Intro to Rust Lang

Ownership (Part 1)

Welcome back!

- Homework 1 due today
- You can use 7 late days over the whole semester
- If you spent over an hour on the assignment, please let us know!

Today: Ownership

- Preliminary Content
  - Review: Scopes
  - String Introduction
- Ownership
  - Motivation
  - Moving, `clone`, and `copy`
- References and Borrowing
- Slices and Owned Types

Review: Scopes

Recall *scopes* in Rust.

```rust
                       // s is not valid here, it’s not yet declared
{
    let s = "hello";   // s is valid from this point forward

    // do stuff with s
}                      // this scope is now over, and s is no longer valid
```

- There are two important points in time here:
  - When `s` comes *into* scope, it is valid
  - It remains valid until it goes *out* of scope

String Literals

We didn't explicitly talk about this last week, but every time you see a text like `"Hello, World!"` surrounded by double quotes, that is a *string literal*.

```rust
fn main() {
    println!("Hello, world!"); // Print a string literal

    let s = "Ferris is our friend"; // Another string literal
}
```

- String literals live inside in the program binary

Problem: String Literals are Immutable

Suppose we wanted to take user input and store it. This is how we might do it in Python:

```python
username = input("Tell me your name!")
```

- We do not know how long `username` will be
- How would we do this in Rust?
- We need a way to store a collection of characters with a dynamic size

The `String` type

- In addition to string literals, Rust has another string type, `String`
- `String` manages data allocated on the heap
- Dynamically stores an amount of text that is unknown at compile time

`String` example

You can create a `String` from a string literal using `String::from()`.

```rust
let s = String::from("hello");
```

This kind of string *can* be mutated:

```rust
let mut s = String::from("hello");

s.push_str(", world!"); // push_str() appends a literal to a String

println!("{}", s); // This will print `hello, world!`
```

Ownership

Ownership

From the official Rust Lang book:

> Ownership is Rust’s most unique feature and has deep implications for the rest of the language. It enables Rust to make memory safety guarantees without needing a garbage collector, so it’s important to understand how ownership works.

- Today we'll introduce *Ownership*, as well as several related features

What is Ownership?

Ownership is a set of rules that govern how a Rust program manages memory.

- Some languages have garbage collection to manage memory
- Other languages require you to explicitly allocate and free memory
- Rust has a third approach:
    - Manage resources via a set of *rules*

Ownership rules

- Each value in Rust has an *owner*
- There can only be one owner at a time
- When the owner goes out of scope, the value will be *dropped*

Example: `String` vs string literals

- Since we know the contents of string literals at compile time, the text is hardcoded directly into the final executable
- To support a fully resizable piece of text, we need to allocate on the *heap*
    - This means we must request memory from the allocator at *runtime*
    - We need a way of returning the memory when we're done using it
    - What 2 C functions does this remind you of?

`malloc` and `free`

In C, we use `malloc` and `free` to manage heap memory for our program.

However, we need to ensure we pair exactly one `malloc` with exactly one `free`.

- If we forget to `free`, we leak memory
- If we `free` too early, we have an invalid variable
- If we `free` twice, that's a "double free" bug
- Undefined behavior!!! ☠️

Manual Memory Management

- Using `malloc` and `free` can lead to all sorts of undefined behavior
    - Unless you are the perfect developer...
    - Who *never* writes a bug...
    - You're bound to shoot yourself in the foot
- It would be great if the compiler knew:
    - At what point the variable needs memory
    - At what point the memory is no longer needed
- Idea: **what if we tied memory allocation to the scope of a variable?**

Rust's approach to memory

Memory is returned once the variable that owns it goes out of scope.

```
{
    let s = String::from("hello"); // s is valid from this point forward

    // do stuff with s
}                                  // this scope is now over,
                                   // and s is no longer valid
```

- When `s` comes into scope, it gets memory from the allocator
- When `s` goes out of scope, it frees all of its memory
    - Rust calls a function called `drop` on `s` automatically once the program reaches the closing bracket

Example: `String` "copying"

```rust
let s1 = String::from("hello");
let s2 = s1;
```

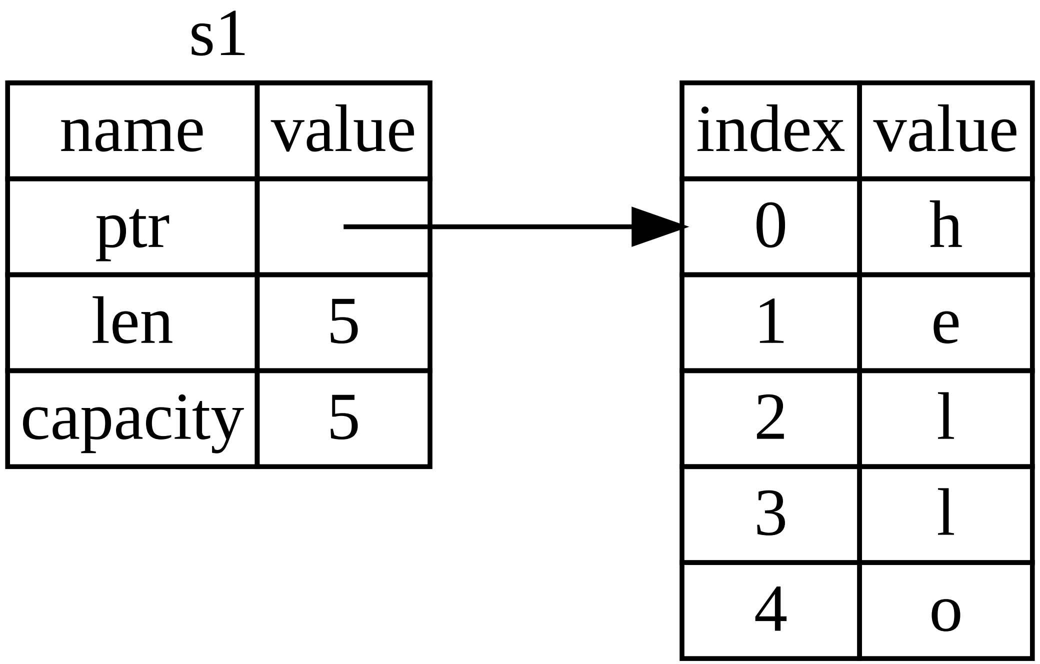
What is this code doing?

- Bind the `String` containing `"hello"` to `s1`
- Now what?
    - Do we make a copy of the `String`?
    - What does a copy actually mean in this case?

`String` data layout

```rust
let s1 = String::from("hello");
```

- A `String` is made up of 3 fields:
  - A pointer to the characters somewhere in memory
  - A length
  - A capacity
- Left diagram is on the stack
- Right diagram is on the heap



s1

name	value
ptr	
len	5
capacity	5

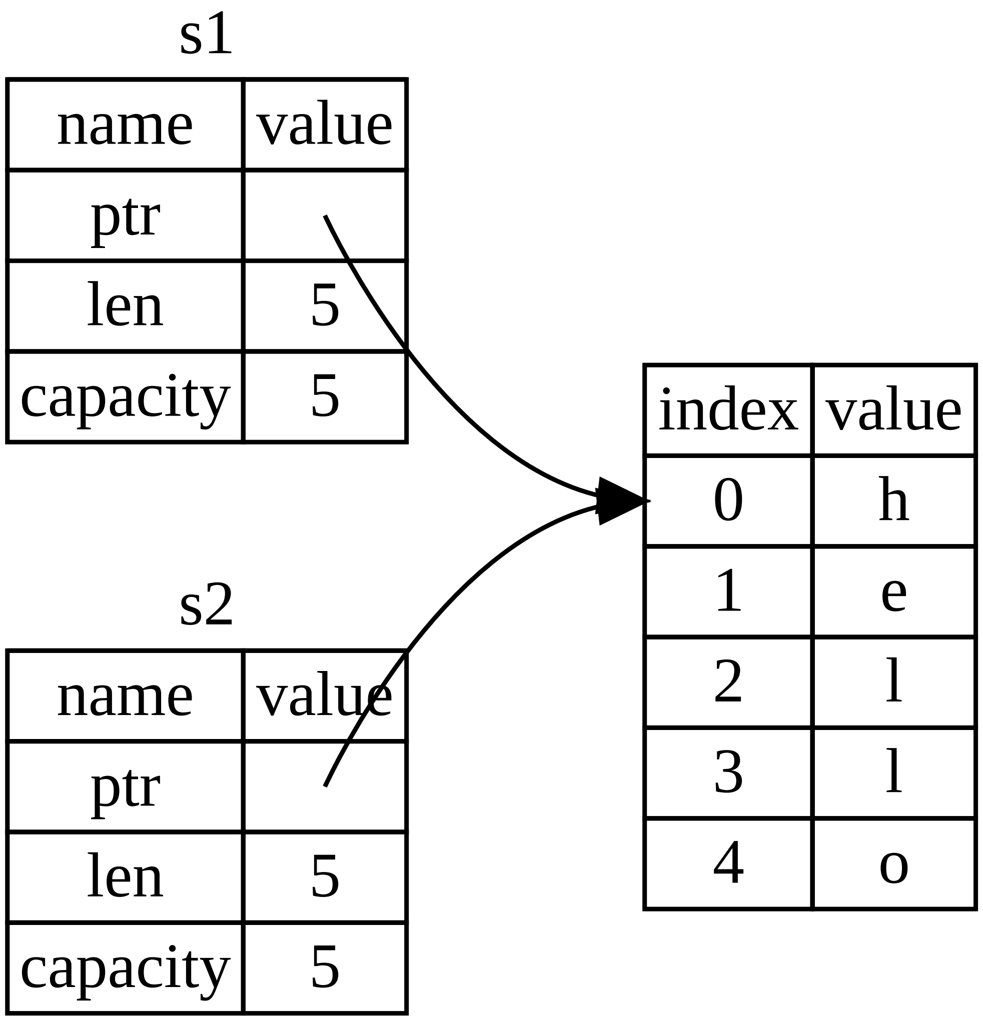
index	value
0	h
1	e
2	l
3	l
4	o

Pointer aliasing 😨

```rust
let s1 = String::from("hello");
let s2 = s1;
```

One way to handle this case is:

- When we assign `s1` to `s2`, only the stack data is copied
- We do *not* create a copy of the contents of the `String`
- Also known as a "shallow copy" in some languages



s1

name	value
ptr	
len	5
capacity	5

s2

name	value
ptr	
len	5
capacity	5

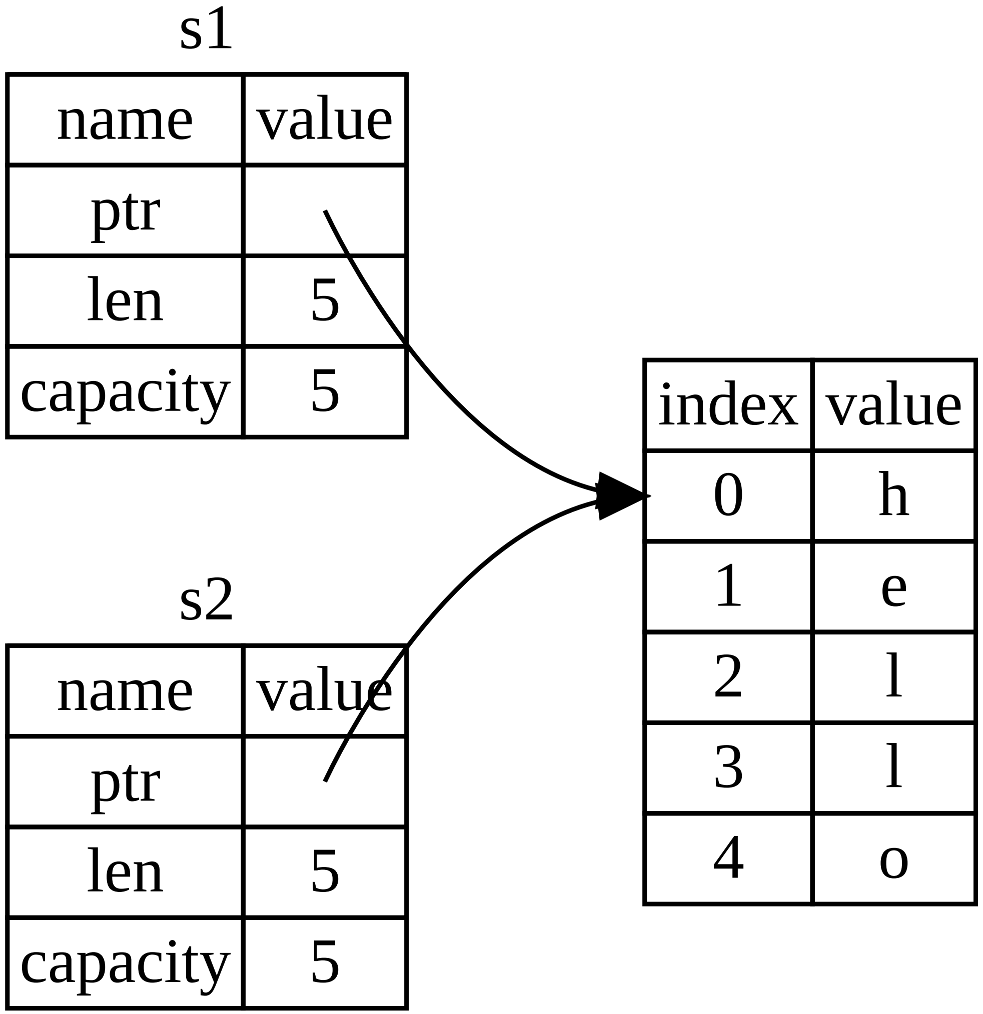
index	value
0	h
1	e
2	l
3	l
4	o

Pointer aliasing ☠️

```
let s1 = String::from("hello");
let s2 = s1;
```

Suppose Rust handled this case with a shallow copy.

- Following Rust's scope rules, what would happen if we tried to drop both `s1` and `s2`?
    - Double free! 🪦
- How can this be prevented?



s1

name	value
ptr	
len	5
capacity	5

s2

name	value
ptr	
len	5
capacity	5

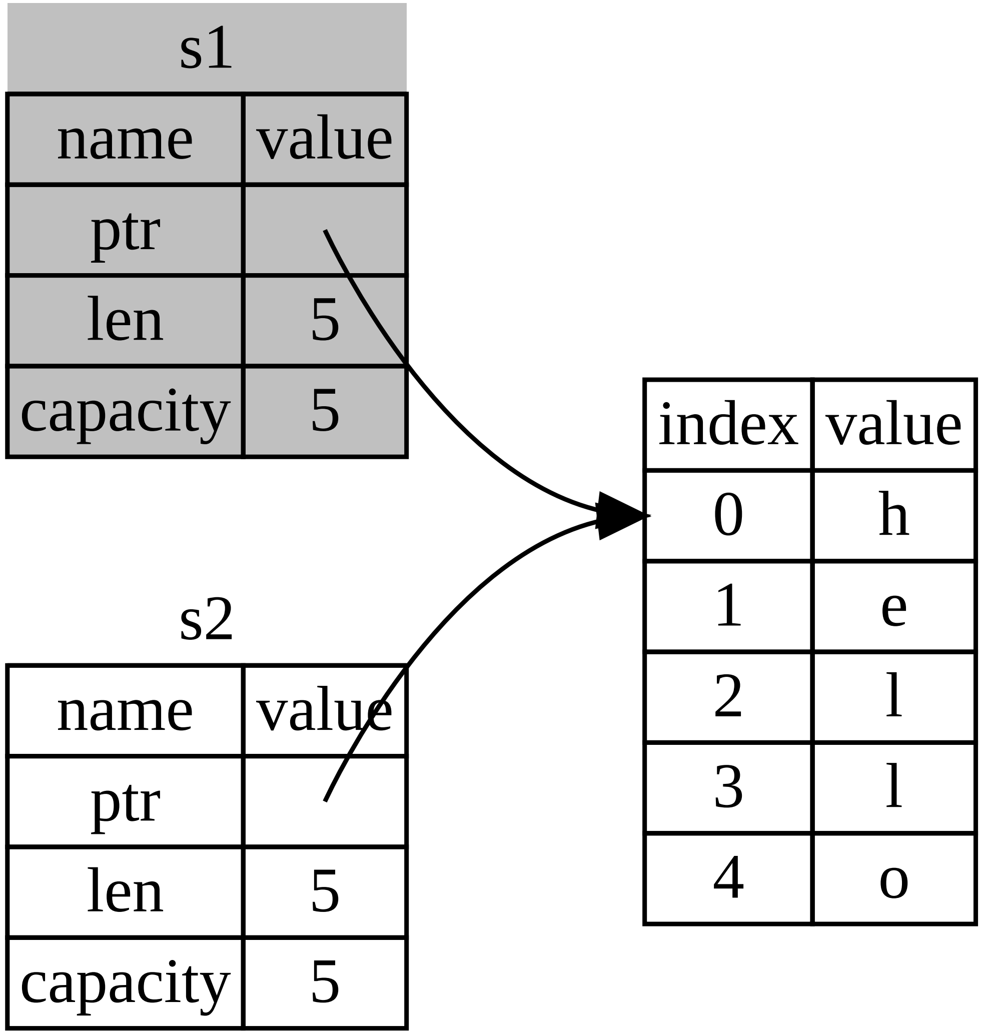
index	value
0	h
1	e
2	l
3	l
4	o

Enforcing one owner at a time

To ensure memory safety, after the second line, `s1` is no longer valid.

```
let s1 = String::from("hello");
let s2 = s1; // s1 is no longer valid
```

- *Grayed out portion is no longer accessible to the program*



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

What happens if we try to use `s1` after it is in invalid?

```
let s1 = String::from("hello");
let s2 = s1;
println!("{}, world!", s1);
```

```
error[E0382]: borrow of moved value: `s1`
  |
2 |     let s1 = String::from("hello");
  |         -- move occurs because `s1` has type `String`,
               which does not implement the `Copy` trait
3 |     let s2 = s1;
  |              -- value moved here
4 |
5 |     println!("{}, world!", s1);
  |                            ^^ value borrowed here after move
  |
help: consider cloning the value if the performance cost is acceptable
  |
3 |     let s2 = s1.clone();
```

Move semantics

```rust
let s1 = String::from("hello");
let s2 = s1;
```

- Rust calls this shallow copy plus invalidation a *move*
- We *moved* `s1` into `s2`
  - Hence `s1` can no longer be accessed

Moving vs cloning

```rust
let s1 = String::from("hello");
let s2 = s1;
```

- What if we copied all of the data instead?
    - Known as deep copying or cloning
- Implicitly copying all of the data would solve the problem
    - But it can get expensive, quickly
- In Rust, cloning must be explicitly performed by the programmer
    - This is very intentional, to avoid accidental performance loss

`Clone`

If we do want to deep copy, we can use a method called `clone`.

```rust
let s1 = String::from("hello");
let s2 = s1.clone();

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

```
s1 = hello, s2 = hello
```

- This copies *all* of the data contained in `s1`, both on the heap and the stack
- We'll talk more about methods next week!

What about integers?

Based on what we have seen, this code should not work.

```rust
let x = 5;
let y = x;

println!("x = {}, y = {}", x, y);
```

```
x = 5, y = 5
```

- `x` is still valid, but it looks like we moved it into `y`
- We just said that this wasn't allowed!

Copy

```
let x = 5;
let y = x;
```

- Types such as integers have a size known at compile time
- Data is stored either in registers or on the stack
- Copies of integers are very quick to make
- There is no difference between a shallow copy and a deep copy here
    - So why not clone implicitly?

`Copy`

Certain types are annotated with a `Copy` trait, which allows implicit copying instead of moving.

Types that are `Copy`:

- All numeric types, including integers and floating points
- Boolean type, `bool`
- Character type, `char`
- Tuples, if they only contain types that are `Copy`
    - `(i32, i32)` is `Copy`, but `(i32, String)` is not

Ownership and Functions

Passing a variable to a function behaves just as assignment does.

Passing a `String`:

```rust
fn main() {
    let s = String::from("hello");
    takes_ownership(s);
} // Because `s`'s value was moved, `s` is not dropped

               // `some_string` comes into scope
fn takes_ownership(some_string: String) {
    println!("{} is mine now!", some_string);
} // `some_string` goes out of scope and `drop` is called.
  // The backing memory is freed.
```

Ownership and Functions

What if we tried to use a value after a function takes ownership of it?

```
fn main() {
  let s = String::from("hello");
  takes_ownership(s);
  println!("{} is invalid now!", s);
}
```

```
error[E0382]: borrow of moved value: `s`
 --> src/main.rs:4:36
  |
2 |     let s = String::from("hello");
  |         - move occurs because `s` has type `String`,
              which does not implement the `Copy` trait
3 |     takes_ownership(s);
  |                     - value moved here
4 |     println!("{} is invalid now!", s);
```

Ownership and Functions

Passing an `i32`:

```rust
fn main() {
    let x = 5;
    makes_copy(x);
    println!("Here is {} again!", x); // x is still valid!
}

fn makes_copy(some_integer: i32) {
    println!("{} just got copied", some_integer);
}
```

Return Values and Scope

Returning values can also transfer ownership.

```rust
fn main() {
    let s1 = gives_ownership();
    println!("{}", s1); // s1 is valid---we have taken ownership
}

fn gives_ownership() -> String {
    let some_string = String::from("yours");

    some_string // `some_string` is returned and
                // moves out to the calling function
}
```

Return Values and Scope

Another example of taking and giving back ownership:

```rust
fn main() {
    let s2 = String::from("hello");
    let s3 = takes_and_gives_back(s2);
    println!("{}", s3);
} // Here, `s3` goes out of scope and is dropped.
  // `s2` was moved, so nothing happens to `s2`.

fn takes_and_gives_back(a_string: String) -> String {
    a_string  // a_string is returned and
              // moves out to the calling function
}
```

Recap: Ownership

- Ownership rules:
  - Each value in Rust has an *owner*
  - There can only be one owner at a time
  - When the owner goes out of scope, the value will be *dropped*
- With just ownership, we can either move, copy, or clone
  - Moving and copying has no overhead
  - Cloning is expensive

Moving is somewhat tedious

```rust
fn main() {
    let s1 = String::from("hello");
    let (s2, len) = calculate_length(s1);
    println!("The length of '{}' is {}.", s2, len);
}

fn calculate_length(s: String) -> (String, usize) {
    let length = s.len();
    (s, length)
}
```

- If we want to give a function some data, it seems we need to *move* the data into the function
- To get it back, it seems we need to also return the data back every time
- *What if we want to let a function use a value but not take ownership?*

References and Borrowing

References

- Moving into and returning data from a function is a lot of work
- Rust has a feature specifically for using a value without transferring ownership called *references*
- We can share memory using these *references*

Reference with `&`

Instead of moving a value into a function, we can provide a *reference* to the value.

We use `&` to define a reference to a value.

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

    let len = calculate_length(&s1);

    println!("The length of '{}' is {}.", s1, len);
}

fn calculate_length(s: &String) -> usize {
    s.len()
}
```

- The `&s1` syntax lets us create a variable that *refers* to the value of `s1`

References as Function Arguments

```
                // `borrowed` is a reference to a String
fn calculate_length(borrowed: &String) -> usize {
    borrowed.len()
} // Here, `borrowed` goes out of scope
```

- `borrowed` is a reference to `s1` (i.e. `&s1`)
- We do not own `s1` with just a reference to it
- This means `s1` will *not* be dropped when `borrowed` goes out of scope
- We call holding a reference *borrowing*

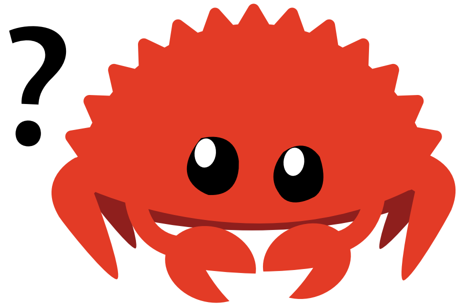
Mutating a Reference

What if we want to modify the value of something we've borrowed through a reference?

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

    change(&s);
}

fn change(some_string: &String) {
    some_string.push_str(", world");
}
```



Modifying a Reference

We get an error if we try to modify a reference.

```
error[E0596]: cannot borrow `*some_string` as mutable,
              as it is behind a `&` reference

 --> src/main.rs:8:5
  |
7 | fn change(some_string: &String) {
  |                        ------- help: consider changing this
                                   to be a mutable reference: `&mut String`
8 |     some_string.push_str(", world");
  |     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ `some_string` is a `&` reference,
                                         so the data it refers to cannot
                                         be borrowed as mutable
```

- Just like variables, references are immutable by default

Mutable References

If we want to modify the value that we've borrowed, we must use a mutable reference, denoted `&mut val`.

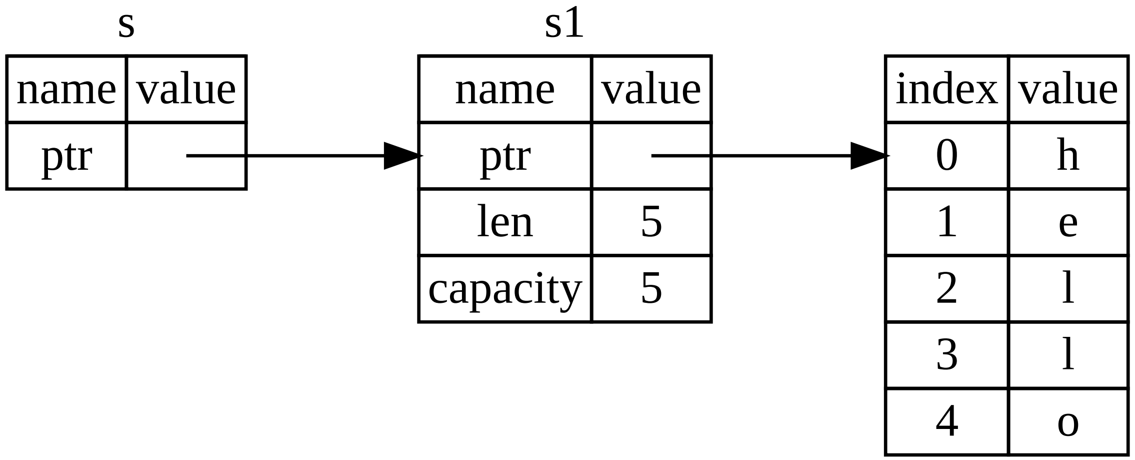
```rust
fn main() {
    let mut s = String::from("hello");

    change(&mut s);
}

fn change(some_string: &mut String) {
    some_string.push_str(", world");
}
```

Reference Data Layout

- In memory, references are just like pointers
- In practice, they have a couple of constraints that make them safer



Reference Constraints

- Mutable References are Exclusive
- No Dangling References

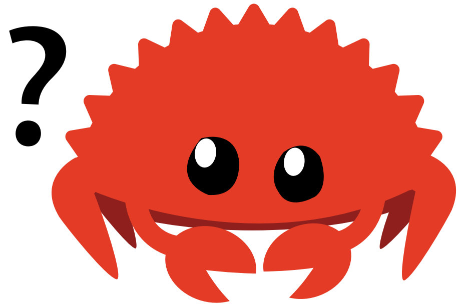
Constraint: Mutable References are Exclusive

If you have a mutable reference to a value, you can have no other references to that value.

```
let mut s = String::from("hello");

let r1 = &mut s;
let r2 = &mut s;

println!("{}, {}", r1, r2);
```



Constraint: Mutable References are Exclusive

```
let mut s = String::from("hello");
let r1 = &mut s;
let r2 = &mut s;
println!("{}, {}", r1, r2);
```

```
error[E0499]: cannot borrow `s` as mutable more than once at a time
 --> src/main.rs:5:14
  |
4 |     let r1 = &mut s;
  |              ------ first mutable borrow occurs here
5 |     let r2 = &mut s;
  |              ^^^^^^ second mutable borrow occurs here
6 |
7 |     println!("{}, {}", r1, r2);
  |                        -- first borrow later used here
```

Constraint: Mutable References are Exclusive

- Most languages will let you mutate anything, whenever you want
- If data can be written to from multiple places, the value can become unpredictable
- Making mutable references exclusive prevents data races at compile time!

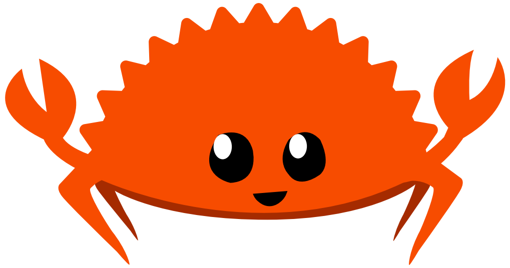
Multiple Mutable References

We are allowed to hold multiple mutable references, just not *simultaneously*.

```rust
let mut s = String::from("hello");

{
    let r1 = &mut s;
} // r1 goes out of scope here, so we can make
  // a new mutable reference with no problems

let r2 = &mut s;
```



- Notice that the scopes of these mutable references do not overlap

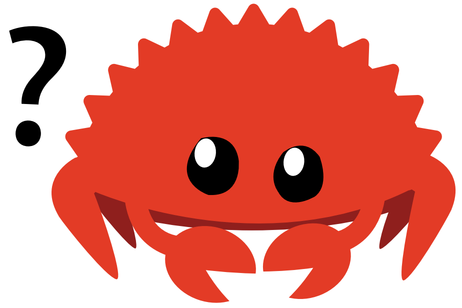
Mutable and Immutable References

We cannot have both an immutable and mutable reference to the same value.

```
let mut s = String::from("hello");

let r1 = &s; // no problem
let r2 = &s; // no problem
let r3 = &mut s; // BIG PROBLEM

println!("{}, {}, and {}", r1, r2, r3);
```



Mutable and Immutable References

```rust
let mut s = String::from("hello");
let r1 = &s; // no problem
let r2 = &s; // no problem
let r3 = &mut s; // BIG PROBLEM
println!("{}, {}, and {}", r1, r2, r3);
```

```
error[E0502]: cannot borrow `s` as mutable because
              it is also borrowed as immutable
 --> src/main.rs:6:14
  |
4 |     let r1 = &s; // no problem
  |              -- immutable borrow occurs here
5 |     let r2 = &s; // no problem
6 |     let r3 = &mut s; // BIG PROBLEM
  |              ^^^^^^ mutable borrow occurs here
7 |
8 |     println!("{}, {}, and {}", r1, r2, r3);
```

Mutable and Immutable References

Note that exclusivity rules only apply for references whose scopes overlap.

```rust
let mut s = String::from("hello");

let r1 = &s; // no problem
let r2 = &s; // no problem
println!("{} and {}", r1, r2);
// variables r1 and r2 will not be used after this point

let r3 = &mut s; // no problem
println!("{}", r3);
```

- The scope of a reference starts when it is initialized
- The scope of a reference **ends at the last point it is used**
- The specific term for reference scopes are *lifetimes*
  - We'll talk about lifetimes in week 8!

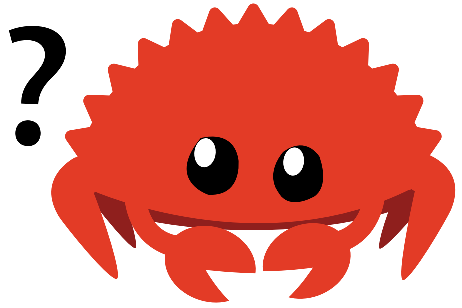
Constraint: No Dangling References

The Rust compiler guarantees that references will never be invalid, which means it will not allow dangling references.

```rust
fn main() {
    let reference_to_nothing = dangle();
}

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

    &s
}
```



Constraint: No Dangling References

```
error[E0106]: missing lifetime specifier
 --> src/main.rs:5:16
  |
5 | fn dangle() -> &String {
  |                ^ expected named lifetime parameter
  |
  = help: this function's return type contains a borrowed value,
    but there is no value for it to be borrowed from
help: consider using the `'static` lifetime
<-- snip -->
```

Focus on this line:

> this function's return type contains a borrowed value, but there is no value for it to be borrowed from

Reference Constraints

- Mutable references are exclusive:
  - At any given time, you can have either one mutable reference or any number of immutable references
    - A book being read by multiple people is fine
    - If more than one person writes, they may overwrite each other's work
    - References are similar to Read-Write locks
- No dangling references:
  - References must always be valid

The Borrow Checker

The Borrow Checker enforces the ownership and borrowing rules by checking:

- That all variables are initialized before they are used
- That you can't move the same value twice
- That you can't move a value while it is borrowed
- That you can't access a place while it is mutably borrowed (except through the mutable reference)
- That you can't mutate a place while it is immutably borrowed
- and more...

Slices

Slices

- *Slices* let you reference a contiguous sequence of elements in a collection rather than the whole collection
- A slice is similar to a reference, so it does not have ownership

Slices

Suppose we want to write this function:

```
fn first_word(s: &String) -> ?
```

- Find the first space and return all the characters before it
- What type should we return?

String Slices

A *string slice* is sometimes a reference to part of a `String`, and it looks like this:

```rust
let s = String::from("hello world");

let hello = &s[0..5];
let world = &s[6..11];
```

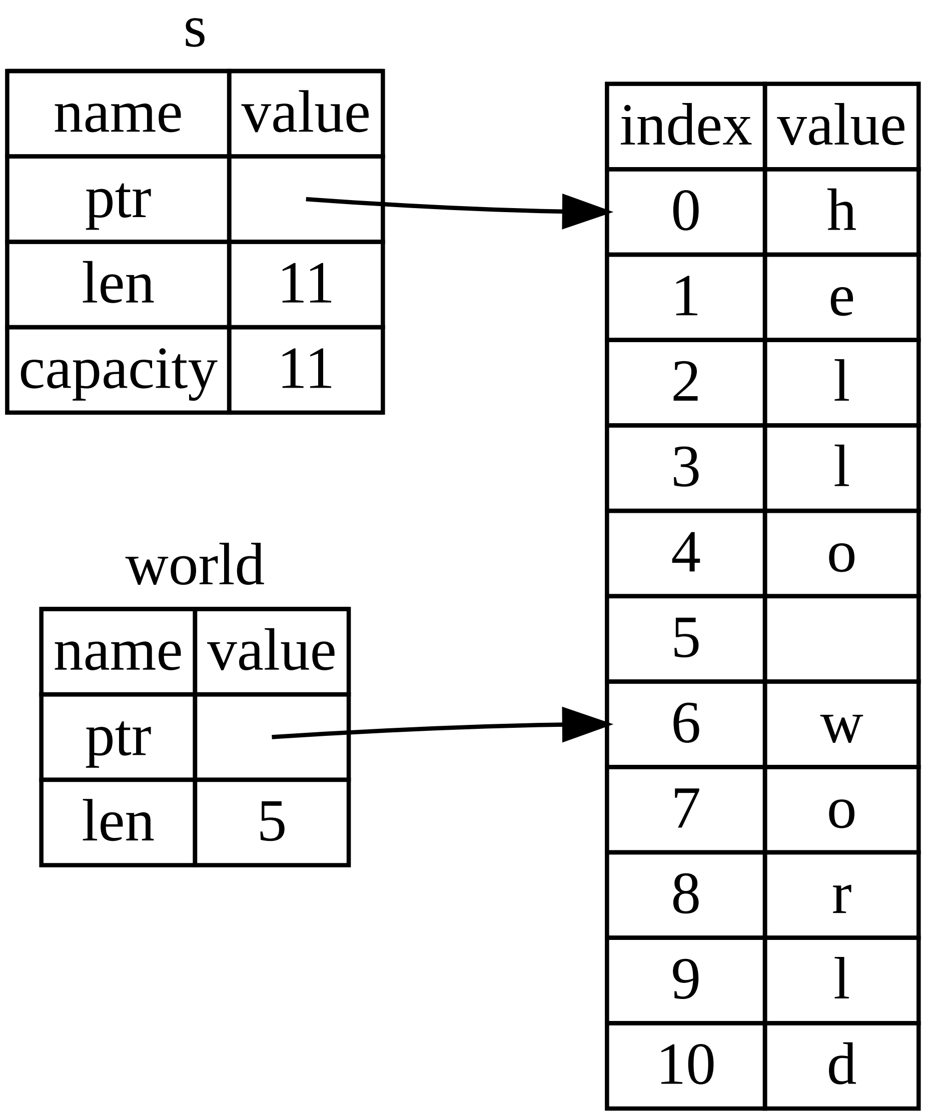
- `hello` contains the first 5 characters of `s`
- `world` contains the 5 characters starting at the 6th index of `s`

String Slices

```
let s = String::from("hello world");

let hello = &s[0..5];
let world = &s[6..11];
```

- A string slice stores a pointer to memory and a length



s

name	value
ptr	
len	11
capacity	11

world

name	value
ptr	
len	5

index	value
0	h
1	e
2	l
3	l
4	o
5	
6	w
7	o
8	r
9	l
10	d

String Slices

You can shorthand ranges with the `..` syntax.

```rust
let s = String::from("hello");

let slice = &s[0..2];
let slice = &s[..2];

let len = s.len();
let slice = &s[3..len];
let slice = &s[3..];

let slice = &s[0..len];
let slice = &s[..];
```

String Literals are Slices

Recall that we talked about string literals being stored inside the binary.

```rust
let s = "Hello, world!";
```

- The type of `s` here is `&str`: it’s a slice pointing to that specific point of the binary with type `str`
- String literals are immutable
  - Their `&str` immutable reference type reflects that

Owned Types

- String slices and string literals are immutable because they are a special type of immutable reference
- String is an owned type
    - i.e. a type that has an owner
- Another owned type is a vector

Vectors

Vectors allow you to store a collection of values of the same type contiguously in memory. Internally, it is a dynamically sized array stored on the heap.

You can create an vector with the method `new`:

```
let v: Vec<i32> = Vec::new();
```

- The `<i32>` just means that the vector stores `i32` values. We'll talk more about this syntax in Week 4!

Updating a `Vec`

To add elements to a `Vec`, we can use the `push` method.

```
let mut v = Vec::new();

v.push(5);
v.push(6);
v.push(7);
v.push(8);

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

```
[5, 6, 7, 8]
```

`vec!` Macro

Rust provides a *macro* to create vectors easily in your programs.

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

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

```
[1, 2, 3]
```

- Briefly: Macros are a special type of function
    - They can take in a variable number of arguments

Reading Elements of Vectors

You can index into a vector to retrieve a reference to an element.

```rust
let v = vec![1, 2, 3, 4, 5];

let third: &i32 = &v[2];
println!("The third element is {}", third);
```

- Note that Rust will panic if you try to index out of the bounds of the `Vec`

More `Vec<T>` to come...

We will talk more about `String` and `Vec<T>` in Week 4!

Homework 2

- The second homework consists of 10 small ownership puzzles
  - Refer to the `README.md` for further instructions
  - Always follow the compiler's advice!
- We ***highly*** recommend reading the Rust Book chapter on ownership
  - Ownership is a very tricky concept that affects almost every aspect of Rust, so understanding it is key to writing more complex Rust code
- Try your best to understand Ownership *before* attempting the homework

Next Lecture: Structs and Enums

Thanks for coming!

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