

# Rust Trainings All in One

- High-level intro about Rust
- Ownership, borrow check, and lifetime
- Typesystem and Generic Programming
- Concurrency - primitives
- Concurrency - async/await
- Networking and security
- FFI with C/Elixir/Swift/Java
- WASM/WASI
- Rust for real-world problems

# High-level Intro About Rust

# Why Rust?

# Let's talk about values and tradeoffs first

- Approachability
- Availability
- Compatibility
- Composability
- Debuggability
- Expressiveness
- Extensibility
- Interoperability
- Integrity
- Maintainability
- Measurability
- Operability
- Performance
- Portability
- Productivity
- Resiliency
- Rigor
- Safety
- Security
- Simplicity
- Stability
- Thoroughness
- Transparent
- Velocity

# C

- Approachability
- Availability
- Compatibility
- Composability
- Debuggability
- Expressiveness
- Extensibility
- Interoperability
- Integrity
- Maintainability
- Measurability
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- **Performance**
- Portability
- Productivity
- Resiliency
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- Safety
- Security
- **Simplicity**
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- Thoroughness
- **Transparent**
- Velocity

# Erlang/Elixir

- Approachability
- Availability
- Compatibility
- Composability
- Debuggability
- Expressiveness
- Extensibility
- Interoperability
- Integrity
- Maintainability
- Measurability
- Operability
- Performance
- Portability
- **Productivity**
- **Resiliency**
- Rigor
- **Safety**
- Security
- **Simplicity**
- Stability
- Thoroughness
- Transparent
- Velocity

# Python

- **Approachability**
- Availability
- Compatibility
- Composability
- Debuggability
- **Expressiveness**
- Extensibility
- Interoperability

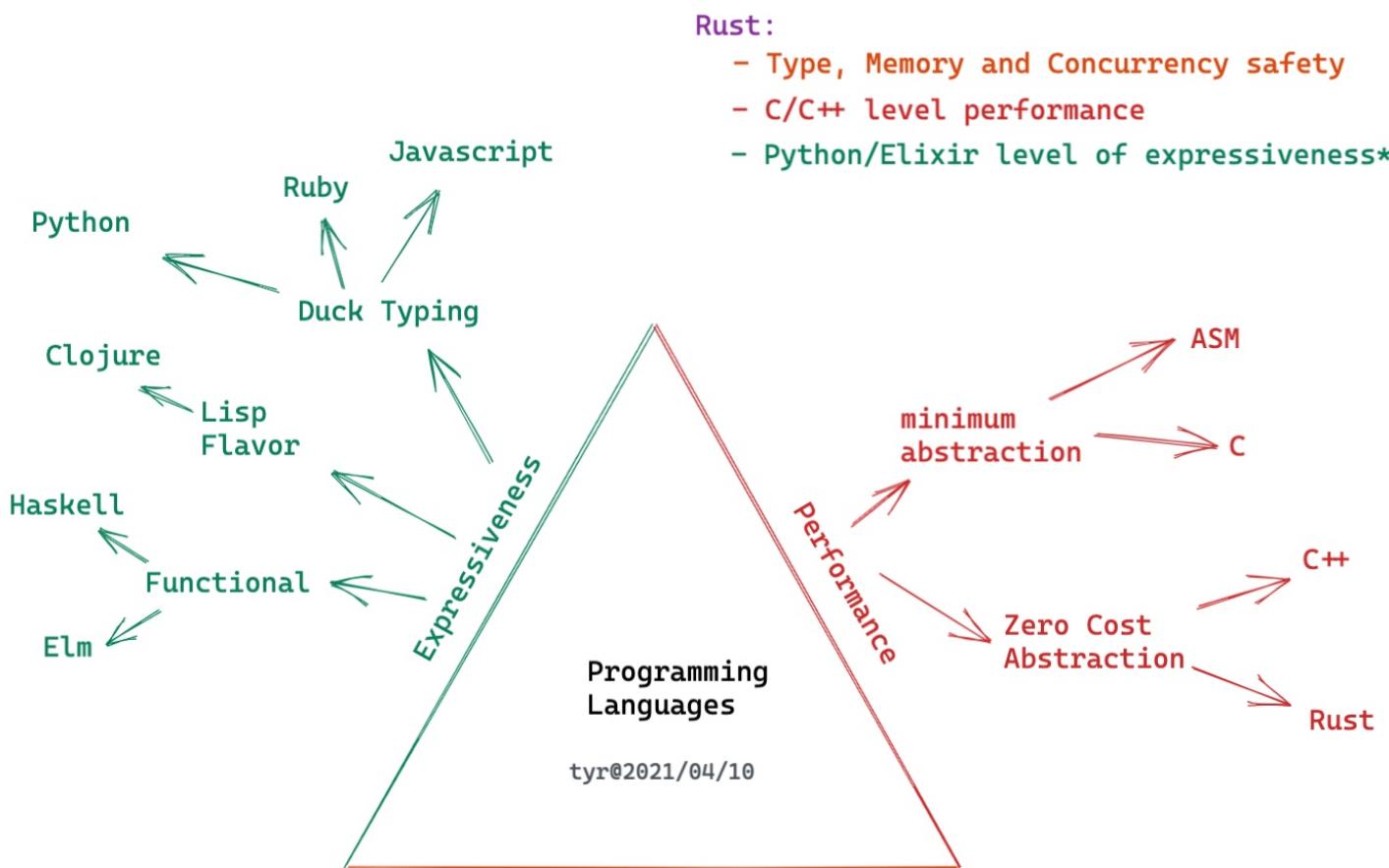
- Integrity
- Maintainability
- Measurability
- Operability
- Performance
- Portability
- **Productivity**
- Resiliency
- Rigor
- Safety
- Security
- **Simplicity**
- Stability
- Thoroughness
- Transparent
- Velocity

# Java (in early days)

- Approachability
- Availability
- Compatibility
- Composability
- Debuggability
- Expressiveness
- Extensibility
- Interoperability
- Integrity
- Maintainability
- Measurability
- Operability
- **Performance**
- **Portability**
- Productivity
- Resiliency
- Rigor
- **Safety (memory)**
- **Security**
- Simplicity
- Stability
- Thoroughness
- Transparent
- Velocity

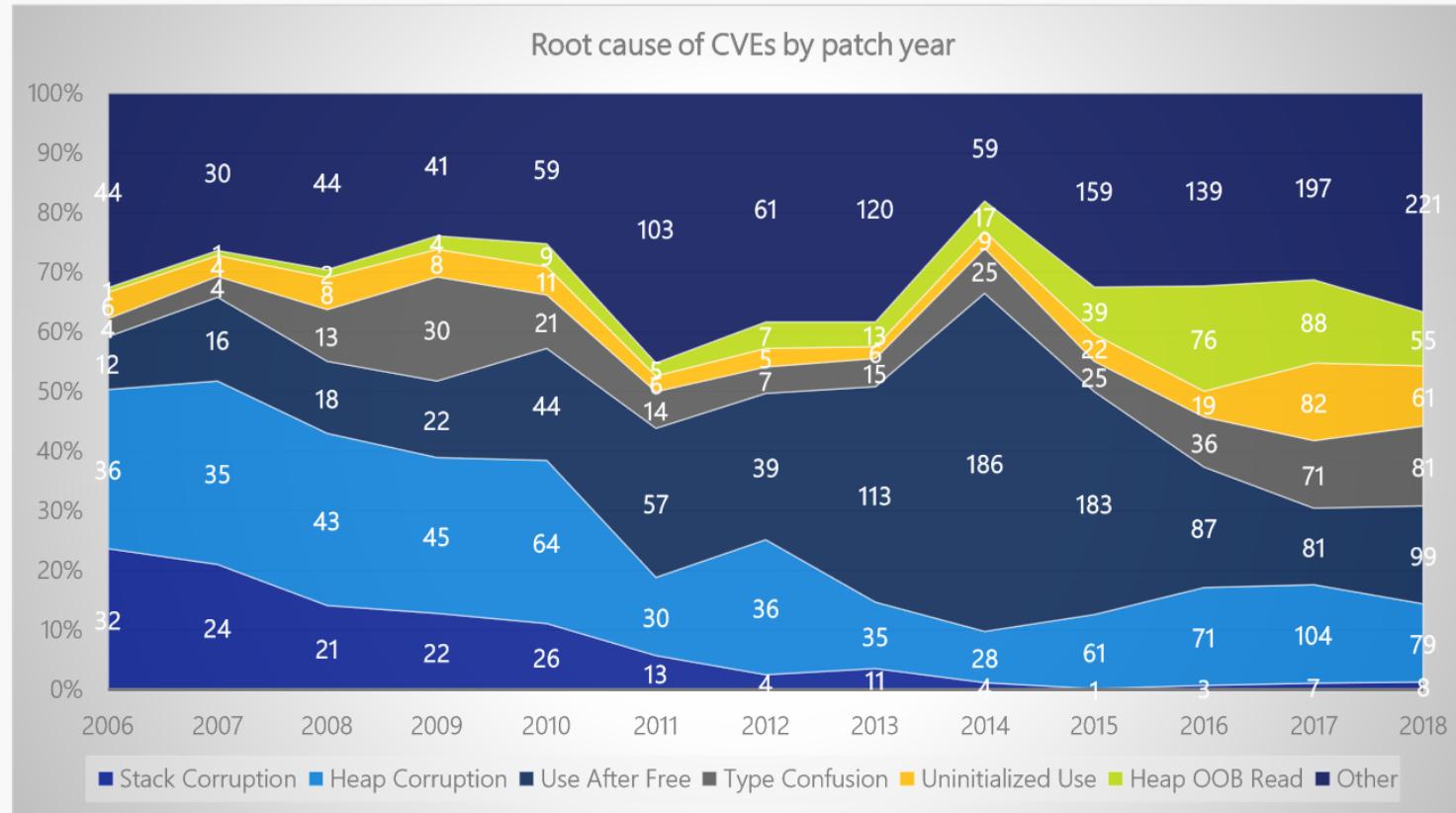
# Rust

- Approachability
- Availability
- Compatibility
- Composability
- Debuggability
- **Expressiveness**
- Extensibility
- Interoperability
- Integrity
- Maintainability
- Measurability
- Operability
- **Performance**
- Portability
- **Productivity**
- Resiliency
- Rigor
- **Safety!!!**
- Security
- Simplicity
- Stability
- Thoroughness
- Transparent
- Velocity



# **Why safety is important?**

# Drilling down into root causes



Stack corruptions are essentially dead

Use after free spiked in 2013-2015 due to web browser UAF, but was mitigated by Mem GC

Heap out-of-bounds read, type confusion, & uninitialized use have generally increased

Spatial safety remains the most common vulnerability category (heap out-of-bounds read/write)

Top root causes since 2016:

#1: heap out-of-bounds

#2: use after free

#3: type confusion

#4: uninitialized use

Note: CVEs may have multiple root causes, so they can be counted in multiple categories

# Safety is hard!

- memory safety is not easy (you need to understand the corner cases)
- concurrency safety is really hard (without certain tradeoffs)
- Often you have to bear the extra layer of abstractions
  - normally it means performance hit

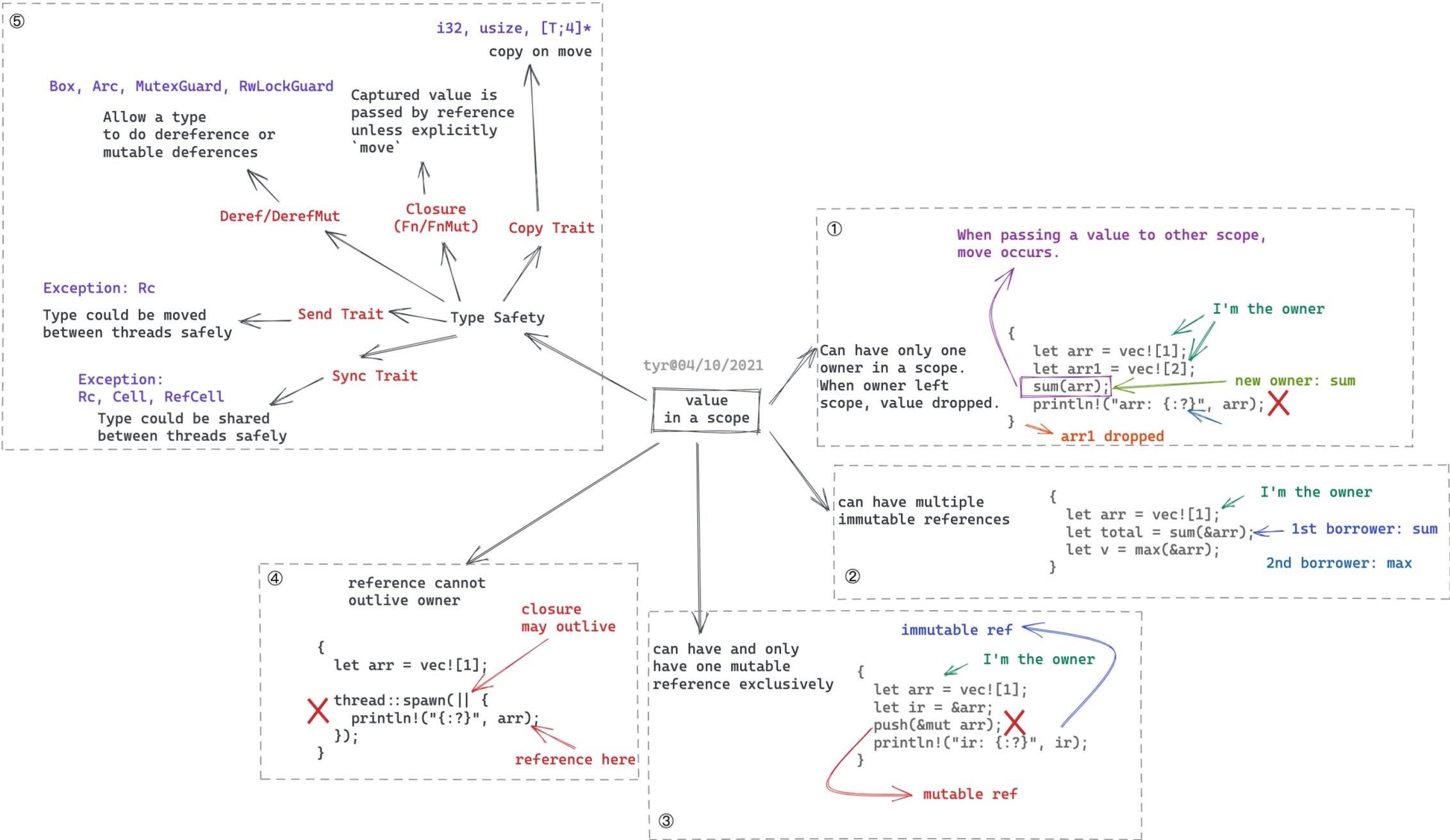
# Memory safety

- Manually - C/C++: painful and error-prone
- Smart Pointers - C++/ObjC/Swift: be aware of cyclical references
- GC - Java/DotNet/Erlang: much bigger memory consumption, and STW
- Ownership - Rust: learning curve

# Concurrency safety

- single-threaded - Javascript: cannot leverage multicore
- GIL - Python/Ruby: multithreading is notorious inefficient
- Actor model - Erlang/Akka: at the cost of memory copy and heap allocation
- CSP - Golang: at the cost of memory copy and heap allocation
- Ownership + Type System - Rust: super **elegant** and **no extra cost!**

How Rust achieves  
**memory and concurrency safety**  
without extra cost?



**Show me the code!**

```
fn main() {
    let mut arr: Vec<i32> = vec![1, 2, 3];      move occurs because `arr` has type `Vec<i32>`, which does not implement the `Copy` trait
    arr.push(4);

    let _result: Result<(), Error> = process(arr);    value moved here
    let _v: Option<i32> = arr.pop(); // failed since arr is moved    borrow of moved value: `arr`

    // you can have multiple immutable references
    let mut arr1: Vec<i32> = vec![1, 2, 3];
    let ir1: &Vec<i32> = &arr1;
    let ir2: &Vec<i32> = &arr1;    immutable borrow occurs here

    println!("ir1: {:?} ir2: {:?}", ir1, ir2);

    // but you can't have both mutable and immutable references
    let mr1: &mut Vec<i32> = &mut arr1;    cannot borrow `arr1` as mutable because it is also borrowed as immutable
    // let mr2 = &mut arr1;

    println!("mr1: {:?} mr2: {:?}", mr1, ir2);    immutable borrow later used here

    // by default, closure borrows the data
    let mut arr2: Vec<i32> = vec![1, 2, 3];
    thread::spawn(|| {    closure may outlive the current function, but it borrows `arr2`, which is owned by the current function
        ... arr2.push(4);    `arr2` is borrowed here
    });
}

// we shall move the data explicitly
let mut arr3: Vec<i32> = vec![1, 2, 3];
thread::spawn(move || arr3.push(4));
}

fn thread_safety() {
    // but certain types cannot be moved to other thread safely
    let mut rc1: Rc<Vec<i32>> = Rc::new(vec![1, 2, 3]);
    thread::spawn(move || {    `Rc<Vec<i32>>` cannot be sent between threads safely
        ... rc1.push(4);
    });
}
```

```
fn thread_safety_reasoning() {
    let mut map: HashMap<&str, &str> = HashMap::new();      move occurs because `map` has type `HashMap<&str, &str>`, which does not implement
    map.insert(k: "hello", v: "world");

    // Arc is an atomic reference counter which can be moved safely across threads
    let mut ir: Arc<HashMap<&str, &str>> = Arc::new(data: map);      variable does not need to be mutable
    map.insert(k: "hello1", v: "world1"); // you can't do this since map is moved      borrow of moved value: `map`
    let ir1: Arc<HashMap<&str, &str>> = ir.clone(); // this is cheap, just reference counter clone
    thread::spawn(move || assert_eq!(ir1.get("hello"), Some(&"world")));
    // but arc is immutable, so this would fail
    thread::spawn(move || ir.insert(k: "hello2", v: "world2"));      cannot borrow data in an `Arc` as mutable

    // the compiler guide you to use types that provides mutable reference for threads

    // use Mutex - you can't clone a Mutex, thus you can't make it available for multiple threads
    let mut map1: HashMap<&str, &str> = HashMap::new();
    map1.insert(k: "hello", v: "world");
    let mr: Mutex<HashMap<&str, &str>> = Mutex::new(map1);
    let mr1 = mr.clone();      no method named `clone` found for struct `Mutex<HashMap<&str, &str>>` in the current scope
    thread::spawn(move || mr.lock().unwrap().insert(k: "hello1", v: "world1"));
    mr1.lock().unwrap().insert("hello2", "world2");

    // use Mutex with Arc - now you have mutable access and multi-thread cloning
    let mut map2: HashMap<&str, &str> = HashMap::new();
    map2.insert(k: "hello", v: "world");
    let mr: Arc<Mutex<HashMap<&str, &str>>> = Arc::new(data: Mutex::new(map2));
    let mr1: Arc<Mutex<HashMap<&str, &str>>> = mr.clone();

    thread::spawn(move || mr.lock().unwrap().insert(k: "hello1", v: "world1"));
    thread::spawn(move || mr1.lock().unwrap().insert(k: "hello2", v: "world2"));

    // can I use Box (smart pointer for heap allocation)?
    let mut map1: HashMap<&str, &str> = HashMap::new();
    map1.insert(k: "hello", v: "world");
    let mr: Arc<Box<HashMap<&str, &str>>> = Arc::new(data: Box::new(map1));
    let mr1: Arc<Box<HashMap<&str, &str>>> = mr.clone();
    thread::spawn(move || (**mr).insert(k: "hello1", v: "world1"));      cannot borrow data in an `Arc` as mutable
    mr1.insert(k: "hello2", v: "world2");      cannot borrow data in an `Arc` as mutable
}
```

## First Principles Thinking



Boiling problems down to their most fundamental truth.

# Recap

- One and only one owner
- Multiple immutable references
- mutable reference is mutual exclusive
- Reference cannot outlive owner
- **use type safety for thread safety**

With these simple rules, Rust achieved safety with  
**zero cost abstraction**

# A glance at Rust Type System

```
Option<T> = Some(T) | None  
Result<T, E> = Ok(T) | Err(E)  
Vec<T>  
HashMap<K, V, H>
```

Common Types

Rust Type System

Trait

```
pub trait Authenticated {  
    fn is_authenticated(&self);  
    fn is_admin(&self);  
}  
  
pub trait Future {  
    type Output;  
    pub fn poll(  
        self: Pin<&mut Self>,  
        cx: &mut Context<'_>  
    ) -> Poll<Self::Output>;  
}
```

Product type

```
#[derive(Clone, Debug)]  
struct User {  
    id: Bytes,  
    name: String,  
    gender: Gender  
}  
  
enum Gender {  
    Unspecified = 0,  
    Female = 1,  
    Male = 2  
}  
  
impl Authenticated for User {}
```

Sum Type

```
enum State {  
    Init,  
    SynSent(ConnState),  
    SynReceived(ConnState),  
    Done(Connection),  
}  
  
struct ConnState {  
    ...  
}  
  
struct Connection {  
    ...  
}
```

# How's Productivity of Rust?

```
1 # client configuration
2
3 domain = "localhost"
4
5 [cert]
6 pem = """-----BEGIN CERTIFICATE-----
7 MIIBeTCCASugAwIBAgIBKjAFBgMrZXAwNzELMAkGA1UEBgwCVVMxFDASBgNVBAoM
8 C0RvbWFpbijBjmMuMRIwEAYDVQQDDAlEb21haW4gQ0EwHhcNMjEwMzE0MTg0NTU2
9 WhcNMzEwMzEyMTg0NTU2WjA3MQswCQYDVQQGDAJVUzEUMBIGA1UECgwLRG9tYWlu
10 IEluYy4xExAQBgNVBAMMCURvbWFpbjBDQTaqMAUGAytlcAMhAAZhorM9IPsXjBTx
11 ZxykG15xZrsj3X2XqKjaAVutnf7po1wwjAUBgNVHREEDTALgglsb2Nhbgvc3Qw
12 HQYDVR00BYEFd+NqChBZD0s5MfMgefHJSIWirthXMBIGA1UDewEB/wQIMAYBaF8C
13 ARAwDwYDVR0PAQH/BAUDAwcGADAFBgMrZXADQQA9sIlgQcYGaBqTxR1+JadSelMK
14 Wp35+yhVvuu4PTL18kWdU819w3cVlRe/GHt+jjlbk1i22Tvf05AaNmdxySk0
15 -----END CERTIFICATE-----"""
16
17 # server configuration
18
19 [identity]
20 key = """-----BEGIN PRIVATE KEY-----
21 MFCAQEwBQYDK2VwBCIEII0kozd0PJsbNfNUS/oqI/Q/enDiLwmdw+JUnTLpR9xs
22 oSMDIQAtkhJiFdF9SYBIMcLikWPRIgca/Rz9ngIgd6HuG6HI3g==
23 -----END PRIVATE KEY-----"""
24
25 [identity.cert]
26 pem = """-----BEGIN CERTIFICATE-----
27 MIIBAzCAR2gAwIBAgIBKjAFBgMrZXAwNzELMAkGA1UEBgwCVVMxFDASBgNVBAoM
28 C0RvbWFpbijBjmMuMRIwEAYDVQQDDAlEb21haW4gQ0EwHhcNMjEwMzE0MTg0NTU2
29 WhcNMjIwMzE0MTg0NTU2WjA5MQswCQYDVQQGDAJVUzEUMBIGA1UECgwLRG9tYWlu
30 IEluYy4xFDASBgNVBAMMC0dSUEmgU2VydMVyMcwBQYDK2VwAyEALZISYhXRFuM
31 SDHC4pFj0SIHGv0c/Z4CIHeh7huhyN6jTDBKMBQGA1UdEQQNMAuCCWxvY2FsaG9z
32 dDATBgnVHSUEDDAKBgggrBgfFBQcDATAMBgnVHRMEBTADAQEA8GA1UdDwEB/wQF
33 AwMH4AwBQYDK2VwA0EAy7EOIZp73XtcqaSopQDGWU7Umi4DVvIgjmY6qbJZP0sj
34 ExGdaVq/7M01ZlI+vY7G0NSZWIZUilX0Co0krn0DA==
35 -----END CERTIFICATE-----"""
36
37
```

```
9   ````rust
10  // you could also build your config with cert and identity separately. See tests.
11  let config: ServerTlsConfig = toml::from_str(config_file).unwrap();
12  let acceptor = config.tls_acceptor().unwrap();
13  let listener = TcpListener::bind(addr).await.unwrap();
14  tokio::spawn(async move {
15      loop {
16          let (stream, peer_addr) = listener.accept().await.unwrap();
17          let stream = acceptor.accept(stream).await.unwrap();
18          info!("server: Accepted client conn with TLS");
19
20          let fut = async move {
21              let (mut reader, mut writer) = split(stream);
22              let n = copy(&mut reader, &mut writer).await?;
23              writer.flush().await?;
24              debug!("Echo: {} - {}", peer_addr, n);
25          }
26
27          tokio::spawn(async move {
28              if let Err(err) = fut.await {
29                  error!("{}: {:?}", err);
30              }
31          });
32      }
33  });
34  ````
35
36 Client: You, a month ago • init the project
37
38 ````rust
39 let msg = b"Hello world\n";
40 let mut buf = [0; 12];
41
42 // you could also build your config with cert and identity separately. See tests.
43 let config: ClientTlsConfig = toml::from_str(config_file).unwrap();
44 let connector = config.tls_connector(Uri::from_static("localhost")).unwrap();
45
46 let stream = TcpStream::connect(addr).await.unwrap();
47 let mut stream = connector.connect(stream).await.unwrap();
48 info!("client: TLS conn established");
49
50 stream.write_all(msg).await.unwrap();
51
52 info!("client: send data");
53
54 let (mut reader, _writer) = split(stream);
55
56 reader.read_exact(buf).await.unwrap();
57
58 info!("client: read echoed data");
59  ````
```

# Things built with Rust



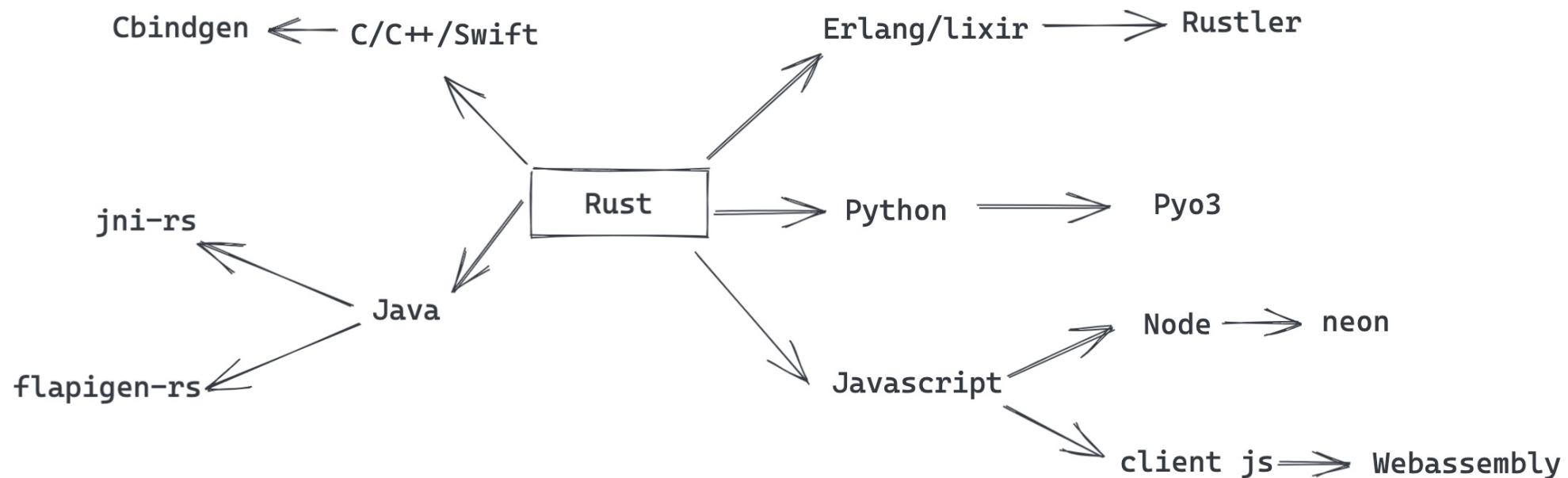
# Should I use Rust?

- Rust is ideal when you need a system that reliable and performant
- Sometimes you don't, sometimes you do, sometimes you need that later
- it's all about tradeoffs

# Rust for our use cases

- parts of the system that are bottlenecks
  - bottleneck on computation
  - bottleneck on memory consumption
  - bottleneck on I/O
- parser/decoder/encoder
- wants to leverage existing C/C++/Rust ecosystem (e.g. you need blake3 for hashing)

# Rust FFI

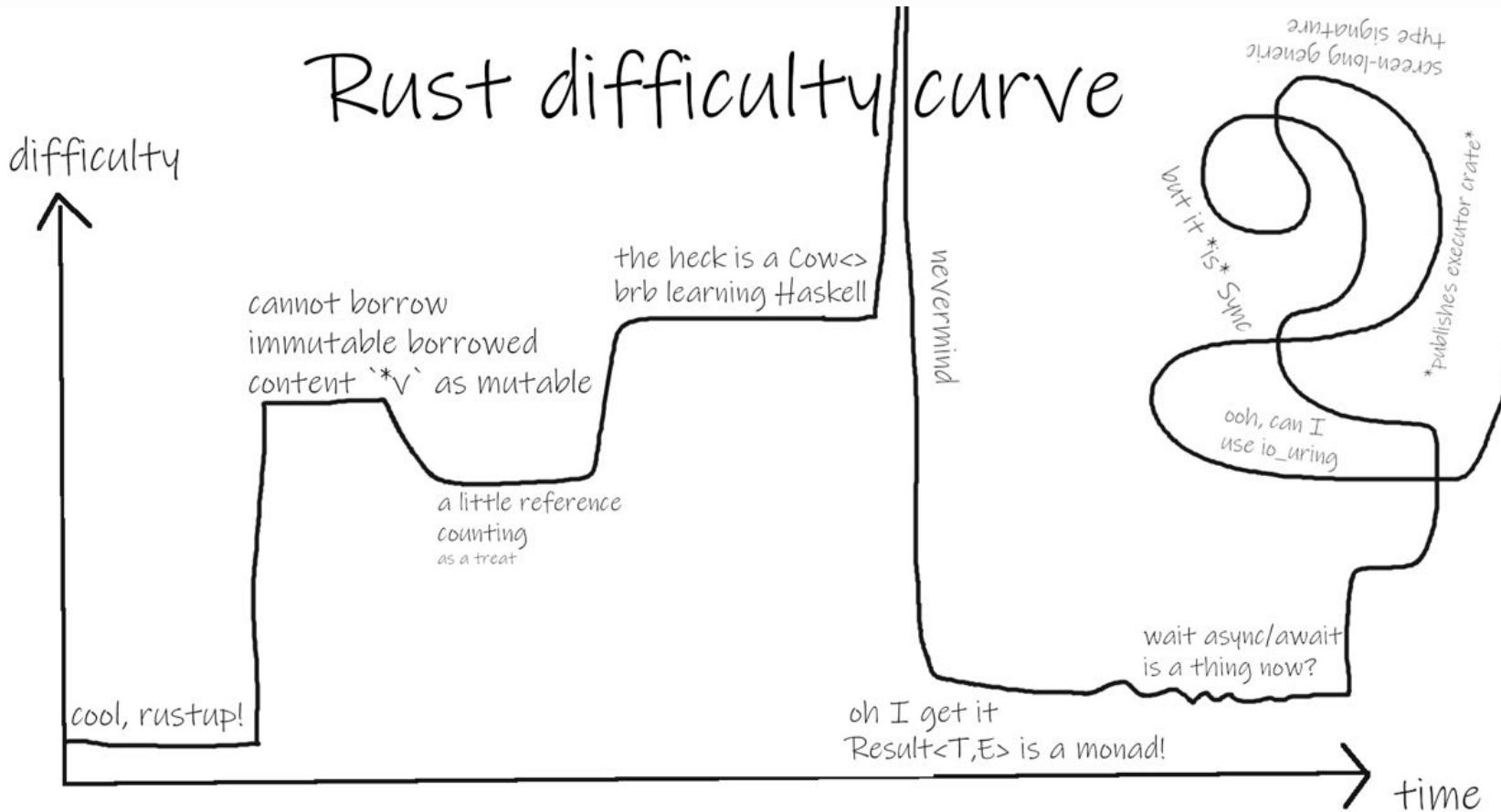


# Learning rust as a(n)...

- Elixir eng: ownership model, type system, oh no mutation
- Scala eng: ownership model, oh no mutation
- Typescript eng: ownership model, multi-threaded programming
- Swift/Java eng: ownership model
- Python eng: ownership model, type system

**The common  
misunderstandings**

# 1. Rust is super hard to learn...



# Rust is explicit

- Lots of knowledge about computer science is suddenly explicit to you
- If all your pain to learn a lang is 100%:
  - Rust:
    - Compiler help to reduce that to 90%
    - Then you suffer 70% the pains in first 3-6 months
    - Then the rest 20% in 3-5 years
  - Other:
    - You suffer 10-30% in first 3-6 months
    - Then 70%-90% in next 3-5 years

## 2. Unsafe Rust is evil...

| Safe Rust                                                                                                                                                          | Unsafe Rust                                                                                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>Compiler will make sure dereference is valid</p>                              | <p>dereference raw pointer is OK</p>                                                                |
| <p>Compiler will guarantee it is OK</p>                                         | <p>deal with FFI</p> <p>impl unsafe trait</p>                                                      |
| <p>peace of mind</p> <p>The compiler will enforce memory and thread safety</p>  | <p>The dev guarantees memory/thread safety</p> <p>Need extra code review<br/>Static analysis</p>  |

# References

- The pain of real linear types in Rust
- Substructural type system
- Rust official book
- Rust official site
- Awesome Rust
- Are we web yet?
- Are we async yet?
- Are we gui yet?
- Are we learning yet?
- Are we game yet?
- Are we quantum yet?
- Are we IDE yet?
- Rust is for Professionals

Ownership, borrow check, and  
lifetime

# Ownership/Borrow Rules Review



**Lifetime, not a new idea**

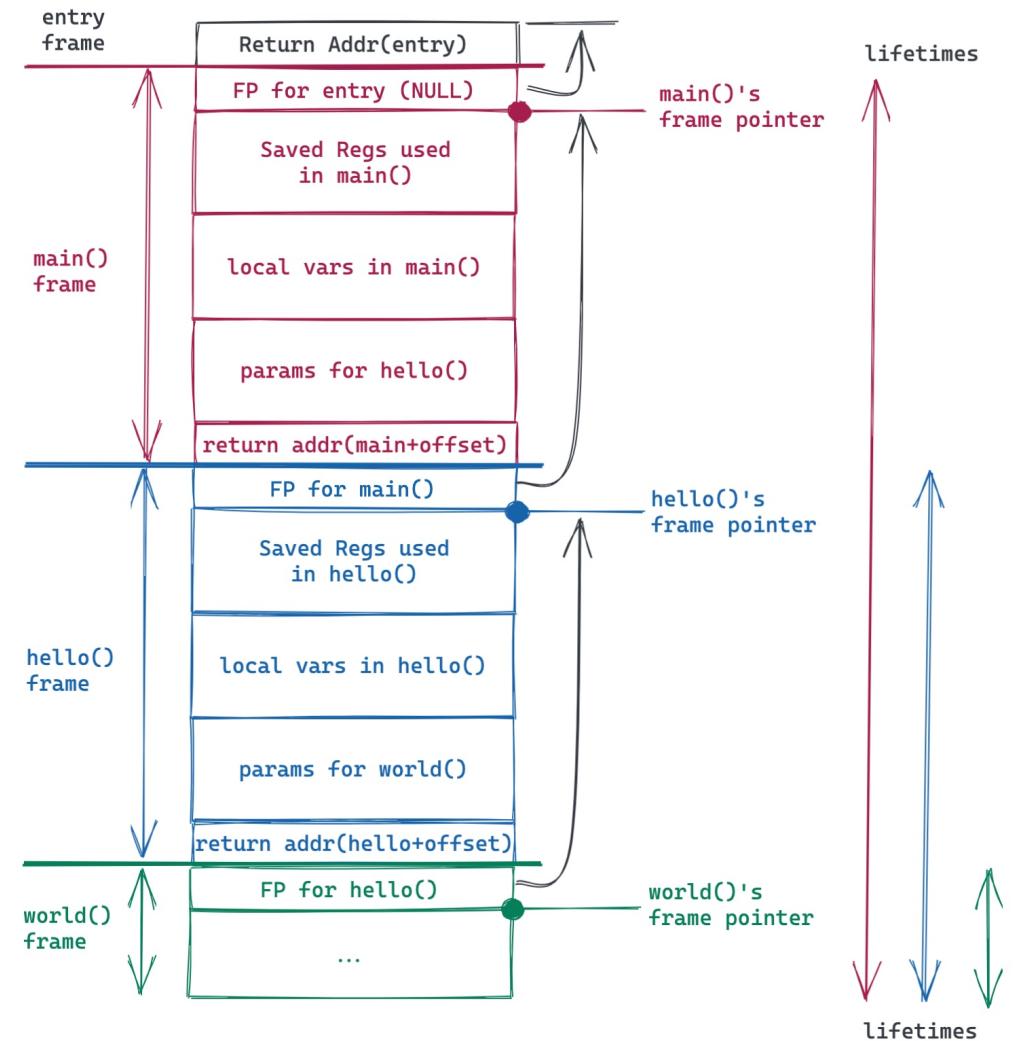
# Lifetime: Stack memory

```
#include <stdio.h>
static int VALUE = 42;

void world(char *st, int num) {
    printf("%s(%d)\n", st, num);
}

void hello(int num) {
    char *st = "hello world";
    int v = VALUE+num;
    world(st, v);
}

int main() {
    hello(2);
}
```



# Lifetime: Heap memory (tracing GC)

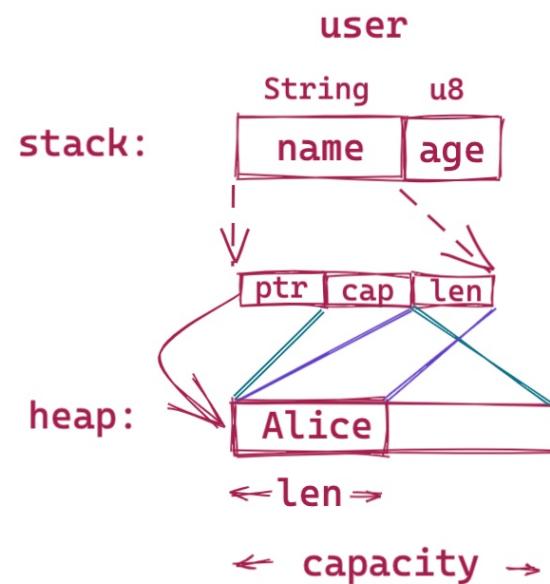


# Lifetime: Heap memory (ARC)

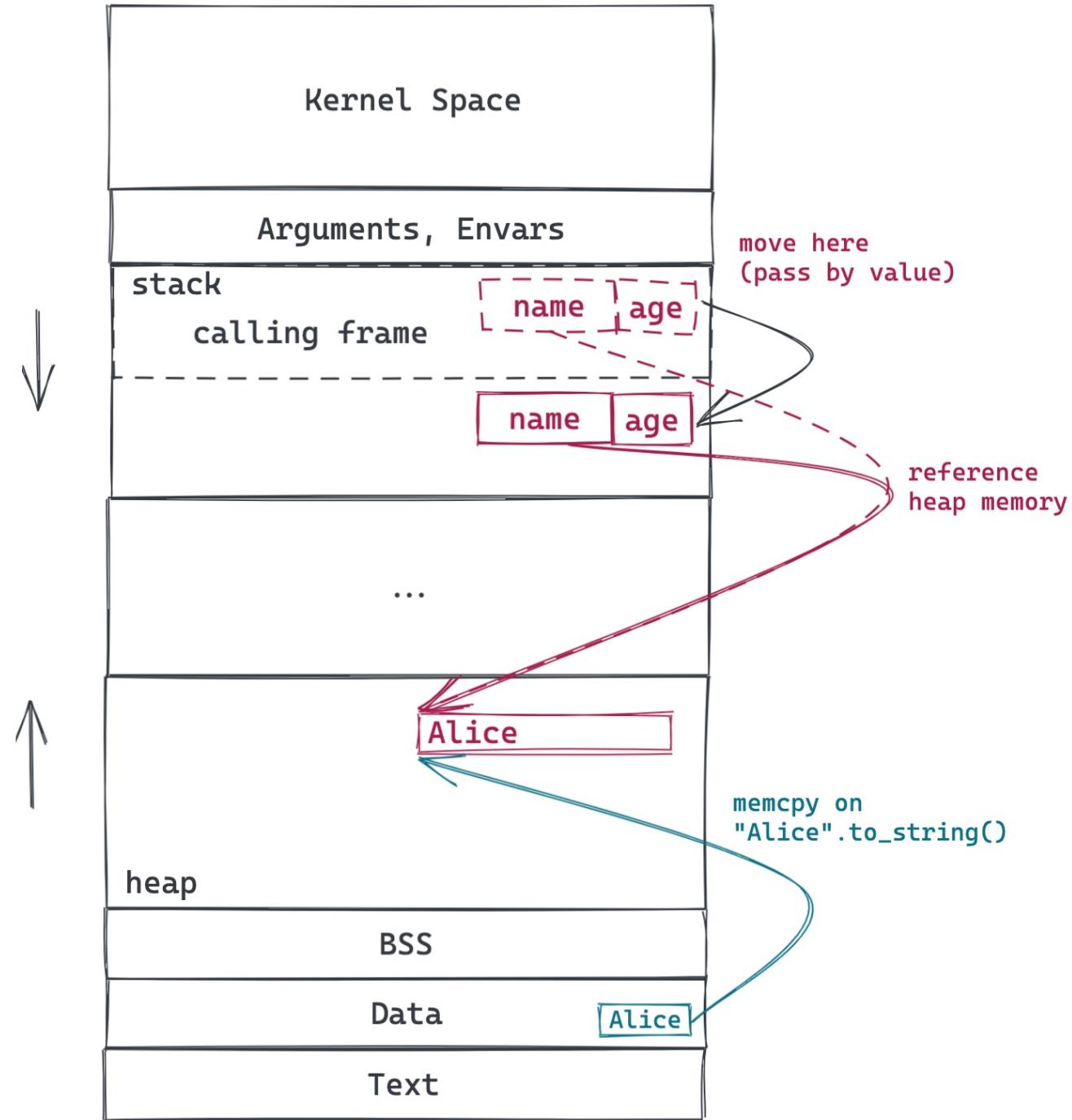


# How Rust handles lifetime?

# **Move semantics**



```
{
  let user = User {
    name: "Alice".to_string(),
    age: 20,
  };
  let result = insert(user);
  ...
}
```

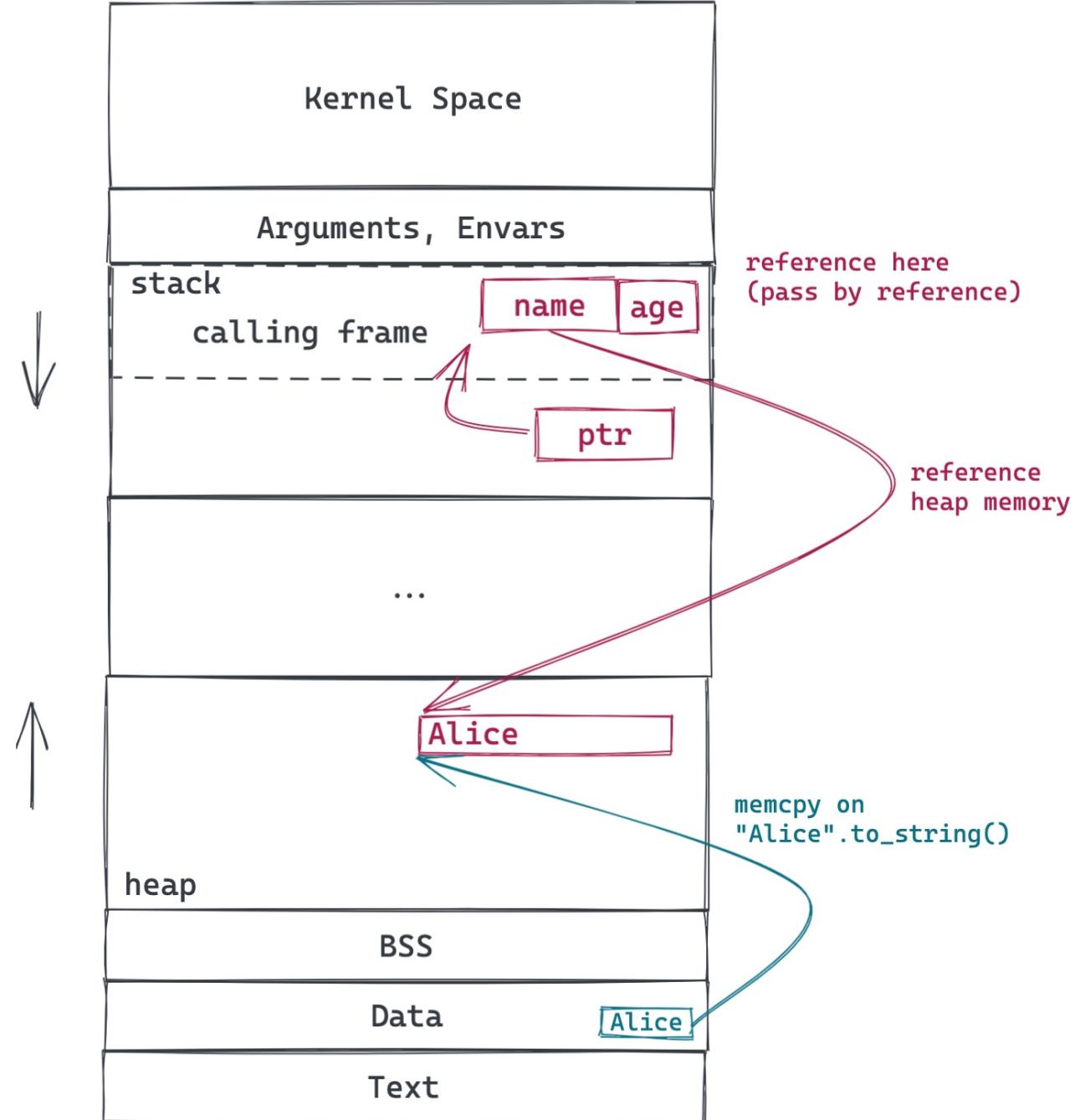


# **What about Borrow?**

Think about: why does this work in Rust, but not C/C++?



```
{
  let user = User {
    name: "Alice".to_string(),
    age: 20,
  };
  let result = insert(&user);
  ...
}
```



# Rust lifetime checker prevents this...



# **Benefit of lifetime-constrained borrow**

- can borrow anything (stack object, heap object)
- safety can be guaranteed at compile-time (no runtime lifetime bookkeeping)
- Rust borrow checker is mostly a lifetime checker

# Lifetime Annotation

- similar as generics, but in lowercase starting with '`'`
- only need to put annotation when there's conflicts

```
// need explicit lifetime
struct User<'a> {
    name: &'a str,
    ...
}
fn process<T, 'a, 'b>(item1: &'a T, item2: &'b T) {}

// &'a User could be written as &User since no confliction
fn lifetime_example(user: &User) { // --- Lifetime 'a
    if user.is_authenticated() { // |--- Lifetime 'b
        let role = user.roles(); // | |
        // | |--- Lifetime 'c
        verify(&role); // | |
        // | |
    } // | ---+
} // ---+}

fn verify(x: &Role) { /*...*/ }
```

# Static Lifetime

- `'static`
- data included in bss / data / text section
  - constants / static variables
  - string literals
  - functions
- if used as trait bound:
  - the type does not contain any non-static references
  - owned data always passes a `'static` lifetime bound, but reference to the owned data does not

# Thread spawn

```
pub fn spawn<F, T>(f: F) -> JoinHandle<T>
where
    F: FnOnce() -> T,
    F: Send + 'static,
    T: Send + 'static,
{
    Builder::new().spawn(f).expect("failed to spawn thread")
}
```

The 'static constraint is a way of saying, roughly, that no borrowed data is permitted in the closure.

# **RAII (Resource Acquisition Is Initialization)**

- initializing the object will also make sure resource is initialized
- releasing the object will also make sure resource is released

# Drop Trait

- memory
- file
- socket
- lock
- any other OS resources

**demo**

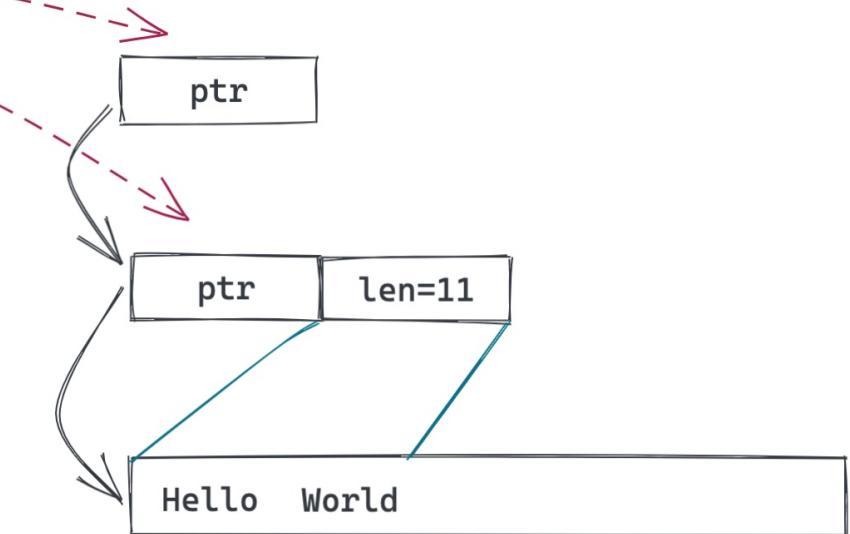
one of 'a can be omitted

```

pub fn strtok<'a>(s: &'a mut &'a str, delimiter: char)
    → &'a str {
    if let Some(i) = s.find(delimiter) {
        let prefix = &s[..i];
        let suffix = &s[(i + delimiter.len_utf8())..];
        *s = suffix;
        prefix
    } else {
        let prefix = *s;
        *s = "";
        prefix
    }
}

fn it_works() {
    let x1 = "hello world".to_owned();
    let mut x = x1.as_str();
    let hello = strtok(&mut x, ' ');
    assert_eq!(hello, "hello");
    // assert_eq!(x, "world");
}

```



# Mental model

- write the code and defer the complexity about ensuring the code is safe/correct
- confront the most of the safety/correctness problems upfront
- Mutate can only happen when you own the data, or you have a mutable reference
  - either way, the thread is guaranteed to be the only one with access at a time
- Fearless Refactoring
- reinforce properties well-behaved software exhibits
- sometimes too strict: rust isn't dogmatic about enforcing it

# References

- [Mark-And-Sweep \(Garbage Collection Algorithm\)](#)
- [Tracing garbage collection](#)
- [Swift: Avoiding Memory Leaks by Examples](#)
- [Reference counting](#)
- [Fearless concurrency with Rust](#)
- [Rust means never having to close a socket](#)
- [Programming Rust: ownership](#)
- [Crust of Rust: lifetime annotation \(recommended\)](#)

# Cost of defects

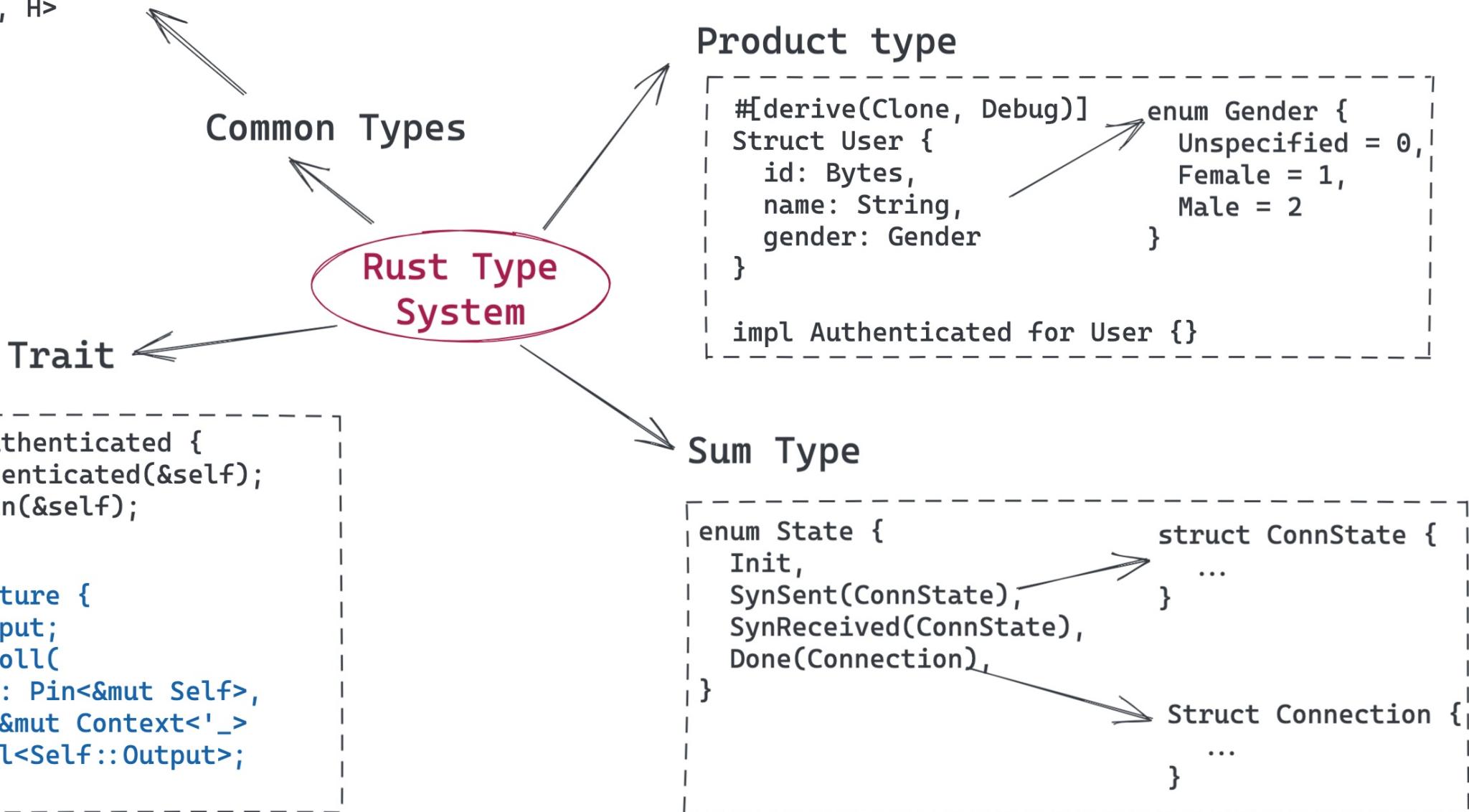
- Don't introduce defect (this is impossible because humans are fallible).
- Detect and correct defect as soon as the bad key press occurs (within reason: you don't want the programmer to lose too much flow) (milliseconds later).
- At next build / test time (seconds or minutes later).
- When code is shared with others (maybe you push a branch and CI tells you something is wrong) (minutes to days later).
- During code review (minutes to days later).
- When code is integrated (e.g. merged) (minutes to days later).
- When code is deployed (minutes to days or even months later).
- When a bug is reported long after the code has been deployed (weeks to years later).

# Ownership and Borrow rules

- Use after free: no more (reference can't point to dropped value)
- Buffer underruns, overflows, illegal memory access: no more (reference must be valid and point to owned value)
- memory level data races: no more (single writer or multiple readers)

# Typesystem and Generic Programming

```
Option<T> = Some(T) | None  
Result<T, E> = Ok(T) | Err(E)  
Vec<T>  
HashMap<K, V, H>
```



**How types are layed out in  
memory?**



## Numeric Types REF



u128, i128

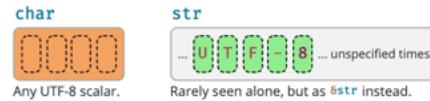


f32

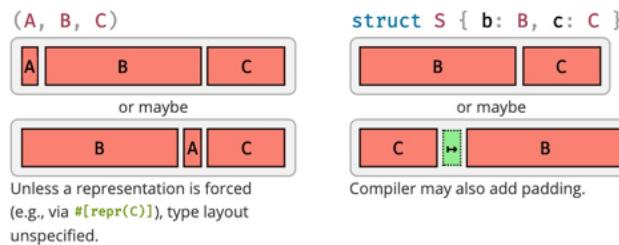


## Textual Types REF

char

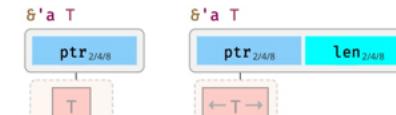


Rarely seen alone, but as &str instead.



## Pointer Meta

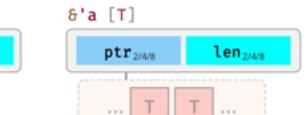
Many reference and pointer types can carry an extra field, **pointer metadata**. STD It can be the element- or byte-length of the target, or a pointer to a *vtable*. Pointers with meta are called **fat**, otherwise **thin**.



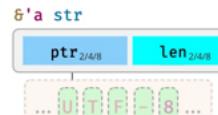
No meta for sized target.  
(pointer is thin).



If T is a DST **struct** such as s { x: [u8] } meta field len is length of dyn. sized content.

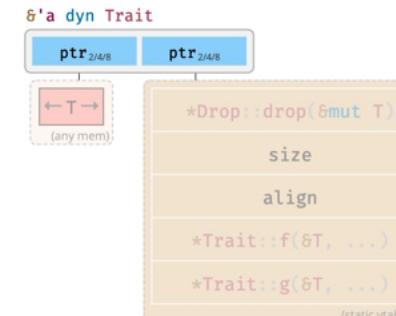
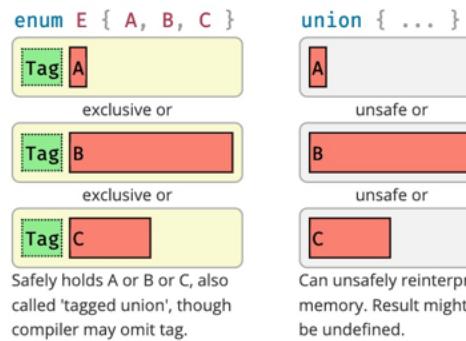


Regular slice reference (i.e., the reference type of a slice type [T])<sup>†</sup> often seen as &[T] if 'a elided.



String slice reference (i.e., the reference type of string type str), with meta len being byte length.

These **sum types** hold a value of one of their sub types:

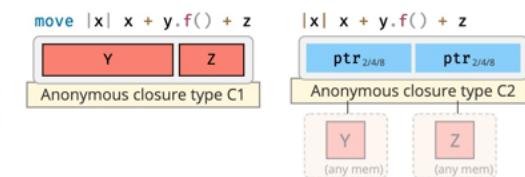


Meta points to vtable, where \*Drop::drop(), \*Trait::f(), ... are pointers to their respective

(static vtable)

## Closures

Ad-hoc functions with an automatically managed data block **capturing** REF environment where closure was defined. For example:

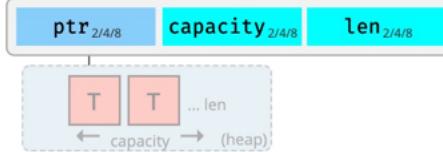


## String



Observe how String differs from &str and &[char].

## Vec<T>



# Trait (Typeclass)

```
refer to the actual data
pub trait Write {
    fn write(&mut self, buf: &[u8]) → Result<usize>;
    fn flush(&mut self) → Result<()>;                                methods must be implemented
}

fn write_all(&mut self, buf: &[u8]) → Result<()> { ... }           methods have a default impl
...
}

struct Sink {
    total: usize,
}                                                               Coherence rule: either trait or type
                                                               must be new in the current crate.
impl Write for Sink {
    fn write(&mut self, buf: &[u8]) → Result<usize> {
        self.total += buf.len();                                         when implementing trait methods,
        Ok(buf.len())                                                 you can access the actual data
    }

    fn flush(&mut self) → Result<()> {
        Ok(())
    }
}
```

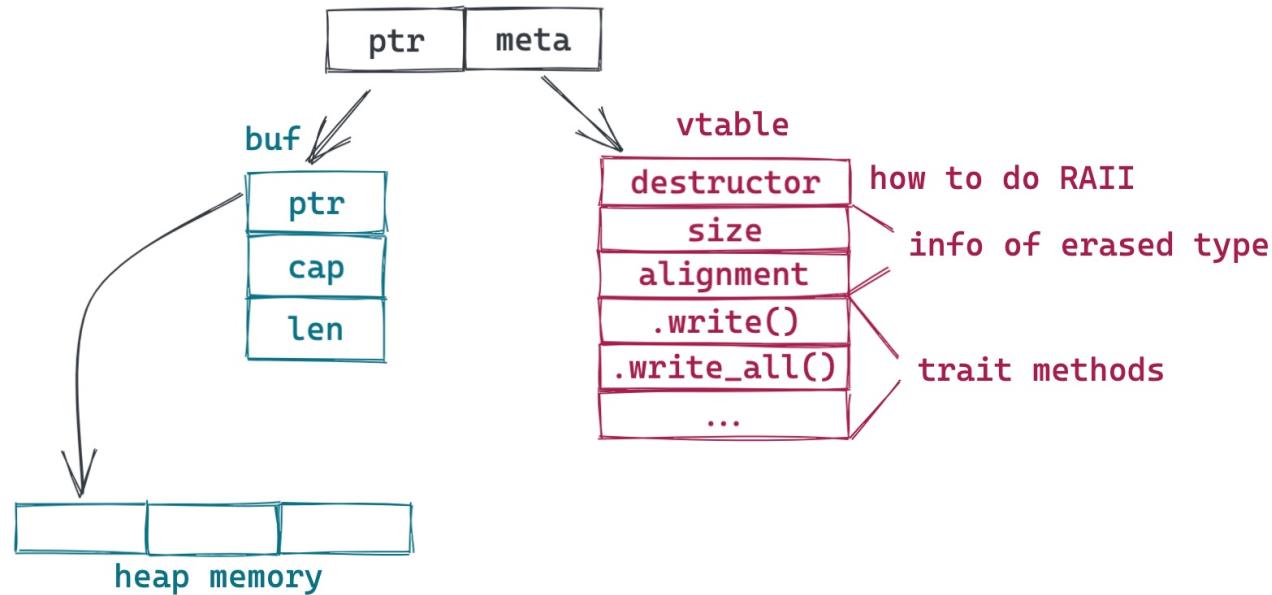
```

use std::io::Write;

let mut buf: Vec<u8> = vec![];
let writer: Write = buf; // `Write` does not have a constant size

let writer: &mut Write = &mut buf; // ok. Trait object

```



# Trait Object

- Unlike java, you can't assign a value to a trait (no implicit reference!!!)
- trait object is a fat pointer (automatically converted)
  - normal pointer reference to the value
  - vtable (vtable pointer)
    - unlike C++/Java, it is not a ptr in struct
- dynamic dispatch

```
pub trait Formatter {
    fn format(&self, input: &mut str) -> bool;
}

struct MarkdownFormatter;
impl Formatter for MarkdownFormatter {
    fn format(&self, input: &mut str) -> bool { todo!() }
}

struct RustFormatter;
impl Formatter for RustFormatter {
    fn format(&self, input: &mut str) -> bool { todo!() }
}

struct HtmlFormatter;
impl Formatter for HtmlFormatter {
    fn format(&self, input: &mut str) -> bool { todo!() }
}

pub fn format(input: &mut str, formatters: Vec<Box<dyn Formatter>>) {
    for formatter in formatters {
        formatter.format(input);
    }
}
```

```
pub trait Iterator {  
    type Item;  
    pub fn next(&mut self) -> Option<Self::Item>;  
    ...  
}
```

associate type

```
pub trait From<T> {  
    pub fn from(T) -> Self;  
}
```

generic type

```
trait Person {  
    fn name(&self) -> String;  
}  
  
trait Student: Person {  
    fn university(&self) -> String;  
}
```

super trait

```
trait Programmer {  
    fn fav_language(&self) -> String;  
}
```

trait composition

```
trait CompSciStudent: Programmer + Student {  
    fn git_username(&self) -> String;  
}
```

## More about trait

- associated type
- generics
- supertrait
- trait composition

# **Generics**

# History of Generic Programming

The first step was a generalized machine architecture, exemplified by the IBM 360, based on a uniform view of the machine memory as a sequence of bytes, referenced by uniform addresses (pointers) independent of the type of data being referenced. The next step was the C programming language [KeRi78], which was effectively a generalized machine language for such architectures, providing composite data types to model objects in memory, and pointers as identifiers for such memory objects with operations (dereferencing and increment/decrement) that were uniform across types. The C++ programming language [Stroustrup97] was the next step. It allows us to generalize the use of C syntax, applying the built-in operators to user types as well, using class definitions, operator overloading, and templates. The final step in this progression is generic programming

(from: Fundamentals of Generic Programming)

# Classification of Abstractions

- **Data Abstractions:** data types and sets of operations defined on them
  - e.g. `Vec<T>`, `HashMap<K, V>`
- **Algorithmic abstractions:** families of data abstractions that have a set of efficient algorithms in common (generic algorithms)
  - e.g. `quicksort`, `binary_search`
- **Structural abstractions:** a data abstraction A belongs to a structural abstraction S if and only if S is an intersection of some of the algorithmic abstractions to which A belongs.
  - e.g. singly-linked-lists
- **Representational abstractions:** mappings from one structural abstraction to another, creating a new type and implementing a set of operations on that type.
  - e.g. `VecDeque<T>`
- Comes from: Generic Programming: <http://stepanovpapers.com/genprog.pdf>

# **Generics to Types**

just like

# **Types to Values**



```
auto add(auto a, auto b) { return a + b; }
```



```
T add(T)(T a, T b) { return a + b; }
```



```
fn add<T>(a: T, b: T) -> T { a + b }
```



```
func add<T>(_ a: T, _ b: T) -> T { a + b }
```



```
add :: t -> t -> t  
add a b = a + b
```



```
auto add(auto a, auto b) { return a + b; }
```



```
T add(T)(T a, T b) { return a + b; }
```



```
fn add<T: std::ops::Add<Output = T>>(a: T, b: T) -> T { a + b }
    pub trait Add<Rhs = Self> {
        type Output;
        pub fn add(self, rhs: Rhs) -> Self::Output;           SystemTime + Duration => SystemTime
    }
```



```
func add<T: Numeric>(_ a: T, _ b: T) -> T { a + b }
```



```
add :: Num t => t -> t -> t
add a b = a + b
```

| Example                                            | Explanation                                                                                                                         |
|----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| <code>S&lt;T&gt;</code>                            | A <b>generic</b> <small>BK EX</small> type with a type parameter ( <code>T</code> is placeholder name here).                        |
| <code>S&lt;T: R&gt;</code>                         | Type short hand <b>trait bound</b> <small>BK EX</small> specification ( <code>R</code> <i>must</i> be actual trait).                |
| <code>T: R, P: S</code>                            | <b>Independent trait bounds</b> (here one for <code>T</code> and one for <code>P</code> ).                                          |
| <code>T: R, S</code>                               | Compile error, <small>⌚</small> you probably want compound bound <code>R + S</code> below.                                          |
| <code>T: R + S</code>                              | <b>Compound trait bound</b> <small>BK EX</small> , <code>T</code> must fulfill <code>R</code> and <code>S</code> .                  |
| <code>T: R + 'a</code>                             | Same, but w. lifetime. <code>T</code> must fulfill <code>R</code> , if <code>T</code> has lifetimes, must outlive <code>'a</code> . |
| <code>T: ?Sized</code>                             | Opt out of a pre-defined trait bound, here <code>Sized</code> .?                                                                    |
| <code>T: 'a</code>                                 | Type <b>lifetime bound</b> <small>EX</small> , if <code>T</code> has references, they must outlive <code>'a</code> .                |
| <code>T: 'static</code>                            | Same; does esp. <i>not</i> mean value <code>t</code> <i>will</i> <small>⌚</small> live <code>'static</code> , only that it could.   |
| <code>'b: 'a</code>                                | Lifetime <code>'b</code> must live at least as long as (i.e., <i>outlive</i> ) <code>'a</code> bound.                               |
| <code>S&lt;const N: usize&gt;</code>               | <b>Generic const bound</b> ; ? user of type <code>S</code> can provide constant value <code>N</code> . <small>⌘</small>             |
| <code>S&lt;10&gt;</code>                           | Where used, const bounds can be provided as primitive values.                                                                       |
| <code>S&lt;{5+5}&gt;</code>                        | Expressions must be put in curly brackets.                                                                                          |
| <code>S&lt;T&gt; where T: R</code>                 | Almost same as <code>S&lt;T: R&gt;</code> but more pleasant to read for longer bounds.                                              |
| <code>S&lt;T&gt; where u8: R&lt;T&gt;</code>       | Also allows you to make conditional statements involving <i>other</i> types.                                                        |
| <code>S&lt;T = R&gt;</code>                        | <b>Default type parameter</b> <small>BK</small> for associated type.                                                                |
| <code>S&lt;'_&gt;</code>                           | Inferred <b>anonymous lifetime</b> ; asks compiler to ' <i>figure it out</i> ' if obvious.                                          |
| <code>S&lt;_&gt;</code>                            | Inferred <b>anonymous type</b> , e.g., as <code>let x: Vec&lt;_&gt; = iter.collect()</code>                                         |
| <code>S:::&lt;T&gt;</code>                         | <b>Turbofish</b> <small>STD</small> call site type disambiguation, e.g. <code>f:::&lt;u32&gt;()</code> .                            |
| <code>trait T&lt;X&gt; {}</code>                   | A trait generic over <code>X</code> . Can have multiple <code>impl T for S</code> (one per <code>X</code> ).                        |
| <code>trait T { type X; }</code>                   | Defines <b>associated type</b> <small>BK REF</small> <code>X</code> . Only one <code>impl T for S</code> possible.                  |
| <code>type X = R;</code>                           | Set associated type within <code>impl T for S { type X = R; }</code> .                                                              |
| <code>impl&lt;T&gt; S&lt;T&gt; {}</code>           | Implement functionality for any <code>T</code> in <code>S&lt;T&gt;</code> , here <code>T</code> type parameter.                     |
| <code>impl S&lt;T&gt; {}</code>                    | Implement functionality for exactly <code>S&lt;T&gt;</code> , here <code>T</code> specific type (e.g., <code>S&lt;u32&gt;</code> ). |
| <code>fn f() -&gt; impl T</code>                   | <b>Existential types</b> , <small>BK</small> returns an unknown-to-caller <code>S</code> that <code>impl T</code> .                 |
| <code>fn f(x: &amp;impl T)</code>                  | Trait bound, "impl traits", <small>BK</small> somewhat similar to <code>fn f&lt;S:T&gt;(x: &amp;S)</code> .                         |
| <code>fn f(x: &amp;dyn T)</code>                   | Marker for <b>dynamic dispatch</b> , <small>BK REF</small> <code>f</code> will not be monomorphized.                                |
| <code>fn f() where Self: R;</code>                 | In <code>trait T {}</code> , make <code>f</code> accessible only on types known to also <code>impl R</code> .                       |
| <code>fn f() where Self: R {}</code>               | Esp. useful w. default methods (non dflt. would need be impl'ed anyway).                                                            |
| <code>for&lt;'a&gt;</code>                         | <b>Higher-ranked trait bounds</b> . <small>NOM REF ⚡</small>                                                                        |
| <code>trait T: for&lt;'a&gt; R&lt;'a&gt; {}</code> | Any <code>S</code> that <code>impl T</code> would also have to fulfill <code>R</code> for any lifetime.                             |

# Generic Programming Example

```
int binary_search(int x[], int n, int v) {
    int l = 0;
    int u = n;

    while (true) {
        if (l > u) return -1;

        int m = (l + u) / 2;

        if (x[m] < v) l = m + 1;
        else if (x[m] == v) return m;
        else u = m - 1;
    }
}
```

→

```
template <class I, class T>
I lower_bound(I f, I l, const T& v) {
    while (f != l) {
        auto m = next(f, distance(f, l) / 2);

        if (*m < v) f = next(m);
        else l = m;
    }
    return f;
}
```

first  
ForwardIterator  
value\_type(I),  
comparable

last  
next(f)  
distance(f, l) / 2;

demo: [rust implementation](#)

# **Realworld GP example**

Underlying protocols: TCP, WebSocket, HTTP/2, QUIC, etc.

```
pub struct AsyncProstWriter<W, T, D> {
    writer: W,
    pub(crate) written: usize,
    pub(crate) buffer: Vec<u8>,
    from: PhantomData<T>,
    dest: PhantomData<D>,
}

pub struct AsyncProstReader<R, T, D> {
    reader: R,
    pub(crate) buffer: BytesMut,
    into: PhantomData<T>,
    dest: PhantomData<D>,
}
```

v1 & v2 shared logic:

- read data based on len
- write data to writer

deferred decision:

- underlying network protocols
- Message types
- decode body or not

```
pub struct Frame<H, T> {
    pub header: Option<H>,
    pub body: Option<Either<Vec<u8>, T>>,
}
impl<H, T> Framed for Frame<H, T>
where
    H: Message + ShallDecodeBody + Default,
    T: Message + Default
```

if exists, check if need to decode body  
otherwise, decode body

```
pub trait ShallDecodeBody {
    fn shall_decode_body(&self) -> bool;
}
```

```
impl<W, T, D> Sink<T> for AsyncProstWriter<W, T, D>
where
    W: AsyncWrite + Unpin,
    Self: ProstWriterFor<T>,

pub trait ProstWriterFor<T> {
    fn append(&mut self, item: T) -> Result<(), io::Error>;
}

impl<W, F: Framed> ProstWriterFor<F>
for AsyncProstWriter<W, F, AsyncFrameDestination> { ... }

impl<W, T: Message> ProstWriterFor<T>
for AsyncProstWriter<W, T, AsyncDestination> { ... }
```

```
impl<R, T> Stream for AsyncProstReader<R, T, AsyncDestination>
where
    T: Message + Default,
    R: AsyncRead + Unpin { ... }

impl<R, T> Stream for AsyncProstReader<R, T, AsyncFrameDestination>
where
    R: AsyncRead + Unpin,
    T: Framed + Default { ... }
```

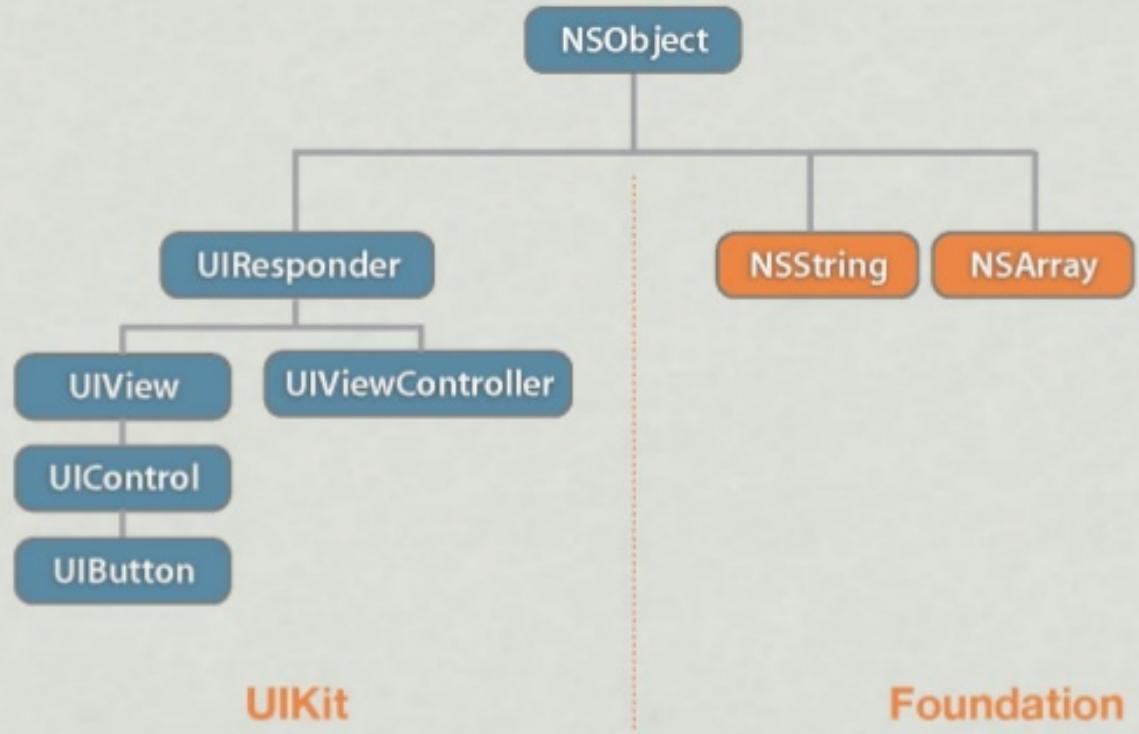
“ Functions delay binding: data structures induce binding.  
Moral: Structure data late in the programming process.  
— Epigrams on programming ”

# References

- All about trait objects
- Protocol-oriented programming in swift
- Generic Data Types
- Generics (Rust by Example)

# Why not object oriented?

## Class Hierarchy



Class is  
awesome

- Encapsulation
- Access control
- Abstraction
- Namespace
- Extensibility

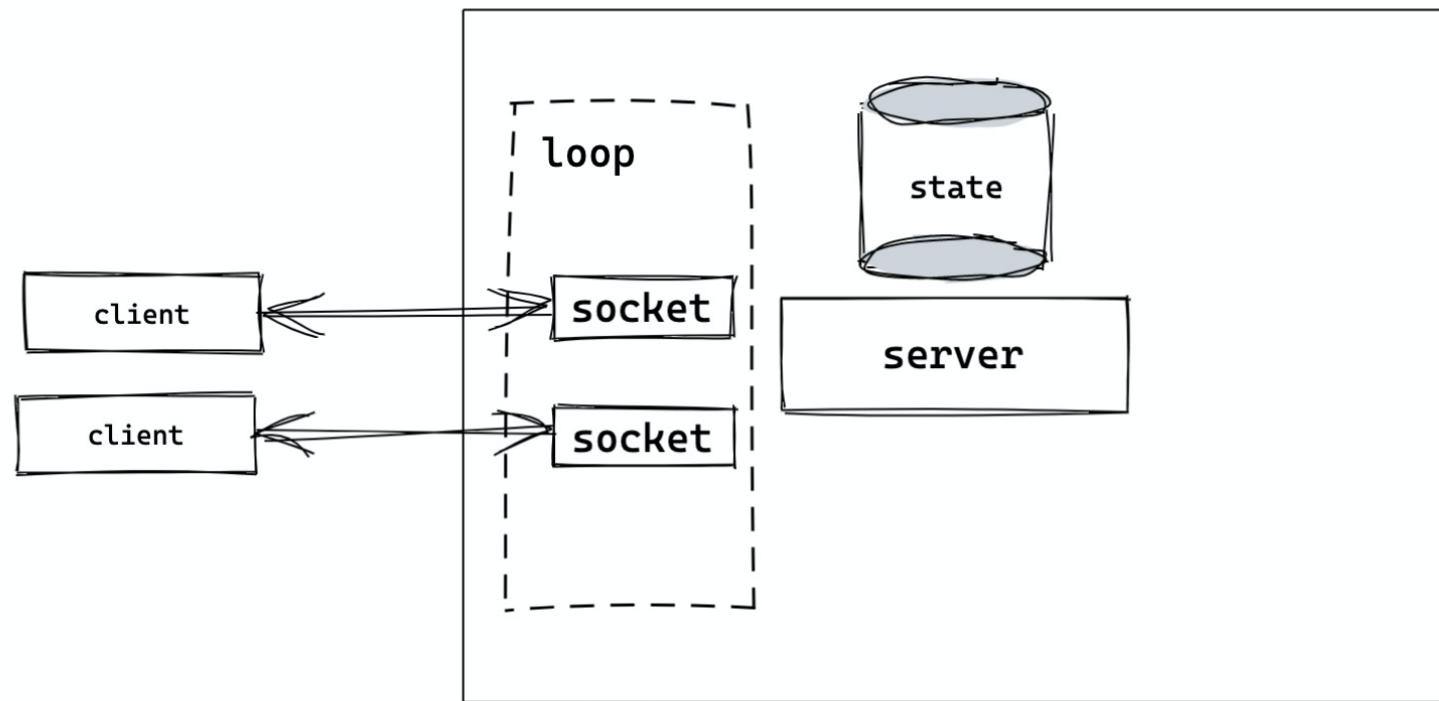
# Class has problems

- inheritance is pretty limited - choose superclass well!
- know what/how to override (and when not to)
- superclass may have properties
  - you have to accept it
  - initialization burden
  - don't break assumptions of superclass
- hard to reuse outside the hierarchy (composition over inheritance)

# **Concurrency - primitives**

**Let's solve a real-world problem**

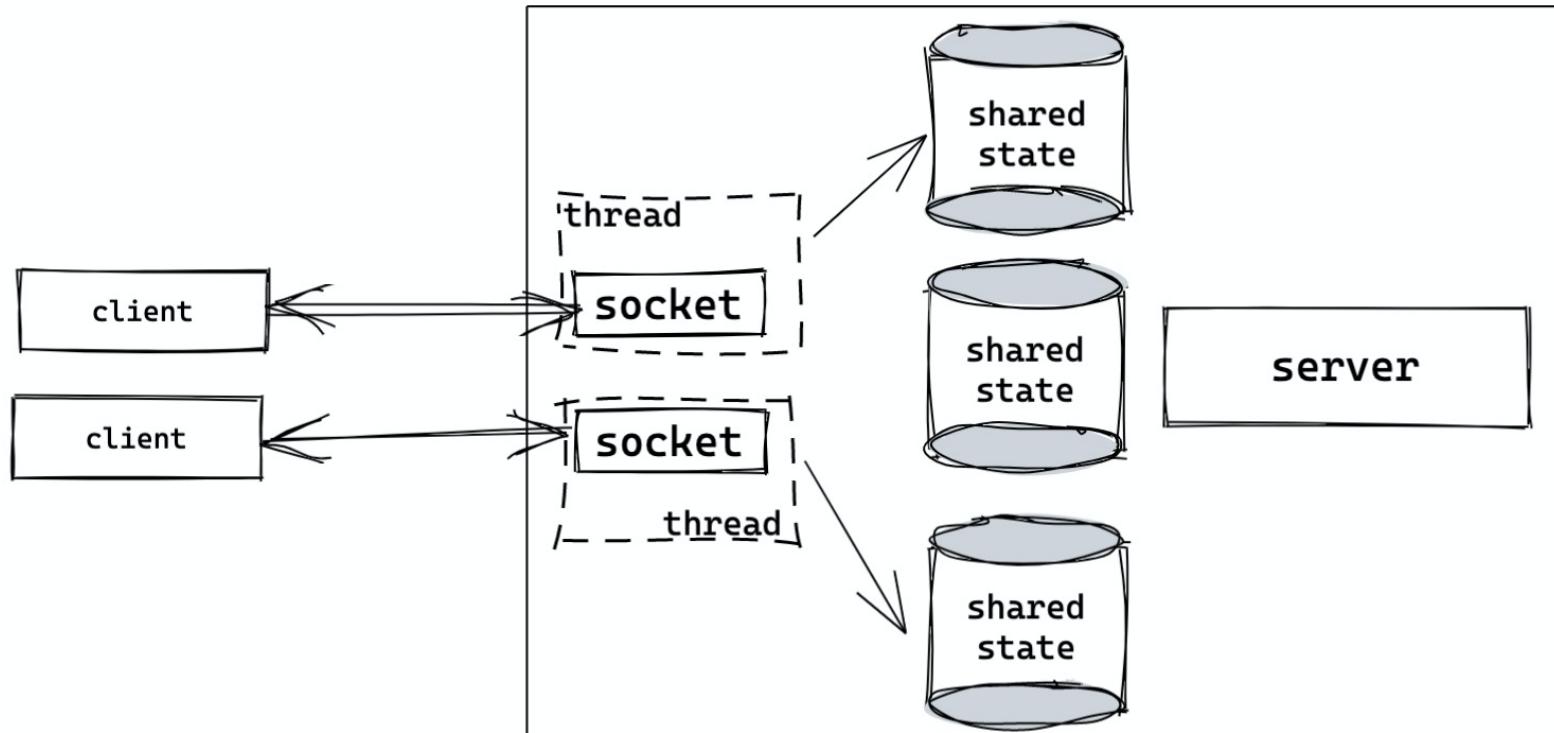
# v1: Simple loop



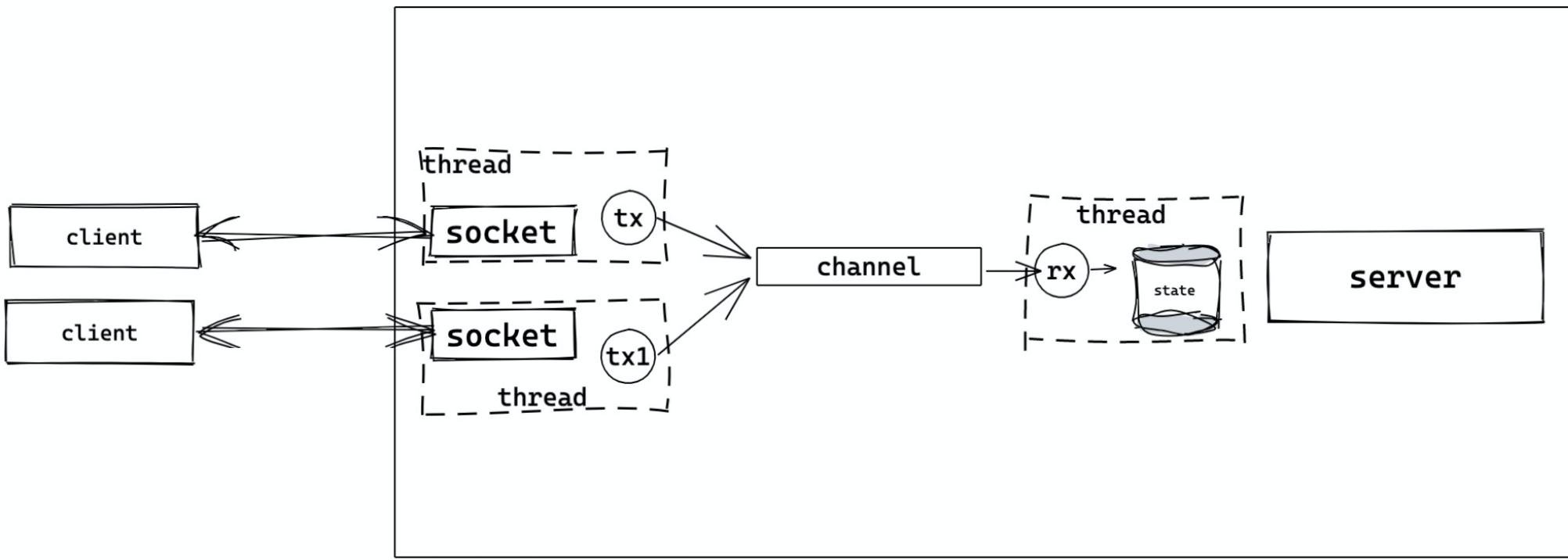
# v2: Multithread with shared state



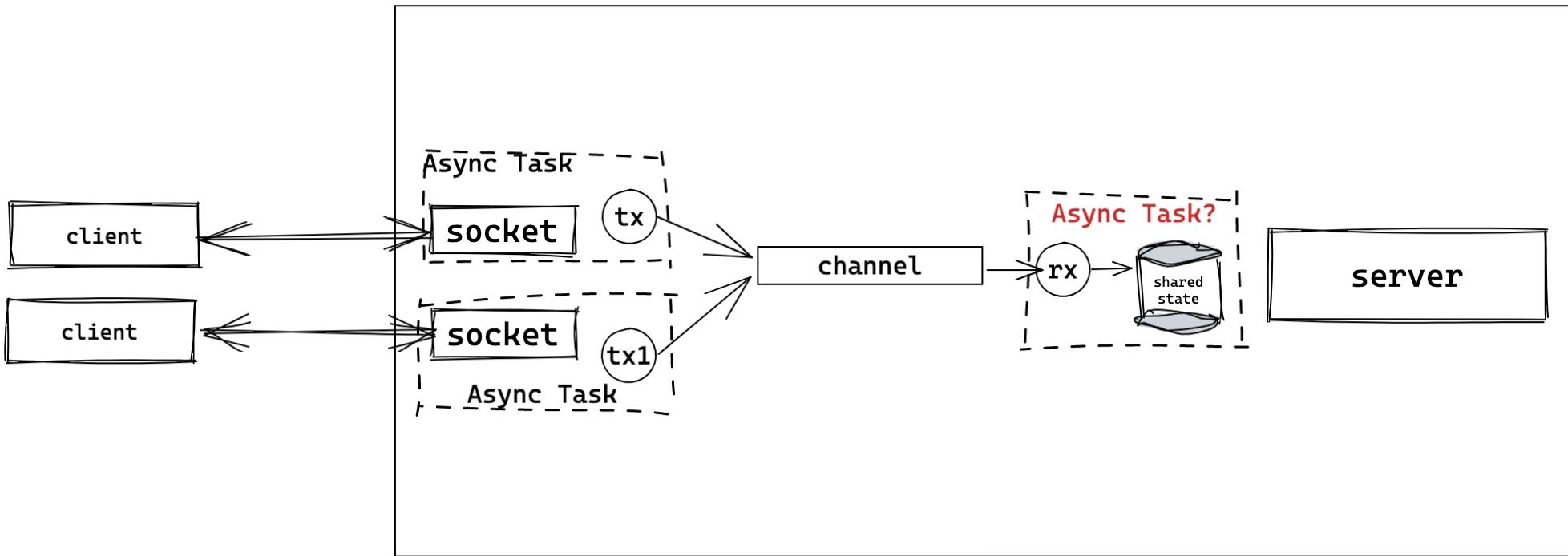
# v3: Optimize the lock



# v4: Share memory by communicating



# v5: Async Task



# What have we used so far?

- Mutex Lock
- Channel/Actor
- Async Task (coroutine, promise, etc.)

# **How is Mutex implemented?**

# An naive implementation

```
struct Lock<T> {
    locked: bool,
    data: T,
}

impl<T> Lock<T> {
    pub fn new(data: T) -> Lock<T> { ... }

    pub fn lock<R>(&mut self, op: impl FnOnce(&mut T) -> R) -> R {
        // spin if we can't get lock
        while self.locked != false {} // **1
        // ha, we can lock and do our job
        self.locked = true; // **2
        // execute the op as we got lock
        let ret = op(self.data); // **3
        // unlock
        self.locked = false; // **4
        ret
    }
}

// You may call it like this:
let l = Lock::new(0);
l.lock(|v| v += 1);
```

# Issues

- Atomicity
  - In multicore environment, race condition between 1 and 2 - other thread may kick in
  - Even in single core environment, OS may do preempted multitasking, causing other thread kick in
- OOO execution
  - Compiler might generate optimized instructions that put 3 before 1
  - CPU may do OOO execution to best utilize pipeline, so putting 3 before 1 might also happen

# How to solve this?

- We need CPU instruction to guarantee Atomicity and non-OOO
- Algorithm: **CAS (Compare-And-Swap)**
- data structure: `AtomicXXX`

# Atomics

# Updated lock

```
struct Lock<T> {
    locked: AtomicBool, // ***
    data: UnsafeCell<T>, // ***
}
unsafe impl<T> Sync for Lock<T> where T: Send {} // need to explicitly impl `Send`

impl<T> Lock<T> {
    pub fn new(data: T) -> Self { ... }
    pub fn lock<R>(&mut self, op: impl FnOnce(&mut T) -> R) -> R {
        // spin if we can't get lock
        while self
            .locked
            .compare_exchange(false, true, Ordering::Acquire, Ordering::Relaxed)
            .is_error() {}
        // execute the op as we got lock
        let ret = op(unsafe { &mut *self.v.get() });
        // unlock
        self.locked.store(false, Ordering::Release);
        ret
    }
}

// You may call it like this:
let l = Lock::new(0);
l.lock(|v| v += 1);
```

# What does ordering mean?

- Relaxed: No restriction to compiler/CPU, OOO is allowed
- Release:
  - for current thread, any read/write inst cannot be OOO after this inst ( `store` );
  - for other thread, if they use `Acquire` to read, they would see the changed value
- Acquire
  - for current thread, any read/write inst cannot be OOO before this inst ( `compare_exchange` )
  - for other thread, if they use `Release` to update data, the modification would be seen by current thread
- AcqRel: combination of Acquire and Release
- SeqCst: besides `AcqRel`, all threads would see same operation order.

# Optimization

```
pub struct Lock<T> {
    locked: AtomicBool,
    data: UnsafeCell<T>,
}
unsafe impl<T> Sync for Lock<T> where T: Send {}

impl<T> Lock<T> {
    pub fn new(data: T) -> Self {...}
    pub fn lock<R>(&self, op: impl FnOnce(&mut T) -> R) -> R {
        while self
            .locked
            .compare_exchange(false, true, Ordering::Acquire, Ordering::Relaxed)
            .is_err()
        {
            while self.locked.load(Ordering::Relaxed) == true {
                std::thread::yield_now(); // we may yield thread now
            }
        }
        let ret = op(unsafe { &mut *self.data.get() });
        self.locked.store(false, Ordering::Release);
        ret
    }
}
```

t1

t2

```
pub fn with_lock<R>(&self, f: impl FnOnce(&mut T) -> R) -> R {  
    while self  
        .locked  
        .compare_exchange(false, true, Ordering::Acquire, Ordering::Relaxed)  
        .is_err()  
    {  
        while self.locked.load(Ordering::Relaxed) == true {}  
    }  
    let ret = op(unsafe { &mut *self.v.get() });  
    self.locked.store(false, Ordering::Release);  
    ret  
}
```



t1 finished op, released lock  
t2 finished spin, entered critical section

t1

t2

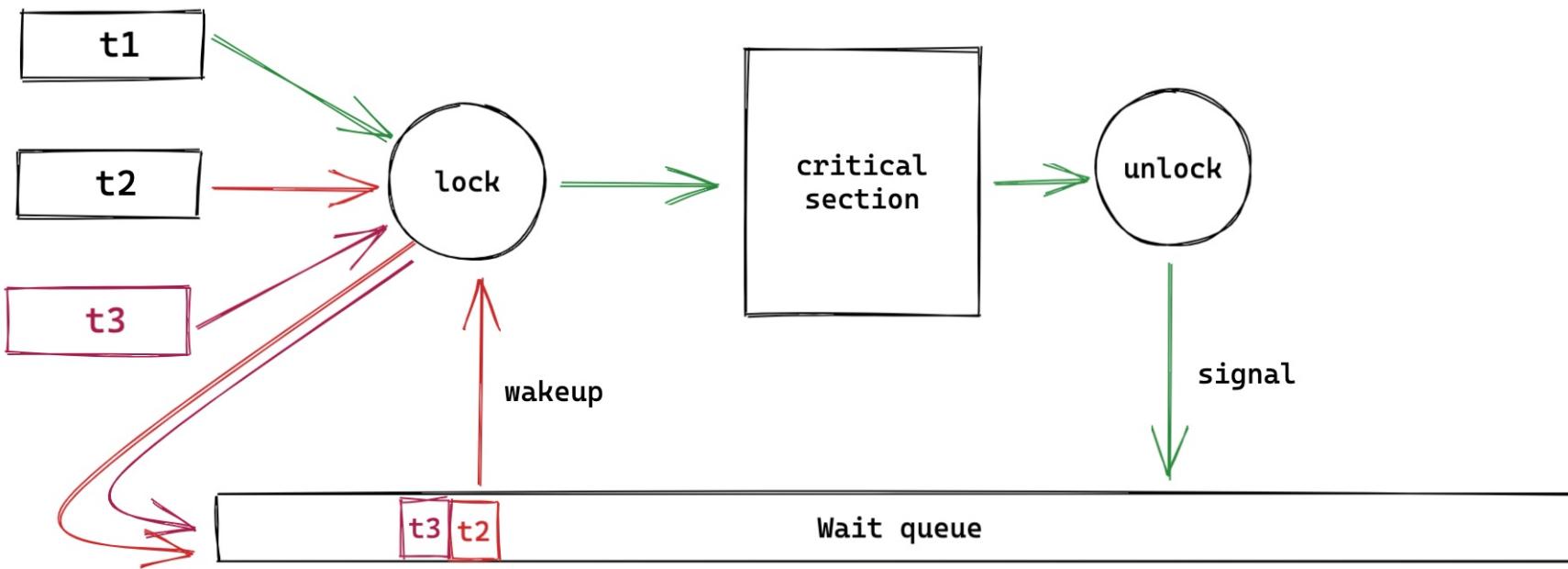
```
pub fn with_lock<R>(&self, f: impl FnOnce(&mut T) -> R) -> R {  
    while self  
        .locked  
        .compare_exchange(false, true, Ordering::Acquire, Ordering::Relaxed)  
        .is_err()  
    {  
        while self.locked.load(Ordering::Relaxed) == true {}  
    }  
    let ret = op(unsafe { &mut *self.v.get() });  
    self.locked.store(false, Ordering::Release);  
    ret  
}
```

This is basically how

**Mutex**

works

# Real world Mutex



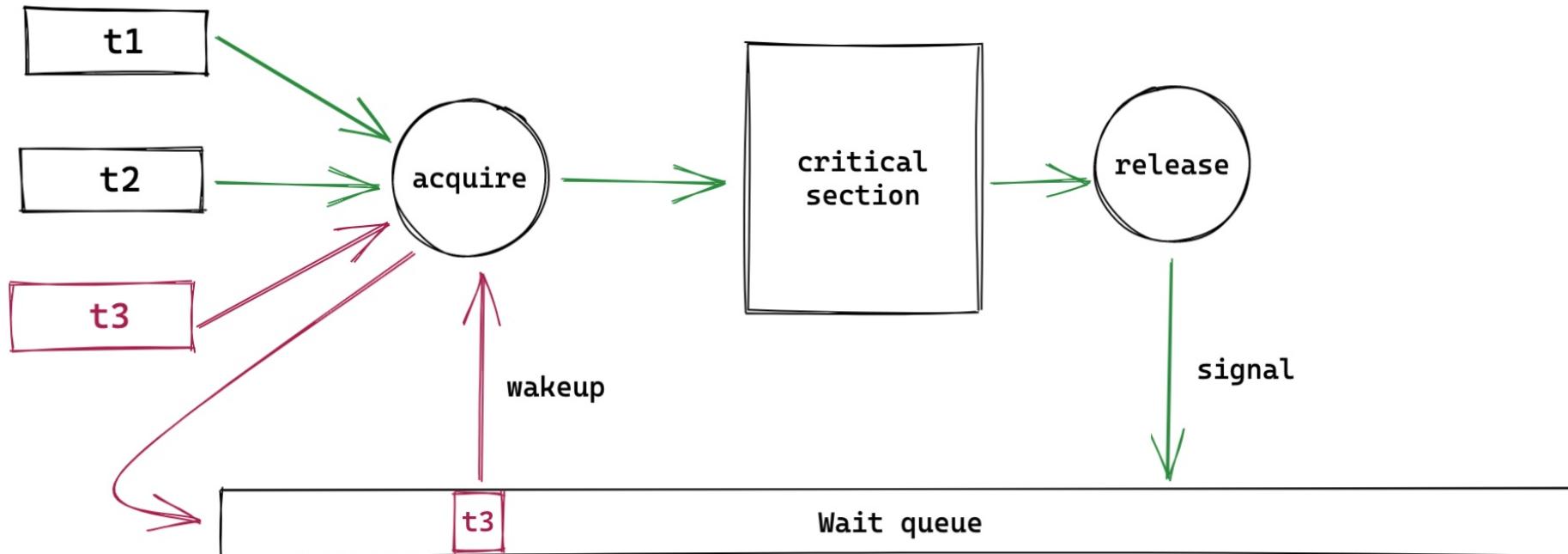
# Semaphore

“ In computer science, a **semaphore** is a variable or abstract data type used to control access to a common resource by multiple processes and avoid critical section problems in a concurrent system such as a multitasking operating system. A trivial semaphore is a plain variable that is changed (for example, incremented or decremented, or toggled) depending on programmer-defined conditions.

A useful way to think of a semaphore as used in a real-world system is as **a record of how many units of a particular resource are available**, coupled with operations to adjust that record safely (i.e., to avoid race conditions) as units are acquired or become free, and, if necessary, wait until a unit of the resource becomes available.

”

# Semaphore as a generalized Mutex



# **Demo code: restricted HTTP client**

[code/primitives/src/http\\_semaphore.rs](#)

# Channel

# Channel basics



# Flavours of Channels

- sync: sender can block, limited capacity
  - Mutex + Condvar + VecDeque
  - Atomic VecDeque (atomic queue) + thread::park + thread::notify
- async: sender cannot block, unbounded
  - Mutex + Condvar + VecDeque
  - Mutex + Condvar + DoubleLinkedList
- rendezvous: sync with capacity = 0. Used for thread sync.
  - Mutex + Condvar
- oneshot: only one call to send(). e.g. Ctrl+C to stop all threads
  - atomic swap
- async/await
  - basically same as sync but waker is different

# Demo code: naive MPSC

[code/primitives/src/channel.rs](#)

# Demo code: naive actor

- Questions:
  - Which type of channel shall we use? SPSC, SPMC, MPSC?
  - When creating an actor, what is its `pid`?
  - When sending a message to an actor, how the actor reply (`handle_call`)?
- Code: [code/primitives/src/actor.rs](#)

# References

- CAS: <https://en.wikipedia.org/wiki/Compare-and-swap>
- Ordering: <https://doc.rust-lang.org/std/sync/atomic/enum.Ordering.html>
- std::memory\_order: [https://en.cppreference.com/w/cpp/atomic/memory\\_order](https://en.cppreference.com/w/cpp/atomic/memory_order)
- Atomics and Memory Ordering: <https://www.youtube.com/watch?v=rMGWeSjctIY>
- spinlock: <https://en.wikipedia.org/wiki/Spinlock>
- spin-rs: <https://github.com/mvdnes/spin-rs>
- parking lot: [https://github.com/Amanieu/parking\\_lot](https://github.com/Amanieu/parking_lot)
- Flume: <https://github.com/zesterer/flume>
- Crossbeam channel: <https://docs.rs/crossbeam-channel>

# Things to do with atomics

- lock free data structure
- in memory metrics
- id generation

# **Concurrency - `async/await`**

# Using threads in Rust

```
use std::thread;

fn main() {
    println!("So we start the program here!");
    let t1 = thread::spawn(move || {
        thread::sleep(std::time::Duration::from_millis(200));
        println!("We create tasks which gets run when they're finished!");
    });

    let t2 = thread::spawn(move || {
        thread::sleep(std::time::Duration::from_millis(100));
        println!("We can even chain callbacks...");
        let t3 = thread::spawn(move || {
            thread::sleep(std::time::Duration::from_millis(50));
            println!("...like this!");
        });
        t3.join().unwrap();
    });
    t1.join().unwrap();
    println!("While our tasks are executing we can do other stuff here.");

    t1.join().unwrap();
    t2.join().unwrap();
}
```

# **Drawbacks of threads**

- large stack (not suitable for heavy loaded concurrent jobs - e.g. a web server)
- context switch is out of your control
- lots of syscall involved (costly when # of threads is high)

**What are alternative solutions?**

# **Green threads/processes**

## **(stackful coroutine)**

Golang/Erlang

# Green Threads

- Run some non-blocking code.
- Make a blocking call to some external resource.
- CPU "jumps" to the "main" thread which schedules a different thread to run and "jumps" to that stack.
- Run some non-blocking code on the new thread until a new blocking call or the task is finished.
- CPU "jumps" back to the "main" thread, schedules a new thread which is ready to make progress, and "jumps" to that thread.

# Green Threads - pros/cons

- Pros:
  - Simple to use. The code will look like it does when using OS threads.
  - A "context switch" is reasonably fast.
  - Each stack only gets a little memory to start with so you can have hundreds of thousands of green threads running.
  - It's easy to incorporate preemption which puts a lot of control in the hands of the runtime implementors.
- Cons:
  - The stacks might need to grow. Solving this is not easy and will have a cost.
  - You need to save the CPU state on every switch.
  - It's not a zero cost abstraction (Rust had green threads early on and this was one of the reasons they were removed).
  - Complicated to implement correctly if you want to support many different platforms.

# **Poll based event loops**

## **(stackless coroutine)**

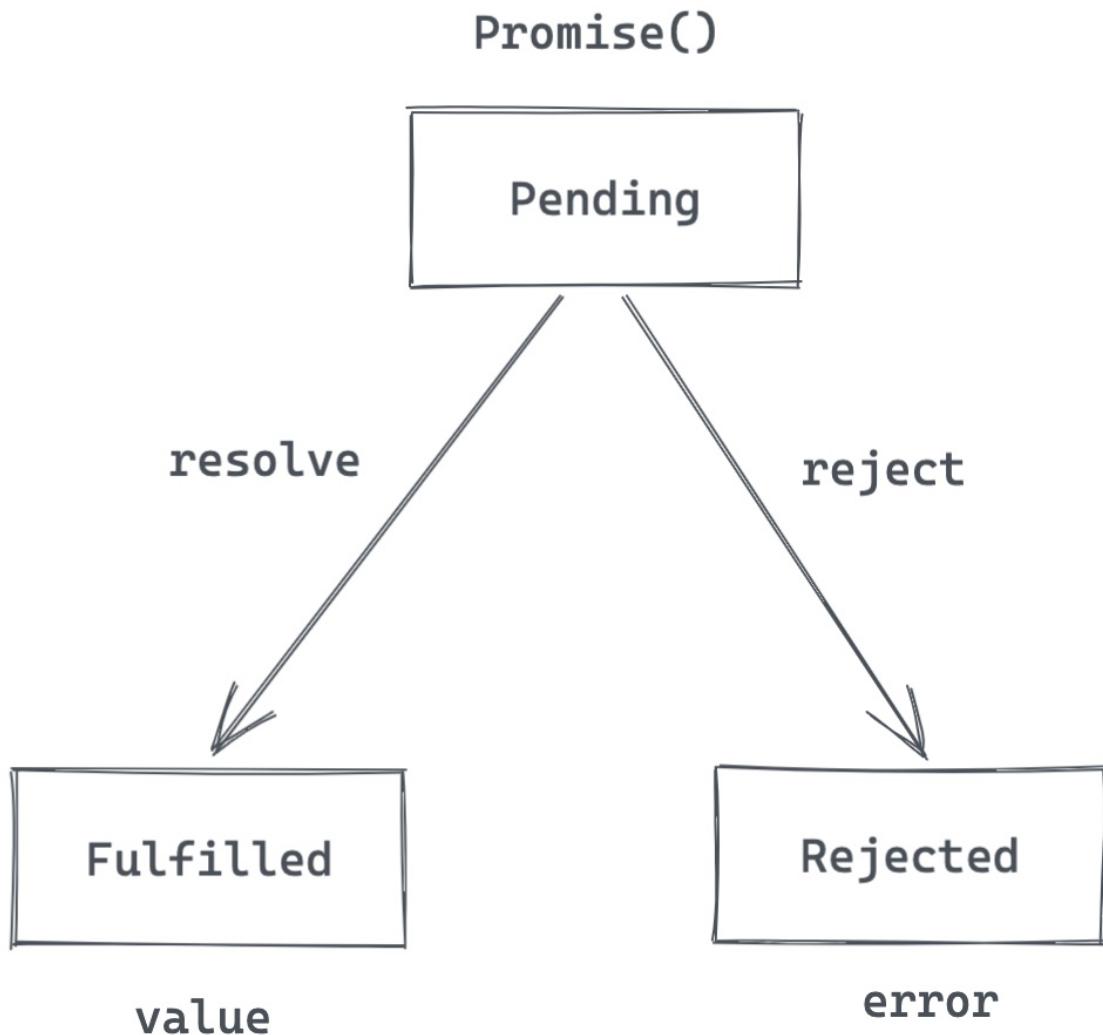
Javascript/Rust



# Callback

```
setTimer(200, () => {
  setTimer(100, () => {
    setTimer(50, () => {
      console.log("I'm the last one");
    });
  });
});
```

# Promise



```
function timer(ms) {
  return new Promise(
    (resolve) => setTimeout(resolve, ms)
  );
}

timer(200)
  .then(() => timer(100))
  .then(() => timer(50))
  .then(() => console.log("I'm the last one"));
```

# Async/Await

```
async function run() {
  await timer(200);
  await timer(100);
  await timer(50);
  console.log("I'm the last one");
}
```

# The Rust approach



# **Demo: writing a server in rust**

It uses [async-prost](#), tokio and prost

# One more thing...



# An event store example

```

pub fn start(&mut self) {
    for _ in 0..self.config.nthreads {
        let (tx, rx) = bounded(QUEUE_SIZE);
        let config = self.config.clone();
        thread::spawn(move || {
            // see code in blue
        });
        self.senders.push(tx);
    }
}

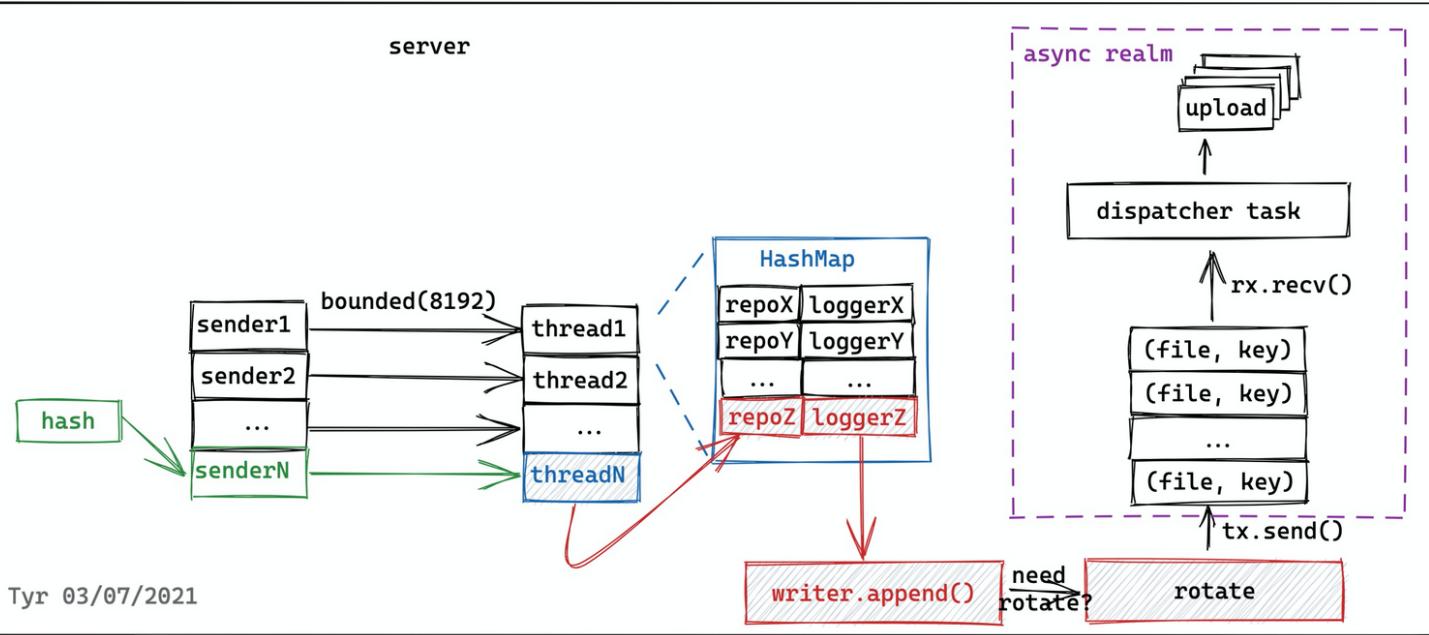
dispatch(repo_id)

```

```

pub fn dispatch(&self, entry: LogEntry<T>) {
    let mut hasher = AHasher::default();
    entry.repo_id.hash(&mut hasher);
    let thread = hasher.finish() as usize % self.config.nthreads as usize;
    self.senders[thread].send(entry).unwrap();
}

```



```

let mut repos: HashMap<Bytes, LoggerWriter> = HashMap::new();

loop {
    let entry: LogEntry<T> = rx.recv().unwrap();
    let repo_id = entry.repo_id.to_vec();
    let writer = repos
        .entry(entry.repo_id)
        .or_insert_with(|| &LoggerWriter::new(
            &repo_id,
            &config,
            Some(uploader_tx.clone())
        ).unwrap()
    );
    writer.append(&entry.msg).unwrap();
}

```

```

let cap = self.config.queue;
let (uploader_tx, mut uploader_rx) = mpsc::channel(cap as usize * 32);
let bucket = self.config.backup.bucket.clone();

let client = self.s3_client.clone();
self.rt.spawn(async move {
    loop {
        if let Some((filename, key)) = uploader_rx.recv().await {
            let bucket = bucket.clone();
            let client = client.clone();
            tokio::spawn(async move {
                let uploader = S3Writer::new(client.clone(), bucket);
                uploader.put_object(filename, key).await.unwrap();
            });
        }
    }
});

```

# References

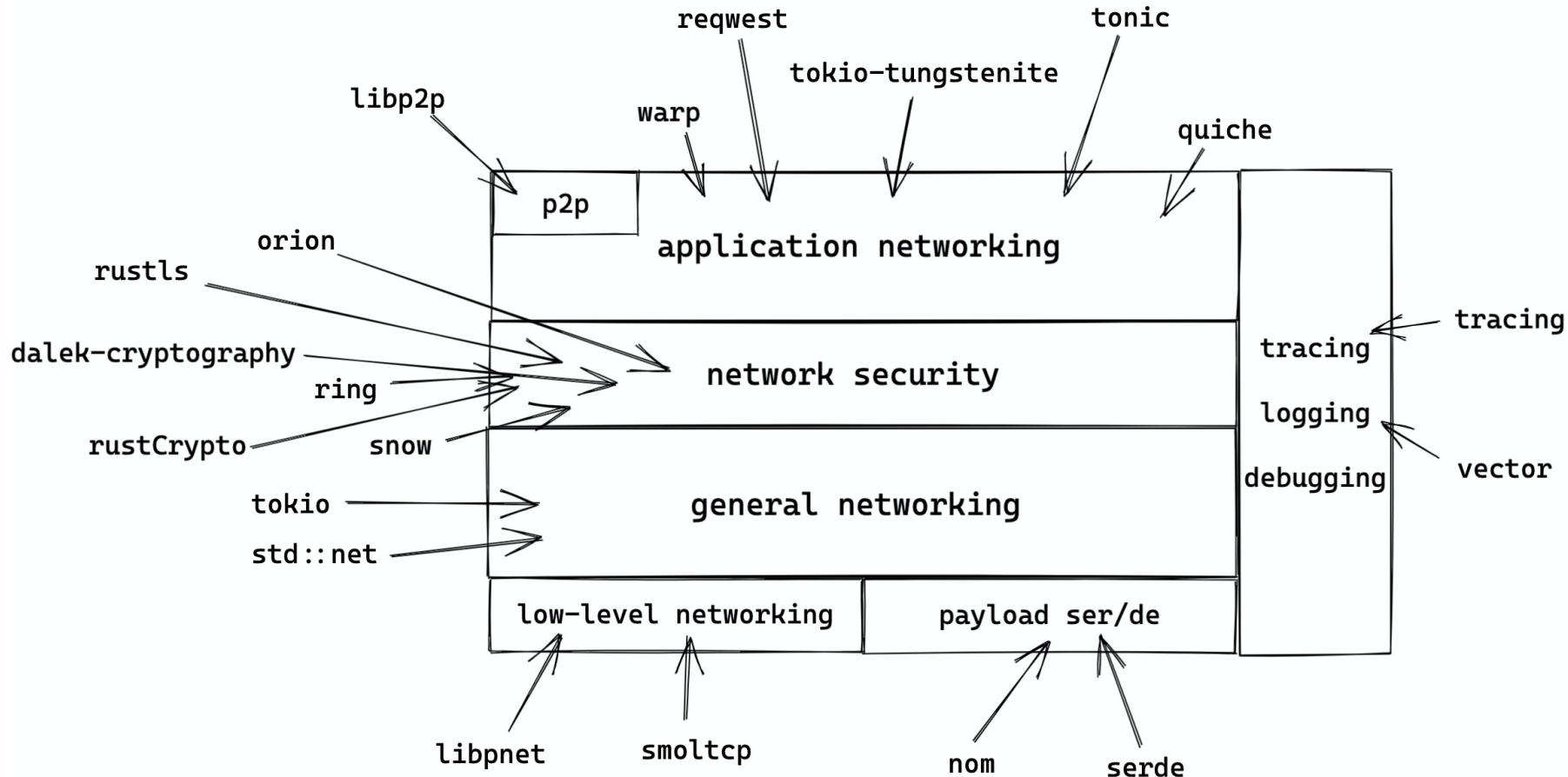
- Future explained
- Rust async book
- calloop: a callback based event loop

# **Networking and security**

# Network Stack



# Rust Network Stacks



# Demo: Build a TCP server (sync/async)

- deps: stdlib / tokio
- (figure tbd)

# Demo: HTTP Client/Server

- deps: reqwest / warp
- (figure tbd)

# Demo: gRPC

- deps: prost / tonic
- build script
- (figure tbd)

# Something more about gRPC

- Length-Prefixed-Message → Compressed-Flag Message-Length Message
- Compressed-Flag → 0 / 1 # encoded as 1 byte unsigned integer
- Message-Length → {length of Message} # encoded as 4 byte unsigned integer (big endian)
- Message → \*{binary octet}

# **Steps to write a server**

- data serialization: serde / protobuf / flatbuffer / capnp / etc.
- transport protocol: tcp / http / websocket / quic / etc.
- security layer: TLS / noise protocol / secio / etc.
- application layer: your own application logic

# **Network Security**

# References

- [<https://github.com/grpc/grpc/blob/master/doc/PROTOCOL-HTTP2.md>](GRPC Protocol)

# FFI with C/Elixir/Swift/Java

# WASM/WASI

# Rust for real-world problems

May the **Rust** be with you