type contains a borrowe
d value, but the signature does not say whether it is bo
rrowed from `x` or `y`
```

The Borrow Checker can’t determine lifetime of the return value, because it’s not clear which input argument the return value will borrow from.

More generally: The borrow checker follows certain patterns when determining lifetime. If none of its patterns apply, we get a lifetime error.

Generic Lifetimes

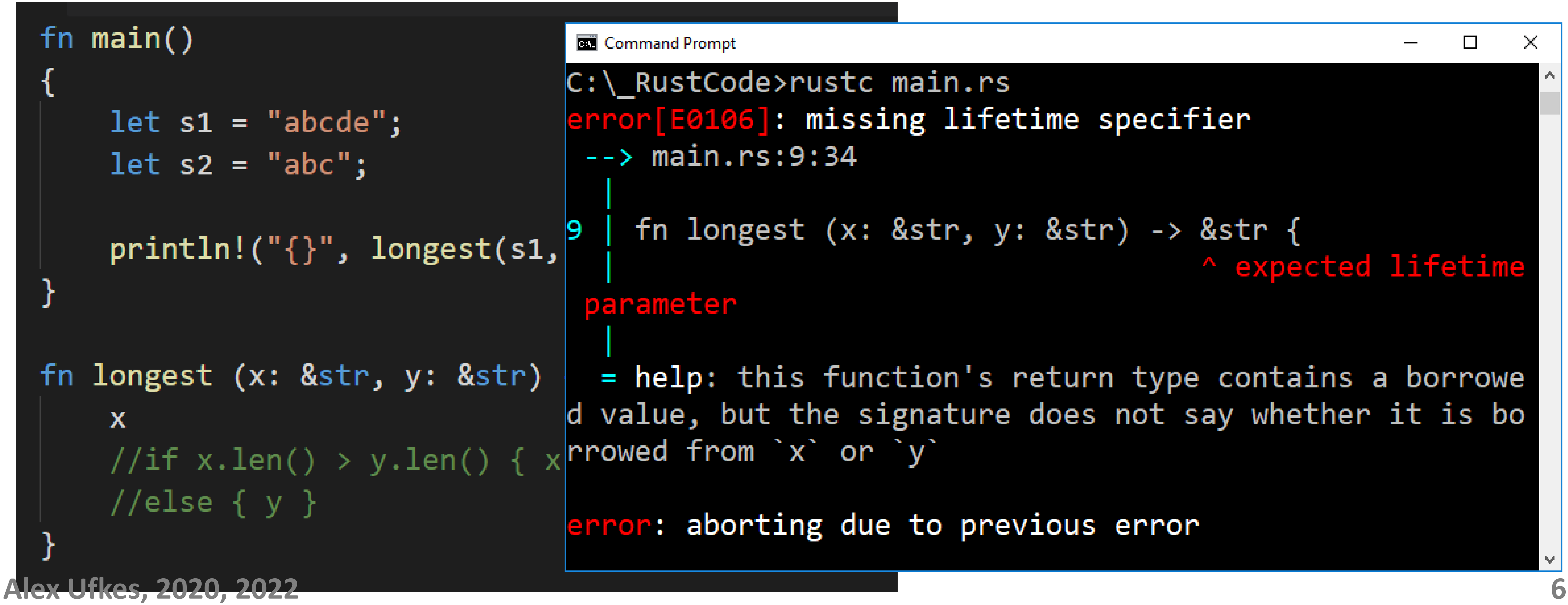


```
fn main()
{
    let s1 = "abcde";
    let s2 = "abc";

    println!("{}", longest(s1, s2));
}

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

- We as programmers know that this function is perfectly safe.
- **x**, **y** refer to string literals which live the entire duration of the program.
- **HOWEVER**
- What’s obvious to us is not necessarily obvious to the compiler.
- Thus, we get compile errors.

Generic Lifetimes

It even happens when the return reference is fixed:

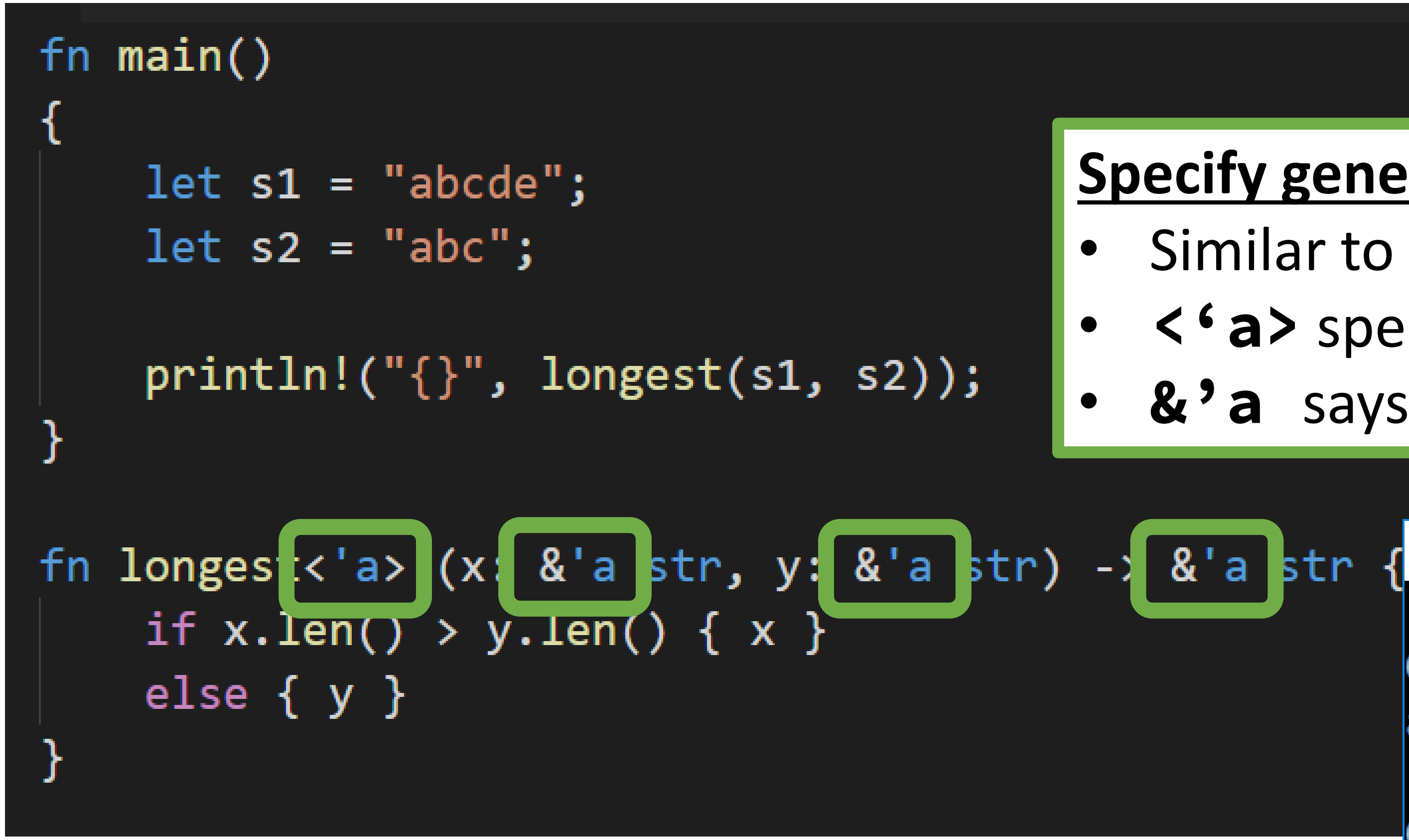


```
fn main()
{
    let s1 = "abcde";
    let s2 = "abc";

    println!("{}", longest(s1,
}

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

```
C:\_RustCode>rustc main.rs
error[E0106]: missing lifetime specifier
 --> main.rs:9:34
  |
9 | fn longest (x: &str, y: &str) -> &str {
  |                                  ^ expected lifetime
 parameter
  |
  = help: this function's return type contains a borrowe
d value, but the signature does not say whether it is bo
rrowed from `x` or `y`

error: aborting due to previous error
```

Lifetime Annotation Syntax

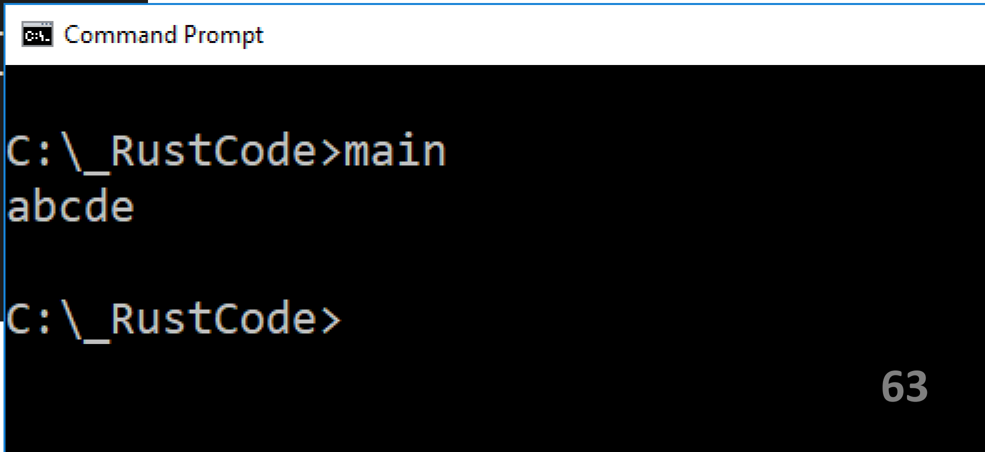
When the borrow checker is confused (for whatever reason), we must be specific:



```
fn main()
{
    let s1 = "abcde";
    let s2 = "abc";

    println!("{}", longest(s1, s2));
}

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

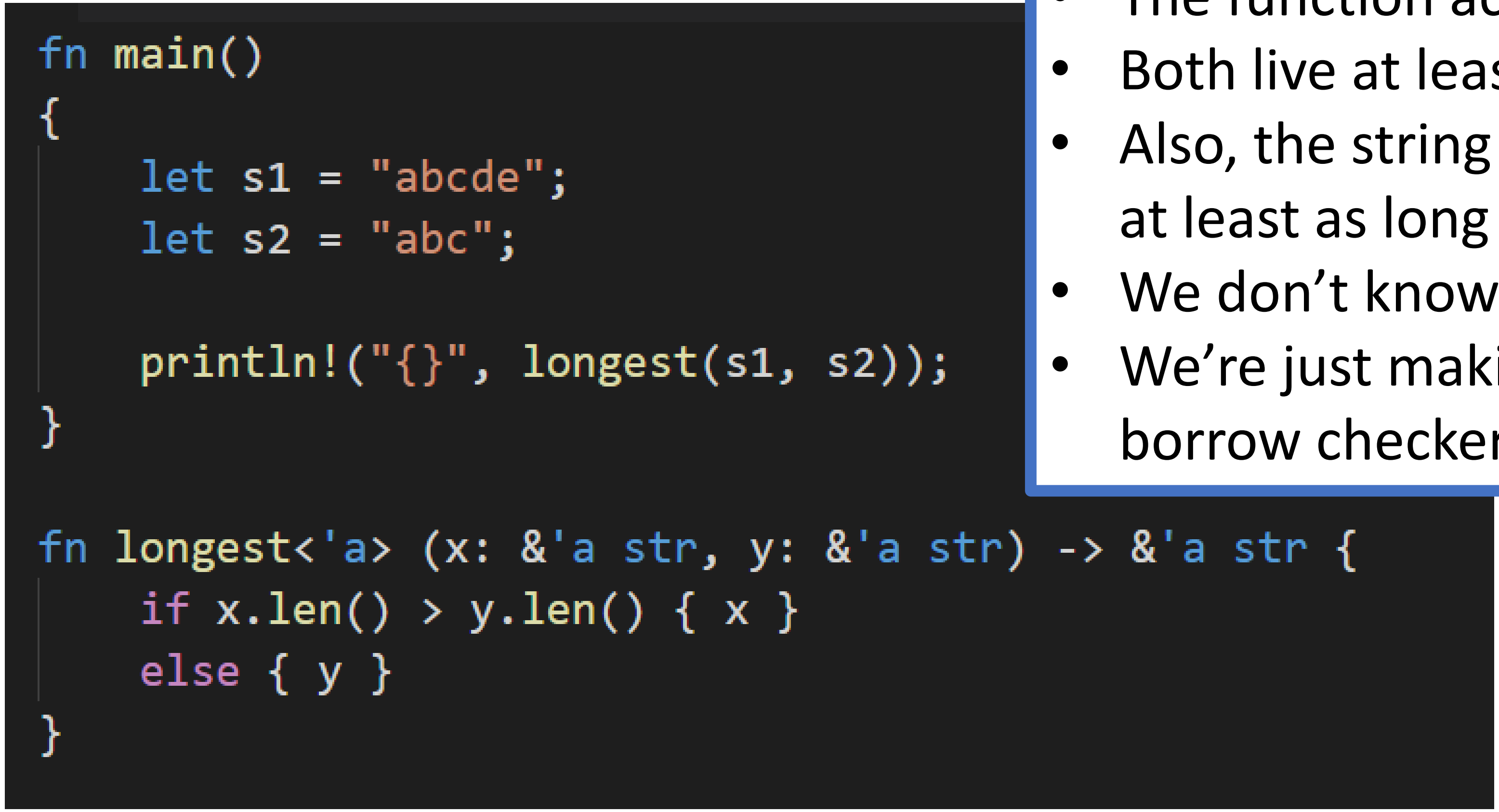
Specify generic lifetime

- Similar to generic type: **<T>**
- **<‘a>** specifies a generic lifetime, **a**
- **&’a** says this reference has lifetime **a**



```
C:\_RustCode>main
abcde

C:\_RustCode>
```

Generic Lifetimes

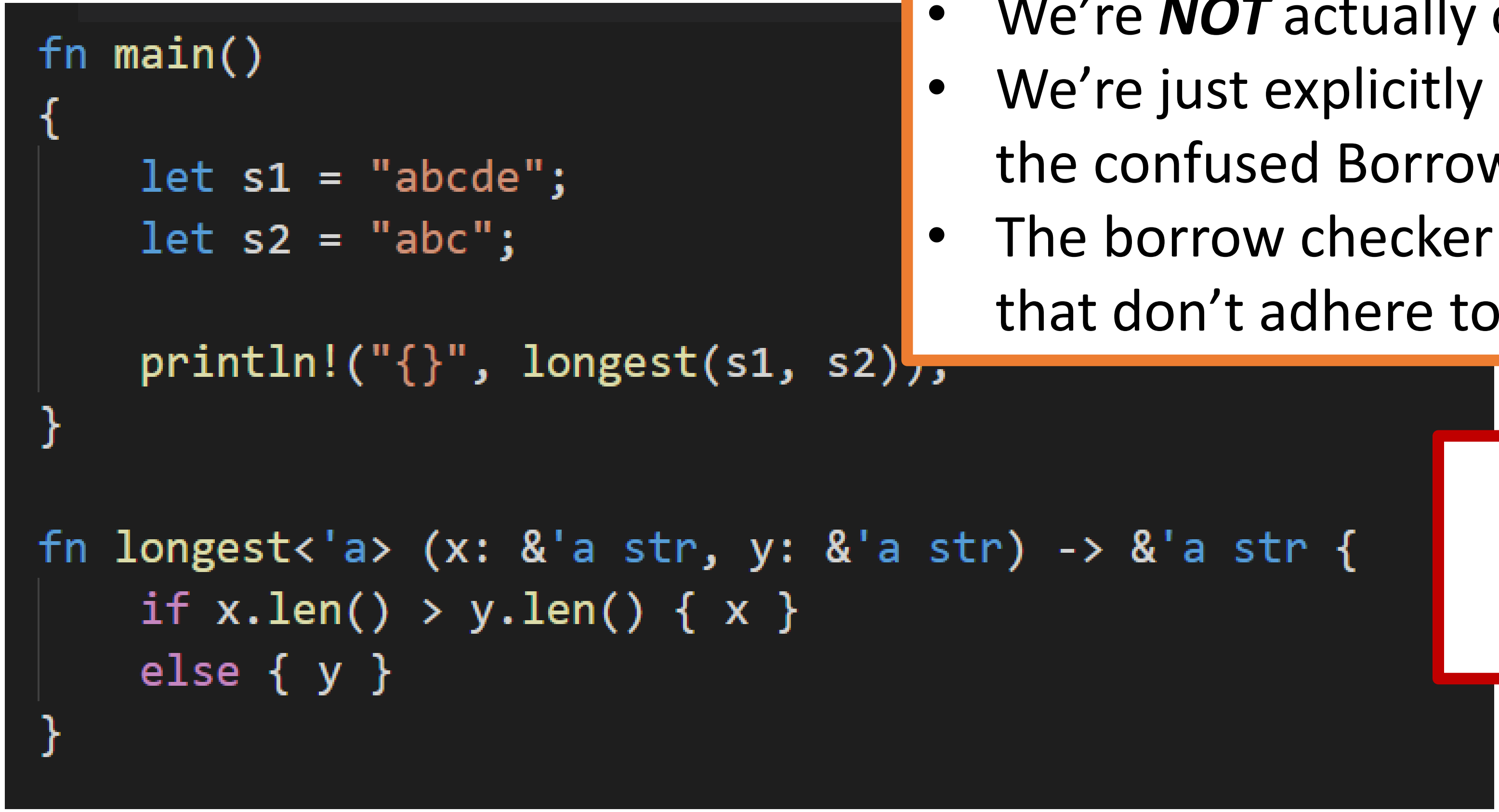


```
fn main()
{
    let s1 = "abcde";
    let s2 = "abc";

    println!("{}", longest(s1, s2));
}

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

What does mean precisely?

- The function accepts two arguments
- Both live at least as long as lifetime **a**
- Also, the string slice returned will live at least as long as lifetime **a**
- We don’t know what **a** is!
- We’re just making this promise to the borrow checker.

Generic Lifetimes



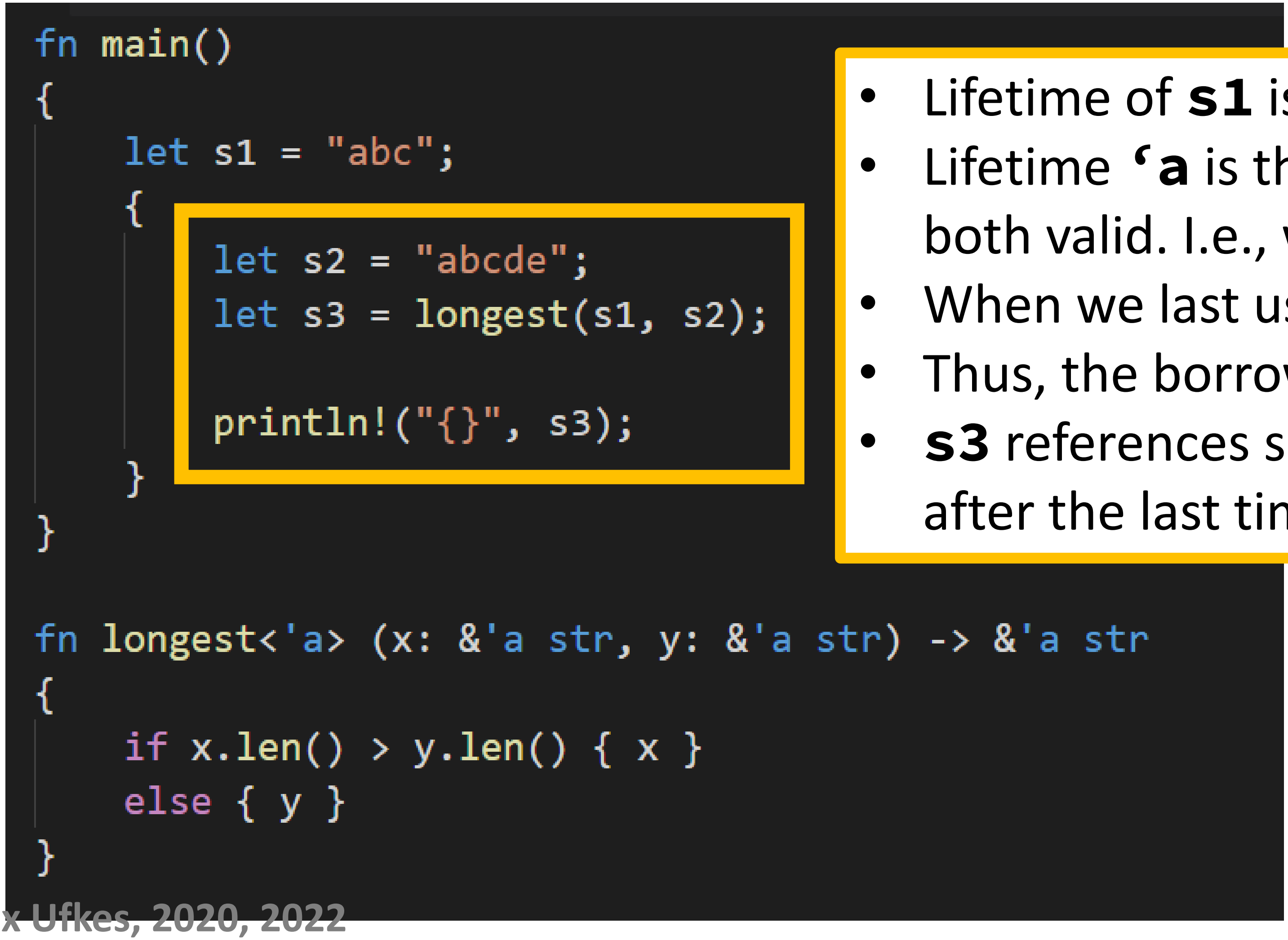
```rust
fn main()
{
    let s1 = "abcde";
    let s2 = "abc";

    println!("{}", longest(s1, s2));
}

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

<u>However!</u>

- We’re ***NOT*** actually changing any lifetimes!
- We’re just explicitly indicating them to help the confused Borrow Checker.
- The borrow checker will reject any values that don’t adhere to these constraints.

So how can we break this?

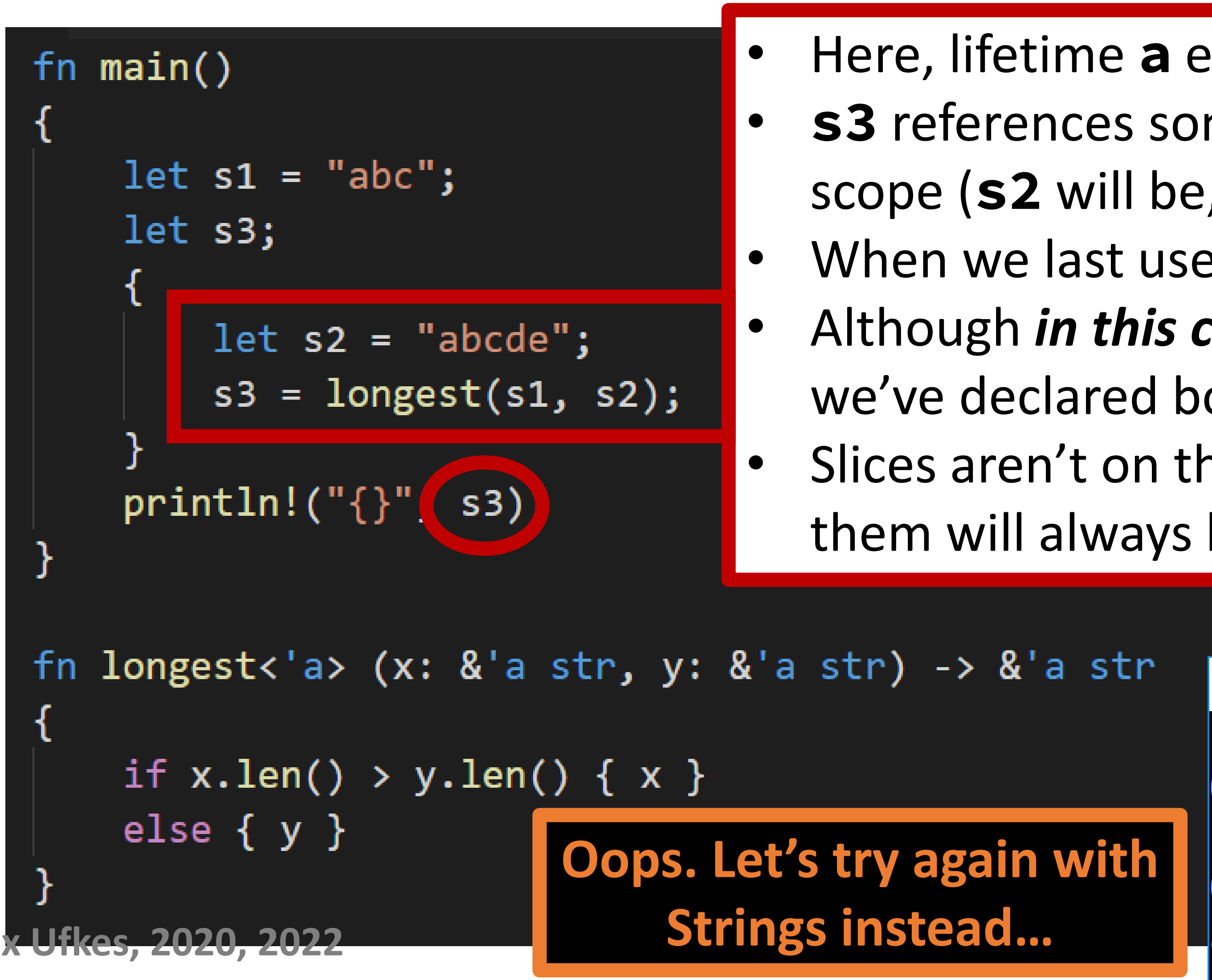
Consider



```
fn main()
{
    let s1 = "abc";
    {
        let s2 = "abcde";
        let s3 = longest(s1, s2);

        println!("{}", s3);
    }
}

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

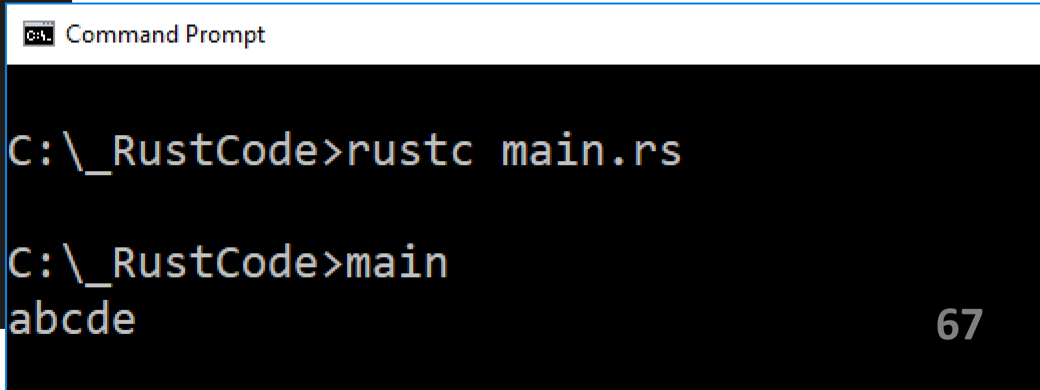
- Lifetime of **s1** is different from **s2** and **s3**.
- Lifetime **‘a** is the scope in which **x** and **y** are both valid. I.e., when **s1** and **s2** are valid.
- When we last use **s3**, **s1** and **s2** are valid.
- Thus, the borrow checker accepts this code.
- **s3** references something that is valid until after the last time **s3** is used.

Now This:



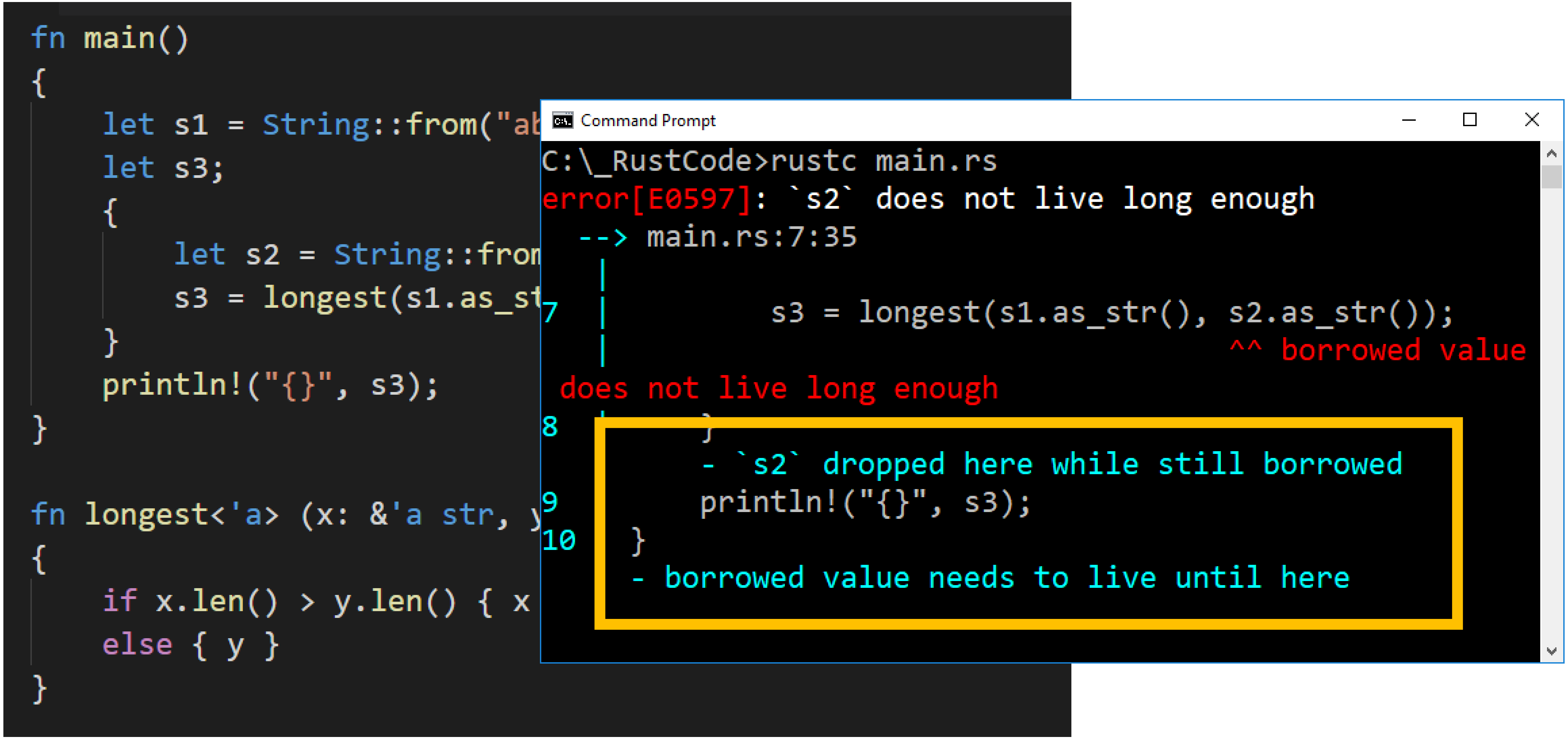
```
fn main()
{
    let s1 = "abc";
    let s3;
    {
        let s2 = "abcde";
        s3 = longest(s1, s2);
    }
    println!("{}", s3)
}

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

- Here, lifetime **a** excludes a reference made by **s3**
- **s3** references something that *might* be out of scope (**s2** will be, **s1** won't be)
- When we last use **s3**, **s2** is no longer valid.
- Although ***in this case*** it doesn't matter, because we've declared both s1 and s2 as string slices.
- Slices aren't on the heap, and thus references to them will always be valid.



```
C:\_RustCode>rustc main.rs

C:\_RustCode>main
abcde
```

Oops. Let's try again with Strings instead…

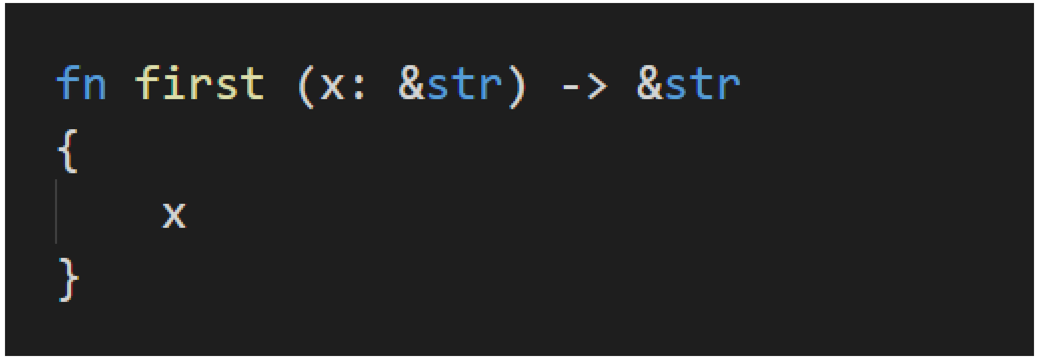


```
fn main()
{
    let s1 = String::from("ab
    let s3;
    {
        let s2 = String::from
        s3 = longest(s1.as_st
    }
    println!("{}", s3);
}

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

```
C:\_RustCode>rustc main.rs
error[E0597]: `s2` does not live long enough
  --> main.rs:7:35
   |
7  |         s3 = longest(s1.as_str(), s2.as_str());
   |                                   ^^ borrowed value
 does not live long enough
8  |     }
          - `s2` dropped here while still borrowed
9         println!("{}", s3);
10    }
      - borrowed value needs to live until here
```

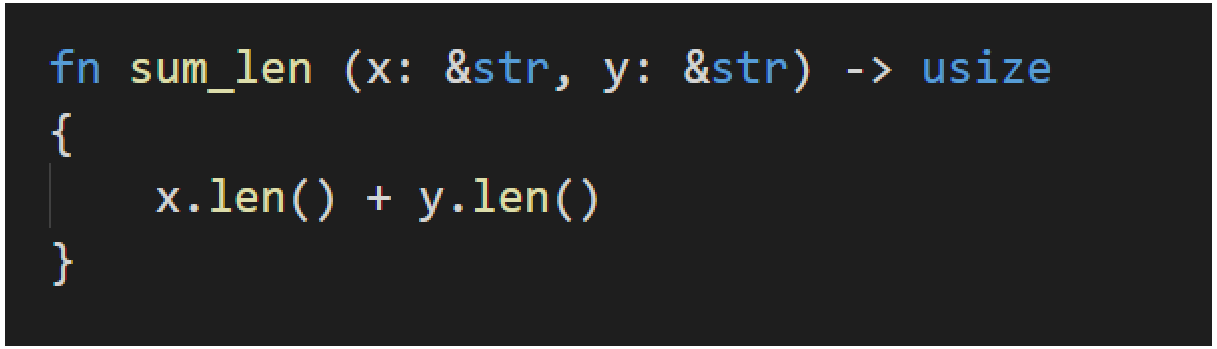
Lifetime Considerations

In general, we need some sort of lifetime indication any time we’re passing in more than one reference and returning a reference.



```rust
fn first (x: &str) -> &str
{
    x
}
```

This is fine



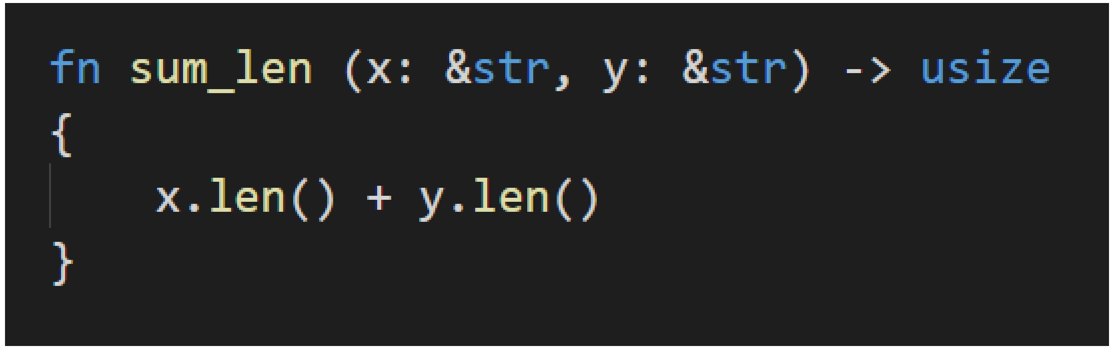
```rust
fn sum_len (x: &str, y: &str) -> usize
{
    x.len() + y.len()
}
```

As is this

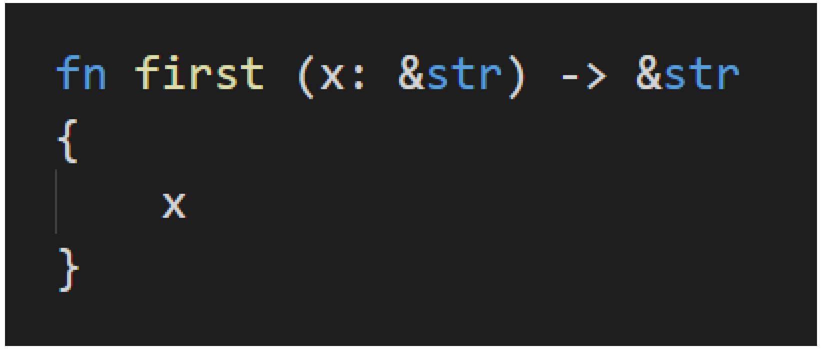
Lifetime Considerations

Originally, every reference required a lifetime specifier.

The Rust developers noticed some cases of reference passing were always the same, and thus added them as patterns for the compiler to recognize without requiring explicit lifetime annotations.



```
fn sum_len (x: &str, y: &str) -> usize
{
    x.len() + y.len()
}
```



```
fn first (x: &str) -> &str
{
    x
}
```

Lifetime Considerations

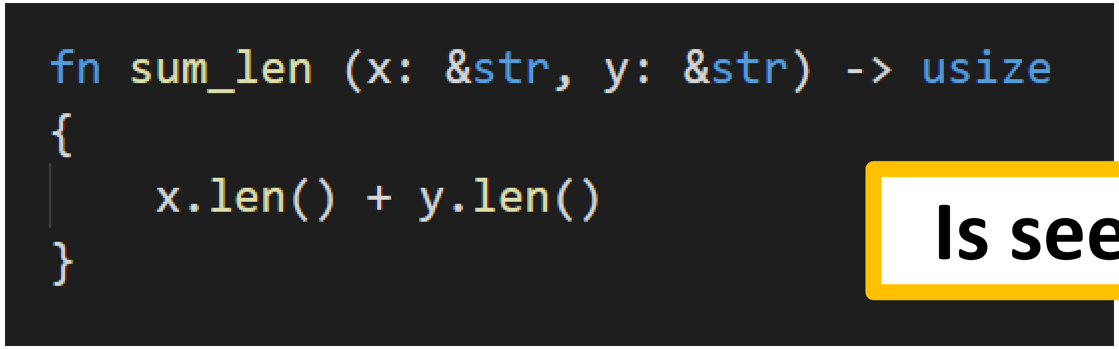
The compiler first checks its list of known patterns

If none are found, we get a compile error such as we’ve been seeing

What are these patterns?

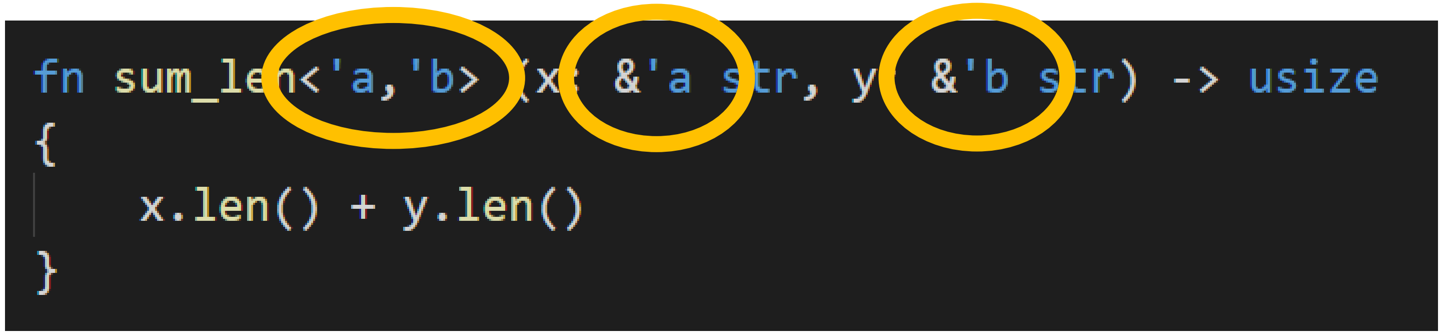
Lifetime Inference Rules

1. The compiler first assigns a *different* lifetime to each reference input parameter.



```
fn sum_len (x: &str, y: &str) -> usize
{
    x.len() + y.len()
}
```

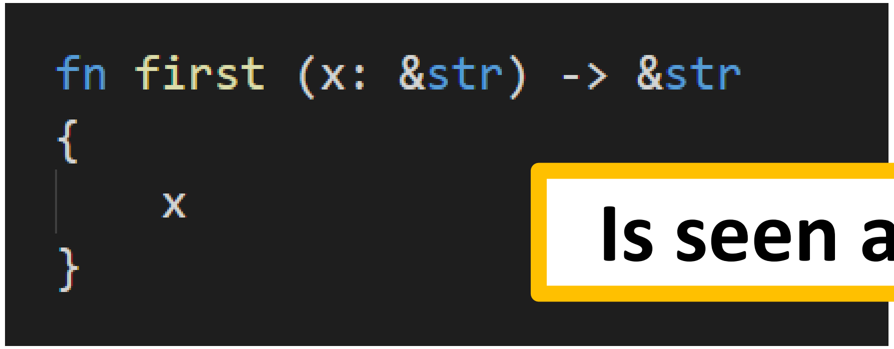
Is seen as:



```
fn sum_len<'a,'b> (x: &'a str, y: &'b str) -> usize
{
    x.len() + y.len()
}
```

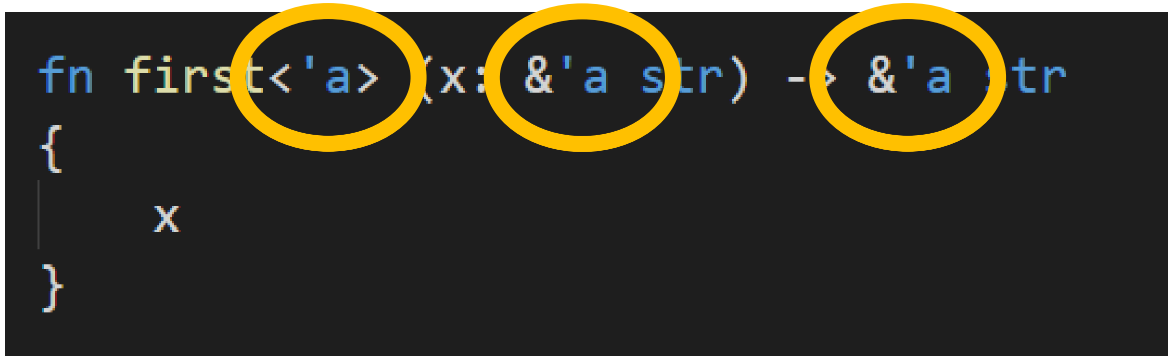
Lifetime Inference Rules

1. The compiler first assigns a *different* lifetime to each reference input parameter.
2. If there is ***one*** input reference parameter, it is assigned the same lifetime as any output references.



```
fn first (x: &str) -> &str
{
    x
}
```

Is seen as:



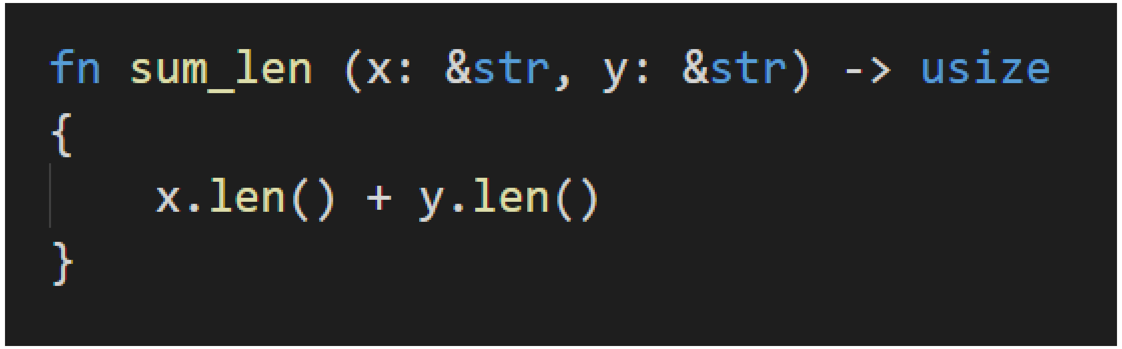
```
fn first<'a> (x: &'a str) -> &'a str
{
    x
}
```

Lifetime Inference Rules

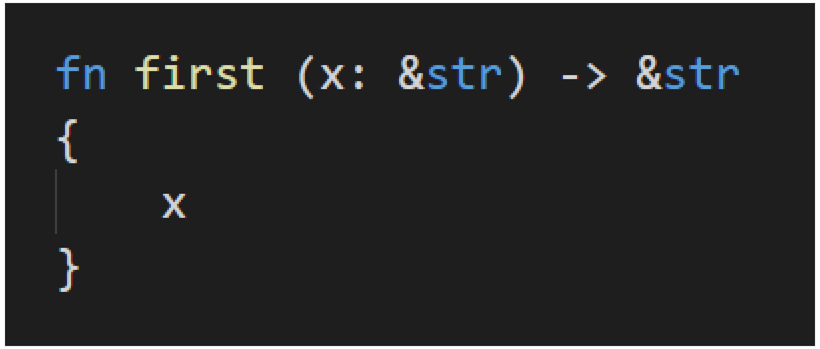
1. The compiler first assigns a *different* lifetime to each reference input parameter.
2. If there is ***one*** input reference parameter, it is assigned the same lifetime as any output references.
3. If there are multiple input references, but one of them is **`&self`**, then the output references have the same lifetime as **`&self`**.

If, after applying these rules, there are still references *without* a lifetime specifier, we get a compile error.

If, after applying these rules, there are still references without a lifetime specifier, we get a compile error.



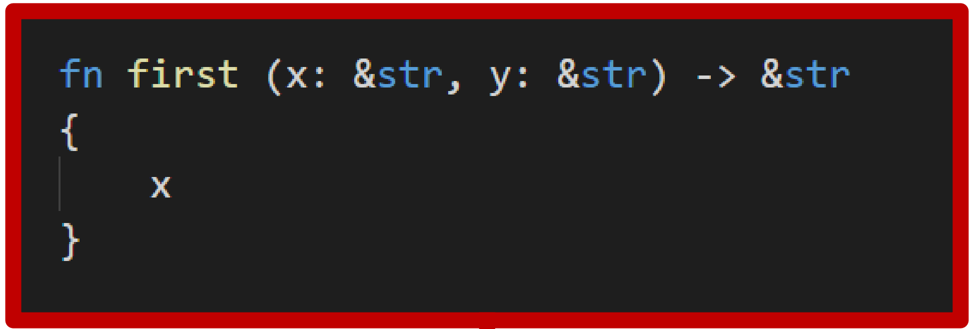
```rust
fn sum_len (x: &str, y: &str) -> usize
{
    x.len() + y.len()
}
```



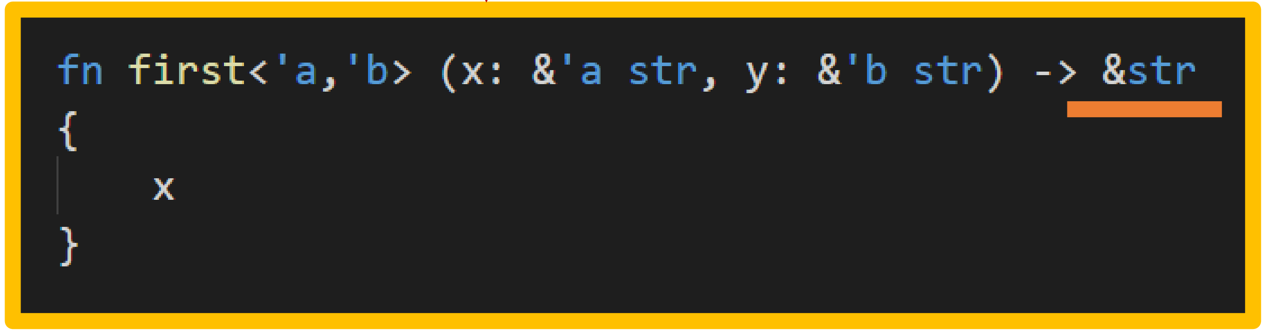
```rust
fn first (x: &str) -> &str
{
    x
}
```

We don’t get errors here, because applying rules 1 and 2 results in all references having annotated lifetimes

We get an error here, because even after applying all three rules, we still don’t have a lifetime annotation for the output:



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



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

1. The compiler first assigns a *different* lifetime to each reference input parameter.
2. If there is ***one*** input reference parameter, it is assigned the same lifetime as any output references.
3. If there are multiple input references, but one of them is **`&self`**, then the output references have the same lifetime as **`&self`**.

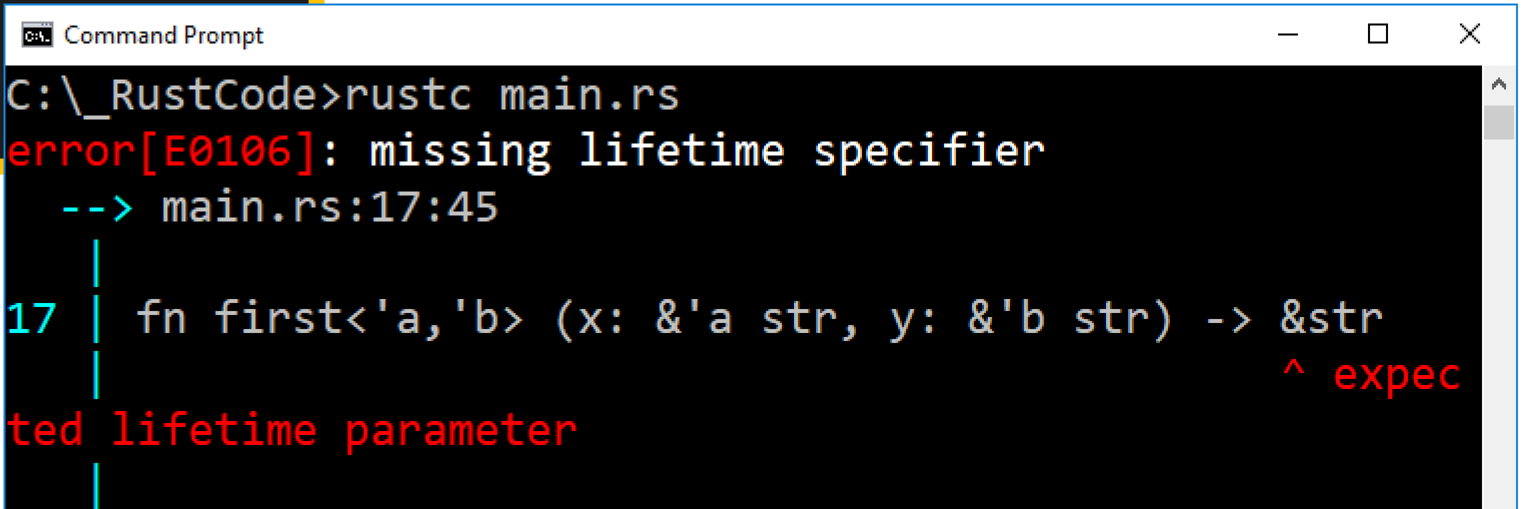
Rule 1 applies, Rules 2 and 3 do not

We get an error here, because even after applying all three rules, we still don’t have a lifetime annotation for the output:

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

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

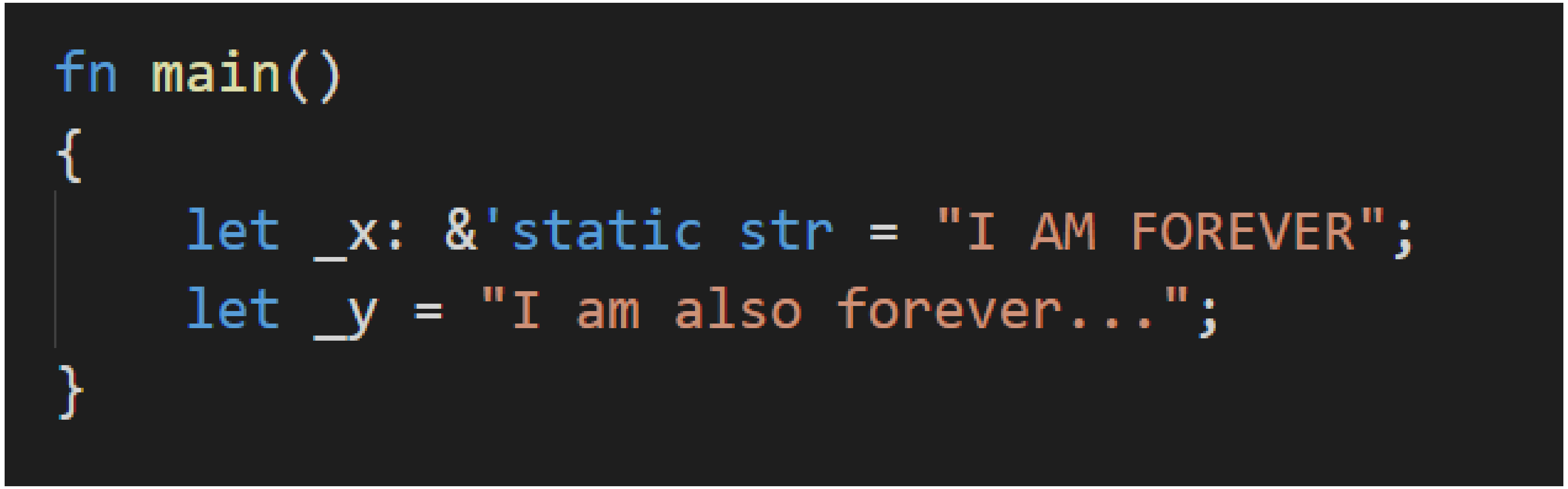
- No lifetime annotation after applying rules.
- Compile error.



```
C:\_RustCode>rustc main.rs
error[E0106]: missing lifetime specifier
  --> main.rs:17:45
   |
17 |  fn first<'a,'b> (x: &'a str, y: &'b str) -> &str
   |                                              ^ expec
ted lifetime parameter
   |
```

Static Lifetime

- A special lifetime that is simply the duration of the program.
- String literals have a static lifetime.
- Makes sense, they’re not on the heap but embedded in the executable



```rust
fn main()
{
    let _x: &'static str = "I AM FOREVER";
    let _y = "I am also forever...";
}
```

Fantastic Rust Reference:

https://doc.rust-lang.org/book/title-page.html