

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

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Erlang/Elixir

- Approachability
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Python

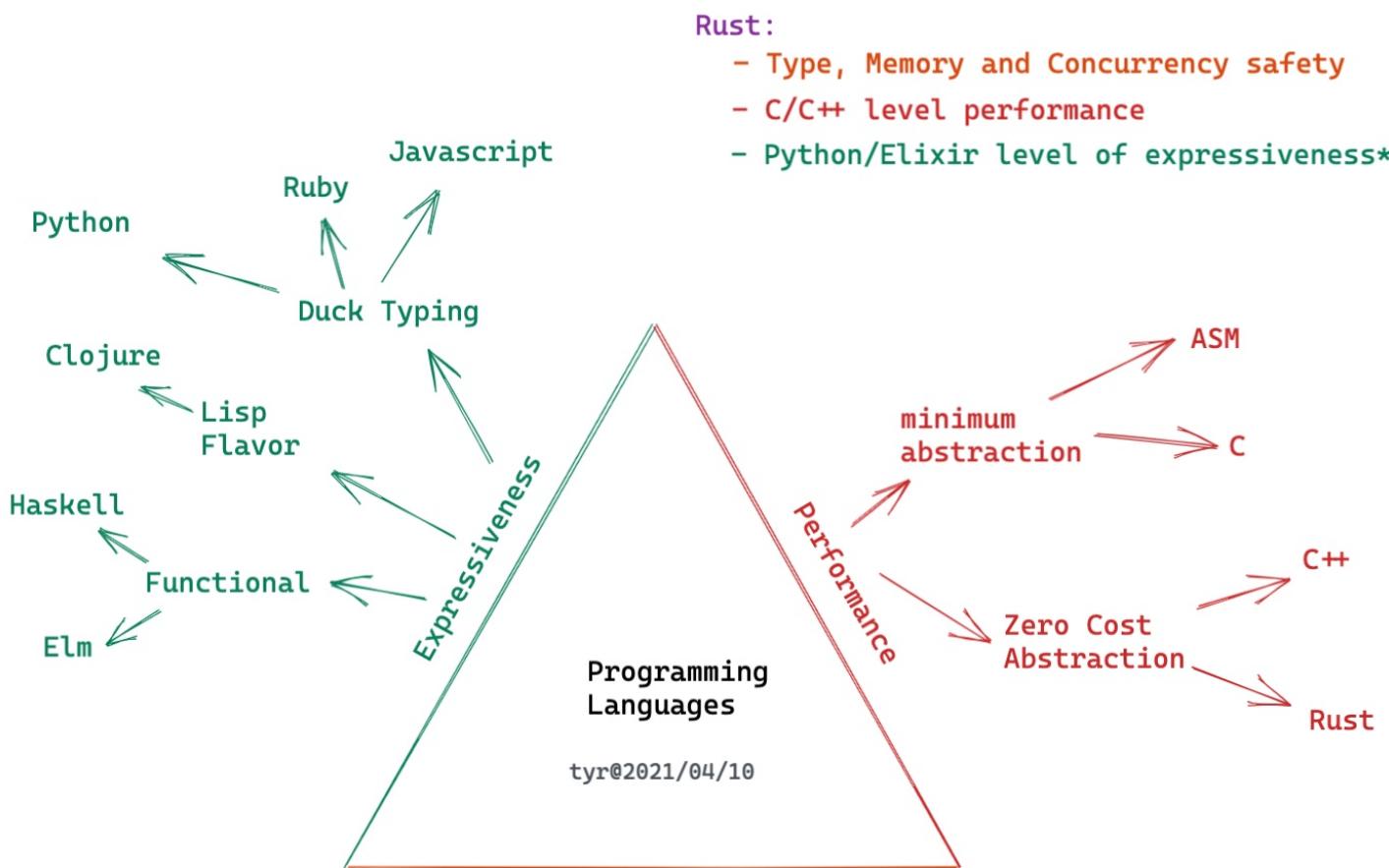
- **Approachability**
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- **Expressiveness**
- Extensibility
- Interoperability
- Integrity
- Maintainability
- Measurability
- Operability
- Performance
- Portability
- **Productivity**
- Resiliency
- Rigor
- Safety
- Security
- **Simplicity**
- Stability
- 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
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- Compatibility
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- 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

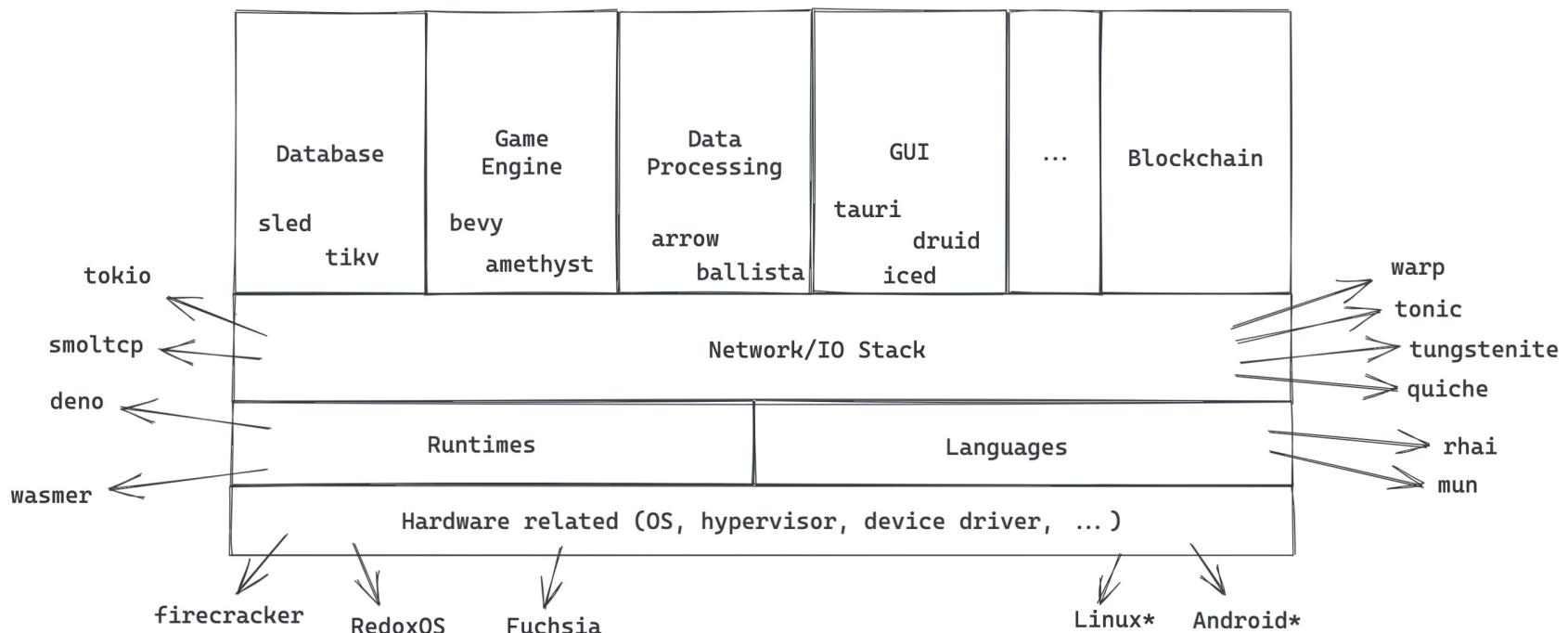
```
enum State {  
    Init,  
    SynSent(ConnState),  
    SynReceived(ConnState),  
    Done(Connection),  
}  
  
struct ConnState {  
    ...  
}  
  
struct Connection {  
    ...  
}
```

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+NqChBZD0s5MgefHJSIWirthXMBIGA1UDewEB/wQIMAYBaF8C
13 ARAwDwYDVR0PAQH/BAUDAwcGADAFBgMrZXADQQA9sIgQcYGaBqTxR1+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 dDATBgnVHSUEDDAKBgggrBqEFBQcDATAMBgnVHRMEBTADAQEA8GA1UdDwEB/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



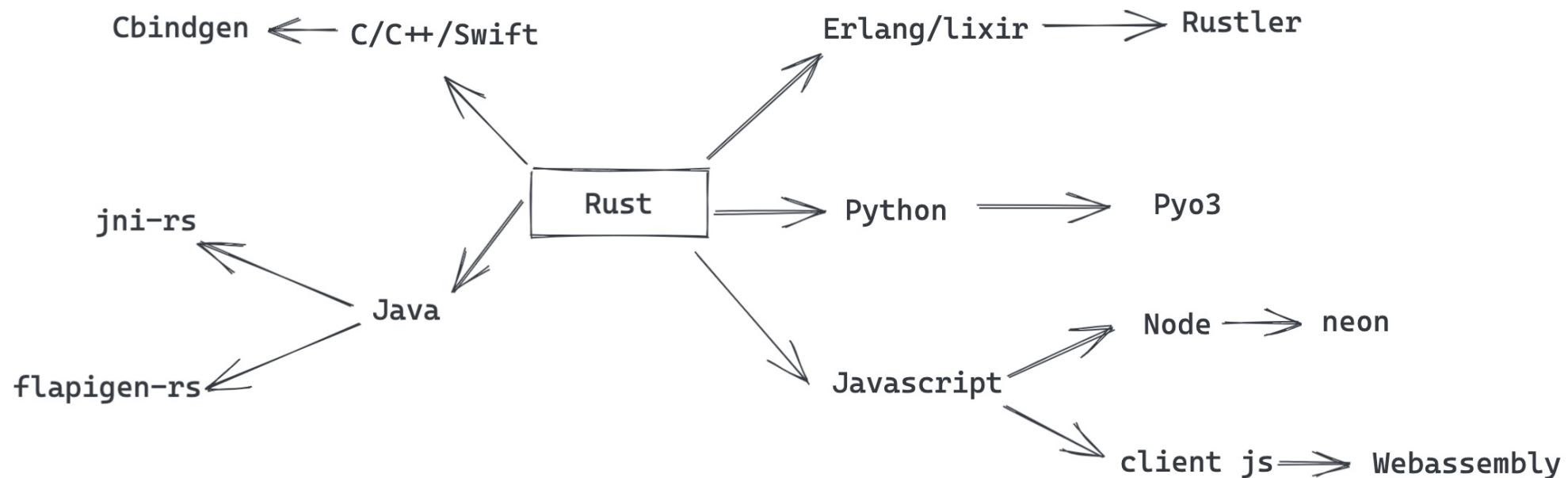
Should I use Rust?

- 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 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)

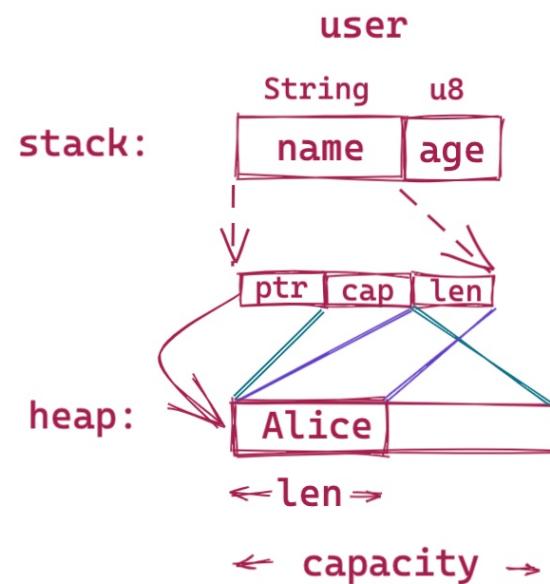


Lifetime: Heap memory (ARC)

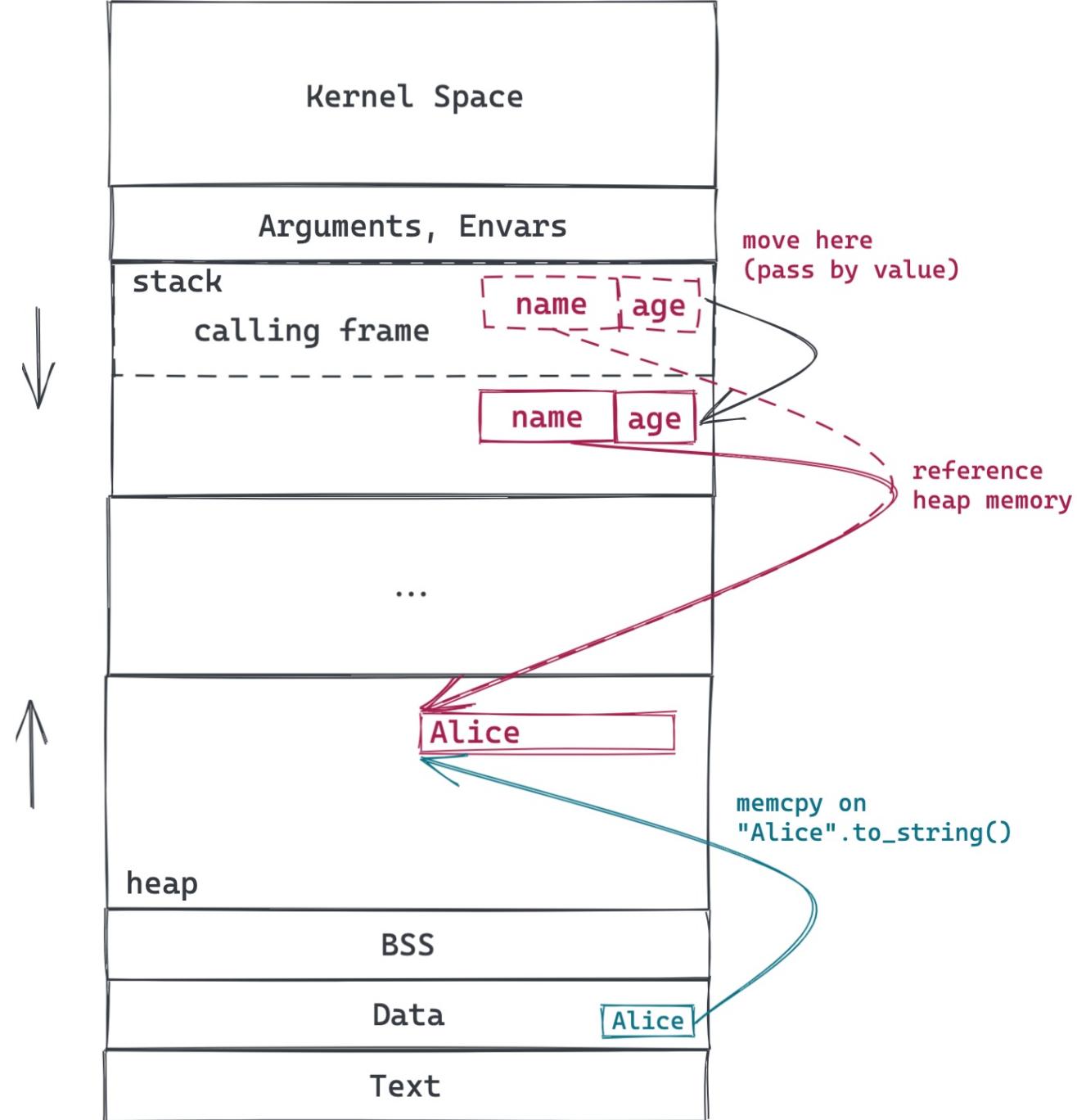


How Rust handles lifetime?

Move semantics



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

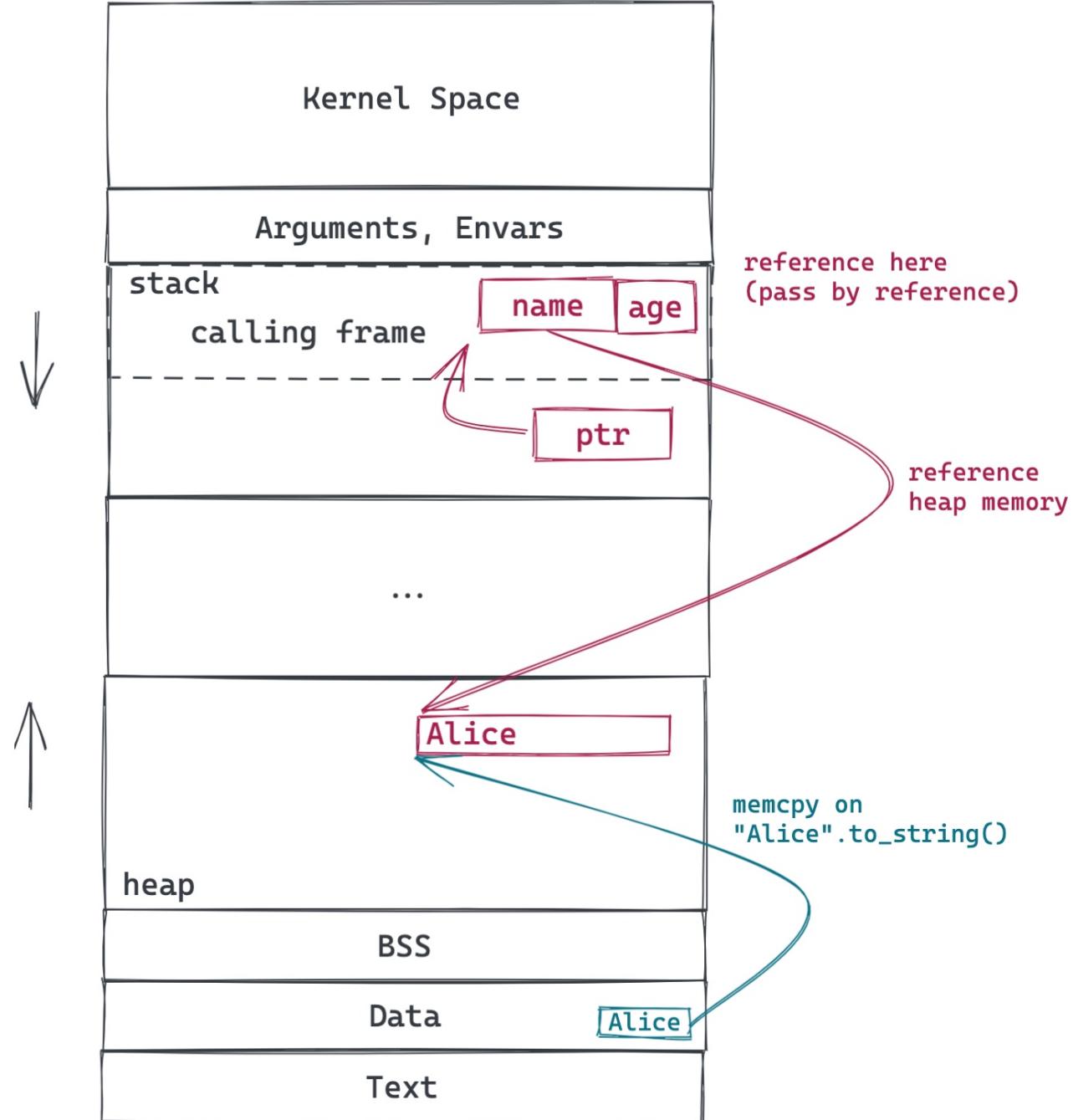


What about Borrow?

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



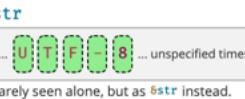
u128, i128



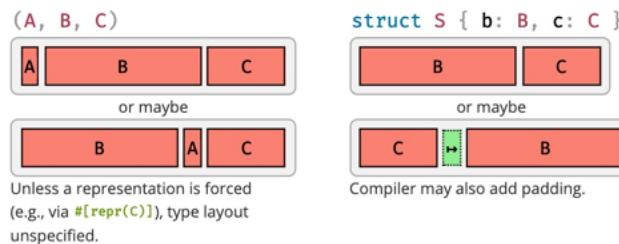
f32



Textual Types REF

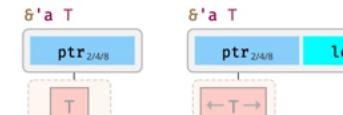


Rarely seen alone, but as &str instead.

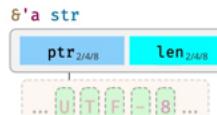
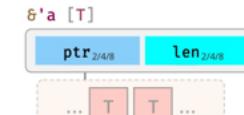


Pointer Meta

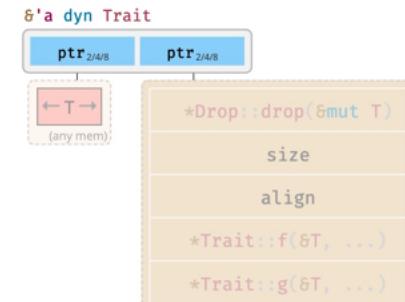
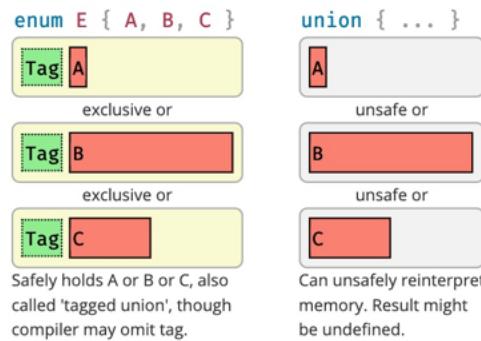
Many reference and pointer types can carry an extra field, **pointer metadata**. STD It can be the element- or byte-length of the target, or a pointer to a *vtable*. Pointers with meta are called **fat**, otherwise **thin**.



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

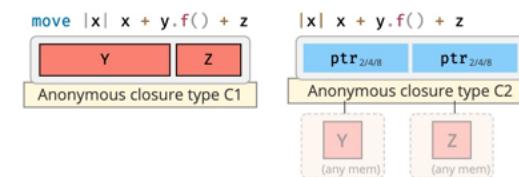


These **sum types** hold a value of one of their sub types:

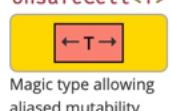


Closures

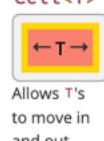
Ad-hoc functions with an automatically managed data block capturing REF environment where closure was defined. For example:



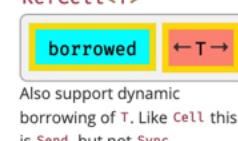
UnsafeCell<T>



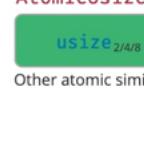
Cell<T>



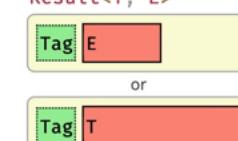
RefCell<T>



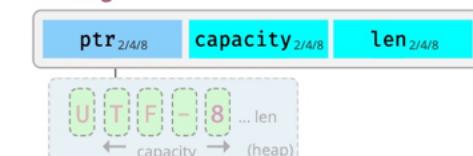
AtomicUsize



Result<T, E>

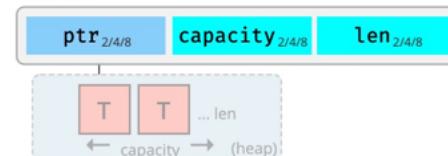


String



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<T></code>	A generic <small>BK EX</small> type with a type parameter (<code>T</code> is placeholder name here).
<code>S<T: R></code>	Type short hand trait bound <small>BK EX</small> specification (<code>R</code> <i>must</i> be actual trait).
<code>T: R, P: S</code>	Independent trait bounds (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>	Compound trait bound <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 lifetime bound <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<const N: usize></code>	Generic const bound ; ? user of type <code>S</code> can provide constant value <code>N</code> . <small>⌘</small>
<code>S<10></code>	Where used, const bounds can be provided as primitive values.
<code>S<{5+5}></code>	Expressions must be put in curly brackets.
<code>S<T> where T: R</code>	Almost same as <code>S<T: R></code> but more pleasant to read for longer bounds.
<code>S<T> where u8: R<T></code>	Also allows you to make conditional statements involving <i>other</i> types.
<code>S<T = R></code>	Default type parameter <small>BK</small> for associated type.
<code>S<'_></code>	Inferred anonymous lifetime ; asks compiler to ' <i>figure it out</i> ' if obvious.
<code>S<_></code>	Inferred anonymous type , e.g., as <code>let x: Vec<_> = iter.collect()</code>
<code>S:::<T></code>	Turbofish <small>STD</small> call site type disambiguation, e.g. <code>f:::<u32>()</code> .
<code>trait T<X> {}</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 associated type <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<T> S<T> {}</code>	Implement functionality for any <code>T</code> in <code>S<T></code> , here <code>T</code> type parameter.
<code>impl S<T> {}</code>	Implement functionality for exactly <code>S<T></code> , here <code>T</code> specific type (e.g., <code>S<u32></code>).
<code>fn f() -> impl T</code>	Existential types , <small>BK</small> returns an unknown-to-caller <code>S</code> that <code>impl T</code> .
<code>fn f(x: &impl T)</code>	Trait bound, "impl traits", <small>BK</small> somewhat similar to <code>fn f<S:T>(x: &S)</code> .
<code>fn f(x: &dyn T)</code>	Marker for dynamic dispatch , <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<'a></code>	Higher-ranked trait bounds . <small>NOM REF ⚡</small>
<code>trait T: for<'a> R<'a> {}</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

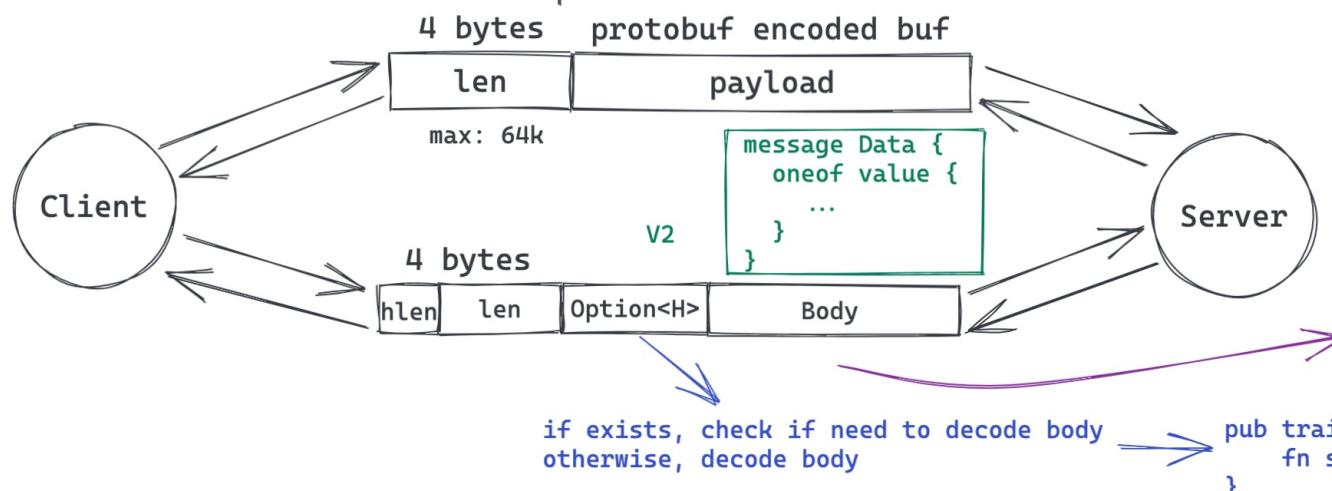
last
next(f)
distance(f, l) / 2;

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
```

```
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

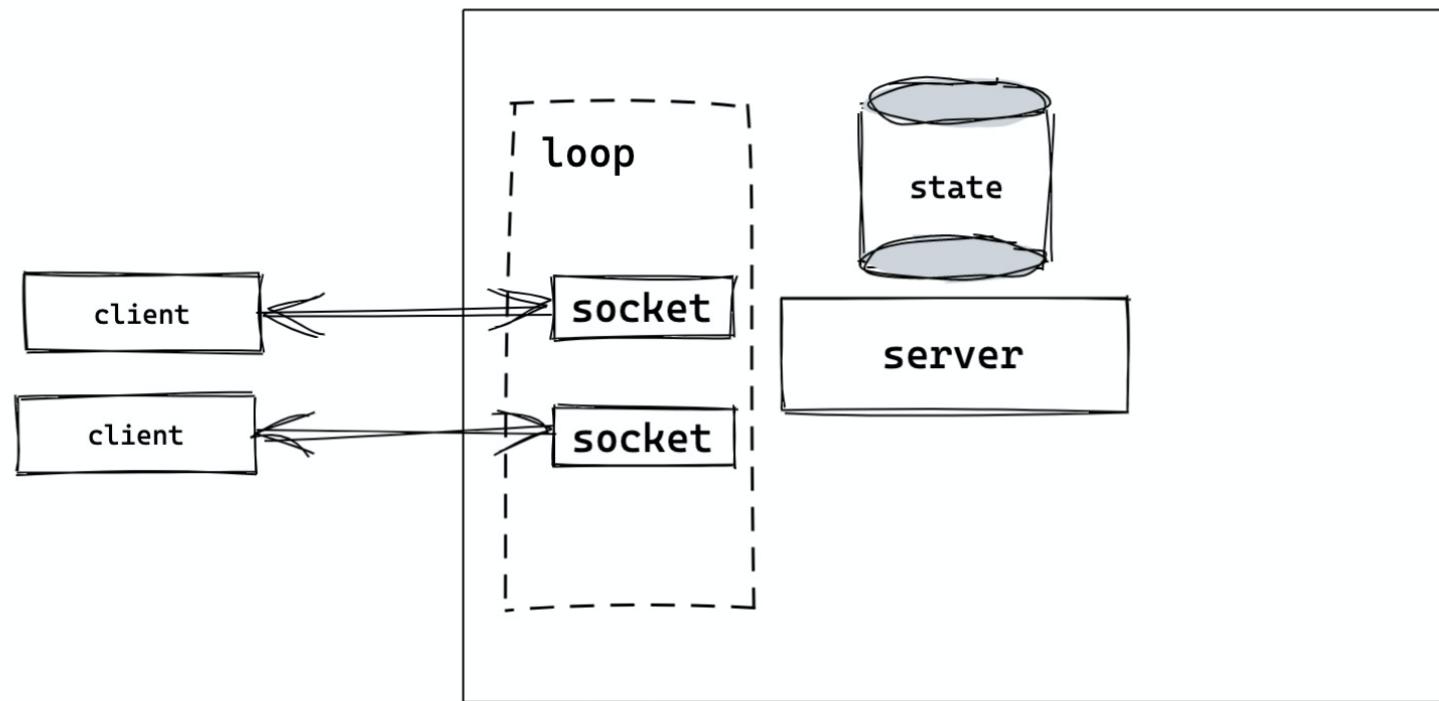
Class has problems

- 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



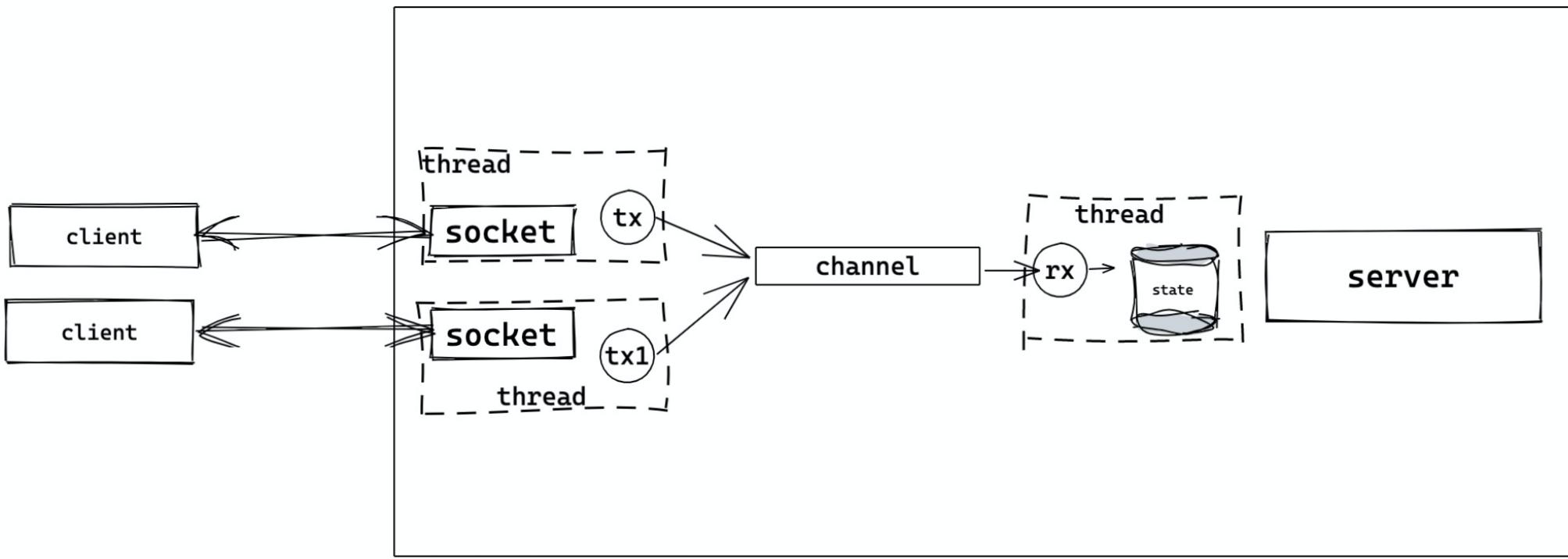
v2: Multithread with shared state



v3: Optimize the lock



v4: Share memory by communicating



v5: Async Task



What have we used so far?

- Mutex Lock
- Channel
- 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
- 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
- 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`

Networking and security

FFI with C/Elixir/Swift/Java

WASM/WASI

Rust for real-world problems

May the **Rust** be with you