

程序君的 Rust 培训课

- Rust 初体验
- 所有权，借用检查，以及生命周期
- 类型系统和泛型编程
- 并发 - 原语
- 并发 - `async/await`

培训中用到的工具

- Rust 1.52 (Rustup 安装)
- Rust search extension
- VSCode + rust analyzer
- Excalidraw

Rust 初体验



为什么要有 Rust?

Rust 解决什么问题？给我们带来什么好处？

我们看看编程语言的 trade off

- 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
- Operability
- **Performance**
- Portability
- Productivity
- Resiliency
- Rigor
- Safety
- Security
- **Simplicity**
- Stability
- 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



为什么语言安全性如此重要？

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

在编程语言级别达到安全性很困难！

- 内存安全并不容易（有很多 corner case）
- 并发安全非常困难（除非做很多妥协）
- 额外的抽象层级（意味着大量性能损失）

如何实现内存安全？

- 人工管理 - C/C++，很痛苦，容易出错
- 智能指针 - C++/ObjC/Swift：性能损失，循环引用问题
- GC - Java/DotNet/Erlang：大量的内存消耗，不必要的堆内存分配，以及（潜在的）STW
- Ownership - Rust：范式转换（paradigm shift），学习曲线

如何实现并发安全？

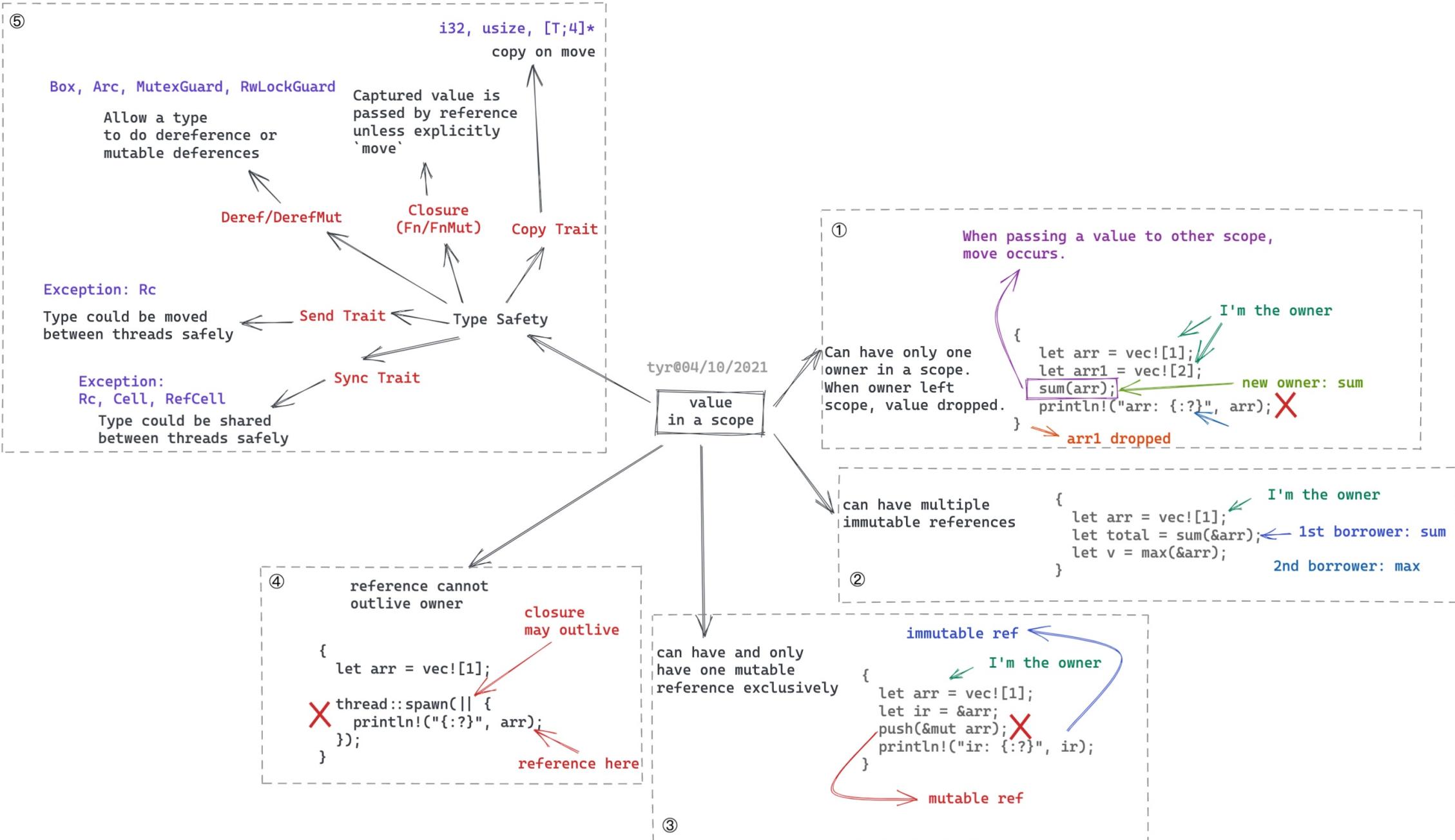
- 单线程 - javascript
 - 最安全的并发是单线程并发
 - 无法有效利用多核
- GIL - Python/Ruby
 - 一把大锁牺牲性能，换来安全
 - 锁粒度太大
- Actor model - Erlang/Akka
 - 通过消息同步 (actor -> actor)
- 额外内存拷贝和堆内存分配
- CSP - Golang
 - 通过消息同步 (coroutine -> channel -> coroutine)
 - 额外内存拷贝和堆内存分配
- Ownership + Type System - Rust
 - 用类型安全来保证并发安全
 - 优雅，无性能损失，且和其它方案无缝兼容

Rust 如何实现 内存安全 和 并发安全？

并且不引入 额外开销？

我们从最基本的语法单元 – 值 说起

Live coding



更多代码示例

```
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.

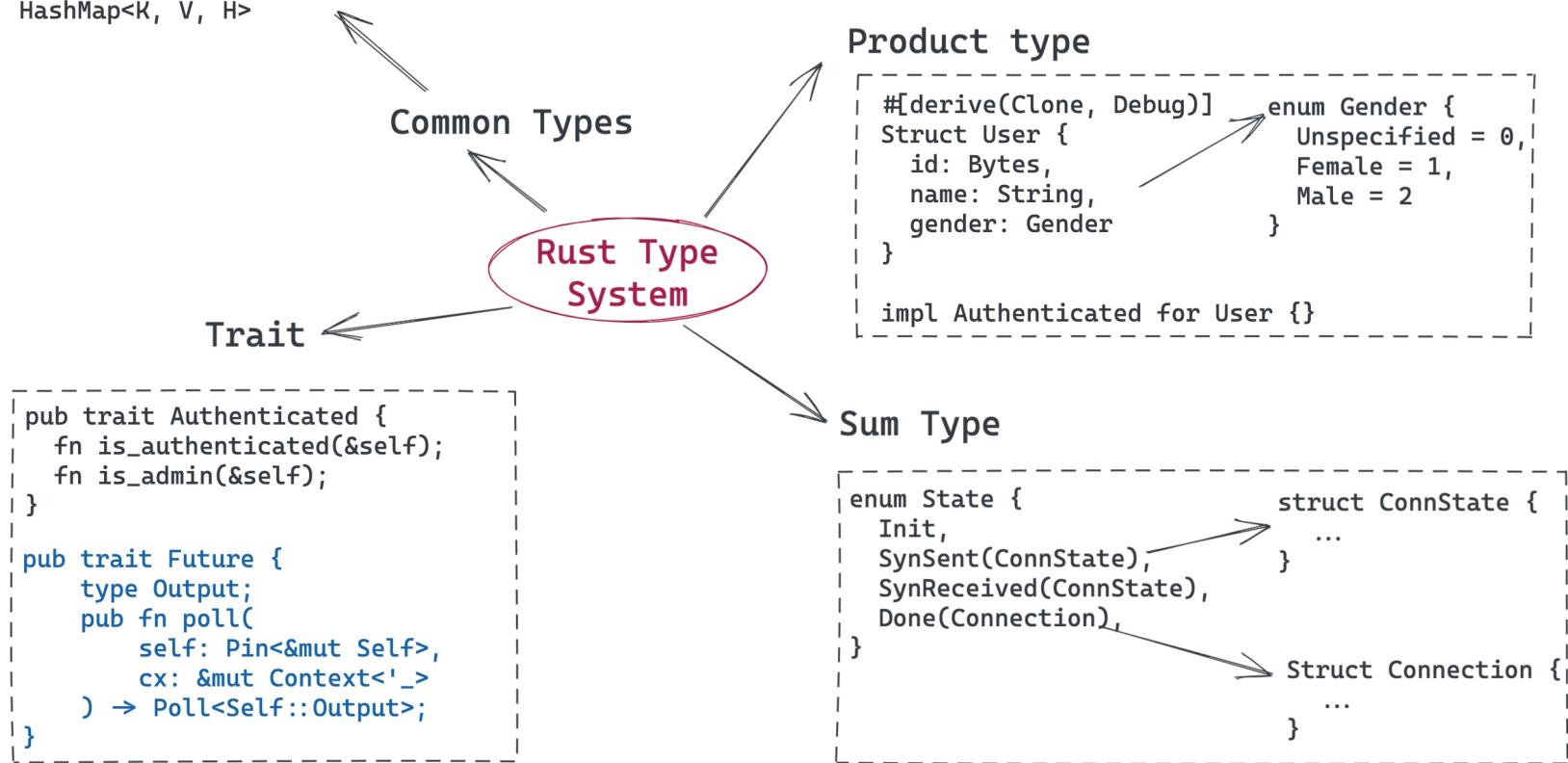
回顾

- 在一个 scope 中
 - 一个值只有一个所有者
 - 但可以有多个不可变引用
 - 以及唯一的可变引用 (mutual exclusive)
 - 引用的生命周期不能超过值的生命周期
- 在多线程环境下
 - 类型安全 (Send / Sync) 保证并发安全

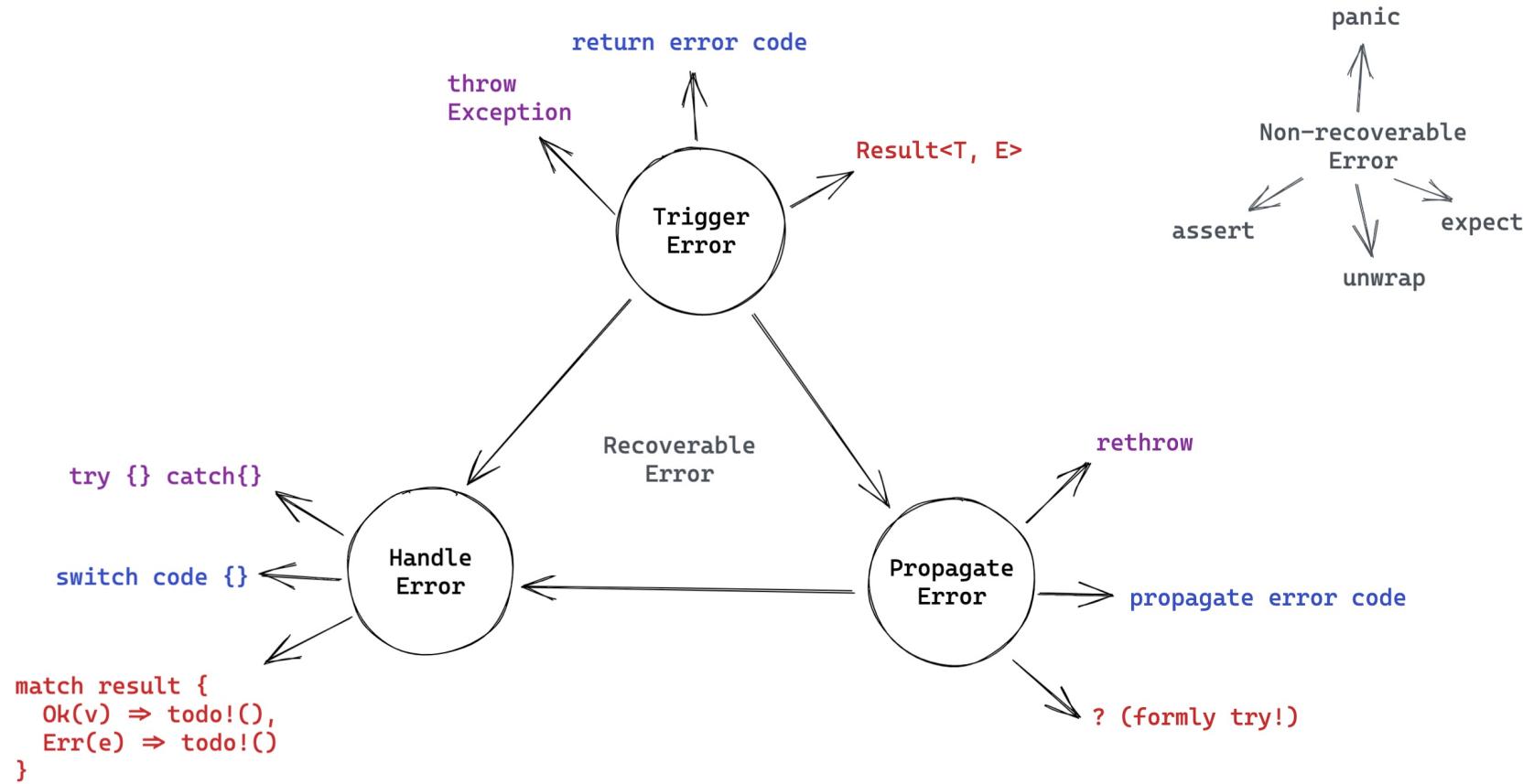
使用这些简单的规则，Rust 实现了 **零成本抽象** 的安全

类型系统

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



错误处理



Live coding: 用文件持久化数据结构

思考：如何在内存和 IO 设备间交换数据？

Rust 开发的效率如何？

```
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  ````
```

Rust 可以用来自做什么？



Rust 和其它语言的互操作

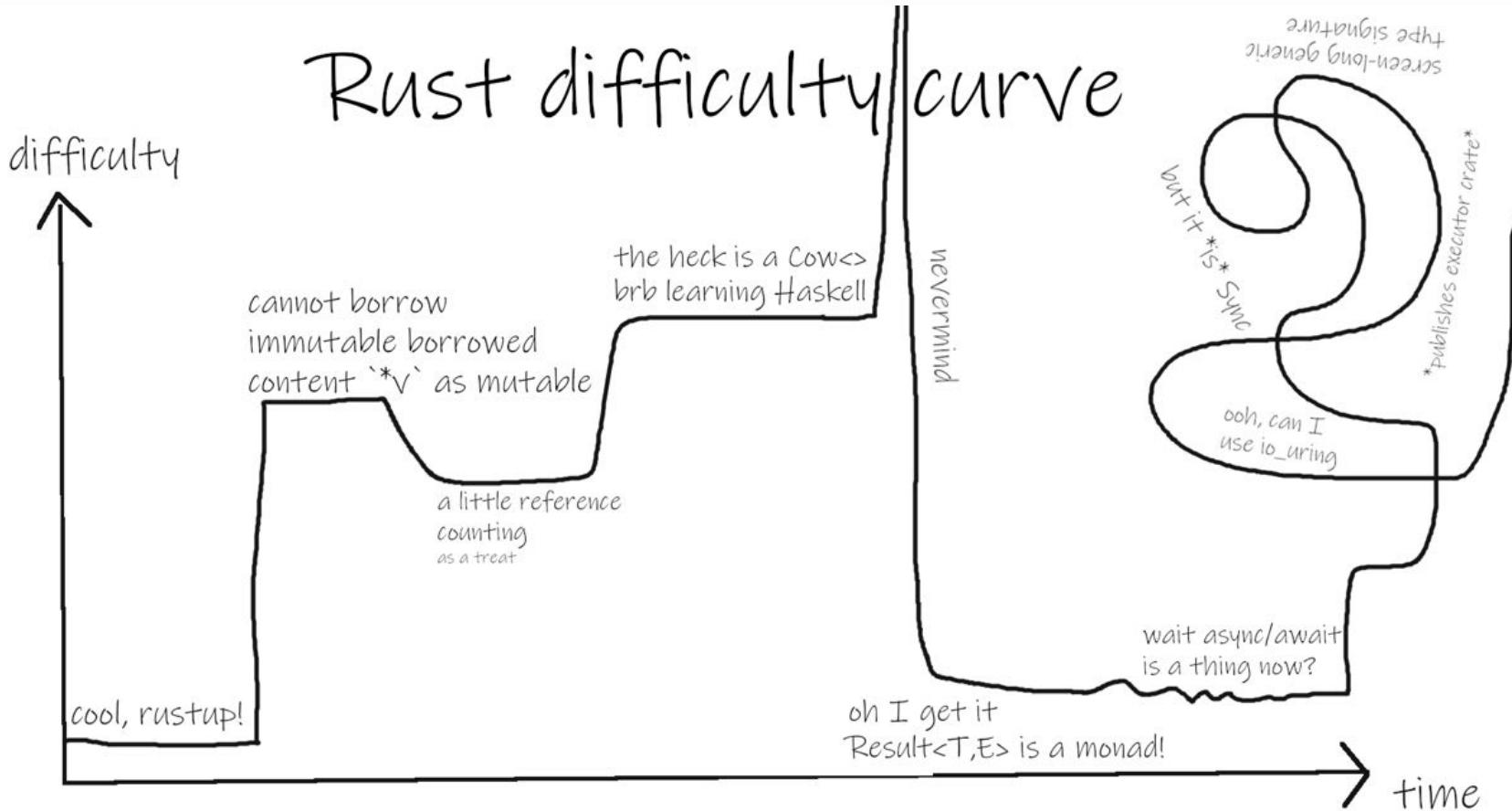


我是个 xyz 程序员，学 Rust 该注意什么？

- Erlang/Elixir: 所有权，类型系统，可变性
- Java/Swift/Scala: 所有权
- Typescript: 所有权，多线程编程
- Python: 所有权，类型系统，并发处理

学习 Rust 的误区...

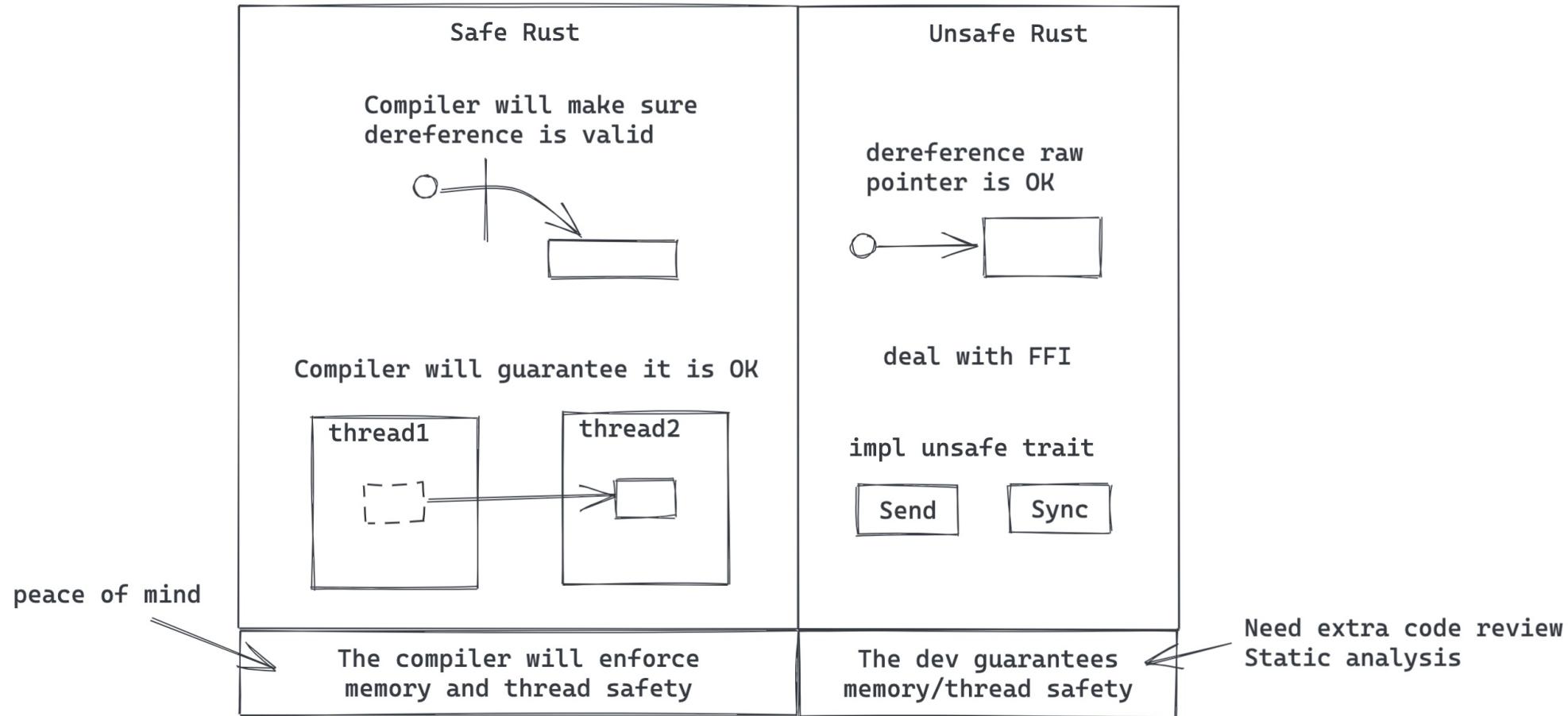
1. Rust 非常难学?



非也，Rust 就是想跟你处得明明白白

- 范式转移 (Paradigm Shift)
- 大量计算机体系结构操作系统相关的知识一下子扑鼻而来
- 如果学习一门语言的痛苦是 100%：
 - Rust：
 - 编译器帮你降低了 10% 的痛苦
 - 然而你需要在头 3-6 个月承受剩下 70% 的痛苦
 - 在接下来 3-5 年承受最后 20% 的痛苦
 - 其它语言：
 - 头 3-6 个月，你只需要承受 10-30% 的痛苦
 - 之后的 3-5 年你可以慢慢承受 70-90% 的痛苦

2. Unsafe Rust 听上去好可怕！



参考资料

- 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

所有权，借用检查，以及生命周期

再探所有权和借用检查



生命周期 (Lifetime) 并非新概念

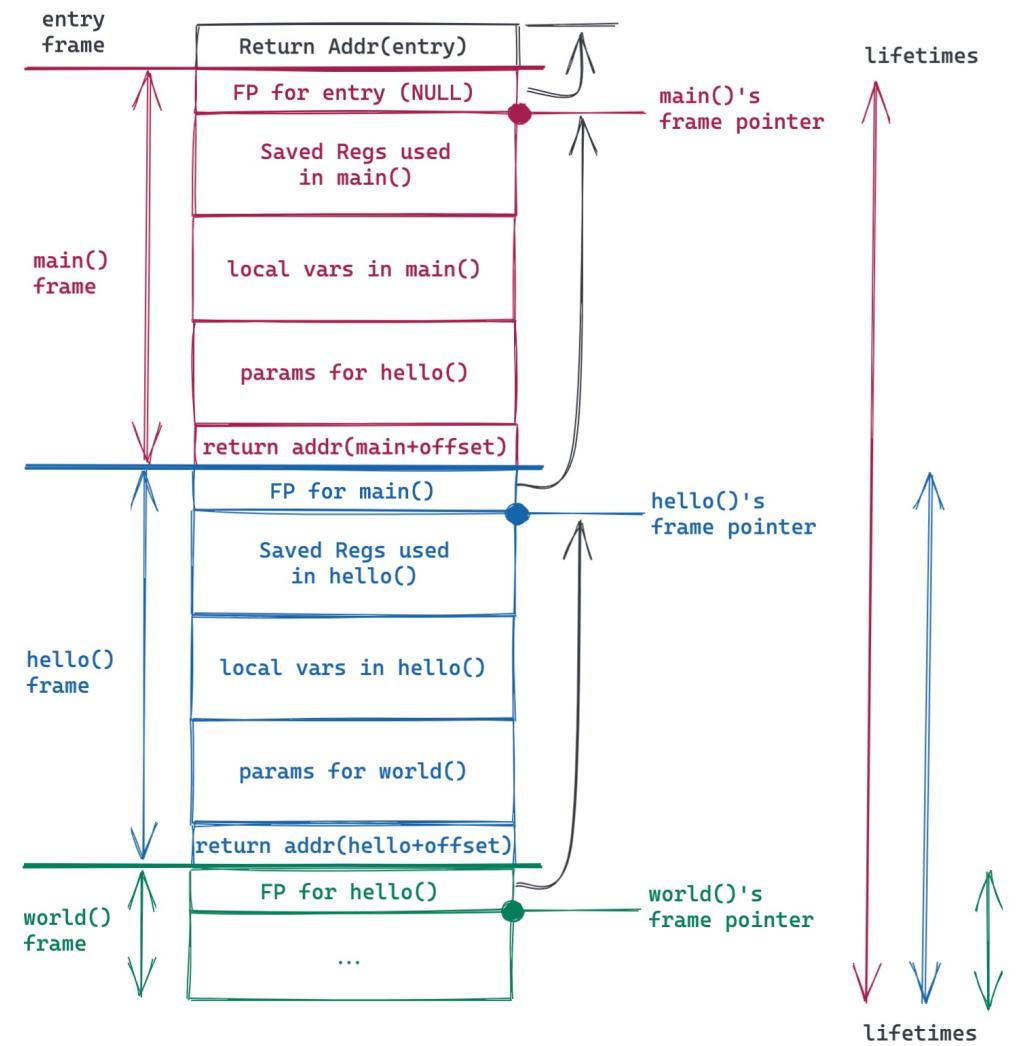
栈内存的生命周期管理

```
#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);
}
```



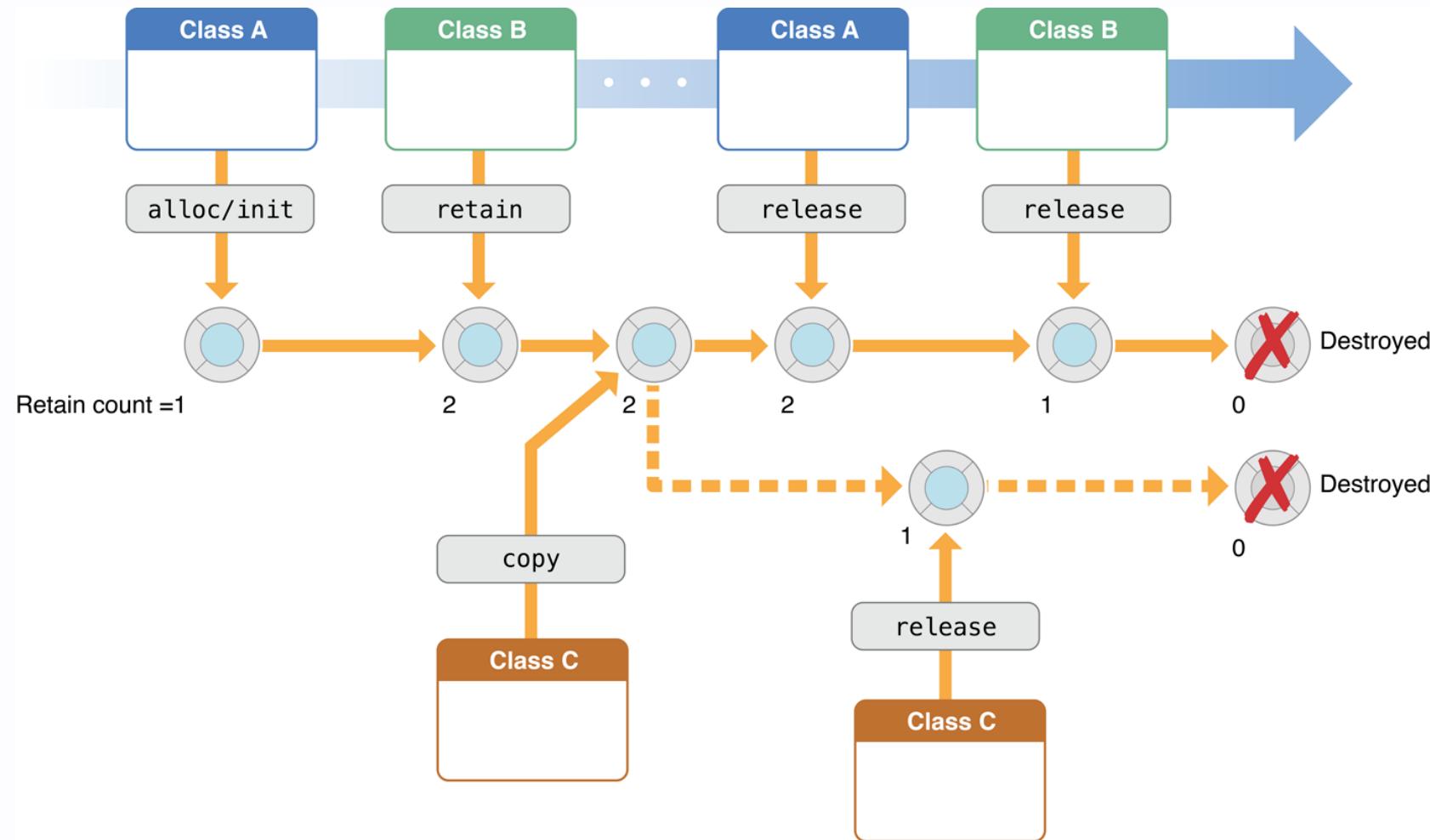
堆内存的生命周期管理

手工管理, GC, ARC, ...

Tracing GC



ARC



Rust 如何打破常规？

Rust 并非独创，它继承了 C++ 和 Cyclone 的很多研究

Move 语义：保证有且只有一个 owner



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

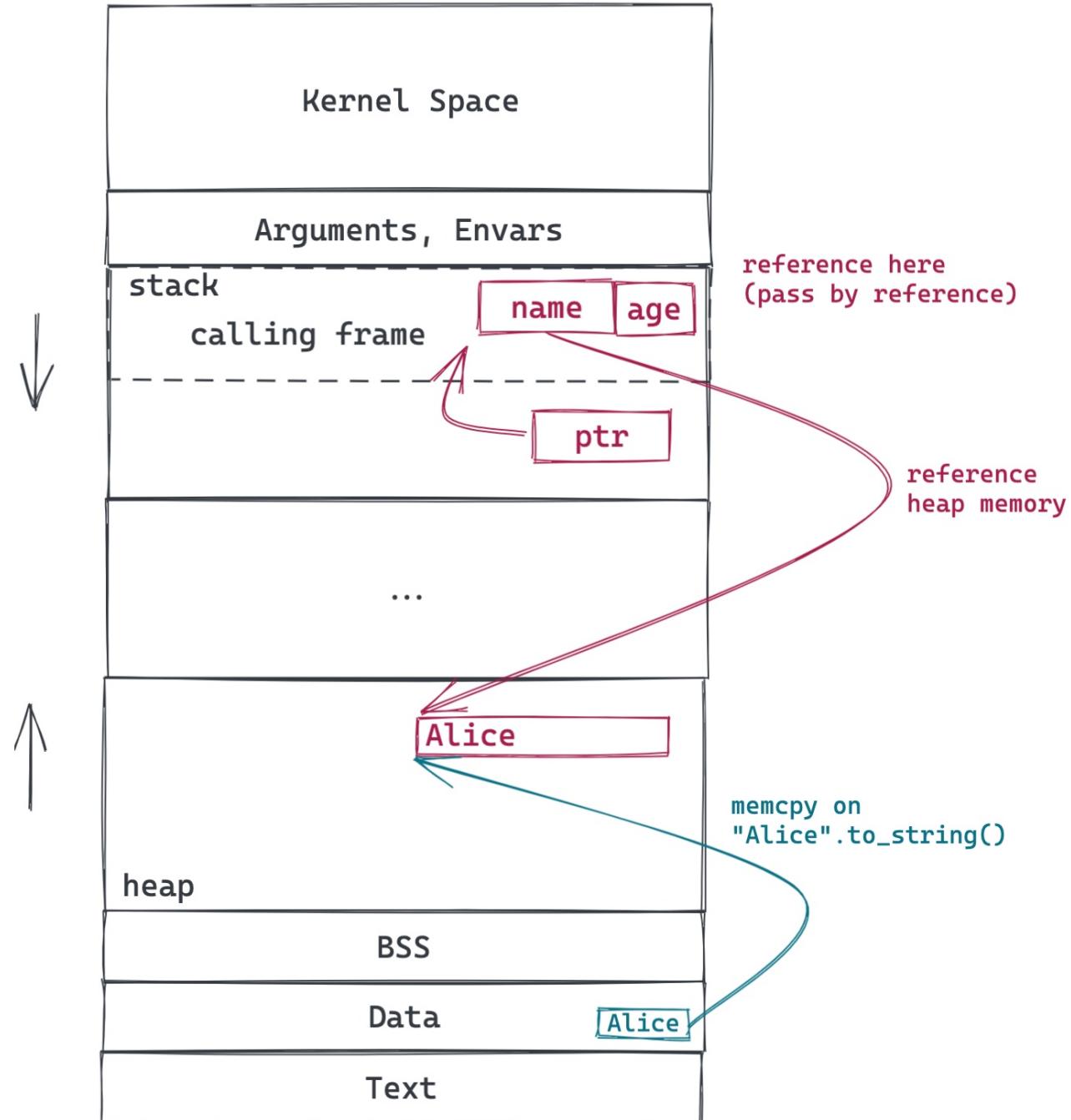


Borrow 语义：共享下的线程安全

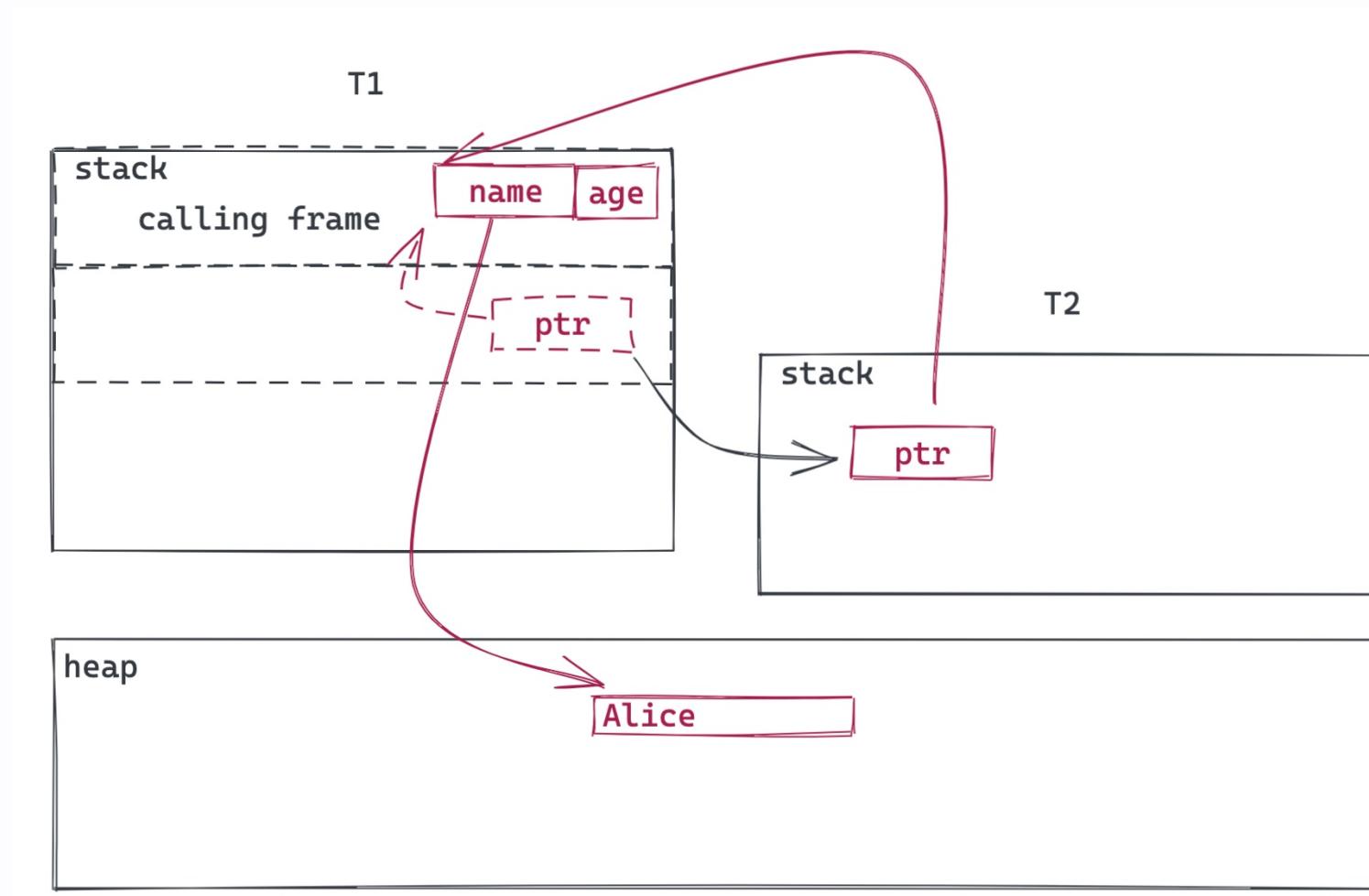
思考题：为什么同样使用了引用，在 Rust 可以保证线程安全，而 C++ 不行？



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



Rust 生命周期检查器如何避免有问题的引用？



带生命周期限制的借用

- 可以借用任何值（栈内存，堆内存）
- 编译期检查（不需要耗费运行期的 CPU）
- Rust 借用检查器基本上是个生命周期检查器

我们如何告诉编译器生命周期？

- 类似泛型，但有其专用符号 '`'`
- 只有生命周期无法被推断出来，才需要声明

```
// 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 on confliction
fn lifetime_example(user: &User) { // --- Lifetime 'a
    if user.is_authed() {           //   |--- Lifetime 'b
        let role = user.roles();    //   |   |
                                    //   |   |--- Lifetime 'c
        verify(&role);             //   |   |
                                    //   |   |
                                    //   |---+
    }
}
fn verify(x: &Role) { /*...*/ }
```

Live coding: strtok

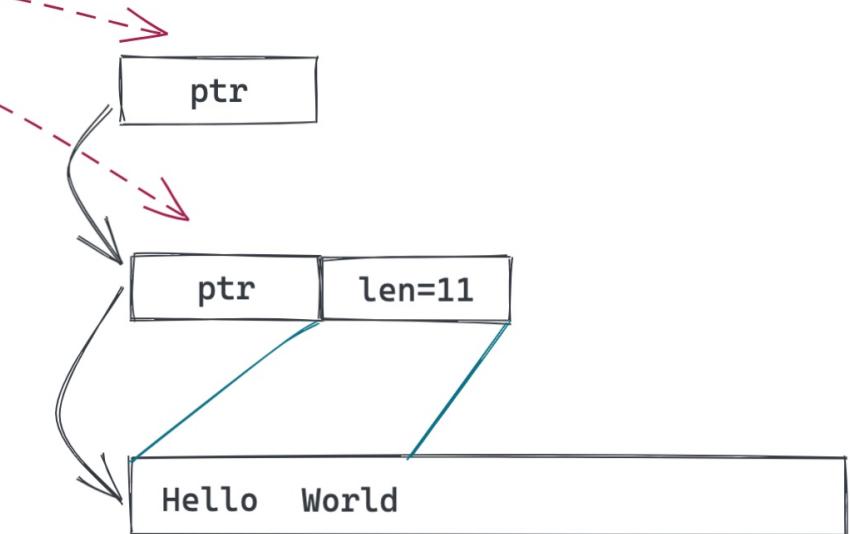
one of 'a can be omitted

```

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");
}

```



Static Lifetime

- `'static`
- 在 bss / data / text section 中的数据
 - constants / static variables
 - string literals
 - functions
- 如果在类型的 trait bound 中使用:
 - 类型不包含任何非静态的引用 (non-static references)
- 有所有权的数据的 lifetime bound 是 `'static`，引用数据不是

我们再回头看： 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")
}
```

这里 `'static lifetime bound` 是说：`F` 不能使用任何借用的数据

RAII (Resource Acquisition Is Initialization)

- 对象的初始化会保证资源的初始化
- 对象的释放会保证资源的释放

Drop Trait

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

RAII live coding: 博物馆门票

疫情期间，博物馆内限流最大容量 50 人，满了之后，出来一个才能进一个，怎么设计？

总结：Cost of defects

- 代码中不引入任何缺陷（只要是人，就无法避免错误）
- 在敲入代码的时候就能被清晰地告知代码中的缺陷（发现问题时间：毫秒级）
- 在编译或者单元测试时发现（秒级/分钟级）
- 代码被 push 到 PR 中，CI 发现错误（分钟级/天级）
- 别人 review 你的代码时发现问题（小时级/天级）
- 代码 merge 到 master，更严格的 CI（比如 end-to-end test）发现错误（小时级/天级）
- 代码被部署后回归测试发现问题（天/周/月）
- 代码被部署后很久用户发现问题（周/月/年）

参考资料

- [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 \(recommended\)](#)

类型系统和泛型编程

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



数据结构在内存中是如何排布的？



Numeric Types REF



u128, i128

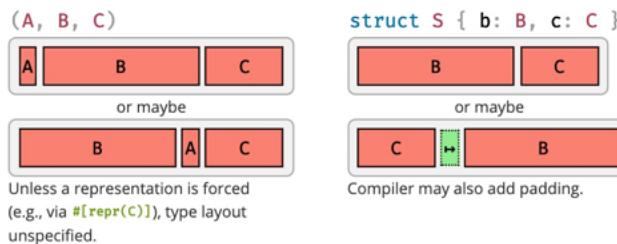
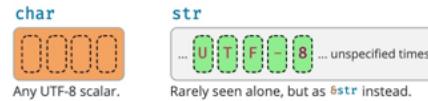


f32



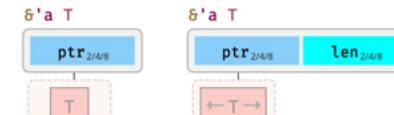
Textual Types REF

char

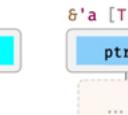


Pointer Meta

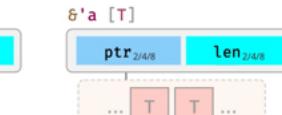
Many reference and pointer types can carry an extra field, **pointer metadata**. STD It can be the element- or byte-length of the target, or a pointer to a *vtable*. Pointers with meta are called **fat**, otherwise **thin**.



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.

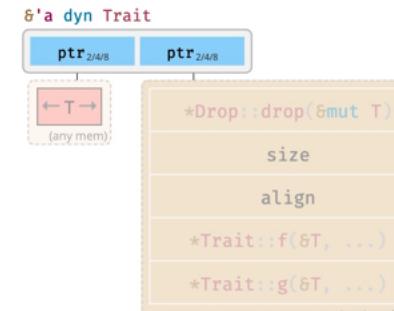
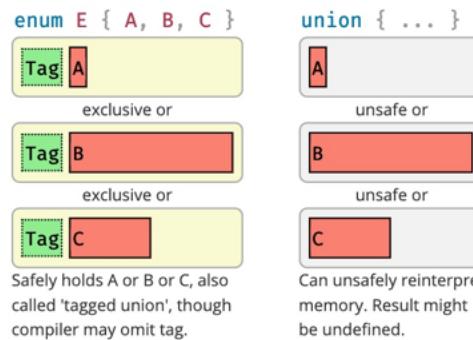


Regular slice reference (i.e., the reference type of a slice type [T])[†] often seen as &[T] if 'a elided.

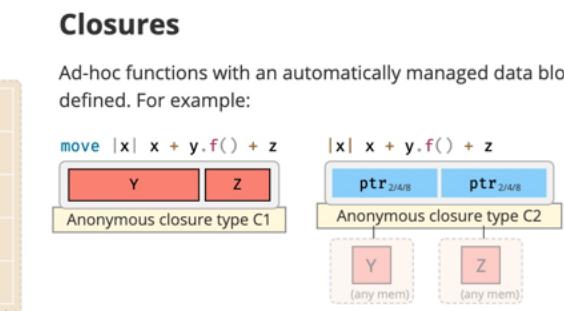


String slice reference (i.e., the reference type of string type str), with meta len being byte length.

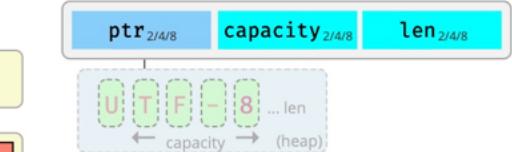
These **sum types** hold a value of one of their sub types:



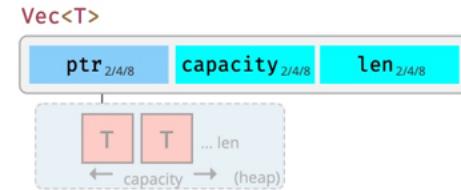
Meta points to vtable, where *Drop::drop(), *Trait::f(), ... are pointers to their respective



String



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



UnsafeCell<T>

Magic type allowing aliased mutability.

Cell<T>

Allows T's to move in and out.

RefCell<T>

Also support dynamic borrowing of T. Like Cell this is Send, but not Sync.

AtomicUsize

usize 2/4/8
Other atomic similarly.

Result<T, E>

Tag E
or
Tag 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(())
    }
}
```

Live coding: Fibonacci 遍历器

```

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

- 你无法直接把值赋给 trait
 - 不像 java, Rust 没有隐式引用
- trait object 是胖指针 (自动生成)
 - `ptr`: 指向数据的指针
 - `vptr`: 指向 `vtable` 的指针
- 动态分发

```
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)

Generics 之于 **Types**

就像

Types 之于 **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](#)

Live coding: Event encoder

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>,
}
```

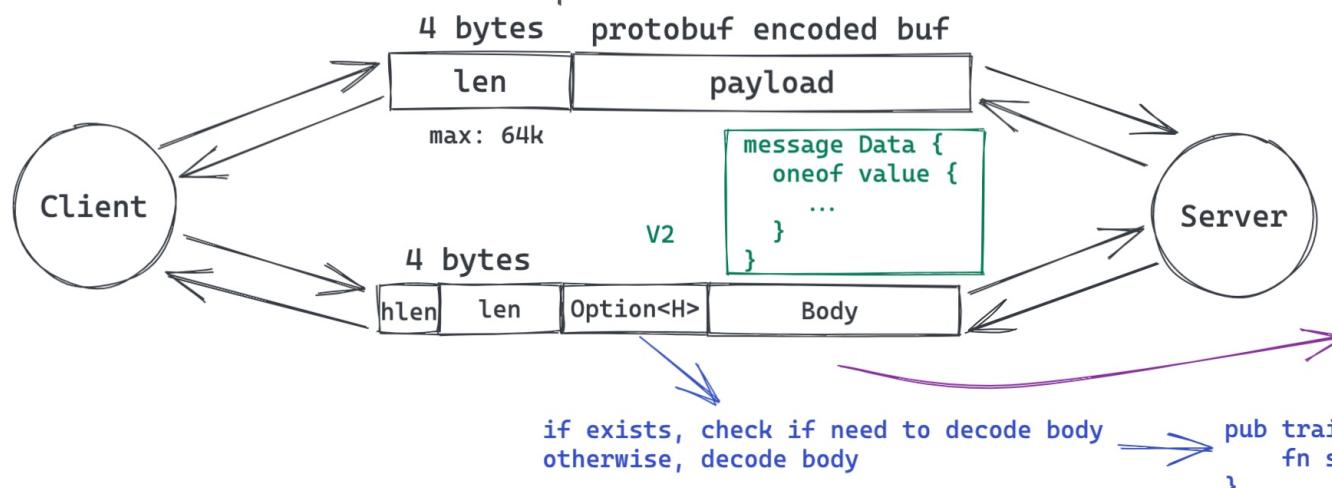
```
pub struct AsyncProstReader<R, T, D> {
    reader: R,
    pub(crate) buffer: BytesMut,
    into: PhantomData<T>,
    dest: PhantomData<D>,
}
```

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 ”

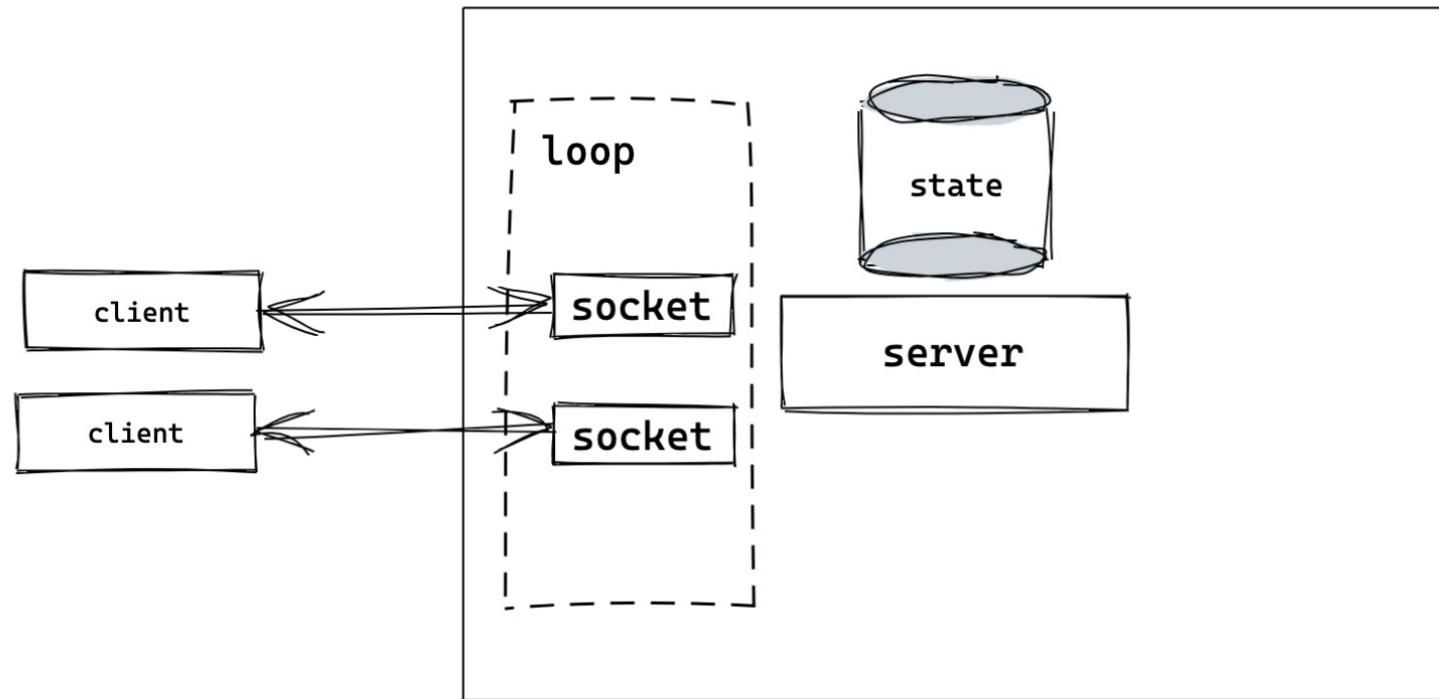
参考文档

- [All about trait objects](#)
- [Protocol-oriented programming in swift](#)
- [Generic Data Types](#)
- [Generics \(Rust by Example\)](#)
- [async prost](#)

并发 - 并发原语

我们来一起构思一个 KV server

v1: 单线程死循环



v2: 多线程，共享数据



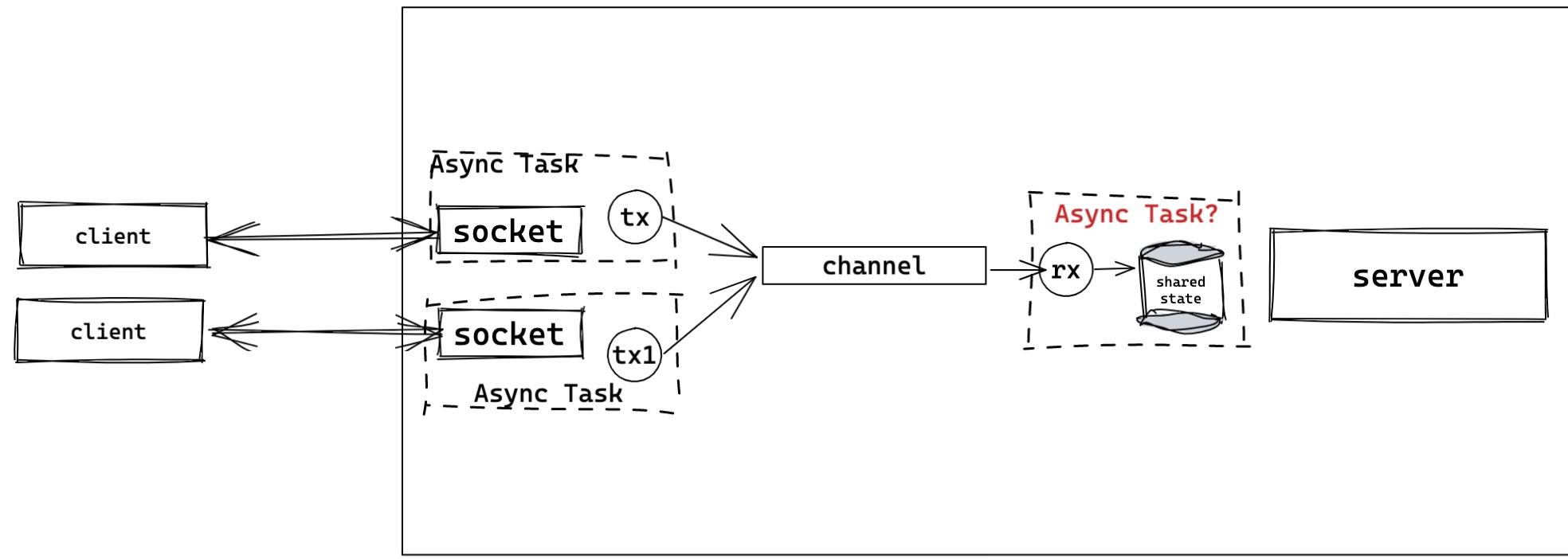
v3: 优化锁的粒度



v4: 使用 Channel



v5: 异步处理



我们目前使用了什么并发原语？

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

Mutex 是如何构建的？

一个比较糙的实现

```
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);
```

问题

- 原子性

- 在多核环境下，1/2 之间会产生竞争（race condition） - 其它线程也许会进入
 - 在单核环境下，OS 抢占多任务依旧可能会在 1/2 间产生竞争

- 乱序

- 编译器也许会优化指令，把 3 放在 1 之前
 - CPU 也许会乱序执行（OOO execution），把 3 放在 1 之前

如何解决这个问题？

- 需要硬件（CPU）来保证原子性和避免 OOO
- 算法：**CAS (Compare-And-Swap)**
- 数据结构（Rust）：AtomicXXX

Atomics

更新之后的 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() }); // **3
        // unlock
        self.locked.store(false, Ordering::Release); // **4
        ret
    }
}

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

Ordering 是什么概念？

- Relaxed: 没有限制，随意 OOO
- Release:
 - 对当前线程，任何 read/write 不能被乱序到这条指令之后（比如：store）
 - 对于其它线程，如果用 Acquire read，会看到变化后的结果
- Acquire:
 - 对当前线程，任何 read/write 不能被乱序到这条指令之后（比如：compare_exchange）
 - 对于其它线程，如果用 Release 来更新数据，更新的数据会被当前线程看到
- AcqRel: Acquire 和 Release 的结合
- SeqCst: AcqRel 之外，所有线程都看到相同的操作顺序

继续优化我们的锁

```
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  
}
```

这是 Mutex 如何运作的基础

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: 更一般化的 Mutex

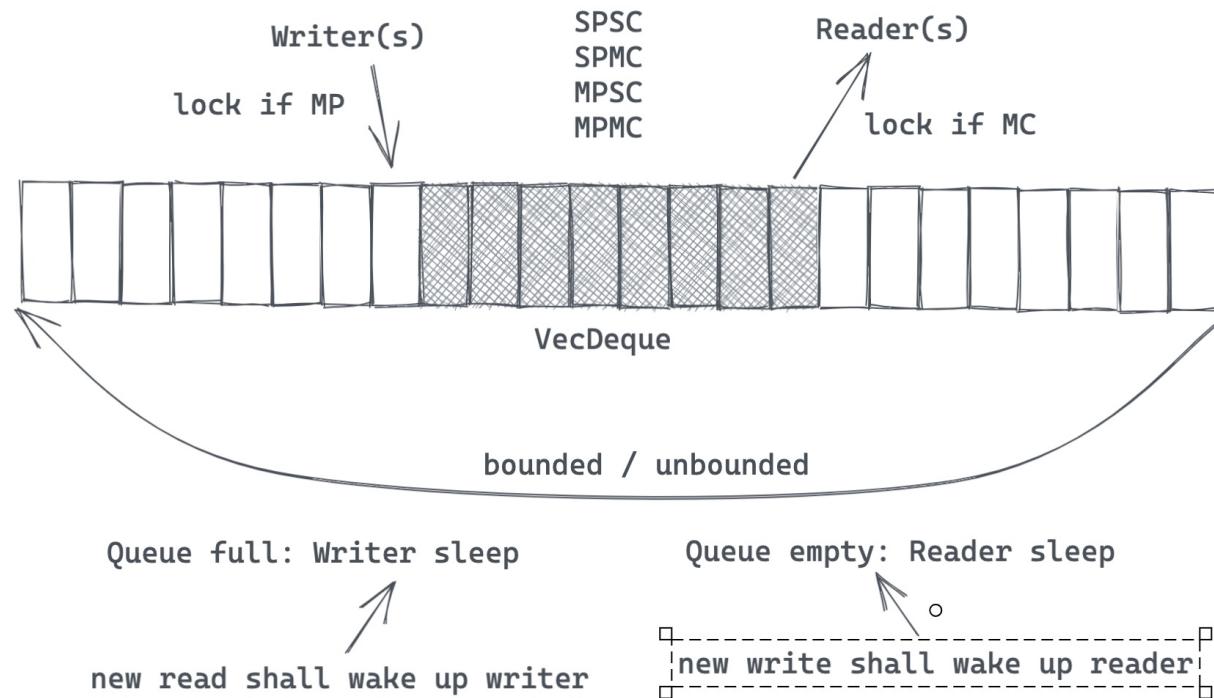


Demo code: restricted HTTP client

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

Channel

Channel 基础



各种 Channel 的实现

- sync: 容量有限，发送者会被 block
 - Mutex + Condvar + VecDeque
 - Atomic VecDeque (atomic queue) + thread::park + thread::notify
- async: 容量无限，发送者不会被 block
 - Mutex + Condvar + VecDeque
 - Mutex + Condvar + DoubleLinkedList
- rendezvous: 容量为 0，用于线程间同步
 - Mutex + Condvar
- oneshot: 只允许发送一次数据 e.g. Ctrl+C to stop all threads
 - atomic swap
- async/await
 - 和 sync channel 类似，但 Waker 不同

Demo code: naive MPSC

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

Live coding: naive actor

- 我们用什么 channel 实现 actor? SPSC, SPMC, MPSC?
- 创建 actor 时, pid 是什么?
- 给 actor 发送一个 message 后, actor 如何回复给发送者 (handle_call) ?

参考资料

- 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>

并发 - `async/await`

在 Rust 中使用线程

```
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();
}
```

线程的缺点

- 调用栈太大 (不适合大量高并发任务 - 如 web server)
- 上下文切换不受控制
- 上下文切换效率不高 (尤其大量线程的环境)

有什么替代方案？

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



Live coding: kv store

One more thing...



Event store 例子

```

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);
    }
}

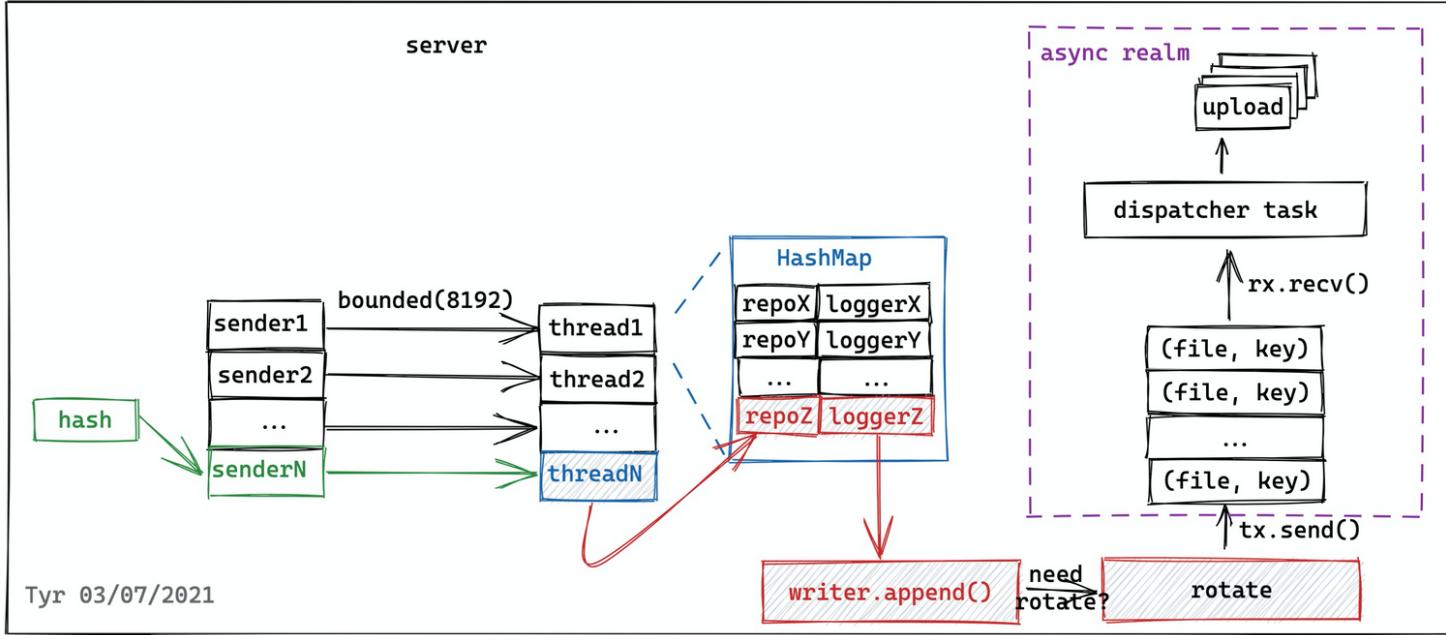
dispatch(repo_id)

```

```

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();
            });
        }
    }
});

```

参考文档

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

回顾第一讲

Copy & Move

```
let a = 10;
let b = vec![1, 2, 3];
{
    let (x, y) = (a, b);
}
let c = a; // ⚡⚡⚡
let d = b; // ⚡⚡⚡
```

Drop

```
{  
    let s1 = "Hello world".to_string();  
    let arr = vec![Box::new(s1)];  
}
```

当 Drop 发生时，谁先被 drop? (lifetime 短的)

Sized / DST

静态分派

最好实现的 Trait

- Debug/Default/Clone
- Send/Sync/Unpin (一般自动实现了)
- PartialEq/PartialOrd/Hash/Eq/Ord
- Serialize/Deserialize (use feature flag)
- Iterator
- Deref / AsRef / From> / Into

Rust Test 是怎么工作的？

- unit test
- integration test
- doctest
- fuzz
- proptest
- benchmark

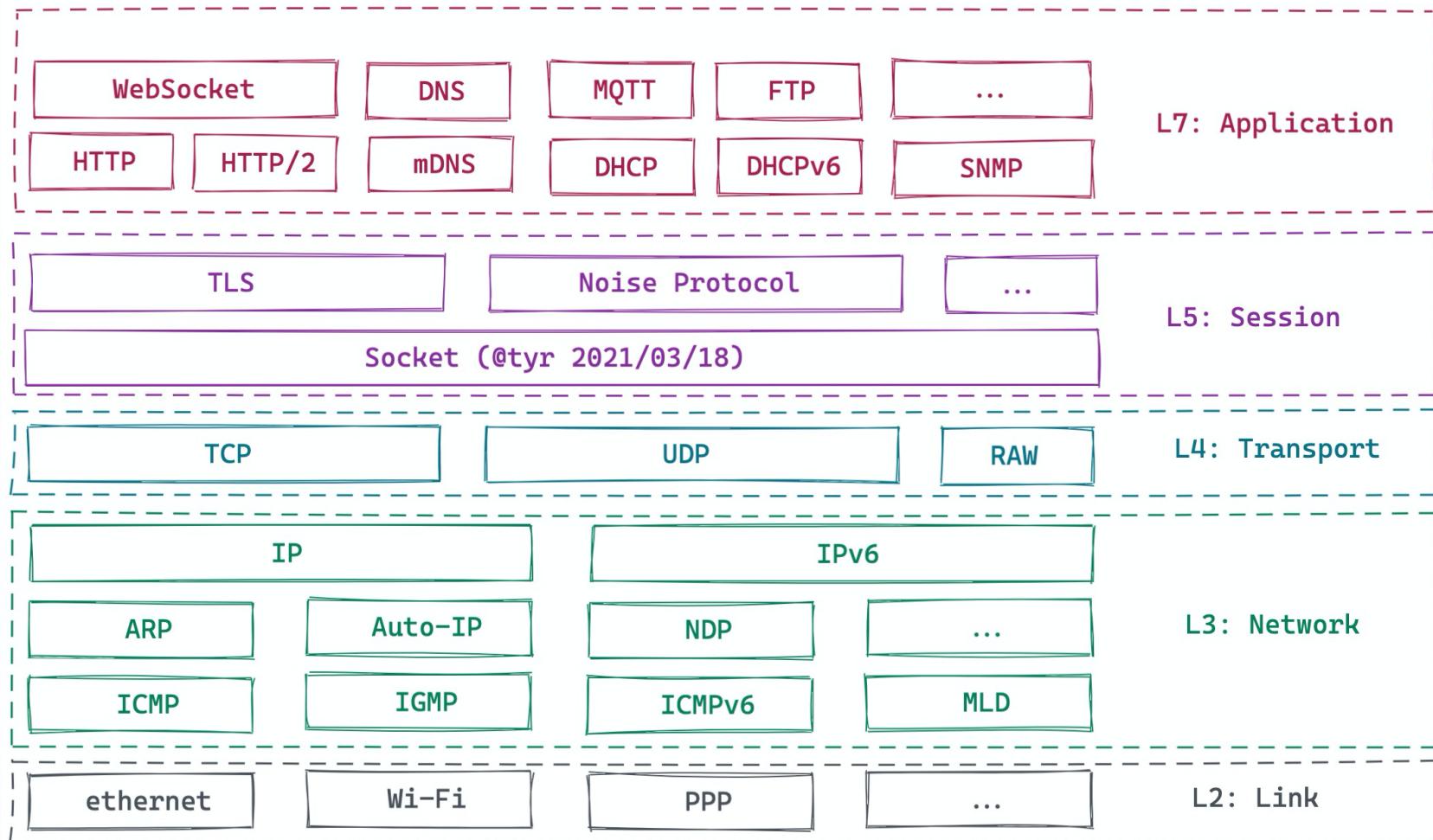
Future: Leaf / Non-leaf

- Leaf: 内部事件 (e.g. event) / 外部事件 (e.g. io)

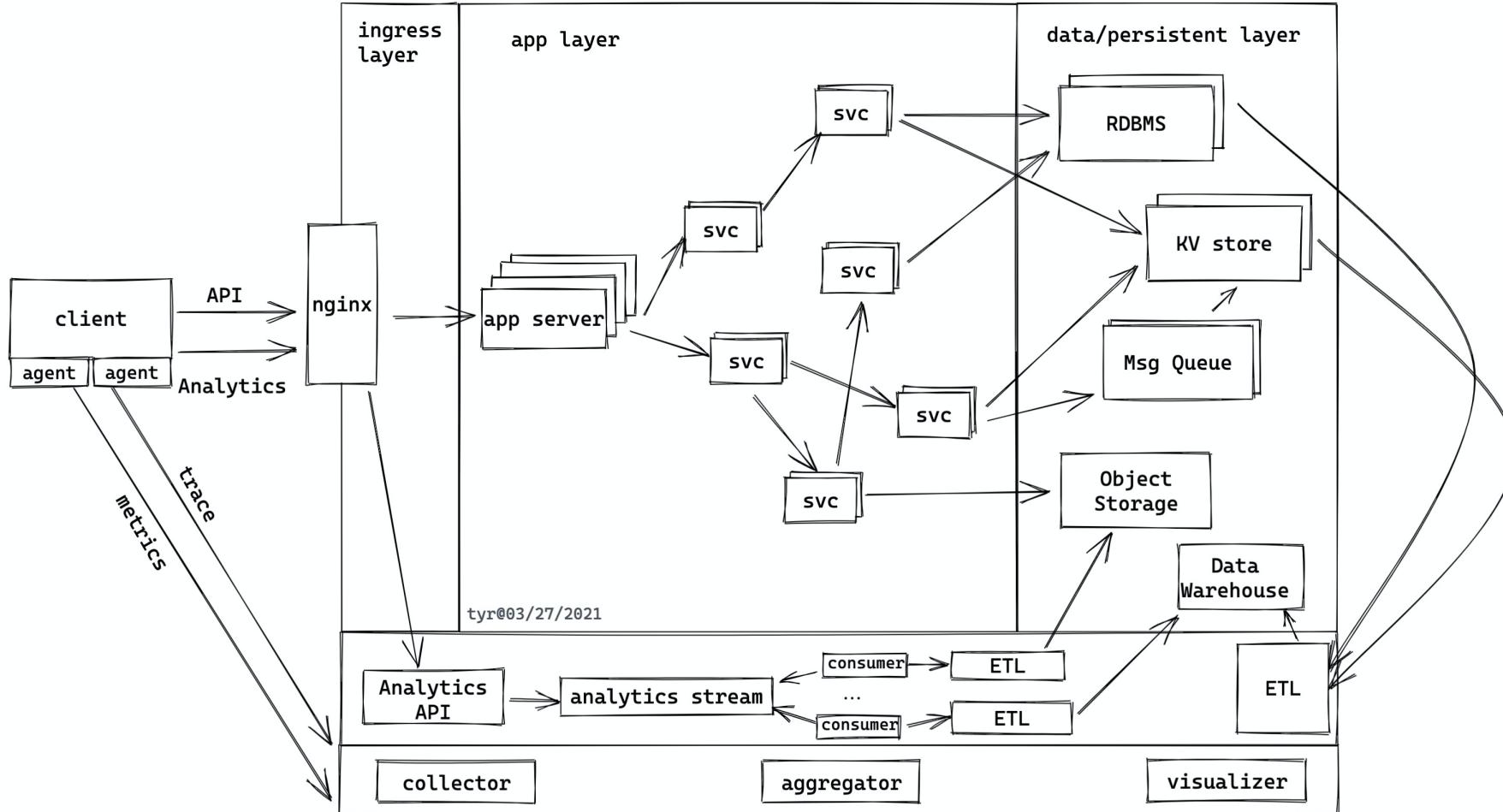
Live coding: ???

Networking and security

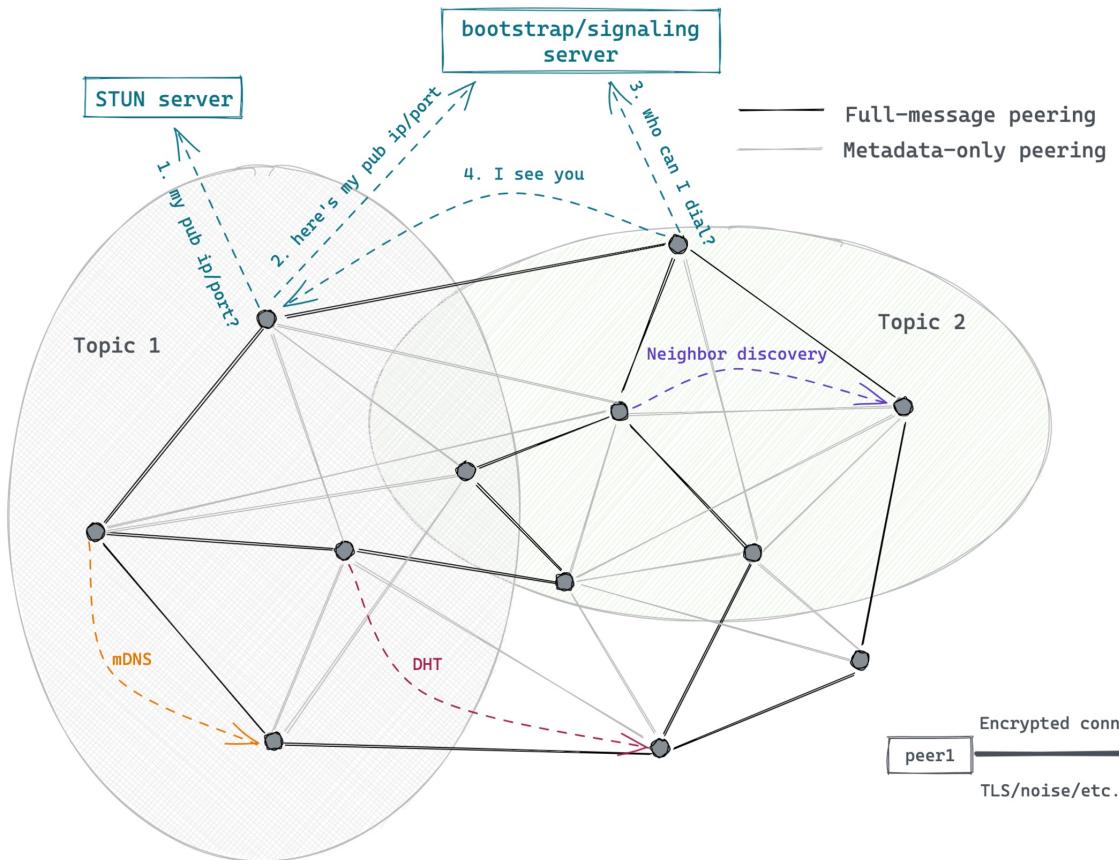
Network Stack



App for centralized network



App for p2p network



Network identity: normally a keypair

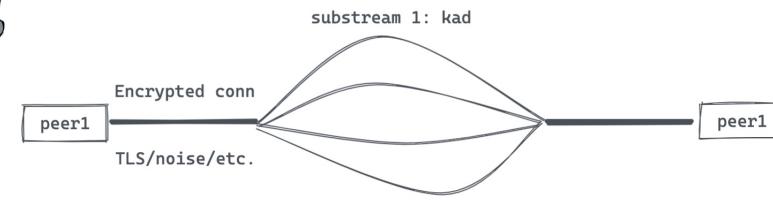
Transport: TCP/QUIC/WS/WebRTC ...

Security: TLS / noise

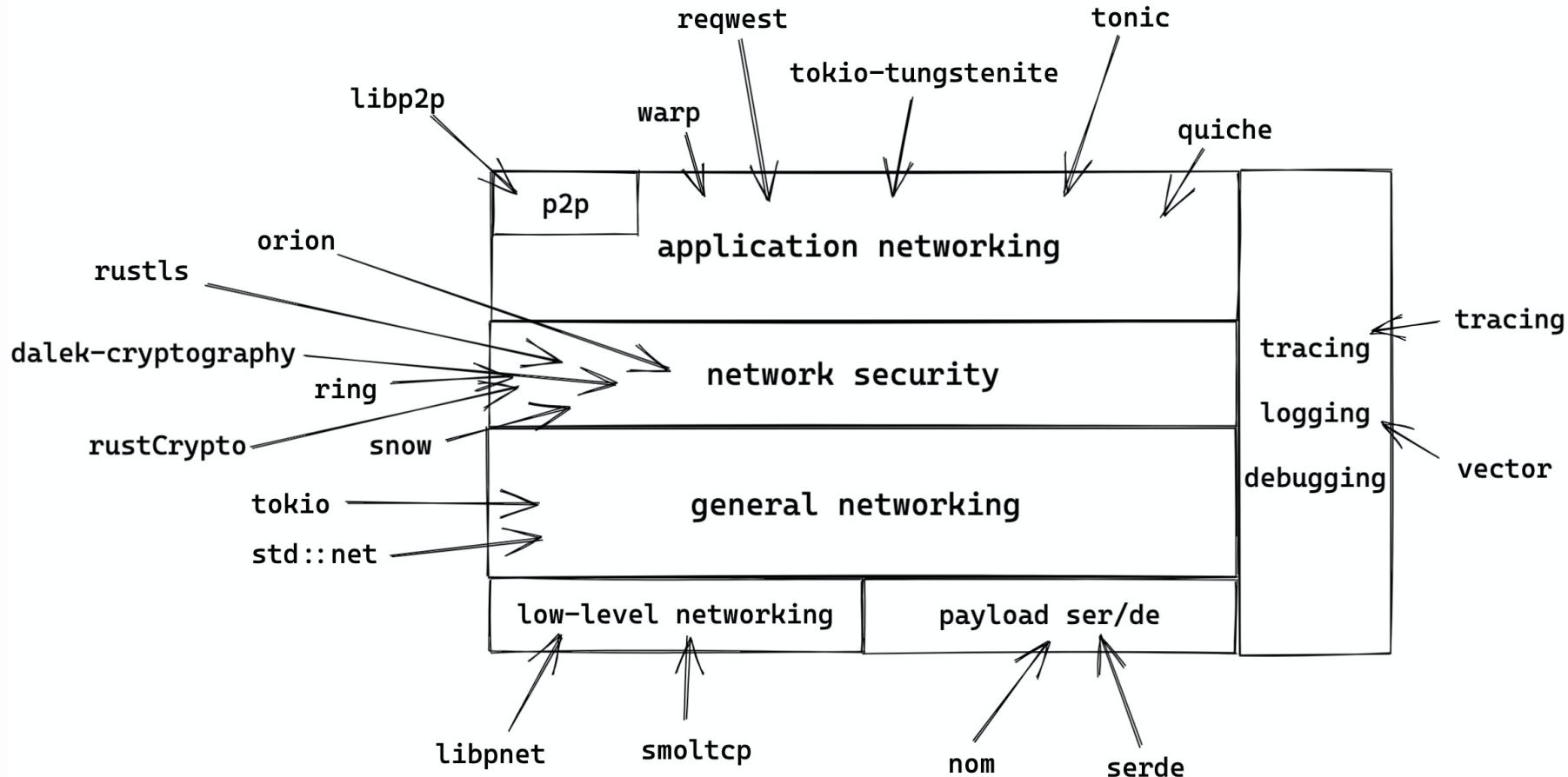
Multiplex: Yamux/Mplex/QUIC

Protocol:

- peer discovery: mDNS, bootstrap, KadDHT
- peer routing: Kad DHT
- content discovery: pubsub, Kad DHT
- NAT traversal: STUN/TURN/ICE
- App protocol: think gRPC



Rust Network Stacks



Demo: Build a TCP server (sync/async)

deps: stdlib / tokio

Demo: HTTP Client/Server

deps: reqwest / actix-web

Demo: gRPC

deps: prost / tonic

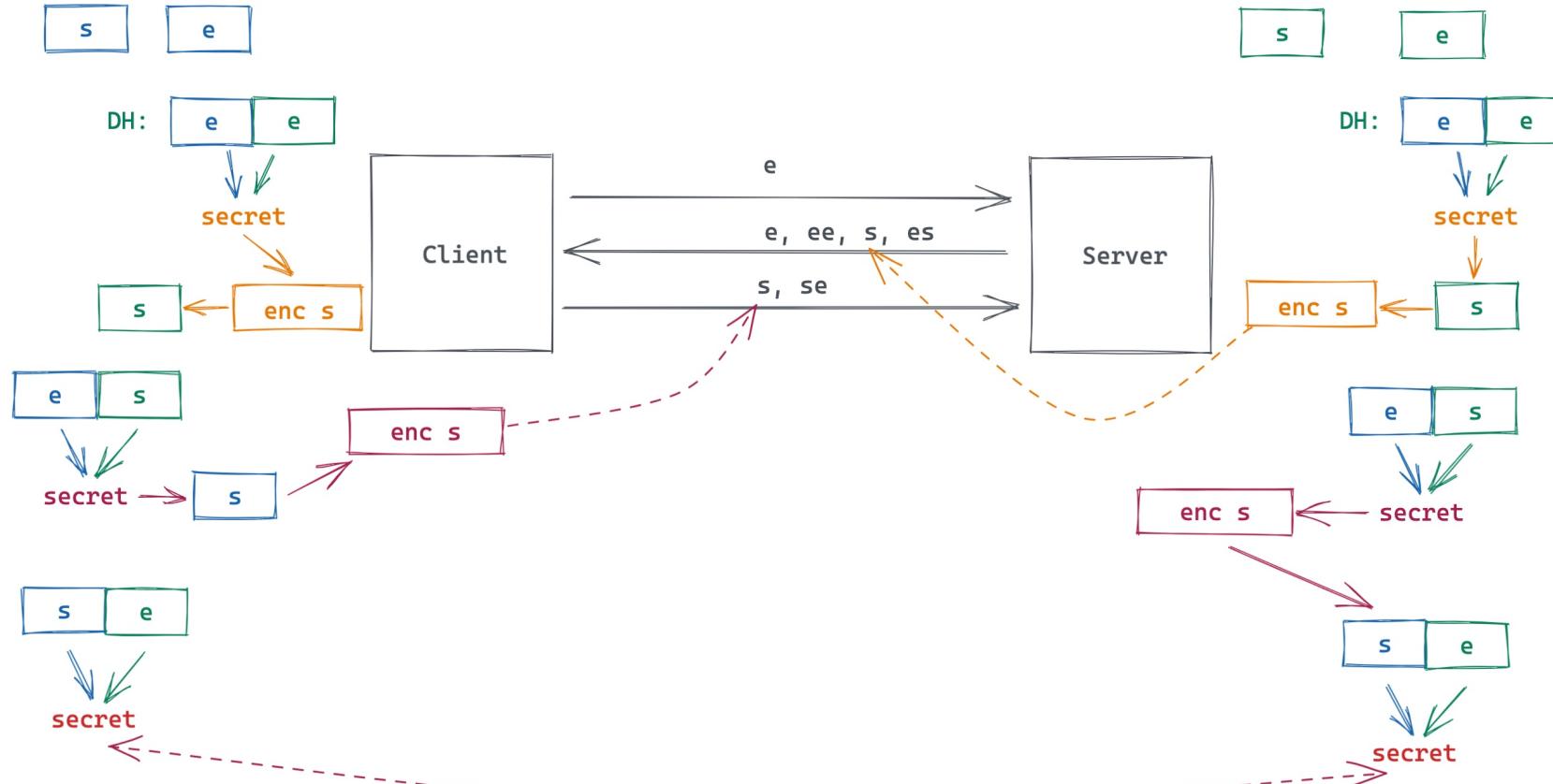
Steps to write a server

- 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

TLS (skip)

Noise Protocol



Demo for noise protocol

References

- GRPC Protocol
- Are we web yet?
- Tonic: rust grpc framework

FFI with C/Elixir/Swift/Java

WASM/WASI

Rust for real-world problems

May the Rust be with you