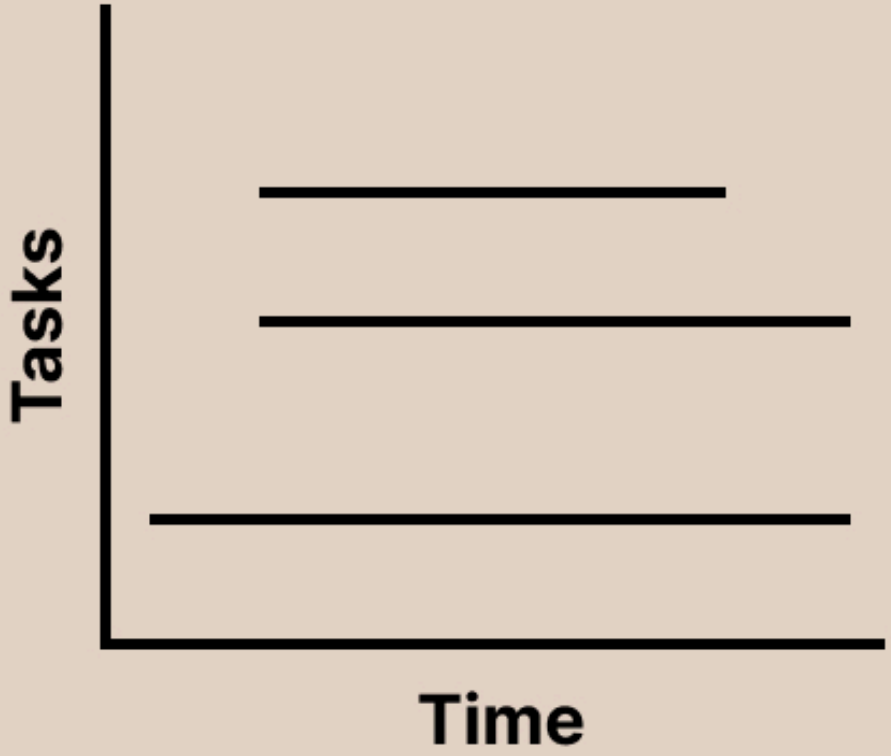

Intro to Rust Lang
Concurrency

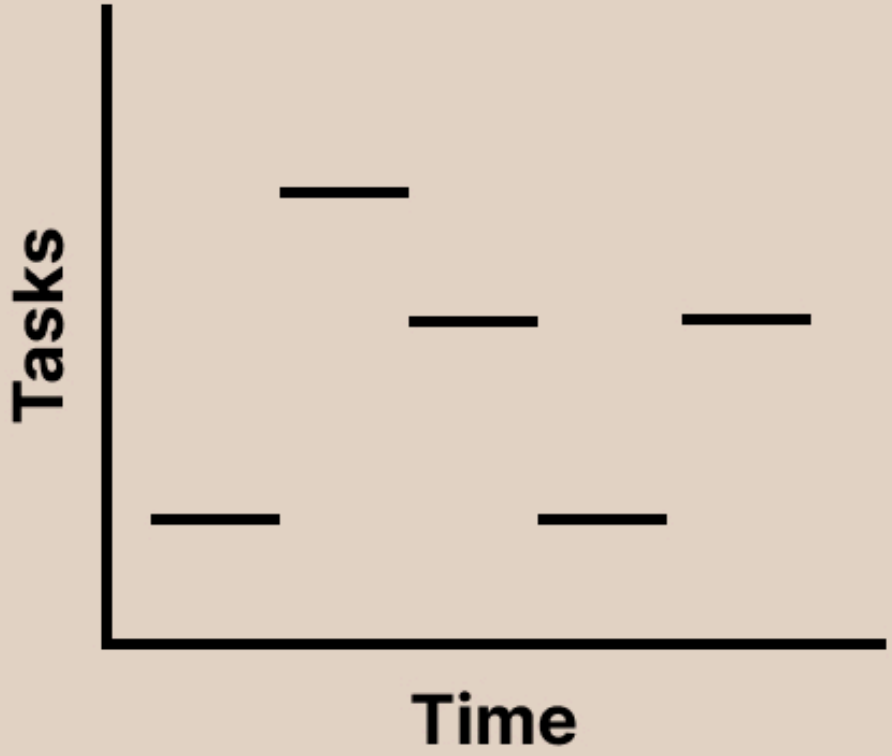
Recap: Parallelism vs Concurrency

- **Concurrency**
  - A **problem** of handling many tasks at once
- **Parallelism**
  - A **solution** to working on multiple tasks at the same time
- Today we're talking about how Rust handles concurrency with `async`

Parallelism



Concurrency



Concurrency

Today, we'll be talking about asynchronous programming in Rust.

- Asynchronous programming is a *solution* to concurrency
- When we say something is **asynchronous**, we generally also mean it is **concurrent**
- Rust approaches asynchronicity differently than other languages
- Rust provides the keywords `async` and `.await` to help write and reason about asynchronous code

Concurrency is Complicated

- Asynchronous execution in *any* language is complicated
- Asynchronicity and parallelism are not mutually exclusive
  - This can make reasoning about concurrency **even harder**!
  - *You can have concurrency and parallelism at the same time in Rust, and we'll see an example of this soon*

Rust's Concurrency is Even More Complicated!

Due to the high complexity of Rust's rules and features, `async` is *even harder* to use in Rust compared to other languages.

- Asynchronous execution is still evolving both as a feature in Rust and as a programming paradigm in general
- The Rust team has prioritized bringing the Async Rust experience closer to parity with synchronous Rust
    - *Lots of exciting work incoming soon!*

Today

- It would be quite challenging to teach you what you need to know about `async` / `.await` in Rust in one lecture
- Instead, we will use `tokio` as a practical medium to learn how to use `async`
- There are **many** online resources dedicated to Async Rust (*see speaker note*)
- We will give you a sneak peek of `async`, and hopefully in the future you will be able to teach yourself how to use it!

Tokio

What is Tokio?

What is Tokio?

> Tokio is an asynchronous runtime for the Rust programming language. It provides the building blocks needed for writing network applications. It gives the flexibility to target a wide range of systems, from large servers with dozens of cores to small embedded devices.

- https://tokio.rs/

What is Tokio?

At a high level, Tokio provides a few major components:

- A **multi-threaded runtime** for **executing asynchronous** code
- An asynchronous version of the standard library
- A large ecosystem of libraries

Why do we need Tokio?

- Making your program asynchronous allows it to scale much better
  - Reduces the cost of doing many things at the same time
- However, asynchronous Rust code does not run on its own
  - You must choose an *asynchronous runtime* to execute it
- The Tokio library is the most widely used runtime

Tokio and the Rust Ecosystem

Tokio is arguably one of the most important libraries in the Rust ecosystem.

- Many *major* Rust libraries built on top of Tokio
- There are large companies relying on Tokio in production

When not to use Tokio

Tokio is useful for many projects, but there are some cases where this isn't true.

- Tokio is designed for IO-bound applications, not CPU-bound
- It is important to note that Tokio is **NOT** the only asynchronous runtime
- We'll come back to this point later

Mini-Redis

We are going to create a miniature Redis client and server.

- We'll start with the basics of asynchronous programming in Rust
- Implement a subset of Redis commands (`GET` and `SET` key-value pairs)
- If you want to do the actual tutorial, follow along here

Starter Code

Set up a new crate called `my-redis` and add some dependencies.

```
$ cargo new my-redis
$ cd my-redis
```

`Cargo.toml`

```
[dependencies]
tokio = { version = "1", features = ["full"] }
mini-redis = "0.4
```

Starter Code

src/main.rs

```rust
use mini_redis::{client, Result};

#[tokio::main]
async fn main() -> Result<()> {
    // Open a connection to the mini-redis address.
    let mut client = client::connect("127.0.0.1:6379").await?;

    // Set the key "hello" with value "world".
    client.set("hello", "world".into()).await?;

    // Get key "hello".
    let result = client.get("hello").await?;

    println!("got value from the server; result={:?}", result);
    Ok(())
}
```

Running our Client

Start the server:

```
$ cargo install mini-redis

# Run the mini server
$ mini-redis-server
```

Run the client:

```
$ cargo run
got value from the server; result=Some(b"world")
```

Lecture Done!

Thanks for coming!

Slides created by:

Connor Tsui, Benjamin Owad, David Rudo,
Jessica Ruan, Fiona Fisher, Terrance Chen

Breaking it down

Okay, let's actually break this down. There isn't much code, but a lot is happening.

```
use mini_redis::{client, Result};

#[tokio::main]
async fn main() -> Result<()> {
    let mut client = client::connect("127.0.0.1:6379").await?;

    client.set("hello", "world".into()).await?;

    let result = client.get("hello").await?;

    println!("got value from the server; result={:?}", result);

    Ok(())
}
```

What's the Difference?

What's going on here?

```
let mut client = client::connect("127.0.0.1:6379").await?;
```

- The `client::connect` function is provided by the `mini-redis` crate
- Establishes a TCP connection with the remote address and returns a handle
- The only indication that this is asynchronous is the `.await` operator

What is Synchronous Programming?

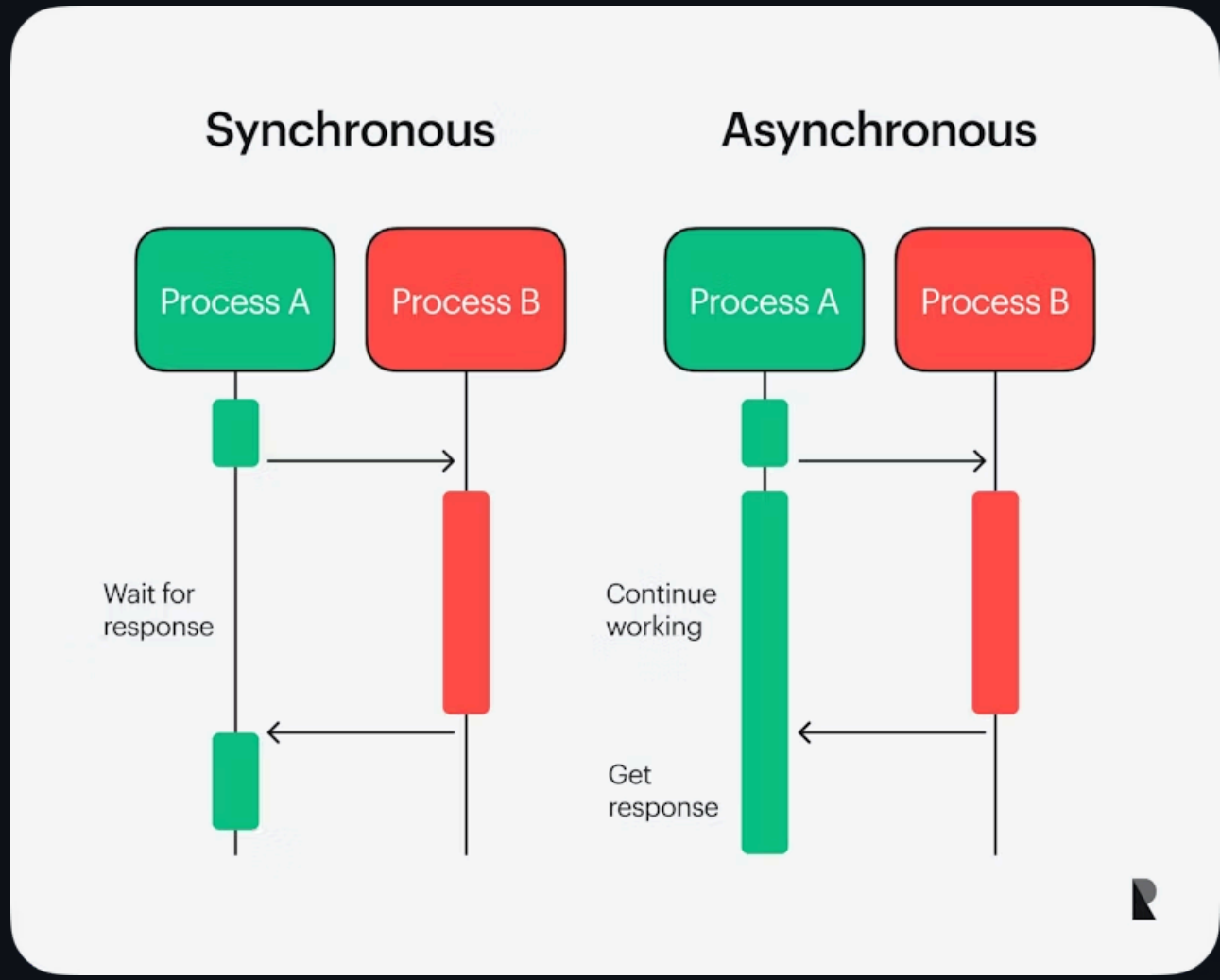
- Most programs are executed in the same order in which they are written
  - *Execute first line of code, then second line, etc.*
- We call this **synchronous** programming
- When a program encounters an operation that cannot be completed immediately, it will **block** until the operation completes
  - For example, establishing a TCP connection over the network

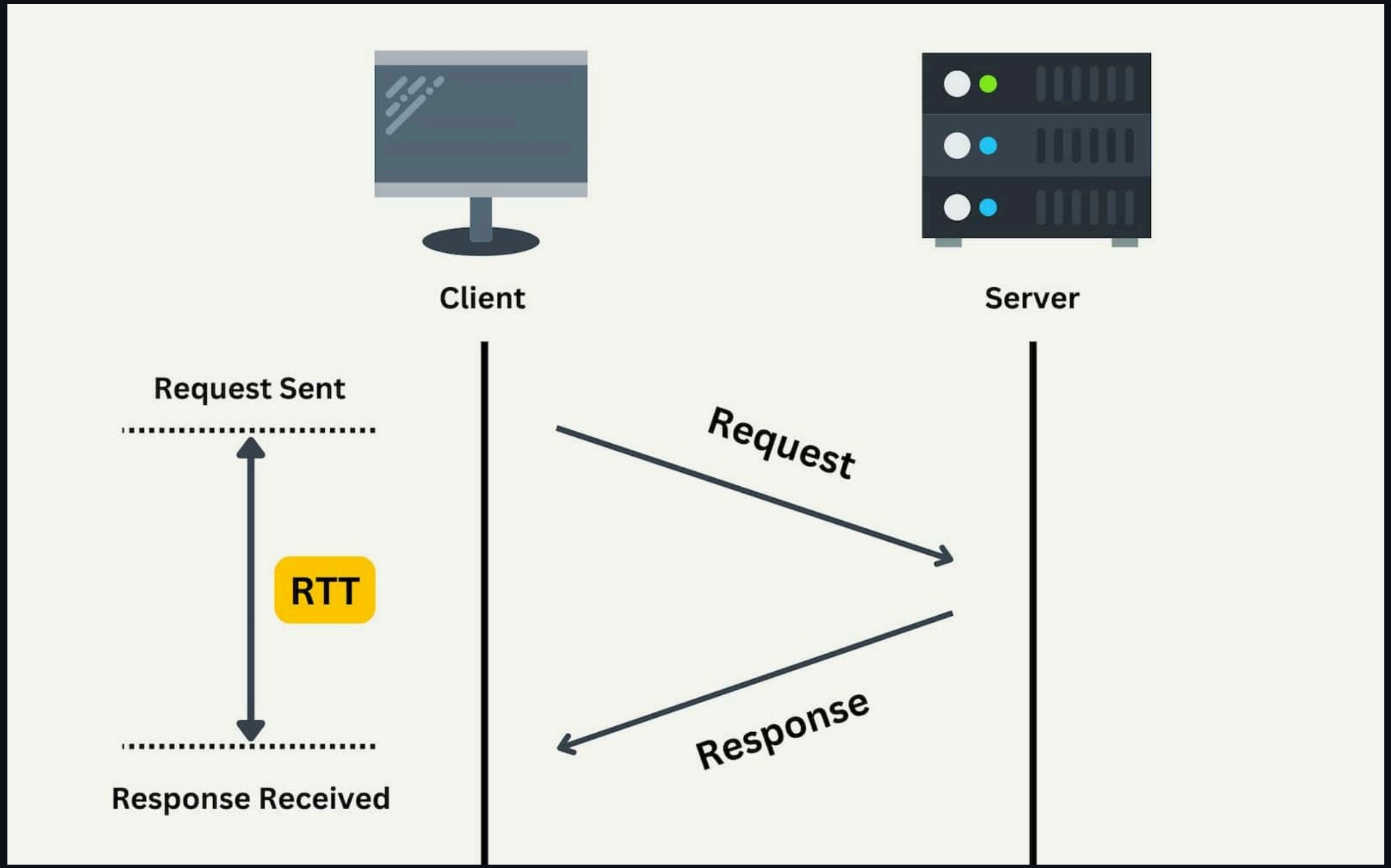
What is Asynchronous Programming?

- In asynchronous programming, operations that cannot complete immediately are *suspended*
- The thread executing is **not blocked** and can instead run other things
- When the operation completes, it becomes *unsuspended* and the thread continues processing it where it left off
- *Note that something will need to "remember" the task's state after pausing so it can resume later*

Sync vs Async

- In synchronous programming, we **wait/block** on the response
- In asynchronous programming, we can do other stuff *while* we are waiting




Client
Server
Request Sent
Request
RTT
Response
Response Received

Asynchronous Programming in Practice

- In our example, we only have one task (a single `client::connect`)
- Usually, asynchronous programs have *many* tasks running at the same time
- This results in much more complicated programs
  - Track all of the state necessary to suspend/resume work

`async`

In Rust, functions that perform asynchronous operations are labeled with the `async` keyword.

```
use mini_redis::Result;
use mini_redis::client::Client;
use tokio::net::ToSocketAddrs;

//  vvvvv
pub async fn connect<T: ToSocketAddrs>(addr: T) -> Result<Client> {
    // <-- snip -->
}
```

`async`

```
//  vvvvv
pub async fn connect<T: ToSocketAddrs>(addr: T) -> Result<Client> { ... }
```

- The `async fn` definition looks like a regular synchronous function!
- The compiler transforms the `async fn` at **compile-time** into a routine
  - You can think of this routine as a low-level state machine

`.await`

```
//                                                  vvvvvv
let mut client = client::connect("127.0.0.1:6379").await?;
```

- When we call `.await` on an `async fn`, we *yield* control back to the thread
- The executing thread is then allowed to go work on other tasks as the current `connect` task is processed in the background
- Once the connection has been established in `connect`, the thread can resume working on this task

Calling `async` Functions

Async functions are similar to normal Rust functions. However, calling these functions does not result in the function body executing.

```
async fn say_world() { // An asynchronous function that prints "world".
    println!("world");
}

#[tokio::main]
async fn main() {
    let op = say_world();

    println!("hello");

    op.await;
}
```

Calling `async` Functions

```
async fn say_world() { println!("world"); }

#[tokio::main]
async fn main() {
    // Calling `say_world()` does not execute the body of `say_world()`.
    let op = say_world();

    println!("hello"); // This `println!` comes first.

    op.await; // Calling `.await` on `op` starts executing `say_world`.
}
```

```
hello
world
```

`async` is Lazy

- Other languages implement `async/await` (notably JavaScript and C#)
- However, Rust async operators are **lazy**
  - Async code will not run without being `.await`ed
- This results in dramatically different runtime semantics

Asynchronous `main` Function

You may have noticed something different about our `main` function.

```
#[tokio::main]
async fn main() { ... }
```

- It is labeled `async fn`
- It is annotated with `#[tokio::main]`

Asynchronous Runtimes

Asynchronous functions (`async fn`) must be **executed** by a **runtime**.

- A runtime provides components needed for running asynchronous programs
  - Task scheduler
  - I/O event handlers
  - Timers
- A runtime must be started by an actual `fn main` function

`#[tokio::main]`

The `#[tokio::main]` function is a macro that transforms the `async fn main()` into a synchronous `fn main()`.

```
#[tokio::main]
async fn main() {
    println!("hello");
}

/// The above gets transformed into:
fn main() {
    let mut rt = tokio::runtime::Runtime::new().unwrap();
    rt.block_on(async {
        println!("hello");
    })
}
```

Back to the Server

Let's go back to implementing the Redis server. We want to:

- Accept inbound TCP sockets in a loop
- Process each socket
  - Read the command
  - Print to `stdout`
  - For now, respond with an "unimplemented" error

Accept TCP Connections

```
use tokio::net::{TcpListener, TcpStream};
use mini_redis::{Connection, Frame};

#[tokio::main]
async fn main() {
    // Bind the listener to the address.
    let listener = TcpListener::bind("127.0.0.1:6379").await.unwrap();

    loop {
        // The second item contains the IP and port of the new connection.
        let (socket, _) = listener.accept().await.unwrap();
        process(socket).await;
    }
}
```

Process Sockets

Now we can write the asynchronous `process` function:

```
async fn process(socket: TcpStream) {
    let mut connection = Connection::new(socket);

    // Read the request.
    if let Some(frame) = connection.read_frame().await.unwrap() {
        println!("GOT: {:?}", frame);

        // Respond with an error.
        let response = Frame::Error("unimplemented".to_string());
        connection.write_frame(&response).await.unwrap();
    }
}
```

Server and Client

If we run both the server and client programs:

Server:

```
GOT: Array([Bulk(b"set"), Bulk(b"hello"), Bulk(b"world")])
```

Client:

```
Error: "unimplemented"
```

Server Problem

Our server has a small problem...

```
#[tokio::main]
async fn main() {
    let listener = TcpListener::bind("127.0.0.1:6379").await.unwrap();

    loop {
        let (socket, _) = listener.accept().await.unwrap();
        process(socket).await;
    }
}
```

- *Other than the fact that it only returns "unimplemented" errors*
- Sockets are processed one at a time!

Limited Concurrency

```
loop {
    let (socket, _) = listener.accept().await.unwrap();
    process(socket).await;
}
```

- When a connection is accepted:
  - The server `process`es the `socket` until completion
  - Goes back to listening
- We are `process`ing sequentially
- Ideally, we want to process many requests concurrently

More Concurrency

If we want to process connections concurrently, we will need to `spawn` new tasks.

- We can spawn a new concurrent task for each socket
- This allows the executor to process each connection concurrently!

`tokio::spawn`

`tokio::spawn` spawns a new task on the `tokio` runtime.

```
loop {
    let (socket, _) = listener.accept().await.unwrap();

    // A new task is spawned for each inbound socket. The socket is
    // moved to the new task and processed there.
    tokio::spawn(async move {
        process(socket).await;
    });
}
```

- Now our server can accept many concurrent requests!

Tasks

You may have noticed we have been using the word "Task".

- A Tokio task is an asynchronous *green thread*
- We create Tokio tasks by passing an `async` block/scope to `tokio::spawn`
- Tokio tasks are *very* lightweight
  - Can spawn millions of tasks without much overhead!

Tasks vs Threads

When we talk about Tokio:

- **Tasks** are lightweight units of execution managed by the Tokio scheduler
  - Tasks can be paused and resumed
- **Threads** are heavyweight units of execution managed by the operating system's scheduler
  - You *cannot* spawn millions of threads without any overhead
- The tokio runtime runs on top of OS threads
  - Many tasks can exist on one thread

Tasks and Threads

Recall that Tokio is a **multi-threaded runtime** for **executing** asynchronous code.

- When tasks are spawned, the Tokio scheduler will ensure that the task executes once it has work to do (when it needs to resume)
- The scheduler might decide to execute the task on a different thread than the one it was originally spawned on
- Tokio implements a **work-stealing** scheduler
- **Important: Not all asynchronous runtimes do this!**

`std::thread::spawn`

Recall that we usually had to `move` variables and values into closures for `std::thread::spawn`.

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

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


```
note: function requires argument type to outlive `'static`
 --> src/main.rs:6:5
  |
6 | /     thread::spawn(|| {
7 | |         println!("Here's a vector: {:?}", v);
8 | |     });
  | |_____^
```

`T: 'static` Bound

More precisely:

- The closure that we pass to `thread::spawn` needs a `'static` bound
- The closure cannot contain references to data owned elsewhere
- Tokio tasks require the exact same `T: 'static` bound for the same reason

`'static` Bound

```
#[tokio::main]
async fn main() {
    let v = vec![1, 2, 3];

    tokio::task::spawn(async {
        println!("Here's a vec: {:?}", v);
    });
}
```

- Here is the asynchronous version of the same code, and we will get a similar error

```
error[E0373]: async block may outlive the current function, but it borrows `v`, which is owned by the current function
 --> src/main.rs:7:23
  |
7 |       task::spawn(async {
  |  _______________________^
8 | |         println!("Here's a vec: {:?}", v);
  | |                                        - `v` is borrowed here
9 | |     });
  | |_____^ may outlive borrowed value `v`
  |

note: function requires argument type to outlive `'static`
 --> src/main.rs:7:17
  |
7 |       task::spawn(async {
  |  _________________^
8 | |         println!("Here's a vector: {:?}", v);
9 | |     });
  | |_____^

help: to force the async block to take ownership of `v` (and any other
      referenced variables), use the `move` keyword
  |
7 |     task::spawn(async move {
8 |         println!("Here's a vec: {:?}", v);
9 |     });
  |
```

`async move`

The solution is similar to the synchronous `thread::spawn` example: Add `move`!

```
#[tokio::main]
async fn main() {
    let v = vec![1, 2, 3];

    //                          vvvv
    tokio::task::spawn(async move {
        println!("Here's a vec: {:?}", v);
    });
}
```

`Send` Bound

Since Tokio is a multi-threaded runtime, it also requires a `Send` bound.

- Because tasks can execute on multiple threads, the runtime needs to be able to `Send` the task between threads
- This is a huge (and almost controversial) topic that we won't get into

The `Send` Bound Error

If you see this error (or something similar):

```
error: future cannot be sent between threads safely
   --> src/main.rs:6:5
    |
6   |     tokio::spawn(async {
    |     ^^^^^^^^^^^^ future created by async block is not `Send`
    |
```

- RUN AWAY!!!
- If you can't run away, then that is a good time to dive deeper into how `async` and `Future`s work under the hood
  - *See the speaker notes for a high-level overview*

Shared State

We still have a major flaw...

```
#[tokio::main]
async fn main() {
    let listener = TcpListener::bind("127.0.0.1:6379").await.unwrap();
    let mut db = HashMap::new(); // <-- What do we do with this?

    loop {
        let (socket, _) = listener.accept().await.unwrap();

        tokio::spawn(async move {
            process(socket).await; // How do we pass `db` to each task?
        });
    }
}
```

Shared State

```
let listener = TcpListener::bind("127.0.0.1:6379").await.unwrap();
let mut db = HashMap::new(); // <-- What do we do with this?

loop {
    let (socket, _) = listener.accept().await.unwrap();

    tokio::spawn(async move {
        process(socket).await; // How do we pass `db` to each task?
    });
}
```

- When we process a request, we want to *share* the database among tasks
  - It's not super useful to reset the database for every connection

Shared State: `Arc<Mutex<T>>`

We can use an `Arc<Mutex<T>>` to allow shared ownership and mutual exclusion!

```
let db = Arc::new(Mutex::new(HashMap::new()));

loop {
    let (socket, _) = listener.accept().await.unwrap();
    // Clone the handle to the hash map.
    let db = db.clone();

    tokio::spawn(async move { process(socket, db).await; });
}
```

- This `Mutex` is the standard library synchronous (blocking) mutex
- See the tutorial for the `process` code

Server Complete!

Our server is essentially done!

- Supports concurrent connections
  - Spawns an asynchronous task for each connection
- Supports concurrent requests and commands
  - Backing database synchronized with a `Mutex`

What else can we do?

- There are *many* more things we can do to improve our client and server:
  - Use a better database
    - Reducing contention with sharding
    - Persistent storage (file I/O)
  - Multi-node servers (distributed systems)
  - Proxy caching
  - Connection Pooling
- If you are interested in this kind of software engineering, make sure to read the rest of the Tokio tutorial!

Recap: When not to use Tokio

Tokio is useful for many projects, but there are some cases where this isn't true.

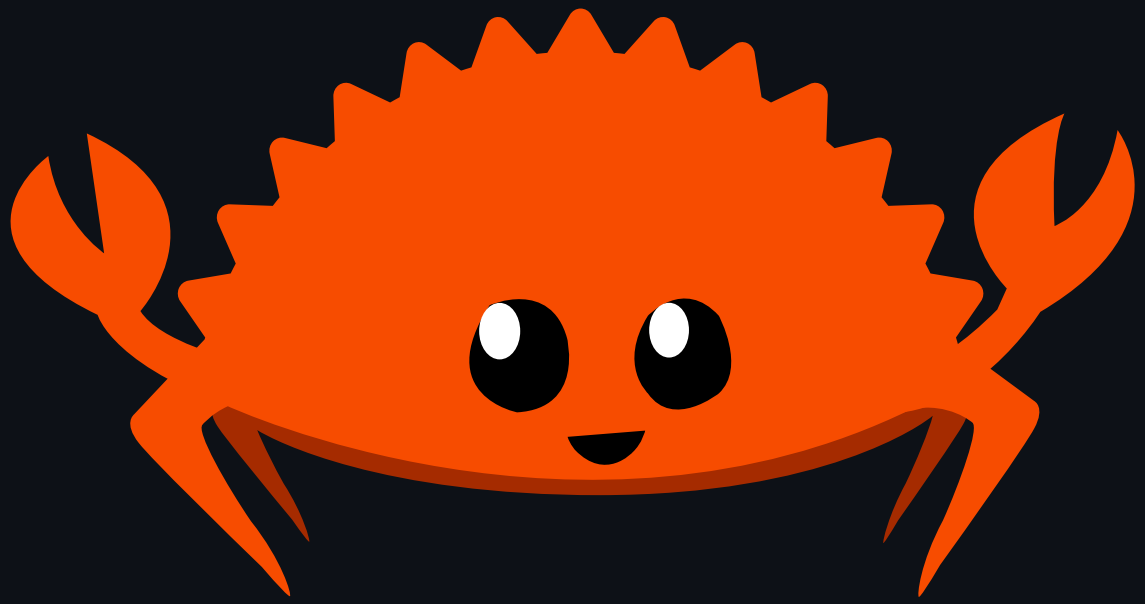
- Tokio is designed for IO-bound applications, not CPU-bound
- No benefit in sequential / low-concurrency programs
- Reading *many* files can also have degrading performance
  - *Operating systems do not provide stable asynchronous file APIs*
- It is important to note that Tokio is **NOT** the only asynchronous runtime

Summary: Tokio

- Rust allows us to write concurrent asynchronous code similar to how we would write synchronous code
- Asynchronous code requires an asynchronous runtime to work
- Tokio is a multi-threaded, work-stealing, high-performance `async` runtime
- We can *easily* engineer massively parallel and concurrent servers with Tokio

The End!

We've reached the end of our prepared content!



Why Rust?

- Déjà vu?

Why Rust?

Let's briefly go back to the very beginning of the semester.

- What is Rust?
- What are the biggest advantages of Rust?
- What are some issues that Rust has?
- Who is Rust for?

What is Rust?

- A language empowering everyone to build reliable and efficient software
- From the official rust website, Rust is:
  - Fast
  - Reliable
  - Productive

Rust's Advantages

- Rust is fast
- Rust is memory safe
- Rust enables fearless concurrency
- Rust is modern

Rust's Pitfalls

- Rust is hard
- Rust is young

Who is Rust for?

- Rust targets complex programs while providing stability and security
- Rust is not a magic silver bullet
- Rust is *not* for everyone
- Rust is arguably the best tool for the specific problems it is trying to solve!

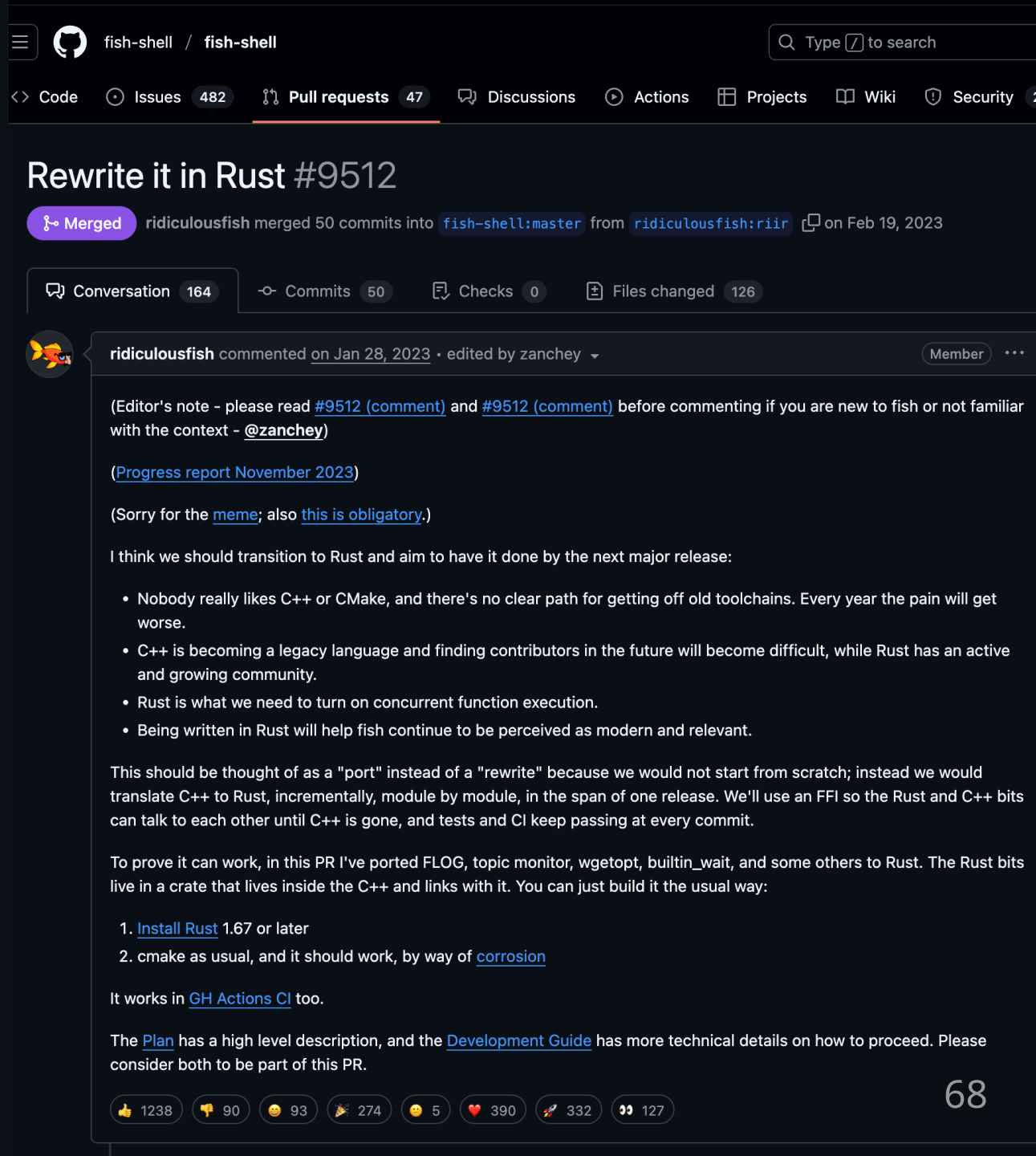
The Future of Rust

We believe that Rust is the future of computer systems.

- We *do not* mean that people will *eventually* start using Rust
- Many companies (large and small) have *already* placed their bets on Rust
  - "Exponential growth" of Rust in big tech
  - Many startups methodically choosing Rust to build their foundation
- Rust will continue to grow, and many more people will continue to adopt it

Fish 4.0

- Completely rewritten in Rust by Feb 27, 2025



fish-shell / fish-shell

Type / to search

Code | Issues 482 | Pull requests 47 | Discussions | Actions | Projects | Wiki | Security

Rewrite it in Rust #9512

Merged ridiculousfish merged 50 commits into fish-shell:master from ridiculousfish:riir on Feb 19, 2023

Conversation 164 | Commits 50 | Checks 0 | Files changed 126

ridiculousfish commented on Jan 28, 2023 • edited by zanchey — Member

(Editor's note - please read #9512 (comment) and #9512 (comment) before commenting if you are new to fish or not familiar with the context - @zanchey)

(Progress report November 2023)

(Sorry for the meme; also this is obligatory.)

I think we should transition to Rust and aim to have it done by the next major release:

- Nobody really likes C++ or CMake, and there's no clear path for getting off old toolchains. Every year the pain will get worse.
- C++ is becoming a legacy language and finding contributors in the future will become difficult, while Rust has an active and growing community.
- Rust is what we need to turn on concurrent function execution.
- Being written in Rust will help fish continue to be perceived as modern and relevant.

This should be thought of as a "port" instead of a "rewrite" because we would not start from scratch; instead we would translate C++ to Rust, incrementally, module by module, in the span of one release. We'll use an FFI so the Rust and C++ bits can talk to each other until C++ is gone, and tests and CI keep passing at every commit.

To prove it can work, in this PR I've ported FLOG, topic monitor, wgetopt, builtin_wait, and some others to Rust. The Rust bits live in a crate that lives inside the C++ and links with it. You can just build it the usual way:

1. Install Rust 1.67 or later
2. cmake as usual, and it should work, by way of corrosion

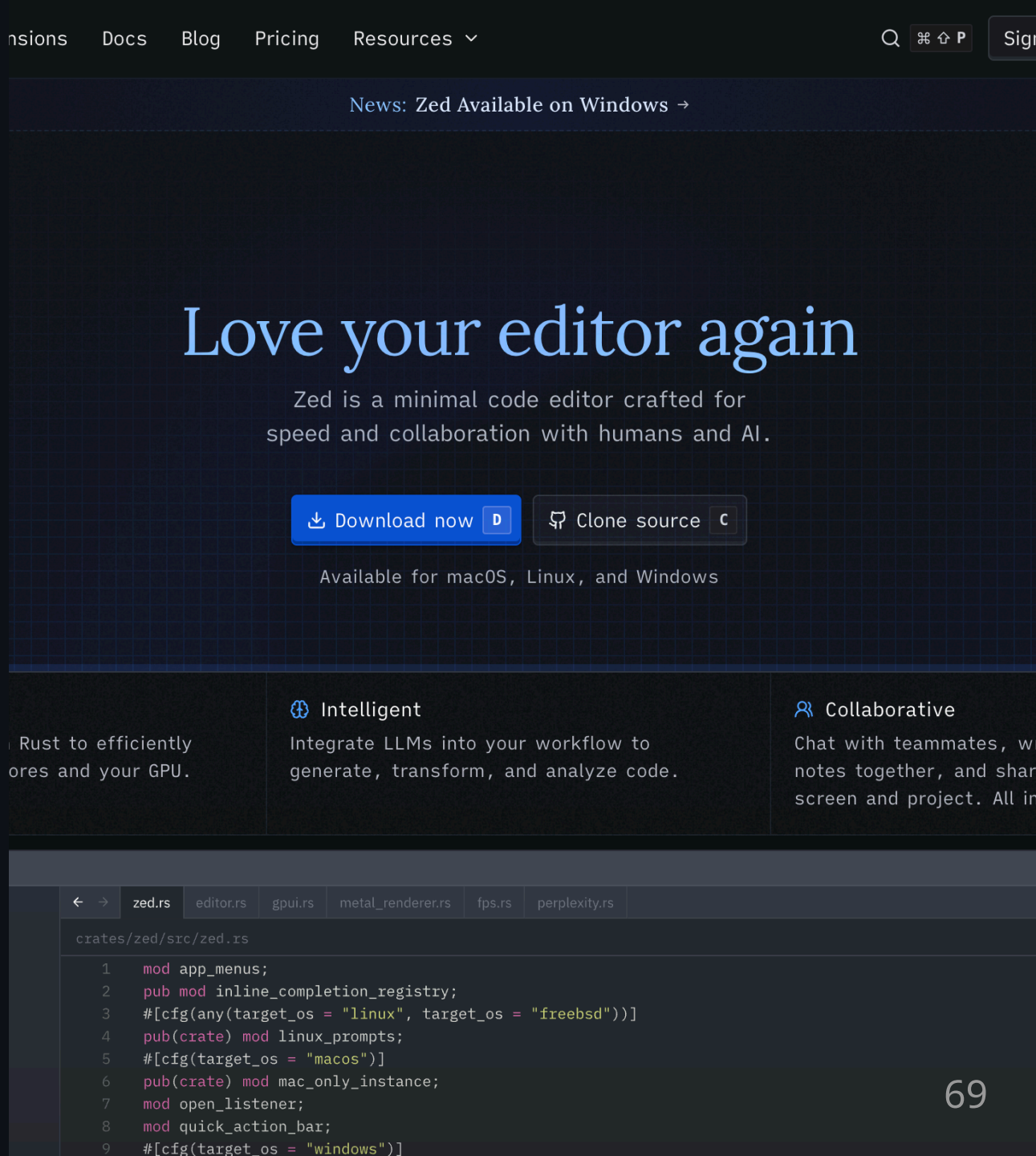
It works in GH Actions CI too.

The Plan has a high level description, and the Development Guide has more technical details on how to proceed. Please consider both to be part of this PR.

1238 | 90 | 93 | 274 | 5 | 390 | 332 | 127

Zed

- A code editor built from scratch in Rust. (not a … Vscode fork …)



Course Goals

We wanted all students to:

- Be able to read, write, and reason about Rust code
- Become an intermediate to advanced Rust developer
- Be confident that you can use Rust going forward!

Why Rust?

We hope that you all can answer this question now!

Thanks for taking Rust StuCo!

Rust StuCo (98-008) has been created by:

Connor Tsui, Benjamin Owad, David Rudo,
Jessica Ruan, Fiona Fisher, Terrance Chen