Writing Safer, Faster, And Highly Concurrent Code With Rust

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@jaredthecoder

KCDC 2017

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Help me help you!

There are note cards on each row and in the back. When this is over, leave one on the back table with any comments.

GREEN - Great job!
YELLOW - It was okay, here's why.
PINK - It was terrible, here's why.

About Me

- From Knoxville, TN
- Cyber Security Researcher and Project Lead at Oak Ridge National Laboratory
- CS PhD Student at the University of Tennessee, Knoxville
- Guest Author at Treehouse
- Avid hiker and reluctant backpacker

OAK RIDGE National Laboratory

University of Tennessee VOLSEC — COMPUTER SECURITY LAB —

treehouse™

my happy place

Agenda

- Background
- Why Rust?
- Rust Features
- Rust in the Wild
- Let’s write a web API!
- Q&A

Background

Where did we come from;
where did we go?

A long time ago in a computer research lab far, far away, the C programming language was invented by Dennis Ritchie...

1970

At Bell Laboratories, where many other amazing things were made, like UNIX, the semiconductor, and telephone.

We use C/C++ everywhere!

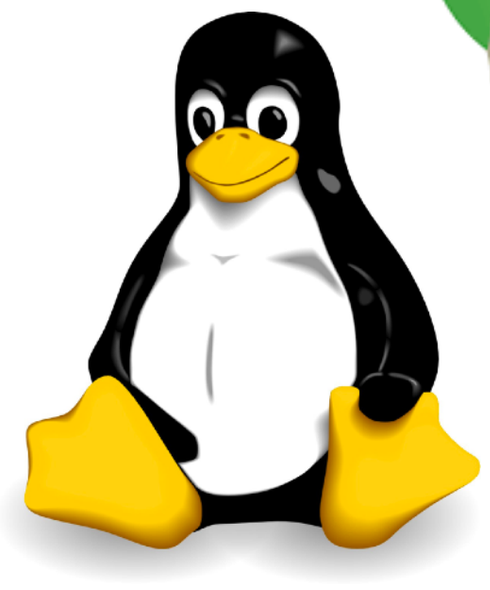
Where we need great performance, tight control over memory, or highly concurrent or parallel applications

OpenSSL™
Cryptography and SSL/TLS Toolkit

PostgreSQL

MySQL®

mongoDB.



JS

python™

Windows

php

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C/C++ gives us great things:

- Direct Memory Access
- Zero Cost Abstractions
- No Garbage Collection
- Compiled

However...

DIRTY COW

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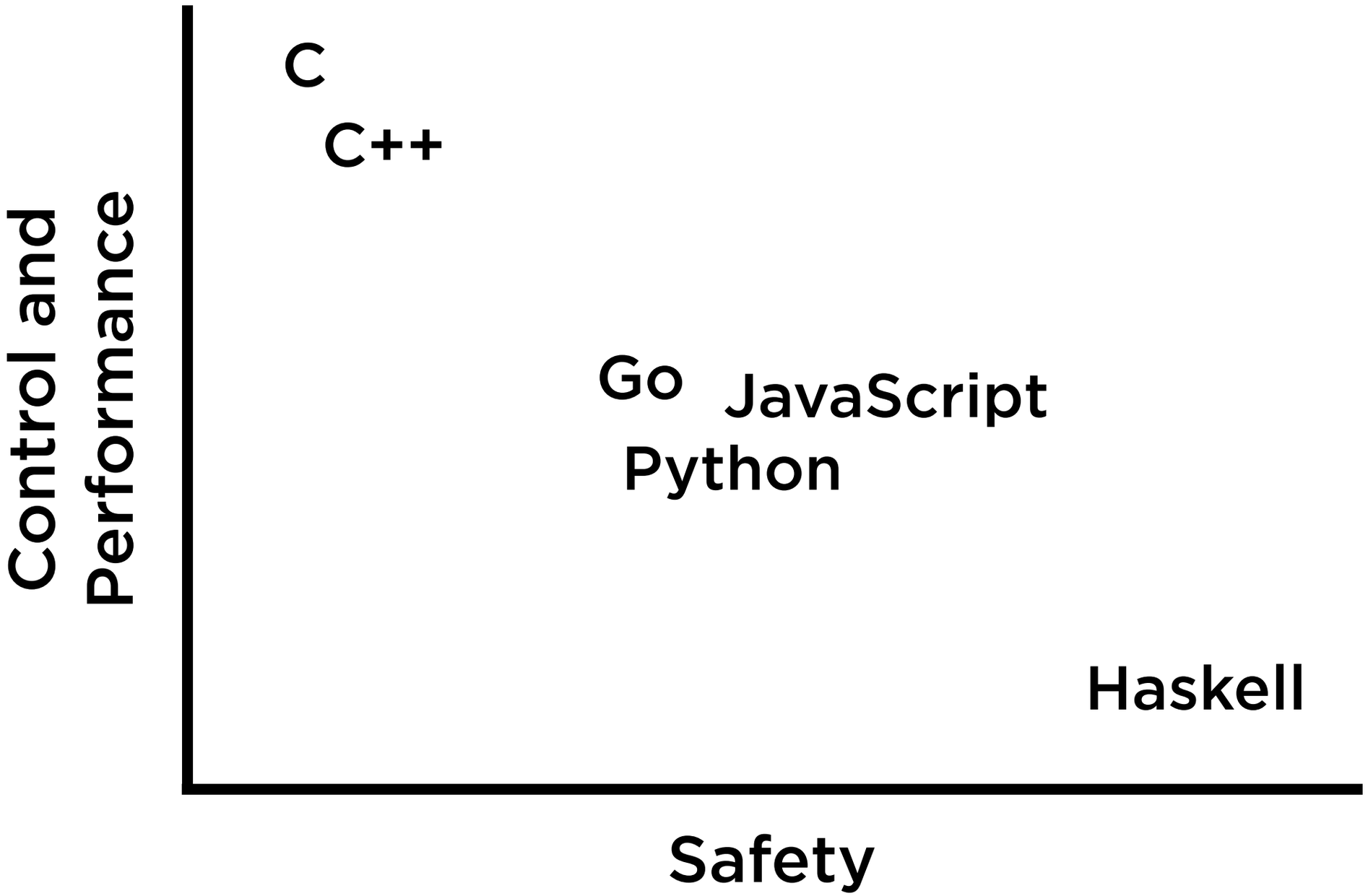
There are many bad things:

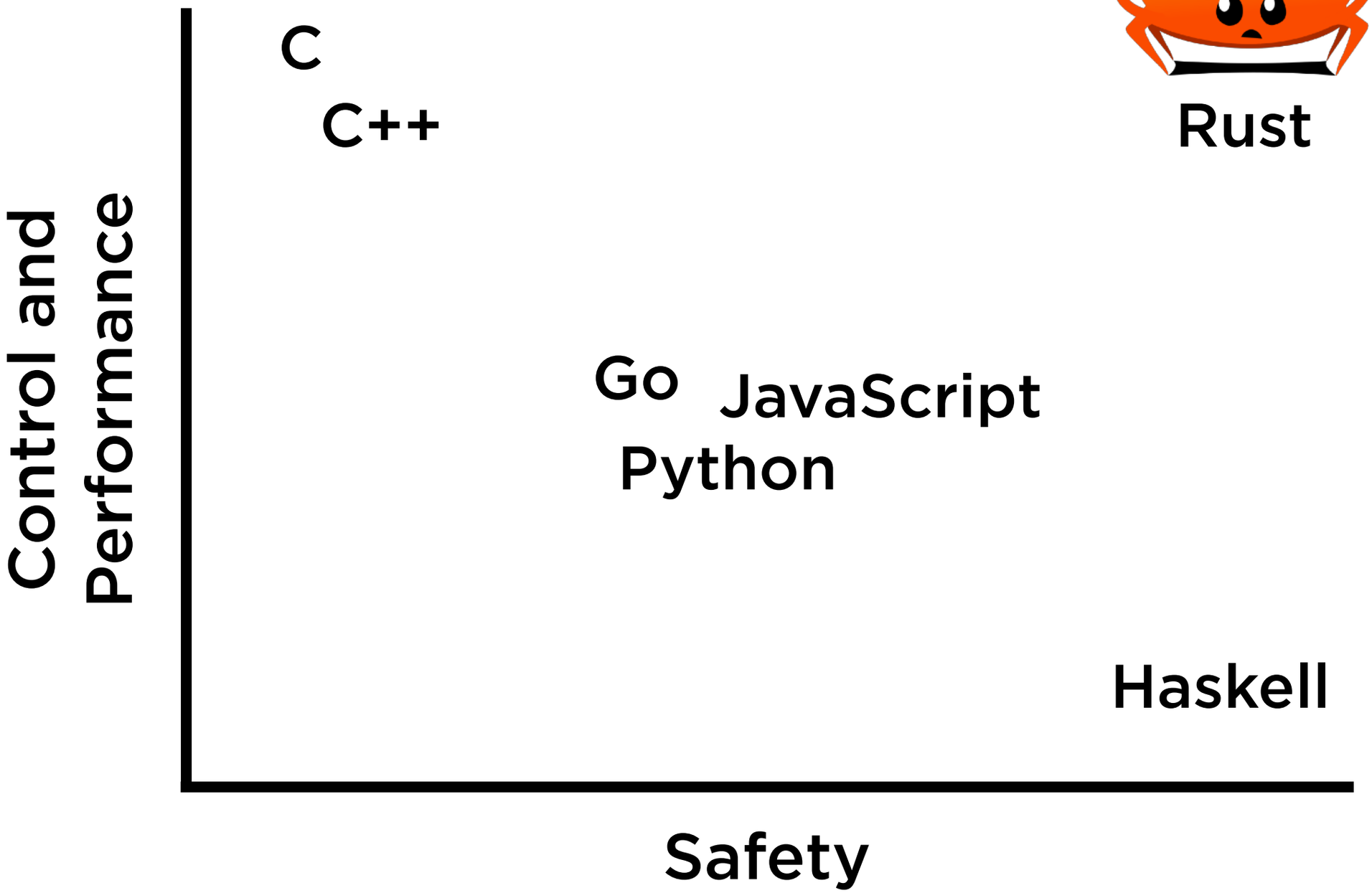
- Manual memory management
- Segfaults
- Data Races
- Tedious to write

Languages like
Python, Java, and
JavaScript save us
from much of this...


Control and
Performance
C
C++
Go
JavaScript
Python
Haskell
Safety

“Rust is a systems programming language that runs blazingly fast, prevents segfaults, and guarantees thread safety.”

- https://www.rust-lang.org


Control and Performance
C
C++
Rust
Go
JavaScript
Python
Haskell
Safety

Rust

Why though?

What's Rust?

- Safe systems language "disguised" as a high-level language
- Rich typesystem
- Statically-typed with type inference
- Strong functional programming influence
- Extensive tooling and well-maintained 3rd-party ecosystem

Rust's Governance Model

- Started as a personal project at Mozilla
- Owned by the community and backed by Mozilla
- Lots of external contributors
- Open RFC process

Complexity versus Speed

*Rust is now approaching or faster than C for many realistic applications

Easier

PHP

Python

Go/Java

Rust

C*

Faster

Key Language Features

- **Immutability**
  - All data is immutable by default
- **Ownership***
  - Every piece of data has an owner
- **Borrowing**
  - To share data, it's ownership must be transferred
- **Lifetimes**
  - Every piece of data can only be used for so long and can only be borrowed in certain ways

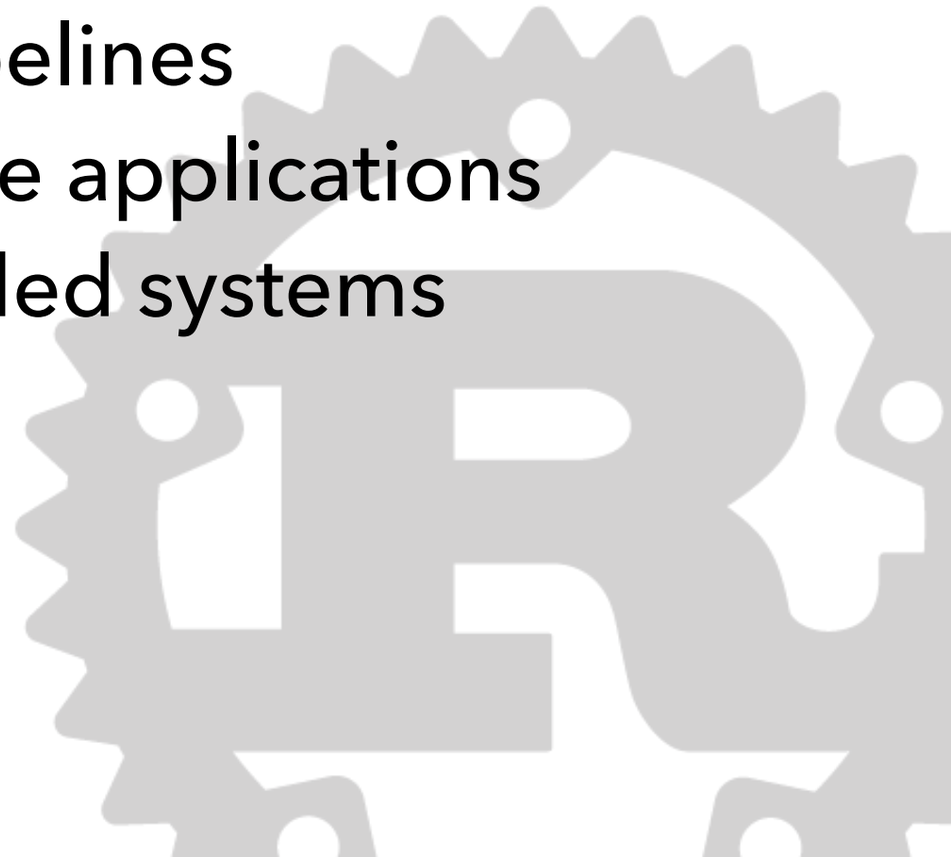
Key Language Features

- **Pattern Matching**
  - Eliminate sequences of complex conditional statements
- **Traits and Generics**
  - Allow for clean code by allowing shared behavior
- **Option and Result Types**
  - No null pointer exceptions!

Where Rust Excels

- Anywhere you want speed and safety, with the ability to write code quickly

  - Servers
  - Operating Systems
  - Compilers
  - Emulators
  - Finance
  - Cryptography
  - Web apps
  - Databases
  - Graphics Programming
  - Data Pipelines
  - Real-time applications
  - Embedded systems



Rust's Features

What's in it for me?

Basics

Expression-oriented language

Data is
immutable by
default!

Statically-typed, Inferred

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Algebric types

-> Enums!

Control Flow

- Basic Control Flow
  - *if*, *else*
  - *loop*, *while*, *for*
- Functions
  - *fn*
  - closures

Match Statements

```
let number = 4;
match number {
    1 => println!("One!"),
    2 | 3 | 5 | 7 | 11 => println!("This is a prime"),
    13...19 => println!("A teen"),
    _ => println!("Ain't special"),
}
```

Match Statements

```
let boolean = true;
let binary = match boolean {
    false => 0,
    // true => 1,
};
```

Match Statements

```
 › cargo run
   Compiling kcdc v0.1.0 (file:///Users/jared/development/rust/projects/kcdc)
error[E0004]: non-exhaustive patterns: `true` not covered
 --> src/main.rs:6:24
  |
6 |     let binary = match boolean {
  |                        ^^^^^^^ pattern `true` not covered
```

Containers and “Inheritance”

Structs

- Structs are lightweight classes

```
struct State;
```

Containers

- Add methods with *impl*

```
impl State {
    fn secede(&self) {
        print!("We, {}, secede from the union!", self.name);
    }
}
```

Structs

- They can have fields

```
struct State {
    name: String,
    capital: String,
    population: i64,
    income_tax: bool
}
```

Structs

- They can be instantiated

```
let kansas = State {
    name: "Kansas".to_owned(),
    capital: "Topeka".to_owned(),
    population: 2_907_000,
};
```

Structs

- But not partially instantiated!

```
› cargo run
   Compiling kcdc v0.1.0 (file:///Users/jared/development/rust/projects/kcdc)
error[E0063]: missing field `income_tax` in initializer of `State`
 --> src/main.rs:2:18
  |
2 |     let kansas = State {
  |                  ^^^^^ missing `income_tax`
```

Structs

- Rust has the *Option* Enum for this

```
struct State {
    name: String,
    capital: String,
    population: i64,
    income_tax: Option<bool>
}
```

Structs

- No more NullPointerExceptions!

```
let kansas = State {
    name: "Kansas".to_owned(),
    capital: "Topeka".to_owned(),
    population: 2_907_000,
    income_tax: None
};
```

- When you unpack the *income_tax*, parameter, you are forced to handle the case where it is None.

Traits

- Let's define two other structs

```
struct County {
    name: String,
    seat: Option<String>,
    population: Option<i64>
}

struct Country {
    name: String,
    capital: Option<String>,
    population: Option<i64>
}
```

Traits

- Traits are similar to interfaces, they define a contract for a type to abide by

```
trait Elect {
    fn elect(&self, leader: String);
}
```

Traits

- We can implement traits for our structs

```
impl Elect for State {
    fn elect(&self, leader: String) {
        println!("We elect {} for Governor!", leader);
    }
}

impl Elect for County {
    fn elect(&self, leader: String) {
        println!("We elect {} for Mayor!", leader);
    }
}
```

Traits

- Then we can use it's interface in the instance

```
let kansas = State { name: "Kansas".to_owned() };
let wyandotte = County { name: "Wyandotte".to_owned() };
let usa = Country { name: "United States of America".to_owned() };

kansas.elect("Michael Scott".to_owned());
wyandotte.elect("Kelly Kapoor".to_owned());
usa.elect("Dwight Schrute".to_owned());
```

Traits

- Unless we didn't implement it!

```
» cargo run                                                    [13:27:49]
   Compiling kcdc v0.1.0 (file:///Users/jared/development/rust/projects/kcdc)
error: no method named `elect` found for type `Country` in the current scope
 --> src/main.rs:9:9
  |
9 |     usa.elect("Dwight Schrute".to_owned());
  |         ^^^^^
  |
  = help: items from traits can only be used if the trait is implemented and in scope; the
following trait defines an item `elect`, perhaps you need to implement it:
  = help: candidate #1: `Elect`
```

Traits

- Default implementations are possible

```
trait Elect {
    fn elect(&self, leader: String) {
        println!("I, for one, welcome our new robot overlords.");
    }
}

impl Elect for Country {}
```

Traits

- You can define traits on foreign types

```
use std::ops::{Range, RangeFrom, RangeTo};

pub trait RangeExt<T> {
    fn before(&self) -> RangeTo<T>;
    fn after(&self) -> RangeFrom<T>;
}

impl<T: Copy> RangeExt<T> for Range<T> {
    fn before(&self) -> RangeTo<T> {
        ..self.start
    }

    fn after(&self) -> RangeFrom<T> {
        self.end..
    }
}
```

Traits

```
#[cfg(test)]
mod tests {
    use super::RangeExt;

    #[test]
    fn range_ext() {
        assert_eq!(..3, (3..5).before());
        assert_eq!(5.., (3..5).after());
    }
}
```

Traits

```
› cargo test                                                    [11:12:57]
   Finished dev [unoptimized + debuginfo] target(s) in 0.0 secs
    Running target/debug/deps/kcdc-bc70f91b4a266db1

running 1 test
test tests::range_ext ... ok

test result: ok. 1 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out
```

Ownership, Borrowing, and Lifetimes

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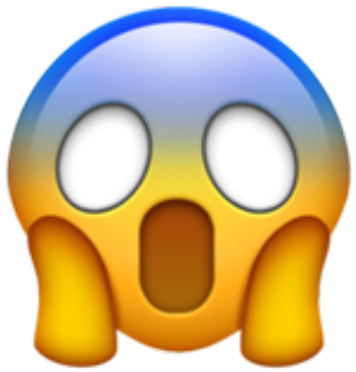


Garbage Collection

- Garbage collectors clean up memory that is no longer used
- Eliminates unreachable objects from memory by tracing root objects
- At the core of C# (CLR), Java (JVM), Python, Go, JavaScript (V8), Ruby, etc.

Garbage Collection Drawbacks

- Must run background threads for the GC
- May require large memory space

Reference Counting

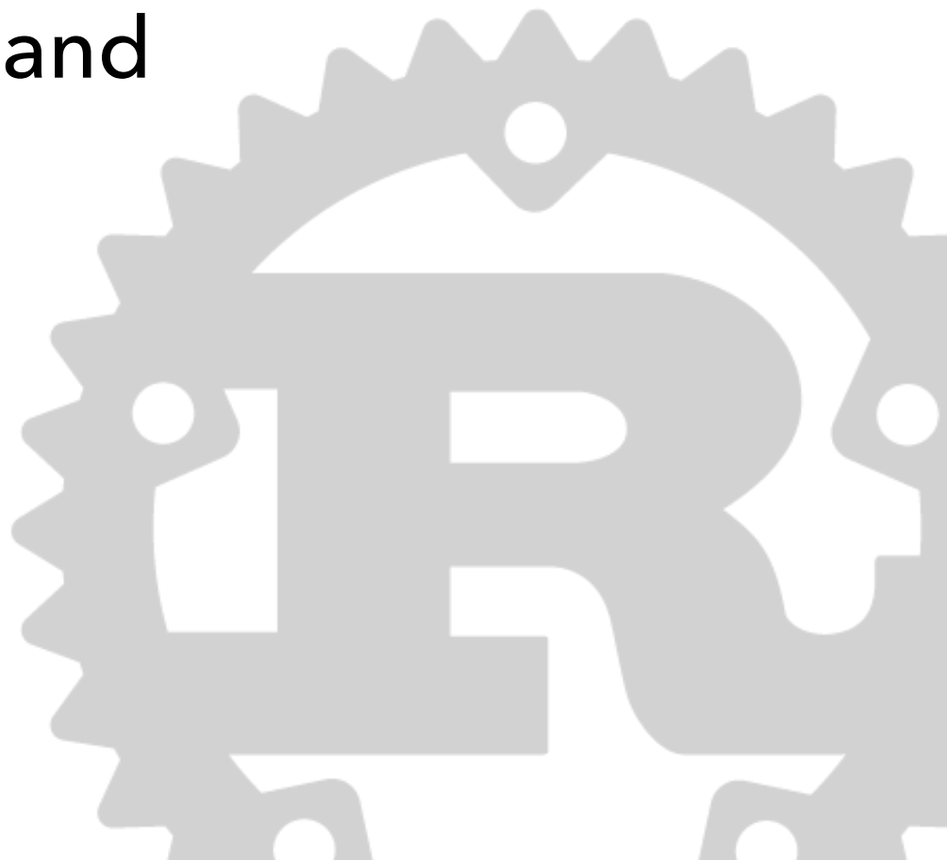
- Automated Reference Counting (ARC) keeps count on references of objects
- Deallocates them when they're no longer referenced
- Swift is a notable example

ARC Drawbacks

- Every assignment/allocation of variable:
  - needs to increment/decrement counters
  - reassign weak references
  - call destructors

Memory Safety

- Garbage collectors, ARC, and other similar memory cleanup methods keep our programs safe
- No segfaults, use-after-free, etc. in those languages
- However, they incur cost at runtime and data races can still exist



Still safe

ZERO runtime cost

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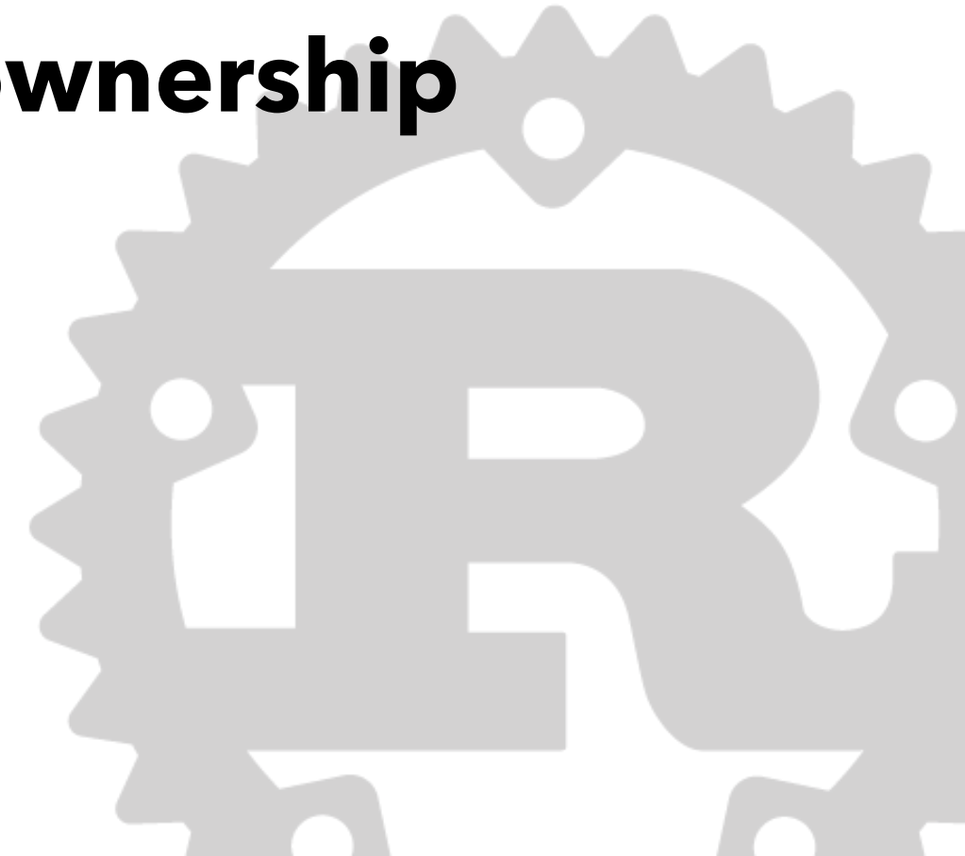
Rust to the Rescue!

- Rust provides the same and often stronger protection than garbage collection/ARC
- With **zero performance cost** at runtime
  - Instead, enforces rules to protect memory at **compile-time**
- It does this with it's system of **ownership**



ENTERING DANGER ZONE

Ownership: You own a resource, and when you are done with it, that resource is no longer in scope and gets deallocated.

References to a resource depend on the **lifetime** of that resource.

(they are only valid until the resource is deallocated)

Move semantics: Giving an owned resource to a function means giving it away, and you can no longer access it.

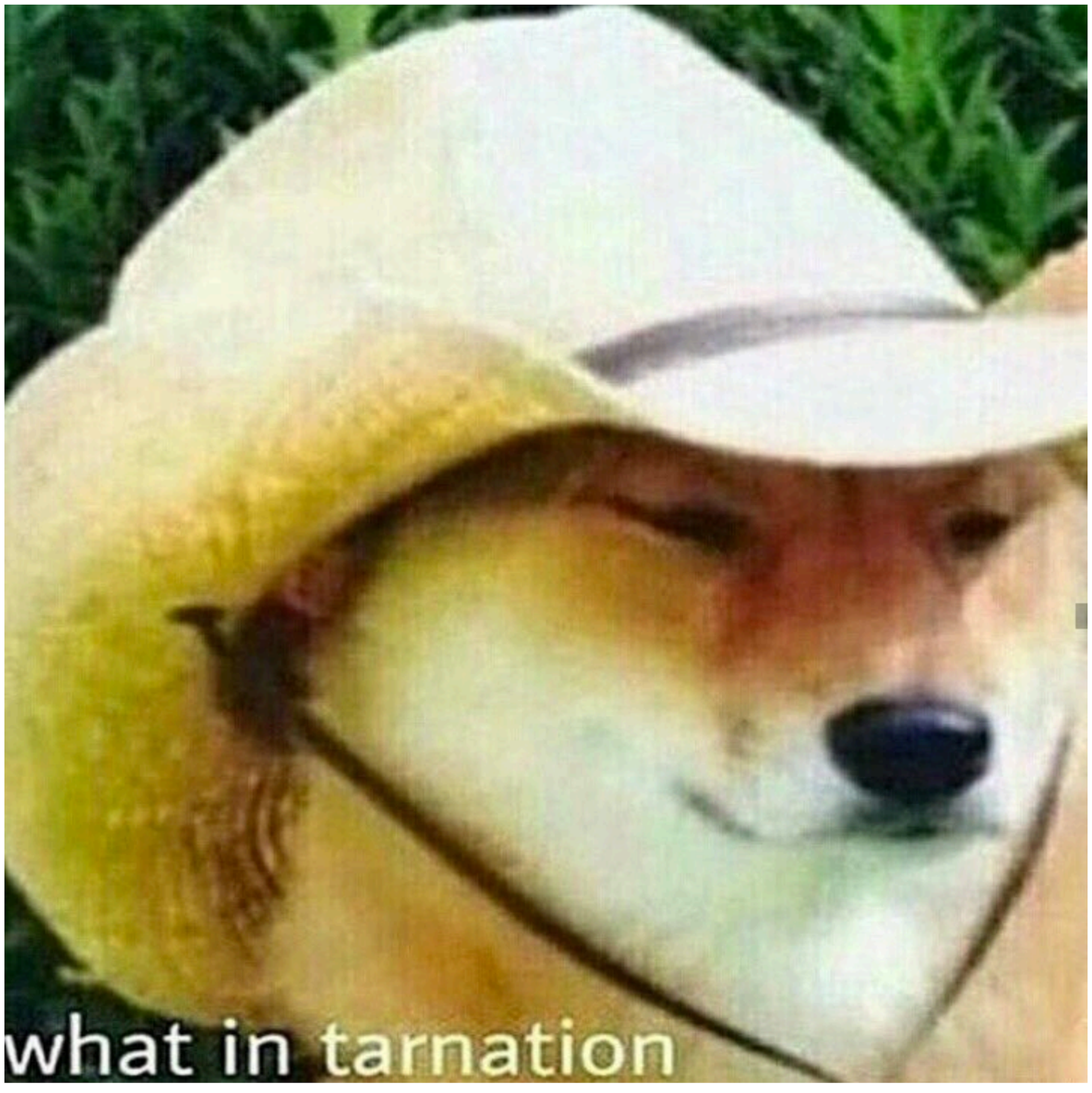
To **not move** a resource, you instead use **borrowing:** You create a reference to the resource, which can be **borrowed** by something else.

Ownership 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 will be dropped.

Reference Rules

1. At any given time, you can have either but not both of:
   - One mutable reference.
   - Any number of immutable references.
2. References must always be valid.


what in tarnation

Stack and Heap: A Review

- The stack and heap are regions of a processes memory that are used by the process at runtime
- Stack stores **known, fixed** values through pointers and can access them **very quickly**
- Heap stores data with **unknown size** at compile time or a size that **might change** and is **slower**

Stack and Heap

- Ownership addresses storing data on the heap:
  - Keeping track of what parts of code are using what data on the heap
  - Minimizing the amount of duplicate data on the heap
  - Cleaning up unused data on the heap so we don’t run out of space

Strings are mutable, and thus we don't know their size at compile-time, so we store them on the heap.

↝ **move (for types that do not implement Copy)**


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

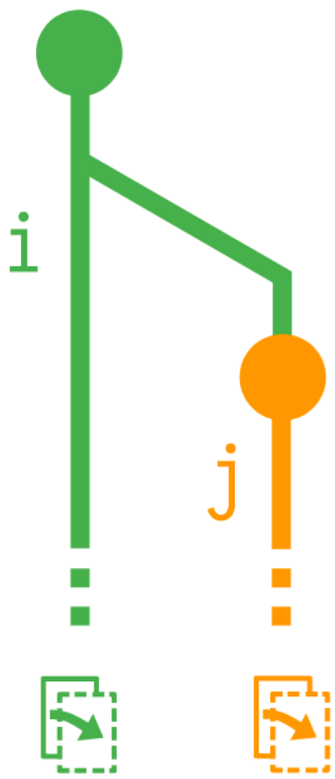
```
let b = s + " world";
```

(**cannot** use s anymore)

https://rufflewind.com/2017-02-15/rust-move-copy-borrow

Integers size is known at compile-time, and thus can be stored on the stack (i.e. no move!)

copy (for types that do implement Copy)




```
let i = 42;
```

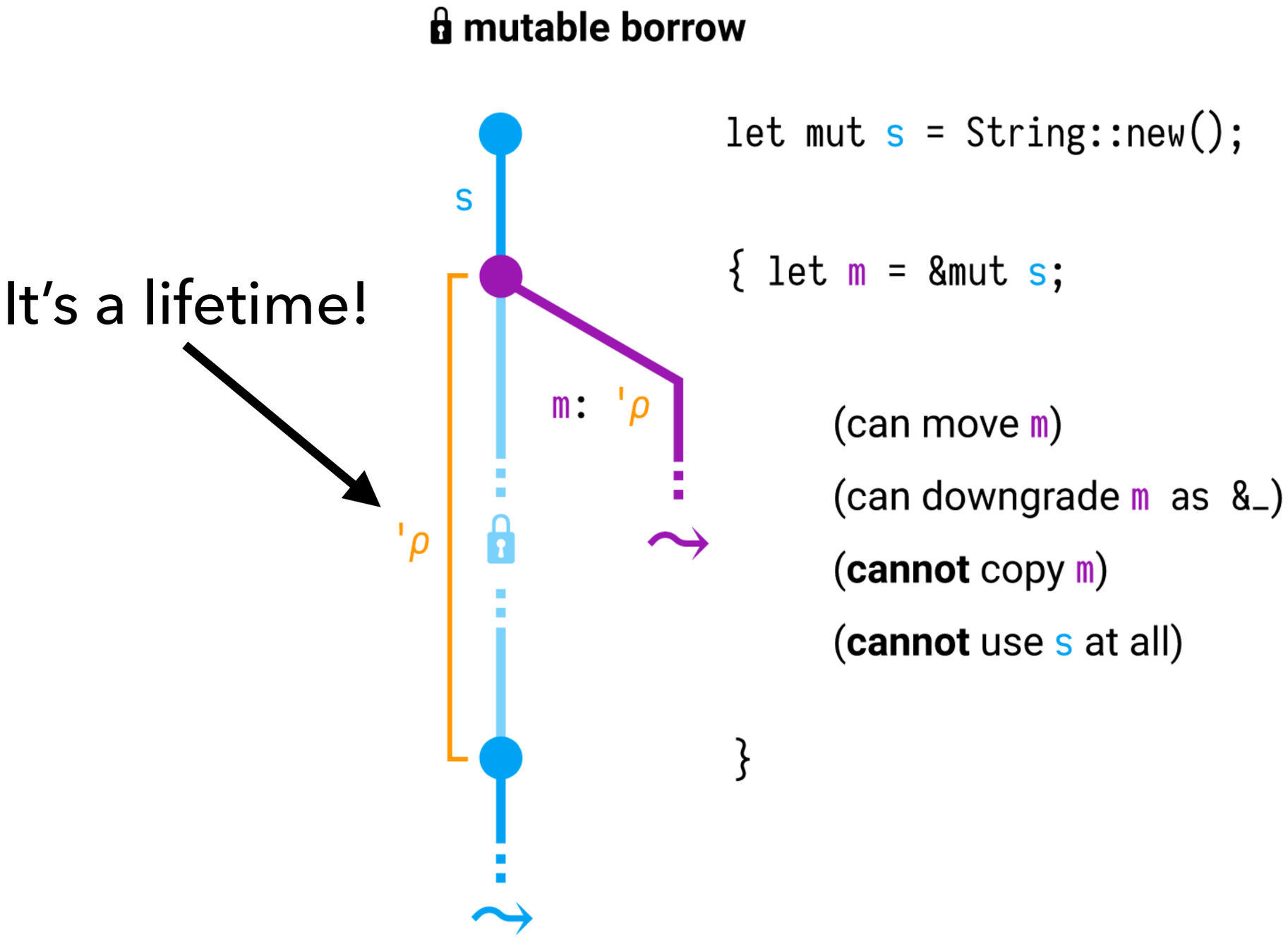
It’s a trait!

```
let j = i + 1;
```

(can still use `i` and `j`)

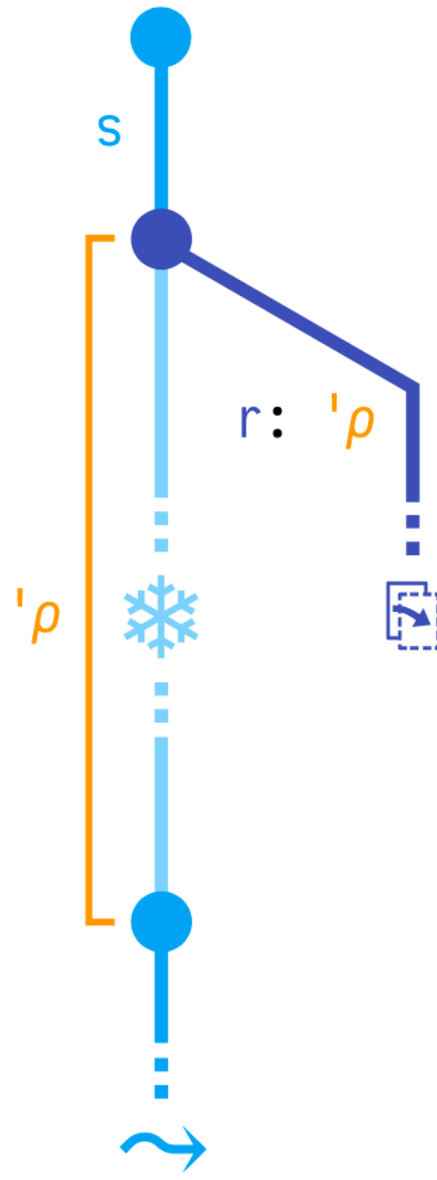
https://rufflewind.com/2017-02-15/rust-move-copy-borrow

Only one shared mutable reference at a time!



https://rufflewind.com/2017-02-15/rust-move-copy-borrow

❄ borrow




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

{ let r = &s;

        (can copy r)
        (can still &s)
        (cannot &mut  s)
        (cannot move s)

}
```

https://rufflewind.com/2017-02-15/rust-move-copy-borrow

Lifetimes

Lifetime Basics

- All references in Rust have a *lifetime*
- Lifetimes are the scopes for which references are valid
- Most lifetimes are implicit and inferred
- Lifetimes eliminate **dangling references**

Lifetimes

- Consider the following program:

```
fn main() {
    let r;

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

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

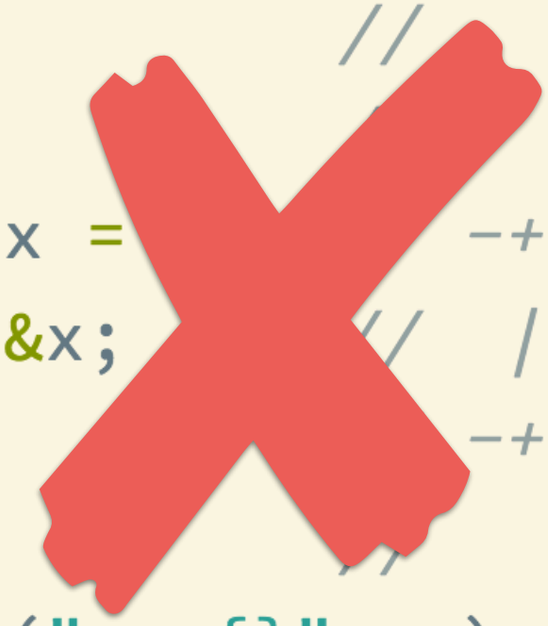
Lifetimes

- Doesn't work!

```
› cargo run
   Compiling kcdc v0.1.0 (file:///Users/jared/development/rust/projects/kcdc)
error: `x` does not live long enough
  --> src/main.rs:9:5
   |
8  |           r = &x;
   |               - borrow occurs here
9  |       }
   |       ^ `x` dropped here while still borrowed
...
12 | }
   | - borrowed value needs to live until here
```

The Borrow Checker

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

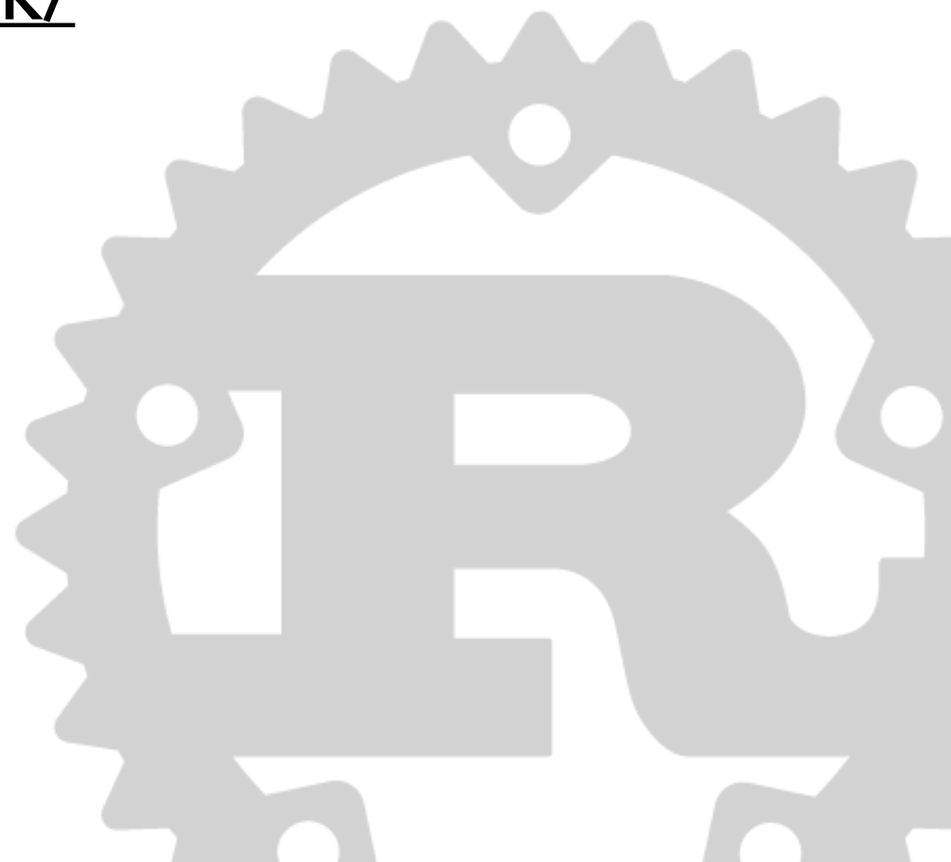


The Borrow Checker

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

Slices

- Slices let you reference a contiguous sequence of elements in a collection rather than the whole collection
- We won't talk about them today, but checkout the Rust book for more on them: https://doc.rust-lang.org/book/second-edition/ch04-03-slices.html



What does this all mean?!

- In Rust, you **can't** have:
  - Segfaults
  - Use-after-free errors
  - Dangling references
  - Data races (race conditions)

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Concurrency

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Fearless
Concurrency

–A Rust Slogan

Concurrency in Rust

- Broad concurrency model
- Ownership prevents safety issues

Concurrency in Rust

- Rust includes support for:
  - Raw threads and processes
  - Message passing
  - Mutexes and Atomic Reference Counter
  - Concurrency traits for objects

Spawning Threads

```
use std::thread;

fn main() {
    let v = vec![1, 2, 3];

    let handle = thread::spawn(move || {
        println!("Here's a vector: {:?}", v);
    });

    handle.join();
}
```

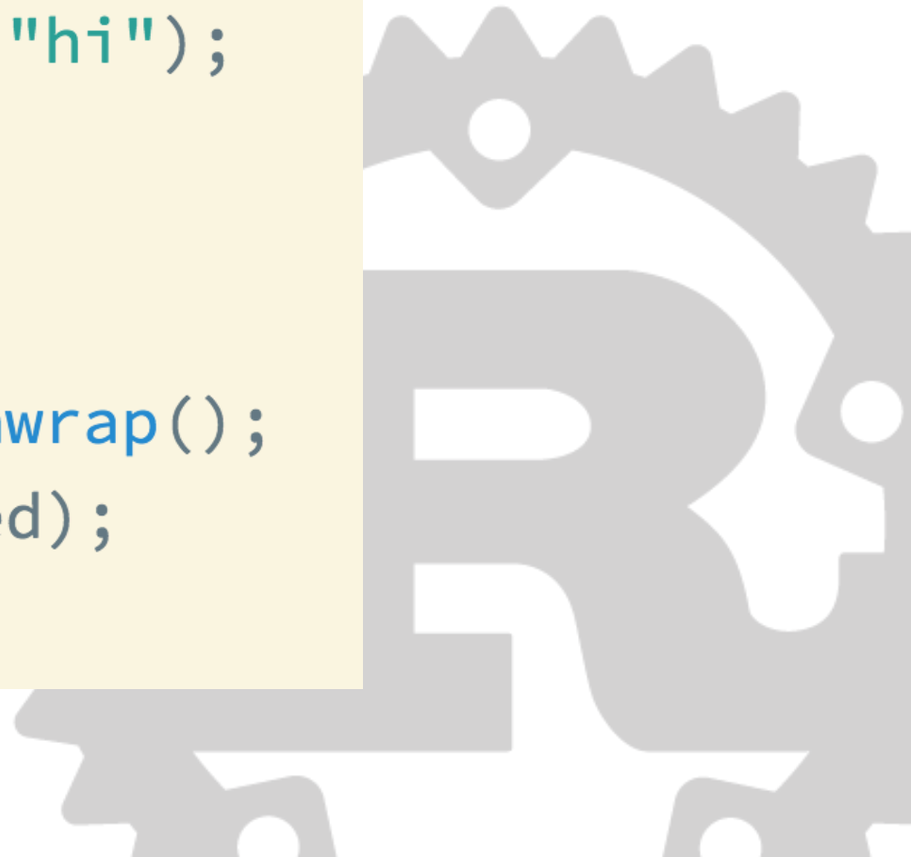
Message Passing

```
use std::thread;
use std::sync::mpsc;

fn main() {
    let (tx, rx) = mpsc::channel();

    thread::spawn(move || {
        let val = String::from("hi");
        tx.send(val).unwrap();
    });

    let received = rx.recv().unwrap();
    println!("Got: {}", received);
}
```



Sharing State

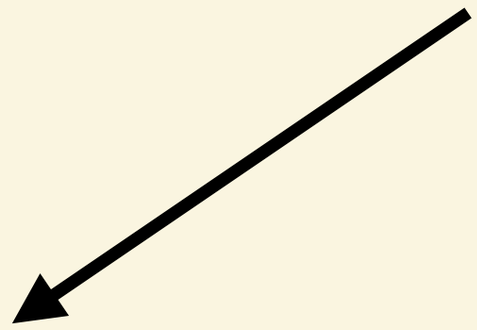
```
use std::sync::Mutex;

fn main() {
    let m = Mutex::new(5);

    {
        let mut num = m.lock().unwrap();
        *num = 6;
    }

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

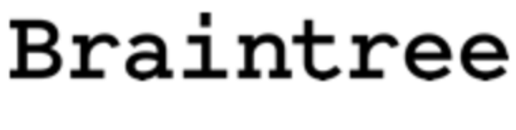
Locking is enforced by the compiler



In the Wild

It isn't just a fad.

Rust in Production



NPM

- NPM, the Node.js package manager, uses Rust to serve up over 350 million packages a day
- Used to eliminate bottlenecks in the package delivery pipeline

Source: https://www.youtube.com/watch?v=GCsxYAxw3JQ

Dropbox

- Uses Rust in multiple, high-impact projects to manage **exabytes of data** on the backend
- Switched off of AWS S3 to homegrown solution built with Rust (Go used too much memory)
- Additionally, Rust is shipped with the Dropbox desktop Windows client to **hundreds of millions** of machines

Source: https://air.mozilla.org/rust-meetup-may-2017/

Mozilla Firefox

- Using Rust in production versions of Firefox shipping to **hundreds of millions** of users
- Used in Servo, in media playback functionality, and other parts of browser
- Used in Project Quantum, a complete rewrite of the Firefox engine in Rust

Source: https://hacks.mozilla.org/2016/07/shipping-rust-in-firefox/

OneSignal

- Push notification delivery system built in Rust
- Delivers over **2 billion push notifications per week**
- Sustained deliveries of up to **125,000/second** and spikes of 175,000/second
- Powers apps at Uber, Cisco, Zillow, Adobe, and Wix

Source: https://onesignal.com/blog/rust-at-onesignal/

Wire

- Used for secure messaging
- Wire's Axolotl protocol implementation and other cryptographic and utility libraries are developed in Rust
- Cross-compiled for iOS and Android

Source: https://github.com/wireapp/proteus

Let’s write some code!

Takeaways

- Rust makes systems programming fun and easy, without compromising speed or safety.
- Try out Rust: https://play.rust-lang.org/
- Read more about Rust: https://doc.rust-lang.org/book/second-edition/

Questions?

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