Comprehensive Rust 🦀

Martin Geisler

Contents

Welcome to Comprehensive Rust 🦀

build passing contributors 335 stars 33k

This is a free Rust course developed by the Android team at Google. The course covers the full spectrum of Rust, from basic syntax to advanced topics like generics and error handling.

> The latest version of the course can be found at https://google.github.io/comprehensive-rust/. If you are reading somewhere else, please check there for updates.
>
> The course is available in other languages. Select your preferred language in the top right corner of the page or check the Translations page for a list of all available translations.
>
> The course is also available as a PDF.

The goal of the course is to teach you Rust. We assume you don't know anything about Rust and hope to:

- Give you a comprehensive understanding of the Rust syntax and language.
- Enable you to modify existing programs and write new programs in Rust.
- Show you common Rust idioms.

We call the first four course days Rust Fundamentals.

Building on this, you're invited to dive into one or more specialized topics:

- Android: a half-day course on using Rust for Android platform development (AOSP). This includes interoperability with C, C++, and Java.
- Chromium: a half-day course on using Rust in Chromium-based browsers. This includes interoperability with C++ and how to include third-party crates in Chromium.
- Bare-metal: a whole-day class on using Rust for bare-metal (embedded) development. Both microcontrollers and application processors are covered.
- Concurrency: a whole-day class on concurrency in Rust. We cover both classical concurrency (preemptively scheduling using threads and mutexes) and async/await concurrency (cooperative multitasking using futures).

Non-Goals

Rust is a large language and we won't be able to cover all of it in a few days. Some non-goals of this course are:

- Learning how to develop macros: please see the Rust Book and Rust by Example instead.

Assumptions

The course assumes that you already know how to program. Rust is a statically-typed language and we will sometimes make comparisons with C and C++ to better explain or contrast the Rust approach.

If you know how to program in a dynamically-typed language such as Python or JavaScript, then you will be able to follow along just fine too.

This is an example of a *speaker note*. We will use these to add additional information to the slides. This could be key points which the instructor should cover as well as answers to typical questions which come up in class.

Chapter 1

Running the Course

> This page is for the course instructor.

Here is a bit of background information about how we've been running the course internally at Google.

We typically run classes from 9:00 am to 4:00 pm, with a 1 hour lunch break in the middle. This leaves 3 hours for the morning class and 3 hours for the afternoon class. Both sessions contain multiple breaks and time for students to work on exercises.

Before you run the course, you will want to:

1. Make yourself familiar with the course material. We've included speaker notes to help highlight the key points (please help us by contributing more speaker notes!). When presenting, you should make sure to open the speaker notes in a popup (click the link with a little arrow next to "Speaker Notes"). This way you have a clean screen to present to the class.

2. Decide on the dates. Since the course takes four days, we recommend that you schedule the days over two weeks. Course participants have said that they find it helpful to have a gap in the course since it helps them process all the information we give them.

3. Find a room large enough for your in-person participants. We recommend a class size of 15-25 people. That's small enough that people are comfortable asking questions --- it's also small enough that one instructor will have time to answer the questions. Make sure the room has *desks* for yourself and for the students: you will all need to be able to sit and work with your laptops. In particular, you will be doing significant live-coding as an instructor, so a lectern won't be very helpful for you.

4. On the day of your course, show up to the room a little early to set things up. We recommend presenting directly using `mdbook serve` running on your laptop (see the installation instructions). This ensures optimal performance with no lag as you change pages. Using your laptop will also allow you to fix typos as you or the course participants spot them.

5. Let people solve the exercises by themselves or in small groups. We typically spend 30-45 minutes on exercises in the morning and in the afternoon (including time to review the solutions). Make sure to ask people if they're stuck or if there is anything you can help with. When you see that several people have the same problem, call it out to the class

and offer a solution, e.g., by showing people where to find the relevant information in the standard library.

That is all, good luck running the course! We hope it will be as much fun for you as it has been for us!

Please provide feedback afterwards so that we can keep improving the course. We would love to hear what worked well for you and what can be made better. Your students are also very welcome to send us feedback!

Instructor Preparation

- **Go through all the material:** Before teaching the course, make sure you have gone through all the slides and exercises yourself. This will help you anticipate questions and potential difficulties.
- **Prepare for live coding:** The course involves significant live coding. Practice the examples and exercises beforehand to ensure you can type them out smoothly during the class. Have the solutions ready in case you get stuck.
- **Familiarize yourself with `mdbook`:** The course is presented using `mdbook`. Knowing how to navigate, search, and use its features will make the presentation smoother.
- **Slice size helper:** Press Ctrl + Alt + B to toggle a visual guide showing the amount of space available when presenting. Expect any content outside of the red box to be hidden initially. Use this as a guide when editing slides. You can also enable it via this link.

Creating a Good Learning Environment

- **Encourage questions:** Reiterate that there are no "stupid" questions. A welcoming atmosphere for questions is crucial for learning.
- **Manage time effectively:** Keep an eye on the schedule, but be flexible. It's more important that students understand the concepts than sticking rigidly to the timeline.
- **Facilitate group work:** During exercises, encourage students to work together. This can help them learn from each other and feel less stuck.

1.1 Course Structure

This page is for the course instructor.

Rust Fundamentals

The first four days make up Rust Fundamentals. The days are fast-paced and we cover a broad range of topics!

Course schedule:

- Day 1 Morning (2 hours and 10 minutes, including breaks)

Segment	Duration
Welcome	5 minutes
Hello, World	15 minutes
Types and Values	40 minutes

Segment	Duration
Control Flow Basics	45 minutes

- Day 1 Afternoon (2 hours and 45 minutes, including breaks)

Segment	Duration
Tuples and Arrays	35 minutes
References	55 minutes
User-Defined Types	1 hour

- Day 2 Morning (2 hours and 50 minutes, including breaks)

Segment	Duration
Welcome	3 minutes
Pattern Matching	50 minutes
Methods and Traits	45 minutes
Generics	50 minutes

- Day 2 Afternoon (2 hours and 50 minutes, including breaks)

Segment	Duration
Closures	30 minutes
Standard Library Types	1 hour
Standard Library Traits	1 hour

- Day 3 Morning (2 hours and 20 minutes, including breaks)

Segment	Duration
Welcome	3 minutes
Memory Management	1 hour
Smart Pointers	55 minutes

- Day 3 Afternoon (2 hours and 30 minutes, including breaks)

Segment	Duration
Borrowing	1 hour and 15 minutes
Lifetimes	1 hour and 5 minutes

- Day 4 Morning (2 hours and 50 minutes, including breaks)

Segment	Duration
Welcome	3 minutes

Segment	Duration
Iterators	55 minutes
Modules	45 minutes
Testing	45 minutes

- Day 4 Afternoon (2 hours and 20 minutes, including breaks)

Segment	Duration
Error Handling	55 minutes
Unsafe Rust	1 hour and 15 minutes

Deep Dives

In addition to the 4-day class on Rust Fundamentals, we cover some more specialized topics:

Rust in Android

The Rust in Android deep dive is a half-day course on using Rust for Android platform development. This includes interoperability with C, C++, and Java.

You will need an AOSP checkout. Make a checkout of the course repository on the same machine and move the `src/android/` directory into the root of your AOSP checkout. This will ensure that the Android build system sees the `Android.bp` files in `src/android/`.

Ensure that `adb sync` works with your emulator or real device and pre-build all Android examples using `src/android/build_all.sh`. Read the script to see the commands it runs and make sure they work when you run them by hand.

Rust in Chromium

The Rust in Chromium deep dive is a half-day course on using Rust as part of the Chromium browser. It includes using Rust in Chromium's `gn` build system, bringing in third-party libraries ("crates") and C++ interoperability.

You will need to be able to build Chromium --- a debug, component build is recommended for speed but any build will work. Ensure that you can run the Chromium browser that you've built.

Bare-Metal Rust

The Bare-Metal Rust deep dive is a full day class on using Rust for bare-metal (embedded) development. Both microcontrollers and application processors are covered.

For the microcontroller part, you will need to buy the BBC micro:bit v2 development board ahead of time. Everybody will need to install a number of packages as described on the welcome page.

Concurrency in Rust

The Concurrency in Rust deep dive is a full day class on classical as well as `async`/`await` concurrency.

You will need a fresh crate set up and the dependencies downloaded and ready to go. You can then copy/paste the examples into `src/main.rs` to experiment with them:

```
cargo init concurrency
cd concurrency
cargo add tokio --features full
cargo run
```

Course schedule:

- Morning (3 hours and 20 minutes, including breaks)

Segment	Duration
Threads	30 minutes
Channels	20 minutes
Send and Sync	15 minutes
Shared State	30 minutes
Exercises	1 hour and 10 minutes

- Afternoon (3 hours and 30 minutes, including breaks)

Segment	Duration
Async Basics	40 minutes
Channels and Control Flow	20 minutes
Pitfalls	55 minutes
Exercises	1 hour and 10 minutes

Idiomatic Rust

The Idiomatic Rust deep dive is a 2-day class on Rust idioms and patterns.

You should be familiar with the material in Rust Fundamentals before starting this course.

Course schedule:

- Morning (14 hours and 25 minutes, including breaks)

Segment	Duration
Foundations of API Design	3 hours and 30 minutes
Leveraging the Type System	7 hours and 30 minutes
Polymorphism	3 hours and 5 minutes

Unsafe (Work in Progress)

The Unsafe deep dive is a two-day class on the *unsafe* Rust language. It covers the fundamentals of Rust's safety guarantees, the motivation for `unsafe`, review process for `unsafe` code, FFI basics, and building data structures that the borrow checker would normally reject.

not found - {{%course outline Unsafe}}

Format

The course is meant to be very interactive and we recommend letting the questions drive the exploration of Rust!

1.2 Keyboard Shortcuts

There are several useful keyboard shortcuts in mdBook:

- Arrow-Left: Navigate to the previous page.
- Arrow-Right: Navigate to the next page.
- Ctrl + Enter: Execute the code sample that has focus.
- s: Activate the search bar.
- Mention that these shortcuts are standard for `mdbook` and can be useful when navigating any `mdbook`-generated site.
- You can demonstrate each shortcut live to the students.
- The `s` key for search is particularly useful for quickly finding topics that have been discussed earlier.
- Ctrl + Enter will be super important for you since you'll do a lot of live coding.

1.3 Translations

The course has been translated into other languages by a set of wonderful volunteers:

- Brazilian Portuguese by @rastringer, @hugojacob, @joaovicmendes, and @henrif75.
- Chinese (Simplified) by @suetfei, @wnghl, @anlunx, @kongy, @noahdragon, @superwhd, @SketchK, and @nodmp.
- Chinese (Traditional) by @hueich, @victorhsieh, @mingyc, @kuanhungchen, and @johnathan79717.
- Farsi by @DannyRavi, @javad-jafari, @Alix1383, @moaminsharifi , @hamidrezakp and @mehrad77.
- Japanese by @CoinEZ-JPN, @momotaro1105, @HidenoriKobayashi and @kantasv.
- Korean by @keispace, @jiyongp, @jooyunghan, and @namhyung.
- Spanish by @deavid.
- Ukrainian by @git-user-cpp, @yaremam and @reta.

Use the language picker in the top-right corner to switch between languages.

Incomplete Translations

There is a large number of in-progress translations. We link to the most recently updated translations:

- Arabic by @younies
- Bengali by @raselmandol.

- French by @KookaS, @vcaen and @AdrienBaudemont.
- German by @Throvn and @ronaldfw.
- Italian by @henrythebuilder and @detro.

The full list of translations with their current status is also available either as of their last update or synced to the latest version of the course.

If you want to help with this effort, please see our instructions for how to get going. Translations are coordinated on the issue tracker.

- This is a good opportunity to thank the volunteers who have contributed to the translations.
- If there are students in the class who speak any of the listed languages, you can encourage them to check out the translated versions and even contribute if they find any issues.
- Highlight that the project is open source and contributions are welcome, not just for translations but for the course content itself.

Chapter 2

Using Cargo

When you start reading about Rust, you will soon meet Cargo, the standard tool used in the Rust ecosystem to build and run Rust applications. Here we want to give a brief overview of what Cargo is and how it fits into the wider ecosystem and how it fits into this training.

Installation

> **Please follow the instructions on https://rustup.rs/.**

This will give you the Cargo build tool (`cargo`) and the Rust compiler (`rustc`). You will also get `rustup`, a command line utility that you can use to install different compiler versions.

After installing Rust, you should configure your editor or IDE to work with Rust. Most editors do this by talking to rust-analyzer, which provides auto-completion and jump-to-definition functionality for VS Code, Emacs, Vim/Neovim, and many others. There is also a different IDE available called RustRover.

- On Debian/Ubuntu, you can install `rustup` via `apt`:

  ```
  sudo apt install rustup
  ```

- On macOS, you can use Homebrew to install Rust, but this may provide an outdated version. Therefore, it is recommended to install Rust from the official site.

2.1 The Rust Ecosystem

The Rust ecosystem consists of a number of tools, of which the main ones are:

- `rustc`: the Rust compiler that turns `.rs` files into binaries and other intermediate formats.
- `cargo`: the Rust dependency manager and build tool. Cargo knows how to download dependencies, usually hosted on https://crates.io, and it will pass them to `rustc` when building your project. Cargo also comes with a built-in test runner which is used to execute unit tests.

- `rustup`: the Rust toolchain installer and updater. This tool is used to install and update `rustc` and `cargo` when new versions of Rust are released. In addition, `rustup` can also download documentation for the standard library. You can have multiple versions of Rust installed at once and `rustup` will let you switch between them as needed.

Key points:

- Rust has a rapid release schedule with a new release coming out every six weeks. New releases maintain backwards compatibility with old releases --- plus they enable new functionality.
- There are three release channels: "stable", "beta", and "nightly".
- New features are being tested on "nightly", "beta" is what becomes "stable" every six weeks.
- Dependencies can also be resolved from alternative registries, git, folders, and more.
- Rust also has editions: the current edition is Rust 2024. Previous editions were Rust 2015, Rust 2018 and Rust 2021.
  - The editions are allowed to make backwards incompatible changes to the language.
  - To prevent breaking code, editions are opt-in: you select the edition for your crate via the `Cargo.toml` file.
  - To avoid splitting the ecosystem, Rust compilers can mix code written for different editions.
  - Mention that it is quite rare to ever use the compiler directly not through `cargo` (most users never do).
  - It might be worth alluding that Cargo itself is an extremely powerful and comprehensive tool. It is capable of many advanced features including but not limited to:
    * Project/package structure
    * workspaces
    * Dev Dependencies and Runtime Dependency management/caching
    * build scripting
    * global installation
    * It is also extensible with sub command plugins as well (such as cargo clippy).
  - Read more from the official Cargo Book

2.2 Code Samples in This Training

For this training, we will mostly explore the Rust language through examples which can be executed through your browser. This makes the setup much easier and ensures a consistent experience for everyone.

Installing Cargo is still encouraged: it will make it easier for you to do the exercises. On the last day, we will do a larger exercise that shows you how to work with dependencies and for that you need Cargo.

The code blocks in this course are fully interactive:

```rust
fn main() {
    println!("Edit me!");
}
```

You can use Ctrl + Enter to execute the code when focus is in the text box.

Most code samples are editable like shown above. A few code samples are not editable for various reasons:

- The embedded playgrounds cannot execute unit tests. Copy-paste the code and open it in the real Playground to demonstrate unit tests.
- The embedded playgrounds lose their state the moment you navigate away from the page! This is the reason that the students should solve the exercises using a local Rust installation or via the Playground.

2.3 Running Code Locally with Cargo

If you want to experiment with the code on your own system, then you will need to first install Rust. Do this by following the instructions in the Rust Book. This should give you a working `rustc` and `cargo`. At the time of writing, the latest stable Rust release has these version numbers:

```
% rustc --version
rustc 1.69.0 (84c898d65 2023-04-16)
% cargo --version
cargo 1.69.0 (6e9a83356 2023-04-12)
```

You can use any later version too since Rust maintains backwards compatibility.

With this in place, follow these steps to build a Rust binary from one of the examples in this training:

1. Click the ”Copy to clipboard” button on the example you want to copy.
2. Use `cargo new exercise` to create a new `exercise/` directory for your code:

   ```
   $ cargo new exercise
        Created binary (application) `exercise` package
   ```

3. Navigate into `exercise/` and use `cargo run` to build and run your binary:

   ```
   $ cd exercise
   $ cargo run
      Compiling exercise v0.1.0 (/home/mgeisler/tmp/exercise)
       Finished dev [unoptimized + debuginfo] target(s) in 0.75s
        Running `target/debug/exercise`
   Hello, world!
   ```

4. Replace the boilerplate code in `src/main.rs` with your own code. For example, using the example on the previous page, make `src/main.rs` look like

   ```rust
   fn main() {
       println!("Edit me!");
   }
   ```

5. Use `cargo run` to build and run your updated binary:

```
$ cargo run
   Compiling exercise v0.1.0 (/home/mgeisler/tmp/exercise)
    Finished dev [unoptimized + debuginfo] target(s) in 0.24s
     Running `target/debug/exercise`
Edit me!
```

6. Use `cargo check` to quickly check your project for errors, use `cargo build` to compile it without running it. You will find the output in `target/debug/` for a normal debug build. Use `cargo build --release` to produce an optimized release build in `target/release/`.

7. You can add dependencies for your project by editing `Cargo.toml`. When you run `cargo` commands, it will automatically download and compile missing dependencies for you.

Try to encourage the class participants to install Cargo and use a local editor. It will make their life easier since they will have a normal development environment.

Part I

Day 1: Morning

Chapter 3

Welcome to Day 1

This is the first day of Rust Fundamentals. We will cover a broad range of topics today:

- Basic Rust syntax: variables, scalar and compound types, enums, structs, references, functions, and methods.
- Types and type inference.
- Control flow constructs: loops, conditionals, and so on.
- User-defined types: structs and enums.

Schedule

Including 10 minute breaks, this session should take about 2 hours and 10 minutes. It contains:

Segment	Duration
Welcome	5 minutes
Hello, World	15 minutes
Types and Values	40 minutes
Control Flow Basics	45 minutes

This slide should take about 5 minutes.

Please remind the students that:

- They should ask questions when they get them, don't save them to the end.
- The class is meant to be interactive and discussions are very much encouraged!
  - As an instructor, you should try to keep the discussions relevant, i.e., keep the discussions related to how Rust does things vs. some other language. It can be hard to find the right balance, but err on the side of allowing discussions since they engage people much more than one-way communication.
- The questions will likely mean that we talk about things ahead of the slides.
  - This is perfectly okay! Repetition is an important part of learning. Remember that the slides are just a support and you are free to skip them as you like.

The idea for the first day is to show the ”basic” things in Rust that should have immediate parallels in other languages. The more advanced parts of Rust come on the subsequent days.

If you're teaching this in a classroom, this is a good place to go over the schedule. Note that there is an exercise at the end of each segment, followed by a break. Plan to cover the exercise solution after the break. The times listed here are a suggestion in order to keep the course on schedule. Feel free to be flexible and adjust as necessary!

Chapter 4

Hello, World

This segment should take about 15 minutes. It contains:

Slide	Duration
What is Rust?	10 minutes
Benefits of Rust	3 minutes
Playground	2 minutes

4.1 What is Rust?

Rust is a new programming language that had its 1.0 release in 2015:

- Rust is a statically compiled language in a similar role as C++
  - `rustc` uses LLVM as its backend.
- Rust supports many platforms and architectures:
  - x86, ARM, WebAssembly, ...
  - Linux, Mac, Windows, ...
- Rust is used for a wide range of devices:
  - firmware and boot loaders,
  - smart displays,
  - mobile phones,
  - desktops,
  - servers.

This slide should take about 10 minutes.

Rust fits in the same area as C++:

- High flexibility.
- High level of control.
- Can be scaled down to very constrained devices such as microcontrollers.
- Has no runtime or garbage collection.
- Focuses on reliability and safety without sacrificing performance.

4.2 Benefits of Rust

Some unique selling points of Rust:

- *Compile time memory safety* - whole classes of memory bugs are prevented at compile time
  - No uninitialized variables.
  - No double-frees.
  - No use-after-free.
  - No `NULL` pointers.
  - No forgotten locked mutexes.
  - No data races between threads.
  - No iterator invalidation.
- *No undefined runtime behavior* - what a Rust statement does is never left unspecified
  - Array access is bounds checked.
  - Integer overflow is defined (panic or wrap-around).
- *Modern language features* - as expressive and ergonomic as higher-level languages
  - Enums and pattern matching.
  - Generics.
  - No overhead FFI.
  - Zero-cost abstractions.
  - Great compiler errors.
  - Built-in dependency manager.
  - Built-in support for testing.
  - Excellent Language Server Protocol support.

This slide should take about 3 minutes.

Do not spend much time here. All of these points will be covered in more depth later.

Make sure to ask the class which languages they have experience with. Depending on the answer you can highlight different features of Rust:

- Experience with C or C++: Rust eliminates a whole class of *runtime errors* via the borrow checker. You get performance like in C and C++, but you don't have the memory unsafety issues. In addition, you get a modern language with constructs like pattern matching and built-in dependency management.
- Experience with Java, Go, Python, JavaScript...: You get the same memory safety as in those languages, plus a similar high-level language feeling. In addition you get fast and predictable performance like C and C++ (no garbage collector) as well as access to low-level hardware (should you need it).

4.3 Playground

The Rust Playground provides an easy way to run short Rust programs, and is the basis for the examples and exercises in this course. Try running the ”hello-world” program it starts with. It comes with a few handy features:

- Under ”Tools”, use the `rustfmt` option to format your code in the ”standard” way.

- Rust has two main ”profiles” for generating code: Debug (extra runtime checks, less optimization) and Release (fewer runtime checks, lots of optimization). These are accessible under ”Debug” at the top.
- If you're interested, use ”ASM” under ”...” to see the generated assembly code.

This slide should take about 2 minutes.

As students head into the break, encourage them to open up the playground and experiment a little. Encourage them to keep the tab open and try things out during the rest of the course. This is particularly helpful for advanced students who want to know more about Rust's optimizations or generated assembly.

Chapter 5

Types and Values

This segment should take about 40 minutes. It contains:

Slide	Duration
Hello, World	5 minutes
Variables	5 minutes
Values	5 minutes
Arithmetic	3 minutes
Type Inference	3 minutes
Exercise: Fibonacci	15 minutes

5.1 Hello, World

Let us jump into the simplest possible Rust program, a classic Hello World program:

```
fn main() {
    println!("Hello 🌍!");
}
```

What you see:

- Functions are introduced with `fn`.
- The `main` function is the entry point of the program.
- Blocks are delimited by curly braces like in C and C++.
- Statements end with `;`.
- `println` is a macro, indicated by the `!` in the invocation.
- Rust strings are UTF-8 encoded and can contain any Unicode character.

This slide should take about 5 minutes.

This slide tries to make the students comfortable with Rust code. They will see a ton of it over the next four days so we start small with something familiar.

Key points:

- Rust is very much like other languages in the C/C++/Java tradition. It is imperative and it doesn't try to reinvent things unless absolutely necessary.

- Rust is modern with full support for Unicode.
- Rust uses macros for situations where you want to have a variable number of arguments (no function overloading).
- `println!` is a macro because it needs to handle an arbitrary number of arguments based on the format string, which can't be done with a regular function. Otherwise it can be treated like a regular function.
- Rust is multi-paradigm. For example, it has powerful object-oriented programming features, and, while it is not a functional language, it includes a range of functional concepts.

5.2 Variables

Rust provides type safety via static typing. Variable bindings are made with `let`:

```rust
fn main() {
    let x: i32 = 10;
    println!("x: {x}");
    // x = 20;
    // println!("x: {x}");
}
```

This slide should take about 5 minutes.

- Uncomment the `x = 20` to demonstrate that variables are immutable by default. Add the `mut` keyword to allow changes.
- Warnings are enabled for this slide, such as for unused variables or unnecessary `mut`. These are omitted in most slides to avoid distracting warnings. Try removing the mutation but leaving the `mut` keyword in place.
- The `i32` here is the type of the variable. This must be known at compile time, but type inference (covered later) allows the programmer to omit it in many cases.

5.3 Values

Here are some basic built-in types, and the syntax for literal values of each type.

Types	Literals	
Signed integers	`i8`, `i16`, `i32`, `i64`, `i128`, `isize`	`-10`, `0`, `1_000`, `123_i64`
Unsigned integers	`u8`, `u16`, `u32`, `u64`, `u128`, `usize`	`0`, `123`, `10_u16`
Floating point numbers	`f32`, `f64`	`3.14`, `-10.0e20`, `2_f32`
Unicode scalar values	`char`	`'a'`, `'α'`, `'∞'`
Booleans	`bool`	`true`, `false`

The types have widths as follows:

- `iN`, `uN`, and `fN` are *N* bits wide,

- `isize` and `usize` are the width of a pointer,
- `char` is 32 bits wide,
- `bool` is 8 bits wide.

This slide should take about 5 minutes.

There are a few syntaxes that are not shown above:

- All underscores in numbers can be left out, they are for legibility only. So `1_000` can be written as `1000` (or `10_00`), and `123_i64` can be written as `123i64`.

5.4 Arithmetic

```
fn interproduct(a: i32, b: i32, c: i32) -> i32 {
    return a * b + b * c + c * a;
}

fn main() {
    println!("result: {}", interproduct(120, 100, 248));
}
```

This slide should take about 3 minutes.

This is the first time we've seen a function other than `main`, but the meaning should be clear: it takes three integers, and returns an integer. Functions will be covered in more detail later.

Arithmetic is very similar to other languages, with similar precedence.

What about integer overflow? In C and C++ overflow of *signed* integers is actually undefined, and might do unknown things at runtime. In Rust, it's defined.

Change the `i32`'s to `i16` to see an integer overflow, which panics (checked) in a debug build and wraps in a release build. There are other options, such as overflowing, saturating, and carrying. These are accessed with method syntax, e.g., `(a * b).saturating_add(b * c).saturating_add(c * a)`.

In fact, the compiler will detect overflow of constant expressions, which is why the example requires a separate function.

5.5 Type Inference

Rust will look at how the variable is *used* to determine the type:

```
fn takes_u32(x: u32) {
    println!("u32: {x}");
}

fn takes_i8(y: i8) {
    println!("i8: {y}");
}

fn main() {
    let x = 10;
    let y = 20;
```

```
    takes_u32(x);
    takes_i8(y);
    // takes_u32(y);
}
```

This slide should take about 3 minutes.

This slide demonstrates how the Rust compiler infers types based on constraints given by variable declarations and usages.

It is very important to emphasize that variables declared like this are not of some sort of dynamic "any type" that can hold any data. The machine code generated by such declaration is identical to the explicit declaration of a type. The compiler does the job for us and helps us write more concise code.

When nothing constrains the type of an integer literal, Rust defaults to `i32`. This sometimes appears as `{integer}` in error messages. Similarly, floating-point literals default to `f64`.

```rust
fn main() {
    let x = 3.14;
    let y = 20;
    assert_eq!(x, y);
    // ERROR: no implementation for `{float} == {integer}`
}
```

5.6 Exercise: Fibonacci

The Fibonacci sequence begins with `[0, 1]`. For `n > 1`, the next number is the sum of the previous two.

Write a function `fib(n)` that calculates the nth Fibonacci number. When will this function panic?

```rust
fn fib(n: u32) -> u32 {
    if n < 2 {
        // The base case.
        return todo!("Implement this");
    } else {
        // The recursive case.
        return todo!("Implement this");
    }
}

fn main() {
    let n = 20;
    println!("fib({n}) = {}", fib(n));
}
```

This slide and its sub-slides should take about 15 minutes.

- This exercise is a classic introduction to recursion.
- Encourage students to think about the base cases and the recursive step.

- The question ”When will this function panic?” is a hint to think about integer overflow. The Fibonacci sequence grows quickly!
- Students might come up with an iterative solution as well, which is a great opportunity to discuss the trade-offs between recursion and iteration (e.g., performance, stack overflow for deep recursion).

5.6.1 Solution

```rust
fn fib(n: u32) -> u32 {
    if n < 2 {
        return n;
    } else {
        return fib(n - 1) + fib(n - 2);
    }
}

fn main() {
    let n = 20;
    println!("fib({n}) = {}", fib(n));
}
```

We use the `return` syntax here to return values from the function. Later in the course, we will see that the last expression in a block is automatically returned, allowing us to omit the `return` keyword for a more concise style.

The `if` condition `n < 2` does not need parentheses, which is standard Rust style.

Panic

The exercise asks when this function will panic. The Fibonacci sequence grows very rapidly. With `u32`, the calculated values will overflow the 32-bit integer limit (4,294,967,295) when `n` reaches 48.

In Rust, integer arithmetic checks for overflow in *debug mode* (which is the default when using `cargo run`). If an overflow occurs, the program will panic (crash with an error message). In *release mode* (`cargo run --release`), overflow checks are disabled by default, and the number will wrap around (modular arithmetic), producing incorrect results.

- Walk through the solution step-by-step.
- Explain the recursive calls and how they lead to the final result.
- Discuss the integer overflow issue. With `u32`, the function will panic for `n` around 47. You can demonstrate this by changing the input to `main`.
- Show an iterative solution as an alternative and compare its performance and memory usage with the recursive one. An iterative solution will be much more efficient.

More to Explore

For a more advanced discussion, you can introduce memoization or dynamic programming to optimize the recursive Fibonacci calculation, although this is beyond the scope of the current topic.

Chapter 6

Control Flow Basics

This segment should take about 45 minutes. It contains:

Slide	Duration
Blocks and Scopes	5 minutes
if Expressions	4 minutes
match Expressions	5 minutes
Loops	5 minutes
break and continue	4 minutes
Functions	3 minutes
Macros	2 minutes
Exercise: Collatz Sequence	15 minutes

- We will now cover the many kinds of flow control found in Rust.
- Most of this will be very familiar to what you have seen in other programming languages.

6.1 Blocks and Scopes

- A block in Rust contains a sequence of expressions, enclosed by braces `{}`.
- The final expression of a block determines the value and type of the whole block.

```
fn main() {
    let z = 13;
    let x = {
        let y = 10;
        dbg!(y);
        z - y
    };
    dbg!(x);
    // dbg!(y);
}
```

If the last expression ends with `;`, then the resulting value and type is `()`.

A variable's scope is limited to the enclosing block.

This slide should take about 5 minutes.

- You can explain that dbg! is a Rust macro that prints and returns the value of a given expression for quick and dirty debugging.
- You can show how the value of the block changes by changing the last line in the block. For instance, adding/removing a semicolon or using a `return`.
- Demonstrate that attempting to access y outside of its scope won't compile.
- Values are effectively "deallocated" when they go out of their scope, even if their data on the stack is still there.

6.2 `if` expressions

You use `if` expressions exactly like `if` statements in other languages:

```
fn main() {
    let x = 10;
    if x == 0 {
        println!("zero!");
    } else if x < 100 {
        println!("biggish");
    } else {
        println!("huge");
    }
}
```

In addition, you can use `if` as an expression. The last expression of each block becomes the value of the `if` expression:

```
fn main() {
    let x = 10;
    let size = if x < 20 { "small" } else { "large" };
    println!("number size: {}", size);
}
```

This slide should take about 4 minutes.

Because `if` is an expression and must have a particular type, both of its branch blocks must have the same type. Show what happens if you add `;` after `"small"` in the second example.

An `if` expression should be used in the same way as the other expressions. For example, when it is used in a `let` statement, the statement must be terminated with a `;` as well. Remove the `;` before `println!` to see the compiler error.

6.3 `match` Expressions

`match` can be used to check a value against one or more options:

```
fn main() {
    let val = 1;
    match val {
        1 => println!("one"),
```

```
        10 => println!("ten"),
        100 => println!("one hundred"),
        _ => {
            println!("something else");
        }
    }
}
```

Like `if` expressions, `match` can also return a value;

```rust
fn main() {
    let flag = true;
    let val = match flag {
        true => 1,
        false => 0,
    };
    println!("The value of {flag} is {val}");
}
```

This slide should take about 5 minutes.

- `match` arms are evaluated from top to bottom, and the first one that matches has its corresponding body executed.
- There is no fall-through between cases the way that `switch` works in other languages.
- The body of a `match` arm can be a single expression or a block. Technically this is the same thing, since blocks are also expressions, but students may not fully understand that symmetry at this point.
- `match` expressions need to be exhaustive, meaning they either need to cover all possible values or they need to have a default case such as `_`. Exhaustiveness is easiest to demonstrate with enums, but enums haven't been introduced yet. Instead we demonstrate matching on a `bool`, which is the simplest primitive type.
- This slide introduces `match` without talking about pattern matching, giving students a chance to get familiar with the syntax without front-loading too much information. We'll be talking about pattern matching in more detail tomorrow, so try not to go into too much detail here.

More to Explore

- To further motivate the usage of `match`, you can compare the examples to their equivalents written with `if`. In the second case, matching on a `bool`, an `if {} else {}` block is pretty similar. But in the first example that checks multiple cases, a `match` expression can be more concise than `if {} else if {} else if {} else`.
- `match` also supports match guards, which allow you to add an arbitrary logical condition that will get evaluated to determine if the match arm should be taken. However talking about match guards requires explaining about pattern matching, which we're trying to avoid on this slide.

6.4 Loops

There are three looping keywords in Rust: `while`, `loop`, and `for`:

while

The `while` keyword works much like in other languages, executing the loop body as long as the condition is true.

```
fn main() {
    let mut x = 200;
    while x >= 10 {
        x = x / 2;
    }
    dbg!(x);
}
```

6.4.1 for

The `for` loop iterates over ranges of values or the items in a collection:

```
fn main() {
    for x in 1..5 {
        dbg!(x);
    }

    for elem in [2, 4, 8, 16, 32] {
        dbg!(elem);
    }
}
```

- Under the hood `for` loops use a concept called "iterators" to handle iterating over different kinds of ranges/collections. Iterators will be discussed in more detail later.
- Note that the first `for` loop only iterates to 4. Show the `1..=5` syntax for an inclusive range.

6.4.2 loop

The `loop` statement just loops forever, until a `break`.

```
fn main() {
    let mut i = 0;
    loop {
        i += 1;
        dbg!(i);
        if i > 100 {
            break;
        }
    }
}
```

- The `loop` statement works like a `while true` loop. Use it for things like servers that will serve connections forever.

6.5 break and continue

If you want to immediately start the next iteration use `continue`.

If you want to exit any kind of loop early, use `break`. With `loop`, this can take an optional expression that becomes the value of the `loop` expression.

```
fn main() {
    let mut i = 0;
    loop {
        i += 1;
        if i > 5 {
            break;
        }
        if i % 2 == 0 {
            continue;
        }
        dbg!(i);
    }
}
```

This slide and its sub-slides should take about 4 minutes.

Note that `loop` is the only looping construct that can return a non-trivial value. This is because it's guaranteed to only return at a `break` statement (unlike `while` and `for` loops, which can also return when the condition fails).

6.5.1 Labels

Both `continue` and `break` can optionally take a label argument that is used to break out of nested loops:

```
fn main() {
    let s = [[5, 6, 7], [8, 9, 10], [21, 15, 32]];
    let mut elements_searched = 0;
    let target_value = 10;
    'outer: for i in 0..=2 {
        for j in 0..=2 {
            elements_searched += 1;
            if s[i][j] == target_value {
                break 'outer;
            }
        }
    }
    dbg!(elements_searched);
}
```

- Labeled break also works on arbitrary blocks, e.g.

  ```
  'label: {
      break 'label;
      println!("This line gets skipped");
  }
  ```

6.6 Functions

```rust
fn gcd(a: u32, b: u32) -> u32 {
    if b > 0 { gcd(b, a % b) } else { a }
}

fn main() {
    dbg!(gcd(143, 52));
}
```

This slide should take about 3 minutes.

- Declaration parameters are followed by a type (the reverse of some programming languages), then a return type.
- The last expression in a function body (or any block) becomes the return value. Simply omit the `;` at the end of the expression. The `return` keyword can be used for early return, but the ”bare value” form is idiomatic at the end of a function (refactor `gcd` to use a `return`).
- Some functions have no return value, and return the 'unit type', `()`. The compiler will infer this if the return type is omitted.
- Overloading is not supported -- each function has a single implementation.
  - Always takes a fixed number of parameters. Default arguments are not supported. Macros can be used to support variadic functions.
  - Always takes a single set of parameter types. These types can be generic, which will be covered later.

6.7 Macros

Macros are expanded into Rust code during compilation, and can take a variable number of arguments. They are distinguished by a `!` at the end. The Rust standard library includes an assortment of useful macros.

- `println!(format, ..)` prints a line to standard output, applying formatting described in `std::fmt`.
- `format!(format, ..)` works just like `println!` but returns the result as a string.
- `dbg!(expression)` logs the value of the expression and returns it.
- `todo!()` marks a bit of code as not-yet-implemented. If executed, it will panic.

```rust
fn factorial(n: u32) -> u32 {
    let mut product = 1;
    for i in 1..=n {
        product *= dbg!(i);
    }
    product
}

fn fizzbuzz(n: u32) -> u32 {
    todo!()
}

fn main() {
    let n = 4;
```

```
    println!("{n}! = {}", factorial(n));
}
```

This slide should take about 2 minutes.

The takeaway from this section is that these common conveniences exist, and how to use them. Why they are defined as macros, and what they expand to, is not especially critical.

The course does not cover defining macros, but a later section will describe use of derive macros.

More To Explore

There are a number of other useful macros provided by the standard library. Some other examples you can share with students if they want to know more:

- `assert!` and related macros can be used to add assertions to your code. These are used heavily in writing tests.
- `unreachable!` is used to mark a branch of control flow that should never be hit.
- `eprintln!` allows you to print to stderr.

6.8 Exercise: Collatz Sequence

The Collatz Sequence is defined as follows, for an arbitrary n_1 greater than zero:

- If n_i is 1, then the sequence terminates at n_i.
- If n_i is even, then $n_{i+1} = n_i / 2$.
- If n_i is odd, then $n_{i+1} = 3 * n_i + 1$.

For example, beginning with n_1 = 3:

- 3 is odd, so n_2 = 3 * 3 + 1 = 10;
- 10 is even, so n_3 = 10 / 2 = 5;
- 5 is odd, so n_4 = 3 * 5 + 1 = 16;
- 16 is even, so n_5 = 16 / 2 = 8;
- 8 is even, so n_6 = 8 / 2 = 4;
- 4 is even, so n_7 = 4 / 2 = 2;
- 2 is even, so n_8 = 1; and
- the sequence terminates.

Write a function to calculate the length of the Collatz sequence for a given initial n.

```
/// Determine the length of the collatz sequence beginning at `n`.
fn collatz_length(mut n: i32) -> u32 {
  todo!("Implement this")
}

fn main() {
    println!("Length: {}", collatz_length(11)); // should be 15
}
```

6.8.1 Solution

```
/// Determine the length of the collatz sequence beginning at `n`.
fn collatz_length(mut n: i32) -> u32 {
    let mut len = 1;
    while n > 1 {
        n = if n % 2 == 0 { n / 2 } else { 3 * n + 1 };
        len += 1;
    }
    len
}

fn main() {
    println!("Length: {}", collatz_length(11)); // should be 15
}
```

This solution demonstrates a few key Rust features:

- **`mut` arguments:** The `n` argument is declared as `mut n`. This makes the local variable `n` mutable within the function scope. It does *not* affect the caller's value, as integers are `Copy` types passed by value.
- **`if` expressions:** Rust's `if` is an expression, meaning it produces a value. We assign the result of the `if`/`else` block directly to `n`. This is more concise than writing `n = ...` inside each branch.
- **Implicit return:** The function ends with `len` (without a semicolon), which is automatically returned.

- Note that `n` must be strictly greater than 0 for the Collatz sequence to be valid. The function signature takes `i32`, but the problem description implies positive integers. A more robust implementation might use `u32` or return an `Option` or `Result` to handle invalid inputs (0 or negative numbers), but panic or infinite loops are potential outcomes here if `n <= 0`.
- The overflow is a potential issue if `n` grows too large, similar to the Fibonacci exercise.

Part II

Day 1: Afternoon

Chapter 7

Welcome Back

Including 10 minute breaks, this session should take about 2 hours and 45 minutes. It contains:

Segment	Duration
Tuples and Arrays	35 minutes
References	55 minutes
User-Defined Types	1 hour

Chapter 8

Tuples and Arrays

This segment should take about 35 minutes. It contains:

Slide	Duration
Arrays	5 minutes
Tuples	5 minutes
Array Iteration	3 minutes
Patterns and Destructuring	5 minutes
Exercise: Nested Arrays	15 minutes

- We have seen how primitive types work in Rust. Now it's time for you to start building new composite types.

8.1 Arrays

```
fn main() {
    let mut a: [i8; 5] = [5, 4, 3, 2, 1];
    a[2] = 0;
    println!("a: {a:?}");
}
```

This slide should take about 5 minutes.

- Arrays can also be initialized using the shorthand syntax, e.g. `[0; 1024]`. This can be useful when you want to initialize all elements to the same value, or if you have a large array that would be hard to initialize manually.
- A value of the array type `[T; N]` holds `N` (a compile-time constant) elements of the same type `T`. Note that the length of the array is *part of its type*, which means that `[u8; 3]` and `[u8; 4]` are considered two different types. Slices, which have a size determined at runtime, are covered later.
- Try accessing an out-of-bounds array element. The compiler is able to determine that the index is unsafe, and will not compile the code:

```rust
fn main() {
    let mut a: [i8; 5] = [5, 4, 3, 2, 1];
    a[6] = 0;
    println!("a: {a:?}");
}
```

- Array accesses are checked at runtime. Rust optimizes these checks away when possible; meaning if the compiler can prove the access is safe, it removes the runtime check for better performance. They can be avoided using unsafe Rust. The optimization is so good that it's hard to give an example of runtime checks failing. The following code will compile but panic at runtime:

```rust
fn get_index() -> usize {
    6
}

fn main() {
    let mut a: [i8; 5] = [5, 4, 3, 2, 1];
    a[get_index()] = 0;
    println!("a: {a:?}");
}
```

- We can use literals to assign values to arrays.
- Arrays are not heap-allocated. They are regular values with a fixed size known at compile time, meaning they go on the stack. This can be different from what students expect if they come from a garbage-collected language, where arrays may be heap allocated by default.
- There is no way to remove elements from an array, nor add elements to an array. The length of an array is fixed at compile-time, and so its length cannot change at runtime.

Debug Printing

- The `println!` macro asks for the debug implementation with the `?` format parameter: `{}` gives the default output, `{:?}` gives the debug output. Types such as integers and strings implement the default output, but arrays only implement the debug output. This means that we must use debug output here.
- Adding `#`, eg `{a:#?}`, invokes a "pretty printing" format, which can be easier to read.

8.2 Tuples

```rust
fn main() {
    let t: (i8, bool) = (7, true);
    dbg!(t.0);
    dbg!(t.1);
}
```

This slide should take about 5 minutes.

- Like arrays, tuples have a fixed length.
- Tuples group together values of different types into a compound type.

- Fields of a tuple can be accessed by the period and the index of the value, e.g. `t.0`, `t.1`.
- The empty tuple `()` is referred to as the "unit type" and signifies absence of a return value, akin to `void` in other languages.
- Unlike arrays, tuples cannot be used in a `for` loop. This is because a `for` loop requires all the elements to have the same type, which may not be the case for a tuple.
- There is no way to add or remove elements from a tuple. The number of elements and their types are fixed at compile time and cannot be changed at runtime.

8.3 Array Iteration

The `for` statement supports iterating over arrays (but not tuples).

```
fn main() {
    let primes = [2, 3, 5, 7, 11, 13, 17, 19];
    for prime in primes {
        for i in 2..prime {
            assert_ne!(prime % i, 0);
        }
    }
}
```

This slide should take about 3 minutes.

This functionality uses the `IntoIterator` trait, but we haven't covered that yet.

The `assert_ne!` macro is new here. There are also `assert_eq!` and `assert!` macros. These are always checked, while debug-only variants like debug_`assert!` compile to nothing in release builds.

8.4 Patterns and Destructuring

Rust supports using pattern matching to destructure a larger value like a tuple into its constituent parts:

```
fn check_order(tuple: (i32, i32, i32)) -> bool {
    let (left, middle, right) = tuple;
    left < middle && middle < right
}

fn main() {
    let tuple = (1, 5, 3);
    println!(
        "{tuple:?}: {}",
        if check_order(tuple) { "ordered" } else { "unordered" }
    );
}
```

This slide should take about 5 minutes.

- The patterns used here are "irrefutable", meaning that the compiler can statically verify that the value on the right of = has the same structure as the pattern.

- A variable name is an irrefutable pattern that always matches any value, hence why we can also use `let` to declare a single variable.
- Rust also supports using patterns in conditionals, allowing for equality comparison and destructuring to happen at the same time. This form of pattern matching will be discussed in more detail later.
- Edit the examples above to show the compiler error when the pattern doesn't match the value being matched on.

8.5 Exercise: Nested Arrays

Arrays can contain other arrays:

```
let array = [[1, 2, 3], [4, 5, 6], [7, 8, 9]];
```

What is the type of this variable?

Use an array such as the above to write a function `transpose` that transposes a matrix (turns rows into columns):

$$\texttt{"transpose"}\begin{pmatrix}\begin{bmatrix}1 & 2 & 3\end{bmatrix}\\ \begin{bmatrix}4 & 5 & 6\end{bmatrix}\\ \begin{bmatrix}7 & 8 & 9\end{bmatrix}\end{pmatrix} \texttt{"=="} \begin{bmatrix}1 & 4 & 7\\ 2 & 5 & 8\\ 3 & 6 & 9\end{bmatrix}$$

Copy the code below to https://play.rust-lang.org/ and implement the function. This function only operates on 3×3 matrices.

```
fn transpose(matrix: [[i32; 3]; 3]) -> [[i32; 3]; 3] {
    todo!()
}

fn main() {
    let matrix = [
        [101, 102, 103], // <-- the comment makes rustfmt add a newline
        [201, 202, 203],
        [301, 302, 303],
    ];

    println!("Original:");
    for row in matrix {
        println!("{row:?}");
    }

    let transposed = transpose(matrix);

    println!("\nTransposed:");
    for row in transposed {
        println!("{row:?}");
    }
}
```

8.5.1 Solution

```rust
fn transpose(matrix: [[i32; 3]; 3]) -> [[i32; 3]; 3] {
    let mut result = [[0; 3]; 3];
    for i in 0..3 {
        for j in 0..3 {
            result[j][i] = matrix[i][j];
        }
    }
    result
}

fn main() {
    let matrix = [
        [101, 102, 103], // <-- the comment makes rustfmt add a newline
        [201, 202, 203],
        [301, 302, 303],
    ];

    println!("Original:");
    for row in matrix {
        println!("{row:?}");
    }

    let transposed = transpose(matrix);

    println!("\nTransposed:");
    for row in transposed {
        println!("{row:?}");
    }
}
```

- **Array Types:** The type `[[i32; 3]; 3]` represents an array of size 3, where each element is itself an array of 3 `i32`s. This is how multi-dimensional arrays are typically represented in Rust.
- **Initialization:** We initialize `result` with zeros (`[[0; 3]; 3]`) before filling it. Rust requires all variables to be initialized before use; there is no concept of "uninitialized memory" in safe Rust.
- **Copy Semantics:** Arrays of `Copy` types (like `i32`) are themselves `Copy`. When we pass `matrix` to the function, it is copied by value. The `result` variable is a new, separate array.
- **Iteration:** We use standard `for` loops with ranges (`0..3`) to iterate over indices. Rust also has powerful iterators, which we will see later, but indexing is straightforward for this matrix transposition.

- Mention that `[i32; 3]` is a distinct type from `[i32; 4]`. Array sizes are part of the type signature.
- Ask students what would happen if they tried to return `matrix` directly after modifying it (if they changed the signature to `mut matrix`). (Answer: It would work, but it would return a modified *copy*, leaving the original in `main` unchanged).

Chapter 9

References

This segment should take about 55 minutes. It contains:

Slide	Duration
Shared References	10 minutes
Exclusive References	5 minutes
Slices	10 minutes
Strings	10 minutes
Reference Validity	3 minutes
Exercise: Geometry	20 minutes

9.1 Shared References

A reference provides a way to access another value without taking ownership of the value, and is also called ”borrowing”. Shared references are read-only, and the referenced data cannot change.

```
fn main() {
    let a = 'A';
    let b = 'B';

    let mut r: &char = &a;
    dbg!(r);

    r = &b;
    dbg!(r);
}
```

A shared reference to a type T has type &T. A reference value is made with the & operator. The * operator ”dereferences” a reference, yielding its value.

This slide should take about 7 minutes.

- References can never be null in Rust, so null checking is not necessary.

- A reference is said to ”borrow” the value it refers to, and this is a good model for students not familiar with pointers: code can use the reference to access the value, but is still ”owned” by the original variable. The course will get into more detail on ownership in day 3.
- References are implemented as pointers, and a key advantage is that they can be much smaller than the thing they point to. Students familiar with C or C++ will recognize references as pointers. Later parts of the course will cover how Rust prevents the memory-safety bugs that come from using raw pointers.
- Explicit referencing with & is required, except when invoking methods, where Rust performs automatic referencing and dereferencing.
- Rust will auto-dereference in some cases, in particular when invoking methods (try `r.is_ascii()`). There is no need for an `->` operator like in C++.
- In this example, `r` is mutable so that it can be reassigned (`r = &b`). Note that this re-binds `r`, so that it refers to something else. This is different from C++, where assignment to a reference changes the referenced value.
- A shared reference does not allow modifying the value it refers to, even if that value was mutable. Try `*r = 'X'`.
- Rust is tracking the lifetimes of all references to ensure they live long enough. Dangling references cannot occur in safe Rust.
- We will talk more about borrowing and preventing dangling references when we get to ownership.

9.2 Exclusive References

Exclusive references, also known as mutable references, allow changing the value they refer to. They have type `&mut T`.

```
fn main() {
    let mut point = (1, 2);
    let x_coord = &mut point.0;
    *x_coord = 20;
    println!("point: {point:?}");
}
```

This slide should take about 5 minutes.

Key points:

- ”Exclusive” means that only this reference can be used to access the value. No other references (shared or exclusive) can exist at the same time, and the referenced value cannot be accessed while the exclusive reference exists. Try making an `&point.0` or changing `point.0` while `x_coord` is alive.
- Be sure to note the difference between `let mut x_coord: &i32` and `let x_coord: &mut i32`. The first one is a shared reference that can be bound to different values, while the second is an exclusive reference to a mutable value.

9.3 Slices

A slice gives you a view into a larger collection:

```
fn main() {
    let a: [i32; 6] = [10, 20, 30, 40, 50, 60];
    println!("a: {a:?}");

    let s: &[i32] = &a[2..4];
    println!("s: {s:?}");
}
```

- Slices borrow data from the sliced type.

This slide should take about 7 minutes.

- We create a slice by borrowing a and specifying the starting and ending indexes in brackets.
- If the slice starts at index 0, Rust's range syntax allows us to drop the starting index, meaning that `&a[0..a.len()]` and `&a[..a.len()]` are identical.
- The same is true for the last index, so `&a[2..a.len()]` and `&a[2..]` are identical.
- To easily create a slice of the full array, we can therefore use `&a[..]`.
- `s` is a reference to a slice of `i32`s. Notice that the type of `s` (`&[i32]`) no longer mentions the array length. This allows us to perform computation on slices of different sizes.
- Slices always borrow from another object. In this example, a has to remain 'alive' (in scope) for at least as long as our slice.
- You can't "grow" a slice once it's created:
  - You can't append elements of the slice, since it doesn't own the backing buffer.
  - You can't grow a slice to point to a larger section of the backing buffer. A slice does not have information about the length of the underlying buffer and so you can't know how large the slice can be grown.
  - To get a larger slice you have to go back to the original buffer and create a larger slice from there.

9.4 Strings

We can now understand the two string types in Rust:

- `&str` is a slice of UTF-8 encoded bytes, similar to `&[u8]`.
- `String` is an owned buffer of UTF-8 encoded bytes, similar to `Vec<T>`.

```
fn main() {
    let s1: &str = "World";
    println!("s1: {s1}");

    let mut s2: String = String::from("Hello ");
    println!("s2: {s2}");

    s2.push_str(s1);
```

```
    println!("s2: {s2}");

    let s3: &str = &s2[2..9];
    println!("s3: {s3}");
}
```

This slide should take about 10 minutes.

- `&str` introduces a string slice, which is an immutable reference to UTF-8 encoded string data stored in a block of memory. String literals (`"Hello"`), are stored in the program's binary.
- Rust's `String` type is a wrapper around a vector of bytes. As with a `Vec<T>`, it is owned.
- As with many other types `String::from()` creates a string from a string literal; `String::new()` creates a new empty string, to which string data can be added using the `push()` and `push_str()` methods.
- The `format!()` macro is a convenient way to generate an owned string from dynamic values. It accepts the same format specification as `println!()`.
- You can borrow `&str` slices from `String` via `&` and optionally range selection. If you select a byte range that is not aligned to character boundaries, the expression will panic. The `chars` iterator iterates over characters and is preferred over trying to get character boundaries right.
- For C++ programmers: think of `&str` as `std::string_view` from C++, but the one that always points to a valid string in memory. Rust `String` is a rough equivalent of `std::string` from C++ (main difference: it can only contain UTF-8 encoded bytes and will never use a small-string optimization).
- Byte strings literals allow you to create a `&[u8]` value directly:

  ```
  fn main() {
      println!("{:?}", b"abc");
      println!("{:?}", &[97, 98, 99]);
  }
  ```

- Raw strings allow you to create a `&str` value with escapes disabled: `r"\n" == "\\n"`. You can embed double-quotes by using an equal amount of # on either side of the quotes:

  ```
  fn main() {
      println!(r#"<a href="link.html">link</a>"#);
      println!("<a href=\"link.html\">link</a>");
  }
  ```

9.5 Reference Validity

Rust enforces a number of rules for references that make them always safe to use. One rule is that references can never be `null`, making them safe to use without `null` checks. The other rule we'll look at for now is that references can't *outlive* the data they point to.

```
fn main() {
    let x_ref = {
        let x = 10;
        &x
```

```
    };
    dbg!(x_ref);
}
```

This slide should take about 3 minutes.

- This slide gets students thinking about references as not simply being pointers, since Rust has different rules for references than other languages.
- We'll look at the rest of Rust's borrowing rules on day 3 when we talk about Rust's ownership system.

More to Explore

- Rust's equivalent of nullability is the `Option` type, which can be used to make any type ”nullable” (not just references/pointers). We haven't yet introduced enums or pattern matching, though, so try not to go into too much detail about this here.

9.6 Exercise: Geometry

We will create a few utility functions for 3-dimensional geometry, representing a point as `[f64;3]`. It is up to you to determine the function signatures.

```
// Calculate the magnitude of a vector by summing the squares of its coordinates
// and taking the square root. Use the `sqrt()` method to calculate the square
// root, like `v.sqrt()`.


fn magnitude(...) -> f64 {
    todo!()
}

// Normalize a vector by calculating its magnitude and dividing all of its
// coordinates by that magnitude.


fn normalize(...) {
    todo!()
}

// Use the following `main` to test your work.

fn main() {
    println!("Magnitude of a unit vector: {}", magnitude(&[0.0, 1.0, 0.0]));

    let mut v = [1.0, 2.0, 9.0];
    println!("Magnitude of {v:?}: {}", magnitude(&v));
    normalize(&mut v);
    println!("Magnitude of {v:?} after normalization: {}", magnitude(&v));
}
```

9.6.1 Solution

```rust
/// Calculate the magnitude of the given vector.
fn magnitude(vector: &[f64; 3]) -> f64 {
    let mut mag_squared = 0.0;
    for coord in vector {
        mag_squared += coord * coord;
    }
    mag_squared.sqrt()
}

/// Change the magnitude of the vector to 1.0 without changing its direction.
fn normalize(vector: &mut [f64; 3]) {
    let mag = magnitude(vector);
    for item in vector {
        *item /= mag;
    }
}

fn main() {
    println!("Magnitude of a unit vector: {}", magnitude(&[0.0, 1.0, 0.0]));

    let mut v = [1.0, 2.0, 9.0];
    println!("Magnitude of {v:?}: {}", magnitude(&v));
    normalize(&mut v);
    println!("Magnitude of {v:?} after normalization: {}", magnitude(&v));
}
```

- Note that in `normalize` we were able to do `*item /= mag` to modify each element. This is because we're iterating using a mutable reference to an array, which causes the `for` loop to give mutable references to each element.
- It is also possible to take slice references here, e.g., `fn magnitude(vector: &[f64]) -> f64`. This makes the function more general, at the cost of a runtime length check.

Chapter 10

User-Defined Types

This segment should take about 1 hour. It contains:

Slide	Duration
Named Structs	10 minutes
Tuple Structs	10 minutes
Enums	5 minutes
Type Aliases	2 minutes
Const	10 minutes
Static	5 minutes
Exercise: Elevator Events	15 minutes

10.1 Named Structs

Like C and C++, Rust has support for custom structs:

```
struct Person {
    name: String,
    age: u8,
}

fn describe(person: &Person) {
    println!("{} is {} years old", person.name, person.age);
}

fn main() {
    let mut peter = Person {
        name: String::from("Peter"),
        age: 27,
    };
    describe(&peter);

    peter.age = 28;
    describe(&peter);
```

```
    let name = String::from("Avery");
    let age = 39;
    let avery = Person { name, age };
    describe(&avery);
}
```

This slide should take about 10 minutes.

Key Points:

- Structs work like in C or C++.
  - Like in C++, and unlike in C, no typedef is needed to define a type.
  - Unlike in C++, there is no inheritance between structs.
- This may be a good time to let people know there are different types of structs.
  - Zero-sized structs (e.g. `struct Foo;`) might be used when implementing a trait on some type but don't have any data that you want to store in the value itself.
  - The next slide will introduce Tuple structs, used when the field names are not important.
- If you already have variables with the right names, then you can create the struct using a shorthand.
- Struct fields do not support default values. Default values are specified by implementing the `Default` trait which we will cover later.

More to Explore

- You can also demonstrate the struct update syntax here:

  ```
  let jackie = Person { name: String::from("Jackie"), ..avery };
  ```

- It allows us to copy the majority of the fields from the old struct without having to explicitly type it all out. It must always be the last element.

- It is mainly used in combination with the `Default` trait. We will talk about struct update syntax in more detail on the slide on the `Default` trait, so we don't need to talk about it here unless students ask about it.

10.2 Tuple Structs

If the field names are unimportant, you can use a tuple struct:

```
struct Point(i32, i32);

fn main() {
    let p = Point(17, 23);
    println!("({}, {})", p.0, p.1);
}
```

This is often used for single-field wrappers (called newtypes):

```
struct PoundsOfForce(f64);
struct Newtons(f64);

fn compute_thruster_force() -> PoundsOfForce {
```

```rust
    todo!("Ask a rocket scientist at NASA")
}

fn set_thruster_force(force: Newtons) {
    // ...
}

fn main() {
    let force = compute_thruster_force();
    set_thruster_force(force);
}
```

This slide should take about 10 minutes.

- Newtypes are a great way to encode additional information about the value in a primitive type, for example:
  - The number is measured in some units: `Newtons` in the example above.
  - The value passed some validation when it was created, so you no longer have to validate it again at every use: `PhoneNumber(String)` or `OddNumber(u32)`.
- The newtype pattern is covered extensively in the ”Idiomatic Rust” module.
- Demonstrate how to add a `f64` value to a `Newtons` type by accessing the single field in the newtype.
  - Rust generally avoids implicit conversions, like automatic unwrapping or using booleans as integers.
    - Operator overloading is discussed on Day 2 (Standard Library Traits).
- When a tuple struct has zero fields, the `()` can be omitted. The result is a zero-sized type (ZST), of which there is only one value (the name of the type).
  - This is common for types that implement some behavior but have no data (imagine a `NullReader` that implements some reader behavior by always returning EOF).
- The example is a subtle reference to the Mars Climate Orbiter failure.

10.3 Enums

The `enum` keyword allows the creation of a type which has a few different variants:

```rust
#[derive(Debug)]
enum Direction {
    Left,
    Right,
}

#[derive(Debug)]
enum PlayerMove {
    Pass,                        // Simple variant
    Run(Direction),              // Tuple variant
    Teleport { x: u32, y: u32 }, // Struct variant
}

fn main() {
    let dir = Direction::Left;
    let player_move: PlayerMove = PlayerMove::Run(dir);
```

```
    println!("On this turn: {player_move:?}");
}
```

This slide should take about 5 minutes.

Key Points:

- Enumerations allow you to collect a set of values under one type.
- `Direction` is a type with variants. There are two values of `Direction`: `Direction::Left` and `Direction::Right`.
- `PlayerMove` is a type with three variants. In addition to the payloads, Rust will store a discriminant so that it knows at runtime which variant is in a `PlayerMove` value.
- This might be a good time to compare structs and enums:
  - In both, you can have a simple version without fields (unit struct) or one with different types of fields (variant payloads).
  - You could even implement the different variants of an enum with separate structs but then they wouldn't be the same type as they would if they were all defined in an enum.
- Rust uses minimal space to store the discriminant.
  - If necessary, it stores an integer of the smallest required size
  - If the allowed variant values do not cover all bit patterns, it will use invalid bit patterns to encode the discriminant (the "niche optimization"). For example, `Option<&u8>` stores either a pointer to an integer or `NULL` for the `None` variant.
  - You can control the discriminant if needed (e.g., for compatibility with C):

    ```
    #[repr(u32)]
    enum Bar {
        A, // 0
        B = 10000,
        C, // 10001
    }

    fn main() {
        println!("A: {}", Bar::A as u32);
        println!("B: {}", Bar::B as u32);
        println!("C: {}", Bar::C as u32);
    }
    ```

    Without `repr`, the discriminant type takes 2 bytes, because 10001 fits 2 bytes.

More to Explore

Rust has several optimizations it can employ to make enums take up less space.

- Null pointer optimization: For some types, Rust guarantees that `size_of::<T>()` equals `size_of::<Option<T>>()`.

  Example code if you want to show how the bitwise representation *may* look like in practice. It's important to note that the compiler provides no guarantees regarding this representation, therefore this is totally unsafe.

  ```
  use std::mem::transmute;

  macro_rules! dbg_bits {
      ($e:expr, $bit_type:ty) => {
          println!("- {}: {:#x}", stringify!($e), transmute::<_, $bit_type>($e));
  ```

```rust
        };
    }

    fn main() {
        unsafe {
            println!("bool:");
            dbg_bits!(false, u8);
            dbg_bits!(true, u8);

            println!("Option<bool>:");
            dbg_bits!(None::<bool>, u8);
            dbg_bits!(Some(false), u8);
            dbg_bits!(Some(true), u8);

            println!("Option<Option<bool>>:");
            dbg_bits!(Some(Some(false)), u8);
            dbg_bits!(Some(Some(true)), u8);
            dbg_bits!(Some(None::<bool>), u8);
            dbg_bits!(None::<Option<bool>>, u8);

            println!("Option<&i32>:");
            dbg_bits!(None::<&i32>, usize);
            dbg_bits!(Some(&0i32), usize);
        }
    }
```

10.4 Type Aliases

A type alias creates a name for another type. The two types can be used interchangeably.

```rust
enum CarryableConcreteItem {
    Left,
    Right,
}

type Item = CarryableConcreteItem;

// Aliases are more useful with long, complex types:
use std::cell::RefCell;
use std::sync::{Arc, RwLock};
type PlayerInventory = RwLock<Vec<Arc<RefCell<Item>>>>;
```

This slide should take about 2 minutes.

- A newtype is often a better alternative since it creates a distinct type. Prefer `struct InventoryCount(usize)` to `type InventoryCount = usize`.
- C programmers will recognize this as similar to a `typedef`.

10.5 const

Constants are evaluated at compile time and their values are inlined wherever they are used:

```
const DIGEST_SIZE: usize = 3;
const FILL_VALUE: u8 = calculate_fill_value();

const fn calculate_fill_value() -> u8 {
    if DIGEST_SIZE < 10 { 42 } else { 13 }
}

fn compute_digest(text: &str) -> [u8; DIGEST_SIZE] {
    let mut digest = [FILL_VALUE; DIGEST_SIZE];
    for (idx, &b) in text.as_bytes().iter().enumerate() {
        digest[idx % DIGEST_SIZE] = digest[idx % DIGEST_SIZE].wrapping_add(b);
    }
    digest
}

fn main() {
    let digest = compute_digest("Hello");
    println!("digest: {digest:?}");
}
```

Only functions marked `const` can be called at compile time to generate `const` values. `const` functions can however be called at runtime.

This slide should take about 10 minutes.

- Mention that `const` behaves semantically similar to C++'s `constexpr`

10.6 static

Static variables will live during the whole execution of the program, and therefore will not move:

```
static BANNER: &str = "Welcome to RustOS 3.14";

fn main() {
    println!("{BANNER}");
}
```

As noted in the Rust RFC Book, these are not inlined upon use and have an actual associated memory location. This is useful for unsafe and embedded code, and the variable lives through the entirety of the program execution. When a globally-scoped value does not have a reason to need object identity, `const` is generally preferred.

This slide should take about 5 minutes.

- `static` is similar to mutable global variables in C++.
- `static` provides object identity: an address in memory and state as required by types with interior mutability such as `Mutex<T>`.

More to Explore

Because `static` variables are accessible from any thread, they must be `Sync`. Interior mutability is possible through a `Mutex`, atomic or similar.

It is common to use `OnceLock` in a static as a way to support initialization on first use. `OnceCell` is not `Sync` and thus cannot be used in this context.

Thread-local data can be created with the macro `std::thread_local`.

10.7 Exercise: Elevator Events

We will create a data structure to represent an event in an elevator control system. It is up to you to define the types and functions to construct various events. Use `#[derive(Debug)]` to allow the types to be formatted with `{:?}`.

This exercise only requires creating and populating data structures so that `main` runs without errors. The next part of the course will cover getting data out of these structures.

```rust
#![allow(dead_code)]

#[derive(Debug)]
/// An event in the elevator system that the controller must react to.
enum Event {
    // TODO: add required variants
}

/// A direction of travel.
#[derive(Debug)]
enum Direction {
    Up,
    Down,
}

/// The car has arrived on the given floor.
fn car_arrived(floor: i32) -> Event {
    todo!()
}

/// The car doors have opened.
fn car_door_opened() -> Event {
    todo!()
}

/// The car doors have closed.
fn car_door_closed() -> Event {
    todo!()
}

/// A directional button was pressed in an elevator lobby on the given floor.
fn lobby_call_button_pressed(floor: i32, dir: Direction) -> Event {
    todo!()
```

```
}

/// A floor button was pressed in the elevator car.
fn car_floor_button_pressed(floor: i32) -> Event {
    todo!()
}

fn main() {
    println!(
        "A ground floor passenger has pressed the up button: {:?}",
        lobby_call_button_pressed(0, Direction::Up)
    );
    println!("The car has arrived on the ground floor: {:?}", car_arrived(0));
    println!("The car door opened: {:?}", car_door_opened());
    println!(
        "A passenger has pressed the 3rd floor button: {:?}",
        car_floor_button_pressed(3)
    );
    println!("The car door closed: {:?}", car_door_closed());
    println!("The car has arrived on the 3rd floor: {:?}", car_arrived(3));
}
```

This slide and its sub-slides should take about 15 minutes.

- If students ask about `#![allow(dead_code)]` at the top of the exercise, it's necessary because the only thing we do with the Event type is print it out. Due to a nuance of how the compiler checks for dead code this causes it to think the code is unused. They can ignore it for the purpose of this exercise.

10.7.1 Solution

```
#![allow(dead_code)]

#[derive(Debug)]
/// An event in the elevator system that the controller must react to.
enum Event {
    /// A button was pressed.
    ButtonPressed(Button),

    /// The car has arrived at the given floor.
    CarArrived(Floor),

    /// The car's doors have opened.
    CarDoorOpened,

    /// The car's doors have closed.
    CarDoorClosed,
}

/// A floor is represented as an integer.
type Floor = i32;
```

```rust
/// A direction of travel.
#[derive(Debug)]
enum Direction {
    Up,
    Down,
}

/// A user-accessible button.
#[derive(Debug)]
enum Button {
    /// A button in the elevator lobby on the given floor.
    LobbyCall(Direction, Floor),

    /// A floor button within the car.
    CarFloor(Floor),
}

/// The car has arrived on the given floor.
fn car_arrived(floor: i32) -> Event {
    Event::CarArrived(floor)
}

/// The car doors have opened.
fn car_door_opened() -> Event {
    Event::CarDoorOpened
}

/// The car doors have closed.
fn car_door_closed() -> Event {
    Event::CarDoorClosed
}

/// A directional button was pressed in an elevator lobby on the given floor.
fn lobby_call_button_pressed(floor: i32, dir: Direction) -> Event {
    Event::ButtonPressed(Button::LobbyCall(dir, floor))
}

/// A floor button was pressed in the elevator car.
fn car_floor_button_pressed(floor: i32) -> Event {
    Event::ButtonPressed(Button::CarFloor(floor))
}

fn main() {
    println!(
        "A ground floor passenger has pressed the up button: {:?}",
        lobby_call_button_pressed(0, Direction::Up)
    );
    println!("The car has arrived on the ground floor: {:?}", car_arrived(0));
    println!("The car door opened: {:?}", car_door_opened());
    println!(
        "A passenger has pressed the 3rd floor button: {:?}",
```

```
        car_floor_button_pressed(3)
    );
    println!("The car door closed: {:?}", car_door_closed());
    println!("The car has arrived on the 3rd floor: {:?}", car_arrived(3));
}
```

- **Enums with Data:** Rust enum variants can carry data. `CarArrived(Floor)` carries an integer, and `ButtonPressed(Button)` carries a nested `Button` enum. This allows `Event` to represent a rich set of states in a type-safe way.
- **Type Aliases:** `type Floor = i32` gives a semantic name to `i32`. This improves readability, but `Floor` is still just an `i32` to the compiler.
- **`#[derive(Debug)]`:** We use this attribute to automatically generate code to format the enums for printing with `{:?}`. Without this, we would have to manually implement the `fmt::Debug` trait.
- **Nested Enums:** The `Button` enum is nested inside `Event::ButtonPressed`. This hierarchical structure is common in Rust for modeling complex domains.

- Note that `Event::CarDoorOpened` is a "unit variant" (it carries no data), while `Event::CarArrived` is a "tuple variant".
- You might discuss why `Button` is a separate enum rather than just having `LobbyCallButtonPressed` and `CarFloorButtonPressed` variants on `Event`. Both are valid, but grouping related concepts (like buttons) can make the code cleaner.

Part III

Day 2: Morning

Chapter 11

Welcome to Day 2

We have covered the foundations of Rust:

- **Basic Types:** Integers, booleans, characters, tuples, and arrays.
- **Control Flow:** `if` expressions, loops, and `match` expressions.
- **Functions:** How to define and call functions.
- **User-Defined Types:** Model data with `struct` and `enum`.
- **References:** Basic borrowing with `&` and `&mut`.

You can now construct any type in Rust and implement basic logic!

Schedule

Including 10 minute breaks, this session should take about 2 hours and 50 minutes. It contains:

Segment	Duration
Welcome	3 minutes
Pattern Matching	50 minutes
Methods and Traits	45 minutes
Generics	50 minutes

Chapter 12

Pattern Matching

This segment should take about 50 minutes. It contains:

Slide	Duration
Irrefutable Patterns	5 minutes
Matching Values	10 minutes
Destructuring Structs	4 minutes
Destructuring Enums	4 minutes
Let Control Flow	10 minutes
Exercise: Expression Evaluation	15 minutes

12.1 Irrefutable Patterns

In day 1 we briefly saw how patterns can be used to *destructure* compound values. Let's review that and talk about a few other things patterns can express:

```
fn takes_tuple(tuple: (char, i32, bool)) {
    let a = tuple.0;
    let b = tuple.1;
    let c = tuple.2;

    // This does the same thing as above.
    let (a, b, c) = tuple;

    // Ignore the first element, only bind the second and third.
    let (_, b, c) = tuple;

    // Ignore everything but the last element.
    let (.., c) = tuple;
}

fn main() {
    takes_tuple(('a', 777, true));
}
```

This slide should take about 5 minutes.

- All of the demonstrated patterns are *irrefutable*, meaning that they will always match the value on the right hand side.
- Patterns are type-specific, including irrefutable patterns. Try adding or removing an element to the tuple and look at the resulting compiler errors.
- Variable names are patterns that always match and bind the matched value into a new variable with that name.
- _ is a pattern that always matches any value, discarding the matched value.
- `..` allows you to ignore multiple values at once.

More to Explore

- You can also demonstrate more advanced usages of `..`, such as ignoring the middle elements of a tuple.

  ```rust
  fn takes_tuple(tuple: (char, i32, bool, u8)) {
      let (first, .., last) = tuple;
  }
  ```

- All of these patterns work with arrays as well:

  ```rust
  fn takes_array(array: [u8; 5]) {
      let [first, .., last] = array;
  }
  ```

12.2 Matching Values

The `match` keyword lets you match a value against one or more *patterns*. The patterns can be simple values, similarly to `switch` in C and C++, but they can also be used to express more complex conditions:

```rust
#[rustfmt::skip]
fn main() {
    let input = 'x';
    match input {
        'q'                       => println!("Quitting"),
        'a' | 's' | 'w' | 'd'     => println!("Moving around"),
        '0'..='9'                 => println!("Number input"),
        key if key.is_lowercase() => println!("Lowercase: {key}"),
        _                         => println!("Something else"),
    }
}
```

A variable in the pattern (key in this example) will create a binding that can be used within the match arm. We will learn more about this on the next slide.

A match guard causes the arm to match only if the condition is true. If the condition is false the match will continue checking later cases.

This slide should take about 10 minutes.

Key Points:

- You might point out how some specific characters are being used when in a pattern
  - `|` as an `or`
  - `..` matches any number of items
  - `1..=5` represents an inclusive range
  - `_` is a wild card
- Match guards as a separate syntax feature are important and necessary when we wish to concisely express more complex ideas than patterns alone would allow.
- Match guards are different from `if` expressions after the `=>`. An `if` expression is evaluated after the match arm is selected. Failing the `if` condition inside of that block won't result in other arms of the original `match` expression being considered. In the following example, the wildcard pattern `_ =>` is never even attempted.

```
#[rustfmt::skip]
fn main() {
    let input = 'a';
    match input {
        key if key.is_uppercase() => println!("Uppercase"),
        key => if input == 'q' { println!("Quitting") },
        _   => println!("Bug: this is never printed"),
    }
}
```

- The condition defined in the guard applies to every expression in a pattern with an `|`.
- Note that you can't use an existing variable as the condition in a match arm, as it will instead be interpreted as a variable name pattern, which creates a new variable that will shadow the existing one. For example:
  ```
  let expected = 5;
  match 123 {
      expected => println!("Expected value is 5, actual is {expected}"),
      _ => println!("Value was something else"),
  }
  ```
  Here we're trying to match on the number 123, where we want the first case to check if the value is 5. The naive expectation is that the first case won't match because the value isn't 5, but instead this is interpreted as a variable pattern which always matches, meaning the first branch will always be taken. If a constant is used instead this will then work as expected.

More To Explore

- Another piece of pattern syntax you can show students is the `@` syntax which binds a part of a pattern to a variable. For example:

  ```
  let opt = Some(123);
  match opt {
      outer @ Some(inner) => {
          println!("outer: {outer:?}, inner: {inner}");
      }
  ```

```
        None => {}
    }
```

In this example inner has the value 123 which it pulled from the Option via destructuring, outer captures the entire Some(inner) expression, so it contains the full Option::Some(123). This is rarely used but can be useful in more complex patterns.

12.3 Structs

Like tuples, structs can also be destructured by matching:

```
struct Move {
    delta: (i32, i32),
    repeat: u32,
}

#[rustfmt::skip]
fn main() {
    let m = Move { delta: (10, 0), repeat: 5 };

    match m {
        Move { delta: (0, 0), .. }          => println!("Standing still"),
        Move { delta: (x, 0), repeat }      => println!("{repeat} step x: {x}"),
        Move { delta: (0, y), repeat: 1 }   => println!("Single step y: {y}"),
        _                                   => println!("Other move"),
    }
}
```

This slide should take about 4 minutes.

- Change the literal values in m to match with the other patterns.
- Add a new field to Movement and make changes to the pattern as needed.
- Note how delta: (x, 0) is a nested pattern.

More to Explore

- Try match &m and check the type of captures. The pattern syntax remains the same, but the captures become shared references. This is match ergonomics and is often useful with match self when implementing methods on an enum.
  - The same effect occurs with match &mut m: the captures become exclusive references.
- The distinction between a capture and a constant expression can be hard to spot. Try changing the 10 in the first arm to a variable, and see that it subtly doesn't work. Change it to a const and see it working again.

12.4 Enums

Like tuples, enums can also be destructured by matching:

Patterns can also be used to bind variables to parts of your values. This is how you inspect the structure of your types. Let us start with a simple enum type:

```rust
enum Result {
    Ok(i32),
    Err(String),
}

fn divide_in_two(n: i32) -> Result {
    if n % 2 == 0 {
        Result::Ok(n / 2)
    } else {
        Result::Err(format!("cannot divide {n} into two equal parts"))
    }
}

fn main() {
    let n = 100;
    match divide_in_two(n) {
        Result::Ok(half) => println!("{n} divided in two is {half}"),
        Result::Err(msg) => println!("sorry, an error happened: {msg}"),
    }
}
```

Here we have used the arms to *destructure* the `Result` value. In the first arm, `half` is bound to the value inside the `Ok` variant. In the second arm, `msg` is bound to the error message.

This slide should take about 4 minutes.

- The `if`/`else` expression is returning an enum that is later unpacked with a `match`.
- You can try adding a third variant to the enum definition and displaying the errors when running the code. Point out the places where your code is now inexhaustive and how the compiler tries to give you hints.
- The values in the enum variants can only be accessed after being pattern matched.
- Demonstrate what happens when the search is inexhaustive. Note the advantage the Rust compiler provides by confirming when all cases are handled.
- Demonstrate the syntax for a struct-style variant by adding one to the enum definition and the `match`. Point out how this is syntactically similar to matching on a struct.

12.5 Let Control Flow

Rust has a few control flow constructs that differ from other languages. They are used for pattern matching:

- `if let` expressions
- `while let` expressions
- `let else` expressions

12.5.1 `if let` Expressions

The `if let` expression lets you execute different code depending on whether a value matches a pattern:

```rust
use std::time::Duration;
```

```rust
fn sleep_for(secs: f32) {
    let result = Duration::try_from_secs_f32(secs);

    if let Ok(duration) = result {
        std::thread::sleep(duration);
        println!("slept for {duration:?}");
    }
}

fn main() {
    sleep_for(-10.0);
    sleep_for(0.8);
}
```

- Unlike `match`, `if let` does not have to cover all branches. This can make it more concise than `match`.
- A common usage is handling `Some` values when working with `Option`.
- Unlike `match`, `if let` does not support guard clauses for pattern matching.
- With an `else` clause, this can be used as an expression.

12.5.2 `while let` Statements

Like with `if let`, there is a `while let` variant that repeatedly tests a value against a pattern:

```rust
fn main() {
    let mut name = String::from("Comprehensive Rust 🦀");
    while let Some(c) = name.pop() {
        dbg!(c);
    }
    // (There are more efficient ways to reverse a string!)
}
```

Here `String::pop` returns `Some(c)` until the string is empty, after which it will return `None`. The `while let` lets us keep iterating through all items.

- Point out that the `while let` loop will keep going as long as the value matches the pattern.
- You could rewrite the `while let` loop as an infinite loop with an if statement that breaks when there is no value to unwrap for `name.pop()`. The `while let` provides syntactic sugar for the above scenario.
- This form cannot be used as an expression, because it may have no value if the condition is false.

12.5.3 `let else` Statements

For the common case of matching a pattern and returning from the function, use `let else`. The "else" case must diverge (`return`, `break`, or panic - anything but falling off the end of the block).

```rust
fn hex_or_die_trying(maybe_string: Option<String>) -> Result<u32, String> {
    let s = if let Some(s) = maybe_string {
        s
    } else {
```

```
        return Err(String::from("got None"));
    };

    let first_byte_char = if let Some(first) = s.chars().next() {
        first
    } else {
        return Err(String::from("got empty string"));
    };

    let digit = if let Some(digit) = first_byte_char.to_digit(16) {
        digit
    } else {
        return Err(String::from("not a hex digit"));
    };

    Ok(digit)
}

fn main() {
    println!("result: {:?}", hex_or_die_trying(Some(String::from("foo"))));
}
```

The rewritten version is:

```
fn hex_or_die_trying(maybe_string: Option<String>) -> Result<u32, String> {
    let Some(s) = maybe_string else {
        return Err(String::from("got None"));
    };

    let Some(first_byte_char) = s.chars().next() else {
        return Err(String::from("got empty string"));
    };

    let Some(digit) = first_byte_char.to_digit(16) else {
        return Err(String::from("not a hex digit"));
    };

    Ok(digit)
}
```

More to Explore

- This early return-based control flow is common in Rust error handling code, where you try to get a value out of a `Result`, returning an error if the `Result` was `Err`.
- If students ask, you can also demonstrate how real error handling code would be written with `?`.

12.6 Exercise: Expression Evaluation

Let's write a simple recursive evaluator for arithmetic expressions.

An example of a small arithmetic expression could be `10 + 20`, which evaluates to `30`. We can represent the expression as a tree:

```
            .-------.
    .------ |   +   | ------.
    |       '-------'       |
    v                       v
.--------.              .--------.
|   10   |              |   20   |
'--------'              '--------'
```

A bigger and more complex expression would be `(10 * 9) + ((3 - 4) * 5)`, which evaluates to 85. We represent this as a much bigger tree:

```
                              .-----.
            .---------------- |  +  | ----------------.
            |                 '-----'                 |
            v                                         v
         .-----.                                   .-----.
   .---- |  *  | ----.                       .---- |  *  | ----.
   |     '-----'     |                       |     '-----'     |
   v                 v                       v                 v
.------.          .-----.                 .-----.           .-----.
|  10  |          |  9  |           .---- |  "-"| ----.     |  5  |
'------'          '-----'           |     '-----'     |     '-----'
                                    v                 v
                                 .-----.           .-----.
                                 |  3  |           |  4  |
                                 '-----'           '-----'
```

In code, we will represent the tree with two types:

```
/// An operation to perform on two subexpressions.
#[derive(Debug)]
enum Operation {
    Add,
    Sub,
    Mul,
    Div,
}

/// An expression, in tree form.
#[derive(Debug)]
enum Expression {
    /// An operation on two subexpressions.
    Op { op: Operation, left: Box<Expression>, right: Box<Expression> },

    /// A literal value
    Value(i64),
}
```

The Box type here is a smart pointer, and will be covered in detail later in the course. An expression can be "boxed" with `Box::new` as seen in the tests. To evaluate a boxed expression, use the deref operator (`*`) to "unbox" it: `eval(*boxed_expr)`.

Copy and paste the code into the Rust playground, and begin implementing `eval`. The final product should pass the tests. It may be helpful to use `todo!()` and get the tests to pass one-by-one. You can also skip a test temporarily with `#[ignore]`:

```
#[test]
#[ignore]
fn test_value() { .. }
```

```rust
/// An operation to perform on two subexpressions.
#[derive(Debug)]
enum Operation {
    Add,
    Sub,
    Mul,
    Div,
}

/// An expression, in tree form.
#[derive(Debug)]
enum Expression {
    /// An operation on two subexpressions.
    Op { op: Operation, left: Box<Expression>, right: Box<Expression> },

    /// A literal value
    Value(i64),
}

fn eval(e: Expression) -> i64 {
    todo!()
}

#[test]
fn test_value() {
    assert_eq!(eval(Expression::Value(19)), 19);
}

#[test]
fn test_sum() {
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Add,
            left: Box::new(Expression::Value(10)),
            right: Box::new(Expression::Value(20)),
        }),
        30
    );
}

#[test]
fn test_recursion() {
    let term1 = Expression::Op {
        op: Operation::Mul,
```

```
        left: Box::new(Expression::Value(10)),
        right: Box::new(Expression::Value(9)),
    };
    let term2 = Expression::Op {
        op: Operation::Mul,
        left: Box::new(Expression::Op {
            op: Operation::Sub,
            left: Box::new(Expression::Value(3)),
            right: Box::new(Expression::Value(4)),
        }),
        right: Box::new(Expression::Value(5)),
    };
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Add,
            left: Box::new(term1),
            right: Box::new(term2),
        }),
        85
    );
}

#[test]
fn test_zeros() {
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Add,
            left: Box::new(Expression::Value(0)),
            right: Box::new(Expression::Value(0))
        }),
        0
    );
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Mul,
            left: Box::new(Expression::Value(0)),
            right: Box::new(Expression::Value(0))
        }),
        0
    );
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Sub,
            left: Box::new(Expression::Value(0)),
            right: Box::new(Expression::Value(0))
        }),
        0
    );
}

#[test]
```

```rust
fn test_div() {
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Div,
            left: Box::new(Expression::Value(10)),
            right: Box::new(Expression::Value(2)),
        }),
        5
    )
}
```

12.6.1 Solution

```rust
/// An operation to perform on two subexpressions.
#[derive(Debug)]
enum Operation {
    Add,
    Sub,
    Mul,
    Div,
}

/// An expression, in tree form.
#[derive(Debug)]
enum Expression {
    /// An operation on two subexpressions.
    Op { op: Operation, left: Box<Expression>, right: Box<Expression> },

    /// A literal value
    Value(i64),
}

fn eval(e: Expression) -> i64 {
    match e {
        Expression::Op { op, left, right } => {
            let left = eval(*left);
            let right = eval(*right);
            match op {
                Operation::Add => left + right,
                Operation::Sub => left - right,
                Operation::Mul => left * right,
                Operation::Div => left / right,
            }
        }
        Expression::Value(v) => v,
    }
}

#[test]
fn test_value() {
    assert_eq!(eval(Expression::Value(19)), 19);
```

```
}

#[test]
fn test_sum() {
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Add,
            left: Box::new(Expression::Value(10)),
            right: Box::new(Expression::Value(20)),
        }),
        30
    );
}

#[test]
fn test_recursion() {
    let term1 = Expression::Op {
        op: Operation::Mul,
        left: Box::new(Expression::Value(10)),
        right: Box::new(Expression::Value(9)),
    };
    let term2 = Expression::Op {
        op: Operation::Mul,
        left: Box::new(Expression::Op {
            op: Operation::Sub,
            left: Box::new(Expression::Value(3)),
            right: Box::new(Expression::Value(4)),
        }),
        right: Box::new(Expression::Value(5)),
    };
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Add,
            left: Box::new(term1),
            right: Box::new(term2),
        }),
        85
    );
}

#[test]
fn test_zeros() {
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Add,
            left: Box::new(Expression::Value(0)),
            right: Box::new(Expression::Value(0))
        }),
        0
    );
    assert_eq!(
```

```rust
        eval(Expression::Op {
            op: Operation::Mul,
            left: Box::new(Expression::Value(0)),
            right: Box::new(Expression::Value(0))
        }),
        0
    );
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Sub,
            left: Box::new(Expression::Value(0)),
            right: Box::new(Expression::Value(0))
        }),
        0
    );
}

#[test]
fn test_div() {
    assert_eq!(
        eval(Expression::Op {
            op: Operation::Div,
            left: Box::new(Expression::Value(10)),
            right: Box::new(Expression::Value(2)),
        }),
        5
    )
}
```

Chapter 13

Methods and Traits

This segment should take about 45 minutes. It contains:

Slide	Duration
Methods	10 minutes
Traits	15 minutes
Deriving	3 minutes
Exercise: Generic Logger	15 minutes

13.1 Methods

Rust allows you to associate functions with your new types. You do this with an `impl` block:

```
#[derive(Debug)]
struct CarRace {
    name: String,
    laps: Vec<i32>,
}

impl CarRace {
    // No receiver, a static method
    fn new(name: &str) -> Self {
        Self { name: String::from(name), laps: Vec::new() }
    }

    // Exclusive borrowed read-write access to self
    fn add_lap(&mut self, lap: i32) {
        self.laps.push(lap);
    }

    // Shared and read-only borrowed access to self
    fn print_laps(&self) {
        println!("Recorded {} laps for {}:", self.laps.len(), self.name);
        for (idx, lap) in self.laps.iter().enumerate() {
```

```rust
            println!("Lap {idx}: {lap} sec");
        }
    }

    // Exclusive ownership of self (covered later)
    fn finish(self) {
        let total: i32 = self.laps.iter().sum();
        println!("Race {} is finished, total lap time: {}", self.name, total);
    }
}

fn main() {
    let mut race = CarRace::new("Monaco Grand Prix");
    race.add_lap(70);
    race.add_lap(68);
    race.print_laps();
    race.add_lap(71);
    race.print_laps();
    race.finish();
    // race.add_lap(42);
}
```

The `self` arguments specify the "receiver" - the object the method acts on. There are several common receivers for a method:

- `&self`: borrows the object from the caller using a shared and immutable reference. The object can be used again afterwards.
- `&mut self`: borrows the object from the caller using a unique and mutable reference. The object can be used again afterwards.
- `self`: takes ownership of the object and moves it away from the caller. The method becomes the owner of the object. The object will be dropped (deallocated) when the method returns, unless its ownership is explicitly transmitted. Complete ownership does not automatically mean mutability.
- `mut self`: same as above, but the method can mutate the object.
- No receiver: this becomes a static method on the struct. Typically used to create constructors that are called `new` by convention.

This slide should take about 8 minutes.

Key Points:

- It can be helpful to introduce methods by comparing them to functions.
  - Methods are called on an instance of a type (such as a struct or enum), the first parameter represents the instance as `self`.
  - Developers may choose to use methods to take advantage of method receiver syntax and to help keep them more organized. By using methods we can keep all the implementation code in one predictable place.
  - Note that methods can also be called like associated functions by explicitly passing the receiver in, e.g. `CarRace::add_lap(&mut race, 20)`.
- Point out the use of the keyword `self`, a method receiver.
  - Show that it is an abbreviated term for `self: Self` and perhaps show how the struct name could also be used.
  - Explain that `Self` is a type alias for the type the `impl` block is in and can be used

elsewhere in the block.
  - Note how `self` is used like other structs and dot notation can be used to refer to individual fields.
  - This might be a good time to demonstrate how the `&self` differs from `self` by trying to run `finish` twice.
  - Beyond variants on `self`, there are also special wrapper types allowed to be receiver types, such as `Box<Self>`.

13.2 Traits

Rust lets you abstract over types with traits. They're similar to interfaces:

```
trait Pet {
    /// Return a sentence from this pet.
    fn talk(&self) -> String;

    /// Print a string to the terminal greeting this pet.
    fn greet(&self);
}
```

This slide and its sub-slides should take about 15 minutes.

- A trait defines a number of methods that types must have in order to implement the trait.
- In the "Generics" segment, next, we will see how to build functionality that is generic over all types implementing a trait.

13.2.1 Implementing Traits

```
trait Pet {
    fn talk(&self) -> String;

    fn greet(&self) {
        println!("Oh you're a cutie! What's your name? {}", self.talk());
    }
}

struct Dog {
    name: String,
    age: i8,
}

impl Pet for Dog {
    fn talk(&self) -> String {
        format!("Woof, my name is {}!", self.name)
    }
}

fn main() {
    let fido = Dog { name: String::from("Fido"), age: 5 };
    dbg!(fido.talk());
```

```
    fido.greet();
}
```

- To implement `Trait` for `Type`, you use an `impl Trait for Type { .. }` block.
- Unlike Go interfaces, just having matching methods is not enough: a `Cat` type with a `talk()` method would not automatically satisfy `Pet` unless it is in an `impl Pet` block.
- Traits may provide default implementations of some methods. Default implementations can rely on all the methods of the trait. In this case, `greet` is provided, and relies on `talk`.
- Multiple `impl` blocks are allowed for a given type. This includes both inherent `impl` blocks and trait `impl` blocks. Likewise multiple traits can be implemented for a given type (and often types implement many traits!). `impl` blocks can even be spread across multiple modules/files.

13.2.2 Supertraits

A trait can require that types implementing it also implement other traits, called *supertraits*. Here, any type implementing `Pet` must implement `Animal`.

```
trait Animal {
    fn leg_count(&self) -> u32;
}

trait Pet: Animal {
    fn name(&self) -> String;
}

struct Dog(String);

impl Animal for Dog {
    fn leg_count(&self) -> u32 {
        4
    }
}

impl Pet for Dog {
    fn name(&self) -> String {
        self.0.clone()
    }
}

fn main() {
    let puppy = Dog(String::from("Rex"));
    println!("{} has {} legs", puppy.name(), puppy.leg_count());
}
```

This is sometimes called ”trait inheritance” but students should not expect this to behave like OO inheritance. It just specifies an additional requirement on implementations of a trait.

13.2.3 Associated Types

Associated types are placeholder types that are supplied by the trait implementation.

```
#[derive(Debug)]
struct Meters(i32);
#[derive(Debug)]
struct MetersSquared(i32);

trait Multiply {
    type Output;
    fn multiply(&self, other: &Self) -> Self::Output;
}

impl Multiply for Meters {
    type Output = MetersSquared;
    fn multiply(&self, other: &Self) -> Self::Output {
        MetersSquared(self.0 * other.0)
    }
}

fn main() {
    println!("{:?}", Meters(10).multiply(&Meters(20)));
}
```

- Associated types are sometimes also called "output types". The key observation is that the implementer, not the caller, chooses this type.
- Many standard library traits have associated types, including arithmetic operators and `Iterator`.

13.3 Deriving

Supported traits can be automatically implemented for your custom types, as follows:

```
#[derive(Debug, Clone, Default)]
struct Player {
    name: String,
    strength: u8,
    hit_points: u8,
}

fn main() {
    let p1 = Player::default(); // Default trait adds `default` constructor.
    let mut p2 = p1.clone(); // Clone trait adds `clone` method.
    p2.name = String::from("EldurScrollz");
    // Debug trait adds support for printing with `{:?}`.
    println!("{p1:?} vs. {p2:?}");
}
```

This slide should take about 3 minutes.

- Derivation is implemented with macros, and many crates provide useful derive macros to add useful functionality. For example, serde can derive serialization support for a struct using #[derive(Serialize)].

- Derivation is usually provided for traits that have a common boilerplate implementation that is correct for most cases. For example, demonstrate how a manual Clone impl can be repetitive compared to deriving the trait:

  ```
  impl Clone for Player {
      fn clone(&self) -> Self {
          Player {
              name: self.name.clone(),
              strength: self.strength.clone(),
              hit_points: self.hit_points.clone(),
          }
      }
  }
  ```

  Not all of the .clone()s in the above are necessary in this case, but this demonstrates the generally boilerplate-y pattern that manual impls would follow, which should help make the use of derive clear to students.

13.4 Exercise: Logger Trait

Let's design a simple logging utility, using a trait Logger with a log method. Code that might log its progress can then take an &impl Logger. In testing, this might put messages in the test logfile, while in a production build it would send messages to a log server.

However, the StderrLogger given below logs all messages, regardless of verbosity. Your task is to write a VerbosityFilter type that will ignore messages above a maximum verbosity.

This is a common pattern: a struct wrapping a trait implementation and implementing that same trait, adding behavior in the process. In the "Generics" segment, we will see how to make the wrapper generic over the wrapped type.

```
trait Logger {
    /// Log a message at the given verbosity level.
    fn log(&self, verbosity: u8, message: &str);
}

struct StderrLogger;

impl Logger for StderrLogger {
    fn log(&self, verbosity: u8, message: &str) {
        eprintln!("verbosity={verbosity}: {message}");
    }
}

/// Only log messages up to the given verbosity level.
struct VerbosityFilter {
    max_verbosity: u8,
    inner: StderrLogger,
}
```

```rust
// TODO: Implement the `Logger` trait for `VerbosityFilter`.

fn main() {
    let logger = VerbosityFilter { max_verbosity: 3, inner: StderrLogger };
    logger.log(5, "FYI");
    logger.log(2, "Uhoh");
}
```

13.4.1 Solution

```rust
trait Logger {
    /// Log a message at the given verbosity level.
    fn log(&self, verbosity: u8, message: &str);
}

struct StderrLogger;

impl Logger for StderrLogger {
    fn log(&self, verbosity: u8, message: &str) {
        eprintln!("verbosity={verbosity}: {message}");
    }
}

/// Only log messages up to the given verbosity level.
struct VerbosityFilter {
    max_verbosity: u8,
    inner: StderrLogger,
}

impl Logger for VerbosityFilter {
    fn log(&self, verbosity: u8, message: &str) {
        if verbosity <= self.max_verbosity {
            self.inner.log(verbosity, message);
        }
    }
}

fn main() {
    let logger = VerbosityFilter { max_verbosity: 3, inner: StderrLogger };
    logger.log(5, "FYI");
    logger.log(2, "Uhoh");
}
```

Chapter 14

Generics

This segment should take about 50 minutes. It contains:

Slide	Duration
Generic Functions	5 minutes
Trait Bounds	10 minutes
Generic Data Types	10 minutes
Generic Traits	5 minutes
impl Trait	5 minutes
dyn Trait	5 minutes
Exercise: Generic min	10 minutes

14.1 Generic Functions

Rust supports generics, which lets you abstract algorithms or data structures (such as sorting or a binary tree) over the types used or stored.

```rust
fn pick<T>(cond: bool, left: T, right: T) -> T {
    if cond { left } else { right }
}

fn main() {
    println!("picked a number: {:?}", pick(true, 222, 333));
    println!("picked a string: {:?}", pick(false, 'L', 'R'));
}
```

This slide should take about 5 minutes.

- It can be helpful to show the monomorphized versions of `pick`, either before talking about the generic `pick` in order to show how generics can reduce code duplication, or after talking about generics to show how monomorphization works.

  ```rust
  fn pick_i32(cond: bool, left: i32, right: i32) -> i32 {
      if cond { left } else { right }
  }
  ```

```rust
fn pick_char(cond: bool, left: char, right: char) -> char {
    if cond { left } else { right }
}
```

- Rust infers a type for T based on the types of the arguments and return value.
- In this example we only use the primitive types `i32` and `char` for `T`, but we can use any type here, including user-defined types:

```rust
struct Foo {
    val: u8,
}

pick(false, Foo { val: 7 }, Foo { val: 99 });
```

- This is similar to C++ templates, but Rust partially compiles the generic function immediately, so that function must be valid for all types matching the constraints. For example, try modifying `pick` to return `left + right` if `cond` is false. Even if only the `pick` instantiation with integers is used, Rust still considers it invalid. C++ would let you do this.
- Generic code is turned into non-generic code based on the call sites. This is a zero-cost abstraction: you get exactly the same result as if you had hand-coded the data structures without the abstraction.

14.2 Trait Bounds

When working with generics, you often want to require the types to implement some trait, so that you can call this trait's methods.

You can do this with `T: Trait`:

```rust
fn duplicate<T: Clone>(a: T) -> (T, T) {
    (a.clone(), a.clone())
}

struct NotCloneable;

fn main() {
    let foo = String::from("foo");
    let pair = duplicate(foo);
    println!("{pair:?}");
}
```

This slide should take about 8 minutes.

- Try making a `NotCloneable` and passing it to `duplicate`.
- When multiple traits are necessary, use `+` to join them.
- Show a `where` clause, students will encounter it when reading code.

```rust
fn duplicate<T>(a: T) -> (T, T)
where
    T: Clone,
```

```
    {
        (a.clone(), a.clone())
    }
```

- It declutters the function signature if you have many parameters.
- It has additional features making it more powerful.
  * If someone asks, the extra feature is that the type on the left of ":" can be arbitrary, like `Option<T>`.

- Note that Rust does not (yet) support specialization. For example, given the original `duplicate`, it is invalid to add a specialized `duplicate(a: u32)`.

14.3 Generic Data Types

You can use generics to abstract over the concrete field type. Returning to the exercise for the previous segment:

```rust
pub trait Logger {
    /// Log a message at the given verbosity level.
    fn log(&self, verbosity: u8, message: &str);
}

struct StderrLogger;

impl Logger for StderrLogger {
    fn log(&self, verbosity: u8, message: &str) {
        eprintln!("verbosity={verbosity}: {message}");
    }
}

/// Only log messages up to the given verbosity level.
struct VerbosityFilter<L> {
    max_verbosity: u8,
    inner: L,
}

impl<L: Logger> Logger for VerbosityFilter<L> {
    fn log(&self, verbosity: u8, message: &str) {
        if verbosity <= self.max_verbosity {
            self.inner.log(verbosity, message);
        }
    }
}

fn main() {
    let logger = VerbosityFilter { max_verbosity: 3, inner: StderrLogger };
    logger.log(5, "FYI");
    logger.log(2, "Uhoh");
}
```

This slide should take about 10 minutes.

- *Q:* Why is L specified twice in impl<L: Logger> .. VerbosityFilter<L>? Isn't that redundant?
  - This is because it is a generic implementation section for generic type. They are independently generic.
  - It means these methods are defined for any L.
  - It is possible to write impl VerbosityFilter<StderrLogger> { .. }.
    - VerbosityFilter is still generic and you can use VerbosityFilter<f64>, but methods in this block will only be available for VerbosityFilter<StderrLogger>.
- Note that we don't put a trait bound on the VerbosityFilter type itself. You can put bounds there as well, but generally in Rust we only put the trait bounds on the impl blocks.

14.4 Generic Traits

Traits can also be generic, just like types and functions. A trait's parameters get concrete types when it is used. For example the From<T> trait is used to define type conversions:

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

#[derive(Debug)]
struct Foo(String);

impl From<u32> for Foo {
    fn from(from: u32) -> Foo {
        Foo(format!("Converted from integer: {from}"))
    }
}

impl From<bool> for Foo {
    fn from(from: bool) -> Foo {
        Foo(format!("Converted from bool: {from}"))
    }
}

fn main() {
    let from_int = Foo::from(123);
    let from_bool = Foo::from(true);
    dbg!(from_int);
    dbg!(from_bool);
}
```

This slide should take about 5 minutes.

- The From trait will be covered later in the course, but its definition in the std docs is simple, and copied here for reference.
- Implementations of the trait do not need to cover all possible type parameters. Here, Foo::from("hello") would not compile because there is no From<&str> implementation for Foo.

- Generic traits take types as ”input”, while associated types are a kind of ”output” type. A trait can have multiple implementations for different input types.
- In fact, Rust requires that at most one implementation of a trait match for any type T. Unlike some other languages, Rust has no heuristic for choosing the ”most specific” match. There is work on adding this support, called specialization.

14.5 impl Trait

Similar to trait bounds, an `impl Trait` syntax can be used in function arguments and return values:

```
// Syntactic sugar for:
//   fn add_42_millions<T: Into<i32>>(x: T) -> i32 {
fn add_42_millions(x: impl Into<i32>) -> i32 {
    x.into() + 42_000_000
}

fn pair_of(x: u32) -> impl std::fmt::Debug {
    (x + 1, x - 1)
}

fn main() {
    let many = add_42_millions(42_i8);
    dbg!(many);
    let many_more = add_42_millions(10_000_000);
    dbg!(many_more);
    let debuggable = pair_of(27);
    dbg!(debuggable);
}
```

This slide should take about 5 minutes.

`impl Trait` allows you to work with types that you cannot name. The meaning of `impl Trait` is a bit different in the different positions.

- For a parameter, `impl Trait` is like an anonymous generic parameter with a trait bound.
- For a return type, it means that the return type is some concrete type that implements the trait, without naming the type. This can be useful when you don't want to expose the concrete type in a public API.

  Inference is hard in return position. A function returning `impl Foo` picks the concrete type it returns, without writing it out in the source. A function returning a generic type like `collect<B>() -> B` can return any type satisfying `B`, and the caller may need to choose one, such as with `let x: Vec<_> = foo.collect()` or with the turbofish, `foo.collect::<Vec<_>>()`.

What is the type of `debuggable`? Try `let debuggable: () = ..` to see what the error message shows.

14.6 dyn Trait

In addition to using traits for static dispatch via generics, Rust also supports using them for type-erased, dynamic dispatch via trait objects:

```rust
struct Dog {
    name: String,
    age: i8,
}
struct Cat {
    lives: i8,
}

trait Pet {
    fn talk(&self) -> String;
}

impl Pet for Dog {
    fn talk(&self) -> String {
        format!("Woof, my name is {}!", self.name)
    }
}

impl Pet for Cat {
    fn talk(&self) -> String {
        String::from("Miau!")
    }
}

// Uses generics and static dispatch.
fn generic(pet: &impl Pet) {
    println!("Hello, who are you? {}", pet.talk());
}

// Uses type-erasure and dynamic dispatch.
fn dynamic(pet: &dyn Pet) {
    println!("Hello, who are you? {}", pet.talk());
}

fn main() {
    let cat = Cat { lives: 9 };
    let dog = Dog { name: String::from("Fido"), age: 5 };

    generic(&cat);
    generic(&dog);

    dynamic(&cat);
    dynamic(&dog);
}
```

This slide should take about 5 minutes.

- Generics, including `impl Trait`, use monomorphization to create a specialized instance of the function for each different type that the generic is instantiated with. This means that calling a trait method from within a generic function still uses static dispatch, as the compiler has full type information and can resolve that type's trait implementation to use.
- When using `dyn Trait`, it instead uses dynamic dispatch through a virtual method table (vtable). This means that there's a single version of `fn dynamic` that is used regardless of what type of `Pet` is passed in.
- When using `dyn Trait`, the trait object needs to be behind some kind of indirection. In this case it's a reference, though smart pointer types like `Box` can also be used (this will be demonstrated on day 3).
- At runtime, a `&dyn Pet` is represented as a "fat pointer", i.e. a pair of two pointers: One pointer points to the concrete object that implements `Pet`, and the other points to the vtable for the trait implementation for that type. When calling the `talk` method on `&dyn Pet` the compiler looks up the function pointer for `talk` in the vtable and then invokes the function, passing the pointer to the `Dog` or `Cat` into that function. The compiler doesn't need to know the concrete type of the `Pet` in order to do this.
- A `dyn Trait` is considered to be "type-erased", because we no longer have compile-time knowledge of what the concrete type is.

14.7 Exercise: Generic `min`

In this short exercise, you will implement a generic `min` function that determines the minimum of two values, using the `Ord` trait.

```rust
use std::cmp::Ordering;

// TODO: implement the `min` function used in the tests.

#[test]
fn integers() {
    assert_eq!(min(0, 10), 0);
    assert_eq!(min(500, 123), 123);
}

#[test]
fn chars() {
    assert_eq!(min('a', 'z'), 'a');
    assert_eq!(min('7', '1'), '1');
}

#[test]
fn strings() {
    assert_eq!(min("hello", "goodbye"), "goodbye");
    assert_eq!(min("bat", "armadillo"), "armadillo");
}
```

This slide and its sub-slides should take about 10 minutes.

- Show students the `Ord` trait and `Ordering` enum.

14.7.1 Solution

```rust
use std::cmp::Ordering;

fn min<T: Ord>(l: T, r: T) -> T {
    match l.cmp(&r) {
        Ordering::Less | Ordering::Equal => l,
        Ordering::Greater => r,
    }
}

#[test]
fn integers() {
    assert_eq!(min(0, 10), 0);
    assert_eq!(min(500, 123), 123);
}

#[test]
fn chars() {
    assert_eq!(min('a', 'z'), 'a');
    assert_eq!(min('7', '1'), '1');
}

#[test]
fn strings() {
    assert_eq!(min("hello", "goodbye"), "goodbye");
    assert_eq!(min("bat", "armadillo"), "armadillo");
}
```

Part IV

Day 2: Afternoon

Chapter 15

Welcome Back

Including 10 minute breaks, this session should take about 2 hours and 50 minutes. It contains:

Segment	Duration
Closures	30 minutes
Standard Library Types	1 hour
Standard Library Traits	1 hour

Chapter 16

Closures

This segment should take about 30 minutes. It contains:

Slide	Duration
Closure Syntax	3 minutes
Capturing	5 minutes
Closure Traits	10 minutes
Exercise: Log Filter	10 minutes

16.1 Closure Syntax

Closures are created with vertical bars: `|..| ..`.

```
fn main() {
    // Argument and return type can be inferred for lightweight syntax:
    let double_it = |n| n * 2;
    dbg!(double_it(50));

    // Or we can specify types and bracket the body to be fully explicit:
    let add_1f32 = |x: f32| -> f32 { x + 1.0 };
    dbg!(add_1f32(50.));
}
```

This slide should take about 3 minutes.

- The arguments go between the `|..|`. The body can be surrounded by `{ .. }`, but if it is a single expression these can be omitted.
- Argument types are optional, and are inferred if not given. The return type is also optional, but can only be written if using `{ .. }` around the body.
- The examples can both be written as mere nested functions instead -- they do not capture any variables from their lexical environment. We will see captures next.

More to Explore

- The ability to store functions in variables doesn't just apply to closures, regular functions can be put in variables and then invoked the same way that closures can: Example in the playground.
  - The linked example also demonstrates that closures that don't capture anything can also coerce to a regular function pointer.

16.2 Capturing

A closure can capture variables from the environment where it was defined.

```
fn main() {
    let max_value = 5;
    let clamp = |v| {
        if v > max_value { max_value } else { v }
    };

    dbg!(clamp(1));
    dbg!(clamp(3));
    dbg!(clamp(5));
    dbg!(clamp(7));
    dbg!(clamp(10));
}
```

This slide should take about 5 minutes.

- By default, a closure captures values by reference. Here `max_value` is captured by `clamp`, but still available to `main` for printing. Try making `max_value` mutable, changing it, and printing the clamped values again. Why doesn't this work?
- If a closure mutates values, it will capture them by mutable reference. Try adding `max_value += 1` to `clamp`.
- You can force a closure to move values instead of referencing them with the `move` keyword. This can help with lifetimes, for example if the closure must outlive the captured values (more on lifetimes later).

  This looks like `move |v| ..`. Try adding this keyword and see if `main` can still access `max_value` after defining `clamp`.
- By default, closures will capture each variable from an outer scope by the least demanding form of access they can (by shared reference if possible, then exclusive reference, then by move). The `move` keyword forces capture by value.

16.3 Closure traits

Closures or lambda expressions have types that cannot be named. However, they implement special `Fn`, `FnMut`, and `FnOnce` traits:

The special types `fn(..) -> T` refer to function pointers - either the address of a function, or a closure that captures nothing.

```rust
fn apply_and_log(
    func: impl FnOnce(&'static str) -> String,
    func_name: &'static str,
    input: &'static str,
) {
    println!("Calling {func_name}({input}): {}", func(input))
}

fn main() {
    let suffix = "-itis";
    let add_suffix = |x| format!("{x}{suffix}");
    apply_and_log(&add_suffix, "add_suffix", "senior");
    apply_and_log(&add_suffix, "add_suffix", "appendix");

    let mut v = Vec::new();
    let mut accumulate = |x| {
        v.push(x);
        v.join("/")
    };
    apply_and_log(&mut accumulate, "accumulate", "red");
    apply_and_log(&mut accumulate, "accumulate", "green");
    apply_and_log(&mut accumulate, "accumulate", "blue");

    let take_and_reverse = |prefix| {
        let mut acc = String::from(prefix);
        acc.push_str(&v.into_iter().rev().collect::<Vec<_>>().join("/"));
        acc
    };
    apply_and_log(take_and_reverse, "take_and_reverse", "reversed: ");
}
```

This slide should take about 10 minutes.

An `Fn` (e.g. `add_suffix`) neither consumes nor mutates captured values. It can be called needing only a shared reference to the closure, which means the closure can be executed repeatedly and even concurrently.

An `FnMut` (e.g. `accumulate`) might mutate captured values. The closure object is accessed via exclusive reference, so it can be called repeatedly but not concurrently.

If you have an `FnOnce` (e.g. `take_and_reverse`), you may only call it once. Doing so consumes the closure and any values captured by move.

`FnMut` is a subtype of `FnOnce`. `Fn` is a subtype of `FnMut` and `FnOnce`. I.e. you can use an `FnMut` wherever an `FnOnce` is called for, and you can use an `Fn` wherever an `FnMut` or `FnOnce` is called for.

When you define a function that takes a closure, you should take `FnOnce` if you can (i.e. you call it once), or `FnMut` else, and last `Fn`. This allows the most flexibility for the caller.

In contrast, when you have a closure, the most flexible you can have is `Fn` (which can be passed to a consumer of any of the three closure traits), then `FnMut`, and lastly `FnOnce`.

The compiler also infers `Copy` (e.g. for `add_suffix`) and `Clone` (e.g. `take_and_reverse`), depending on what the closure captures. Function pointers (references to `fn` items) implement

Copy and Fn.

16.4 Exercise: Log Filter

Building on the generic logger from this morning, implement a `Filter` that uses a closure to filter log messages, sending those that pass the filtering predicate to an inner logger.

```
pub trait Logger {
    /// Log a message at the given verbosity level.
    fn log(&self, verbosity: u8, message: &str);
}

struct StderrLogger;

impl Logger for StderrLogger {
    fn log(&self, verbosity: u8, message: &str) {
        eprintln!("verbosity={verbosity}: {message}");
    }
}

// TODO: Define and implement `Filter`.

fn main() {
    let logger = Filter::new(StderrLogger, |_verbosity, msg| msg.contains("yikes"));
    logger.log(5, "FYI");
    logger.log(1, "yikes, something went wrong");
    logger.log(2, "uhoh");
}
```

16.4.1 Solution

```
pub trait Logger {
    /// Log a message at the given verbosity level.
    fn log(&self, verbosity: u8, message: &str);
}

struct StderrLogger;

impl Logger for StderrLogger {
    fn log(&self, verbosity: u8, message: &str) {
        eprintln!("verbosity={verbosity}: {message}");
    }
}

/// Only log messages matching a filtering predicate.
struct Filter<L, P> {
    inner: L,
    predicate: P,
}
```

```rust
impl<L, P> Filter<L, P>
where
    L: Logger,
    P: Fn(u8, &str) -> bool,
{
    fn new(inner: L, predicate: P) -> Self {
        Self { inner, predicate }
    }
}
impl<L, P> Logger for Filter<L, P>
where
    L: Logger,
    P: Fn(u8, &str) -> bool,
{
    fn log(&self, verbosity: u8, message: &str) {
        if (self.predicate)(verbosity, message) {
            self.inner.log(verbosity, message);
        }
    }
}

fn main() {
    let logger = Filter::new(StderrLogger, |_verbosity, msg| msg.contains("yikes"));
    logger.log(5, "FYI");
    logger.log(1, "yikes, something went wrong");
    logger.log(2, "uhoh");
}
```

- **Storing Closures:** To store a closure in a struct, we use a generic type parameter (here `P`). This is because every closure in Rust has a unique, anonymous type generated by the compiler.
- **Fn Trait Bound:** The bound `P: Fn(u8, &str) -> bool` tells the compiler that `P` can be called as a function with the specified arguments and return type. We use `Fn` (instead of `FnMut` or `FnOnce`) because `log` takes `&self`, so we can only access the predicate immutably.
- **Calling fields:** We invoke the closure using `(self.predicate)(...)`. The parentheses around `self.predicate` are necessary to disambiguate between calling a method named `predicate` and calling the field itself.

- Discuss why `Fn` is required. If we used `FnMut`, `log` would need to take `&mut self`, which conflicts with the `Logger` trait signature. If we used `FnOnce`, we could only log a single message!
- The `impl` block for `new` also includes the bounds. While technically not strictly required for the struct definition itself (bounds can be placed only on `impl` blocks that use them), putting them on `new` helps type inference.

Chapter 17

Standard Library Types

This segment should take about 1 hour. It contains:

Slide	Duration
Standard Library	3 minutes
Documentation	5 minutes
Option	10 minutes
Result	5 minutes
String	5 minutes
Vec	5 minutes
HashMap	5 minutes
Exercise: Counter	20 minutes

For each of the slides in this section, spend some time reviewing the documentation pages, highlighting some of the more common methods.

17.1 Standard Library

Rust comes with a standard library that helps establish a set of common types used by Rust libraries and programs. This way, two libraries can work together smoothly because they both use the same `String` type.

In fact, Rust contains several layers of the Standard Library: `core`, `alloc` and `std`.

- `core` includes the most basic types and functions that don't depend on `libc`, allocator or even the presence of an operating system.
- `alloc` includes types that require a global heap allocator, such as `Vec`, `Box` and `Arc`.
- Embedded Rust applications typically only use `core`, and sometimes `alloc`.

17.2 Documentation

Rust comes with extensive documentation. For example:

- All of the details about loops.
- Primitive types like u8.
- Standard library types like `Option` or `BinaryHeap`.

Use `rustup doc --std` or https://std.rs to view the documentation.

In fact, you can document your own code:

```
/// Determine whether the first argument is divisible by the second argument.
///
/// If the second argument is zero, the result is false.
fn is_divisible_by(lhs: u32, rhs: u32) -> bool {
    if rhs == 0 {
        return false;
    }
    lhs % rhs == 0
}
```

The contents are treated as Markdown. All published Rust library crates are automatically documented at `docs.rs` using the rustdoc tool. It is idiomatic to document all public items in an API using this pattern.

To document an item from inside the item (such as inside a module), use `//!` or `/*! .. */`, called "inner doc comments":

```
//! This module contains functionality relating to divisibility of integers.
```

This slide should take about 5 minutes.

- Show students the generated docs for the `rand` crate at https://docs.rs/rand.

17.3 Option

We have already seen some use of `Option<T>`. It stores either a value of type `T` or nothing. For example, `String::find` returns an `Option<usize>`.

```
fn main() {
    let name = "Löwe 老虎 Léopard Gepardi";
    let mut position: Option<usize> = name.find('é');
    dbg!(position);
    assert_eq!(position.unwrap(), 14);
    position = name.find('Z');
    dbg!(position);
    assert_eq!(position.expect("Character not found"), 0);
}
```

This slide should take about 10 minutes.

- `Option` is widely used, not just in the standard library.
- `unwrap` will return the value in an `Option`, or panic. `expect` is similar but takes an error message.
  - You can panic on None, but you can't "accidentally" forget to check for None.
  - It's common to `unwrap`/`expect` all over the place when hacking something together, but production code typically handles None in a nicer fashion.

- The ”niche optimization” means that `Option<T>` typically has the same size in memory as `T`, if there is some representation that is not a valid value of T. For example, a reference cannot be NULL, so `Option<&T>` automatically uses NULL to represent the `None` variant, and thus can be stored in the same memory as `&T`.

17.4 Result

`Result` is similar to `Option`, but indicates the success or failure of an operation, each with a different enum variant. It is generic: `Result<T, E>` where `T` is used in the `Ok` variant and `E` appears in the `Err` variant.

```
use std::fs::File;
use std::io::Read;

fn main() {
    let file: Result<File, std::io::Error> = File::open("diary.txt");
    match file {
        Ok(mut file) => {
            let mut contents = String::new();
            if let Ok(bytes) = file.read_to_string(&mut contents) {
                println!("Dear diary: {contents} ({bytes} bytes)");
            } else {
                println!("Could not read file content");
            }
        }
        Err(err) => {
            println!("The diary could not be opened: {err}");
        }
    }
}
```

This slide should take about 5 minutes.

- As with `Option`, the successful value sits inside of `Result`, forcing the developer to explicitly extract it. This encourages error checking. In the case where an error should never happen, `unwrap()` or `expect()` can be called, and this is a signal of the developer intent too.
- `Result` documentation is a recommended read. Not during the course, but it is worth mentioning. It contains many convenience methods and functions that help functional-style programming.
- `Result` is the standard type to implement error handling as we will see on Day 4.

17.5 String

`String` is a growable UTF-8 encoded string:

```
fn main() {
    let mut s1 = String::new();
    s1.push_str("Hello");
    println!("s1: len = {}, capacity = {}", s1.len(), s1.capacity());
```

```rust
    let mut s2 = String::with_capacity(s1.len() + 1);
    s2.push_str(&s1);
    s2.push('!');
    println!("s2: len = {}, capacity = {}", s2.len(), s2.capacity());

    let s3 = String::from("🇨🇭");
    println!("s3: len = {}, number of chars = {}", s3.len(), s3.chars().count());
}
```

`String` implements `Deref<Target = str>`, which means that you can call all `str` methods on a `String`.

This slide should take about 5 minutes.

- `String::new` returns a new empty string, use `String::with_capacity` when you know how much data you want to push to the string.
- `String::len` returns the size of the `String` in bytes (which can be different from its length in characters).
- `String::chars` returns an iterator over the actual characters. Note that a `char` can be different from what a human will consider a "character" due to grapheme clusters.
- When people refer to strings they could either be talking about `&str` or `String`.
- When a type implements `Deref<Target = T>`, the compiler will let you transparently call methods from `T`.
  - We haven't discussed the `Deref` trait yet, so at this point this mostly explains the structure of the sidebar in the documentation.
  - `String` implements `Deref<Target = str>` which transparently gives it access to `str`'s methods.
  - Write and compare `let s3 = s1.deref();` and `let s3 = &*s1;`.
- `String` is implemented as a wrapper around a vector of bytes, many of the operations you see supported on vectors are also supported on `String`, but with some extra guarantees.
- Compare the different ways to index a `String`:
  - To a character by using `s3.chars().nth(i).unwrap()` where `i` is in-bound, out-of-bounds.
  - To a substring by using `s3[0..4]`, where that slice is on character boundaries or not.
- Many types can be converted to a string with the `to_string` method. This trait is automatically implemented for all types that implement `Display`, so anything that can be formatted can also be converted to a string.

17.6 Vec

`Vec` is the standard resizable heap-allocated buffer:

```rust
fn main() {
    let mut v1 = Vec::new();
    v1.push(42);
    println!("v1: len = {}, capacity = {}", v1.len(), v1.capacity());

    let mut v2 = Vec::with_capacity(v1.len() + 1);
    v2.extend(v1.iter());
    v2.push(9999);
```

```rust
    println!("v2: len = {}, capacity = {}", v2.len(), v2.capacity());

    // Canonical macro to initialize a vector with elements.
    let mut v3 = vec![0, 0, 1, 2, 3, 4];

    // Retain only the even elements.
    v3.retain(|x| x % 2 == 0);
    println!("{v3:?}");

    // Remove consecutive duplicates.
    v3.dedup();
    println!("{v3:?}");
}
```

Vec implements `Deref<Target = [T]>`, which means that you can call slice methods on a `Vec`.

This slide should take about 5 minutes.

- `Vec` is a type of collection, along with `String` and `HashMap`. The data it contains is stored on the heap. This means the amount of data doesn't need to be known at compile time. It can grow or shrink at runtime.
- Notice how `Vec<T>` is a generic type too, but you don't have to specify `T` explicitly. As always with Rust type inference, the `T` was established during the first `push` call.
- `vec![...]` is a canonical macro to use instead of `Vec::new()` and it supports adding initial elements to the vector.
- To index the vector you use `[ ]`, but they will panic if out of bounds. Alternatively, using `get` will return an `Option`. The `pop` function will remove the last element.

17.7 HashMap

Standard hash map with protection against HashDoS attacks:

```rust
use std::collections::HashMap;

fn main() {
    let mut page_counts = HashMap::new();
    page_counts.insert("Adventures of Huckleberry Finn", 207);
    page_counts.insert("Grimms' Fairy Tales", 751);
    page_counts.insert("Pride and Prejudice", 303);

    if !page_counts.contains_key("Les Misérables") {
        println!(
            "We know about {} books, but not Les Misérables.",
            page_counts.len()
        );
    }

    for book in ["Pride and Prejudice", "Alice's Adventure in Wonderland"] {
        match page_counts.get(book) {
            Some(count) => println!("{book}: {count} pages"),
            None => println!("{book} is unknown."),
```

```rust
        }
    }

    // Use the .entry() method to insert a value if nothing is found.
    for book in ["Pride and Prejudice", "Alice's Adventure in Wonderland"] {
        let page_count: &mut i32 = page_counts.entry(book).or_insert(0);
        *page_count += 1;
    }

    dbg!(page_counts);
}
```

This slide should take about 5 minutes.

- `HashMap` is not defined in the prelude and needs to be brought into scope.
- Try the following lines of code. The first line will see if a book is in the hashmap and if not return an alternative value. The second line will insert the alternative value in the hashmap if the book is not found.

  ```rust
  let pc1 = page_counts
      .get("Harry Potter and the Sorcerer's Stone")
      .unwrap_or(&336);
  let pc2 = page_counts
      .entry("The Hunger Games")
      .or_insert(374);
  ```

- Unlike `vec!`, there is unfortunately no standard `hashmap!` macro.
  - Although, since Rust 1.56, HashMap implements `From<[(K, V); N]>`, which allows us to easily initialize a hash map from a literal array:

    ```rust
    let page_counts = HashMap::from([
      ("Harry Potter and the Sorcerer's Stone".to_string(), 336),
      ("The Hunger Games".to_string(), 374),
    ]);
    ```

- Alternatively HashMap can be built from any `Iterator` that yields key-value tuples.
- This type has several ”method-specific” return types, such as `std::collections::hash_map::Keys`. These types often appear in searches of the Rust docs. Show students the docs for this type, and the helpful link back to the `keys` method.

17.8 Exercise: Counter

In this exercise you will take a very simple data structure and make it generic. It uses a `std::collections::HashMap` to keep track of what values have been seen and how many times each one has appeared.

The initial version of `Counter` is hardcoded to only work for `u32` values. Make the struct and its methods generic over the type of value being tracked, that way `Counter` can track any type of value.

If you finish early, try using the `entry` method to halve the number of hash lookups required to implement the `count` method.

```rust
use std::collections::HashMap;

/// Counter counts the number of times each value of type T has been seen.
struct Counter {
    values: HashMap<u32, u64>,
}

impl Counter {
    /// Create a new Counter.
    fn new() -> Self {
        Counter {
            values: HashMap::new(),
        }
    }

    /// Count an occurrence of the given value.
    fn count(&mut self, value: u32) {
        if self.values.contains_key(&value) {
            *self.values.get_mut(&value).unwrap() += 1;
        } else {
            self.values.insert(value, 1);
        }
    }

    /// Return the number of times the given value has been seen.
    fn times_seen(&self, value: u32) -> u64 {
        self.values.get(&value).copied().unwrap_or_default()
    }
}

fn main() {
    let mut ctr = Counter::new();
    ctr.count(13);
    ctr.count(14);
    ctr.count(16);
    ctr.count(14);
    ctr.count(14);
    ctr.count(11);

    for i in 10..20 {
        println!("saw {} values equal to {}", ctr.times_seen(i), i);
    }

    let mut strctr = Counter::new();
    strctr.count("apple");
    strctr.count("orange");
    strctr.count("apple");
    println!("got {} apples", strctr.times_seen("apple"));
}
```

17.8.1 Solution

```rust
use std::collections::HashMap;
use std::hash::Hash;

/// Counter counts the number of times each value of type T has been seen.
struct Counter<T> {
    values: HashMap<T, u64>,
}

impl<T: Eq + Hash> Counter<T> {
    /// Create a new Counter.
    fn new() -> Self {
        Counter { values: HashMap::new() }
    }

    /// Count an occurrence of the given value.
    fn count(&mut self, value: T) {
        *self.values.entry(value).or_default() += 1;
    }

    /// Return the number of times the given value has been seen.
    fn times_seen(&self, value: T) -> u64 {
        self.values.get(&value).copied().unwrap_or_default()
    }
}

fn main() {
    let mut ctr = Counter::new();
    ctr.count(13);
    ctr.count(14);
    ctr.count(16);
    ctr.count(14);
    ctr.count(14);
    ctr.count(11);

    for i in 10..20 {
        println!("saw {} values equal to {}", ctr.times_seen(i), i);
    }

    let mut strctr = Counter::new();
    strctr.count("apple");
    strctr.count("orange");
    strctr.count("apple");
    println!("got {} apples", strctr.times_seen("apple"));
}
```

Chapter 18

Standard Library Traits

This segment should take about 1 hour. It contains:

Slide	Duration
Comparisons	5 minutes
Operators	5 minutes
From and Into	5 minutes
Casting	5 minutes
Read and Write	5 minutes
Default, struct update syntax	5 minutes
Exercise: ROT13	30 minutes

As with the standard library types, spend time reviewing the documentation for each trait.

This section is long. Take a break midway through.

18.1 Comparisons

These traits support comparisons between values. All traits can be derived for types containing fields that implement these traits.

`PartialEq` and `Eq`

`PartialEq` is a partial equivalence relation, with required method `eq` and provided method `ne`. The `==` and `!=` operators will call these methods.

```
struct Key {
    id: u32,
    metadata: Option<String>,
}
impl PartialEq for Key {
    fn eq(&self, other: &Self) -> bool {
        self.id == other.id
```

```
    }
}
```

Eq is a full equivalence relation (reflexive, symmetric, and transitive) and implies PartialEq. Functions that require full equivalence will use Eq as a trait bound.

PartialOrd and Ord

PartialOrd defines a partial ordering, with a partial_cmp method. It is used to implement the <, <=, >=, and > operators.

```
use std::cmp::Ordering;
#[derive(Eq, PartialEq)]
struct Citation {
    author: String,
    year: u32,
}
impl PartialOrd for Citation {
    fn partial_cmp(&self, other: &Self) -> Option<Ordering> {
        match self.author.partial_cmp(&other.author) {
            Some(Ordering::Equal) => self.year.partial_cmp(&other.year),
            author_ord => author_ord,
        }
    }
}
```

Ord is a total ordering, with cmp returning Ordering.

This slide should take about 5 minutes.

- PartialEq can be implemented between different types, but Eq cannot, because it is reflexive:

  ```
  struct Key {
      id: u32,
      metadata: Option<String>,
  }
  impl PartialEq<u32> for Key {
      fn eq(&self, other: &u32) -> bool {
          self.id == *other
      }
  }
  ```

- In practice, it's common to derive these traits, but uncommon to implement them.
- When comparing references in Rust, it will compare the value of the things pointed to, it will NOT compare the references themselves. That means that references to two different things can compare as equal if the values pointed to are the same:

  ```
  fn main() {
      let a = "Hello";
      let b = String::from("Hello");
      assert_eq!(a, b);
  }
  ```

18.2 Operators

Operator overloading is implemented via traits in `std::ops`:

```rust
#[derive(Debug, Copy, Clone)]
struct Point {
    x: i32,
    y: i32,
}

impl std::ops::Add for Point {
    type Output = Self;

    fn add(self, other: Self) -> Self {
        Self { x: self.x + other.x, y: self.y + other.y }
    }
}

fn main() {
    let p1 = Point { x: 10, y: 20 };
    let p2 = Point { x: 100, y: 200 };
    println!("{p1:?} + {p2:?} = {:?}", p1 + p2);
}
```

This slide should take about 5 minutes.

Discussion points:

- You could implement Add for `&Point`. In which situations is that useful?
  - Answer: `Add:add` consumes `self`. If type `T` for which you are overloading the operator is not Copy, you should consider overloading the operator for `&T` as well. This avoids unnecessary cloning on the call site.
- Why is `Output` an associated type? Could it be made a type parameter of the method?
  - Short answer: Function type parameters are controlled by the caller, but associated types (like `Output`) are controlled by the implementer of a trait.
- You could implement Add for two different types, e.g. `impl Add<(i32, i32)> for Point` would add a tuple to a `Point`.

The `Not` trait (`!` operator) is notable because it does not convert the argument to `bool` like the same operator in C-family languages; instead, for integer types it flips each bit of the number, which, arithmetically, is equivalent to subtracting the argument from `-1`: `!5 == -6`.

18.3 `From` and `Into`

Types implement `From` and `Into` to facilitate type conversions. Unlike `as`, these traits correspond to lossless, infallible conversions.

```rust
fn main() {
    let s = String::from("hello");
    let addr = std::net::Ipv4Addr::from([127, 0, 0, 1]);
    let one = i16::from(true);
    let bigger = i32::from(123_i16);
```

```
    println!("{s}, {addr}, {one}, {bigger}");
}
```

Into is automatically implemented when From is implemented:

```
fn main() {
    let s: String = "hello".into();
    let addr: std::net::Ipv4Addr = [127, 0, 0, 1].into();
    let one: i16 = true.into();
    let bigger: i32 = 123_i16.into();
    println!("{s}, {addr}, {one}, {bigger}");
}
```

This slide should take about 5 minutes.

- That's why it is common to only implement `From`, as your type will get `Into` implementation too.
- When declaring a function argument input type like "anything that can be converted into a `String`", the rule is opposite, you should use `Into`. Your function will accept types that implement `From` and those that *only* implement `Into`.

18.4 Casting

Rust has no *implicit* type conversions, but does support explicit casts with `as`. These generally follow C semantics where those are defined.

```
fn main() {
    let value: i64 = 1000;
    println!("as u16: {}", value as u16);
    println!("as i16: {}", value as i16);
    println!("as u8: {}", value as u8);
}
```

The results of `as` are *always* defined in Rust and consistent across platforms. This might not match your intuition for changing sign or casting to a smaller type -- check the docs, and comment for clarity.

Casting with `as` is a relatively sharp tool that is easy to use incorrectly, and can be a source of subtle bugs as future maintenance work changes the types that are used or the ranges of values in types. Casts are best used only when the intent is to indicate unconditional truncation (e.g. selecting the bottom 32 bits of a `u64` with `as u32`, regardless of what was in the high bits).

For infallible casts (e.g. `u32` to `u64`), prefer using `From` or `Into` over `as` to confirm that the cast is in fact infallible. For fallible casts, `TryFrom` and `TryInto` are available when you want to handle casts that fit differently from those that don't.

This slide should take about 5 minutes.

Consider taking a break after this slide.

`as` is similar to a C++ static cast. Use of `as` in cases where data might be lost is generally discouraged, or at least deserves an explanatory comment.

This is common in casting integers to `usize` for use as an index.

18.5 Read and Write

Using Read and BufRead, you can abstract over u8 sources:

```
use std::io::{BufRead, BufReader, Read, Result};

fn count_lines<R: Read>(reader: R) -> usize {
    let buf_reader = BufReader::new(reader);
    buf_reader.lines().count()
}

fn main() -> Result<()> {
    let slice: &[u8] = b"foo\nbar\nbaz\n";
    println!("lines in slice: {}", count_lines(slice));

    let file = std::fs::File::open(std::env::current_exe()?)?;
    println!("lines in file: {}", count_lines(file));
    Ok(())
}
```

Similarly, Write lets you abstract over u8 sinks:

```
use std::io::{Result, Write};

fn log<W: Write>(writer: &mut W, msg: &str) -> Result<()> {
    writer.write_all(msg.as_bytes())?;
    writer.write_all("\n".as_bytes())
}

fn main() -> Result<()> {
    let mut buffer = Vec::new();
    log(&mut buffer, "Hello")?;
    log(&mut buffer, "World")?;
    println!("Logged: {buffer:?}");
    Ok(())
}
```

18.6 The Default Trait

The Default trait produces a default value for a type.

```
#[derive(Debug, Default)]
struct Derived {
    x: u32,
    y: String,
    z: Implemented,
}

#[derive(Debug)]
struct Implemented(String);

impl Default for Implemented {
```

```
    fn default() -> Self {
        Self("John Smith".into())
    }
}

fn main() {
    let default_struct = Derived::default();
    dbg!(default_struct);

    let almost_default_struct =
        Derived { y: "Y is set!".into(), ..Derived::default() };
    dbg!(almost_default_struct);

    let nothing: Option<Derived> = None;
    dbg!(nothing.unwrap_or_default());
}
```

This slide should take about 5 minutes.

- It can be implemented directly or it can be derived via `#[derive(Default)]`.
- A derived implementation will produce a value where all fields are set to their default values.
  - This means all types in the struct must implement `Default` too.
- Standard Rust types commonly implement `Default` with reasonable values (e.g. `0`, `""`, etc).
- The partial struct initialization works nicely with default.
- The Rust standard library is aware that types can implement `Default` and provides convenience methods that use it.
- The `..` syntax is called struct update syntax.

18.7 Exercise: ROT13

In this example, you will implement the classic "ROT13" cipher. Copy this code to the playground, and implement the missing bits. Only rotate ASCII alphabetic characters, to ensure the result is still valid UTF-8.

```
use std::io::Read;

struct RotDecoder<R: Read> {
    input: R,
    rot: u8,
}

// Implement the `Read` trait for `RotDecoder`.

#[cfg(test)]
mod test {
    use super::*;

    #[test]
    fn joke() {
```

```
        let mut rot =
            RotDecoder { input: "Gb trg gb gur bgure fvqr!".as_bytes(), rot: 13 };
        let mut result = String::new();
        rot.read_to_string(&mut result).unwrap();
        assert_eq!(&result, "To get to the other side!");
    }

    #[test]
    fn binary() {
        let input: Vec<u8> = (0..=255u8).collect();
        let mut rot = RotDecoder::<&[u8]> { input: input.as_slice(), rot: 13 };
        let mut buf = [0u8; 256];
        assert_eq!(rot.read(&mut buf).unwrap(), 256);
        for i in 0..=255 {
            if input[i] != buf[i] {
                assert!(input[i].is_ascii_alphabetic());
                assert!(buf[i].is_ascii_alphabetic());
            }
        }
    }
}
```

What happens if you chain two `RotDecoder` instances together, each rotating by 13 characters?

18.7.1 Solution

```
use std::io::Read;

struct RotDecoder<R: Read> {
    input: R,
    rot: u8,
}

impl<R: Read> Read for RotDecoder<R> {
    fn read(&mut self, buf: &mut [u8]) -> std::io::Result<usize> {
        let size = self.input.read(buf)?;
        for b in &mut buf[..size] {
            if b.is_ascii_alphabetic() {
                let base = if b.is_ascii_uppercase() { 'A' } else { 'a' } as u8;
                *b = (*b - base + self.rot) % 26 + base;
            }
        }
        Ok(size)
    }
}

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

```rust
    #[test]
    fn joke() {
        let mut rot =
            RotDecoder { input: "Gb trg gb gur bgure fvqr!".as_bytes(), rot: 13 };
        let mut result = String::new();
        rot.read_to_string(&mut result).unwrap();
        assert_eq!(&result, "To get to the other side!");
    }

    #[test]
    fn binary() {
        let input: Vec<u8> = (0..=255u8).collect();
        let mut rot = RotDecoder::<&[u8]> { input: input.as_slice(), rot: 13 };
        let mut buf = [0u8; 256];
        assert_eq!(rot.read(&mut buf).unwrap(), 256);
        for i in 0..=255 {
            if input[i] != buf[i] {
                assert!(input[i].is_ascii_alphabetic());
                assert!(buf[i].is_ascii_alphabetic());
            }
        }
    }
}
```

Part V

Day 3: Morning

Chapter 19

Welcome to Day 3

We have now seen all the core language features:

- **Foundations:** Basic types, control flow, functions, and data structures.
- **Pattern Matching:** Destructuring data effectively.
- **Polymorphism:** Methods, Traits, and Generics.
- **Standard Library:** Using essential types like `Option`, `Result`, `Vec`, and `String`.
- **Closures:** Anonymous functions that can capture their environment.

You can write any type and associate behavior with it. We are now shifting gears to apply these concepts to memory management and system design.

Schedule

Including 10 minute breaks, this session should take about 2 hours and 20 minutes. It contains:

Segment	Duration
Welcome	3 minutes
Memory Management	1 hour
Smart Pointers	55 minutes

Chapter 20

Memory Management

This segment should take about 1 hour. It contains:

Slide	Duration
Review of Program Memory	5 minutes
Approaches to Memory Management	10 minutes
Ownership	5 minutes
Move Semantics	5 minutes
Clone	2 minutes
Copy Types	5 minutes
Drop	10 minutes
Exercise: Builder Type	20 minutes

20.1 Review of Program Memory

Programs allocate memory in two ways:

- Stack: Continuous area of memory for local variables.
  - Values have fixed sizes known at compile time.
  - Extremely fast: just move a stack pointer.
  - Easy to manage: follows function calls.
  - Great memory locality.
- Heap: Storage of values outside of function calls.
  - Values have dynamic sizes determined at runtime.
  - Slightly slower than the stack: some bookkeeping needed.
  - No guarantee of memory locality.

Example

Creating a `String` puts fixed-sized metadata on the stack and dynamically sized data, the actual string, on the heap:

```rust
fn main() {
    let s1 = String::from("Hello");
}
```

```
 Stack
.- - - - - - - - - - - - - -.      Heap
:                           :     .- - - - - - - - - - - - - - - -.
:    s1                     :     :                               :
:   +-----------+-------+   :     :                               :
:   | capacity  |     5 |   :     :   +----+----+----+----+----+  :
:   | ptr       |     o-+---+-----+-->| H  | e  | l  | l  | o  |  :
:   | len       |     5 |   :     :   +----+----+----+----+----+  :
:   +-----------+-------+   :     :                               :
:                           :     :                               :
`- - - - - - - - - - - - - -'     `- - - - - - - - - - - - - - - -'
```

This slide should take about 5 minutes.

- Mention that a `String` is backed by a `Vec`, so it has a capacity and length and can grow if mutable via reallocation on the heap.
- If students ask about it, you can mention that the underlying memory is heap allocated using the System Allocator and custom allocators can be implemented using the Allocator API

More to Explore

We can inspect the memory layout with `unsafe` Rust. However, you should point out that this is rightfully unsafe!

```rust
fn main() {
    let mut s1 = String::from("Hello");
    s1.push(' ');
    s1.push_str("world");
    // DON'T DO THIS AT HOME! For educational purposes only.
    // String provides no guarantees about its layout, so this could lead to
    // undefined behavior.
    unsafe {
        let (capacity, ptr, len): (usize, usize, usize) = std::mem::transmute(s1);
        println!("capacity = {capacity}, ptr = {ptr:#x}, len = {len}");
    }
}
```

20.2 Approaches to Memory Management

Traditionally, languages have fallen into two broad categories:

- Full control via manual memory management: C, C++, Pascal, …
  - Programmer decides when to allocate or free heap memory.
  - Programmer must determine whether a pointer still points to valid memory.
  - Studies show, programmers make mistakes.
- Full safety via automatic memory management at runtime: Java, Python, Go, Haskell, …

  - A runtime system ensures that memory is not freed until it can no longer be referenced.
  - Typically implemented with reference counting or garbage collection.

Rust offers a new mix:

> Full control *and* safety via compile time enforcement of correct memory management.

It does this with an explicit ownership concept.

This slide should take about 10 minutes.

This slide is intended to help students coming from other languages to put Rust in context.

- C must manage heap manually with `malloc` and `free`. Common errors include forgetting to call `free`, calling it multiple times for the same pointer, or dereferencing a pointer after the memory it points to has been freed.
- C++ has tools like smart pointers (`unique_ptr`, `shared_ptr`) that take advantage of language guarantees about calling destructors to ensure memory is freed when a function returns. It is still quite easy to misuse these tools and create similar bugs to C.
- Java, Go, and Python rely on the garbage collector to identify memory that is no longer reachable and discard it. This guarantees that any pointer can be dereferenced, eliminating use-after-free and other classes of bugs. But, GC has a runtime cost and is difficult to tune properly.

Rust's ownership and borrowing model can, in many cases, get the performance of C, with alloc and free operations precisely where they are required -- zero-cost. It also provides tools similar to C++'s smart pointers. When required, other options such as reference counting are available, and there are even crates available to support runtime garbage collection (not covered in this class).

20.3 Ownership

All variable bindings have a *scope* where they are valid and it is an error to use a variable outside its scope:

```rust
struct Point(i32, i32);

fn main() {
    {
        let p = Point(3, 4);
        dbg!(p.0);
    }
    dbg!(p.1);
}
```

We say that the variable *owns* the value. Every Rust value has precisely one owner at all times.

At the end of the scope, the variable is *dropped* and the data is freed. A destructor can run here to free up resources.

This slide should take about 5 minutes.

Students familiar with garbage collection implementations will know that a garbage collector starts with a set of "roots" to find all reachable memory. Rust's "single owner" principle is a similar idea.

20.4 Move Semantics

An assignment will transfer *ownership* between variables:

```rust
fn main() {
    let s1 = String::from("Hello!");
    let s2 = s1;
    dbg!(s2);
    // dbg!(s1);
}
```

- The assignment of `s1` to `s2` transfers ownership.
- When `s1` goes out of scope, nothing happens: it does not own anything.
- When `s2` goes out of scope, the string data is freed.

Before move to `s2`:

```
 Stack                             Heap
.- - - - - - - - - - - - - -.     .- - - - - - - - - - - - - - - - - - -.
:                           :     :                                     :
:    s1                     :     :                                     :
:   +-----------+-------+   :     :   +----+----+----+----+----+----+   :
:   | ptr       |   o---+---+-----+-->| H  | e  | l  | l  | o  | !  |   :
:   | len       |     6 |   :     :   +----+----+----+----+----+----+   :
:   | capacity  |     6 |   :     :                                     :
:   +-----------+-------+   :     :                                     :
:                           :     `- - - - - - - - - - - - - - - - - - -'
:                           :
`- - - - - - - - - - - - - -'
```

After move to `s2`:

```
 Stack                             Heap
.- - - - - - - - - - - - - -.     .- - - - - - - - - - - - - - - - - - -.
:                           :     :                                     :
:    s1 "(inaccessible)"    :     :                                     :
:   +-----------+-------+   :     :   +----+----+----+----+----+----+   :
:   | ptr       |   o---+---+--+--+-->| H  | e  | l  | l  | o  | !  |   :
:   | len       |     6 |   :  |  :   +----+----+----+----+----+----+   :
:   | capacity  |     6 |   :  |  :                                     :
:   +-----------+-------+   :  |  :                                     :
:                           :  |  `- - - - - - - - - - - - - - - - - - -'
:    s2                     :  |
:   +-----------+-------+   :  |
:   | ptr       |   o---+---+--'
:   | len       |     6 |   :
:   | capacity  |     6 |   :
:   +-----------+-------+   :
```

```
:                           :
`- - - - - - - - - - - - - - -'
```

When you pass a value to a function, the value is assigned to the function parameter. This transfers ownership:

```rust
fn say_hello(name: String) {
    println!("Hello {name}")
}

fn main() {
    let name = String::from("Alice");
    say_hello(name);
    // say_hello(name);
}
```

This slide should take about 5 minutes.

- Mention that this is the opposite of the defaults in C++, which copies by value unless you use `std::move` (and the move constructor is defined!).
- It is only the ownership that moves. Whether any machine code is generated to manipulate the data itself is a matter of optimization, and such copies are aggressively optimized away.
- Simple values (such as integers) can be marked `Copy` (see later slides).
- In Rust, clones are explicit (by using `clone`).

In the `say_hello` example:

- With the first call to `say_hello`, `main` gives up ownership of `name`. Afterwards, `name` cannot be used anymore within `main`.
- The heap memory allocated for `name` will be freed at the end of the `say_hello` function.
- `main` can retain ownership if it passes `name` as a reference (`&name`) and if `say_hello` accepts a reference as a parameter.
- Alternatively, `main` can pass a clone of `name` in the first call (`name.clone()`).
- Rust makes it harder than C++ to inadvertently create copies by making move semantics the default, and by forcing programmers to make clones explicit.

More to Explore

Defensive Copies in Modern C++

Modern C++ solves this differently:

```cpp
std::string s1 = "Cpp";
std::string s2 = s1;  // Duplicate the data in s1.
```

- The heap data from `s1` is duplicated and `s2` gets its own independent copy.
- When `s1` and `s2` go out of scope, they each free their own memory.

Before copy-assignment:

```
 Stack                              Heap
.- - - - - - - - - - - - - - -.     .- - - - - - - - - - - - -.
```

```
:                           :     :                       :
:    s1                     :     :                       :
:   +-----------+-------+   :     :   +----+----+----+    :
:   | ptr       |   o---+---+--+--+-->| C  | p  | p  |    :
:   | len       |     3 |   :     :   +----+----+----+    :
:   | capacity  |     3 |   :     :                       :
:   +-----------+-------+   :     :                       :
:                           :     `- - - - - - - - - - - -'
`- - - - - - - - - - - - - -'
```

After copy-assignment:

```
 Stack                            Heap
.- - - - - - - - - - - - - -.     .- - - - - - - - - - - -.
:                           :     :                       :
:    s1                     :     :                       :
:   +-----------+-------+   :     :   +----+----+----+    :
:   | ptr       |   o---+---+--+--+-->| C  | p  | p  |    :
:   | len       |     3 |   :     :   +----+----+----+    :
:   | capacity  |     3 |   :     :                       :
:   +-----------+-------+   :     :                       :
:                           :     :                       :
:    s2                     :     :                       :
:   +-----------+-------+   :     :   +----+----+----+    :
:   | ptr       |   o---+---+-----+-->| C  | p  | p  |    :
:   | len       |     3 |   :     :   +----+----+----+    :
:   | capacity  |     3 |   :     :                       :
:   +-----------+-------+   :     :                       :
:                           :     `- - - - - - - - - - - -'
`- - - - - - - - - - - - - -'
```

Key points:

- C++ has made a slightly different choice than Rust. Because `=` copies data, the string data has to be cloned. Otherwise we would get a double-free when either string goes out of scope.
- C++ also has `std::move`, which is used to indicate when a value may be moved from. If the example had been `s2 = std::move(s1)`, no heap allocation would take place. After the move, `s1` would be in a valid but unspecified state. Unlike Rust, the programmer is allowed to keep using `s1`.
- Unlike Rust, `=` in C++ can run arbitrary code as determined by the type that is being copied or moved.

20.5 Clone

Sometimes you *want* to make a copy of a value. The `Clone` trait accomplishes this.

```
fn say_hello(name: String) {
    println!("Hello {name}")
}
```

```rust
fn main() {
    let name = String::from("Alice");
    say_hello(name.clone());
    say_hello(name);
}
```

This slide should take about 2 minutes.

- The idea of `Clone` is to make it easy to spot where heap allocations are occurring. Look for `.clone()` and a few others like `vec!` or `Box::new`.
- It's common to "clone your way out" of problems with the borrow checker, and return later to try to optimize those clones away.
- `clone` generally performs a deep copy of the value, meaning that if you e.g. clone an array, all of the elements of the array are cloned as well.
- The behavior for `clone` is user-defined, so it can perform custom cloning logic if needed.

20.6 Copy Types

While move semantics are the default, certain types are copied by default:

```rust
fn main() {
    let x = 42;
    let y = x;
    dbg!(x); // would not be accessible if not Copy
    dbg!(y);
}
```

These types implement the `Copy` trait.

You can opt-in your own types to use copy semantics:

```rust
#[derive(Copy, Clone, Debug)]
struct Point(i32, i32);

fn main() {
    let p1 = Point(3, 4);
    let p2 = p1;
    println!("p1: {p1:?}");
    println!("p2: {p2:?}");
}
```

- After the assignment, both `p1` and `p2` own their own data.
- We can also use `p1.clone()` to explicitly copy the data.

This slide should take about 5 minutes.

Copying and cloning are not the same thing:

- Copying refers to bitwise copies of memory regions and does not work on arbitrary objects.
- Copying does not allow for custom logic (unlike copy constructors in C++).
- Cloning is a more general operation and also allows for custom behavior by implementing the `Clone` trait.

- Copying does not work on types that implement the `Drop` trait.

In the above example, try the following:

- Add a `String` field to `struct Point`. It will not compile because `String` is not a `Copy` type.
- Remove `Copy` from the `derive` attribute. The compiler error is now in the `println!` for `p1`.
- Show that it works if you clone `p1` instead.

More to Explore

- Shared references are `Copy`/`Clone`, mutable references are not. This is because Rust requires that mutable references be exclusive, so while it's valid to make a copy of a shared reference, creating a copy of a mutable reference would violate Rust's borrowing rules.

20.7 The Drop Trait

Values which implement Drop can specify code to run when they go out of scope:

```rust
struct Droppable {
    name: &'static str,
}

impl Drop for Droppable {
    fn drop(&mut self) {
        println!("Dropping {}", self.name);
    }
}

fn main() {
    let a = Droppable { name: "a" };
    {
        let b = Droppable { name: "b" };
        {
            let c = Droppable { name: "c" };
            let d = Droppable { name: "d" };
            println!("Exiting innermost block");
        }
        println!("Exiting next block");
    }
    drop(a);
    println!("Exiting main");
}
```

This slide should take about 8 minutes.

- Note that `std::mem::drop` is not the same as `std::ops::Drop::drop`.
- Values are automatically dropped when they go out of scope.

- When a value is dropped, if it implements `std::ops::Drop` then its `Drop::drop` implementation will be called.
- All its fields will then be dropped too, whether or not it implements `Drop`.
- `std::mem::drop` is just an empty function that takes any value. The significance is that it takes ownership of the value, so at the end of its scope it gets dropped. This makes it a convenient way to explicitly drop values earlier than they would otherwise go out of scope.
  - This is useful for objects that do some work on `drop`: releasing locks, closing files, etc.

Discussion points:

- Why doesn't `Drop::drop` take `self`?
  - Short-answer: If it did, `std::mem::drop` would be called at the end of the block, resulting in another call to `Drop::drop`, and a stack overflow!
- Try replacing `drop(a)` with `a.drop()`.

20.8 Exercise: Builder Type

In this example, we will implement a complex data type that owns all of its data. We will use the "builder pattern" to support building a new value piece-by-piece, using convenience functions.

Fill in the missing pieces.

```
#[derive(Debug)]
enum Language {
    Rust,
    Java,
    Perl,
}

#[derive(Clone, Debug)]
struct Dependency {
    name: String,
    version_expression: String,
}

/// A representation of a software package.
#[derive(Debug)]
struct Package {
    name: String,
    version: String,
    authors: Vec<String>,
    dependencies: Vec<Dependency>,
    language: Option<Language>,
}

impl Package {
    /// Return a representation of this package as a dependency, for use in
    /// building other packages.
    fn as_dependency(&self) -> Dependency {
```

```rust
        todo!("1")
    }
}

/// A builder for a Package. Use `build()` to create the `Package` itself.
struct PackageBuilder(Package);

impl PackageBuilder {
    fn new(name: impl Into<String>) -> Self {
        todo!("2")
    }

    /// Set the package version.
    fn version(mut self, version: impl Into<String>) -> Self {
        self.0.version = version.into();
        self
    }

    /// Set the package authors.
    fn authors(mut self, authors: Vec<String>) -> Self {
        todo!("3")
    }

    /// Add an additional dependency.
    fn dependency(mut self, dependency: Dependency) -> Self {
        todo!("4")
    }

    /// Set the language. If not set, language defaults to None.
    fn language(mut self, language: Language) -> Self {
        todo!("5")
    }

    fn build(self) -> Package {
        self.0
    }
}

fn main() {
    let base64 = PackageBuilder::new("base64").version("0.13").build();
    dbg!(&base64);
    let log =
        PackageBuilder::new("log").version("0.4").language(Language::Rust).build();
    dbg!(&log);
    let serde = PackageBuilder::new("serde")
        .authors(vec!["djmitche".into()])
        .version(String::from("4.0"))
        .dependency(base64.as_dependency())
        .dependency(log.as_dependency())
        .build();
    dbg!(serde);
```

```
}
```

20.8.1 Solution

```rust
#[derive(Debug)]
enum Language {
    Rust,
    Java,
    Perl,
}

#[derive(Clone, Debug)]
struct Dependency {
    name: String,
    version_expression: String,
}

/// A representation of a software package.
#[derive(Debug)]
struct Package {
    name: String,
    version: String,
    authors: Vec<String>,
    dependencies: Vec<Dependency>,
    language: Option<Language>,
}

impl Package {
    /// Return a representation of this package as a dependency, for use in
    /// building other packages.
    fn as_dependency(&self) -> Dependency {
        Dependency {
            name: self.name.clone(),
            version_expression: self.version.clone(),
        }
    }
}

/// A builder for a Package. Use `build()` to create the `Package` itself.
struct PackageBuilder(Package);

impl PackageBuilder {
    fn new(name: impl Into<String>) -> Self {
        Self(Package {
            name: name.into(),
            version: "0.1".into(),
            authors: Vec::new(),
            dependencies: Vec::new(),
            language: None,
        })
    }
```

```rust
    /// Set the package version.
    fn version(mut self, version: impl Into<String>) -> Self {
        self.0.version = version.into();
        self
    }

    /// Set the package authors.
    fn authors(mut self, authors: Vec<String>) -> Self {
        self.0.authors = authors;
        self
    }

    /// Add an additional dependency.
    fn dependency(mut self, dependency: Dependency) -> Self {
        self.0.dependencies.push(dependency);
        self
    }

    /// Set the language. If not set, language defaults to None.
    fn language(mut self, language: Language) -> Self {
        self.0.language = Some(language);
        self
    }

    fn build(self) -> Package {
        self.0
    }
}

fn main() {
    let base64 = PackageBuilder::new("base64").version("0.13").build();
    dbg!(&base64);
    let log =
        PackageBuilder::new("log").version("0.4").language(Language::Rust).build();
    dbg!(&log);
    let serde = PackageBuilder::new("serde")
        .authors(vec!["djmitche".into()])
        .version(String::from("4.0"))
        .dependency(base64.as_dependency())
        .dependency(log.as_dependency())
        .build();
    dbg!(serde);
}
```

Chapter 21

Smart Pointers

This segment should take about 55 minutes. It contains:

Slide	Duration
Box	10 minutes
Rc	5 minutes
Owned Trait Objects	10 minutes
Exercise: Binary Tree	30 minutes

21.1 `Box<T>`

`Box` is an owned pointer to data on the heap:

```rust
fn main() {
    let five = Box::new(5);
    println!("five: {}", *five);
}
```

```
 Stack                           Heap
.- - - - - - - -.     .- - - - - - - -.
:               :     :               :
:    five       :     :               :
:   +-----+     :     :  +-----+      :
:   | o---|---+-----+-->|  5  |       :
:   +-----+     :     :  +-----+      :
:               :     :               :
:               :     :               :
`- - - - - - - -'     `- - - - - - - -'
```

`Box<T>` implements `Deref<Target = T>`, which means that you can call methods from `T` directly on a `Box<T>`.

Recursive data types or data types with dynamic sizes cannot be stored inline without a pointer indirection. `Box` accomplishes that indirection:

```rust
#[derive(Debug)]
enum List<T> {
    /// A non-empty list: first element and the rest of the list.
    Element(T, Box<List<T>>),
    /// An empty list.
    Nil,
}

fn main() {
    let list: List<i32> =
        List::Element(1, Box::new(List::Element(2, Box::new(List::Nil))));
    println!("{list:?}");
}
```

```
 Stack                           Heap
.- - - - - - - - - - - - - - .     .- - - - - - - - - - - - - - - - - - - - - - - - -.
:                            :     :                                                 :
:    list                    :     :                                                 :
:   +---------+----+----+    :     :    +---------+----+----+    +------+----+----+  :
:   | Element | 1  | o--+----+-----+--->| Element | 2  | o--+--->| Nil  | // | // |  :
:   +---------+----+----+    :     :    +---------+----+----+    +------+----+----+  :
:                            :     :                                                 :
:                            :     :                                                 :
'- - - - - - - - - - - - - - '     '- - - - - - - - - - - - - - - - - - - - - - - - -'
```

This slide should take about 8 minutes.

- Box is like `std::unique_ptr` in C++, except that it's guaranteed to be not null.
- A Box can be useful when you:
  - have a type whose size can't be known at compile time, but the Rust compiler wants to know an exact size.
  - want to transfer ownership of a large amount of data. To avoid copying large amounts of data on the stack, instead store the data on the heap in a Box so only the pointer is moved.
- If Box was not used and we attempted to embed a `List` directly into the `List`, the compiler would not be able to compute a fixed size for the struct in memory (the `List` would be of infinite size).
- Box solves this problem as it has the same size as a regular pointer and just points at the next element of the `List` in the heap.
- Remove the Box in the List definition and show the compiler error. We get the message "recursive without indirection", because for data recursion, we have to use indirection, a Box or reference of some kind, instead of storing the value directly.
- Though Box looks like `std::unique_ptr` in C++, it cannot be empty/null. This makes Box one of the types that allow the compiler to optimize storage of some enums (the "niche optimization").

21.2 Rc

Rc is a reference-counted shared pointer. Use this when you need to refer to the same data from multiple places:

```rust
use std::rc::Rc;

fn main() {
    let a = Rc::new(10);
    let b = Rc::clone(&a);

    dbg!(a);
    dbg!(b);
}
```

Each Rc points to the same shared data structure, containing strong and weak pointers and the value:

```
 Stack                          Heap
.- - - - - - - - -.      .- - - - - - - - - - - - - - - - -.
:                 :      :                                 :
:     +-----+     :      :   +-----------+-------------+   :
:  a: | o---|---:--+--:-->|  count: 2 |  value: 10  |   :
:     +-----+     :   |   :   +-----------+-------------+   :
:  b: | o---|---:--+   :                                 :
:     +-----+     :      `- - - - - - - - - - - - - - - - -'
:                 :
`- - - - - - - - -'
```

- See Arc and Mutex if you are in a multi-threaded context.
- You can *downgrade* a shared pointer into a Weak pointer to create cycles that will get dropped.

This slide should take about 5 minutes.

- Rc's count ensures that its contained value is valid for as long as there are references.
- Rc in Rust is like `std::shared_ptr` in C++.
- `Rc::clone` is cheap: it creates a pointer to the same allocation and increases the reference count. Does not make a deep clone and can generally be ignored when looking for performance issues in code.
- `make_mut` actually clones the inner value if necessary ("clone-on-write") and returns a mutable reference.
- Use `Rc::strong_count` to check the reference count.
- `Rc::downgrade` gives you a *weakly reference-counted* object to create cycles that will be dropped properly (likely in combination with `RefCell`).

21.3 Owned Trait Objects

We previously saw how trait objects can be used with references, e.g `&dyn Pet`. However, we can also use trait objects with smart pointers like Box to create an owned trait object: `Box<dyn Pet>`.

```rust
struct Dog {
    name: String,
    age: i8,
}
struct Cat {
    lives: i8,
}

trait Pet {
    fn talk(&self) -> String;
}

impl Pet for Dog {
    fn talk(&self) -> String {
        format!("Woof, my name is {}!", self.name)
    }
}

impl Pet for Cat {
    fn talk(&self) -> String {
        String::from("Miau!")
    }
}

fn main() {
    let pets: Vec<Box<dyn Pet>> = vec![
        Box::new(Cat { lives: 9 }),
        Box::new(Dog { name: String::from("Fido"), age: 5 }),
    ];
    for pet in pets {
        println!("Hello, who are you? {}", pet.talk());
    }
}
```

Memory layout after allocating `pets`:

```
 Stack                             Heap
.- - - - - - - - - - - - - - - -.     .- - - - - - - - - - - - - - - - - - - - - - -.
:                               :     :                                             :
:    "pets: Vec<Box<dyn Pet>>"  :     :   "data: Cat"         +----+----+----+----+ :
:   +-----------+-------+       :     :  +-------+-------+    | F  | i  | d  | o  | :
:   | ptr       |   o---+-------+--.  :  | lives |     9 |    +----+----+----+----+ :
:   | len       |     2 |       :  |  :  +-------+-------+      ^                   :
:   | capacity  |     2 |       :  |  :       ^                 |                   :
:   +-----------+-------+       :  |  :       |                 '-------.           :
:                               :  |  :       |               data:"Dog"|           :
:                               :  |  :       |              +-------+--|-------+   :
`- - - - - - - - - - - - - - - -'  |  :   +---|-+-----+      | name  |  o, 4, 4 |   :
                                   `--+-->| o o | o o-|----->| age   |        5 |   :
                                      :   +-|---+-|---+      +-------+----------+   :
                                      :     |     |                                 :
                                      `- - -| - - |- - - - - - - - - - - - - - - - -'
```

```
      |     |
      |     |                     "Program text"
.- - -| - - |- - - - - - - - - - - - - - - - -.
:     |     |      vtable                     :
:     |     |     +----------------------+    :
:     |     `---->| "<Dog as Pet>::talk" |    :
:     |           +----------------------+    :
:     |            vtable                     :
:     |           +----------------------+    :
:     '---------->| "<Cat as Pet>::talk" |    :
:                 +----------------------+    :
:                                             :
'- - - - - - - - - - - - - - - - - - - - - - -'
```

This slide should take about 10 minutes.

- Types that implement a given trait may be of different sizes. This makes it impossible to have things like `Vec<dyn Pet>` in the example above.
- `dyn Pet` is a way to tell the compiler about a dynamically sized type that implements `Pet`.
- In the example, `pets` is allocated on the stack and the vector data is on the heap. The two vector elements are *fat pointers*:
  - A fat pointer is a double-width pointer. It has two components: a pointer to the actual object and a pointer to the virtual method table (vtable) for the `Pet` implementation of that particular object.
  - The data for the `Dog` named Fido is the `name` and `age` fields. The `Cat` has a `lives` field.
- Compare these outputs in the above example:

```
println!("{} {}", std::mem::size_of::<Dog>(), std::mem::size_of::<Cat>());
println!("{} {}", std::mem::size_of::<&Dog>(), std::mem::size_of::<&Cat>());
println!("{}", std::mem::size_of::<&dyn Pet>());
println!("{}", std::mem::size_of::<Box<dyn Pet>>());
```

21.4 Exercise: Binary Tree

A binary tree is a tree-type data structure where every node has two children (left and right). We will create a tree where each node stores a value. For a given node N, all nodes in a N's left subtree contain smaller values, and all nodes in N's right subtree will contain larger values. A given value should only be stored in the tree once, i.e. no duplicate nodes.

Implement the following types, so that the given tests pass.

```rust
/// A node in the binary tree.
#[derive(Debug)]
struct Node<T: Ord> {
    value: T,
    left: Subtree<T>,
    right: Subtree<T>,
}

/// A possibly-empty subtree.
#[derive(Debug)]
```

```rust
struct Subtree<T: Ord>(Option<Box<Node<T>>>);

/// A container storing a set of values, using a binary tree.
///
/// If the same value is added multiple times, it is only stored once.
#[derive(Debug)]
pub struct BinaryTree<T: Ord> {
    root: Subtree<T>,
}

impl<T: Ord> BinaryTree<T> {
    fn new() -> Self {
        Self { root: Subtree::new() }
    }

    fn insert(&mut self, value: T) {
        self.root.insert(value);
    }

    fn has(&self, value: &T) -> bool {
        self.root.has(value)
    }

    fn len(&self) -> usize {
        self.root.len()
    }
}

// Implement `new` for `Node`.
// Implement `new`, `insert`, `len`, and `has` for `Subtree`.

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

    #[test]
    fn len() {
        let mut tree = BinaryTree::new();
        assert_eq!(tree.len(), 0);
        tree.insert(2);
        assert_eq!(tree.len(), 1);
        tree.insert(1);
        assert_eq!(tree.len(), 2);
        tree.insert(2); // not a unique item
        assert_eq!(tree.len(), 2);
        tree.insert(3);
        assert_eq!(tree.len(), 3);
    }

    #[test]
    fn has() {
```

```rust
        let mut tree = BinaryTree::new();
        fn check_has(tree: &BinaryTree<i32>, exp: &[bool]) {
            let got: Vec<bool> =
                (0..exp.len()).map(|i| tree.has(&(i as i32))).collect();
            assert_eq!(&got, exp);
        }

        check_has(&tree, &[false, false, false, false, false]);
        tree.insert(0);
        check_has(&tree, &[true, false, false, false, false]);
        tree.insert(4);
        check_has(&tree, &[true, false, false, false, true]);
        tree.insert(4);
        check_has(&tree, &[true, false, false, false, true]);
        tree.insert(3);
        check_has(&tree, &[true, false, false, true, true]);
    }

    #[test]
    fn unbalanced() {
        let mut tree = BinaryTree::new();
        for i in 0..100 {
            tree.insert(i);
        }
        assert_eq!(tree.len(), 100);
        assert!(tree.has(&50));
    }
}
```

21.4.1 Solution

```rust
use std::cmp::Ordering;

/// A node in the binary tree.
#[derive(Debug)]
struct Node<T: Ord> {
    value: T,
    left: Subtree<T>,
    right: Subtree<T>,
}

/// A possibly-empty subtree.
#[derive(Debug)]
struct Subtree<T: Ord>(Option<Box<Node<T>>>);

/// A container storing a set of values, using a binary tree.
///
/// If the same value is added multiple times, it is only stored once.
#[derive(Debug)]
pub struct BinaryTree<T: Ord> {
    root: Subtree<T>,
```

```
}

impl<T: Ord> BinaryTree<T> {
    fn new() -> Self {
        Self { root: Subtree::new() }
    }

    fn insert(&mut self, value: T) {
        self.root.insert(value);
    }

    fn has(&self, value: &T) -> bool {
        self.root.has(value)
    }

    fn len(&self) -> usize {
        self.root.len()
    }
}

impl<T: Ord> Subtree<T> {
    fn new() -> Self {
        Self(None)
    }

    fn insert(&mut self, value: T) {
        match &mut self.0 {
            None => self.0 = Some(Box::new(Node::new(value))),
            Some(n) => match value.cmp(&n.value) {
                Ordering::Less => n.left.insert(value),
                Ordering::Equal => {}
                Ordering::Greater => n.right.insert(value),
            },
        }
    }

    fn has(&self, value: &T) -> bool {
        match &self.0 {
            None => false,
            Some(n) => match value.cmp(&n.value) {
                Ordering::Less => n.left.has(value),
                Ordering::Equal => true,
                Ordering::Greater => n.right.has(value),
            },
        }
    }

    fn len(&self) -> usize {
        match &self.0 {
            None => 0,
            Some(n) => 1 + n.left.len() + n.right.len(),
```

```
        }
    }
}

impl<T: Ord> Node<T> {
    fn new(value: T) -> Self {
        Self { value, left: Subtree::new(), right: Subtree::new() }
    }
}

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

    #[test]
    fn len() {
        let mut tree = BinaryTree::new();
        assert_eq!(tree.len(), 0);
        tree.insert(2);
        assert_eq!(tree.len(), 1);
        tree.insert(1);
        assert_eq!(tree.len(), 2);
        tree.insert(2); // not a unique item
        assert_eq!(tree.len(), 2);
        tree.insert(3);
        assert_eq!(tree.len(), 3);
    }

    #[test]
    fn has() {
        let mut tree = BinaryTree::new();
        fn check_has(tree: &BinaryTree<i32>, exp: &[bool]) {
            let got: Vec<bool> =
                (0..exp.len()).map(|i| tree.has(&(i as i32))).collect();
            assert_eq!(&got, exp);
        }

        check_has(&tree, &[false, false, false, false, false]);
        tree.insert(0);
        check_has(&tree, &[true, false, false, false, false]);
        tree.insert(4);
        check_has(&tree, &[true, false, false, false, true]);
        tree.insert(4);
        check_has(&tree, &[true, false, false, false, true]);
        tree.insert(3);
        check_has(&tree, &[true, false, false, true, true]);
    }

    #[test]
    fn unbalanced() {
        let mut tree = BinaryTree::new();
```

```
        for i in 0..100 {
            tree.insert(i);
        }
        assert_eq!(tree.len(), 100);
        assert!(tree.has(&50));
    }
}
```

Part VI

Day 3: Afternoon

Chapter 22

Welcome Back

Including 10 minute breaks, this session should take about 2 hours and 30 minutes. It contains:

Segment	Duration
Borrowing	1 hour and 15 minutes
Lifetimes	1 hour and 5 minutes

Chapter 23

Borrowing

This segment should take about 1 hour and 15 minutes. It contains:

Slide	Duration
Borrowing a Value	10 minutes
Borrow Checking	10 minutes
Borrow Errors	3 minutes
Interior Mutability	10 minutes
Exercise: Wizard's Inventory	40 minutes

23.1 Borrowing a Value

As we saw before, instead of transferring ownership when calling a function, you can let a function *borrow* the value:

```rust
#[derive(Debug)]
struct Point(i32, i32);

fn add(p1: &Point, p2: &Point) -> Point {
    Point(p1.0 + p2.0, p1.1 + p2.1)
}

fn main() {
    let p1 = Point(3, 4);
    let p2 = Point(10, 20);
    let p3 = add(&p1, &p2);
    println!("{p1:?} + {p2:?} = {p3:?}");
}
```

- The add function *borrows* two points and returns a new point.
- The caller retains ownership of the inputs.

This slide should take about 10 minutes.

This slide is a review of the material on references from day 1, expanding slightly to include function arguments and return values.

More to Explore

Notes on stack returns and inlining:

- Demonstrate that the return from add is cheap because the compiler can eliminate the copy operation, by inlining the call to add into main. Change the above code to print stack addresses and run it on the Playground or look at the assembly in Godbolt. In the "DEBUG" optimization level, the addresses should change, while they stay the same when changing to the "RELEASE" setting:

  ```rust
  #[derive(Debug)]
  struct Point(i32, i32);

  fn add(p1: &Point, p2: &Point) -> Point {
      let p = Point(p1.0 + p2.0, p1.1 + p2.1);
      println!("&p.0: {:p}", &p.0);
      p
  }

  pub fn main() {
      let p1 = Point(3, 4);
      let p2 = Point(10, 20);
      let p3 = add(&p1, &p2);
      println!("&p3.0: {:p}", &p3.0);
      println!("{p1:?} + {p2:?} = {p3:?}");
  }
  ```

- The Rust compiler can do automatic inlining, that can be disabled on a function level with `#[inline(never)]`.

- Once disabled, the printed address will change on all optimization levels. Looking at Godbolt or Playground, one can see that in this case, the return of the value depends on the ABI, e.g. on amd64 the two i32 that is making up the point will be returned in 2 registers (eax and edx).

23.2 Borrow Checking

Rust's *borrow checker* puts constraints on the ways you can borrow values. We've already seen that a reference cannot *outlive* the value it borrows:

```rust
fn main() {
    let x_ref = {
        let x = 10;
        &x
    };
    dbg!(x_ref);
}
```

There's also a second main rule that the borrow checker enforces: The *aliasing* rule. For a given value, at any time:

- You can have one or more shared references to the value, *or*
- You can have exactly one exclusive reference to the value.

```rust
fn main() {
    let mut a = 10;
    let b = &a;

    {
        let c = &mut a;
        *c = 20;
    }

    dbg!(a);
    dbg!(b);
}
```

This slide should take about 10 minutes.

- The ”outlives” rule was demonstrated previously when we first looked at references. We review it here to show students that the borrow checking is following a few different rules to validate borrowing.
- The above code does not compile because `a` is borrowed as mutable (through `c`) and as immutable (through `b`) at the same time.
  - Note that the requirement is that conflicting references not *exist* at the same point. It does not matter where the reference is dereferenced. Try commenting out `*c = 20` and show that the compiler error still occurs even if we never use `c`.
  - Note that the intermediate reference `c` isn't necessary to trigger a borrow conflict. Replace `c` with a direct mutation of `a` and demonstrate that this produces a similar error. This is because direct mutation of a value effectively creates a temporary mutable reference.
- Move the `dbg!` statement for `b` before the scope that introduces `c` to make the code compile.
  - After that change, the compiler realizes that `b` is only ever used before the new mutable borrow of `a` through `c`. This is a feature of the borrow checker called ”non-lexical lifetimes”.

More to Explore

- Technically, multiple mutable references to a piece of data can exist at the same time via re-borrowing. This is what allows you to pass a mutable reference into a function without invalidating the original reference. This playground example demonstrates that behavior.
- Rust uses the exclusive reference constraint to ensure that data races do not occur in multi-threaded code, since only one thread can have mutable access to a piece of data at a time.
- Rust also uses this constraint to optimize code. For example, a value behind a shared reference can be safely cached in a register for the lifetime of that reference.
- Fields of a struct can be borrowed independently of each other, but calling a method on a struct will borrow the whole struct, potentially invalidating references to individual fields. See this playground snippet for an example of this.

23.3 Borrow Errors

As a concrete example of how these borrowing rules prevent memory errors, consider the case of modifying a collection while there are references to its elements:

```
fn main() {
    let mut vec = vec![1, 2, 3, 4, 5];
    let elem = &vec[2];
    vec.push(6);
    dbg!(elem);
}
```

Similarly, consider the case of iterator invalidation:

```
fn main() {
    let mut vec = vec![1, 2, 3, 4, 5];
    for elem in &vec {
        vec.push(elem * 2);
    }
}
```

This slide should take about 3 minutes.

- In both of these cases, modifying the collection by pushing new elements into it can potentially invalidate existing references to the collection's elements if the collection has to reallocate.

23.4 Interior Mutability

In some situations, it's necessary to modify data behind a shared (read-only) reference. For example, a shared data structure might have an internal cache, and wish to update that cache from read-only methods.

The ”interior mutability” pattern allows exclusive (mutable) access behind a shared reference. The standard library provides several ways to do this, all while still ensuring safety, typically by performing a runtime check.

This slide and its sub-slides should take about 10 minutes.

The main thing to take away from this slide is that Rust provides *safe* ways to modify data behind a shared reference. There are a variety of ways to ensure that safety, and the next sub-slides present a few of them.

23.4.1 `Cell`

`Cell` wraps a value and allows getting or setting the value using only a shared reference to the `Cell`. However, it does not allow any references to the inner value. Since there are no references, borrowing rules cannot be broken.

```
use std::cell::Cell;

fn main() {
    // Note that `cell` is NOT declared as mutable.
    let cell = Cell::new(5);
```

```
    cell.set(123);
    dbg!(cell.get());
}
```

- `Cell` is a simple means to ensure safety: it has a `set` method that takes `&self`. This needs no runtime check, but requires moving values, which can have its own cost.

23.4.2 RefCell

`RefCell` allows accessing and mutating a wrapped value by providing alternative types `Ref` and `RefMut` that emulate `&T`/`&mut T` without actually being Rust references.

These types perform dynamic checks using a counter in the `RefCell` to prevent existence of a `RefMut` alongside another `Ref`/`RefMut`.

By implementing `Deref` (and `DerefMut` for `RefMut`), these types allow calling methods on the inner value without allowing references to escape.

```
use std::cell::RefCell;

fn main() {
    // Note that `cell` is NOT declared as mutable.
    let cell = RefCell::new(5);

    {
        let mut cell_ref = cell.borrow_mut();
        *cell_ref = 123;

        // This triggers an error at runtime.
        // let other = cell.borrow();
        // println!("{}", other);
    }

    println!("{cell:?}");
}
```

- `RefCell` enforces Rust's usual borrowing rules (either multiple shared references or a single exclusive reference) with a runtime check. In this case, all borrows are very short and never overlap, so the checks always succeed.
- The extra block in the example is to end the borrow created by the call to `borrow_mut` before we print the cell. Trying to print a borrowed `RefCell` just shows the message `"{borrowed}"`.

More to Explore

There are also `OnceCell` and `OnceLock`, which allow initialization on first use. Making these useful requires some more knowledge than students have at this time.

23.5 Exercise: Wizard's Inventory

In this exercise, you will manage a wizard's inventory using what you have learned about borrowing and ownership.

- The wizard has a collection of spells. You need to implement functions to add spells to the inventory and to cast spells from them.
- Spells have a limited number of uses. When a spell has no uses left, it must be removed from the wizard's inventory.

```rust
struct Spell {
    name: String,
    cost: u32,
    uses: u32,
}

struct Wizard {
    spells: Vec<Spell>,
    mana: u32,
}

impl Wizard {
    fn new(mana: u32) -> Self {
        Wizard { spells: vec![], mana }
    }

    // TODO: Implement `add_spell` to take ownership of a spell and add it to
    // the wizard's inventory.
    fn add_spell(..., spell: ...) {
        todo!()
    }

    // TODO: Implement `cast_spell` to borrow a spell from the inventory and
    // cast it. The wizard's mana should decrease by the spell's cost and the
    // number of uses for the spell should decrease by 1.
    //
    // If the wizard doesn't have enough mana, the spell should fail.
    // If the spell has no uses left, it is removed from the inventory.
    fn cast_spell(..., name: ...) {
        todo!()
    }
}

fn main() {
    let mut merlin = Wizard::new(20);
    let fireball = Spell { name: String::from("Fireball"), cost: 10, uses: 2 };
    let ice_blast = Spell { name: String::from("Ice Blast"), cost: 15, uses: 1 };

    merlin.add_spell(fireball);
    merlin.add_spell(ice_blast);
```

```
    merlin.cast_spell("Fireball"); // Casts successfully
    merlin.cast_spell("Ice Blast"); // Casts successfully, then removed
    merlin.cast_spell("Ice Blast"); // Fails (not found)
    merlin.cast_spell("Fireball"); // Casts successfully, then removed
    merlin.cast_spell("Fireball"); // Fails (not found)
}

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

    #[test]
    fn test_add_spell() {
        let mut wizard = Wizard::new(10);
        let spell = Spell { name: String::from("Fireball"), cost: 5, uses: 3 };
        wizard.add_spell(spell);
        assert_eq!(wizard.spells.len(), 1);
    }

    #[test]
    fn test_cast_spell() {
        let mut wizard = Wizard::new(10);
        let spell = Spell { name: String::from("Fireball"), cost: 5, uses: 3 };
        wizard.add_spell(spell);

        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 5);
        assert_eq!(wizard.spells.len(), 1);
        assert_eq!(wizard.spells[0].uses, 2);
    }

    #[test]
    fn test_cast_spell_insufficient_mana() {
        let mut wizard = Wizard::new(10);
        let spell = Spell { name: String::from("Fireball"), cost: 15, uses: 3 };
        wizard.add_spell(spell);

        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 10);
        assert_eq!(wizard.spells.len(), 1);
        assert_eq!(wizard.spells[0].uses, 3);
    }

    #[test]
    fn test_cast_spell_not_found() {
        let mut wizard = Wizard::new(10);
        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 10);
    }

    #[test]
```

```rust
    fn test_cast_spell_removal() {
        let mut wizard = Wizard::new(10);
        let spell = Spell { name: String::from("Fireball"), cost: 5, uses: 1 };
        wizard.add_spell(spell);

        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 5);
        assert_eq!(wizard.spells.len(), 0);
    }
}
```

This slide and its sub-slides should take about 40 minutes.

- The goal of this exercise is to practice the core concepts of ownership and borrowing, specifically the rule that you cannot mutate a collection while holding a reference to one of its elements.
- `add_spell` should take ownership of a `Spell` and move it into the `Wizard`'s inventory.
- `cast_spell` is the core of the exercise. It needs to:
  1. Find the spell (by index or by reference).
  2. Check mana and decrement it.
  3. Decrement the spell's `uses`.
  4. Remove the spell if `uses == 0`.
- **Borrow Checker Conflict:** If students try to hold a reference to the spell (e.g., `let spell = &mut self.spells[i]`) and then call `self.spells.remove(i)` while that reference is still "alive" in the same scope, the borrow checker will complain. This is a great opportunity to show how to structure code to satisfy the borrow checker (e.g., by using indices or by ensuring the borrow ends before the mutation).

23.5.1 Solution: Wizard's Inventory

```rust
struct Spell {
    name: String,
    cost: u32,
    uses: u32,
}

struct Wizard {
    spells: Vec<Spell>,
    mana: u32,
}

impl Wizard {
    fn new(mana: u32) -> Self {
        Wizard { spells: vec![], mana }
    }

    fn add_spell(&mut self, spell: Spell) {
        self.spells.push(spell);
    }

    fn cast_spell(&mut self, name: &str) {
        let mut spell_idx = None;
```

```
        for idx in 0..self.spells.len() {
            if self.spells[idx].name == name {
                spell_idx = Some(idx);
                break;
            }
        }

        let Some(idx) = spell_idx else {
            println!("Spell {} not found!", name);
            return;
        };

        let spell = &mut self.spells[idx];
        if self.mana >= spell.cost {
            self.mana -= spell.cost;
            spell.uses -= 1;
            println!(
                "Casting {}! Mana left: {}. Uses left: {}",
                spell.name, self.mana, spell.uses
            );
            if spell.uses == 0 {
                self.spells.remove(idx);
            }
        } else {
            println!("Not enough mana to cast {}!", spell.name);
        }
    }
}

fn main() {
    let mut merlin = Wizard::new(20);
    let fireball = Spell { name: String::from("Fireball"), cost: 10, uses: 2 };
    let ice_blast = Spell { name: String::from("Ice Blast"), cost: 15, uses: 1 };

    merlin.add_spell(fireball);
    merlin.add_spell(ice_blast);

    merlin.cast_spell("Fireball"); // Casts successfully
    merlin.cast_spell("Ice Blast"); // Casts successfully, then removed
    merlin.cast_spell("Ice Blast"); // Fails (not found)
    merlin.cast_spell("Fireball"); // Casts successfully, then removed
    merlin.cast_spell("Fireball"); // Fails (not found)
}

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

    #[test]
    fn test_add_spell() {
        let mut wizard = Wizard::new(10);
```

```rust
        let spell = Spell { name: String::from("Fireball"), cost: 5, uses: 3 };
        wizard.add_spell(spell);
        assert_eq!(wizard.spells.len(), 1);
    }

    #[test]
    fn test_cast_spell() {
        let mut wizard = Wizard::new(10);
        let spell = Spell { name: String::from("Fireball"), cost: 5, uses: 3 };
        wizard.add_spell(spell);

        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 5);
        assert_eq!(wizard.spells.len(), 1);
        assert_eq!(wizard.spells[0].uses, 2);
    }

    #[test]
    fn test_cast_spell_insufficient_mana() {
        let mut wizard = Wizard::new(10);
        let spell = Spell { name: String::from("Fireball"), cost: 15, uses: 3 };
        wizard.add_spell(spell);

        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 10);
        assert_eq!(wizard.spells.len(), 1);
        assert_eq!(wizard.spells[0].uses, 3);
    }

    #[test]
    fn test_cast_spell_not_found() {
        let mut wizard = Wizard::new(10);
        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 10);
    }

    #[test]
    fn test_cast_spell_removal() {
        let mut wizard = Wizard::new(10);
        let spell = Spell { name: String::from("Fireball"), cost: 5, uses: 1 };
        wizard.add_spell(spell);

        wizard.cast_spell("Fireball");
        assert_eq!(wizard.mana, 5);
        assert_eq!(wizard.spells.len(), 0);
    }
}
```

Chapter 24

Lifetimes

This segment should take about 1 hour and 5 minutes. It contains:

Slide	Duration
Borrowing and Functions	3 minutes
Returning Borrows	5 minutes
Multiple Borrows	5 minutes
Borrow Both	5 minutes
Borrow One	5 minutes
Lifetime Elision	5 minutes
Lifetimes in Data Structures	5 minutes
Exercise: Protobuf Parsing	30 minutes

24.1 Borrowing with Functions

As part of borrow checking, the compiler needs to reason about how borrows flow into and out of functions. In the simplest case borrows last for the duration of the function call:

```rust
fn borrows(x: &i32) {
    dbg!(x);
}

fn main() {
    let mut val = 123;

    // Borrow `val` for the function call.
    borrows(&val);

    // Borrow has ended and we're free to mutate.
    val += 5;
}
```

This slide should take about 3 minutes.

- In this example we borrow `val` for the call to `borrows`. This would limit our ability to mutate `val`, but once the function call returns the borrow has ended and we're free to mutate again.

24.2 Returning Borrows

But we can also have our function return a reference! This means that a borrow flows back out of a function:

```
fn identity(x: &i32) -> &i32 {
    x
}

fn main() {
    let mut x = 123;

    let out = identity(&x);

    // x = 5; // 🛠️❌ `x` is still borrowed!

    dbg!(out);
}
```

This slide should take about 5 minutes.

- Rust functions can return references, meaning that a borrow can flow back out of a function.
- If a function returns a reference (or another kind of borrow), it was likely derived from one of its arguments. This means that the return value of the function will extend the borrow for one or more argument borrows.
- This case is still fairly simple, in that only one borrow is passed into the function, so the returned borrow has to be the same one.

24.3 Multiple Borrows

But what about when there are multiple borrows passed into a function and one being returned?

```
fn multiple(a: &i32, b: &i32) -> &i32 {
    todo!("Return either `a` or `b`")
}

fn main() {
    let mut a = 5;
    let mut b = 10;

    let r = multiple(&a, &b);

    // Which one is still borrowed?
    // Should either mutation be allowed?
```

```
    a += 7;
    b += 7;

    dbg!(r);
}
```

This slide should take about 5 minutes.

- This code does not compile right now because it is missing lifetime annotations. Before we get it to compile, use this opportunity to have students to think about which of our argument borrows should be extended by the return value.
- We pass two borrows into `multiple` and one is going to come back out, which means we will need to extend the borrow of one of the argument lifetimes. Which one should be extended? Do we need to see the body of `multiple` to figure this out?
- When borrow checking, the compiler doesn't look at the body of `multiple` to reason about the borrows flowing out, instead it looks only at the signature of the function for borrow analysis.
- In this case there is not enough information to determine if `a` or `b` will be borrowed by the returned reference. Show students the compiler errors and introduce the lifetime syntax:

  ```
  fn multiple<'a>(a: &'a i32, b: &'a i32) -> &'a i32 { ... }
  ```

24.4 Borrow Both

In this case, we have a function where either `a` or `b` may be returned. In this case we use the lifetime annotations to tell the compiler that both borrows may flow into the return value.

```
fn pick<'a>(c: bool, a: &'a i32, b: &'a i32) -> &'a i32 {
    if c { a } else { b }
}

fn main() {
    let mut a = 5;
    let mut b = 10;

    let r = pick(true, &a, &b);

    // Which one is still borrowed?
    // Should either mutation be allowed?
    // a += 7;
    // b += 7;

    dbg!(r);
}
```

This slide should take about 5 minutes.

- The `pick` function will return either `a` or `b` depending on the value of `c`, which means we can't know at compile time which one will be returned.

- To express this to the compiler, we use the same lifetime for both a and b, along with the return type. This means that the returned reference will borrow BOTH a and b!
- Uncomment both of the commented lines and show that `r` is borrowing both a and b, even though at runtime it will only point to one of them.
- Change the first argument to `pick` to show that the result is the same regardless of if a or b is returned.

24.5 Borrow One

In this example `find_nearest` takes in multiple borrows but returns only one of them. The lifetime annotations explicitly tie the returned borrow to the corresponding argument borrow.

```
#[derive(Debug)]
struct Point(i32, i32);

/// Searches `points` for the point closest to `query`.
/// Assumes there's at least one point in `points`.
fn find_nearest<'a>(points: &'a [Point], query: &Point) -> &'a Point {
    fn cab_distance(p1: &Point, p2: &Point) -> i32 {
        (p1.0 - p2.0).abs() + (p1.1 - p2.1).abs()
    }

    let mut nearest = None;
    for p in points {
        if let Some((_, nearest_dist)) = nearest {
            let dist = cab_distance(p, query);
            if dist < nearest_dist {
                nearest = Some((p, dist));
            }
        } else {
            nearest = Some((p, cab_distance(p, query)));
        };
    }

    nearest.map(|(p, _)| p).unwrap()
    // query // What happens if we do this instead?
}

fn main() {
    let points = &[Point(1, 0), Point(1, 0), Point(-1, 0), Point(0, -1)];
    let query = Point(0, 2);
    let nearest = find_nearest(points, &query);

    // `query` isn't borrowed at this point.
    drop(query);

    dbg!(nearest);
}
```

This slide should take about 5 minutes.

- It may be helpful to collapse the definition of `find_nearest` to put more focus on the signature of the function. The actual logic in the function is somewhat complex and isn't important for the purpose of borrow analysis.
- When we call `find_nearest` the returned reference doesn't borrow `query`, and so we are free to drop it while `nearest` is still active.
- But what happens if we return the wrong borrow? Change the last line of `find_nearest` to return `query` instead. Show the compiler error to the students.
- The first thing we have to do is add a lifetime annotation to `query`. Show students that we can add a second lifetime `'b` to `find_nearest`.
- Show the new error to the students. The borrow checker verifies that the logic in the function body actually returns a reference with the correct lifetime, enforcing that the function adheres to the contract set by the function's signature.

More to Explore

- The "help" message in the error notes that we can add a lifetime bound `'b: 'a` to say that `'b` will live at least as long as `'a`, which would then allow us to return `query`. This is an example of lifetime subtyping, which allows us to return a longer lifetime where a shorter one is expected.
- We can do something similar by returning a `'static` lifetime, e.g., a reference to a `static` variable. The `'static` lifetime is guaranteed to be longer than any other lifetime, so it's always safe to return in place of a shorter lifetime.

24.6 Lifetime Elision

Lifetimes for function arguments and return values must be fully specified, but Rust allows lifetimes to be elided in most cases with a few simple rules. This is not inference -- it is just a syntactic shorthand.

- Each argument which does not have a lifetime annotation is given one.
- If there is only one argument lifetime, it is given to all un-annotated return values.
- If there are multiple argument lifetimes, but the first one is for `self`, that lifetime is given to all un-annotated return values.

```
fn only_args(a: &i32, b: &i32) {
    todo!();
}

fn identity(a: &i32) -> &i32 {
    a
}

struct Foo(i32);
impl Foo {
    fn get(&self, other: &i32) -> &i32 {
        &self.0
```

```
    }
}
```

This slide should take about 5 minutes.

- Walk through applying the lifetime elision rules to each of the example functions. `only_args` is completed by the first rule, `identity` is completed by the second, and `Foo::get` is completed by the third.
- If all lifetimes have not been filled in by applying the three elision rules then you will get a compiler error telling you to add annotations manually.

24.7 Lifetimes in Data Structures

If a data type stores borrowed data, it must be annotated with a lifetime:

```
#[derive(Debug)]
enum HighlightColor {
    Pink,
    Yellow,
}

#[derive(Debug)]
struct Highlight<'document> {
    slice: &'document str,
    color: HighlightColor,
}

fn main() {
    let doc = String::from("The quick brown fox jumps over the lazy dog.");
    let noun = Highlight { slice: &doc[16..19], color: HighlightColor::Yellow };
    let verb = Highlight { slice: &doc[20..25], color: HighlightColor::Pink };
    // drop(doc);
    dbg!(noun);
    dbg!(verb);
}
```

This slide should take about 5 minutes.

- In the above example, the annotation on `Highlight` enforces that the data underlying the contained `&str` lives at least as long as any instance of `Highlight` that uses that data. A struct cannot live longer than the data it references.
- If doc is dropped before the end of the lifetime of noun or `verb`, the borrow checker throws an error.
- Types with borrowed data force users to hold on to the original data. This can be useful for creating lightweight views, but it generally makes them somewhat harder to use.
- When possible, make data structures own their data directly.
- Some structs with multiple references inside can have more than one lifetime annotation. This can be necessary if there is a need to describe lifetime relationships between the references themselves, in addition to the lifetime of the struct itself. Those are very advanced use cases.

24.8 Exercise: Protobuf Parsing

In this exercise, you will build a parser for the protobuf binary encoding. Don't worry, it's simpler than it seems! This illustrates a common parsing pattern, passing slices of data. The underlying data itself is never copied.

Fully parsing a protobuf message requires knowing the types of the fields, indexed by their field numbers. That is typically provided in a `proto` file. In this exercise, we'll encode that information into `match` statements in functions that get called for each field.

We'll use the following proto:

```
message PhoneNumber {
  optional string number = 1;
  optional string type = 2;
}

message Person {
  optional string name = 1;
  optional int32 id = 2;
  repeated PhoneNumber phones = 3;
}
```

Messages

A proto message is encoded as a series of fields, one after the next. Each is implemented as a ”tag” followed by the value. The tag contains a field number (e.g., 2 for the `id` field of a `Person` message) and a wire type defining how the payload should be determined from the byte stream. These are combined into a single integer, as decoded in `unpack_tag` below.

Varint

Integers, including the tag, are represented with a variable-length encoding called VARINT. Luckily, `parse_varint` is defined for you below.

Wire Types

Proto defines several wire types, only two of which are used in this exercise.

The `Varint` wire type contains a single varint, and is used to encode proto values of type `int32` such as `Person.id`.

The `Len` wire type contains a length expressed as a varint, followed by a payload of that number of bytes. This is used to encode proto values of type `string` such as `Person.name`. It is also used to encode proto values containing sub-messages such as `Person.phones`, where the payload contains an encoding of the sub-message.

Exercise

The given code also defines callbacks to handle `Person` and `PhoneNumber` fields, and to parse a message into a series of calls to those callbacks.

What remains for you is to implement the parse_field function and the ProtoMessage trait for Person and PhoneNumber.

```
/// A wire type as seen on the wire.
enum WireType {
    /// The Varint WireType indicates the value is a single VARINT.
    Varint,
    // The I64 WireType indicates that the value is precisely 8 bytes in
    // little-endian order containing a 64-bit signed integer or double type.
    //I64,  -- not needed for this exercise
    /// The Len WireType indicates that the value is a length represented as a
    /// VARINT followed by exactly that number of bytes.
    Len,
    // The I32 WireType indicates that the value is precisely 4 bytes in
    // little-endian order containing a 32-bit signed integer or float type.
    //I32,  -- not needed for this exercise
}

#[derive(Debug)]
/// A field's value, typed based on the wire type.
enum FieldValue<'a> {
    Varint(u64),
    //I64(i64),  -- not needed for this exercise
    Len(&'a [u8]),
    //I32(i32),  -- not needed for this exercise
}

#[derive(Debug)]
/// A field, containing the field number and its value.
struct Field<'a> {
    field_num: u64,
    value: FieldValue<'a>,
}

trait ProtoMessage<'a>: Default {
    fn add_field(&mut self, field: Field<'a>);
}

impl From<u64> for WireType {
    fn from(value: u64) -> Self {
        match value {
            0 => WireType::Varint,
            //1 => WireType::I64,  -- not needed for this exercise
            2 => WireType::Len,
            //5 => WireType::I32,  -- not needed for this exercise
            _ => panic!("Invalid wire type: {value}"),
        }
    }
}

impl<'a> FieldValue<'a> {
```

```rust
    fn as_str(&self) -> &'a str {
        let FieldValue::Len(data) = self else {
            panic!("Expected string to be a `Len` field");
        };
        std::str::from_utf8(data).expect("Invalid string")
    }

    fn as_bytes(&self) -> &'a [u8] {
        let FieldValue::Len(data) = self else {
            panic!("Expected bytes to be a `Len` field");
        };
        data
    }

    fn as_u64(&self) -> u64 {
        let FieldValue::Varint(value) = self else {
            panic!("Expected `u64` to be a `Varint` field");
        };
        *value
    }
}

/// Parse a VARINT, returning the parsed value and the remaining bytes.
fn parse_varint(data: &[u8]) -> (u64, &[u8]) {
    for i in 0..7 {
        let Some(b) = data.get(i) else {
            panic!("Not enough bytes for varint");
        };
        if b & 0x80 == 0 {
            // This is the last byte of the VARINT, so convert it to
            // a u64 and return it.
            let mut value = 0u64;
            for b in data[..=i].iter().rev() {
                value = (value << 7) | (b & 0x7f) as u64;
            }
            return (value, &data[i + 1..]);
        }
    }

    // More than 7 bytes is invalid.
    panic!("Too many bytes for varint");
}

/// Convert a tag into a field number and a WireType.
fn unpack_tag(tag: u64) -> (u64, WireType) {
    let field_num = tag >> 3;
    let wire_type = WireType::from(tag & 0x7);
    (field_num, wire_type)
}
```

```rust
/// Parse a field, returning the remaining bytes
fn parse_field(data: &[u8]) -> (Field<'_>, &[u8]) {
    let (tag, remainder) = parse_varint(data);
    let (field_num, wire_type) = unpack_tag(tag);
    let (fieldvalue, remainder) = match wire_type {
        _ => todo!("Based on the wire type, build a Field, consuming as many bytes as ne
    };
    todo!("Return the field, and any un-consumed bytes.")
}

/// Parse a message in the given data, calling `T::add_field` for each field in
/// the message.
///
/// The entire input is consumed.
fn parse_message<'a, T: ProtoMessage<'a>>(mut data: &'a [u8]) -> T {
    let mut result = T::default();
    while !data.is_empty() {
        let parsed = parse_field(data);
        result.add_field(parsed.0);
        data = parsed.1;
    }
    result
}

#[derive(Debug, Default)]
struct PhoneNumber<'a> {
    number: &'a str,
    type_: &'a str,
}

#[derive(Debug, Default)]
struct Person<'a> {
    name: &'a str,
    id: u64,
    phone: Vec<PhoneNumber<'a>>,
}

// TODO: Implement ProtoMessage for Person and PhoneNumber.

#[test]
fn test_id() {
    let person_id: Person = parse_message(&[0x10, 0x2a]);
    assert_eq!(person_id, Person { name: "", id: 42, phone: vec![] });
}

#[test]
fn test_name() {
    let person_name: Person = parse_message(&[
        0x0a, 0x0e, 0x62, 0x65, 0x61, 0x75, 0x74, 0x69, 0x66, 0x75, 0x6c, 0x20,
        0x6e, 0x61, 0x6d, 0x65,
    ]);
```

```rust
    assert_eq!(person_name, Person { name: "beautiful name", id: 0, phone: vec![] });
}

#[test]
fn test_just_person() {
    let person_name_id: Person =
        parse_message(&[0x0a, 0x04, 0x45, 0x76, 0x61, 0x6e, 0x10, 0x16]);
    assert_eq!(person_name_id, Person { name: "Evan", id: 22, phone: vec![] });
}

#[test]
fn test_phone() {
    let phone: Person = parse_message(&[
        0x0a, 0x00, 0x10, 0x00, 0x1a, 0x16, 0x0a, 0x0e, 0x2b, 0x31, 0x32, 0x33,
        0x34, 0x2d, 0x37, 0x37, 0x37, 0x2d, 0x39, 0x30, 0x39, 0x30, 0x12, 0x04,
        0x68, 0x6f, 0x6d, 0x65,
    ]);
    assert_eq!(
        phone,
        Person {
            name: "",
            id: 0,
            phone: vec![PhoneNumber { number: "+1234-777-9090", type_: "home" },],
        }
    );
}

// Put that all together into a single parse.
#[test]
fn test_full_person() {
    let person: Person = parse_message(&[
        0x0a, 0x07, 0x6d, 0x61, 0x78, 0x77, 0x65, 0x6c, 0x6c, 0x10, 0x2a, 0x1a,
        0x16, 0x0a, 0x0e, 0x2b, 0x31, 0x32, 0x30, 0x32, 0x2d, 0x35, 0x35, 0x35,
        0x2d, 0x31, 0x32, 0x31, 0x32, 0x12, 0x04, 0x68, 0x6f, 0x6d, 0x65, 0x1a,
        0x18, 0x0a, 0x0e, 0x2b, 0x31, 0x38, 0x30, 0x30, 0x2d, 0x38, 0x36, 0x37,
        0x2d, 0x35, 0x33, 0x30, 0x38, 0x12, 0x06, 0x6d, 0x6f, 0x62, 0x69, 0x6c,
        0x65,
    ]);
    assert_eq!(
        person,
        Person {
            name: "maxwell",
            id: 42,
            phone: vec![
                PhoneNumber { number: "+1202-555-1212", type_: "home" },
                PhoneNumber { number: "+1800-867-5308", type_: "mobile" },
            ]
        }
    );
}
```

This slide and its sub-slides should take about 30 minutes.

- In this exercise there are various cases where protobuf parsing might fail, e.g. if you try to parse an `i32` when there are fewer than 4 bytes left in the data buffer. In normal Rust code we'd handle this with the `Result` enum, but for simplicity in this exercise we panic if any errors are encountered. On day 4 we'll cover error handling in Rust in more detail.

24.8.1 Solution

```rust
/// A wire type as seen on the wire.
enum WireType {
    /// The Varint WireType indicates the value is a single VARINT.
    Varint,
    // The I64 WireType indicates that the value is precisely 8 bytes in
    // little-endian order containing a 64-bit signed integer or double type.
    //I64,  -- not needed for this exercise
    /// The Len WireType indicates that the value is a length represented as a
    /// VARINT followed by exactly that number of bytes.
    Len,
    // The I32 WireType indicates that the value is precisely 4 bytes in
    // little-endian order containing a 32-bit signed integer or float type.
    //I32,  -- not needed for this exercise
}

#[derive(Debug)]
/// A field's value, typed based on the wire type.
enum FieldValue<'a> {
    Varint(u64),
    //I64(i64),  -- not needed for this exercise
    Len(&'a [u8]),
    //I32(i32),  -- not needed for this exercise
}

#[derive(Debug)]
/// A field, containing the field number and its value.
struct Field<'a> {
    field_num: u64,
    value: FieldValue<'a>,
}

trait ProtoMessage<'a>: Default {
    fn add_field(&mut self, field: Field<'a>);
}

impl From<u64> for WireType {
    fn from(value: u64) -> Self {
        match value {
            0 => WireType::Varint,
            //1 => WireType::I64,  -- not needed for this exercise
            2 => WireType::Len,
```

```rust
            //5 => WireType::I32,  -- not needed for this exercise
            _ => panic!("Invalid wire type: {value}"),
        }
    }
}

impl<'a> FieldValue<'a> {
    fn as_str(&self) -> &'a str {
        let FieldValue::Len(data) = self else {
            panic!("Expected string to be a `Len` field");
        };
        std::str::from_utf8(data).expect("Invalid string")
    }

    fn as_bytes(&self) -> &'a [u8] {
        let FieldValue::Len(data) = self else {
            panic!("Expected bytes to be a `Len` field");
        };
        data
    }

    fn as_u64(&self) -> u64 {
        let FieldValue::Varint(value) = self else {
            panic!("Expected `u64` to be a `Varint` field");
        };
        *value
    }
}

/// Parse a VARINT, returning the parsed value and the remaining bytes.
fn parse_varint(data: &[u8]) -> (u64, &[u8]) {
    for i in 0..7 {
        let Some(b) = data.get(i) else {
            panic!("Not enough bytes for varint");
        };
        if b & 0x80 == 0 {
            // This is the last byte of the VARINT, so convert it to
            // a u64 and return it.
            let mut value = 0u64;
            for b in data[..=i].iter().rev() {
                value = (value << 7) | (b & 0x7f) as u64;
            }
            return (value, &data[i + 1..]);
        }
    }

    // More than 7 bytes is invalid.
    panic!("Too many bytes for varint");
}

/// Convert a tag into a field number and a WireType.
```

```rust
fn unpack_tag(tag: u64) -> (u64, WireType) {
    let field_num = tag >> 3;
    let wire_type = WireType::from(tag & 0x7);
    (field_num, wire_type)
}

/// Parse a field, returning the remaining bytes
fn parse_field(data: &[u8]) -> (Field<'_>, &[u8]) {
    let (tag, remainder) = parse_varint(data);
    let (field_num, wire_type) = unpack_tag(tag);
    let (fieldvalue, remainder) = match wire_type {
        WireType::Varint => {
            let (value, remainder) = parse_varint(remainder);
            (FieldValue::Varint(value), remainder)
        }
        WireType::Len => {
            let (len, remainder) = parse_varint(remainder);
            let len = len as usize; // cast for simplicity
            let (value, remainder) = remainder.split_at(len);
            (FieldValue::Len(value), remainder)
        }
    };
    (Field { field_num, value: fieldvalue }, remainder)
}

/// Parse a message in the given data, calling `T::add_field` for each field in
/// the message.
///
/// The entire input is consumed.
fn parse_message<'a, T: ProtoMessage<'a>>(mut data: &'a [u8]) -> T {
    let mut result = T::default();
    while !data.is_empty() {
        let parsed = parse_field(data);
        result.add_field(parsed.0);
        data = parsed.1;
    }
    result
}

#[derive(PartialEq)]
#[derive(Debug, Default)]
struct PhoneNumber<'a> {
    number: &'a str,
    type_: &'a str,
}

#[derive(PartialEq)]
#[derive(Debug, Default)]
struct Person<'a> {
    name: &'a str,
    id: u64,
```

```rust
    phone: Vec<PhoneNumber<'a>>,
}

impl<'a> ProtoMessage<'a> for Person<'a> {
    fn add_field(&mut self, field: Field<'a>) {
        match field.field_num {
            1 => self.name = field.value.as_str(),
            2 => self.id = field.value.as_u64(),
            3 => self.phone.push(parse_message(field.value.as_bytes())),
            _ => {} // skip everything else
        }
    }
}

impl<'a> ProtoMessage<'a> for PhoneNumber<'a> {
    fn add_field(&mut self, field: Field<'a>) {
        match field.field_num {
            1 => self.number = field.value.as_str(),
            2 => self.type_ = field.value.as_str(),
            _ => {} // skip everything else
        }
    }
}

#[test]
fn test_id() {
    let person_id: Person = parse_message(&[0x10, 0x2a]);
    assert_eq!(person_id, Person { name: "", id: 42, phone: vec![] });
}

#[test]
fn test_name() {
    let person_name: Person = parse_message(&[
        0x0a, 0x0e, 0x62, 0x65, 0x61, 0x75, 0x74, 0x69, 0x66, 0x75, 0x6c, 0x20,
        0x6e, 0x61, 0x6d, 0x65,
    ]);
    assert_eq!(person_name, Person { name: "beautiful name", id: 0, phone: vec![] });
}

#[test]
fn test_just_person() {
    let person_name_id: Person =
        parse_message(&[0x0a, 0x04, 0x45, 0x76, 0x61, 0x6e, 0x10, 0x16]);
    assert_eq!(person_name_id, Person { name: "Evan", id: 22, phone: vec![] });
}

#[test]
fn test_phone() {
    let phone: Person = parse_message(&[
        0x0a, 0x00, 0x10, 0x00, 0x1a, 0x16, 0x0a, 0x0e, 0x2b, 0x31, 0x32, 0x33,
        0x34, 0x2d, 0x37, 0x37, 0x37, 0x2d, 0x39, 0x30, 0x39, 0x30, 0x12, 0x04,
```

```
        0x68, 0x6f, 0x6d, 0x65,
    ]);
    assert_eq!(
        phone,
        Person {
            name: "",
            id: 0,
            phone: vec![PhoneNumber { number: "+1234-777-9090", type_: "home" },],
        }
    );
}

// Put that all together into a single parse.
#[test]
fn test_full_person() {
    let person: Person = parse_message(&[
        0x0a, 0x07, 0x6d, 0x61, 0x78, 0x77, 0x65, 0x6c, 0x6c, 0x10, 0x2a, 0x1a,
        0x16, 0x0a, 0x0e, 0x2b, 0x31, 0x32, 0x30, 0x32, 0x2d, 0x35, 0x35, 0x35,
        0x2d, 0x31, 0x32, 0x31, 0x32, 0x12, 0x04, 0x68, 0x6f, 0x6d, 0x65, 0x1a,
        0x18, 0x0a, 0x0e, 0x2b, 0x31, 0x38, 0x30, 0x30, 0x2d, 0x38, 0x36, 0x37,
        0x2d, 0x35, 0x33, 0x30, 0x38, 0x12, 0x06, 0x6d, 0x6f, 0x62, 0x69, 0x6c,
        0x65,
    ]);
    assert_eq!(
        person,
        Person {
            name: "maxwell",
            id: 42,
            phone: vec![
                PhoneNumber { number: "+1202-555-1212", type_: "home" },
                PhoneNumber { number: "+1800-867-5308", type_: "mobile" },
            ]
        }
    );
}
```

Part VII

Day 4: Morning

Chapter 25

Welcome to Day 4

We have mastered the core language and its unique safety model:

- **Foundations & Abstraction:** Traits, generics, and the standard library.
- **Ownership:** Move semantics and the `Drop` trait.
- **Memory Management:** Borrowing rules (& vs `&mut`) and lifetimes.
- **Smart Pointers:** `Box`, `Rc`, and `RefCell` for complex data structures.

You now understand how Rust guarantees memory safety at compile time! Today we focus on applying this knowledge to build robust, large-scale applications.

Schedule

Including 10 minute breaks, this session should take about 2 hours and 50 minutes. It contains:

Segment	Duration
Welcome	3 minutes
Iterators	55 minutes
Modules	45 minutes
Testing	45 minutes

Chapter 26

Iterators

This segment should take about 55 minutes. It contains:

Slide	Duration
Motivation	3 minutes
Iterator Trait	5 minutes
Iterator Helper Methods	5 minutes
collect	5 minutes
IntoIterator	5 minutes
Exercise: Iterator Method Chaining	30 minutes

26.1 Motivating Iterators

If you want to iterate over the contents of an array, you'll need to define:

- Some state to keep track of where you are in the iteration process, e.g. an index.
- A condition to determine when iteration is done.
- Logic for updating the state of iteration each loop.
- Logic for fetching each element using that iteration state.

In a C-style for loop you declare these things directly:

```
for (int i = 0; i < array_len; i += 1) {
    int elem = array[i];
}
```

In Rust we bundle this state and logic together into an object known as an "iterator".

This slide should take about 3 minutes.

- This slide provides context for what Rust iterators do under the hood. We use the (hopefully) familiar construct of a C-style `for` loop to show how iteration requires some state and some logic, that way on the next slide we can show how an iterator bundles these together.

- Rust doesn't have a C-style `for` loop, but we can express the same thing with `while`:

```rust
    let array = [2, 4, 6, 8];
    let mut i = 0;
    while i < array.len() {
        let elem = array[i];
        i += 1;
    }
```

More to Explore

There's another way to express array iteration using `for` in C and C++: You can use a pointer to the front and a pointer to the end of the array and then compare those pointers to determine when the loop should end.

```c
for (int *ptr = array; ptr < array + len; ptr += 1) {
    int elem = *ptr;
}
```

If students ask, you can point out that this is how Rust's slice and array iterators work under the hood (though implemented as a Rust iterator).

26.2 Iterator Trait

The `Iterator` trait defines how an object can be used to produce a sequence of values. For example, if we wanted to create an iterator that can produce the elements of a slice it might look something like this:

```rust
struct SliceIter<'s> {
    slice: &'s [i32],
    i: usize,
}

impl<'s> Iterator for SliceIter<'s> {
    type Item = &'s i32;

    fn next(&mut self) -> Option<Self::Item> {
        if self.i == self.slice.len() {
            None
        } else {
            let next = &self.slice[self.i];
            self.i += 1;
            Some(next)
        }
    }
}

fn main() {
    let slice = &[2, 4, 6, 8];
    let iter = SliceIter { slice, i: 0 };
    for elem in iter {
        dbg!(elem);
```

```
    }
}
```

This slide should take about 5 minutes.

- The `SliceIter` example implements the same logic as the C-style `for` loop demonstrated on the last slide.
- Point out to the students that iterators are lazy: Creating the iterator just initializes the struct but does not otherwise do any work. No work happens until the `next` method is called.
- Iterators don't need to be finite! It's entirely valid to have an iterator that will produce values forever. For example, a half open range like `0..` will keep going until integer overflow occurs.

More to Explore

- The "real" version of `SliceIter` is the `slice::Iter` type in the standard library, however the real version uses pointers under the hood instead of an index in order to eliminate bounds checks.
- The `SliceIter` example is a good example of a struct that contains a reference and therefore uses lifetime annotations.
- You can also demonstrate adding a generic parameter to `SliceIter` to allow it to work with any kind of slice (not just `&[i32]`).

26.3 `Iterator` Helper Methods

In addition to the `next` method that defines how an iterator behaves, the `Iterator` trait provides 70+ helper methods that can be used to build customized iterators.

```
fn main() {
    let result: i32 = (1..=10) // Create a range from 1 to 10
        .filter(|x| x % 2 == 0) // Keep only even numbers
        .map(|x| x * x) // Square each number
        .sum(); // Sum up all the squared numbers

    println!("The sum of squares of even numbers from 1 to 10 is: {}", result);
}
```

This slide should take about 5 minutes.

- The `Iterator` trait implements many common functional programming operations over collections (e.g. `map`, `filter`, `reduce`, etc). This is the trait where you can find all the documentation about them.
- Many of these helper methods take the original iterator and produce a new iterator with different behavior. These are know as "iterator adapter methods".
- Some methods, like `sum` and `count`, consume the iterator and pull all of the elements out of it.
- These methods are designed to be chained together so that it's easy to build a custom iterator that does exactly what you need.

More to Explore

- Rust's iterators are extremely efficient and highly optimizable. Even complex iterators made by combining many adapter methods will still result in code as efficient as equivalent imperative implementations.

26.4 collect

The `collect` method lets you build a collection from an `Iterator`.

```
fn main() {
    let primes = vec![2, 3, 5, 7];
    let prime_squares = primes.into_iter().map(|p| p * p).collect::<Vec<_>>();
    println!("prime_squares: {prime_squares:?}");
}
```

This slide should take about 5 minutes.

- Any iterator can be collected in to a `Vec`, `VecDeque`, or `HashSet`. Iterators that produce key-value pairs (i.e. a two-element tuple) can also be collected into `HashMap` and `BTreeMap`.

Show the students the definition for `collect` in the standard library docs. There are two ways to specify the generic type `B` for this method:

- With the ”turbofish”: `some_iterator.collect::<COLLECTION_TYPE>()`, as shown. The `_` shorthand used here lets Rust infer the type of the `Vec` elements.
- With type inference: `let prime_squares: Vec<_> = some_iterator.collect()`. Rewrite the example to use this form.

More to Explore

- If students are curious about how this works, you can bring up the `FromIterator` trait, which defines how each type of collection gets built from an iterator.
- In addition to the basic implementations of `FromIterator` for `Vec`, `HashMap`, etc., there are also more specialized implementations which let you do cool things like convert an `Iterator<Item = Result<V, E>>` into a `Result<Vec<V>, E>`.
- The reason type annotations are often needed with `collect` is because it's generic over its return type. This makes it harder for the compiler to infer the correct type in many cases.

26.5 IntoIterator

The `Iterator` trait tells you how to *iterate* once you have created an iterator. The related trait `IntoIterator` defines how to create an iterator for a type. It is used automatically by the `for` loop.

```
struct Grid {
    x_coords: Vec<u32>,
    y_coords: Vec<u32>,
}
```

```rust
impl IntoIterator for Grid {
    type Item = (u32, u32);
    type IntoIter = GridIter;
    fn into_iter(self) -> GridIter {
        GridIter { grid: self, i: 0, j: 0 }
    }
}

struct GridIter {
    grid: Grid,
    i: usize,
    j: usize,
}

impl Iterator for GridIter {
    type Item = (u32, u32);

    fn next(&mut self) -> Option<(u32, u32)> {
        if self.i >= self.grid.x_coords.len() {
            self.i = 0;
            self.j += 1;
            if self.j >= self.grid.y_coords.len() {
                return None;
            }
        }
        let res = Some((self.grid.x_coords[self.i], self.grid.y_coords[self.j]));
        self.i += 1;
        res
    }
}

fn main() {
    let grid = Grid { x_coords: vec![3, 5, 7, 9], y_coords: vec![10, 20, 30, 40] };
    for (x, y) in grid {
        println!("point = {x}, {y}");
    }
}
```

This slide should take about 5 minutes.

- `IntoIterator` is the trait that makes for loops work. It is implemented by collection types such as `Vec<T>` and references to them such as `&Vec<T>` and `&[T]`. Ranges also implement it. This is why you can iterate over a vector with `for i in some_vec { .. }` but `some_vec.next()` doesn't exist.

Click through to the docs for `IntoIterator`. Every implementation of `IntoIterator` must declare two types:

- `Item`: the type to iterate over, such as `i8`,
- `IntoIter`: the `Iterator` type returned by the `into_iter` method.

Note that `IntoIter` and `Item` are linked: the iterator must have the same `Item` type, which means that it returns `Option<Item>`

The example iterates over all combinations of x and y coordinates.

Try iterating over the grid twice in `main`. Why does this fail? Note that `IntoIterator::into_iter` takes ownership of `self`.

Fix this issue by implementing `IntoIterator` for `&Grid` and creating a `GridRefIter` that iterates by reference. A version with both `GridIter` and `GridRefIter` is available in this playground.

The same problem can occur for standard library types: `for e in some_vector` will take ownership of `some_vector` and iterate over owned elements from that vector. Use `for e in &some_vector` instead, to iterate over references to elements of `some_vector`.

26.6 Exercise: Iterator Method Chaining

In this exercise, you will need to find and use some of the provided methods in the `Iterator` trait to implement a complex calculation.

Copy the following code to https://play.rust-lang.org/ and make the tests pass. Use an iterator expression and `collect` the result to construct the return value.

```rust
/// Calculate the differences between elements of `values` offset by `offset`,
/// wrapping around from the end of `values` to the beginning.
///
/// Element `n` of the result is `values[(n+offset)%len] - values[n]`.
fn offset_differences(offset: usize, values: Vec<i32>) -> Vec<i32> {
    todo!()
}

#[test]
fn test_offset_one() {
    assert_eq!(offset_differences(1, vec![1, 3, 5, 7]), vec![2, 2, 2, -6]);
    assert_eq!(offset_differences(1, vec![1, 3, 5]), vec![2, 2, -4]);
    assert_eq!(offset_differences(1, vec![1, 3]), vec![2, -2]);
}

#[test]
fn test_larger_offsets() {
    assert_eq!(offset_differences(2, vec![1, 3, 5, 7]), vec![4, 4, -4, -4]);
    assert_eq!(offset_differences(3, vec![1, 3, 5, 7]), vec![6, -2, -2, -2]);
    assert_eq!(offset_differences(4, vec![1, 3, 5, 7]), vec![0, 0, 0, 0]);
    assert_eq!(offset_differences(5, vec![1, 3, 5, 7]), vec![2, 2, 2, -6]);
}

#[test]
fn test_degenerate_cases() {
    assert_eq!(offset_differences(1, vec![0]), vec![0]);
    assert_eq!(offset_differences(1, vec![1]), vec![0]);
    let empty: Vec<i32> = vec![];
    assert_eq!(offset_differences(1, empty), vec![]);
}
```

26.6.1 Solution

```rust
/// Calculate the differences between elements of `values` offset by `offset`,
/// wrapping around from the end of `values` to the beginning.
///
/// Element `n` of the result is `values[(n+offset)%len] - values[n]`.
fn offset_differences(offset: usize, values: Vec<i32>) -> Vec<i32> {
    let a = values.iter();
    let b = values.iter().cycle().skip(offset);
    a.zip(b).map(|(a, b)| *b - *a).collect()
}

#[test]
fn test_offset_one() {
    assert_eq!(offset_differences(1, vec![1, 3, 5, 7]), vec![2, 2, 2, -6]);
    assert_eq!(offset_differences(1, vec![1, 3, 5]), vec![2, 2, -4]);
    assert_eq!(offset_differences(1, vec![1, 3]), vec![2, -2]);
}

#[test]
fn test_larger_offsets() {
    assert_eq!(offset_differences(2, vec![1, 3, 5, 7]), vec![4, 4, -4, -4]);
    assert_eq!(offset_differences(3, vec![1, 3, 5, 7]), vec![6, -2, -2, -2]);
    assert_eq!(offset_differences(4, vec![1, 3, 5, 7]), vec![0, 0, 0, 0]);
    assert_eq!(offset_differences(5, vec![1, 3, 5, 7]), vec![2, 2, 2, -6]);
}

#[test]
fn test_degenerate_cases() {
    assert_eq!(offset_differences(1, vec![0]), vec![0]);
    assert_eq!(offset_differences(1, vec![1]), vec![0]);
    let empty: Vec<i32> = vec![];
    assert_eq!(offset_differences(1, empty), vec![]);
}
```

Chapter 27

Modules

This segment should take about 45 minutes. It contains:

Slide	Duration
Modules	3 minutes
Filesystem Hierarchy	5 minutes
Visibility	5 minutes
Encapsulation	5 minutes
use, super, self	10 minutes
Exercise: Modules for a GUI Library	15 minutes

27.1 Modules

We have seen how `impl` blocks let us namespace functions to a type.

Similarly, `mod` lets us namespace types and functions:

```rust
mod foo {
    pub fn do_something() {
        println!("In the foo module");
    }
}

mod bar {
    pub fn do_something() {
        println!("In the bar module");
    }
}

fn main() {
    foo::do_something();
    bar::do_something();
}
```

This slide should take about 3 minutes.

- Packages provide functionality and include a `Cargo.toml` file that describes how to build a bundle of 1+ crates.
- Crates are a tree of modules, where a binary crate creates an executable and a library crate compiles to a library.
- Modules define organization, scope, and are the focus of this section.

27.2 Filesystem Hierarchy

Omitting the module content will tell Rust to look for it in another file:

```rust
mod garden;
```

This tells Rust that the `garden` module content is found at `src/garden.rs`. Similarly, a `garden::vegetables` module can be found at `src/garden/vegetables.rs`.

The `crate` root is in:

- `src/lib.rs` (for a library crate)
- `src/main.rs` (for a binary crate)

Modules defined in files can be documented, too, using "inner doc comments". These document the item that contains them -- in this case, a module.

```rust
//! This module implements the garden, including a highly performant germination
//! implementation.

// Re-export types from this module.
pub use garden::Garden;
pub use seeds::SeedPacket;

/// Sow the given seed packets.
pub fn sow(seeds: Vec<SeedPacket>) {
    todo!()
}

/// Harvest the produce in the garden that is ready.
pub fn harvest(garden: &mut Garden) {
    todo!()
}
```

This slide should take about 5 minutes.

- Before Rust 2018, modules needed to be located at `module/mod.rs` instead of `module.rs`, and this is still a working alternative for editions after 2018.
- The main reason to introduce `filename.rs` as alternative to `filename/mod.rs` was because many files named `mod.rs` can be hard to distinguish in IDEs.
- Deeper nesting can use folders, even if the main module is a file:

```
src/
├── main.rs
├── top_module.rs
└── top_module/
    └── sub_module.rs
```

- The place Rust will look for modules can be changed with a compiler directive:

  ```
  #[path = "some/path.rs"]
  mod some_module;
  ```

  This is useful, for example, if you would like to place tests for a module in a file named `some_module_test.rs`, similar to the convention in Go.

27.3 Visibility

Modules are a privacy boundary:

- Module items are private by default (hides implementation details).
- Parent and sibling items are always visible.
- In other words, if an item is visible in module `foo`, it's visible in all the descendants of `foo`.

```
mod outer {
    fn private() {
        println!("outer::private");
    }

    pub fn public() {
        println!("outer::public");
    }

    mod inner {
        fn private() {
            println!("outer::inner::private");
        }

        pub fn public() {
            println!("outer::inner::public");
            super::private();
        }
    }
}

fn main() {
    outer::public();
}
```

This slide should take about 5 minutes.

- Use the pub keyword to make modules public.

Additionally, there are advanced `pub(...)` specifiers to restrict the scope of public visibility.

- See the Rust Reference.
- Configuring `pub(crate)` visibility is a common pattern.
- Less commonly, you can give visibility to a specific path.
- In any case, visibility must be granted to an ancestor module (and all of its descendants).

27.4 Visibility and Encapsulation

Like with items in a module, struct fields are also private by default. Private fields are likewise visible within the rest of the module (including child modules). This allows us to encapsulate implementation details of struct, controlling what data and functionality is visible externally.

```rust
use outer::Foo;

mod outer {
    pub struct Foo {
        pub val: i32,
        is_big: bool,
    }

    impl Foo {
        pub fn new(val: i32) -> Self {
            Self { val, is_big: val > 100 }
        }
    }

    pub mod inner {
        use super::Foo;

        pub fn print_foo(foo: &Foo) {
            println!("Is {} big? {}", foo.val, foo.is_big);
        }
    }
}

fn main() {
    let foo = Foo::new(42);
    println!("foo.val = {}", foo.val);
    // let foo = Foo { val: 42, is_big: true };

    outer::inner::print_foo(&foo);
    // println!("Is {} big? {}", foo.val, foo.is_big);
}
```

This slide should take about 5 minutes.

- This slide demonstrates how privacy in structs is module-based. Students coming from object-oriented languages may be used to types being the encapsulation boundary, so this demonstrates how Rust behaves differently while showing how we can still achieve encapsulation.
- Note how the `is_big` field is fully controlled by `Foo`, allowing `Foo` to control how it's initialized and enforce any invariants it needs to (e.g. that `is_big` is only `true` if `val > 100`).
- Point out how helper functions can be defined in the same module (including child modules) in order to get access to the type's private fields/methods.
- The first commented out line demonstrates that you cannot initialize a struct with private fields. The second one demonstrates that you also can't directly access private

fields.

- Enums do not support privacy: Variants and data within those variants is always public.

More to Explore

- If students want more information about privacy (or lack thereof) in enums, you can bring up `#[doc_hidden]` and `#[non_exhaustive]` and show how they're used to limit what can be done with an enum.
- Module privacy still applies when there are `impl` blocks in other modules (example in the playground).

27.5 use, super, self

A module can bring symbols from another module into scope with `use`. You will typically see something like this at the top of each module:

```
use std::collections::HashSet;
use std::process::abort;
```

Paths

Paths are resolved as follows:

1. As a relative path:
   - `foo` or `self::foo` refers to `foo` in the current module,
   - `super::foo` refers to `foo` in the parent module.
2. As an absolute path:
   - `crate::foo` refers to `foo` in the root of the current crate,
   - `bar::foo` refers to `foo` in the `bar` crate.

This slide should take about 8 minutes.

- It is common to "re-export" symbols at a shorter path. For example, the top-level `lib.rs` in a crate might have

  ```
  mod storage;

  pub use storage::disk::DiskStorage;
  pub use storage::network::NetworkStorage;
  ```

  making `DiskStorage` and `NetworkStorage` available to other crates with a convenient, short path.
- For the most part, only items that appear in a module need to be `use`'d. However, a trait must be in scope to call any methods on that trait, even if a type implementing that trait is already in scope. For example, to use the `read_to_string` method on a type implementing the `Read` trait, you need to `use std::io::Read`.
- The `use` statement can have a wildcard: `use std::io::*`. This is discouraged because it is not clear which items are imported, and those might change over time.

27.6 Exercise: Modules for a GUI Library

In this exercise, you will reorganize a small GUI Library implementation. This library defines a `Widget` trait and a few implementations of that trait, as well as a `main` function.

It is typical to put each type or set of closely-related types into its own module, so each widget type should get its own module.

Cargo Setup

The Rust playground only supports one file, so you will need to make a Cargo project on your local filesystem:

```
cargo init gui-modules
cd gui-modules
cargo run
```

Edit the resulting `src/main.rs` to add `mod` statements, and add additional files in the `src` directory.

Source

Here's the single-module implementation of the GUI library:

```rust
pub trait Widget {
    /// Natural width of `self`.
    fn width(&self) -> usize;

    /// Draw the widget into a buffer.
    fn draw_into(&self, buffer: &mut dyn std::fmt::Write);

    /// Draw the widget on standard output.
    fn draw(&self) {
        let mut buffer = String::new();
        self.draw_into(&mut buffer);
        println!("{buffer}");
    }
}

pub struct Label {
    label: String,
}

impl Label {
    fn new(label: &str) -> Label {
        Label { label: label.to_owned() }
    }
}

pub struct Button {
    label: Label,
}
```

```rust
impl Button {
    fn new(label: &str) -> Button {
        Button { label: Label::new(label) }
    }
}

pub struct Window {
    title: String,
    widgets: Vec<Box<dyn Widget>>,
}

impl Window {
    fn new(title: &str) -> Window {
        Window { title: title.to_owned(), widgets: Vec::new() }
    }

    fn add_widget(&mut self, widget: Box<dyn Widget>) {
        self.widgets.push(widget);
    }

    fn inner_width(&self) -> usize {
        std::cmp::max(
            self.title.chars().count(),
            self.widgets.iter().map(|w| w.width()).max().unwrap_or(0),
        )
    }
}

impl Widget for Window {
    fn width(&self) -> usize {
        // Add 4 paddings for borders
        self.inner_width() + 4
    }

    fn draw_into(&self, buffer: &mut dyn std::fmt::Write) {
        let mut inner = String::new();
        for widget in &self.widgets {
            widget.draw_into(&mut inner);
        }

        let inner_width = self.inner_width();

        // TODO: Change draw_into to return Result<(), std::fmt::Error>. Then use the
        // ?-operator here instead of .unwrap().
        writeln!(buffer, "+-{:-<inner_width$}-+", "").unwrap();
        writeln!(buffer, "| {:^inner_width$} |", &self.title).unwrap();
        writeln!(buffer, "+={:=<inner_width$}=+", "").unwrap();
        for line in inner.lines() {
            writeln!(buffer, "| {:inner_width$} |", line).unwrap();
        }
```

```rust
        writeln!(buffer, "+-{:-<inner_width$}-+", "").unwrap();
    }
}

impl Widget for Button {
    fn width(&self) -> usize {
        self.label.width() + 8 // add a bit of padding
    }

    fn draw_into(&self, buffer: &mut dyn std::fmt::Write) {
        let width = self.width();
        let mut label = String::new();
        self.label.draw_into(&mut label);

        writeln!(buffer, "+{:-<width$}+", "").unwrap();
        for line in label.lines() {
            writeln!(buffer, "|{:^width$}|", &line).unwrap();
        }
        writeln!(buffer, "+{:-<width$}+", "").unwrap();
    }
}

impl Widget for Label {
    fn width(&self) -> usize {
        self.label.lines().map(|line| line.chars().count()).max().unwrap_or(0)
    }

    fn draw_into(&self, buffer: &mut dyn std::fmt::Write) {
        writeln!(buffer, "{}", &self.label).unwrap();
    }
}

fn main() {
    let mut window = Window::new("Rust GUI Demo 1.23");
    window.add_widget(Box::new(Label::new("This is a small text GUI demo.")));
    window.add_widget(Box::new(Button::new("Click me!")));
    window.draw();
}
```

This slide and its sub-slides should take about 15 minutes.

Encourage students to divide the code in a way that feels natural for them, and get accustomed to the required mod, use, and pub declarations. Afterward, discuss what organizations are most idiomatic.

27.6.1 Solution

```
src
├── main.rs
├── widgets
│   ├── button.rs
```

```
│   ├── label.rs
│   └── window.rs
└── widgets.rs
```

```rust
// ---- src/widgets.rs ----
pub use button::Button;
pub use label::Label;
pub use window::Window;

mod button;
mod label;
mod window;

pub trait Widget {
    /// Natural width of `self`.
    fn width(&self) -> usize;

    /// Draw the widget into a buffer.
    fn draw_into(&self, buffer: &mut dyn std::fmt::Write);

    /// Draw the widget on standard output.
    fn draw(&self) {
        let mut buffer = String::new();
        self.draw_into(&mut buffer);
        println!("{buffer}");
    }
}
// ---- src/widgets/label.rs ----
use super::Widget;

pub struct Label {
    label: String,
}

impl Label {
    pub fn new(label: &str) -> Label {
        Label { label: label.to_owned() }
    }
}

impl Widget for Label {
    fn width(&self) -> usize {
        // ANCHOR_END: Label-width
        self.label.lines().map(|line| line.chars().count()).max().unwrap_or(0)
    }

    // ANCHOR: Label-draw_into
    fn draw_into(&self, buffer: &mut dyn std::fmt::Write) {
        // ANCHOR_END: Label-draw_into
        writeln!(buffer, "{}", &self.label).unwrap();
    }
```

```rust
}

// ---- src/widgets/button.rs ----
use super::{Label, Widget};

pub struct Button {
    label: Label,
}

impl Button {
    pub fn new(label: &str) -> Button {
        Button { label: Label::new(label) }
    }
}

impl Widget for Button {
    fn width(&self) -> usize {
        // ANCHOR_END: Button-width
        self.label.width() + 8 // add a bit of padding
    }

    // ANCHOR: Button-draw_into
    fn draw_into(&self, buffer: &mut dyn std::fmt::Write) {
        // ANCHOR_END: Button-draw_into
        let width = self.width();
        let mut label = String::new();
        self.label.draw_into(&mut label);

        writeln!(buffer, "+{:-<width$}+", "").unwrap();
        for line in label.lines() {
            writeln!(buffer, "|{:^width$}|", &line).unwrap();
        }
        writeln!(buffer, "+{:-<width$}+", "").unwrap();
    }
}

// ---- src/widgets/window.rs ----
use super::Widget;

pub struct Window {
    title: String,
    widgets: Vec<Box<dyn Widget>>,
}

impl Window {
    pub fn new(title: &str) -> Window {
        Window { title: title.to_owned(), widgets: Vec::new() }
    }

    pub fn add_widget(&mut self, widget: Box<dyn Widget>) {
        self.widgets.push(widget);
    }
```

```rust
    fn inner_width(&self) -> usize {
        std::cmp::max(
            self.title.chars().count(),
            self.widgets.iter().map(|w| w.width()).max().unwrap_or(0),
        )
    }
}

impl Widget for Window {
    fn width(&self) -> usize {
        // ANCHOR_END: Window-width
        // Add 4 paddings for borders
        self.inner_width() + 4
    }

    // ANCHOR: Window-draw_into
    fn draw_into(&self, buffer: &mut dyn std::fmt::Write) {
        // ANCHOR_END: Window-draw_into
        let mut inner = String::new();
        for widget in &self.widgets {
            widget.draw_into(&mut inner);
        }

        let inner_width = self.inner_width();

        // TODO: after learning about error handling, you can change
        // draw_into to return Result<(), std::fmt::Error>. Then use
        // the ?-operator here instead of .unwrap().
        writeln!(buffer, "+-{:-<inner_width$}-+", "").unwrap();
        writeln!(buffer, "| {:^inner_width$} |", &self.title).unwrap();
        writeln!(buffer, "+={:=<inner_width$}=+", "").unwrap();
        for line in inner.lines() {
            writeln!(buffer, "| {:inner_width$} |", line).unwrap();
        }
        writeln!(buffer, "+-{:-<inner_width$}-+", "").unwrap();
    }
}

// ---- src/main.rs ----
mod widgets;

use widgets::{Button, Label, Widget, Window};

fn main() {
    let mut window = Window::new("Rust GUI Demo 1.23");
    window.add_widget(Box::new(Label::new("This is a small text GUI demo.")));
    window.add_widget(Box::new(Button::new("Click me!")));
    window.draw();
}
```

Chapter 28

Testing

This segment should take about 45 minutes. It contains:

Slide	Duration
Unit Tests	5 minutes
Other Types of Tests	5 minutes
Compiler Lints and Clippy	3 minutes
Exercise: Luhn Algorithm	30 minutes

28.1 Unit Tests

Rust and Cargo come with a simple unit test framework. Tests are marked with `#[test]`. Unit tests are often put in a nested `tests` module, using `#[cfg(test)]` to conditionally compile them only when building tests.

```
fn first_word(text: &str) -> &str {
    match text.find(' ') {
        Some(idx) => &text[..idx],
        None => &text,
    }
}

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

    #[test]
    fn test_empty() {
        assert_eq!(first_word(""), "");
    }

    #[test]
    fn test_single_word() {
        assert_eq!(first_word("Hello"), "Hello");
```

```
    }

    #[test]
    fn test_multiple_words() {
        assert_eq!(first_word("Hello World"), "Hello");
    }
}
```

- This lets you unit test private helpers.
- The `#[cfg(test)]` attribute is only active when you run `cargo test`.

28.2 Other Types of Tests

Integration Tests

If you want to test your library as a client, use an integration test.

Create a `.rs` file under `tests/`:

```
// tests/my_library.rs
use my_library::init;

#[test]
fn test_init() {
    assert!(init().is_ok());
}
```

These tests only have access to the public API of your crate.

Documentation Tests

Rust has built-in support for documentation tests:

```
/// Shortens a string to the given length.
///
/// ```
/// # use playground::shorten_string;
/// assert_eq!(shorten_string("Hello World", 5), "Hello");
/// assert_eq!(shorten_string("Hello World", 20), "Hello World");
/// ```
pub fn shorten_string(s: &str, length: usize) -> &str {
    &s[..std::cmp::min(length, s.len())]
}
```

- Code blocks in `///` comments are automatically seen as Rust code.
- The code will be compiled and executed as part of `cargo test`.
- Adding `#` in the code will hide it from the docs, but will still compile/run it.
- Test the above code on the Rust Playground.

28.3 Compiler Lints and Clippy

The Rust compiler produces fantastic error messages, as well as helpful built-in lints. Clippy provides even more lints, organized into groups that can be enabled per-project.

```
#[deny(clippy::cast_possible_truncation)]
fn main() {
    let mut x = 3;
    while (x < 70000) {
        x *= 2;
    }
    println!("X probably fits in a u16, right? {}", x as u16);
}
```

This slide should take about 3 minutes.

There are compiler lints visible here, but not clippy lints. Run `clippy` on the playground site to show clippy warnings. Clippy has extensive documentation of its lints, and adds new lints (including default-deny lints) all the time.

Note that errors or warnings with `help: ...` can be fixed with `cargo fix` or via your editor.

28.4 Exercise: Luhn Algorithm

The Luhn algorithm is used to validate credit card numbers. The algorithm takes a string as input and does the following to validate the credit card number:

- Ignore all spaces. Reject numbers with fewer than two digits. Reject letters and other non-digit characters.
- Moving from **right to left**, double every second digit: for the number 1234, we double 3 and 1. For the number 98765, we double 6 and 8.
- After doubling a digit, sum the digits if the result is greater than 9. So doubling 7 becomes 14 which becomes `1 + 4 = 5`.
- Sum all the undoubled and doubled digits.
- The credit card number is valid if the sum ends with `0`.

The provided code provides a buggy implementation of the Luhn algorithm, along with two basic unit tests that confirm that most of the algorithm is implemented correctly.

Copy the code below to https://play.rust-lang.org/ and write additional tests to uncover bugs in the provided implementation, fixing any bugs you find.

```
pub fn luhn(cc_number: &str) -> bool {
    let mut sum = 0;
    let mut double = false;

    for c in cc_number.chars().rev() {
        if let Some(digit) = c.to_digit(10) {
            if double {
                let double_digit = digit * 2;
                sum +=
                    if double_digit > 9 { double_digit - 9 } else { double_digit };
```

```rust
            } else {
                sum += digit;
            }
            double = !double;
        } else {
            continue;
        }
    }

    sum % 10 == 0
}

#[cfg(test)]
mod test {
    use super::*;

    #[test]
    fn test_valid_cc_number() {
        assert!(luhn("4263 9826 4026 9299"));
        assert!(luhn("4539 3195 0343 6467"));
        assert!(luhn("7992 7398 713"));
    }

    #[test]
    fn test_invalid_cc_number() {
        assert!(!luhn("4223 9826 4026 9299"));
        assert!(!luhn("4539 3195 0343 6476"));
        assert!(!luhn("8273 1232 7352 0569"));
    }
}
```

28.4.1 Solution

```rust
pub fn luhn(cc_number: &str) -> bool {
    let mut sum = 0;
    let mut double = false;
    let mut digits = 0;

    for c in cc_number.chars().rev() {
        if let Some(digit) = c.to_digit(10) {
            digits += 1;
            if double {
                let double_digit = digit * 2;
                sum +=
                    if double_digit > 9 { double_digit - 9 } else { double_digit };
            } else {
                sum += digit;
            }
            double = !double;
        } else if c.is_whitespace() {
            // New: accept whitespace.
```

```rust
            continue;
        } else {
            // New: reject all other characters.
            return false;
        }
    }

    // New: check that we have at least two digits
    digits >= 2 && sum % 10 == 0
}

#[cfg(test)]
mod test {
    use super::*;

    #[test]
    fn test_valid_cc_number() {
        assert!(luhn("4263 9826 4026 9299"));
        assert!(luhn("4539 3195 0343 6467"));
        assert!(luhn("7992 7398 713"));
    }

    #[test]
    fn test_invalid_cc_number() {
        assert!(!luhn("4223 9826 4026 9299"));
        assert!(!luhn("4539 3195 0343 6476"));
        assert!(!luhn("8273 1232 7352 0569"));
    }

    #[test]
    fn test_non_digit_cc_number() {
        assert!(!luhn("foo"));
        assert!(!luhn("foo 0 0"));
    }

    #[test]
    fn test_empty_cc_number() {
        assert!(!luhn(""));
        assert!(!luhn(" "));
        assert!(!luhn("  "));
        assert!(!luhn("    "));
    }

    #[test]
    fn test_single_digit_cc_number() {
        assert!(!luhn("0"));
    }

    #[test]
    fn test_two_digit_cc_number() {
        assert!(luhn(" 0 0 "));
```

```
    }
}
```

Part VIII

Day 4: Afternoon

Chapter 29

Welcome Back

Including 10 minute breaks, this session should take about 2 hours and 20 minutes. It contains:

Segment	Duration
Error Handling	55 minutes
Unsafe Rust	1 hour and 15 minutes

Chapter 30

Error Handling

This segment should take about 55 minutes. It contains:

Slide	Duration
Panics	3 minutes
Result	5 minutes
Try Operator	5 minutes
Try Conversions	5 minutes
Error Trait	5 minutes
thiserror	5 minutes
anyhow	5 minutes
Exercise: Rewriting with Result	20 minutes

30.1 Panics

In case of a fatal runtime error, Rust triggers a ”panic”:

```
fn main() {
    let v = vec![10, 20, 30];
    dbg!(v[100]);
}
```

- Panics are for unrecoverable and unexpected errors.
  - Panics are symptoms of bugs in the program.
  - Runtime failures like failed bounds checks can panic.
  - Assertions (such as `assert!`) panic on failure.
  - Purpose-specific panics can use the `panic!` macro.
- A panic will ”unwind” the stack, dropping values just as if the functions had returned.
- Use non-panicking APIs (such as `Vec::get`) if crashing is not acceptable.

This slide should take about 3 minutes.

By default, a panic will cause the stack to unwind. The unwinding can be caught:

```
use std::panic;
```

```rust
fn main() {
    let result = panic::catch_unwind(|| "No problem here!");
    dbg!(result);

    let result = panic::catch_unwind(|| {
        panic!("oh no!");
    });
    dbg!(result);
}
```

- Catching is unusual; do not attempt to implement exceptions with `catch_unwind`!
- This can be useful in servers which should keep running even if a single request crashes.
- This does not work if `panic = 'abort'` is set in your `Cargo.toml`.

30.2 Result

Our primary mechanism for error handling in Rust is the `Result` enum, which we briefly saw when discussing standard library types.

```rust
use std::fs::File;
use std::io::Read;

fn main() {
    let file: Result<File, std::io::Error> = File::open("diary.txt");
    match file {
        Ok(mut file) => {
            let mut contents = String::new();
            if let Ok(bytes) = file.read_to_string(&mut contents) {
                println!("Dear diary: {contents} ({bytes} bytes)");
            } else {
                println!("Could not read file content");
            }
        }
        Err(err) => {
            println!("The diary could not be opened: {err}");
        }
    }
}
```

This slide should take about 5 minutes.

- `Result` has two variants: `Ok` which contains the success value, and `Err` which contains an error value of some kind.
- Whether or not a function can produce an error is encoded in the function's type signature by having the function return a `Result` value.
- Like with `Option`, there is no way to forget to handle an error: You cannot access either the success value or the error value without first pattern matching on the `Result` to check which variant you have. Methods like `unwrap` make it easier to write quick-and-dirty code that doesn't do robust error handling, but means that you can always see in your source code where proper error handling is being skipped.

More to Explore

It may be helpful to compare error handling in Rust to error handling conventions that students may be familiar with from other programming languages.

Exceptions

- Many languages use exceptions, e.g. C++, Java, Python.
- In most languages with exceptions, whether or not a function can throw an exception is not visible as part of its type signature. This generally means that you can't tell when calling a function if it may throw an exception or not.
- Exceptions generally unwind the call stack, propagating upward until a `try` block is reached. An error originating deep in the call stack may impact an unrelated function further up.

Error Numbers

- Some languages have functions return an error number (or some other error value) separately from the successful return value of the function. Examples include C and Go.
- Depending on the language it may be possible to forget to check the error value, in which case you may be accessing an uninitialized or otherwise invalid success value.

30.3 Try Operator

Runtime errors like connection-refused or file-not-found are handled with the `Result` type, but matching this type on every call can be cumbersome. The try-operator `?` is used to return errors to the caller. It lets you turn the common

```
match some_expression {
    Ok(value) => value,
    Err(err) => return Err(err),
}
```

into the much simpler

```
some_expression?
```

We can use this to simplify our error handling code:

```
use std::io::Read;
use std::{fs, io};

fn read_username(path: &str) -> Result<String, io::Error> {
    let username_file_result = fs::File::open(path);
    let mut username_file = match username_file_result {
        Ok(file) => file,
        Err(err) => return Err(err),
    };

    let mut username = String::new();
```

```
    match username_file.read_to_string(&mut username) {
        Ok(_) => Ok(username),
        Err(err) => Err(err),
    }
}

fn main() {
    //fs::write("config.dat", "alice").unwrap();
    let username = read_username("config.dat");
    println!("username or error: {username:?}");
}
```

This slide should take about 5 minutes.

Simplify the `read_username` function to use `?`.

Key points:

- The `username` variable can be either `Ok(string)` or `Err(error)`.
- Use the `fs::write` call to test out the different scenarios: no file, empty file, file with username.
- Note that `main` can return a `Result<(), E>` as long as it implements `std::process::Termination`. In practice, this means that `E` implements `Debug`. The executable will print the `Err` variant and return a nonzero exit status on error.

30.4 Try Conversions

The effective expansion of `?` is a little more complicated than previously indicated:

```
expression?
```

works the same as

```
match expression {
    Ok(value) => value,
    Err(err)  => return Err(From::from(err)),
}
```

The `From::from` call here means we attempt to convert the error type to the type returned by the function. This makes it easy to encapsulate errors into higher-level errors.

Example

```
use std::error::Error;
use std::io::Read;
use std::{fmt, fs, io};

#[derive(Debug)]
enum ReadUsernameError {
    IoError(io::Error),
    EmptyUsername(String),
}

impl Error for ReadUsernameError {}
```

```rust
impl fmt::Display for ReadUsernameError {
    fn fmt(&self, f: &mut fmt::Formatter) -> fmt::Result {
        match self {
            Self::IoError(e) => write!(f, "I/O error: {e}"),
            Self::EmptyUsername(path) => write!(f, "Found no username in {path}"),
        }
    }
}

impl From<io::Error> for ReadUsernameError {
    fn from(err: io::Error) -> Self {
        Self::IoError(err)
    }
}

fn read_username(path: &str) -> Result<String, ReadUsernameError> {
    let mut username = String::with_capacity(100);
    fs::File::open(path)?.read_to_string(&mut username)?;
    if username.is_empty() {
        return Err(ReadUsernameError::EmptyUsername(String::from(path)));
    }
    Ok(username)
}

fn main() {
    //std::fs::write("config.dat", "").unwrap();
    let username = read_username("config.dat");
    println!("username or error: {username:?}");
}
```

This slide should take about 5 minutes.

The `?` operator must return a value compatible with the return type of the function. For `Result`, it means that the error types have to be compatible. A function that returns `Result<T, ErrorOuter>` can only use `?` on a value of type `Result<U, ErrorInner>` if `ErrorOuter` and `ErrorInner` are the same type or if `ErrorOuter` implements `From<ErrorInner>`.

A common alternative to a `From` implementation is `Result::map_err`, especially when the conversion only happens in one place.

There is no compatibility requirement for `Option`. A function returning `Option<T>` can use the `?` operator on `Option<U>` for arbitrary `T` and `U` types.

A function that returns `Result` cannot use `?` on `Option` and vice versa. However, `Option::ok_or` converts `Option` to `Result` whereas `Result::ok` turns `Result` into `Option`.

30.5 Dynamic Error Types

Sometimes we want to allow any type of error to be returned without writing our own enum covering all the different possibilities. The `std::error::Error` trait makes it easy to create a trait object that can contain any error.

```
use std::error::Error;
use std::fs;
use std::io::Read;

fn read_count(path: &str) -> Result<i32, Box<dyn Error>> {
    let mut count_str = String::new();
    fs::File::open(path)?.read_to_string(&mut count_str)?;
    let count: i32 = count_str.parse()?;
    Ok(count)
}

fn main() {
    fs::write("count.dat", "1i3").unwrap();
    match read_count("count.dat") {
        Ok(count) => println!("Count: {count}"),
        Err(err) => println!("Error: {err}"),
    }
}
```

This slide should take about 5 minutes.

The `read_count` function can return `std::io::Error` (from file operations) or `std::num::ParseIntError` (from `String::parse`).

Boxing errors saves on code, but gives up the ability to cleanly handle different error cases differently in the program. As such it's generally not a good idea to use `Box<dyn Error>` in the public API of a library, but it can be a good option in a program where you just want to display the error message somewhere.

Make sure to implement the `std::error::Error` trait when defining a custom error type so it can be boxed.

30.6 `thiserror`

The `thiserror` crate provides macros to help avoid boilerplate when defining error types. It provides derive macros that assist in implementing `From<T>`, `Display`, and the `Error` trait.

```
use std::io::Read;
use std::{fs, io};
use thiserror::Error;

#[derive(Debug, Error)]
enum ReadUsernameError {
    #[error("I/O error: {0}")]
    IoError(#[from] io::Error),
    #[error("Found no username in {0}")]
    EmptyUsername(String),
```

```
}

fn read_username(path: &str) -> Result<String, ReadUsernameError> {
    let mut username = String::with_capacity(100);
    fs::File::open(path)?.read_to_string(&mut username)?;
    if username.is_empty() {
        return Err(ReadUsernameError::EmptyUsername(String::from(path)));
    }
    Ok(username)
}

fn main() {
    //fs::write("config.dat", "").unwrap();
    match read_username("config.dat") {
        Ok(username) => println!("Username: {username}"),
        Err(err) => println!("Error: {err}"),
    }
}
```

This slide should take about 5 minutes.

- The `Error` derive macro is provided by `thiserror`, and has lots of useful attributes to help define error types in a compact way.
- The message from `#[error]` is used to derive the `Display` trait.
- Note that the (`thiserror::`)`Error` derive macro, while it has the effect of implementing the (`std::error::`)`Error` trait, is not the same this; traits and macros do not share a namespace.

30.7 anyhow

The anyhow crate provides a rich error type with support for carrying additional contextual information, which can be used to provide a semantic trace of what the program was doing leading up to the error.

This can be combined with the convenience macros from `thiserror` to avoid writing out trait impls explicitly for custom error types.

```
use anyhow::{Context, Result, bail};
use std::fs;
use std::io::Read;
use thiserror::Error;

#[derive(Clone, Debug, Eq, Error, PartialEq)]
#[error("Found no username in {0}")]
struct EmptyUsernameError(String);

fn read_username(path: &str) -> Result<String> {
    let mut username = String::with_capacity(100);
    fs::File::open(path)
        .with_context(|| format!("Failed to open {path}"))?
        .read_to_string(&mut username)
        .context("Failed to read")?;
```

```rust
    if username.is_empty() {
        bail!(EmptyUsernameError(path.to_string()));
    }
    Ok(username)
}

fn main() {
    //fs::write("config.dat", "").unwrap();
    match read_username("config.dat") {
        Ok(username) => println!("Username: {username}"),
        Err(err) => println!("Error: {err:?}"),
    }
}
```

This slide should take about 5 minutes.

- `anyhow::Error` is essentially a wrapper around `Box<dyn Error>`. As such it's again generally not a good choice for the public API of a library, but is widely used in applications.
- `anyhow::Result<V>` is a type alias for `Result<V, anyhow::Error>`.
- Functionality provided by `anyhow::Error` may be familiar to Go developers, as it provides similar behavior to the Go `error` type and `Result<T, anyhow::Error>` is much like a Go `(T, error)` (with the convention that only one element of the pair is meaningful).
- `anyhow::Context` is a trait implemented for the standard `Result` and `Option` types. `use anyhow::Context` is necessary to enable `.context()` and `.with_context()` on those types.

More to Explore

- `anyhow::Error` has support for downcasting, much like `std::any::Any`; the specific error type stored inside can be extracted for examination if desired with `Error::downcast`.

30.8 Exercise: Rewriting with Result

In this exercise we're revisiting the expression evaluator exercise that we did in day 2. Our initial solution ignores a possible error case: Dividing by zero! Rewrite `eval` to instead use idiomatic error handling to handle this error case and return an error when it occurs. We provide a simple `DivideByZeroError` type to use as the error type for `eval`.

```rust
/// An operation to perform on two subexpressions.
#[derive(Debug)]
enum Operation {
    Add,
    Sub,
    Mul,
    Div,
}
```

```rust
/// An expression, in tree form.
#[derive(Debug)]
enum Expression {
    /// An operation on two subexpressions.
    Op { op: Operation, left: Box<Expression>, right: Box<Expression> },

    /// A literal value
    Value(i64),
}

#[derive(PartialEq, Eq, Debug)]
struct DivideByZeroError;

// The original implementation of the expression evaluator. Update this to
// return a `Result` and produce an error when dividing by 0.
fn eval(e: Expression) -> i64 {
    match e {
        Expression::Op { op, left, right } => {
            let left = eval(*left);
            let right = eval(*right);
            match op {
                Operation::Add => left + right,
                Operation::Sub => left - right,
                Operation::Mul => left * right,
                Operation::Div => if right != 0 {
                    left / right
                } else {
                    panic!("Cannot divide by zero!");
                },
            }
        }
        Expression::Value(v) => v,
    }
}

#[cfg(test)]
mod test {
    use super::*;

    #[test]
    fn test_error() {
        assert_eq!(
            eval(Expression::Op {
                op: Operation::Div,
                left: Box::new(Expression::Value(99)),
                right: Box::new(Expression::Value(0)),
            }),
            Err(DivideByZeroError)
        );
    }
```

```rust
    #[test]
    fn test_ok() {
        let expr = Expression::Op {
            op: Operation::Sub,
            left: Box::new(Expression::Value(20)),
            right: Box::new(Expression::Value(10)),
        };
        assert_eq!(eval(expr), Ok(10));
    }
}
```

This slide and its sub-slides should take about 20 minutes.

- The starting code here isn't exactly the same as the previous exercise's solution: We've added in an explicit panic to show students where the error case is. Point this out if students get confused.

30.8.1 Solution

```rust
/// An operation to perform on two subexpressions.
#[derive(Debug)]
enum Operation {
    Add,
    Sub,
    Mul,
    Div,
}

/// An expression, in tree form.
#[derive(Debug)]
enum Expression {
    /// An operation on two subexpressions.
    Op { op: Operation, left: Box<Expression>, right: Box<Expression> },

    /// A literal value
    Value(i64),
}

#[derive(PartialEq, Eq, Debug)]
struct DivideByZeroError;

fn eval(e: Expression) -> Result<i64, DivideByZeroError> {
    match e {
        Expression::Op { op, left, right } => {
            let left = eval(*left)?;
            let right = eval(*right)?;
            Ok(match op {
                Operation::Add => left + right,
                Operation::Sub => left - right,
                Operation::Mul => left * right,
                Operation::Div => {
                    if right == 0 {
```

```rust
                    return Err(DivideByZeroError);
                } else {
                    left / right
                }
            }
        })
    }
    Expression::Value(v) => Ok(v),
    }
}

#[cfg(test)]
mod test {
    use super::*;

    #[test]
    fn test_error() {
        assert_eq!(
            eval(Expression::Op {
                op: Operation::Div,
                left: Box::new(Expression::Value(99)),
                right: Box::new(Expression::Value(0)),
            }),
            Err(DivideByZeroError)
        );
    }

    #[test]
    fn test_ok() {
        let expr = Expression::Op {
            op: Operation::Sub,
            left: Box::new(Expression::Value(20)),
            right: Box::new(Expression::Value(10)),
        };
        assert_eq!(eval(expr), Ok(10));
    }
}
```

- **Result Return Type:** The function signature changes to return `Result<i64, DivideByZeroError>`. This explicit type signature forces the caller to handle the possibility of failure.
- **The ? Operator:** We use `?` on the recursive calls: `eval(*left)?`. This cleanly propagates errors. If `eval` returns `Err`, the function immediately returns that `Err`. If it returns `Ok(v)`, `v` is assigned to `left` (or `right`).
- **`Ok` Wrapping:** Successful results must be wrapped in `Ok(...)`.
- **Handling Division by Zero:** We explicitly check for `right == 0` and return `Err(DivideByZeroError)`. This replaces the panic in the original code.

- Mention that `DivideByZeroError` is a unit struct (no fields), which is sufficient here since there's no extra context to provide about the error.
- Discuss how `?` makes error handling almost as concise as exceptions, but with explicit control flow.

Chapter 31

Unsafe Rust

This segment should take about 1 hour and 15 minutes. It contains:

Slide	Duration
Unsafe	5 minutes
Dereferencing Raw Pointers	10 minutes
Mutable Static Variables	5 minutes
Unions	5 minutes
Unsafe Functions	15 minutes
Unsafe Traits	5 minutes
Exercise: FFI Wrapper	30 minutes

31.1 Unsafe Rust

The Rust language has two parts:

- **Safe Rust:** memory safe, no undefined behavior possible.
- **Unsafe Rust:** can trigger undefined behavior if preconditions are violated.

We saw mostly safe Rust in this course, but it's important to know what Unsafe Rust is.

Unsafe code should be small and isolated, and its correctness should be carefully documented. It should be wrapped in a safe abstraction layer.

Unsafe Rust gives you access to five new capabilities:

- Dereference raw pointers.
- Access or modify mutable static variables.
- Access `union` fields.
- Call `unsafe` functions, including `extern` functions.
- Implement `unsafe` traits.

We will briefly cover unsafe capabilities next. For full details, please see Chapter 19.1 in the Rust Book and the Rustonomicon.

This slide should take about 5 minutes.

Unsafe Rust does not mean the code is incorrect. It means that developers have turned off some compiler safety features and have to write correct code by themselves. It means the compiler no longer enforces Rust's memory-safety rules.

31.2 Dereferencing Raw Pointers

Creating pointers is safe, but dereferencing them requires `unsafe`:

```rust
fn main() {
    let mut x = 10;

    let p1: *mut i32 = &raw mut x;
    let p2 = p1 as *const i32;

    // SAFETY: p1 and p2 were created by taking raw pointers to a local, so they
    // are guaranteed to be non-null, aligned, and point into a single (stack-)
    // allocated object.
    //
    // The object underlying the raw pointers lives for the entire function, so
    // it is not deallocated while the raw pointers still exist. It is not
    // accessed through references while the raw pointers exist, nor is it
    // accessed from other threads concurrently.
    unsafe {
        dbg!(*p1);
        *p1 = 6;
        // Mutation may soundly be observed through a raw pointer, like in C.
        dbg!(*p2);
    }

    // UNSOUND. DO NOT DO THIS.
    /*
    let r: &i32 = unsafe { &*p1 };
    dbg!(r);
    x = 50;
    dbg!(r); // Object underlying the reference has been mutated. This is UB.
    */
}
```

This slide should take about 10 minutes.

It is good practice (and required by the Android Rust style guide) to write a comment for each `unsafe` block explaining how the code inside it satisfies the safety requirements of the unsafe operations it is doing.

In the case of pointer dereferences, this means that the pointers must be *valid*, i.e.:

- The pointer must be non-null.
- The pointer must be *dereferenceable* (within the bounds of a single allocated object).
- The object must not have been deallocated.
- There must not be concurrent accesses to the same location.
- If the pointer was obtained by casting a reference, the underlying object must be live and no reference may be used to access the memory.

In most cases the pointer must also be properly aligned.

The "UNSOUND" section gives an example of a common kind of UB bug: naïvely taking a reference to the dereference of a raw pointer sidesteps the compiler's knowledge of what object the reference is actually pointing to. As such, the borrow checker does not freeze `x` and so we are able to modify it despite the existence of a reference to it. Creating a reference from a pointer requires *great care*.

31.3 Mutable Static Variables

It is safe to read an immutable static variable:

```rust
static HELLO_WORLD: &str = "Hello, world!";

fn main() {
    println!("HELLO_WORLD: {HELLO_WORLD}");
}
```

However, mutable static variables are unsafe to read and write because multiple threads could do so concurrently without synchronization, constituting a data race.

Using mutable statics soundly requires reasoning about concurrency without the compiler's help:

```rust
static mut COUNTER: u32 = 0;

fn add_to_counter(inc: u32) {
    // SAFETY: There are no other threads which could be accessing `COUNTER`.
    unsafe {
        COUNTER += inc;
    }
}

fn main() {
    add_to_counter(42);

    // SAFETY: There are no other threads which could be accessing `COUNTER`.
    unsafe {
        dbg!(COUNTER);
    }
}
```

This slide should take about 5 minutes.

- The program here is sound because it is single-threaded. However, the Rust compiler reasons about functions individually so can't assume that. Try removing the `unsafe` and see how the compiler explains that it is undefined behavior to access a mutable static from multiple threads.
- The 2024 Rust edition goes further and makes accessing a mutable static by reference an error by default.
- Using a mutable static is rarely a good idea, you should use interior mutability instead.
- There are some cases where it might be necessary in low-level `no_std` code, such as implementing a heap allocator or working with some C APIs. In this case you should

use pointers rather than references.

31.4 Unions

Unions are like enums, but you need to track the active field yourself:

```
#[repr(C)]
union MyUnion {
    i: u8,
    b: bool,
}

fn main() {
    let u = MyUnion { i: 42 };
    println!("int: {}", unsafe { u.i });
    println!("bool: {}", unsafe { u.b }); // Undefined behavior!
}
```

This slide should take about 5 minutes.

Unions are rarely needed in Rust as enums provide a superior alternative. They are occasionally needed for interacting with C library APIs.

If you just want to reinterpret bytes as a different type, you probably want `std::mem::transmute` or a safe wrapper such as the `zerocopy` crate.

31.5 Unsafe Functions

A function or method can be marked `unsafe` if it has extra preconditions you must uphold to avoid undefined behaviour.

Unsafe functions may come from two places:

- Rust functions declared unsafe.
- Unsafe foreign functions in `extern "C"` blocks.

This slide and its sub-slides should take about 15 minutes.

We will look at the two kinds of unsafe functions next.

31.5.1 Unsafe Rust Functions

You can mark your own functions as `unsafe` if they require particular preconditions to avoid undefined behaviour.

```
/// Swaps the values pointed to by the given pointers.
///
/// # Safety
///
/// The pointers must be valid, properly aligned, and not otherwise accessed for
/// the duration of the function call.
unsafe fn swap(a: *mut u8, b: *mut u8) {
    // SAFETY: Our caller promised that the pointers are valid, properly aligned
```

```rust
    // and have no other access.
    unsafe {
        let temp = *a;
        *a = *b;
        *b = temp;
    }
}

fn main() {
    let mut a = 42;
    let mut b = 66;

    // SAFETY: The pointers must be valid, aligned and unique because they came
    // from references.
    unsafe {
        swap(&mut a, &mut b);
    }

    println!("a = {}, b = {}", a, b);
}
```

We wouldn't actually use pointers for a `swap` function --- it can be done safely with references.

Note that Rust 2021 and earlier allow unsafe code within an unsafe function without an `unsafe` block. This changed in the 2024 edition. We can prohibit it in older editions with `#[deny(unsafe_op_in_unsafe_fn)]`. Try adding it and see what happens.

31.5.2 Unsafe External Functions

You can declare foreign functions for access from Rust with `unsafe extern`. This is unsafe because the compiler has no way to reason about their behavior. Functions declared in an `extern` block must be marked as `safe` or `unsafe`, depending on whether they have preconditions for safe use:

```rust
use std::ffi::c_char;

unsafe extern "C" {
    // `abs` doesn't deal with pointers and doesn't have any safety requirements.
    safe fn abs(input: i32) -> i32;

    /// # Safety
    ///
    /// `s` must be a pointer to a NUL-terminated C string which is valid and
    /// not modified for the duration of this function call.
    unsafe fn strlen(s: *const c_char) -> usize;
}

fn main() {
    println!("Absolute value of -3 according to C: {}", abs(-3));

    unsafe {
        // SAFETY: We pass a pointer to a C string literal which is valid for
```

```
        // the duration of the program.
        println!("String length: {}", strlen(c"String".as_ptr()));
    }
}
```

- Rust used to consider all extern functions unsafe, but this changed in Rust 1.82 with `unsafe extern` blocks.
- `abs` must be explicitly marked as `safe` because it is an external function (FFI). Calling external functions is only a problem when those functions do things with pointers which might violate Rust's memory model, but in general any C function might have undefined behaviour under any arbitrary circumstances.
- The `"C"` in this example is the ABI; other ABIs are available too.
- Note that there is no verification that the Rust function signature matches that of the function definition -- that's up to you!

31.5.3 Calling Unsafe Functions

Failing to uphold the safety requirements breaks memory safety!

```
#[derive(Debug)]
#[repr(C)]
struct KeyPair {
    pk: [u16; 4], // 8 bytes
    sk: [u16; 4], // 8 bytes
}

const PK_BYTE_LEN: usize = 8;

fn log_public_key(pk_ptr: *const u16) {
    let pk: &[u16] = unsafe { std::slice::from_raw_parts(pk_ptr, PK_BYTE_LEN) };
    println!("{pk:?}");
}

fn main() {
    let key_pair = KeyPair { pk: [1, 2, 3, 4], sk: [0, 0, 42, 0] };
    log_public_key(key_pair.pk.as_ptr());
}
```

Always include a safety comment for each `unsafe` block. It must explain why the code is actually safe. This example is missing a safety comment and is unsound.

Key points:

- The second argument to `slice::from_raw_parts` is the number of *elements*, not bytes! This example demonstrates unexpected behavior by reading past the end of one array and into another.
- This is undefined behavior because we're reading past the end of the array that the pointer was derived from.
- `log_public_key` should be unsafe, because `pk_ptr` must meet certain prerequisites to avoid undefined behaviour. A safe function which can cause undefined behaviour is said to be `unsound`. What should its safety documentation say?
- The standard library contains a number of low-level unsafe functions. Prefer the safe alternatives when possible!

- If you use an unsafe function as an optimization, make sure to add a benchmark to demonstrate the gain.

31.6 Implementing Unsafe Traits

Like with functions, you can mark a trait as `unsafe` if the implementation must guarantee particular conditions to avoid undefined behaviour.

For example, the `zerocopy` crate has an unsafe trait that looks something like this:

```rust
use std::{mem, slice};

/// ...
/// # Safety
/// The type must have a defined representation and no padding.
pub unsafe trait IntoBytes {
    fn as_bytes(&self) -> &[u8] {
        let len = mem::size_of_val(self);
        let slf: *const Self = self;
        unsafe { slice::from_raw_parts(slf.cast::<u8>(), len) }
    }
}

// SAFETY: `u32` has a defined representation and no padding.
unsafe impl IntoBytes for u32 {}
```

This slide should take about 5 minutes.

There should be a `# Safety` section on the Rustdoc for the trait explaining the requirements for the trait to be safely implemented.

The actual safety section for `IntoBytes` is rather longer and more complicated.

The built-in Send and Sync traits are unsafe.

31.7 Safe FFI Wrapper

Rust has great support for calling functions through a *foreign function interface* (FFI). We will use this to build a safe wrapper for the `libc` functions you would use from C to read the names of files in a directory.

You will want to consult the manual pages:

- `opendir(3)`
- `readdir(3)`
- `closedir(3)`

You will also want to browse the `std::ffi` module. There you find a number of string types which you need for the exercise:

Types	Encoding	Use
`str` and `String`	UTF-8	Text processing in Rust

Types	Encoding	Use
CStr and CString	NUL-terminated	Communicating with C functions
OsStr and OsString	OS-specific	Communicating with the OS

You will convert between all these types:

- &str to CString: you need to allocate space for a trailing \0 character,
- CString to *const c_char: you need a pointer to call C functions,
- *const c_char to &CStr: you need something which can find the trailing \0 character,
- &CStr to &[u8]: a slice of bytes is the universal interface for "some unknown data",
- &[u8] to &OsStr: &OsStr is a step towards OsString, use OsStrExt to create it,
- &OsStr to OsString: you need to clone the data in &OsStr to be able to return it and call readdir again.

The Nomicon also has a very useful chapter about FFI.

Copy the code below to https://play.rust-lang.org/ and fill in the missing functions and methods:

```
// TODO: remove this when you're done with your implementation.
#![allow(unused_imports, unused_variables, dead_code)]

mod ffi {
    use std::os::raw::{c_char, c_int};
    #[cfg(not(target_os = "macos"))]
    use std::os::raw::{c_long, c_uchar, c_ulong, c_ushort};

    // Opaque type. See https://doc.rust-lang.org/nomicon/ffi.html.
    #[repr(C)]
    pub struct DIR {
        _data: [u8; 0],
        _marker: core::marker::PhantomData<(*mut u8, core::marker::PhantomPinned)>,
    }

    // Layout according to the Linux man page for readdir(3), where ino_t and
    // off_t are resolved according to the definitions in
    // /usr/include/x86_64-linux-gnu/{sys/types.h, bits/typesizes.h}.
    #[cfg(not(target_os = "macos"))]
    #[repr(C)]
    pub struct dirent {
        pub d_ino: c_ulong,
        pub d_off: c_long,
        pub d_reclen: c_ushort,
        pub d_type: c_uchar,
        pub d_name: [c_char; 256],
    }

    // Layout according to the macOS man page for dir(5).
    #[cfg(target_os = "macos")]
    #[repr(C)]
    pub struct dirent {
        pub d_fileno: u64,
```

```
        pub d_seekoff: u64,
        pub d_reclen: u16,
        pub d_namlen: u16,
        pub d_type: u8,
        pub d_name: [c_char; 1024],
    }

    unsafe extern "C" {
        pub unsafe fn opendir(s: *const c_char) -> *mut DIR;

        #[cfg(not(all(target_os = "macos", target_arch = "x86_64")))]
        pub unsafe fn readdir(s: *mut DIR) -> *const dirent;

        // See https://github.com/rust-lang/libc/issues/414 and the section on
        // _DARWIN_FEATURE_64_BIT_INODE in the macOS man page for stat(2).
        //
        // "Platforms that existed before these updates were available" refers
        // to macOS (as opposed to iOS / wearOS / etc.) on Intel and PowerPC.
        #[cfg(all(target_os = "macos", target_arch = "x86_64"))]
        #[link_name = "readdir$INODE64"]
        pub unsafe fn readdir(s: *mut DIR) -> *const dirent;

        pub unsafe fn closedir(s: *mut DIR) -> c_int;
    }
}

use std::ffi::{CStr, CString, OsStr, OsString};
use std::os::unix::ffi::OsStrExt;

#[derive(Debug)]
struct DirectoryIterator {
    path: CString,
    dir: *mut ffi::DIR,
}

impl DirectoryIterator {
    fn new(path: &str) -> Result<DirectoryIterator, String> {
        // Call opendir and return a Ok value if that worked,
        // otherwise return Err with a message.
        todo!()
    }
}

impl Iterator for DirectoryIterator {
    type Item = OsString;
    fn next(&mut self) -> Option<OsString> {
        // Keep calling readdir until we get a NULL pointer back.
        todo!()
    }
}
```

```rust
impl Drop for DirectoryIterator {
    fn drop(&mut self) {
        // Call closedir as needed.
        todo!()
    }
}

fn main() -> Result<(), String> {
    let iter = DirectoryIterator::new(".")?;
    println!("files: {:#?}", iter.collect::<Vec<_>>());
    Ok(())
}
```

This slide and its sub-slides should take about 30 minutes.

FFI binding code is typically generated by tools like bindgen, rather than being written manually as we are doing here. However, bindgen can't run in an online playground.

31.7.1 Solution

```rust
mod ffi {
    use std::os::raw::{c_char, c_int};
    #[cfg(not(target_os = "macos"))]
    use std::os::raw::{c_long, c_uchar, c_ulong, c_ushort};

    // Opaque type. See https://doc.rust-lang.org/nomicon/ffi.html.
    #[repr(C)]
    pub struct DIR {
        _data: [u8; 0],
        _marker: core::marker::PhantomData<(*mut u8, core::marker::PhantomPinned)>,
    }

    // Layout according to the Linux man page for readdir(3), where ino_t and
    // off_t are resolved according to the definitions in
    // /usr/include/x86_64-linux-gnu/{sys/types.h, bits/typesizes.h}.
    #[cfg(not(target_os = "macos"))]
    #[repr(C)]
    pub struct dirent {
        pub d_ino: c_ulong,
        pub d_off: c_long,
        pub d_reclen: c_ushort,
        pub d_type: c_uchar,
        pub d_name: [c_char; 256],
    }

    // Layout according to the macOS man page for dir(5).
    #[cfg(target_os = "macos")]
    #[repr(C)]
    pub struct dirent {
        pub d_fileno: u64,
        pub d_seekoff: u64,
        pub d_reclen: u16,
```

```rust
        pub d_namlen: u16,
        pub d_type: u8,
        pub d_name: [c_char; 1024],
    }

    unsafe extern "C" {
        pub unsafe fn opendir(s: *const c_char) -> *mut DIR;

        #[cfg(not(all(target_os = "macos", target_arch = "x86_64")))]
        pub unsafe fn readdir(s: *mut DIR) -> *const dirent;

        // See https://github.com/rust-lang/libc/issues/414 and the section on
        // _DARWIN_FEATURE_64_BIT_INODE in the macOS man page for stat(2).
        //
        // "Platforms that existed before these updates were available" refers
        // to macOS (as opposed to iOS / wearOS / etc.) on Intel and PowerPC.
        #[cfg(all(target_os = "macos", target_arch = "x86_64"))]
        #[link_name = "readdir$INODE64"]
        pub unsafe fn readdir(s: *mut DIR) -> *const dirent;

        pub unsafe fn closedir(s: *mut DIR) -> c_int;
    }
}

use std::ffi::{CStr, CString, OsStr, OsString};
use std::os::unix::ffi::OsStrExt;

#[derive(Debug)]
struct DirectoryIterator {
    path: CString,
    dir: *mut ffi::DIR,
}

impl DirectoryIterator {
    fn new(path: &str) -> Result<DirectoryIterator, String> {
        // Call opendir and return a Ok value if that worked,
        // otherwise return Err with a message.
        let path =
            CString::new(path).map_err(|err| format!("Invalid path: {err}"))?;
        // SAFETY: path.as_ptr() cannot be NULL.
        let dir = unsafe { ffi::opendir(path.as_ptr()) };
        if dir.is_null() {
            Err(format!("Could not open {path:?}"))
        } else {
            Ok(DirectoryIterator { path, dir })
        }
    }
}

impl Iterator for DirectoryIterator {
    type Item = OsString;
```

```
    fn next(&mut self) -> Option<OsString> {
        // Keep calling readdir until we get a NULL pointer back.
        // SAFETY: self.dir is never NULL.
        let dirent = unsafe { ffi::readdir(self.dir) };
        if dirent.is_null() {
            // We have reached the end of the directory.
            return None;
        }
        // SAFETY: dirent is not NULL and dirent.d_name is NUL
        // terminated.
        let d_name = unsafe { CStr::from_ptr((*dirent).d_name.as_ptr()) };
        let os_str = OsStr::from_bytes(d_name.to_bytes());
        Some(os_str.to_owned())
    }
}

impl Drop for DirectoryIterator {
    fn drop(&mut self) {
        // Call closedir as needed.
        // SAFETY: self.dir is never NULL.
        if unsafe { ffi::closedir(self.dir) } != 0 {
            panic!("Could not close {:?}", self.path);
        }
    }
}

fn main() -> Result<(), String> {
    let iter = DirectoryIterator::new(".")?;
    println!("files: {:#?}", iter.collect::<Vec<_>>());
    Ok(())
}

#[cfg(test)]
mod tests {
    use super::*;
    use std::error::Error;

    #[test]
    fn test_nonexisting_directory() {
        let iter = DirectoryIterator::new("no-such-directory");
        assert!(iter.is_err());
    }

    #[test]
    fn test_empty_directory() -> Result<(), Box<dyn Error>> {
        let tmp = tempfile::TempDir::new()?;
        let iter = DirectoryIterator::new(
            tmp.path().to_str().ok_or("Non UTF-8 character in path")?,
        )?;
        let mut entries = iter.collect::<Vec<_>>();
        entries.sort();
```

```
        assert_eq!(entries, &[".", ".."]);
        Ok(())
    }

    #[test]
    fn test_nonempty_directory() -> Result<(), Box<dyn Error>> {
        let tmp = tempfile::TempDir::new()?;
        std::fs::write(tmp.path().join("foo.txt"), "The Foo Diaries\n")?;
        std::fs::write(tmp.path().join("bar.png"), "<PNG>\n")?;
        std::fs::write(tmp.path().join("crab.rs"), "//! Crab\n")?;
        let iter = DirectoryIterator::new(
            tmp.path().to_str().ok_or("Non UTF-8 character in path")?,
        )?;
        let mut entries = iter.collect::<Vec<_>>();
        entries.sort();
        assert_eq!(entries, &[".", "..", "bar.png", "crab.rs", "foo.txt"]);
        Ok(())
    }
}
```

- **Safety Comments:** Each `unsafe` block is preceded by a `// SAFETY:` comment explaining why the operation is safe. This is standard practice in Rust to aid auditing.
- **String conversions:** The code demonstrates the conversions required for FFI:
  - `&str` -> `CString`: To create a null-terminated string for C.
  - `CString` -> `*const c_char`: To pass the pointer to C.
  - `*const c_char` -> `&CStr`: To wrap the returned C string.
  - `&CStr` -> `&[u8]` -> `&OsStr` -> `OsString`: To convert the bytes back to a Rust OS string.
- **RAII (Drop):** We implement `Drop` to call `closedir` automatically when the iterator goes out of scope. This ensures we don't leak file descriptors.
- **Iterator Interface:** We wrap the C API in a Rust `Iterator`, providing a safe and idiomatic interface (`next` returns `Option<OsString>`) to the underlying unsafe C functions.

- Explain that `CString` owns the data (like `String`), while `CStr` is a borrowed reference (like `&str`).
- The `OsStrExt` trait is needed on Unix systems to convert bytes directly to `OsStr`.

Part IX

Android

Chapter 32

Welcome to Rust in Android

Rust is supported for system software on Android. This means that you can write new services, libraries, drivers or even firmware in Rust (or improve existing code as needed).

The speaker may mention any of the following given the increased use of Rust in Android:

- Service example: DNS over HTTP.
- Libraries: Rutabaga Virtual Graphics Interface.
- Kernel Drivers: Binder.
- Firmware: pKVM firmware.

Chapter 33

Setup

We will be using a Cuttlefish Android Virtual Device to test our code. Make sure you have access to one or create a new one with:

```
source build/envsetup.sh
lunch aosp_cf_x86_64_phone-trunk_staging-userdebug
acloud create
```

Please see the Android Developer Codelab for details.

The code on the following pages can be found in the `src/android/` directory of the course material. Please `git clone` the repository to follow along.

Key points:

- Cuttlefish is a reference Android device designed to work on generic Linux desktops. MacOS support is also planned.
- The Cuttlefish system image maintains high fidelity to real devices, and is the ideal emulator to run many Rust use cases.

Chapter 34

Build Rules

The Android build system (Soong) supports Rust through several modules:

Module Type	Description
`rust_binary`	Produces a Rust binary.
`rust_library`	Produces a Rust library, and provides both `rlib` and `dylib` variants.
`rust_ffi`	Produces a Rust C library usable by `cc` modules, and provides both static and shared variants.
`rust_proc_macro`	Produces a `proc-macro` Rust library. These are analogous to compiler plugins.
`rust_test`	Produces a Rust test binary that uses the standard Rust test harness.
`rust_fuzz`	Produces a Rust fuzz binary leveraging `libfuzzer`.
`rust_protobuf`	Generates source and produces a Rust library that provides an interface for a particular protobuf.
`rust_bindgen`	Generates source and produces a Rust library containing Rust bindings to C libraries.

We will look at `rust_binary` and `rust_library` next.

Additional items the speaker may mention:

- Cargo is not optimized for multi-language repositories, and also downloads packages from the internet.
- For compliance and performance, Android must have crates in-tree. It must also interoperate with C/C++/Java code. Soong fills that gap.
- Soong has many similarities to Bazel, which is the open-source variant of Blaze (used in google3).
- Fun fact: Data from Star Trek is a Soong-type Android.

34.1 Rust Binaries

Let's start with a simple application. At the root of an AOSP checkout, create the following files:

hello_rust/Android.bp:

```
rust_binary {
    name: "hello_rust",
    crate_name: "hello_rust",
    srcs: ["src/main.rs"],
}
```

hello_rust/src/main.rs:

```rust
//! Rust demo.

/// Prints a greeting to standard output.
fn main() {
    println!("Hello from Rust!");
}
```

You can now build, push, and run the binary:

```
m hello_rust
adb push "$ANDROID_PRODUCT_OUT/system/bin/hello_rust" /data/local/tmp
adb shell /data/local/tmp/hello_rust
```

```
Hello from Rust!
```

- Go through the build steps and demonstrate them running in your emulator.
- Notice the extensive documentation comments? The Android build rules enforce that all modules have documentation. Try removing it and see what error you get.
- Stress that the Rust build rules look like the other Soong rules. This is by design, to make using Rust as easy as C++ or Java.

34.2 Rust Libraries

You use `rust_library` to create a new Rust library for Android.

Here we declare a dependency on two libraries:

- `libgreeting`, which we define below,
- `libtextwrap`, which is a crate already vendored in `external/rust/android-crates-io/crates/`.

hello_rust/Android.bp:

```
rust_binary {
    name: "hello_rust_with_dep",
    crate_name: "hello_rust_with_dep",
    srcs: ["src/main.rs"],
    rustlibs: [
        "libgreetings",
        "libtextwrap",
    ],
    prefer_rlib: true, // Need this to avoid dynamic link error.
}
```

```
rust_library {
    name: "libgreetings",
    crate_name: "greetings",
    srcs: ["src/lib.rs"],
}
```

hello_rust/src/main.rs:

```rust
//! Rust demo.

use greetings::greeting;
use textwrap::fill;

/// Prints a greeting to standard output.
fn main() {
    println!("{}", fill(&greeting("Bob"), 24));
}
```

hello_rust/src/lib.rs:

```rust
//! Greeting library.

/// Greet `name`.
pub fn greeting(name: &str) -> String {
    format!("Hello {name}, it is very nice to meet you!")
}
```

You build, push, and run the binary like before:

```
m hello_rust_with_dep
adb push "$ANDROID_PRODUCT_OUT/system/bin/hello_rust_with_dep" /data/local/tmp
adb shell /data/local/tmp/hello_rust_with_dep
```

```
Hello Bob, it is very
nice to meet you!
```

- Go through the build steps and demonstrate them running in your emulator.
- A Rust crate named `greetings` must be built by a rule called `libgreetings`. Note how the Rust code uses the crate name, as is normal in Rust.
- Again, the build rules enforce that we add documentation comments to all public items.

Chapter 35

AIDL

Rust supports the Android Interface Definition Language (AIDL):

- Rust code can call existing AIDL servers.
- You can create new AIDL servers in Rust.
- AIDL enables Android apps to interact with each other.
- Since Rust is a first-class citizen in this ecosystem, other processes on the device can call Rust services.

35.1 Birthday Service Tutorial

To illustrate using Rust with Binder, we will create a Binder interface. Then, we'll implement the service and write a client that talks to it.

35.1.1 AIDL Interfaces

You declare the API of your service using an AIDL interface:

birthday_service/aidl/com/example/birthdayservice/IBirthdayService.aidl:

```
package com.example.birthdayservice;

/** Birthday service interface. */
interface IBirthdayService {
    /** Generate a Happy Birthday message. */
    String wishHappyBirthday(String name, int years);
}
```

birthday_service/aidl/Android.bp:

```
aidl_interface {
    name: "com.example.birthdayservice",
    srcs: ["com/example/birthdayservice/*.aidl"],
    unstable: true,
    backend: {
        rust: { // Rust is not enabled by default
```

```
                enabled: true,
            },
        },
}
```

- Note that the directory structure under the `aidl/` directory needs to match the package name used in the AIDL file, i.e. the package is `com.example.birthdayservice` and the file is at `aidl/com/example/IBirthdayService.aidl`.

35.1.2 Generated Service API

Binder generates a trait for each interface definition.

birthday_service/aidl/com/example/birthdayservice/IBirthdayService.aidl:

```
/** Birthday service interface. */
interface IBirthdayService {
    /** Generate a Happy Birthday message. */
    String wishHappyBirthday(String name, int years);
}
```

out/soong/.intermediates/.../com_example_birthdayservice.rs:

```
trait IBirthdayService {
    fn wishHappyBirthday(&self, name: &str, years: i32) -> binder::Result<String>;
}
```

Your service will need to implement this trait, and your client will use this trait to talk to the service.

- Point out how the generated function signature, specifically the argument and return types, correspond to the interface definition.
  - `String` for an argument results in a different Rust type than `String` as a return type.

35.1.3 Service Implementation

We can now implement the AIDL service:

birthday_service/src/lib.rs:

```
//! Implementation of the `IBirthdayService` AIDL interface.
use com_example_birthdayservice::aidl::com::example::birthdayservice::IBirthdayService:
use com_example_birthdayservice::binder;

/// The `IBirthdayService` implementation.
pub struct BirthdayService;

impl binder::Interface for BirthdayService {}

impl IBirthdayService for BirthdayService {
    fn wishHappyBirthday(&self, name: &str, years: i32) -> binder::Result<String> {
        Ok(format!("Happy Birthday {name}, congratulations with the {years} years!"))
    }
}
```

birthday_service/Android.bp:

```
rust_library {
    name: "libbirthdayservice",
    crate_name: "birthdayservice",
    srcs: ["src/lib.rs"],
    rustlibs: [
        "com.example.birthdayservice-rust",
    ],
}
```

- Point out the path to the generated `IBirthdayService` trait, and explain why each of the segments is necessary.
- Note that `wishHappyBirthday` and other AIDL IPC methods take `&self` (instead of `&mut self`).
  - This is necessary because Binder responds to incoming requests on a thread pool, allowing for multiple requests to be processed in parallel. This requires that the service methods only get a shared reference to `self`.
  - Any state that needs to be modified by the service will have to be put in something like a `Mutex` to allow for safe mutation.
  - The correct approach for managing service state depends heavily on the details of your service.
- TODO: What does the `binder::Interface` trait do? Are there methods to override? Where is the source?

35.1.4 AIDL Server

Finally, we can create a server which exposes the service:

birthday_service/src/server.rs:

```
//! Birthday service.
use birthdayservice::BirthdayService;
use com_example_birthdayservice::aidl::com::example::birthdayservice::IBirthdayService:
use com_example_birthdayservice::binder;

const SERVICE_IDENTIFIER: &str = "birthdayservice";

/// Entry point for birthday service.
fn main() {
    let birthday_service = BirthdayService;
    let birthday_service_binder = BnBirthdayService::new_binder(
        birthday_service,
        binder::BinderFeatures::default(),
    );
    binder::add_service(SERVICE_IDENTIFIER, birthday_service_binder.as_binder())
        .expect("Failed to register service");
    binder::ProcessState::join_thread_pool();
}
```

birthday_service/Android.bp:

```
rust_binary {
    name: "birthday_server",
```

```
    crate_name: "birthday_server",
    srcs: ["src/server.rs"],
    rustlibs: [
        "com.example.birthdayservice-rust",
        "libbirthdayservice",
    ],
    prefer_rlib: true, // To avoid dynamic link error.
}
```

The process for taking a user-defined service implementation (in this case, the `BirthdayService` type, which implements the `IBirthdayService`) and starting it as a Binder service has multiple steps. This may appear more complicated than students are used to if they've used Binder from C++ or another language. Explain to students why each step is necessary.

1. Create an instance of your service type (`BirthdayService`).
2. Wrap the service object in the corresponding `Bn*` type (`BnBirthdayService` in this case). This type is generated by Binder and provides common Binder functionality, similar to the `BnBinder` base class in C++. Since Rust doesn't have inheritance, we use composition, putting our `BirthdayService` within the generated `BnBinderService`.
3. Call `add_service`, giving it a service identifier and your service object (the `BnBirthdayService` object in the example).
4. Call `join_thread_pool` to add the current thread to Binder's thread pool and start listening for connections.

35.1.5 Deploy

We can now build, push, and start the service:

```
m birthday_server
adb push "$ANDROID_PRODUCT_OUT/system/bin/birthday_server" /data/local/tmp
adb root
adb shell /data/local/tmp/birthday_server
```

In another terminal, check that the service runs:

```
adb shell service check birthdayservice
```

```
Service birthdayservice: found
```

You can also call the service with `service call`:

```
adb shell service call birthdayservice 1 s16 Bob i32 24
```

```
Result: Parcel(
  0x00000000: 00000000 00000036 00610048 00700070 '....6...H.a.p.p.'
  0x00000010: 00200079 00690042 00740072 00640068 'y. .B.i.r.t.h.d.'
  0x00000020: 00790061 00420020 0062006f 0020002c 'a.y. .B.o.b.,. .'
  0x00000030: 006f0063 0067006e 00610072 00750074 'c.o.n.g.r.a.t.u.'
  0x00000040: 0061006c 00690074 006e006f 00200073 'l.a.t.i.o.n.s. .'
  0x00000050: 00690077 00680074 00740020 00650068 'w.i.t.h. .t.h.e.'
  0x00000060: 00320020 00200034 00650079 00720061 ' .2.4. .y.e.a.r.'
  0x00000070: 00210073 00000000                   's.!.....       ')
```

35.1.6 AIDL Client

Finally, we can create a Rust client for our new service.

birthday_service/src/client.rs:

```
use com_example_birthdayservice::aidl::com::example::birthdayservice::IBirthdayService:
use com_example_birthdayservice::binder;

const SERVICE_IDENTIFIER: &str = "birthdayservice";

/// Call the birthday service.
fn main() -> Result<(), Box<dyn Error>> {
    let name = std::env::args().nth(1).unwrap_or_else(|| String::from("Bob"));
    let years = std::env::args()
        .nth(2)
        .and_then(|arg| arg.parse::<i32>().ok())
        .unwrap_or(42);

    binder::ProcessState::start_thread_pool();
    let service = binder::get_interface::<dyn IBirthdayService>(SERVICE_IDENTIFIER)
        .map_err(|_| "Failed to connect to BirthdayService")?;

    // Call the service.
    let msg = service.wishHappyBirthday(&name, years)?;
    println!("{msg}");
}
```

birthday_service/Android.bp:

```
rust_binary {
    name: "birthday_client",
    crate_name: "birthday_client",
    srcs: ["src/client.rs"],
    rustlibs: [
        "com.example.birthdayservice-rust",
    ],
    prefer_rlib: true, // To avoid dynamic link error.
}
```

Notice that the client does not depend on `libbirthdayservice`.

Build, push, and run the client on your device:

```
m birthday_client
adb push "$ANDROID_PRODUCT_OUT/system/bin/birthday_client" /data/local/tmp
adb shell /data/local/tmp/birthday_client Charlie 60
```

```
Happy Birthday Charlie, congratulations with the 60 years!
```

- `Strong<dyn IBirthdayService>` is the trait object representing the service that the client has connected to.
  - `Strong` is a custom smart pointer type for Binder. It handles both an in-process ref count for the service trait object, and the global Binder ref count that tracks how many processes have a reference to the object.

  - Note that the trait object that the client uses to talk to the service uses the exact same trait that the server implements. For a given Binder interface, there is a single Rust trait generated that both client and server use.
- Use the same service identifier used when registering the service. This should ideally be defined in a common crate that both the client and server can depend on.

35.1.7 Changing API

Let's extend the API: we'll let clients specify a list of lines for the birthday card:

```
package com.example.birthdayservice;

/** Birthday service interface. */
interface IBirthdayService {
    /** Generate a Happy Birthday message. */
    String wishHappyBirthday(String name, int years, in String[] text);
}
```

This results in an updated trait definition for `IBirthdayService`:

```
trait IBirthdayService {
    fn wishHappyBirthday(
        &self,
        name: &str,
        years: i32,
        text: &[String],
    ) -> binder::Result<String>;
}
```

- Note how the `String[]` in the AIDL definition is translated as a `&[String]` in Rust, i.e. that idiomatic Rust types are used in the generated bindings wherever possible:
  - `in` array arguments are translated to slices.
  - `out` and `inout` args are translated to `&mut Vec<T>`.
  - Return values are translated to returning a `Vec<T>`.

35.1.8 Updating Client and Service

Update the client and server code to account for the new API.

birthday_service/src/lib.rs:

```
impl IBirthdayService for BirthdayService {
    fn wishHappyBirthday(
        &self,
        name: &str,
        years: i32,
        text: &[String],
    ) -> binder::Result<String> {
        let mut msg = format!(
            "Happy Birthday {name}, congratulations with the {years} years!",
        );

        for line in text {
```

```
            msg.push('\n');
            msg.push_str(line);
        }

        Ok(msg)
    }
}
```

birthday_service/src/client.rs:

```
let msg = service.wishHappyBirthday(
    &name,
    years,
    &[
        String::from("Habby birfday to yuuuuu"),
        String::from("And also: many more"),
    ],
)?;
```

- TODO: Move code snippets into project files where they'll actually be built?

35.2 Working With AIDL Types

AIDL types translate into the appropriate idiomatic Rust type:

- Primitive types map (mostly) to idiomatic Rust types.
- Collection types like slices, `Vec`s and string types are supported.
- References to AIDL objects and file handles can be sent between clients and services.
- File handles and parcelables are fully supported.

35.2.1 Primitive Types

Primitive types map (mostly) idiomatically:

AIDL Type	Rust Type	Note
`boolean`	`bool`	
`byte`	`i8`	Note that bytes are signed.
`char`	`u16`	Note the usage of u16, NOT u32.
`int`	`i32`	
`long`	`i64`	
`float`	`f32`	
`double`	`f64`	
`String`	`String`	

35.2.2 Array Types

The array types (`T[]`, `byte[]`, and `List<T>`) are translated to the appropriate Rust array type depending on how they are used in the function signature:

Position	Rust Type
in argument	`&[T]`
out/inout argument	`&mut Vec<T>`
Return	`Vec<T>`

- In Android 13 or higher, fixed-size arrays are supported, i.e. `T[N]` becomes `[T; N]`. Fixed-size arrays can have multiple dimensions (e.g. `int[3][4]`). In the Java backend, fixed-size arrays are represented as array types.
- Arrays in parcelable fields always get translated to `Vec<T>`.

35.2.3 Sending Objects

AIDL objects can be sent either as a concrete AIDL type or as the type-erased `IBinder` interface:

birthday_service/aidl/com/example/birthdayservice/IBirthdayInfoProvider.aidl:

```
package com.example.birthdayservice;

interface IBirthdayInfoProvider {
    String name();
    int years();
}
```

birthday_service/aidl/com/example/birthdayservice/IBirthdayService.aidl:

```
import com.example.birthdayservice.IBirthdayInfoProvider;

interface IBirthdayService {
    /** The same thing, but using a binder object. */
    String wishWithProvider(IBirthdayInfoProvider provider);

    /** The same thing, but using `IBinder`. */
    String wishWithErasedProvider(IBinder provider);
}
```

birthday_service/src/client.rs:

```
/// Rust struct implementing the `IBirthdayInfoProvider` interface.
struct InfoProvider {
    name: String,
    age: u8,
}

impl binder::Interface for InfoProvider {}

impl IBirthdayInfoProvider for InfoProvider {
    fn name(&self) -> binder::Result<String> {
        Ok(self.name.clone())
    }

    fn years(&self) -> binder::Result<i32> {
```

```
        Ok(self.age as i32)
    }
}

fn main() {
    binder::ProcessState::start_thread_pool();
    let service = connect().expect("Failed to connect to BirthdayService");

    // Create a binder object for the `IBirthdayInfoProvider` interface.
    let provider = BnBirthdayInfoProvider::new_binder(
        InfoProvider { name: name.clone(), age: years as u8 },
        BinderFeatures::default(),
    );

    // Send the binder object to the service.
    service.wishWithProvider(&provider)?;

    // Perform the same operation but passing the provider as an `SpIBinder`.
    service.wishWithErasedProvider(&provider.as_binder())?;
}
```

- Note the usage of `BnBirthdayInfoProvider`. This serves the same purpose as `BnBirthdayService` that we saw previously.

35.2.4 Parcelables

Binder for Rust supports sending parcelables directly:

birthday_service/aidl/com/example/birthdayservice/BirthdayInfo.aidl:

```
package com.example.birthdayservice;

parcelable BirthdayInfo {
    String name;
    int years;
}
```

birthday_service/aidl/com/example/birthdayservice/IBirthdayService.aidl:

```
import com.example.birthdayservice.BirthdayInfo;

interface IBirthdayService {
    /** The same thing, but with a parcelable. */
    String wishWithInfo(in BirthdayInfo info);
}
```

birthday_service/src/client.rs:

```
fn main() {
    binder::ProcessState::start_thread_pool();
    let service = connect().expect("Failed to connect to BirthdayService");

    let info = BirthdayInfo { name: "Alice".into(), years: 123 };
```

```
    service.wishWithInfo(&info)?;
}
```

35.2.5 Sending Files

Files can be sent between Binder clients/servers using the `ParcelFileDescriptor` type:

birthday_service/aidl/com/example/birthdayservice/IBirthdayService.aidl:

```
interface IBirthdayService {
    /** The same thing, but loads info from a file. */
    String wishFromFile(in ParcelFileDescriptor infoFile);
}
```

birthday_service/src/client.rs:

```
fn main() {
    binder::ProcessState::start_thread_pool();
    let service = connect().expect("Failed to connect to BirthdayService");

    // Open a file and put the birthday info in it.
    let mut file = File::create("/data/local/tmp/birthday.info").unwrap();
    writeln!(file, "{name}")?;
    writeln!(file, "{years}")?;

    // Create a `ParcelFileDescriptor` from the file and send it.
    let file = ParcelFileDescriptor::new(file);
    service.wishFromFile(&file)?;
}
```

birthday_service/src/lib.rs:

```
impl IBirthdayService for BirthdayService {
    fn wishFromFile(
        &self,
        info_file: &ParcelFileDescriptor,
    ) -> binder::Result<String> {
        // Convert the file descriptor to a `File`. `ParcelFileDescriptor` wraps
        // an `OwnedFd`, which can be cloned and then used to create a `File`
        // object.
        let mut info_file = info_file
            .as_ref()
            .try_clone()
            .map(File::from)
            .expect("Invalid file handle");

        let mut contents = String::new();
        info_file.read_to_string(&mut contents).unwrap();

        let mut lines = contents.lines();
        let name = lines.next().unwrap();
        let years: i32 = lines.next().unwrap().parse().unwrap();

        Ok(format!("Happy Birthday {name}, congratulations with the {years} years!"))
```

```
    }
}
```

- `ParcelFileDescriptor` wraps an `OwnedFd`, and so can be created from a `File` (or any other type that wraps an `OwnedFd`), and can be used to create a new `File` handle on the other side.
- Other types of file descriptors can be wrapped and sent, e.g. TCP, UDP, and UNIX sockets.

Chapter 36

Testing in Android

Building on Testing, we will now look at how unit tests work in AOSP. Use the `rust_test` module for your unit tests:

testing/Android.bp:

```
rust_library {
    name: "libleftpad",
    crate_name: "leftpad",
    srcs: ["src/lib.rs"],
}

rust_test {
    name: "libleftpad_test",
    crate_name: "leftpad_test",
    srcs: ["src/lib.rs"],
    host_supported: true,
    test_suites: ["general-tests"],
}

rust_test {
    name: "libgoogletest_example",
    crate_name: "googletest_example",
    srcs: ["googletest.rs"],
    rustlibs: ["libgoogletest_rust"],
    host_supported: true,
}

rust_test {
    name: "libmockall_example",
    crate_name: "mockall_example",
    srcs: ["mockall.rs"],
    rustlibs: ["libmockall"],
    host_supported: true,
}
```

testing/src/lib.rs:

```rust
//! Left-padding library.

/// Left-pad `s` to `width`.
pub fn leftpad(s: &str, width: usize) -> String {
    format!("{s:>width$}")
}

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

    #[test]
    fn short_string() {
        assert_eq!(leftpad("foo", 5), "  foo");
    }

    #[test]
    fn long_string() {
        assert_eq!(leftpad("foobar", 6), "foobar");
    }
}
```

You can now run the test with

```
atest --host libleftpad_test
```

The output looks like this:

```
INFO: Elapsed time: 2.666s, Critical Path: 2.40s
INFO: 3 processes: 2 internal, 1 linux-sandbox.
INFO: Build completed successfully, 3 total actions
//comprehensive-rust-android/testing:libleftpad_test_host            PASSED in 2.3s
    PASSED  libleftpad_test.tests::long_string (0.0s)
    PASSED  libleftpad_test.tests::short_string (0.0s)
Test cases: finished with 2 passing and 0 failing out of 2 test cases
```

Notice how you only mention the root of the library crate. Tests are found recursively in nested modules.

36.1 GoogleTest

The GoogleTest crate allows for flexible test assertions using *matchers*:

```rust
use googletest::prelude::*;

#[googletest::test]
fn test_elements_are() {
    let value = vec!["foo", "bar", "baz"];
    expect_that!(value, elements_are!(eq(&"foo"), lt(&"xyz"), starts_with("b")));
}
```

If we change the last element to "!", the test fails with a structured error message pin-pointing the error:

```
---- test_elements_are stdout ----
Value of: value
Expected: has elements:
  0. is equal to "foo"
  1. is less than "xyz"
  2. starts with prefix "!"
Actual: ["foo", "bar", "baz"],
  where element #2 is "baz", which does not start with "!"
  at src/testing/googletest.rs:6:5
Error: See failure output above
```

This slide should take about 5 minutes.

- GoogleTest is not part of the Rust Playground, so you need to run this example in a local environment. Use `cargo add googletest` to quickly add it to an existing Cargo project.
- The `use googletest::prelude::*;` line imports a number of commonly used macros and types.
- This just scratches the surface, there are many builtin matchers. Consider going through the first chapter of "Advanced testing for Rust applications", a self-guided Rust course: it provides a guided introduction to the library, with exercises to help you get comfortable with `googletest` macros, its matchers and its overall philosophy.
- A particularly nice feature is that mismatches in multi-line strings are shown as a diff:

```rust
#[test]
fn test_multiline_string_diff() {
    let haiku = "Memory safety found,\n\
                 Rust's strong typing guides the way,\n\
                 Secure code you'll write.";
    assert_that!(
        haiku,
        eq("Memory safety found,\n\
            Rust's silly humor guides the way,\n\
            Secure code you'll write.")
    );
}
```

shows a color-coded diff (colors not shown here):

```
    Value of: haiku
Expected: is equal to "Memory safety found,\nRust's silly humor guides the way,\nSecure
Actual: "Memory safety found,\nRust's strong typing guides the way,\nSecure code you'll
  which isn't equal to "Memory safety found,\nRust's silly humor guides the way,\nSecure
Difference(-actual / +expected):
 Memory safety found,
-Rust's strong typing guides the way,
+Rust's silly humor guides the way,
 Secure code you'll write.
  at src/testing/googletest.rs:17:5
```

- The crate is a Rust port of GoogleTest for C++.

36.2 Mocking

For mocking, Mockall is a widely used library. You need to refactor your code to use traits, which you can then quickly mock:

```
use std::time::Duration;

#[mockall::automock]
pub trait Pet {
    fn is_hungry(&self, since_last_meal: Duration) -> bool;
}

#[test]
fn test_robot_dog() {
    let mut mock_dog = MockPet::new();
    mock_dog.expect_is_hungry().return_const(true);
    assert!(mock_dog.is_hungry(Duration::from_secs(10)));
}
```

This slide should take about 5 minutes.

- Mockall is the recommended mocking library in Android (AOSP). There are other mocking libraries available on crates.io, in particular in the area of mocking HTTP services. The other mocking libraries work in a similar fashion as Mockall, meaning that they make it easy to get a mock implementation of a given trait.
- Note that mocking is somewhat *controversial*: mocks allow you to completely isolate a test from its dependencies. The immediate result is faster and more stable test execution. On the other hand, the mocks can be configured wrongly and return output different from what the real dependencies would do.

  If at all possible, it is recommended that you use the real dependencies. As an example, many databases allow you to configure an in-memory backend. This means that you get the correct behavior in your tests, plus they are fast and will automatically clean up after themselves.

  Similarly, many web frameworks allow you to start an in-process server which binds to a random port on `localhost`. Always prefer this over mocking away the framework since it helps you test your code in the real environment.
- Mockall is not part of the Rust Playground, so you need to run this example in a local environment. Use `cargo add mockall` to quickly add Mockall to an existing Cargo project.
- Mockall has extensive functionality. In particular, you can set up expectations which depend on the arguments passed. Here we use this to mock a cat which becomes hungry 3 hours after the last time it was fed:

```
#[test]
fn test_robot_cat() {
    let mut mock_cat = MockPet::new();
    mock_cat
        .expect_is_hungry()
        .with(mockall::predicate::gt(Duration::from_secs(3 * 3600)))
        .return_const(true);
```

```rust
    mock_cat.expect_is_hungry().return_const(false);
    assert!(mock_cat.is_hungry(Duration::from_secs(5 * 3600)));
    assert!(!mock_cat.is_hungry(Duration::from_secs(5)));
}
```

- You can use `.times(n)` to limit the number of times a mock method can be called to `n` --- the mock will automatically panic when dropped if this isn't satisfied.

Chapter 37

Logging

You should use the `log` crate to automatically log to `logcat` (on-device) or `stdout` (on-host):

hello_rust_logs/Android.bp:

```
rust_binary {
    name: "hello_rust_logs",
    crate_name: "hello_rust_logs",
    srcs: ["src/main.rs"],
    rustlibs: [
        "liblog_rust",
        "liblogger",
    ],
    host_supported: true,
}
```

hello_rust_logs/src/main.rs:

```rust
//! Rust logging demo.

use log::{debug, error, info};

/// Logs a greeting.
fn main() {
    logger::init(
        logger::Config::default()
            .with_tag_on_device("rust")
            .with_max_level(log::LevelFilter::Trace),
    );
    debug!("Starting program.");
    info!("Things are going fine.");
    error!("Something went wrong!");
}
```

Build, push, and run the binary on your device:

```
m hello_rust_logs
adb push "$ANDROID_PRODUCT_OUT/system/bin/hello_rust_logs" /data/local/tmp
```

```
adb shell /data/local/tmp/hello_rust_logs
```

The logs show up in `adb logcat`:

```
adb logcat -s rust
```

```
09-08 08:38:32.454  2420  2420 D rust: hello_rust_logs: Starting program.
09-08 08:38:32.454  2420  2420 I rust: hello_rust_logs: Things are going fine.
09-08 08:38:32.454  2420  2420 E rust: hello_rust_logs: Something went wrong!
```

- The logger implementation in `liblogger` is only needed in the final binary, if you're logging from a library you only need the `log` facade crate.

Chapter 38

Interoperability

Rust has excellent support for interoperability with other languages. This means that you can:

- Call Rust functions from other languages.
- Call functions written in other languages from Rust.

When you call functions in a foreign language, you're using a *foreign function interface*, also known as FFI.

- This is a key ability of Rust: compiled code becomes indistinguishable from compiled C or C++ code.

- Technically, we say that Rust can be compiled to the same ABI (application binary interface) as C code.

38.1 Interoperability with C

Rust has full support for linking object files with a C calling convention. Similarly, you can export Rust functions and call them from C.

You can do it by hand if you want:

```
unsafe extern "C" {
    safe fn abs(x: i32) -> i32;
}

fn main() {
    let x = -42;
    let abs_x = abs(x);
    println!("{x}, {abs_x}");
}
```

We already saw this in the Safe FFI Wrapper exercise.

> This assumes full knowledge of the target platform. Not recommended for production.

We will look at better options next.

- The "C" part of the `extern` block tells Rust that `abs` can be called using the C ABI (application binary interface).
- The `safe fn abs` part tells Rust that `abs` is a safe function. By default, extern functions are unsafe, but since `abs(x)` can't trigger undefined behavior with any `x`, we can declare it safe.

38.1.1 A Simple C Library

Let's first create a small C library:

interoperability/bindgen/libbirthday.h:

```
typedef struct card {
  const char* name;
  int years;
} card;

void print_card(const card* card);
```

interoperability/bindgen/libbirthday.c:

```
#include <stdio.h>
#include "libbirthday.h"

void print_card(const card* card) {
  printf("+--------------\n");
  printf("| Happy Birthday %s!\n", card->name);
  printf("| Congratulations with the %i years!\n", card->years);
  printf("+--------------\n");
}
```

Add this to your `Android.bp` file:

interoperability/bindgen/Android.bp:

```
cc_library {
    name: "libbirthday",
    srcs: ["libbirthday.c"],
}
```

38.1.2 Using Bindgen

The bindgen tool can auto-generate bindings from a C header file.

Create a wrapper header file for the library (not strictly needed in this example):

interoperability/bindgen/libbirthday_wrapper.h:

```
#include "libbirthday.h"
```

interoperability/bindgen/Android.bp:

```
rust_bindgen {
    name: "libbirthday_bindgen",
    crate_name: "birthday_bindgen",
    wrapper_src: "libbirthday_wrapper.h",
```

```
    source_stem: "bindings",
    static_libs: ["libbirthday"],
}
```

Finally, we can use the bindings in our Rust program:

interoperability/bindgen/Android.bp:

```
rust_binary {
    name: "print_birthday_card",
    srcs: ["main.rs"],
    rustlibs: ["libbirthday_bindgen"],
    static_libs: ["libbirthday"],
}
```

interoperability/bindgen/main.rs:

```
//! Bindgen demo.

use birthday_bindgen::{card, print_card};

fn main() {
    let name = std::ffi::CString::new("Peter").unwrap();
    let card = card { name: name.as_ptr(), years: 42 };
    // SAFETY: The pointer we pass is valid because it came from a Rust
    // reference, and the `name` it contains refers to `name` above which also
    // remains valid. `print_card` doesn't store either pointer to use later
    // after it returns.
    unsafe {
        print_card(&card);
    }
}
```

- The Android build rules will automatically call `bindgen` for you behind the scenes.
- Notice that the Rust code in `main` is still hard to write. It is good practice to encapsulate the output of `bindgen` in a Rust library which exposes a safe interface to caller.

38.1.3 Running Our Binary

Build, push, and run the binary on your device:

```
m print_birthday_card
adb push "$ANDROID_PRODUCT_OUT/system/bin/print_birthday_card" /data/local/tmp
adb shell /data/local/tmp/print_birthday_card
```

Finally, we can run auto-generated tests to ensure the bindings work:

interoperability/bindgen/Android.bp:

```
rust_test {
    name: "libbirthday_bindgen_test",
    srcs: [":libbirthday_bindgen"],
    crate_name: "libbirthday_bindgen_test",
    test_suites: ["general-tests"],
    auto_gen_config: true,
```

```
    clippy_lints: "none", // Generated file, skip linting
    lints: "none",
}
```

atest libbirthday_bindgen_test

38.1.4 A Simple Rust Library

Exporting Rust functions and types to C is easy. Here's a simple Rust library:

interoperability/rust/libanalyze/analyze.rs

```
//! Rust FFI demo.
#![deny(improper_ctypes_definitions)]

use std::os::raw::c_int;

/// Analyze the numbers.
// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
pub extern "C" fn analyze_numbers(x: c_int, y: c_int) {
    if x < y {
        println!("x ({x}) is smallest!");
    } else {
        println!("y ({y}) is probably larger than x ({x})");
    }
}
```

interoperability/rust/libanalyze/Android.bp

```
rust_ffi {
    name: "libanalyze_ffi",
    crate_name: "analyze_ffi",
    srcs: ["analyze.rs"],
    include_dirs: ["."],
}
```

`#[unsafe(no_mangle)]` disables Rust's usual name mangling, so the exported symbol will just be the name of the function. You can also use `#[unsafe(export_name = "some_name")]` to specify whatever name you want.

38.1.5 Calling Rust

We can now call this from a C binary:

interoperability/rust/libanalyze/analyze.h

```
#ifndef ANALYZE_H
#define ANALYZE_H

void analyze_numbers(int x, int y);

#endif
```

interoperability/rust/analyze/main.c

```
#include "analyze.h"

int main() {
  analyze_numbers(10, 20);
  analyze_numbers(123, 123);
  return 0;
}
```

interoperability/rust/analyze/Android.bp

```
cc_binary {
    name: "analyze_numbers",
    srcs: ["main.c"],
    static_libs: ["libanalyze_ffi"],
}
```

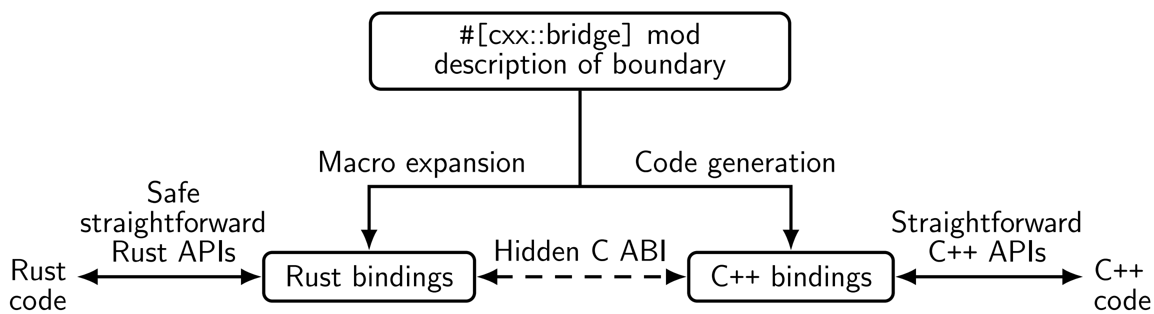
Build, push, and run the binary on your device:

```
m analyze_numbers
adb push "$ANDROID_PRODUCT_OUT/system/bin/analyze_numbers" /data/local/tmp
adb shell /data/local/tmp/analyze_numbers
```

38.2 With C++

The CXX crate enables safe interoperability between Rust and C++.

The overall approach looks like this:



38.2.1 The Bridge Module

CXX relies on a description of the function signatures that will be exposed from each language to the other. You provide this description using extern blocks in a Rust module annotated with the `#[cxx::bridge]` attribute macro.

```
#[allow(unsafe_op_in_unsafe_fn)]
#[cxx::bridge(namespace = "org::blobstore")]
mod ffi {
    // Shared structs with fields visible to both languages.
    struct BlobMetadata {
        size: usize,
        tags: Vec<String>,
    }
```

```rust
    // Rust types and signatures exposed to C++.
    extern "Rust" {
        type MultiBuf;

        fn next_chunk(buf: &mut MultiBuf) -> &[u8];
    }

    // C++ types and signatures exposed to Rust.
    unsafe extern "C++" {
        include!("include/blobstore.h");

        type BlobstoreClient;

        fn new_blobstore_client() -> UniquePtr<BlobstoreClient>;
        fn put(self: Pin<&mut BlobstoreClient>, parts: &mut MultiBuf) -> u64;
        fn tag(self: Pin<&mut BlobstoreClient>, blobid: u64, tag: &str);
        fn metadata(&self, blobid: u64) -> BlobMetadata;
    }
}
```

- The bridge is generally declared in an `ffi` module within your crate.
- From the declarations made in the bridge module, CXX will generate matching Rust and C++ type/function definitions in order to expose those items to both languages.
- To view the generated Rust code, use cargo-expand to view the expanded proc macro. For most of the examples you would use `cargo expand ::ffi` to expand just the `ffi` module (though this doesn't apply for Android projects).
- To view the generated C++ code, look in `target/cxxbridge`.

38.2.2 Rust Bridge Declarations

```rust
#[cxx::bridge]
mod ffi {
    extern "Rust" {
        type MyType; // Opaque type
        fn foo(&self); // Method on `MyType`
        fn bar() -> Box<MyType>; // Free function
    }
}

struct MyType(i32);

impl MyType {
    fn foo(&self) {
        println!("{}", self.0);
    }
}

fn bar() -> Box<MyType> {
    Box::new(MyType(123))
}
```

- Items declared in the `extern "Rust"` reference items that are in scope in the parent module.
- The CXX code generator uses your `extern "Rust"` section(s) to produce a C++ header file containing the corresponding C++ declarations. The generated header has the same path as the Rust source file containing the bridge, except with a .rs.h file extension.

38.2.3 Generated C++

```
#[cxx::bridge]
mod ffi {
    // Rust types and signatures exposed to C++.
    extern "Rust" {
        type MultiBuf;

        fn next_chunk(buf: &mut MultiBuf) -> &[u8];
    }
}
```

Results in (roughly) the following C++:

```
struct MultiBuf final : public ::rust::Opaque {
  ~MultiBuf() = delete;

private:
  friend ::rust::layout;
  struct layout {
    static ::std::size_t size() noexcept;
    static ::std::size_t align() noexcept;
  };
};

::rust::Slice<::std::uint8_t const> next_chunk(::org::blobstore::MultiBuf &buf) noexcept
```

38.2.4 C++ Bridge Declarations

```
#[cxx::bridge]
mod ffi {
    // C++ types and signatures exposed to Rust.
    unsafe extern "C++" {
        include!("include/blobstore.h");

        type BlobstoreClient;

        fn new_blobstore_client() -> UniquePtr<BlobstoreClient>;
        fn put(self: Pin<&mut BlobstoreClient>, parts: &mut MultiBuf) -> u64;
        fn tag(self: Pin<&mut BlobstoreClient>, blobid: u64, tag: &str);
        fn metadata(&self, blobid: u64) -> BlobMetadata;
    }
}
```

Results in (roughly) the following Rust:

```rust
#[repr(C)]
pub struct BlobstoreClient {
    _private: ::cxx::private::Opaque,
}

pub fn new_blobstore_client() -> ::cxx::UniquePtr<BlobstoreClient> {
    extern "C" {
        #[link_name = "org$blobstore$cxxbridge1$new_blobstore_client"]
        fn __new_blobstore_client() -> *mut BlobstoreClient;
    }
    unsafe { ::cxx::UniquePtr::from_raw(__new_blobstore_client()) }
}

impl BlobstoreClient {
    pub fn put(&self, parts: &mut MultiBuf) -> u64 {
        extern "C" {
            #[link_name = "org$blobstore$cxxbridge1$BlobstoreClient$put"]
            fn __put(
                _: &BlobstoreClient,
                parts: *mut ::cxx::core::ffi::c_void,
            ) -> u64;
        }
        unsafe {
            __put(self, parts as *mut MultiBuf as *mut ::cxx::core::ffi::c_void)
        }
    }
}

// ...
```

- The programmer does not need to promise that the signatures they have typed in are accurate. CXX performs static assertions that the signatures exactly correspond with what is declared in C++.
- `unsafe extern` blocks allow you to declare C++ functions that are safe to call from Rust.

38.2.5 Shared Types

```rust
#[cxx::bridge]
mod ffi {
    #[derive(Clone, Debug, Hash)]
    struct PlayingCard {
        suit: Suit,
        value: u8,  // A=1, J=11, Q=12, K=13
    }

    enum Suit {
        Clubs,
        Diamonds,
        Hearts,
        Spades,
```

```
    }
}
```

- Only C-like (unit) enums are supported.
- A limited number of traits are supported for `#[derive()]` on shared types. Corresponding functionality is also generated for the C++ code, e.g. if you derive `Hash` also generates an implementation of `std::hash` for the corresponding C++ type.

38.2.6 Shared Enums

```rust
#[cxx::bridge]
mod ffi {
    enum Suit {
        Clubs,
        Diamonds,
        Hearts,
        Spades,
    }
}
```

Generated Rust:

```rust
#[derive(Copy, Clone, PartialEq, Eq)]
#[repr(transparent)]
pub struct Suit {
    pub repr: u8,
}

#[allow(non_upper_case_globals)]
impl Suit {
    pub const Clubs: Self = Suit { repr: 0 };
    pub const Diamonds: Self = Suit { repr: 1 };
    pub const Hearts: Self = Suit { repr: 2 };
    pub const Spades: Self = Suit { repr: 3 };
}
```

Generated C++:

```cpp
enum class Suit : uint8_t {
  Clubs = 0,
  Diamonds = 1,
  Hearts = 2,
  Spades = 3,
};
```

- On the Rust side, the code generated for shared enums is actually a struct wrapping a numeric value. This is because it is not UB in C++ for an enum class to hold a value different from all of the listed variants, and our Rust representation needs to have the same behavior.

38.2.7 Rust Error Handling

```
#[cxx::bridge]
mod ffi {
    extern "Rust" {
        fn fallible(depth: usize) -> Result<String>;
    }
}

fn fallible(depth: usize) -> anyhow::Result<String> {
    if depth == 0 {
        return Err(anyhow::Error::msg("fallible1 requires depth > 0"));
    }

    Ok("Success!".into())
}
```

- Rust functions that return `Result` are translated to exceptions on the C++ side.
- The exception thrown will always be of type `rust::Error`, which primarily exposes a way to get the error message string. The error message will come from the error type's `Display` impl.
- A panic unwinding from Rust to C++ will always cause the process to immediately terminate.

38.2.8 C++ Error Handling

```
#[cxx::bridge]
mod ffi {
    unsafe extern "C++" {
        include!("example/include/example.h");
        fn fallible(depth: usize) -> Result<String>;
    }
}

fn main() {
    if let Err(err) = ffi::fallible(99) {
        eprintln!("Error: {}", err);
        process::exit(1);
    }
}
```

- C++ functions declared to return a `Result` will catch any thrown exception on the C++ side and return it as an `Err` value to the calling Rust function.
- If an exception is thrown from an extern "C++" function that is not declared by the CXX bridge to return `Result`, the program calls C++'s `std::terminate`. The behavior is equivalent to the same exception being thrown through a `noexcept` C++ function.

38.2.9 Additional Types

Rust Type	C++ Type
`String`	`rust::String`
`&str`	`rust::Str`
`CxxString`	`std::string`
`&[T]/&mut [T]`	`rust::Slice`
`Box<T>`	`rust::Box<T>`
`UniquePtr<T>`	`std::unique_ptr<T>`
`Vec<T>`	`rust::Vec<T>`
`CxxVector<T>`	`std::vector<T>`

- These types can be used in the fields of shared structs and the arguments and returns of extern functions.
- Note that Rust's `String` does not map directly to `std::string`. There are a few reasons for this:
  - `std::string` does not uphold the UTF-8 invariant that `String` requires.
  - The two types have different layouts in memory and so can't be passed directly between languages.
  - `std::string` requires move constructors that don't match Rust's move semantics, so a `std::string` can't be passed by value to Rust.

38.2.10 Building in Android

Create two genrules: One to generate the CXX header, and one to generate the CXX source file. These are then used as inputs to the `cc_library_static`.

```
// Generate a C++ header containing the C++ bindings
// to the Rust exported functions in lib.rs.
genrule {
    name: "libcxx_test_bridge_header",
    tools: ["cxxbridge"],
    cmd: "$(location cxxbridge) $(in) --header > $(out)",
    srcs: ["lib.rs"],
    out: ["lib.rs.h"],
}

// Generate the C++ code that Rust calls into.
genrule {
    name: "libcxx_test_bridge_code",
    tools: ["cxxbridge"],
    cmd: "$(location cxxbridge) $(in) > $(out)",
    srcs: ["lib.rs"],
    out: ["lib.rs.cc"],
}
```

- The `cxxbridge` tool is a standalone tool that generates the C++ side of the bridge module. It is included in Android and available as a Soong tool.
- By convention, if your Rust source file is `lib.rs` your header file will be named `lib.rs.h` and your source file will be named `lib.rs.cc`. This naming convention isn't enforced, though.

38.2.11 Building in Android

Create a `cc_library_static` to build the C++ library, including the CXX generated header and source file.

```
cc_library_static {
    name: "libcxx_test_cpp",
    srcs: ["cxx_test.cpp"],
    generated_headers: [
        "cxx-bridge-header",
        "libcxx_test_bridge_header"
    ],
    generated_sources: ["libcxx_test_bridge_code"],
}
```

- Point out that `libcxx_test_bridge_header` and `libcxx_test_bridge_code` are the dependencies for the CXX-generated C++ bindings. We'll show how these are setup on the next slide.
- Note that you also need to depend on the `cxx-bridge-header` library in order to pull in common CXX definitions.
- Full docs for using CXX in Android can be found in the Android docs. You may want to share that link with the class so that students know where they can find these instructions again in the future.

38.2.12 Building in Android

Create a `rust_binary` that depends on `libcxx` and your `cc_library_static`.

```
rust_binary {
    name: "cxx_test",
    srcs: ["lib.rs"],
    rustlibs: ["libcxx"],
    static_libs: ["libcxx_test_cpp"],
}
```

38.3 Interoperability with Java

Java can load shared objects via Java Native Interface (JNI). The `jni` crate allows you to create a compatible library.

First, we create a Rust function to export to Java:

interoperability/java/src/lib.rs:

```
//! Rust <-> Java FFI demo.

use jni::JNIEnv;
use jni::objects::{JClass, JString};
use jni::sys::jstring;

/// HelloWorld::hello method implementation.
// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
```

```rust
pub extern "system" fn Java_HelloWorld_hello(
    mut env: JNIEnv,
    _class: JClass,
    name: JString,
) -> jstring {
    let input: String = env.get_string(&name).unwrap().into();
    let greeting = format!("Hello, {input}!");
    let output = env.new_string(greeting).unwrap();
    output.into_raw()
}
```

interoperability/java/Android.bp:

```
rust_ffi_shared {
    name: "libhello_jni",
    crate_name: "hello_jni",
    srcs: ["src/lib.rs"],
    rustlibs: ["libjni"],
}
```

We then call this function from Java:

interoperability/java/HelloWorld.java:

```java
class HelloWorld {
    private static native String hello(String name);

    static {
        System.loadLibrary("hello_jni");
    }

    public static void main(String[] args) {
        String output = HelloWorld.hello("Alice");
        System.out.println(output);
    }
}
```

interoperability/java/Android.bp:

```
java_binary {
    name: "helloworld_jni",
    srcs: ["HelloWorld.java"],
    main_class: "HelloWorld",
    jni_libs: ["libhello_jni"],
}
```

Finally, you can build, sync, and run the binary:

```shell
m helloworld_jni
adb sync  # requires adb root && adb remount
adb shell /system/bin/helloworld_jni
```

- The `unsafe(no_mangle)` attribute instructs Rust to emit the `Java_HelloWorld_hello` symbol exactly as written. This is important so that Java can recognize the symbol as a `hello` method on the `HelloWorld` class.

- By default, Rust will mangle (rename) symbols so that a binary can link in two versions of the same Rust crate.

Part X

Chromium

Chapter 39

Welcome to Rust in Chromium

Rust is supported for third-party libraries in Chromium, with first-party glue code to connect between Rust and existing Chromium C++ code.

> Today, we'll call into Rust to do something silly with strings. If you've got a corner of the code where you're displaying a UTF-8 string to the user, feel free to follow this recipe in your part of the codebase instead of the exact part we talk about.

Chapter 40

Setup

Make sure you can build and run Chromium. Any platform and set of build flags is OK, so long as your code is relatively recent (commit position 1223636 onwards, corresponding to November 2023):

```
gn gen out/Debug
autoninja -C out/Debug chrome
out/Debug/chrome # or on Mac, out/Debug/Chromium.app/Contents/MacOS/Chromium
```

(A component, debug build is recommended for quickest iteration time. This is the default!)

See How to build Chromium if you aren't already at that point. Be warned: setting up to build Chromium takes time.

It's also recommended that you have Visual Studio code installed.

About the exercises

This part of the course has a series of exercises that build on each other. We'll be doing them spread throughout the course instead of just at the end. If you don't have time to complete a certain part, don't worry: you can catch up in the next slot.

Chapter 41

Comparing Chromium and Cargo Ecosystems

The Rust community typically uses `cargo` and libraries from crates.io. Chromium is built using `gn` and `ninja` and a curated set of dependencies.

When writing code in Rust, your choices are:

- Use `gn` and `ninja` with the help of the templates from `//build/rust/*.gni` (e.g. `rust_static_library` that we'll meet later). This uses Chromium's audited toolchain and crates.
- Use `cargo`, but restrict yourself to Chromium's audited toolchain and crates
- Use `cargo`, trusting a toolchain and/or crates downloaded from the internet

From here on we'll be focusing on `gn` and `ninja`, because this is how Rust code can be built into the Chromium browser. At the same time, Cargo is an important part of the Rust ecosystem and you should keep it in your toolbox.

Mini exercise

Split into small groups and:

- Brainstorm scenarios where `cargo` may offer an advantage and assess the risk profile of these scenarios.
- Discuss which tools, libraries, and groups of people need to be trusted when using `gn` and `ninja`, offline `cargo`, etc.

Ask students to avoid peeking at the speaker notes before completing the exercise. Assuming folks taking the course are physically together, ask them to discuss in small groups of 3-4 people.

Notes/hints related to the first part of the exercise ("scenarios where Cargo may offer an advantage"):

- It's fantastic that when writing a tool, or prototyping a part of Chromium, one has access to the rich ecosystem of crates.io libraries. There is a crate for almost anything and they are typically quite pleasant to use. (`clap` for command-line parsing, `serde` for serializing/deserializing to/from various formats, `itertools` for working with iterators, etc.).

  - `cargo` makes it easy to try a library (just add a single line to `Cargo.toml` and start writing code)
  - It may be worth comparing how CPAN helped make `perl` a popular choice. Or comparing with `python` + `pip`.

- Development experience is made really nice not only by core Rust tools (e.g. using `rustup` to switch to a different `rustc` version when testing a crate that needs to work on nightly, current stable, and older stable) but also by an ecosystem of third-party tools (e.g. Mozilla provides `cargo vet` for streamlining and sharing security audits; `criterion` crate gives a streamlined way to run benchmarks).

  - `cargo` makes it easy to add a tool via `cargo install --locked cargo-vet`.
  - It may be worth comparing with Chrome Extensions or VScode extensions.

- Broad, generic examples of projects where `cargo` may be the right choice:

  - Perhaps surprisingly, Rust is becoming increasingly popular in the industry for writing command line tools. The breadth and ergonomics of libraries is comparable to Python, while being more robust (thanks to the rich type system) and running faster (as a compiled, rather than interpreted language).
  - Participating in the Rust ecosystem requires using standard Rust tools like Cargo. Libraries that want to get external contributions, and want to be used outside of Chromium (e.g. in Bazel or Android/Soong build environments) should use Cargo.

- Examples of Chromium-related projects that are `cargo`-based:

  - `serde_json_lenient` (experimented with in other parts of Google which resulted in PRs with performance improvements)
  - Fontations libraries like `font-types`
  - `gnrt` tool (we will meet it later in the course) which depends on `clap` for command-line parsing and on `toml` for configuration files.
    * Disclaimer: a unique reason for using `cargo` was unavailability of gn when building and bootstrapping Rust standard library when building Rust toolchain.
    * `run_gnrt.py` uses Chromium's copy of `cargo` and `rustc`. `gnrt` depends on third-party libraries downloaded from the internet, but `run_gnrt.py` asks `cargo` that only `--locked` content is allowed via `Cargo.lock`.)

Students may identify the following items as being implicitly or explicitly trusted:

- `rustc` (the Rust compiler) which in turn depends on the LLVM libraries, the Clang compiler, the `rustc` sources (fetched from GitHub, reviewed by Rust compiler team), binary Rust compiler downloaded for bootstrapping
- `rustup` (it may be worth pointing out that `rustup` is developed under the umbrella of the https://github.com/rust-lang/ organization - same as `rustc`)
- `cargo`, `rustfmt`, etc.
- Various internal infrastructure (bots that build `rustc`, system for distributing the pre-built toolchain to Chromium engineers, etc.)
- Cargo tools like `cargo audit`, `cargo vet`, etc.
- Rust libraries vendored into `//third_party/rust` (audited by security@chromium.org)
- Other Rust libraries (some niche, some quite popular and commonly used)

Chapter 42

Chromium Rust policy

Chromium's Rust policy can be found here. Rust can be used for both first-party and third-party code.

Using Rust for pure first-party code looks like this:

```
"C++"                           Rust
.- - - - - - - - - -.           .- - - - - - - - - - -.
:                   :           :                     :
: Existing Chromium :           :  Chromium Rust      :
: "C++"             :           :  code               :
: +---------------+ :           : +----------------+  :
: |               | :           : |                |  :
: |         o-----+-+-----------+-+->              |  :
: |               | : Language  : |                |  :
: +---------------+ : boundary  : +----------------+  :
:                   :           :                     :
`- - - - - - - - - -'           `- - - - - - - - - - -'
```

The third-party case is also common. You will typically also need a small amount of first-party glue code, because very few Rust libraries directly expose a C/C++ API.

```
"C++"                           Rust
.- - - - - - - - - -.           .- - - - - - - - - - - - - - - - - - - - - - -.
:                   :           :                                             :
: Existing Chromium :           :  Chromium Rust                Existing Rust :
: "C++"             :           :  "wrapper"                    crate         :
: +---------------+ :           : +----------------+          +-------------+ :
: |               | :           : |                |          |             | :
: |         o-----+-+-----------+-+->            o-+----------+-->          | :
: |               | : Language  : |                | Crate    |             | :
: +---------------+ : boundary  : +----------------+ API      +-------------+ :
:                   :           :                                             :
`- - - - - - - - - -'           `- - - - - - - - - - - - - - - - - - - - - - -'
```

The scenario of using a third-party crate is the more complex one, so today's course will focus on:

- Bringing in third-party Rust libraries (”crates”)
- Writing glue code to be able to use those crates from Chromium C++. (The same techniques are used when working with first-party Rust code).

Chapter 43

Build rules

Rust code is typically built using `cargo`. Chromium builds with gn and `ninja` for efficiency --- its static rules allow maximum parallelism. Rust is no exception.

Adding Rust code to Chromium

In some existing Chromium `BUILD.gn` file, declare a `rust_static_library`:

```
import("//build/rust/rust_static_library.gni")

rust_static_library("my_rust_lib") {
  crate_root = "lib.rs"
  sources = [ "lib.rs" ]
}
```

You can also add `deps` on other Rust targets. Later we'll use this to depend upon third party code.

You must specify *both* the crate root, *and* a full list of sources. The `crate_root` is the file given to the Rust compiler representing the root file of the compilation unit --- typically `lib.rs`. `sources` is a complete list of all source files which `ninja` needs in order to determine when rebuilds are necessary.

(There's no such thing as a Rust `source_set`, because in Rust, an entire crate is a compilation unit. A `static_library` is the smallest unit.)

Students might be wondering why we need a gn template, rather than using gn's built-in support for Rust static libraries. The answer is that this template provides support for CXX interop, Rust features, and unit tests, some of which we'll use later.

43.1 Including `unsafe` Rust Code

Unsafe Rust code is forbidden in `rust_static_library` by default --- it won't compile. If you need unsafe Rust code, add `allow_unsafe = true` to the gn target. (Later in the course we'll see circumstances where this is necessary.)

```
import("//build/rust/rust_static_library.gni")

rust_static_library("my_rust_lib") {
  crate_root = "lib.rs"
  sources = [
    "lib.rs",
    "hippopotamus.rs"
  ]
  allow_unsafe = true
}
```

43.2 Depending on Rust Code from Chromium C++

Simply add the above target to the `deps` of some Chromium C++ target.

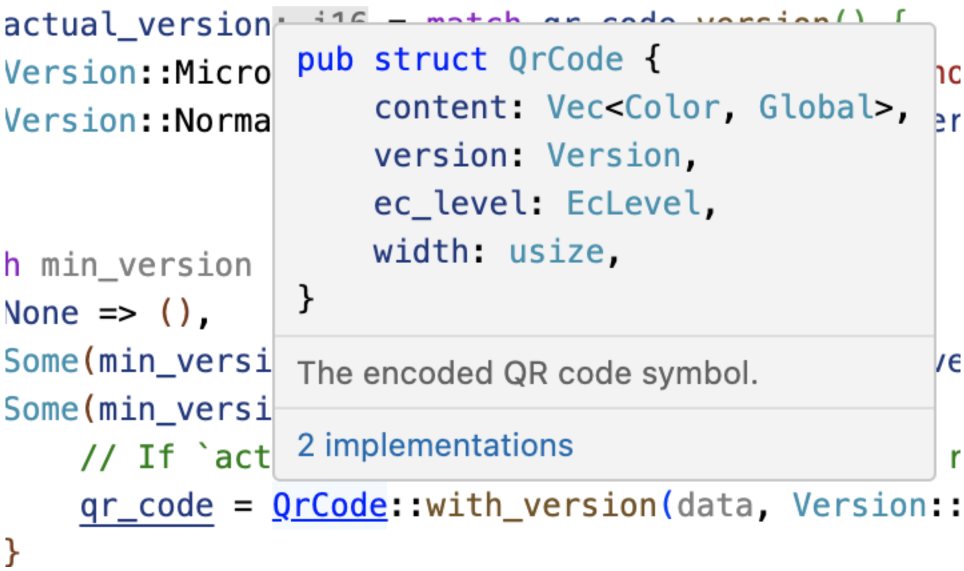
```
import("//build/rust/rust_static_library.gni")

rust_static_library("my_rust_lib") {
  crate_root = "lib.rs"
  sources = [ "lib.rs" ]
}

# or source_set, static_library etc.
component("preexisting_cpp") {
  deps = [ ":my_rust_lib" ]
}
```

We'll see that this relationship only works if the Rust code exposes plain C APIs which can be called from C++, or if we use a C++/Rust interop tool.

43.3 Visual Studio Code

Types are elided in Rust code, which makes a good IDE even more useful than for C++. Visual Studio code works well for Rust in Chromium. To use it,

- Ensure your VSCode has the `rust-analyzer` extension, not earlier forms of Rust support
- `gn gen out/Debug --export-rust-project` (or equivalent for your output directory)
- `ln -s out/Debug/rust-project.json rust-project.json`



A demo of some of the code annotation and exploration features of rust-analyzer might be beneficial if the audience are naturally skeptical of IDEs.

The following steps may help with the demo (but feel free to instead use a piece of Chromium-related Rust that you are most familiar with):

- Open `components/qr_code_generator/qr_code_generator_ffi_glue.rs`
- Place the cursor over the `QrCode::new` call (around line 26) in 'qr_code_generator_ffi_glue.rs
- Demo **show documentation** (typical bindings: vscode = ctrl k i; vim/CoC = K).
- Demo **go to definition** (typical bindings: vscode = F12; vim/CoC = g d). (This will take you to `//third_party/rust/.../qr_code-.../src/lib.rs`.)
- Demo **outline** and navigate to the `QrCode::with_bits` method (around line 164; the outline is in the file explorer pane in vscode; typical vim/CoC bindings = space o)
- Demo **type annotations** (there are quite a few nice examples in the `QrCode::with_bits` method)

It may be worth pointing out that `gn gen ... --export-rust-project` will need to be rerun after editing `BUILD.gn` files (which we will do a few times throughout the exercises in this session).

43.4 Build rules exercise

In your Chromium build, add a new Rust target to `//ui/base/BUILD.gn` containing:

```rust
// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
pub extern "C" fn hello_from_rust() {
    println!("Hello from Rust!")
}
```

Important: note that `no_mangle` here is considered a type of unsafety by the Rust compiler, so you'll need to allow unsafe code in your gn target.

Add this new Rust target as a dependency of `//ui/base:base`. Declare this function at the top of `ui/base/resource/resource_bundle.cc` (later, we'll see how this can be automated by bindings generation tools):

```
extern "C" void hello_from_rust();
```

Call this function from somewhere in `ui/base/resource/resource_bundle.cc` - we suggest the top of `ResourceBundle::MaybeMangleLocalizedString`. Build and run Chromium, and ensure that "Hello from Rust!" is printed lots of times.

If you use VSCode, now set up Rust to work well in VSCode. It will be useful in subsequent exercises. If you've succeeded, you will be able to use right-click "Go to definition" on `println!`.

Where to find help

- The options available to the `rust_static_library` gn template
- Information about `#[unsafe(no_mangle)]`
- Information about `extern "C"`
- Information about gn's `--export-rust-project` switch
- How to install rust-analyzer in VSCode

It's really important that students get this running, because future exercises will build on it.

This example is unusual because it boils down to the lowest-common-denominator interop language, C. Both C++ and Rust can natively declare and call C ABI functions. Later in the course, we'll connect C++ directly to Rust.

`allow_unsafe = true` is required here because `#[unsafe(no_mangle)]` might allow Rust to generate two functions with the same name, and Rust can no longer guarantee that the right one is called.

If you need a pure Rust executable, you can also do that using the `rust_executable` gn template.

Chapter 44

Testing

Rust community typically authors unit tests in a module placed in the same source file as the code being tested. This was covered earlier in the course and looks like this:

```
#[cfg(test)]
mod tests {
    #[test]
    fn my_test() {
        todo!()
    }
}
```

In Chromium we place unit tests in a separate source file and we continue to follow this practice for Rust --- this makes tests consistently discoverable and helps to avoid rebuilding `.rs` files a second time (in the `test` configuration).

This results in the following options for testing Rust code in Chromium:

- Native Rust tests (i.e. `#[test]`). Discouraged outside of `//third_party/rust`.
- `gtest` tests authored in C++ and exercising Rust via FFI calls. Sufficient when Rust code is just a thin FFI layer and the existing unit tests provide sufficient coverage for the feature.
- `gtest` tests authored in Rust and using the crate under test through its public API (using `pub mod for_testing { ... }` if needed). This is the subject of the next few slides.

Mention that native Rust tests of third-party crates should eventually be exercised by Chromium bots. (Such testing is needed rarely --- only after adding or updating third-party crates.)

Some examples may help illustrate when C++ `gtest` vs Rust `gtest` should be used:

- QR has very little functionality in the first-party Rust layer (it's just a thin FFI glue) and therefore uses the existing C++ unit tests for testing both the C++ and the Rust implementation (parameterizing the tests so they enable or disable Rust using a `ScopedFeatureList`).
- Hypothetical/WIP PNG integration may need memory-safe implementations of pixel transformations that are provided by `libpng` but missing in the png crate - e.g. RGBA

=> BGRA, or gamma correction. Such functionality may benefit from separate tests authored in Rust.

44.1 `rust_gtest_interop` Library

The `rust_gtest_interop` library provides a way to:

- Use a Rust function as a `gtest` testcase (using the `#[gtest(...)]` attribute)
- Use `expect_eq!` and similar macros (similar to `assert_eq!` but not panicking and not terminating the test when the assertion fails).

Example:

```rust
use rust_gtest_interop::prelude::*;

#[gtest(MyRustTestSuite, MyAdditionTest)]
fn test_addition() {
    expect_eq!(2 + 2, 4);
}
```

44.2 GN Rules for Rust Tests

The simplest way to build Rust `gtest` tests is to add them to an existing test binary that already contains tests authored in C++. For example:

```
test("ui_base_unittests") {
  ...
  sources += [ "my_rust_lib_unittest.rs" ]
  deps += [ ":my_rust_lib" ]
}
```

Authoring Rust tests in a separate `static_library` also works, but requires manually declaring the dependency on the support libraries:

```
rust_static_library("my_rust_lib_unittests") {
  testonly = true
  is_gtest_unittests = true
  crate_root = "my_rust_lib_unittest.rs"
  sources = [ "my_rust_lib_unittest.rs" ]
  deps = [
    ":my_rust_lib",
    "//testing/rust_gtest_interop",
  ]
}

test("ui_base_unittests") {
  ...
  deps += [ ":my_rust_lib_unittests" ]
}
```

44.3 `chromium::import!` Macro

After adding `:my_rust_lib` to GN `deps`, we still need to learn how to import and use `my_rust_lib` from `my_rust_lib_unittest.rs`. We haven't provided an explicit `crate_name` for `my_rust_lib` so its crate name is computed based on the full target path and name. Fortunately we can avoid working with such an unwieldy name by using the `chromium::import!` macro from the automatically-imported `chromium` crate:

```
chromium::import! {
    "//ui/base:my_rust_lib";
}

use my_rust_lib::my_function_under_test;
```

Under the covers the macro expands to something similar to:

```
extern crate ui_sbase_cmy_urust_ulib as my_rust_lib;

use my_rust_lib::my_function_under_test;
```

More information can be found in the doc comment of the `chromium::import` macro.

`rust_static_library` supports specifying an explicit name via `crate_name` property, but doing this is discouraged. And it is discouraged because the crate name has to be globally unique. crates.io guarantees uniqueness of its crate names so `cargo_crate` GN targets (generated by the `gnrt` tool covered in a later section) use short crate names.

44.4 Testing exercise

Time for another exercise!

In your Chromium build:

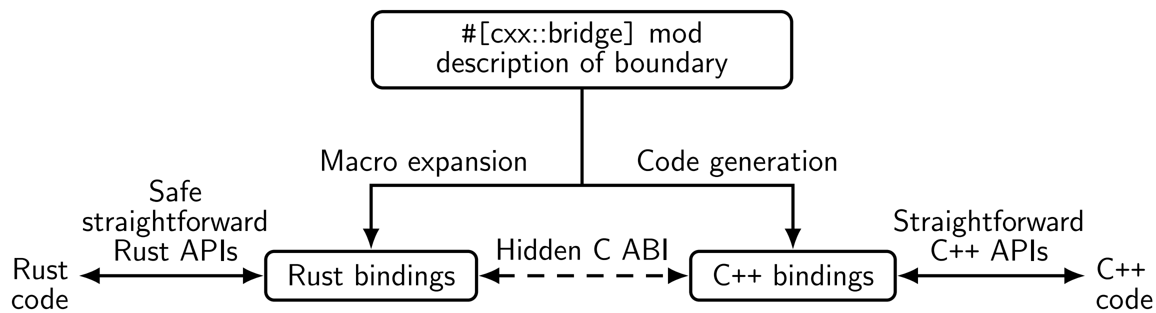
- Add a testable function next to `hello_from_rust`. Some suggestions: adding two integers received as arguments, computing the nth Fibonacci number, summing integers in a slice, etc.
- Add a separate `..._unittest.rs` file with a test for the new function.
- Add the new tests to `BUILD.gn`.
- Build the tests, run them, and verify that the new test works.

Chapter 45

Interoperability with C++

The Rust community offers multiple options for C++/Rust interop, with new tools being developed all the time. At the moment, Chromium uses a tool called CXX.

You describe your whole language boundary in an interface definition language (which closely resembles Rust) and then CXX tools generate declarations for functions and types in both Rust and C++.



See the CXX tutorial for a full example of using this.

Talk through the diagram. Explain that behind the scenes, this is doing just the same as you previously did. Point out that automating the process has the following benefits:

- The tool guarantees that the C++ and Rust sides match (e.g. you get compile errors if the `#[cxx::bridge]` doesn't match the actual C++ or Rust definitions, but with out-of-sync manual bindings you'd get Undefined Behavior)
- The tool automates generation of FFI thunks (small, C-ABI-compatible, free functions) for non-C features (e.g. enabling FFI calls into Rust or C++ methods; manual bindings would require authoring such top-level, free functions manually)
- The tool and the library can handle a set of core types - for example:
  - `&[T]` can be passed across the FFI boundary, even though it doesn't guarantee any particular ABI or memory layout. With manual bindings `std::span<T>` / `&[T]` have to be manually destructured and rebuilt out of a pointer and length - this is error-prone given that each language represents empty slices slightly differently)
  - Smart pointers like `std::unique_ptr<T>`, `std::shared_ptr<T>`, and/or `Box` are natively supported. With manual bindings, one would have to pass C-ABI-compatible raw pointers, which would increase lifetime and memory-safety

risks.
  – `rust::String` and `CxxString` types understand and maintain differences in string representation across the languages (e.g. `rust::String::lossy` can build a Rust string from non-UTF-8 input and `rust::String::c_str` can NUL-terminate a string).

45.1 Example Bindings

CXX requires that the whole C++/Rust boundary is declared in `cxx::bridge` modules inside `.rs` source code.

```
#[cxx::bridge]
mod ffi {
    extern "Rust" {
        type MultiBuf;

        fn next_chunk(buf: &mut MultiBuf) -> &[u8];
    }

    unsafe extern "C++" {
        include!("example/include/blobstore.h");

        type BlobstoreClient;

        fn new_blobstore_client() -> UniquePtr<BlobstoreClient>;
        fn put(self: &BlobstoreClient, buf: &mut MultiBuf) -> Result<u64>;
    }
}

// Definitions of Rust types and functions go here
```

Point out:

- Although this looks like a regular Rust `mod`, the `#[cxx::bridge]` procedural macro does complex things to it. The generated code is quite a bit more sophisticated - though this does still result in a `mod` called `ffi` in your code.
- Native support for C++'s `std::unique_ptr` in Rust
- Native support for Rust slices in C++
- Calls from C++ to Rust, and Rust types (in the top part)
- Calls from Rust to C++, and C++ types (in the bottom part)

Common misconception: It *looks* like a C++ header is being parsed by Rust, but this is misleading. This header is never interpreted by Rust, but simply `#include`d in the generated C++ code for the benefit of C++ compilers.

45.2 Limitations of CXX

By far the most useful page when using CXX is the type reference.

CXX fundamentally suits cases where:

- Your Rust-C++ interface is sufficiently simple that you can declare all of it.

- You're using only the types natively supported by CXX already, for example `std::unique_ptr`, `std::string`, `&[u8]` etc.

It has many limitations --- for example lack of support for Rust's `Option` type.

These limitations constrain us to using Rust in Chromium only for well isolated "leaf nodes" rather than for arbitrary Rust-C++ interop. When considering a use-case for Rust in Chromium, a good starting point is to draft the CXX bindings for the language boundary to see if it appears simple enough.

In addition, right now, Rust code in one component cannot depend on Rust code in another, due to linking details in our component build. That's another reason to restrict Rust to use in leaf nodes.

You should also discuss some of the other sticky points with CXX, for example:

- Its error handling is based around C++ exceptions (given on the next slide)
- Function pointers are awkward to use.

45.3 CXX Error Handling

CXX's support for `Result<T,E>` relies on C++ exceptions, so we can't use that in Chromium. Alternatives:

- The `T` part of `Result<T, E>` can be:
  - Returned via out parameters (e.g. via `&mut T`). This requires that `T` can be passed across the FFI boundary - for example `T` has to be:
    - A primitive type (like `u32` or `usize`)
    - A type natively supported by `cxx` (like `UniquePtr<T>`) that has a suitable default value to use in a failure case (*unlike* `Box<T>`).
  - Retained on the Rust side, and exposed via reference. This may be needed when `T` is a Rust type, which cannot be passed across the FFI boundary, and cannot be stored in `UniquePtr<T>`.
- The `E` part of `Result<T, E>` can be:
  - Returned as a boolean (e.g. `true` representing success, and `false` representing failure)
  - Preserving error details is in theory possible, but so far hasn't been needed in practice.

45.3.1 CXX Error Handling: QR Example

The QR code generator is an example where a boolean is used to communicate success vs failure, and where the successful result can be passed across the FFI boundary:

```rust
#[cxx::bridge(namespace = "qr_code_generator")]
mod ffi {
    extern "Rust" {
        fn generate_qr_code_using_rust(
            data: &[u8],
            min_version: i16,
            out_pixels: Pin<&mut CxxVector<u8>>,
            out_qr_size: &mut usize,
```

```
        ) -> bool;
    }
}
```

Students may be curious about the semantics of the `out_qr_size` output. This is not the size of the vector, but the size of the QR code (and admittedly it is a bit redundant - this is the square root of the size of the vector).

It may be worth pointing out the importance of initializing `out_qr_size` before calling into the Rust function. Creation of a Rust reference that points to uninitialized memory results in Undefined Behavior (unlike in C++, when only the act of dereferencing such memory results in UB).

If students ask about `Pin`, then explain why CXX needs it for mutable references to C++ data: the answer is that C++ data can't be moved around like Rust data, because it may contain self-referential pointers.

45.3.2 CXX Error Handling: PNG Example

A prototype of a PNG decoder illustrates what can be done when the successful result cannot be passed across the FFI boundary:

```
#[cxx::bridge(namespace = "gfx::rust_bindings")]
mod ffi {
    extern "Rust" {
        /// This returns an FFI-friendly equivalent of `Result<PngReader<'a>,
        /// ()>`.
        fn new_png_reader<'a>(input: &'a [u8]) -> Box<ResultOfPngReader<'a>>;

        /// C++ bindings for the `crate::png::ResultOfPngReader` type.
        type ResultOfPngReader<'a>;
        fn is_err(self: &ResultOfPngReader) -> bool;
        fn unwrap_as_mut<'a, 'b>(
            self: &'b mut ResultOfPngReader<'a>,
        ) -> &'b mut PngReader<'a>;

        /// C++ bindings for the `crate::png::PngReader` type.
        type PngReader<'a>;
        fn height(self: &PngReader) -> u32;
        fn width(self: &PngReader) -> u32;
        fn read_rgba8(self: &mut PngReader, output: &mut [u8]) -> bool;
    }
}
```

`PngReader` and `ResultOfPngReader` are Rust types --- objects of these types cannot cross the FFI boundary without indirection of a `Box<T>`. We can't have an `out_parameter: &mut PngReader`, because CXX doesn't allow C++ to store Rust objects by value.

This example illustrates that even though CXX doesn't support arbitrary generics nor templates, we can still pass them across the FFI boundary by manually specializing / monomorphizing them into a non-generic type. In the example `ResultOfPngReader` is a non-generic type that forwards into appropriate methods of `Result<T, E>` (e.g. into `is_err`, `unwrap`, and/or `as_mut`).

45.4 Using cxx in Chromium

In Chromium, we define an independent `#[cxx::bridge]` mod for each leaf-node where we want to use Rust. You'd typically have one for each `rust_static_library`. Just add

```
cxx_bindings = [ "my_rust_file.rs" ]
   # list of files containing #[cxx::bridge], not all source files
allow_unsafe = true
```

to your existing `rust_static_library` target alongside `crate_root` and `sources`.

C++ headers will be generated at a sensible location, so you can just

```
#include "ui/base/my_rust_file.rs.h"
```

You will find some utility functions in `//base` to convert to/from Chromium C++ types to CXX Rust types --- for example `SpanToRustSlice`.

Students may ask --- why do we still need `allow_unsafe = true`?

The broad answer is that no C/C++ code is "safe" by the normal Rust standards. Calling back and forth to C/C++ from Rust may do arbitrary things to memory, and compromise the safety of Rust's own data layouts. Presence of *too many* `unsafe` keywords in C/C++ interop can harm the signal-to-noise ratio of such a keyword, and is controversial, but strictly, bringing any foreign code into a Rust binary can cause unexpected behavior from Rust's perspective.

The narrow answer lies in the diagram at the top of this page --- behind the scenes, CXX generates Rust `unsafe` and `extern "C"` functions just like we did manually in the previous section.

45.5 Exercise: Interoperability with C++

Part one

- In the Rust file you previously created, add a `#[cxx::bridge]` which specifies a single function, to be called from C++, called `hello_from_rust`, taking no parameters and returning no value.
- Modify your previous `hello_from_rust` function to remove `extern "C"` and `#[unsafe(no_mangle)]`. This is now just a standard Rust function.
- Modify your gn target to build these bindings.
- In your C++ code, remove the forward-declaration of `hello_from_rust`. Instead, include the generated header file.
- Build and run!

Part two

It's a good idea to play with CXX a little. It helps you think about how flexible Rust in Chromium actually is.

Some things to try:

- Call back into C++ from Rust. You will need:
  - An additional header file which you can `include!` from your `cxx::bridge`. You'll need to declare your C++ function in that new header file.

  - An `unsafe` block to call such a function, or alternatively specify the `unsafe` keyword in your `#[cxx::bridge]` as described here.
  - You may also need to `#include "third_party/rust/cxx/v1/crate/include/cxx.h"`
- Pass a C++ string from C++ into Rust.
- Pass a reference to a C++ object into Rust.
- Intentionally get the Rust function signatures mismatched from the `#[cxx::bridge]`, and get used to the errors you see.
- Intentionally get the C++ function signatures mismatched from the `#[cxx::bridge]`, and get used to the errors you see.
- Pass a `std::unique_ptr` of some type from C++ into Rust, so that Rust can own some C++ object.
- Create a Rust object and pass it into C++, so that C++ owns it. (Hint: you need a Box).
- Declare some methods on a C++ type. Call them from Rust.
- Declare some methods on a Rust type. Call them from C++.

Part three

Now you understand the strengths and limitations of CXX interop, think of a couple of use-cases for Rust in Chromium where the interface would be sufficiently simple. Sketch how you might define that interface.

Where to find help

- The `cxx` binding reference
- The `rust_static_library` gn template

As students explore Part Two, they're bound to have lots of questions about how to achieve these things, and also how CXX works behind the scenes.

Some of the questions you may encounter:

- I'm seeing a problem initializing a variable of type X with type Y, where X and Y are both function types. This is because your C++ function doesn't quite match the declaration in your `cxx::bridge`.
- I seem to be able to freely convert C++ references into Rust references. Doesn't that risk UB? For CXX's *opaque* types, no, because they are zero-sized. For CXX trivial types yes, it's *possible* to cause UB, although CXX's design makes it quite difficult to craft such an example.

Chapter 46

Adding Third Party Crates

Rust libraries are called ”crates” and are found at crates.io. It's *very easy* for Rust crates to depend upon one another. So they do!

Property	C++ library	Rust crate
Build system	Lots	Consistent: `Cargo.toml`
Typical library size	Large-ish	Small
Transitive dependencies	Few	Lots

For a Chromium engineer, this has pros and cons:

- All crates use a common build system so we can automate their inclusion into Chromium...
- ... but, crates typically have transitive dependencies, so you will likely have to bring in multiple libraries.

We'll discuss:

- How to put a crate in the Chromium source code tree
- How to make gn build rules for it
- How to audit its source code for sufficient safety.

All of the things in the table on this slide are generalizations, and counter-examples can be found. But in general it's important for students to understand that most Rust code depends on other Rust libraries, because it's easy to do so, and that this has both benefits and costs.

46.1 Configuring the `Cargo.toml` file to add crates

Chromium has a single set of centrally-managed direct crate dependencies. These are managed through a single `Cargo.toml`:

```
[dependencies]
bitflags = "1"
cfg-if = "1"
cxx = "1"
# lots more...
```

As with any other Cargo.toml, you can specify more details about the dependencies --- typically, you'll want to specify the features that you wish to enable in the crate.

When adding a crate to Chromium, you'll frequently need to provide additional information in an additional file, gnrt_config.toml, which we'll meet next.

46.2 Configuring gnrt_config.toml

Alongside Cargo.toml is gnrt_config.toml. This contains Chromium-specific extensions to crate handling.

If you add a new crate, you should specify at least the group. This is one of:

```
#   'safe': The library satisfies the rule-of-2 and can be used in any process.
#   'sandbox': The library does not satisfy the rule-of-2 and must be used in
#              a sandboxed process such as the renderer or a utility process.
#   'test': The library is only used in tests.
```

For instance,

```
[crate.my-new-crate]
group = 'test' # only used in test code
```

Depending on the crate source code layout, you may also need to use this file to specify where its LICENSE file(s) can be found.

Later, we'll see some other things you will need to configure in this file to resolve problems.

46.3 Downloading Crates

A tool called gnrt knows how to download crates and how to generate BUILD.gn rules.

To start, download the crate you want like this:

```
cd chromium/src
vpython3 tools/crates/run_gnrt.py -- vendor
```

> Although the gnrt tool is part of the Chromium source code, by running this command you will be downloading and running its dependencies from crates.io. See the earlier section discussing this security decision.

This vendor command may download:

- Your crate
- Direct and transitive dependencies
- New versions of other crates, as required by cargo to resolve the complete set of crates required by Chromium.

Chromium maintains patches for some crates, kept in //third_party/rust/chromium_crates_io/patches. These will be reapplied automatically, but if patching fails you may need to take manual action.

46.4 Generating gn Build Rules

Once you've downloaded the crate, generate the BUILD.gn files like this:

```
vpython3 tools/crates/run_gnrt.py -- gen
```

Now run `git status`. You should find:

- At least one new crate source code in `third_party/rust/chromium_crates_io/vendor`
- At least one new BUILD.gn in `third_party/rust/<crate name>/v<major semver version>`
- An appropriate `README.chromium`

The "major semver version" is a Rust "semver" version number.

Take a close look, especially at the things generated in `third_party/rust`.

Talk a little about semver --- and specifically the way that in Chromium it's to allow multiple incompatible versions of a crate, which is discouraged but sometimes necessary in the Cargo ecosystem.

46.5 Resolving Problems

If your build fails, it may be because of a `build.rs`: programs which do arbitrary things at build time. This is fundamentally at odds with the design of gn and `ninja` which aim for static, deterministic, build rules to maximize parallelism and repeatability of builds.

Some `build.rs` actions are automatically supported; others require action:

build script effect	Supported by our gn templates	Work required by you
Checking rustc version to configure features on and off	Yes	None
Checking platform or CPU to configure features on and off	Yes	None
Generating code	Yes	Yes - specify in `gnrt_config.toml`
Building C/C++	No	Patch around it
Arbitrary other actions	No	Patch around it

Fortunately, most crates don't contain a build script, and fortunately, most build scripts only do the top two actions.

46.5.1 Build Scripts Which Generate Code

If `ninja` complains about missing files, check the `build.rs` to see if it writes source code files.

If so, modify `gnrt_config.toml` to add `build-script-outputs` to the crate. If this is a transitive dependency, that is, one on which Chromium code should not directly depend, also add `allow-first-party-usage=false`. There are several examples already in that file:

```toml
[crate.unicode-linebreak]
allow-first-party-usage = false
build-script-outputs = ["tables.rs"]
```

Now rerun `gnrt.py -- gen` to regenerate `BUILD.gn` files to inform ninja that this particular output file is input to subsequent build steps.

46.5.2 Build Scripts Which Build C++ or Take Arbitrary Actions

Some crates use the `cc` crate to build and link C/C++ libraries. Other crates parse C/C++ using `bindgen` within their build scripts. These actions can't be supported in a Chromium context --- our gn, ninja and LLVM build system is very specific in expressing relationships between build actions.

So, your options are:

- Avoid these crates
- Apply a patch to the crate.

Patches should be kept in `third_party/rust/chromium_crates_io/patches/<crate>` - see for example the patches against the `cxx` crate - and will be applied automatically by `gnrt` each time it upgrades the crate.

46.6 Depending on a Crate

Once you've added a third-party crate and generated build rules, depending on a crate is simple. Find your `rust_static_library` target, and add a dep on the `:lib` target within your crate.

Specifically,

```
                     +------------+      +----------------------+
"//third_party/rust" | crate name | "/v" | major semver version | ":lib"
                     +------------+      +----------------------+
```

For instance,

```
rust_static_library("my_rust_lib") {
  crate_root = "lib.rs"
  sources = [ "lib.rs" ]
  deps = [ "//third_party/rust/example_rust_crate/v1:lib" ]
}
```

46.7 Auditing Third Party Crates

Adding new libraries is subject to Chromium's standard policies, but of course also subject to security review. As you may be bringing in not just a single crate but also transitive dependencies, there may be a substantial amount of code to review. On the other hand, safe Rust code can have limited negative side effects. How should you review it?

Over time Chromium aims to move to a process based around cargo vet.

Meanwhile, for each new crate addition, we are checking for the following:

- Understand why each crate is used. What's the relationship between crates? If the build system for each crate contains a build.rs or procedural macros, work out what they're for. Are they compatible with the way Chromium is normally built?
- Check each crate seems to be reasonably well maintained
- Use cd third-party/rust/chromium_crates_io; cargo audit to check for known vulnerabilities (first you'll need to cargo install cargo-audit, which ironically involves downloading lots of dependencies from the internet[2])
- Ensure any unsafe code is good enough for the Rule of Two
- Check for any use of fs or net APIs
- Read all the code at a sufficient level to look for anything out of place that might have been maliciously inserted. (You can't realistically aim for 100% perfection here: there is often too much code.)

These are just guidelines --- work with reviewers from security@chromium.org to work out the right way to become confident of the crate.

46.8 Checking Crates into Chromium Source Code

git status should reveal:

- Crate code in //third_party/rust/chromium_crates_io
- Metadata (BUILD.gn and README.chromium) in //third_party/rust/<crate>/<version>

Please also add an OWNERS file in the latter location.

You should land all this, along with your Cargo.toml and gnrt_config.toml changes, into the Chromium repo.

Important: you need to use git add -f because otherwise .gitignore files may result in some files being skipped.

As you do so, you might find presubmit checks fail because of non-inclusive language. This is because Rust crate data tends to include names of git branches, and many projects still use non-inclusive terminology there. So you may need to run:

```
infra/update_inclusive_language_presubmit_exempt_dirs.sh > infra/inclusive_language_pres
git add -p infra/inclusive_language_presubmit_exempt_dirs.txt # add whatever changes are
```

46.9 Keeping Crates Up to Date

As the OWNER of any third party Chromium dependency, you are expected to keep it up to date with any security fixes. It is hoped that we will soon automate this for Rust crates, but for now, it's still your responsibility just as it is for any other third party dependency.

46.10 Exercise

Add uwuify to Chromium, turning off the crate's default features. Assume that the crate will be used in shipping Chromium, but won't be used to handle untrustworthy input.

(In the next exercise we'll use uwuify from Chromium, but feel free to skip ahead and do that now if you like. Or, you could create a new rust_executable target which uses uwuify).

Students will need to download lots of transitive dependencies.

The total crates needed are:

- `instant`,
- `lock_api`,
- `parking_lot`,
- `parking_lot_core`,
- `redox_syscall`,
- `scopeguard`,
- `smallvec`, and
- `uwuify`.

If students are downloading even more than that, they likely forgot to turn off the default features.

Thanks to Daniel Liu for this crate!

Chapter 47

Bringing It Together --- Exercise

In this exercise, you're going to add a whole new Chromium feature, bringing together everything you already learned.

The Brief from Product Management

A community of pixies has been discovered living in a remote rainforest. It's important that we get Chromium for Pixies delivered to them as soon as possible.

The requirement is to translate all Chromium's UI strings into Pixie language.

There's not time to wait for proper translations, but fortunately pixie language is very close to English, and it turns out there's a Rust crate which does the translation.

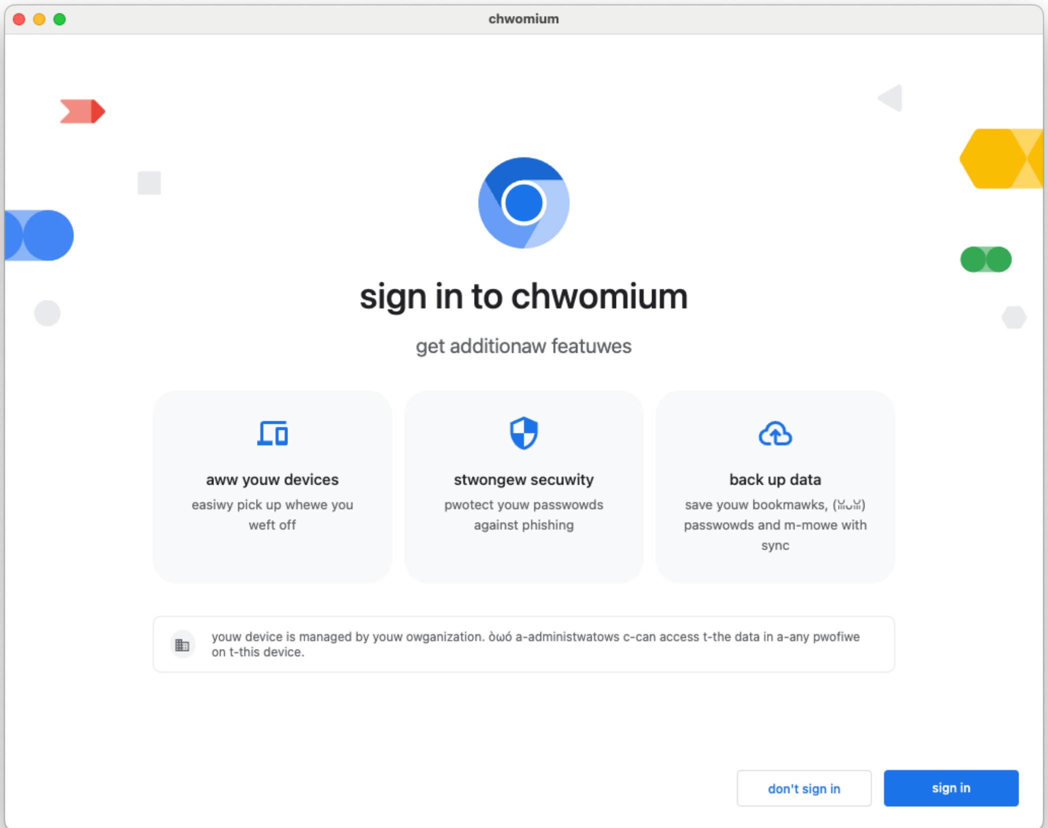
In fact, you already imported that crate in the previous exercise.

(Obviously, real translations of Chrome require incredible care and diligence. Don't ship this!)

Steps

Modify `ResourceBundle::MaybeMangleLocalizedString` so that it uwuifies all strings before display. In this special build of Chromium, it should always do this irrespective of the setting of `mangle_localized_strings_`.

If you've done everything right across all these exercises, congratulations, you should have created Chrome for pixies!



Students will likely need some hints here. Hints include:

- UTF-16 vs UTF-8. Students should be aware that Rust strings are always UTF-8, and will typically decide that it's better to do the conversion on the C++ side using `base::UTF16ToUTF8` and back again.
- If students decide to do the conversion on the Rust side, they'll need to consider `String::from_utf16`, consider error handling, and consider which CXX supported types can transfer many u16s.
- Students may design the C++/Rust boundary in several different ways, e.g. taking and returning strings by value, or taking a mutable reference to a string. If a mutable reference is used, CXX will likely tell the student that they need to use `Pin`. You may need to explain what `Pin` does, and then explain why CXX needs it for mutable references to C++ data: the answer is that C++ data can't be moved around like Rust data, because it may contain self-referential pointers.
- The C++ target containing `ResourceBundle::MaybeMangleLocalizedString` will need to depend on a `rust_static_library` target. The student likely already did this.
- The `rust_static_library` target will need to depend on `//third_party/rust/uwuify/v0_2:lib`.

Chapter 48

Exercise Solutions

Solutions to the Chromium exercises can be found in this series of CLs.

Or, if you'd prefer "standalone" solutions that don't require applying patchsets or integration with core Chromium code, you can find them in the `//chromium/src/codelabs/rust` subdirectory in Chromium.

Part XI

Bare Metal: Morning

Chapter 49

Welcome to Bare Metal Rust

This is a standalone one-day course about bare-metal Rust, aimed at people who are familiar with the basics of Rust (perhaps from completing the Comprehensive Rust course), and ideally also have some experience with bare-metal programming in some other language such as C.

Today we will talk about 'bare-metal' Rust: running Rust code without an OS underneath us. This will be divided into several parts:

- What is `no_std` Rust?
- Writing firmware for microcontrollers.
- Writing bootloader / kernel code for application processors.
- Some useful crates for bare-metal Rust development.

For the microcontroller part of the course we will use the BBC micro:bit v2 as an example. It's a development board based on the Nordic nRF52833 microcontroller with some LEDs and buttons, an I2C-connected accelerometer and compass, and an on-board SWD debugger.

To get started, install some tools we'll need later. On gLinux or Debian:

```
sudo apt install gdb-multiarch libudev-dev picocom pkg-config qemu-system-arm build-esse
rustup update
rustup target add aarch64-unknown-none thumbv7em-none-eabihf
rustup component add llvm-tools-preview
cargo install cargo-binutils
curl --proto '=https' --tlsv1.2 -LsSf https://github.com/probe-rs/probe-rs/releases/late
```

And give users in the `plugdev` group access to the micro:bit programmer:

```
echo 'SUBSYSTEM=="hidraw", ATTRS{idVendor}=="0d28", MODE="0660", GROUP="logindev", TAG+=
  sudo tee /etc/udev/rules.d/50-microbit.rules
sudo udevadm control --reload-rules
```

You should see "NXP ARM mbed" in the output of `lsusb` if the device is available. If you are using a Linux environment on a Chromebook, you will need to share the USB device with Linux, via `chrome://os-settings/crostini/sharedUsbDevices`.

On MacOS:

```
xcode-select --install
brew install gdb picocom qemu
rustup update
```

```
rustup target add aarch64-unknown-none thumbv7em-none-eabihf
rustup component add llvm-tools-preview
cargo install cargo-binutils
curl --proto '=https' --tlsv1.2 -LsSf https://github.com/probe-rs/probe-rs/releases/late
```

Chapter 50

`no_std`

`core`

`alloc`

`std`

- Slices, `&str`, `CStr`
- `NonZeroU8`...
- `Option`, `Result`
- `Display`, `Debug`, `write!`...
- `Iterator`
- `Error`
- `panic!`, `assert_eq!`...
- `NonNull` and all the usual pointer-related functions
- `Future` and `async/await`
- `fence`, `AtomicBool`, `AtomicPtr`, `AtomicU32`...
- `Duration`

- `Box`, `Cow`, `Arc`, `Rc`
- `Vec`, `BinaryHeap`, `BtreeMap`, `LinkedList`, `VecDeque`
- `String`, `CString`, `format!`

- `HashMap`
- `Mutex`, `Condvar`, `Barrier`, `Once`, `RwLock`, `mpsc`
- `File` and the rest of `fs`
- `println!`, `Read`, `Write`, `Stdin`, `Stdout` and the rest of `io`
- `Path`, `OsString`
- `net`
- `Command`, `Child`, `ExitCode`
- `spawn`, `sleep` and the rest of `thread`
- `SystemTime`, `Instant`

- `HashMap` depends on RNG.
- `std` re-exports the contents of both `core` and `alloc`.

50.1 A minimal no_std program

```rust
#![no_main]
#![no_std]

use core::panic::PanicInfo;

#[panic_handler]
fn panic(_panic: &PanicInfo) -> ! {
    loop {}
}
```

- This will compile to an empty binary.
- `std` provides a panic handler; without it we must provide our own.
- It can also be provided by another crate, such as `panic-halt`.
- Depending on the target, you may need to compile with `panic = "abort"` to avoid an error about `eh_personality`.
- Note that there is no `main` or any other entry point; it's up to you to define your own entry point. This will typically involve a linker script and some assembly code to set things up ready for Rust code to run.

50.2 alloc

To use `alloc` you must implement a global (heap) allocator.

```rust
#![no_main]
#![no_std]

extern crate alloc;
extern crate panic_halt as _;

use alloc::string::ToString;
use alloc::vec::Vec;
use buddy_system_allocator::LockedHeap;

#[global_allocator]
static HEAP_ALLOCATOR: LockedHeap<32> = LockedHeap::<32>::new();

const HEAP_SIZE: usize = 65536;
static mut HEAP: [u8; HEAP_SIZE] = [0; HEAP_SIZE];

pub fn entry() {
    // SAFETY: `HEAP` is only used here and `entry` is only called once.
    unsafe {
        // Give the allocator some memory to allocate.
        HEAP_ALLOCATOR.lock().init(&raw mut HEAP as usize, HEAP_SIZE);
    }

    // Now we can do things that require heap allocation.
    let mut v = Vec::new();
    v.push("A string".to_string());
```

```
}
```

- `buddy_system_allocator` is a crate implementing a basic buddy system allocator. Other crates are available, or you can write your own or hook into your existing allocator.
- The const parameter of `LockedHeap` is the max order of the allocator; i.e. in this case it can allocate regions of up to 2**32 bytes.
- If any crate in your dependency tree depends on `alloc` then you must have exactly one global allocator defined in your binary. Usually this is done in the top-level binary crate.
- `extern crate panic_halt as _` is necessary to ensure that the `panic_halt` crate is linked in so we get its panic handler.
- This example will build but not run, as it doesn't have an entry point.

Chapter 51

Microcontrollers

The `cortex_m_rt` crate provides (among other things) a reset handler for Cortex M microcontrollers.

```
#![no_main]
#![no_std]

extern crate panic_halt as _;

mod interrupts;

use cortex_m_rt::entry;

#[entry]
fn main() -> ! {
    loop {}
}
```

Next we'll look at how to access peripherals, with increasing levels of abstraction.

- The `cortex_m_rt::entry` macro requires that the function have type `fn() -> !`, because returning to the reset handler doesn't make sense.
- Run the example with `cargo embed --bin minimal`

51.1 Raw MMIO

Most microcontrollers access peripherals via memory-mapped IO. Let's try turning on an LED on our micro:bit:

```
#![no_main]
#![no_std]

extern crate panic_halt as _;

mod interrupts;

use core::mem::size_of;
```

```rust
use cortex_m_rt::entry;

/// GPIO port 0 peripheral address
const GPIO_P0: usize = 0x5000_0000;

// GPIO peripheral offsets
const PIN_CNF: usize = 0x700;
const OUTSET: usize = 0x508;
const OUTCLR: usize = 0x50c;

// PIN_CNF fields
const DIR_OUTPUT: u32 = 0x1;
const INPUT_DISCONNECT: u32 = 0x1 << 1;
const PULL_DISABLED: u32 = 0x0 << 2;
const DRIVE_S0S1: u32 = 0x0 << 8;
const SENSE_DISABLED: u32 = 0x0 << 16;

#[entry]
fn main() -> ! {
    // Configure GPIO 0 pins 21 and 28 as push-pull outputs.
    let pin_cnf_21 = (GPIO_P0 + PIN_CNF + 21 * size_of::<u32>()) as *mut u32;
    let pin_cnf_28 = (GPIO_P0 + PIN_CNF + 28 * size_of::<u32>()) as *mut u32;
    // SAFETY: The pointers are to valid peripheral control registers, and no
    // aliases exist.
    unsafe {
        pin_cnf_21.write_volatile(
            DIR_OUTPUT
                | INPUT_DISCONNECT
                | PULL_DISABLED
                | DRIVE_S0S1
                | SENSE_DISABLED,
        );
        pin_cnf_28.write_volatile(
            DIR_OUTPUT
                | INPUT_DISCONNECT
                | PULL_DISABLED
                | DRIVE_S0S1
                | SENSE_DISABLED,
        );
    }

    // Set pin 28 low and pin 21 high to turn the LED on.
    let gpio0_outset = (GPIO_P0 + OUTSET) as *mut u32;
    let gpio0_outclr = (GPIO_P0 + OUTCLR) as *mut u32;
    // SAFETY: The pointers are to valid peripheral control registers, and no
    // aliases exist.
    unsafe {
        gpio0_outclr.write_volatile(1 << 28);
        gpio0_outset.write_volatile(1 << 21);
    }
```

```
    loop {}
}
```

- GPIO 0 pin 21 is connected to the first column of the LED matrix, and pin 28 to the first row.

Run the example with:

```
cargo embed --bin mmio
```

51.2 Peripheral Access Crates

svd2rust generates mostly-safe Rust wrappers for memory-mapped peripherals from CMSIS-SVD files.

```
#![no_main]
#![no_std]

extern crate panic_halt as _;

use cortex_m_rt::entry;
use nrf52833_pac::Peripherals;

#[entry]
fn main() -> ! {
    let p = Peripherals::take().unwrap();
    let gpio0 = p.P0;

    // Configure GPIO 0 pins 21 and 28 as push-pull outputs.
    gpio0.pin_cnf[21].write(|w| {
        w.dir().output();
        w.input().disconnect();
        w.pull().disabled();
        w.drive().s0s1();
        w.sense().disabled();
        w
    });
    gpio0.pin_cnf[28].write(|w| {
        w.dir().output();
        w.input().disconnect();
        w.pull().disabled();
        w.drive().s0s1();
        w.sense().disabled();
        w
    });

    // Set pin 28 low and pin 21 high to turn the LED on.
    gpio0.outclr.write(|w| w.pin28().clear());
    gpio0.outset.write(|w| w.pin21().set());

    loop {}
}
```

- SVD (System View Description) files are XML files typically provided by silicon vendors that describe the memory map of the device.
  - They are organized by peripheral, register, field and value, with names, descriptions, addresses and so on.
  - SVD files are frequently buggy and incomplete, so there are various projects that patch the mistakes, add missing details, and publish the generated crates.
- `cortex-m-rt` provides the vector table, among other things.
- If you `cargo install cargo-binutils` then you can run `cargo objdump --bin pac -- -d --no-show-raw-insn` to see the resulting binary.

Run the example with:

```
cargo embed --bin pac
```

51.3 HAL crates

HAL crates for many microcontrollers provide wrappers around various peripherals. These generally implement traits from `embedded-hal`.

```rust
#![no_main]
#![no_std]

extern crate panic_halt as _;

use cortex_m_rt::entry;
use embedded_hal::digital::OutputPin;
use nrf52833_hal::gpio::{Level, p0};
use nrf52833_hal::pac::Peripherals;

#[entry]
fn main() -> ! {
    let p = Peripherals::take().unwrap();

    // Create HAL wrapper for GPIO port 0.
    let gpio0 = p0::Parts::new(p.P0);

    // Configure GPIO 0 pins 21 and 28 as push-pull outputs.
    let mut col1 = gpio0.p0_28.into_push_pull_output(Level::High);
    let mut row1 = gpio0.p0_21.into_push_pull_output(Level::Low);

    // Set pin 28 low and pin 21 high to turn the LED on.
    col1.set_low().unwrap();
    row1.set_high().unwrap();

    loop {}
}
```

- `set_low` and `set_high` are methods on the embedded_hal `OutputPin` trait.
- HAL crates exist for many Cortex-M and RISC-V devices, including various STM32, GD32, nRF, NXP, MSP430, AVR and PIC microcontrollers.

Run the example with:

```
cargo embed --bin hal
```

51.4 Board support crates

Board support crates provide a further level of wrapping for a specific board for convenience.

```
#![no_main]
#![no_std]

extern crate panic_halt as _;

use cortex_m_rt::entry;
use embedded_hal::digital::OutputPin;
use microbit::Board;

#[entry]
fn main() -> ! {
    let mut board = Board::take().unwrap();

    board.display_pins.col1.set_low().unwrap();
    board.display_pins.row1.set_high().unwrap();

    loop {}
}
```

- In this case the board support crate is just providing more useful names, and a bit of initialization.
- The crate may also include drivers for some on-board devices outside of the microcontroller itself.
  - `microbit-v2` includes a simple driver for the LED matrix.

Run the example with:

```
cargo embed --bin board_support
```

51.5 The type state pattern

```
#[entry]
fn main() -> ! {
    let p = Peripherals::take().unwrap();
    let gpio0 = p0::Parts::new(p.P0);

    let pin: P0_01<Disconnected> = gpio0.p0_01;

    // let gpio0_01_again = gpio0.p0_01; // Error, moved.
    let mut pin_input: P0_01<Input<Floating>> = pin.into_floating_input();
    if pin_input.is_high().unwrap() {
        // ...
    }
    let mut pin_output: P0_01<Output<OpenDrain>> = pin_input
        .into_open_drain_output(OpenDrainConfig::Disconnect0Standard1, Level::Low);
```

```rust
    pin_output.set_high().unwrap();
    // pin_input.is_high(); // Error, moved.

    let _pin2: P0_02<Output<OpenDrain>> = gpio0
        .p0_02
        .into_open_drain_output(OpenDrainConfig::Disconnect0Standard1, Level::Low);
    let _pin3: P0_03<Output<PushPull>> =
        gpio0.p0_03.into_push_pull_output(Level::Low);

    loop {}
}
```

- Pins don't implement `Copy` or `Clone`, so only one instance of each can exist. Once a pin is moved out of the port struct, nobody else can take it.
- Changing the configuration of a pin consumes the old pin instance, so you can't use the old instance afterwards.
- The type of a value indicates the state it is in: e.g., in this case, the configuration state of a GPIO pin. This encodes the state machine into the type system and ensures that you don't try to use a pin in a certain way without properly configuring it first. Illegal state transitions are caught at compile time.
- You can call `is_high` on an input pin and `set_high` on an output pin, but not vice-versa.
- Many HAL crates follow this pattern.

51.6 `embedded-hal`

The `embedded-hal` crate provides a number of traits covering common microcontroller peripherals:

- GPIO
- PWM
- Delay timers
- I2C and SPI buses and devices

Similar traits for byte streams (e.g. UARTs), CAN buses and RNGs are broken out into `embedded-io`, `embedded-can` and `rand_core` respectively.

Other crates then implement drivers in terms of these traits, e.g. an accelerometer driver might need an I2C or SPI device instance.

- The traits cover using the peripherals but not initializing or configuring them, as initialization and configuration is highly platform-specific.
- There are implementations for many microcontrollers, as well as other platforms such as Linux on Raspberry Pi.
- `embedded-hal-async` provides async versions of the traits.
- `embedded-hal-nb` provides another approach to non-blocking I/O, based on the `nb` crate.

51.7 `probe-rs` and `cargo-embed`

probe-rs is a handy toolset for embedded debugging, like OpenOCD but better integrated.

- SWD (Serial Wire Debug) and JTAG via CMSIS-DAP, ST-Link and J-Link probes

- GDB stub and Microsoft DAP (Debug Adapter Protocol) server
- Cargo integration

`cargo-embed` is a cargo subcommand to build and flash binaries, log RTT (Real Time Transfers) output and connect GDB. It's configured by an `Embed.toml` file in your project directory.

- CMSIS-DAP is an Arm standard protocol over USB for an in-circuit debugger to access the CoreSight Debug Access Port of various Arm Cortex processors. It's what the on-board debugger on the BBC micro:bit uses.
- ST-Link is a range of in-circuit debuggers from ST Microelectronics, J-Link is a range from SEGGER.
- The Debug Access Port is usually either a 5-pin JTAG interface or 2-pin Serial Wire Debug.
- probe-rs is a library that you can integrate into your own tools if you want to.
- The Microsoft Debug Adapter Protocol lets VSCode and other IDEs debug code running on any supported microcontroller.
- cargo-embed is a binary built using the probe-rs library.
- RTT (Real Time Transfers) is a mechanism to transfer data between the debug host and the target through a number of ring buffers.

51.7.1 Debugging

Embed.toml:

```toml
[default.general]
chip = "nrf52833_xxAA"

[debug.gdb]
enabled = true
```

In one terminal under `src/bare-metal/microcontrollers/examples/`:

```
cargo embed --bin board_support debug
```

In another terminal in the same directory:

On gLinux or Debian:

```
gdb-multiarch target/thumbv7em-none-eabihf/debug/board_support --eval-command="target re
```

On MacOS:

```
arm-none-eabi-gdb target/thumbv7em-none-eabihf/debug/board_support --eval-command="targe
```

In GDB, try running:

```
b src/bin/board_support.rs:29
b src/bin/board_support.rs:30
b src/bin/board_support.rs:32
c
c
c
```

51.8 Other projects

- RTIC
  - ”Real-Time Interrupt-driven Concurrency”.

    - Shared resource management, message passing, task scheduling, timer queue.
- Embassy
    - `async` executors with priorities, timers, networking, USB.
- TockOS
    - Security-focused RTOS with preemptive scheduling and Memory Protection Unit support.
- Hubris
    - Microkernel RTOS from Oxide Computer Company with memory protection, unprivileged drivers, IPC.
- Bindings for FreeRTOS.

Some platforms have `std` implementations, e.g. esp-idf.

- RTIC can be considered either an RTOS or a concurrency framework.
    - It doesn't include any HALs.
    - It uses the Cortex-M NVIC (Nested Virtual Interrupt Controller) for scheduling rather than a proper kernel.
    - Cortex-M only.
- Google uses TockOS on the Haven microcontroller for Titan security keys.
- FreeRTOS is mostly written in C, but there are Rust bindings for writing applications.

Chapter 52

Exercises

We will read the direction from an I2C compass, and log the readings to a serial port.

After looking at the exercises, you can look at the solutions provided.

52.1 Compass

We will read the direction from an I2C compass, and log the readings to a serial port. If you have time, try displaying it on the LEDs somehow too, or use the buttons somehow.

Hints:

- Check the documentation for the `lsm303agr` and `microbit-v2` crates, as well as the micro:bit hardware.
- The LSM303AGR Inertial Measurement Unit is connected to the internal I2C bus.
- TWI is another name for I2C, so the I2C master peripheral is called TWIM.
- The LSM303AGR driver needs something implementing the `embedded_hal::i2c::I2c` trait. The `microbit::hal::Twim` struct implements this.
- You have a `microbit::Board` struct with fields for the various pins and peripherals.
- You can also look at the nRF52833 datasheet if you want, but it shouldn't be necessary for this exercise.

Download the exercise template and look in the `compass` directory for the following files.

src/main.rs:

```
#![no_main]
#![no_std]

extern crate panic_halt as _;

use core::fmt::Write;
use cortex_m_rt::entry;
use microbit::{hal::{Delay, uarte::{Baudrate, Parity, Uarte}}, Board};

#[entry]
fn main() -> ! {
    let mut board = Board::take().unwrap();
```

```rust
    // Configure serial port.
    let mut serial = Uarte::new(
        board.UARTE0,
        board.uart.into(),
        Parity::EXCLUDED,
        Baudrate::BAUD115200,
    );

    // Use the system timer as a delay provider.
    let mut delay = Delay::new(board.SYST);

    // Set up the I2C controller and Inertial Measurement Unit.
    // TODO

    writeln!(serial, "Ready.").unwrap();

    loop {
        // Read compass data and log it to the serial port.
        // TODO
    }
}
```

Cargo.toml (you shouldn't need to change this):

```toml
[workspace]

[package]
name = "compass"
version = "0.1.0"
edition = "2024"
publish = false

[dependencies]
cortex-m-rt = "0.7.5"
embedded-hal = "1.0.0"
lsm303agr = "1.1.0"
microbit-v2 = "0.16.0"
panic-halt = "1.0.0"
```

Embed.toml (you shouldn't need to change this):

```toml
[default.general]
chip = "nrf52833_xxAA"

[debug.gdb]
enabled = true

[debug.reset]
halt_afterwards = true
```

.cargo/config.toml (you shouldn't need to change this):

```toml
[build]
```

```
target = "thumbv7em-none-eabihf" # Cortex-M4F

[target.'cfg(all(target_arch = "arm", target_os = "none"))']
rustflags = ["-C", "link-arg=-Tlink.x"]
```

See the serial output on Linux with:

```
picocom --baud 115200 --imap lfcrlf /dev/ttyACM0
```

Or on Mac OS something like (the device name may be slightly different):

```
picocom --baud 115200 --imap lfcrlf /dev/tty.usbmodem14502
```

Use Ctrl+A Ctrl+Q to quit picocom.

52.2 Bare Metal Rust Morning Exercise

Compass

(back to exercise)

```
#![no_main]
#![no_std]

extern crate panic_halt as _;

use core::fmt::Write;
use cortex_m_rt::entry;
use embedded_hal::digital::InputPin;
use lsm303agr::{
    AccelMode, AccelOutputDataRate, Lsm303agr, MagMode, MagOutputDataRate,
};
use microbit::Board;
use microbit::display::blocking::Display;
use microbit::hal::twim::Twim;
use microbit::hal::uarte::{Baudrate, Parity, Uarte};
use microbit::hal::{Delay, Timer};
use microbit::pac::twim0::frequency::FREQUENCY_A;

const COMPASS_SCALE: i32 = 30000;
const ACCELEROMETER_SCALE: i32 = 700;

#[entry]
fn main() -> ! {
    let mut board = Board::take().unwrap();

    // Configure serial port.
    let mut serial = Uarte::new(
        board.UARTE0,
        board.uart.into(),
        Parity::EXCLUDED,
        Baudrate::BAUD115200,
    );
```

```rust
// Use the system timer as a delay provider.
let mut delay = Delay::new(board.SYST);

// Set up the I2C controller and Inertial Measurement Unit.
writeln!(serial, "Setting up IMU...").unwrap();
let i2c = Twim::new(board.TWIM0, board.i2c_internal.into(), FREQUENCY_A::K100);
let mut imu = Lsm303agr::new_with_i2c(i2c);
imu.init().unwrap();
imu.set_mag_mode_and_odr(
    &mut delay,
    MagMode::HighResolution,
    MagOutputDataRate::Hz50,
)
.unwrap();
imu.set_accel_mode_and_odr(
    &mut delay,
    AccelMode::Normal,
    AccelOutputDataRate::Hz50,
)
.unwrap();
let mut imu = imu.into_mag_continuous().ok().unwrap();

// Set up display and timer.
let mut timer = Timer::new(board.TIMER0);
let mut display = Display::new(board.display_pins);

let mut mode = Mode::Compass;
let mut button_pressed = false;

writeln!(serial, "Ready.").unwrap();

loop {
    // Read compass data and log it to the serial port.
    while !(imu.mag_status().unwrap().xyz_new_data()
        && imu.accel_status().unwrap().xyz_new_data())
    {}
    let compass_reading = imu.magnetic_field().unwrap();
    let accelerometer_reading = imu.acceleration().unwrap();
    writeln!(
        serial,
        "{},{},{}\t{},{},{}",
        compass_reading.x_nt(),
        compass_reading.y_nt(),
        compass_reading.z_nt(),
        accelerometer_reading.x_mg(),
        accelerometer_reading.y_mg(),
        accelerometer_reading.z_mg(),
    )
    .unwrap();
```

```rust
        let mut image = [[0; 5]; 5];
        let (x, y) = match mode {
            Mode::Compass => (
                scale(-compass_reading.x_nt(), -COMPASS_SCALE, COMPASS_SCALE, 0, 4)
                    as usize,
                scale(compass_reading.y_nt(), -COMPASS_SCALE, COMPASS_SCALE, 0, 4)
                    as usize,
            ),
            Mode::Accelerometer => (
                scale(
                    accelerometer_reading.x_mg(),
                    -ACCELEROMETER_SCALE,
                    ACCELEROMETER_SCALE,
                    0,
                    4,
                ) as usize,
                scale(
                    -accelerometer_reading.y_mg(),
                    -ACCELEROMETER_SCALE,
                    ACCELEROMETER_SCALE,
                    0,
                    4,
                ) as usize,
            ),
        };
        image[y][x] = 255;
        display.show(&mut timer, image, 100);

        // If button A is pressed, switch to the next mode and briefly blink all LEDs
        // on.
        if board.buttons.button_a.is_low().unwrap() {
            if !button_pressed {
                mode = mode.next();
                display.show(&mut timer, [[255; 5]; 5], 200);
            }
            button_pressed = true;
        } else {
            button_pressed = false;
        }
    }
}

#[derive(Copy, Clone, Debug, Eq, PartialEq)]
enum Mode {
    Compass,
    Accelerometer,
}

impl Mode {
    fn next(self) -> Self {
        match self {
```

```
            Self::Compass => Self::Accelerometer,
            Self::Accelerometer => Self::Compass,
        }
    }
}

fn scale(value: i32, min_in: i32, max_in: i32, min_out: i32, max_out: i32) -> i32 {
    let range_in = max_in - min_in;
    let range_out = max_out - min_out;
    let scaled = min_out + range_out * (value - min_in) / range_in;
    scaled.clamp(min_out, max_out)
}
```

Part XII

Bare Metal: Afternoon

Chapter 53

Application processors

So far we've talked about microcontrollers, such as the Arm Cortex-M series. These are typically small systems with very limited resources.

Larger systems with more resources are typically called application processors, built around processors such as the ARM Cortex-A or Intel Atom.

For simplicity we'll just work with QEMU's aarch64 'virt' board.

- Broadly speaking, microcontrollers don't have an MMU or multiple levels of privilege (exception levels on Arm CPUs, rings on x86).
- Application processors have more resources, and often run an operating system, instead of directly executing the target application on startup.
- QEMU supports emulating various different machines or board models for each architecture. The 'virt' board doesn't correspond to any particular real hardware, but is designed purely for virtual machines.
- We will still address this board as bare-metal, as if we were writing an operating system.

53.1 Getting Ready to Rust

Before we can start running Rust code, we need to do some initialization.

```
/**
 * This is a generic entry point for an image. It carries out the
 * operations required to prepare the loaded image to be run.
 * Specifically, it
 *
 * - sets up the MMU with an identity map of virtual to physical
 *   addresses, and enables caching
 * - enables floating point
 * - zeroes the bss section using registers x25 and above
 * - prepares the stack, pointing to a section within the image
 * - sets up the exception vector
 * - branches to the Rust `main` function
 *
 * It preserves x0-x3 for the Rust entry point, as these may contain
```

```
 * boot parameters.
 */
.section .init.entry, "ax"
.global entry
entry:
    /*
     * Load and apply the memory management configuration, ready to
     * enable MMU and caches.
     */
    adrp x30, idmap
    msr ttbr0_el1, x30

    mov_i x30, .Lmairval
    msr mair_el1, x30

    mov_i x30, .Ltcrval
    /* Copy the supported PA range into TCR_EL1.IPS. */
    mrs x29, id_aa64mmfr0_el1
    bfi x30, x29, #32, #4

    msr tcr_el1, x30

    mov_i x30, .Lsctlrval

    /*
     * Ensure everything before this point has completed, then
     * invalidate any potentially stale local TLB entries before they
     * start being used.
     */
    isb
    tlbi vmalle1
    ic iallu
    dsb nsh
    isb

    /*
     * Configure sctlr_el1 to enable MMU and cache and don't proceed
     * until this has completed.
     */
    msr sctlr_el1, x30
    isb

    /* Disable trapping floating point access in EL1. */
    mrs x30, cpacr_el1
    orr x30, x30, #(0x3 << 20)
    msr cpacr_el1, x30
    isb

    /* Zero out the bss section. */
    adr_l x29, bss_begin
    adr_l x30, bss_end
```

```
0:  cmp x29, x30
    b.hs 1f
    stp xzr, xzr, [x29], #16
    b 0b

1:  /* Prepare the stack. */
    adr_l x30, boot_stack_end
    mov sp, x30

    /* Set up exception vector. */
    adr x30, vector_table_el1
    msr vbar_el1, x30

    /* Call into Rust code. */
    bl main

    /* Loop forever waiting for interrupts. */
2:  wfi
    b 2b
```

This code is in `src/bare-metal/aps/examples/src/entry.S`. It's not necessary to understand this in detail – the takeaway is that some low-level setup is needed to meet Rust's expectations of the system.

- This is the same as it would be for C: initializing the processor state, zeroing the BSS, and setting up the stack pointer.
  - The BSS (block starting symbol, for historical reasons) is the part of the object file that contains statically allocated variables that are initialized to zero. They are omitted from the image, to avoid wasting space on zeroes. The compiler assumes that the loader will take care of zeroing them.
- The BSS may already be zeroed, depending on how memory is initialized and the image is loaded, but we zero it to be sure.
- We need to enable the MMU and cache before reading or writing any memory. If we don't:
  - Unaligned accesses will fault. We build the Rust code for the `aarch64-unknown-none` target that sets `+strict-align` to prevent the compiler from generating unaligned accesses, so it should be fine in this case, but this is not necessarily the case in general.
  - If it were running in a VM, this can lead to cache coherency issues. The problem is that the VM is accessing memory directly with the cache disabled, while the host has cacheable aliases to the same memory. Even if the host doesn't explicitly access the memory, speculative accesses can lead to cache fills, and then changes from one or the other will get lost when the cache is cleaned or the VM enables the cache. (Cache is keyed by physical address, not VA or IPA.)
- For simplicity, we just use a hardcoded pagetable (see `idmap.S`) that identity maps the first 1 GiB of address space for devices, the next 1 GiB for DRAM, and another 1 GiB higher up for more devices. This matches the memory layout that QEMU uses.
- We also set up the exception vector (`vbar_el1`), which we'll see more about later.
- All examples this afternoon assume we will be running at exception level 1 (EL1). If you need to run at a different exception level, you'll need to modify `entry.S` accordingly.

53.2 Inline assembly

Sometimes we need to use assembly to do things that aren't possible with Rust code. For example, to make an HVC (hypervisor call) to tell the firmware to power off the system:

```
#![no_main]
#![no_std]

use core::arch::asm;
use core::panic::PanicInfo;

mod asm;
mod exceptions;

const PSCI_SYSTEM_OFF: u32 = 0x84000008;

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn main(_x0: u64, _x1: u64, _x2: u64, _x3: u64) {
    // SAFETY: this only uses the declared registers and doesn't do anything
    // with memory.
    unsafe {
        asm!("hvc #0",
            inout("w0") PSCI_SYSTEM_OFF => _,
            inout("w1") 0 => _,
            inout("w2") 0 => _,
            inout("w3") 0 => _,
            inout("w4") 0 => _,
            inout("w5") 0 => _,
            inout("w6") 0 => _,
            inout("w7") 0 => _,
            options(nomem, nostack)
        );
    }

    loop {}
}
```

(If you actually want to do this, use the `smccc` crate which has wrappers for all these functions.)

- PSCI is the Arm Power State Coordination Interface, a standard set of functions to manage system and CPU power states, among other things. It is implemented by EL3 firmware and hypervisors on many systems.
- The `0 => _` syntax means initialize the register to 0 before running the inline assembly code, and ignore its contents afterwards. We need to use `inout` rather than `in` because the call could potentially clobber the contents of the registers.
- This `main` function needs to be `#[unsafe(no_mangle)]` and `extern "C"` because it is called from our entry point in `entry.S`.
  - Just `#[no_mangle]` would be sufficient but RFC3325 uses this notation to draw reviewer attention to attributes that might cause undefined behavior if used incorrectly.
- `_x0`–`_x3` are the values of registers `x0`–`x3`, which are conventionally used by the boot-

loader to pass things like a pointer to the device tree. According to the standard aarch64 calling convention (which is what `extern "C"` specifies to use), registers `x0`–`x7` are used for the first 8 arguments passed to a function, so `entry.S` doesn't need to do anything special except make sure it doesn't change these registers.
- Run the example in QEMU with `make qemu_psci` under `src/bare-metal/aps/examples`.

53.3 Volatile memory access for MMIO

- Use `pointer::read_volatile` and `pointer::write_volatile`.
- Never hold a reference to a location being accessed with these methods. Rust may read from (or write to, for &mut) a reference at any time.
- Use `&raw` to get fields of structs without creating an intermediate reference.

```
const SOME_DEVICE_REGISTER: *mut u64 = 0x800_0000 as _;
// SAFETY: Some device is mapped at this address.
unsafe {
    SOME_DEVICE_REGISTER.write_volatile(0xff);
    SOME_DEVICE_REGISTER.write_volatile(0x80);
    assert_eq!(SOME_DEVICE_REGISTER.read_volatile(), 0xaa);
}
```

- Volatile access: read or write operations may have side-effects, so prevent the compiler or hardware from reordering, duplicating or eliding them.
  - If you write and then read, e.g. via a mutable reference, the compiler may assume that the value read is the same as the value just written, and not bother actually reading memory.
- Some existing crates for volatile access to hardware do hold references, but this is unsound. Whenever a reference exists, the compiler may choose to dereference it.
- Use `&raw` to get struct field pointers from a pointer to the struct.
- For compatibility with old versions of Rust you can use the `addr_of!` macro instead.

53.4 Let's write a UART driver

The QEMU 'virt' machine has a PL011 UART, so let's write a driver for that.

```
const FLAG_REGISTER_OFFSET: usize = 0x18;
const FR_BUSY: u8 = 1 << 3;
const FR_TXFF: u8 = 1 << 5;

/// Minimal driver for a PL011 UART.
#[derive(Debug)]
pub struct Uart {
    base_address: *mut u8,
}

impl Uart {
    /// Constructs a new instance of the UART driver for a PL011 device at the
    /// given base address.
    ///
    /// # Safety
```

```rust
    ///
    /// The given base address must point to the 8 MMIO control registers of a
    /// PL011 device, which must be mapped into the address space of the process
    /// as device memory and not have any other aliases.
    pub unsafe fn new(base_address: *mut u8) -> Self {
        Self { base_address }
    }

    /// Writes a single byte to the UART.
    pub fn write_byte(&self, byte: u8) {
        // Wait until there is room in the TX buffer.
        while self.read_flag_register() & FR_TXFF != 0 {}

        // SAFETY: We know that the base address points to the control
        // registers of a PL011 device which is appropriately mapped.
        unsafe {
            // Write to the TX buffer.
            self.base_address.write_volatile(byte);
        }

        // Wait until the UART is no longer busy.
        while self.read_flag_register() & FR_BUSY != 0 {}
    }

    fn read_flag_register(&self) -> u8 {
        // SAFETY: We know that the base address points to the control
        // registers of a PL011 device which is appropriately mapped.
        unsafe { self.base_address.add(FLAG_REGISTER_OFFSET).read_volatile() }
    }
}
```

- Note that `Uart::new` is unsafe while the other methods are safe. This is because as long as the caller of `Uart::new` guarantees that its safety requirements are met (i.e. that there is only ever one instance of the driver for a given UART, and nothing else aliasing its address space), then it is always safe to call `write_byte` later because we can assume the necessary preconditions.
- We could have done it the other way around (making `new` safe but `write_byte` unsafe), but that would be much less convenient to use as every place that calls `write_byte` would need to reason about the safety
- This is a common pattern for writing safe wrappers of unsafe code: moving the burden of proof for soundness from a large number of places to a smaller number of places.

53.4.1 More traits

We derived the Debug trait. It would be useful to implement a few more traits too.

```rust
use core::fmt::{self, Write};

impl Write for Uart {
    fn write_str(&mut self, s: &str) -> fmt::Result {
        for c in s.as_bytes() {
            self.write_byte(*c);
```

```
        }
        Ok(())
    }
}

// SAFETY: `Uart` just contains a pointer to device memory, which can be
// accessed from any context.
unsafe impl Send for Uart {}
```

- Implementing `Write` lets us use the `write!` and `writeln!` macros with our `Uart` type.
- Send is an auto-trait, but not implemented automatically because it is not implemented for pointers.

53.4.2 Using it

Let's write a small program using our driver to write to the serial console.

```
#![no_main]
#![no_std]

mod asm;
mod exceptions;
mod pl011_minimal;

use crate::pl011_minimal::Uart;
use core::fmt::Write;
use core::panic::PanicInfo;
use log::error;
use smccc::Hvc;
use smccc::psci::system_off;

/// Base address of the primary PL011 UART.
const PL011_BASE_ADDRESS: *mut u8 = 0x900_0000 as _;

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn main(x0: u64, x1: u64, x2: u64, x3: u64) {
    // SAFETY: `PL011_BASE_ADDRESS` is the base address of a PL011 device, and
    // nothing else accesses that address range.
    let mut uart = unsafe { Uart::new(PL011_BASE_ADDRESS) };

    writeln!(uart, "main({x0:#x}, {x1:#x}, {x2:#x}, {x3:#x})").unwrap();

    system_off::<Hvc>().unwrap();
}
```

- As in the inline assembly example, this `main` function is called from our entry point code in `entry.S`. See the speaker notes there for details.
- Run the example in QEMU with `make qemu_minimal` under `src/bare-metal/aps/examples`.

53.5 A better UART driver

The PL011 actually has more registers, and adding offsets to construct pointers to access them is error-prone and hard to read. Additionally, some of them are bit fields, which would be nice to access in a structured way.

Offset	Register name	Width
0x00	DR	12
0x04	RSR	4
0x18	FR	9
0x20	ILPR	8
0x24	IBRD	16
0x28	FBRD	6
0x2c	LCR_H	8
0x30	CR	16
0x34	IFLS	6
0x38	IMSC	11
0x3c	RIS	11
0x40	MIS	11
0x44	ICR	11
0x48	DMACR	3

- There are also some ID registers that have been omitted for brevity.

53.5.1 Bitflags

The `bitflags` crate is useful for working with bitflags.

```
use bitflags::bitflags;

bitflags! {
    /// Flags from the UART flag register.
    #[repr(transparent)]
    #[derive(Copy, Clone, Debug, Eq, PartialEq)]
    struct Flags: u16 {
        /// Clear to send.
        const CTS = 1 << 0;
        /// Data set ready.
        const DSR = 1 << 1;
        /// Data carrier detect.
        const DCD = 1 << 2;
        /// UART busy transmitting data.
        const BUSY = 1 << 3;
        /// Receive FIFO is empty.
        const RXFE = 1 << 4;
        /// Transmit FIFO is full.
        const TXFF = 1 << 5;
        /// Receive FIFO is full.
        const RXFF = 1 << 6;
        /// Transmit FIFO is empty.
```

```rust
        const TXFE = 1 << 7;
        /// Ring indicator.
        const RI = 1 << 8;
    }
}
```

- The `bitflags!` macro creates a newtype something like `struct Flags(u16)`, along with a bunch of method implementations to get and set flags.

53.5.2 Multiple registers

We can use a struct to represent the memory layout of the UART's registers.

```rust
#[repr(C, align(4))]
pub struct Registers {
    dr: u16,
    _reserved0: [u8; 2],
    rsr: ReceiveStatus,
    _reserved1: [u8; 19],
    fr: Flags,
    _reserved2: [u8; 6],
    ilpr: u8,
    _reserved3: [u8; 3],
    ibrd: u16,
    _reserved4: [u8; 2],
    fbrd: u8,
    _reserved5: [u8; 3],
    lcr_h: u8,
    _reserved6: [u8; 3],
    cr: u16,
    _reserved7: [u8; 3],
    ifls: u8,
    _reserved8: [u8; 3],
    imsc: u16,
    _reserved9: [u8; 2],
    ris: u16,
    _reserved10: [u8; 2],
    mis: u16,
    _reserved11: [u8; 2],
    icr: u16,
    _reserved12: [u8; 2],
    dmacr: u8,
    _reserved13: [u8; 3],
}
```

- `#[repr(C)]` tells the compiler to lay the struct fields out in order, following the same rules as C. This is necessary for our struct to have a predictable layout, as default Rust representation allows the compiler to (among other things) reorder fields however it sees fit.

53.5.3 Driver

Now let's use the new `Registers` struct in our driver.

```
/// Driver for a PL011 UART.
#[derive(Debug)]
pub struct Uart {
    registers: *mut Registers,
}

impl Uart {
    /// Constructs a new instance of the UART driver for a PL011 device with the
    /// given set of registers.
    ///
    /// # Safety
    ///
    /// The given pointer must point to the 8 MMIO control registers of a PL011
    /// device, which must be mapped into the address space of the process as
    /// device memory and not have any other aliases.
    pub unsafe fn new(registers: *mut Registers) -> Self {
        Self { registers }
    }

    /// Writes a single byte to the UART.
    pub fn write_byte(&mut self, byte: u8) {
        // Wait until there is room in the TX buffer.
        while self.read_flag_register().contains(Flags::TXFF) {}

        // SAFETY: We know that self.registers points to the control registers
        // of a PL011 device which is appropriately mapped.
        unsafe {
            // Write to the TX buffer.
            (&raw mut (*self.registers).dr).write_volatile(byte.into());
        }

        // Wait until the UART is no longer busy.
        while self.read_flag_register().contains(Flags::BUSY) {}
    }

    /// Reads and returns a pending byte, or `None` if nothing has been
    /// received.
    pub fn read_byte(&mut self) -> Option<u8> {
        if self.read_flag_register().contains(Flags::RXFE) {
            None
        } else {
            // SAFETY: We know that self.registers points to the control
            // registers of a PL011 device which is appropriately mapped.
            let data = unsafe { (&raw const (*self.registers).dr).read_volatile() };
            // TODO: Check for error conditions in bits 8-11.
            Some(data as u8)
        }
    }
```

```
    fn read_flag_register(&self) -> Flags {
        // SAFETY: We know that self.registers points to the control registers
        // of a PL011 device which is appropriately mapped.
        unsafe { (&raw const (*self.registers).fr).read_volatile() }
    }
}
```

- Note the use of `&raw const` / `&raw mut` to get pointers to individual fields without creating an intermediate reference, which would be unsound.
- The example isn't included in the slides because it is very similar to the `safe-mmio` example which comes next. You can run it in QEMU with `make qemu` under `src/bare-metal/aps/examples` if you need to.

53.6 safe-mmio

The `safe-mmio` crate provides types to wrap registers that can be read or written safely.

Can't read	Read has no side-effects	Read has side-effects	
Can't write		`ReadPure`	`ReadOnly`
Can write	`WriteOnly`	`ReadPureWrite`	`ReadWrite`

```
use safe_mmio::fields::{ReadPure, ReadPureWrite, ReadWrite, WriteOnly};

#[repr(C, align(4))]
pub struct Registers {
    dr: ReadWrite<u16>,
    _reserved0: [u8; 2],
    rsr: ReadPure<ReceiveStatus>,
    _reserved1: [u8; 19],
    fr: ReadPure<Flags>,
    _reserved2: [u8; 6],
    ilpr: ReadPureWrite<u8>,
    _reserved3: [u8; 3],
    ibrd: ReadPureWrite<u16>,
    _reserved4: [u8; 2],
    fbrd: ReadPureWrite<u8>,
    _reserved5: [u8; 3],
    lcr_h: ReadPureWrite<u8>,
    _reserved6: [u8; 3],
    cr: ReadPureWrite<u16>,
    _reserved7: [u8; 3],
    ifls: ReadPureWrite<u8>,
    _reserved8: [u8; 3],
    imsc: ReadPureWrite<u16>,
    _reserved9: [u8; 2],
    ris: ReadPure<u16>,
    _reserved10: [u8; 2],
```

```
    mis: ReadPure<u16>,
    _reserved11: [u8; 2],
    icr: WriteOnly<u16>,
    _reserved12: [u8; 2],
    dmacr: ReadPureWrite<u8>,
    _reserved13: [u8; 3],
}
```

- Reading `dr` has a side effect: it pops a byte from the receive FIFO.
- Reading `rsr` (and other registers) has no side-effects. It is a 'pure' read.

- There are a number of different crates providing safe abstractions around MMIO operations; we recommend the `safe-mmio` crate.
- The difference between `ReadPure` or `ReadOnly` (and likewise between `ReadPureWrite` and `ReadWrite`) is whether reading a register can have side-effects that change the state of the device, e.g., reading the data register pops a byte from the receive FIFO. `ReadPure` means that reads have no side-effects, they are purely reading data.

53.6.1 Driver

Now let's use the new `Registers` struct in our driver.

```
use safe_mmio::{UniqueMmioPointer, field, field_shared};

/// Driver for a PL011 UART.
#[derive(Debug)]
pub struct Uart<'a> {
    registers: UniqueMmioPointer<'a, Registers>,
}

impl<'a> Uart<'a> {
    /// Constructs a new instance of the UART driver for a PL011 device with the
    /// given set of registers.
    pub fn new(registers: UniqueMmioPointer<'a, Registers>) -> Self {
        Self { registers }
    }

    /// Writes a single byte to the UART.
    pub fn write_byte(&mut self, byte: u8) {
        // Wait until there is room in the TX buffer.
        while self.read_flag_register().contains(Flags::TXFF) {}

        // Write to the TX buffer.
        field!(self.registers, dr).write(byte.into());

        // Wait until the UART is no longer busy.
        while self.read_flag_register().contains(Flags::BUSY) {}
    }

    /// Reads and returns a pending byte, or `None` if nothing has been
    /// received.
    pub fn read_byte(&mut self) -> Option<u8> {
```

```
        if self.read_flag_register().contains(Flags::RXFE) {
            None
        } else {
            let data = field!(self.registers, dr).read();
            // TODO: Check for error conditions in bits 8-11.
            Some(data as u8)
        }
    }

    fn read_flag_register(&self) -> Flags {
        field_shared!(self.registers, fr).read()
    }
}
```

- The driver no longer needs any unsafe code!
- `UniqueMmioPointer` is a wrapper around a raw pointer to an MMIO device or register. The caller of `UniqueMmioPointer::new` promises that it is valid and unique for the given lifetime, so it can provide safe methods to read and write fields.
- Note that `Uart::new` is now safe; `UniqueMmioPointer::new` is unsafe instead.
- These MMIO accesses are generally a wrapper around `read_volatile` and `write_volatile`, though on aarch64 they are instead implemented in assembly to work around a bug where the compiler can emit instructions that prevent MMIO virtualization.
- The `field!` and `field_shared!` macros internally use `&raw mut` and `&raw const` to get pointers to individual fields without creating an intermediate reference, which would be unsound.
- `field!` needs a mutable reference to a `UniqueMmioPointer`, and returns a `UniqueMmioPointer` that allows reads with side effects and writes.
- `field_shared!` works with a shared reference to either a `UniqueMmioPointer` or a `SharedMmioPointer`. It returns a `SharedMmioPointer` that only allows pure reads.

53.6.2 Using It

Let's write a small program using our driver to write to the serial console, and echo incoming bytes.

```
#![no_main]
#![no_std]

mod asm;
mod exceptions;
mod pl011;

use crate::pl011::Uart;
use core::fmt::Write;
use core::panic::PanicInfo;
use core::ptr::NonNull;
use log::error;
use safe_mmio::UniqueMmioPointer;
use smccc::Hvc;
use smccc::psci::system_off;
```

```rust
/// Base address of the primary PL011 UART.
const PL011_BASE_ADDRESS: NonNull<pl011::Registers> =
    NonNull::new(0x900_0000 as _).unwrap();

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn main(x0: u64, x1: u64, x2: u64, x3: u64) {
    // SAFETY: `PL011_BASE_ADDRESS` is the base address of a PL011 device, and
    // nothing else accesses that address range.
    let mut uart = Uart::new(unsafe { UniqueMmioPointer::new(PL011_BASE_ADDRESS) });

    writeln!(uart, "main({x0:#x}, {x1:#x}, {x2:#x}, {x3:#x})").unwrap();

    loop {
        if let Some(byte) = uart.read_byte() {
            uart.write_byte(byte);
            match byte {
                b'\r' => uart.write_byte(b'\n'),
                b'q' => break,
                _ => continue,
            }
        }
    }

    writeln!(uart, "\n\nBye!").unwrap();
    system_off::<Hvc>().unwrap();
}
```

- Run the example in QEMU with `make qemu_safemmio` under `src/bare-metal/aps/examples`.

53.7 Logging

It would be nice to be able to use the logging macros from the log crate. We can do this by implementing the Log trait.

```rust
use crate::pl011::Uart;
use core::fmt::Write;
use log::{LevelFilter, Log, Metadata, Record, SetLoggerError};
use spin::mutex::SpinMutex;

static LOGGER: Logger = Logger { uart: SpinMutex::new(None) };

struct Logger {
    uart: SpinMutex<Option<Uart<'static>>>,
}

impl Log for Logger {
    fn enabled(&self, _metadata: &Metadata) -> bool {
        true
    }
```

```rust
    fn log(&self, record: &Record) {
        writeln!(
            self.uart.lock().as_mut().unwrap(),
            "[{}] {}",
            record.level(),
            record.args()
        )
        .unwrap();
    }

    fn flush(&self) {}
}

/// Initialises UART logger.
pub fn init(
    uart: Uart<'static>,
    max_level: LevelFilter,
) -> Result<(), SetLoggerError> {
    LOGGER.uart.lock().replace(uart);

    log::set_logger(&LOGGER)?;
    log::set_max_level(max_level);
    Ok(())
}
```

- The first unwrap in log will succeed because we initialize LOGGER before calling set_logger. The second will succeed because Uart::write_str always returns Ok.

53.7.1 Using it

We need to initialise the logger before we use it.

```rust
#![no_main]
#![no_std]

mod asm;
mod exceptions;
mod logger;
mod pl011;

use crate::pl011::Uart;
use core::panic::PanicInfo;
use core::ptr::NonNull;
use log::{LevelFilter, error, info};
use safe_mmio::UniqueMmioPointer;
use smccc::Hvc;
use smccc::psci::system_off;

/// Base address of the primary PL011 UART.
const PL011_BASE_ADDRESS: NonNull<pl011::Registers> =
    NonNull::new(0x900_0000 as _).unwrap();
```

```rust
// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn main(x0: u64, x1: u64, x2: u64, x3: u64) {
    // SAFETY: `PL011_BASE_ADDRESS` is the base address of a PL011 device, and
    // nothing else accesses that address range.
    let uart = unsafe { Uart::new(UniqueMmioPointer::new(PL011_BASE_ADDRESS)) };
    logger::init(uart, LevelFilter::Trace).unwrap();

    info!("main({x0:#x}, {x1:#x}, {x2:#x}, {x3:#x})");

    assert_eq!(x1, 42);

    system_off::<Hvc>().unwrap();
}

#[panic_handler]
fn panic(info: &PanicInfo) -> ! {
    error!("{info}");
    system_off::<Hvc>().unwrap();
    loop {}
}
```

- Note that our panic handler can now log details of panics.
- Run the example in QEMU with `make qemu_logger` under `src/bare-metal/aps/examples`.

53.8 Exceptions

AArch64 defines an exception vector table with 16 entries, for 4 types of exceptions (synchronous, IRQ, FIQ, SError) from 4 states (current EL with SP0, current EL with SPx, lower EL using AArch64, lower EL using AArch32). We implement this in assembly to save volatile registers to the stack before calling into Rust code:

```rust
use log::error;
use smccc::Hvc;
use smccc::psci::system_off;

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn sync_current(_elr: u64, _spsr: u64) {
    error!("sync_current");
    system_off::<Hvc>().unwrap();
}

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn irq_current(_elr: u64, _spsr: u64) {
    error!("irq_current");
    system_off::<Hvc>().unwrap();
}

// SAFETY: There is no other global function of this name.
```

```rust
#[unsafe(no_mangle)]
extern "C" fn fiq_current(_elr: u64, _spsr: u64) {
    error!("fiq_current");
    system_off::<Hvc>().unwrap();
}

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn serror_current(_elr: u64, _spsr: u64) {
    error!("serror_current");
    system_off::<Hvc>().unwrap();
}

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn sync_lower(_elr: u64, _spsr: u64) {
    error!("sync_lower");
    system_off::<Hvc>().unwrap();
}

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn irq_lower(_elr: u64, _spsr: u64) {
    error!("irq_lower");
    system_off::<Hvc>().unwrap();
}

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn fiq_lower(_elr: u64, _spsr: u64) {
    error!("fiq_lower");
    system_off::<Hvc>().unwrap();
}

// SAFETY: There is no other global function of this name.
#[unsafe(no_mangle)]
extern "C" fn serror_lower(_elr: u64, _spsr: u64) {
    error!("serror_lower");
    system_off::<Hvc>().unwrap();
}
```

- EL is exception level; all our examples this afternoon run in EL1.
- For simplicity we aren't distinguishing between SP0 and SPx for the current EL exceptions, or between AArch32 and AArch64 for the lower EL exceptions.
- For this example we just log the exception and power down, as we don't expect any of them to actually happen.
- We can think of exception handlers and our main execution context more or less like different threads. Send and Sync will control what we can share between them, just like with threads. For example, if we want to share some value between exception handlers and the rest of the program, and it's `Send` but not `Sync`, then we'll need to wrap it in something like a `Mutex` and put it in a static.

The assembly code for the exception vector:

```
/**
 * Saves the volatile registers onto the stack. This currently takes
 * 14 instructions, so it can be used in exception handlers with 18
 * instructions left.
 *
 * On return, x0 and x1 are initialised to elr_el2 and spsr_el2
 * respectively, which can be used as the first and second arguments
 * of a subsequent call.
 */
.macro save_volatile_to_stack
    /* Reserve stack space and save registers x0-x18, x29 & x30. */
    stp x0, x1, [sp, #-(8 * 24)]!
    stp x2, x3, [sp, #8 * 2]
    stp x4, x5, [sp, #8 * 4]
    stp x6, x7, [sp, #8 * 6]
    stp x8, x9, [sp, #8 * 8]
    stp x10, x11, [sp, #8 * 10]
    stp x12, x13, [sp, #8 * 12]
    stp x14, x15, [sp, #8 * 14]
    stp x16, x17, [sp, #8 * 16]
    str x18, [sp, #8 * 18]
    stp x29, x30, [sp, #8 * 20]

    /*
     * Save elr_el1 & spsr_el1. This such that we can take nested
     * exception and still be able to unwind.
     */
    mrs x0, elr_el1
    mrs x1, spsr_el1
    stp x0, x1, [sp, #8 * 22]
.endm

/**
 * Restores the volatile registers from the stack. This currently
 * takes 14 instructions, so it can be used in exception handlers
 * while still leaving 18 instructions left; if paired with
 * save_volatile_to_stack, there are 4 instructions to spare.
 */
.macro restore_volatile_from_stack
    /* Restore registers x2-x18, x29 & x30. */
    ldp x2, x3, [sp, #8 * 2]
    ldp x4, x5, [sp, #8 * 4]
    ldp x6, x7, [sp, #8 * 6]
    ldp x8, x9, [sp, #8 * 8]
    ldp x10, x11, [sp, #8 * 10]
    ldp x12, x13, [sp, #8 * 12]
    ldp x14, x15, [sp, #8 * 14]
    ldp x16, x17, [sp, #8 * 16]
    ldr x18, [sp, #8 * 18]
```

```
    ldp x29, x30, [sp, #8 * 20]

    /*
     * Restore registers elr_el1 & spsr_el1, using x0 & x1 as scratch.
     */
    ldp x0, x1, [sp, #8 * 22]
    msr elr_el1, x0
    msr spsr_el1, x1

    /* Restore x0 & x1, and release stack space. */
    ldp x0, x1, [sp], #8 * 24
.endm

/**
 * This is a generic handler for exceptions taken at the current EL. It saves
 * volatile registers to the stack, calls the Rust handler, restores volatile
 * registers, then returns.
 *
 * This also works for exceptions taken from lower ELs, if we don't care about
 * non-volatile registers.
 *
 * Saving state and jumping to the Rust handler takes 15 instructions, and
 * restoring and returning also takes 15 instructions, so we can fit the whole
 * handler in 30 instructions, under the limit of 32.
 */
.macro current_exception handler:req
    save_volatile_to_stack
    bl \handler
    restore_volatile_from_stack
    eret
.endm

.section .text.vector_table_el1, "ax"
.global vector_table_el1
.balign 0x800
vector_table_el1:
sync_cur_sp0:
    current_exception sync_current

.balign 0x80
irq_cur_sp0:
    current_exception irq_current

.balign 0x80
fiq_cur_sp0:
    current_exception fiq_current

.balign 0x80
serr_cur_sp0:
    current_exception serror_current
```

```
.balign 0x80
sync_cur_spx:
    current_exception sync_current

.balign 0x80
irq_cur_spx:
    current_exception irq_current

.balign 0x80
fiq_cur_spx:
    current_exception fiq_current

.balign 0x80
serr_cur_spx:
    current_exception serror_current

.balign 0x80
sync_lower_64:
    current_exception sync_lower

.balign 0x80
irq_lower_64:
    current_exception irq_lower

.balign 0x80
fiq_lower_64:
    current_exception fiq_lower

.balign 0x80
serr_lower_64:
    current_exception serror_lower

.balign 0x80
sync_lower_32:
    current_exception sync_lower

.balign 0x80
irq_lower_32:
    current_exception irq_lower

.balign 0x80
fiq_lower_32:
    current_exception fiq_lower

.balign 0x80
serr_lower_32:
    current_exception serror_lower
```

53.9 aarch64-rt

The `aarch64-rt` crate provides the assembly entry point and exception vector that we implemented before. We just need to mark our main function with the `entry!` macro.

It also provides the `initial_pagetable!` macro to let us define an initial static pagetable in Rust, rather than in assembly code like we did before.

We can also use the UART driver from the `arm-pl011-uart` crate rather than writing our own.

```
#![no_main]
#![no_std]

mod exceptions_rt;

use aarch64_paging::descriptor::Attributes;
use aarch64_rt::{InitialPagetable, entry, initial_pagetable};
use arm_pl011_uart::{PL011Registers, Uart, UniqueMmioPointer};
use core::fmt::Write;
use core::panic::PanicInfo;
use core::ptr::NonNull;
use smccc::Hvc;
use smccc::psci::system_off;

/// Base address of the primary PL011 UART.
const PL011_BASE_ADDRESS: NonNull<PL011Registers> =
    NonNull::new(0x900_0000 as _).unwrap();

/// Attributes to use for device memory in the initial identity map.
const DEVICE_ATTRIBUTES: Attributes = Attributes::VALID
    .union(Attributes::ATTRIBUTE_INDEX_0)
    .union(Attributes::ACCESSED)
    .union(Attributes::UXN);

/// Attributes to use for normal memory in the initial identity map.
const MEMORY_ATTRIBUTES: Attributes = Attributes::VALID
    .union(Attributes::ATTRIBUTE_INDEX_1)
    .union(Attributes::INNER_SHAREABLE)
    .union(Attributes::ACCESSED)
    .union(Attributes::NON_GLOBAL);

initial_pagetable!({
    let mut idmap = [0; 512];
    // 1 GiB of device memory.
    idmap[0] = DEVICE_ATTRIBUTES.bits();
    // 1 GiB of normal memory.
    idmap[1] = MEMORY_ATTRIBUTES.bits() | 0x40000000;
    // Another 1 GiB of device memory starting at 256 GiB.
    idmap[256] = DEVICE_ATTRIBUTES.bits() | 0x4000000000;
    InitialPagetable(idmap)
});
```

```rust
entry!(main);
fn main(x0: u64, x1: u64, x2: u64, x3: u64) -> ! {
    // SAFETY: `PL011_BASE_ADDRESS` is the base address of a PL011 device, and
    // nothing else accesses that address range.
    let mut uart = unsafe { Uart::new(UniqueMmioPointer::new(PL011_BASE_ADDRESS)) };

    writeln!(uart, "main({x0:#x}, {x1:#x}, {x2:#x}, {x3:#x})").unwrap();

    system_off::<Hvc>().unwrap();
    panic!("system_off returned");
}

#[panic_handler]
fn panic(_info: &PanicInfo) -> ! {
    system_off::<Hvc>().unwrap();
    loop {}
}
```

- Run the example in QEMU with `make qemu_rt` under `src/bare-metal/aps/examples`.

53.9.1 Exceptions

`aarch64-rt` provides a trait to define exception handlers, and a macro to generate the assembly code for the exception vector to call them.

The trait has default implementations for each method which simply panic, so we can omit methods for exceptions we don't expect to happen.

```rust
use aarch64_rt::{ExceptionHandlers, RegisterStateRef, exception_handlers};
use log::error;
use smccc::Hvc;
use smccc::psci::system_off;

struct Handlers;

impl ExceptionHandlers for Handlers {
    extern "C" fn sync_current(_state: RegisterStateRef) {
        error!("sync_current");
        system_off::<Hvc>().unwrap();
    }

    extern "C" fn irq_current(_state: RegisterStateRef) {
        error!("irq_current");
        system_off::<Hvc>().unwrap();
    }

    extern "C" fn fiq_current(_state: RegisterStateRef) {
        error!("fiq_current");
        system_off::<Hvc>().unwrap();
    }
```

```rust
    extern "C" fn serror_current(_state: RegisterStateRef) {
        error!("serror_current");
        system_off::<Hvc>().unwrap();
    }
}

exception_handlers!(Handlers);
```

- The `exception_handlers` macro generates a `global_asm!` block with the exception vector to call into the Rust code, similar to the `exceptions.S` we had before.
- `RegisterStateRef` wraps a reference to the stack frame where the register values were saved by the assembly code when the exception happed. This can be used for example to extract the parameters for an SMC or HVC call from a lower EL, and update the values to be restored when the exception handler returns.

53.10 Other projects

- oreboot
  - ”coreboot without the C”.
  - Supports x86, aarch64 and RISC-V.
  - Relies on LinuxBoot rather than having many drivers itself.
- Rust RaspberryPi OS tutorial
  - Initialization, UART driver, simple bootloader, JTAG, exception levels, exception handling, page tables.
  - Some caveats around cache maintenance and initialization in Rust, not necessarily a good example to copy for production code.
- `cargo-call-stack`
  - Static analysis to determine maximum stack usage.

- The RaspberryPi OS tutorial runs Rust code before the MMU and caches are enabled. This will read and write memory (e.g. the stack). However, this has the problems mentioned at the beginning of this session regarding unaligned access and cache coherency.

Chapter 54

Useful crates

We'll look at a few crates that solve some common problems in bare-metal programming.

54.1 zerocopy

The zerocopy crate (from Fuchsia) provides traits and macros for safely converting between byte sequences and other types.

```
use zerocopy::{Immutable, IntoBytes};

#[repr(u32)]
#[derive(Debug, Default, Immutable, IntoBytes)]
enum RequestType {
    #[default]
    In = 0,
    Out = 1,
    Flush = 4,
}

#[repr(C)]
#[derive(Debug, Default, Immutable, IntoBytes)]
struct VirtioBlockRequest {
    request_type: RequestType,
    reserved: u32,
    sector: u64,
}

fn main() {
    let request = VirtioBlockRequest {
        request_type: RequestType::Flush,
        sector: 42,
        ..Default::default()
    };

    assert_eq!(
```

```
        request.as_bytes(),
        &[4, 0, 0, 0, 0, 0, 0, 0, 42, 0, 0, 0, 0, 0, 0, 0]
    );
}
```

This is not suitable for MMIO (as it doesn't use volatile reads and writes), but can be useful for working with structures shared with hardware e.g. by DMA, or sent over some external interface.

- `FromBytes` can be implemented for types for which any byte pattern is valid, and so can safely be converted from an untrusted sequence of bytes.
- Attempting to derive `FromBytes` for these types would fail, because `RequestType` doesn't use all possible u32 values as discriminants, so not all byte patterns are valid.
- `zerocopy::byteorder` has types for byte-order aware numeric primitives.
- Run the example with `cargo run` under `src/bare-metal/useful-crates/zerocopy-example/`. (It won't run in the Playground because of the crate dependency.)

54.2 aarch64-paging

The `aarch64-paging` crate lets you create page tables according to the AArch64 Virtual Memory System Architecture.

```
use aarch64_paging::{
    idmap::IdMap,
    paging::{Attributes, MemoryRegion},
};

const ASID: usize = 1;
const ROOT_LEVEL: usize = 1;

// Create a new page table with identity mapping.
let mut idmap = IdMap::new(ASID, ROOT_LEVEL);
// Map a 2 MiB region of memory as read-only.
idmap.map_range(
    &MemoryRegion::new(0x80200000, 0x80400000),
    Attributes::NORMAL | Attributes::NON_GLOBAL | Attributes::READ_ONLY,
).unwrap();
// Set `TTBR0_EL1` to activate the page table.
idmap.activate();
```

- This is used in Android for the Protected VM Firmware.
- There's no easy way to run this example by itself, as it needs to run on real hardware or under QEMU.

54.3 buddy_system_allocator

`buddy_system_allocator` is a crate that implements a basic buddy system allocator. It can be used both to implement `GlobalAlloc` (using `LockedHeap`) so you can use the standard `alloc` crate (as we saw before), or for allocating other address space (using `FrameAllocator`) . For example, we might want to allocate MMIO space for PCI BARs:

```rust
use buddy_system_allocator::FrameAllocator;
use core::alloc::Layout;

fn main() {
    let mut allocator = FrameAllocator::<32>::new();
    allocator.add_frame(0x200_0000, 0x400_0000);

    let layout = Layout::from_size_align(0x100, 0x100).unwrap();
    let bar = allocator
        .alloc_aligned(layout)
        .expect("Failed to allocate 0x100 byte MMIO region");
    println!("Allocated 0x100 byte MMIO region at {:#x}", bar);
}
```

- PCI BARs always have alignment equal to their size.
- Run the example with `cargo run` under `src/bare-metal/useful-crates/allocator-example/`. (It won't run in the Playground because of the crate dependency.)

54.4 tinyvec

Sometimes you want something that can be resized like a `Vec`, but without heap allocation. `tinyvec` provides this: a vector backed by an array or slice, which could be statically allocated or on the stack, that keeps track of how many elements are used and panics if you try to use more than are allocated.

```rust
use tinyvec::{ArrayVec, array_vec};

fn main() {
    let mut numbers: ArrayVec<[u32; 5]> = array_vec!(42, 66);
    println!("{numbers:?}");
    numbers.push(7);
    println!("{numbers:?}");
    numbers.remove(1);
    println!("{numbers:?}");
}
```

- `tinyvec` requires that the element type implement `Default` for initialization.
- The Rust Playground includes `tinyvec`, so this example will run fine inline.

54.5 spin

`std::sync::Mutex` and the other synchronisation primitives from `std::sync` are not available in `core` or `alloc`. How can we manage synchronisation or interior mutability, such as for sharing state between different CPUs?

The `spin` crate provides spinlock-based equivalents of many of these primitives.

```rust
use spin::mutex::SpinMutex;

static COUNTER: SpinMutex<u32> = SpinMutex::new(0);
```

```rust
fn main() {
    dbg!(COUNTER.lock());
    *COUNTER.lock() += 2;
    dbg!(COUNTER.lock());
}
```

- Be careful to avoid deadlock if you take locks in interrupt handlers.
- `spin` also has a ticket lock mutex implementation; equivalents of `RwLock`, `Barrier` and `Once` from `std::sync`; and `Lazy` for lazy initialization.
- The `once_cell` crate also has some useful types for late initialization with a slightly different approach to `spin::once::Once`.
- The Rust Playground includes `spin`, so this example will run fine inline.

Chapter 55

Bare-Metal on Android

To build a bare-metal Rust binary in AOSP, you need to use a `rust_ffi_static` Soong rule to build your Rust code, then a `cc_binary` with a linker script to produce the binary itself, and then a `raw_binary` to convert the ELF to a raw binary ready to be run.

```
rust_ffi_static {
    name: "libvmbase_example",
    defaults: ["vmbase_ffi_defaults"],
    crate_name: "vmbase_example",
    srcs: ["src/main.rs"],
    rustlibs: [
        "libvmbase",
    ],
}

cc_binary {
    name: "vmbase_example",
    defaults: ["vmbase_elf_defaults"],
    srcs: [
        "idmap.S",
    ],
    static_libs: [
        "libvmbase_example",
    ],
    linker_scripts: [
        "image.ld",
        ":vmbase_sections",
    ],
}

raw_binary {
    name: "vmbase_example_bin",
    stem: "vmbase_example.bin",
    src: ":vmbase_example",
    enabled: false,
    target: {
```

```
        android_arm64: {
            enabled: true,
        },
    },
}
```

55.1 vmbase

For VMs running under crosvm on aarch64, the vmbase library provides a linker script and useful defaults for the build rules, along with an entry point, UART console logging and more.

```rust
#![no_main]
#![no_std]

use vmbase::{main, println};

main!(main);

pub fn main(arg0: u64, arg1: u64, arg2: u64, arg3: u64) {
    println!("Hello world");
}
```

- The `main!` macro marks your main function, to be called from the `vmbase` entry point.
- The `vmbase` entry point handles console initialisation, and issues a PSCI_SYSTEM_OFF to shutdown the VM if your main function returns.

Chapter 56

Exercises

We will write a driver for the PL031 real-time clock device.

After looking at the exercises, you can look at the solutions provided.

56.1 RTC driver

The QEMU aarch64 virt machine has a PL031 real-time clock at 0x9010000. For this exercise, you should write a driver for it.

1. Use it to print the current time to the serial console. You can use the `chrono` crate for date/time formatting.
2. Use the match register and raw interrupt status to busy-wait until a given time, e.g. 3 seconds in the future. (Call `core::hint::spin_loop` inside the loop.)
3. *Extension if you have time:* Enable and handle the interrupt generated by the RTC match. You can use the driver provided in the `arm-gic` crate to configure the Arm Generic Interrupt Controller.
   - Use the RTC interrupt, which is wired to the GIC as `IntId::spi(2)`.
   - Once the interrupt is enabled, you can put the core to sleep via `arm_gic::wfi()`, which will cause the core to sleep until it receives an interrupt.

Download the exercise template and look in the `rtc` directory for the following files.

src/main.rs:

```
#![no_main]
#![no_std]

mod exceptions;
mod logger;

use aarch64_paging::descriptor::Attributes;
use aarch64_rt::{InitialPagetable, entry, initial_pagetable};
use arm_gic::gicv3::registers::{Gicd, GicrSgi};
use arm_gic::gicv3::{GicCpuInterface, GicV3};
use arm_pl011_uart::{PL011Registers, Uart, UniqueMmioPointer};
use core::panic::PanicInfo;
```

```rust
use core::ptr::NonNull;
use log::{LevelFilter, error, info, trace};
use smccc::Hvc;
use smccc::psci::system_off;

/// Base addresses of the GICv3.
const GICD_BASE_ADDRESS: NonNull<Gicd> = NonNull::new(0x800_0000 as _).unwrap();
const GICR_BASE_ADDRESS: NonNull<GicrSgi> = NonNull::new(0x80A_0000 as _).unwrap();

/// Base address of the primary PL011 UART.
const PL011_BASE_ADDRESS: NonNull<PL011Registers> =
    NonNull::new(0x900_0000 as _).unwrap();

/// Attributes to use for device memory in the initial identity map.
const DEVICE_ATTRIBUTES: Attributes = Attributes::VALID
    .union(Attributes::ATTRIBUTE_INDEX_0)
    .union(Attributes::ACCESSED)
    .union(Attributes::UXN);

/// Attributes to use for normal memory in the initial identity map.
const MEMORY_ATTRIBUTES: Attributes = Attributes::VALID
    .union(Attributes::ATTRIBUTE_INDEX_1)
    .union(Attributes::INNER_SHAREABLE)
    .union(Attributes::ACCESSED)
    .union(Attributes::NON_GLOBAL);

initial_pagetable!({
    let mut idmap = [0; 512];
    // 1 GiB of device memory.
    idmap[0] = DEVICE_ATTRIBUTES.bits();
    // 1 GiB of normal memory.
    idmap[1] = MEMORY_ATTRIBUTES.bits() | 0x40000000;
    // Another 1 GiB of device memory starting at 256 GiB.
    idmap[256] = DEVICE_ATTRIBUTES.bits() | 0x4000000000;
    InitialPagetable(idmap)
});

entry!(main);
fn main(x0: u64, x1: u64, x2: u64, x3: u64) -> ! {
    // SAFETY: `PL011_BASE_ADDRESS` is the base address of a PL011 device, and
    // nothing else accesses that address range.
    let uart = unsafe { Uart::new(UniqueMmioPointer::new(PL011_BASE_ADDRESS)) };
    logger::init(uart, LevelFilter::Trace).unwrap();

    info!("main({:#x}, {:#x}, {:#x}, {:#x})", x0, x1, x2, x3);

    // SAFETY: `GICD_BASE_ADDRESS` and `GICR_BASE_ADDRESS` are the base
    // addresses of a GICv3 distributor and redistributor respectively, and
    // nothing else accesses those address ranges.
    let mut gic = unsafe {
        GicV3::new(
```

```
            UniqueMmioPointer::new(GICD_BASE_ADDRESS),
            GICR_BASE_ADDRESS,
            1,
            false,
        )
    };
    gic.setup(0);

    // TODO: Create instance of RTC driver and print current time.

    // TODO: Wait for 3 seconds.

    system_off::<Hvc>().unwrap();
    panic!("system_off returned");
}

#[panic_handler]
fn panic(info: &PanicInfo) -> ! {
    error!("{info}");
    system_off::<Hvc>().unwrap();
    loop {}
}
```

src/exceptions.rs (you should only need to change this for the 3rd part of the exercise):

```
// Copyright 2023 Google LLC
// SPDX-License-Identifier: Apache-2.0
//
// Licensed under the Apache License, Version 2.0 (the "License");
// you may not use this file except in compliance with the License.
// You may obtain a copy of the License at
//
//      http://www.apache.org/licenses/LICENSE-2.0
//
// Unless required by applicable law or agreed to in writing, software
// distributed under the License is distributed on an "AS IS" BASIS,
// WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
// See the License for the specific language governing permissions and
// limitations under the License.

use aarch64_rt::{ExceptionHandlers, RegisterStateRef, exception_handlers};
use arm_gic::gicv3::{GicCpuInterface, InterruptGroup};
use log::{error, info, trace};
use smccc::Hvc;
use smccc::psci::system_off;

struct Handlers;

impl ExceptionHandlers for Handlers {
    extern "C" fn sync_current(_state: RegisterStateRef) {
        error!("sync_current");
        system_off::<Hvc>().unwrap();
```

```
    }

    extern "C" fn irq_current(_state: RegisterStateRef) {
        trace!("irq_current");
        let intid =
            GicCpuInterface::get_and_acknowledge_interrupt(InterruptGroup::Group1)
                .expect("No pending interrupt");
        info!("IRQ {intid:?}");
    }

    extern "C" fn fiq_current(_state: RegisterStateRef) {
        error!("fiq_current");
        system_off::<Hvc>().unwrap();
    }

    extern "C" fn serror_current(_state: RegisterStateRef) {
        error!("serror_current");
        system_off::<Hvc>().unwrap();
    }

    extern "C" fn sync_lower(_state: RegisterStateRef) {
        error!("sync_lower");
        system_off::<Hvc>().unwrap();
    }

    extern "C" fn irq_lower(_state: RegisterStateRef) {
        error!("irq_lower");
        system_off::<Hvc>().unwrap();
    }

    extern "C" fn fiq_lower(_state: RegisterStateRef) {
        error!("fiq_lower");
        system_off::<Hvc>().unwrap();
    }

    extern "C" fn serror_lower(_state: RegisterStateRef) {
        error!("serror_lower");
        system_off::<Hvc>().unwrap();
    }
}

exception_handlers!(Handlers);
```

src/logger.rs (you shouldn't need to change this):

```
// Copyright 2023 Google LLC
// SPDX-License-Identifier: Apache-2.0
//
// Licensed under the Apache License, Version 2.0 (the "License");
// you may not use this file except in compliance with the License.
// You may obtain a copy of the License at
//
```

```rust
//      http://www.apache.org/licenses/LICENSE-2.0
//
// Unless required by applicable law or agreed to in writing, software
// distributed under the License is distributed on an "AS IS" BASIS,
// WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
// See the License for the specific language governing permissions and
// limitations under the License.

use arm_pl011_uart::Uart;
use core::fmt::Write;
use log::{LevelFilter, Log, Metadata, Record, SetLoggerError};
use spin::mutex::SpinMutex;

static LOGGER: Logger = Logger { uart: SpinMutex::new(None) };

struct Logger {
    uart: SpinMutex<Option<Uart<'static>>>,
}

impl Log for Logger {
    fn enabled(&self, _metadata: &Metadata) -> bool {
        true
    }

    fn log(&self, record: &Record) {
        writeln!(
            self.uart.lock().as_mut().unwrap(),
            "[{}] {}",
            record.level(),
            record.args()
        )
        .unwrap();
    }

    fn flush(&self) {}
}

/// Initialises UART logger.
pub fn init(
    uart: Uart<'static>,
    max_level: LevelFilter,
) -> Result<(), SetLoggerError> {
    LOGGER.uart.lock().replace(uart);

    log::set_logger(&LOGGER)?;
    log::set_max_level(max_level);
    Ok(())
}
```

Cargo.toml (you shouldn't need to change this):

```toml
[workspace]
```

```toml
[package]
name = "rtc"
version = "0.1.0"
edition = "2024"
publish = false

[dependencies]
aarch64-paging = { version = "0.11.0", default-features = false }
aarch64-rt = "0.4.3"
arm-gic = "0.7.2"
arm-pl011-uart = "0.4.0"
bitflags = "2.11.0"
chrono = { version = "0.4.44", default-features = false }
log = "0.4.29"
safe-mmio = "0.2.7"
smccc = "0.2.2"
spin = "0.10.0"
zerocopy = "0.8.37"
```

build.rs (you shouldn't need to change this):

```rust
// Copyright 2025 Google LLC
// SPDX-License-Identifier: Apache-2.0
//
// Licensed under the Apache License, Version 2.0 (the "License");
// you may not use this file except in compliance with the License.
// You may obtain a copy of the License at
//
//      http://www.apache.org/licenses/LICENSE-2.0
//
// Unless required by applicable law or agreed to in writing, software
// distributed under the License is distributed on an "AS IS" BASIS,
// WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
// See the License for the specific language governing permissions and
// limitations under the License.

fn main() {
    println!("cargo:rustc-link-arg=-Timage.ld");
    println!("cargo:rustc-link-arg=-Tmemory.ld");
    println!("cargo:rerun-if-changed=memory.ld");
}
```

memory.ld (you shouldn't need to change this):

```
/*
 * Copyright 2023 Google LLC
 * SPDX-License-Identifier: Apache-2.0
 *
 * Licensed under the Apache License, Version 2.0 (the "License");
 * you may not use this file except in compliance with the License.
 * You may obtain a copy of the License at
 *
```

```
 *     https://www.apache.org/licenses/LICENSE-2.0
 *
 * Unless required by applicable law or agreed to in writing, software
 * distributed under the License is distributed on an "AS IS" BASIS,
 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
 * See the License for the specific language governing permissions and
 * limitations under the License.
 */

MEMORY
{
    image : ORIGIN = 0x40080000, LENGTH = 2M
}
```

Makefile (you shouldn't need to change this):

```
# Copyright 2023 Google LLC
# SPDX-License-Identifier: Apache-2.0
#
# Licensed under the Apache License, Version 2.0 (the "License");
# you may not use this file except in compliance with the License.
# You may obtain a copy of the License at
#
#      http://www.apache.org/licenses/LICENSE-2.0
#
# Unless required by applicable law or agreed to in writing, software
# distributed under the License is distributed on an "AS IS" BASIS,
# WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
# See the License for the specific language governing permissions and
# limitations under the License.

.PHONY: build qemu_minimal qemu qemu_logger

all: rtc.bin

build:
    cargo build

rtc.bin: build
    cargo objcopy -- -O binary $@

qemu: rtc.bin
    qemu-system-aarch64 -machine virt,gic-version=3 -cpu max -serial mon:stdio -display

clean:
    cargo clean
    rm -f *.bin
```

.cargo/config.toml (you shouldn't need to change this):

```
[build]
target = "aarch64-unknown-none"
```

Run the code in QEMU with `make qemu`.

56.2 Bare Metal Rust Afternoon

RTC driver

(back to exercise)

main.rs:

```
#![no_main]
#![no_std]

mod exceptions;
mod logger;
mod pl031;

use crate::pl031::Rtc;
use arm_gic::{IntId, Trigger, irq_enable, wfi};
use chrono::{TimeZone, Utc};
use core::hint::spin_loop;
use aarch64_paging::descriptor::Attributes;
use aarch64_rt::{InitialPagetable, entry, initial_pagetable};
use arm_gic::gicv3::registers::{Gicd, GicrSgi};
use arm_gic::gicv3::{GicCpuInterface, GicV3};
use arm_pl011_uart::{PL011Registers, Uart, UniqueMmioPointer};
use core::panic::PanicInfo;
use core::ptr::NonNull;
use log::{LevelFilter, error, info, trace};
use smccc::Hvc;
use smccc::psci::system_off;

/// Base addresses of the GICv3.
const GICD_BASE_ADDRESS: NonNull<Gicd> = NonNull::new(0x800_0000 as _).unwrap();
const GICR_BASE_ADDRESS: NonNull<GicrSgi> = NonNull::new(0x80A_0000 as _).unwrap();

/// Base address of the primary PL011 UART.
const PL011_BASE_ADDRESS: NonNull<PL011Registers> =
    NonNull::new(0x900_0000 as _).unwrap();

/// Attributes to use for device memory in the initial identity map.
const DEVICE_ATTRIBUTES: Attributes = Attributes::VALID
    .union(Attributes::ATTRIBUTE_INDEX_0)
    .union(Attributes::ACCESSED)
    .union(Attributes::UXN);

/// Attributes to use for normal memory in the initial identity map.
const MEMORY_ATTRIBUTES: Attributes = Attributes::VALID
    .union(Attributes::ATTRIBUTE_INDEX_1)
    .union(Attributes::INNER_SHAREABLE)
    .union(Attributes::ACCESSED)
```

```rust
    .union(Attributes::NON_GLOBAL);

initial_pagetable!({
    let mut idmap = [0; 512];
    // 1 GiB of device memory.
    idmap[0] = DEVICE_ATTRIBUTES.bits();
    // 1 GiB of normal memory.
    idmap[1] = MEMORY_ATTRIBUTES.bits() | 0x40000000;
    // Another 1 GiB of device memory starting at 256 GiB.
    idmap[256] = DEVICE_ATTRIBUTES.bits() | 0x4000000000;
    InitialPagetable(idmap)
});

/// Base address of the PL031 RTC.
const PL031_BASE_ADDRESS: NonNull<pl031::Registers> =
    NonNull::new(0x901_0000 as _).unwrap();
/// The IRQ used by the PL031 RTC.
const PL031_IRQ: IntId = IntId::spi(2);

entry!(main);
fn main(x0: u64, x1: u64, x2: u64, x3: u64) -> ! {
    // SAFETY: `PL011_BASE_ADDRESS` is the base address of a PL011 device, and
    // nothing else accesses that address range.
    let uart = unsafe { Uart::new(UniqueMmioPointer::new(PL011_BASE_ADDRESS)) };
    logger::init(uart, LevelFilter::Trace).unwrap();

    info!("main({:#x}, {:#x}, {:#x}, {:#x})", x0, x1, x2, x3);

    // SAFETY: `GICD_BASE_ADDRESS` and `GICR_BASE_ADDRESS` are the base
    // addresses of a GICv3 distributor and redistributor respectively, and
    // nothing else accesses those address ranges.
    let mut gic = unsafe {
        GicV3::new(
            UniqueMmioPointer::new(GICD_BASE_ADDRESS),
            GICR_BASE_ADDRESS,
            1,
            false,
        )
    };
    gic.setup(0);

    // SAFETY: `PL031_BASE_ADDRESS` is the base address of a PL031 device, and
    // nothing else accesses that address range.
    let mut rtc = unsafe { Rtc::new(UniqueMmioPointer::new(PL031_BASE_ADDRESS)) };
    let timestamp = rtc.read();
    let time = Utc.timestamp_opt(timestamp.into(), 0).unwrap();
    info!("RTC: {time}");

    GicCpuInterface::set_priority_mask(0xff);
    gic.set_interrupt_priority(PL031_IRQ, None, 0x80).unwrap();
    gic.set_trigger(PL031_IRQ, None, Trigger::Level).unwrap();
```

```rust
    irq_enable();
    gic.enable_interrupt(PL031_IRQ, None, true).unwrap();

    // Wait for 3 seconds, without interrupts.
    let target = timestamp + 3;
    rtc.set_match(target);
    info!("Waiting for {}", Utc.timestamp_opt(target.into(), 0).unwrap());
    trace!(
        "matched={}, interrupt_pending={}",
        rtc.matched(),
        rtc.interrupt_pending()
    );
    while !rtc.matched() {
        spin_loop();
    }
    trace!(
        "matched={}, interrupt_pending={}",
        rtc.matched(),
        rtc.interrupt_pending()
    );
    info!("Finished waiting");

    // Wait another 3 seconds for an interrupt.
    let target = timestamp + 6;
    info!("Waiting for {}", Utc.timestamp_opt(target.into(), 0).unwrap());
    rtc.set_match(target);
    rtc.clear_interrupt();
    rtc.enable_interrupt(true);
    trace!(
        "matched={}, interrupt_pending={}",
        rtc.matched(),
        rtc.interrupt_pending()
    );
    while !rtc.interrupt_pending() {
        wfi();
    }
    trace!(
        "matched={}, interrupt_pending={}",
        rtc.matched(),
        rtc.interrupt_pending()
    );
    info!("Finished waiting");

    system_off::<Hvc>().unwrap();
    panic!("system_off returned");
}

#[panic_handler]
fn panic(info: &PanicInfo) -> ! {
    error!("{info}");
    system_off::<Hvc>().unwrap();
```

```
    loop {}
}
```

pl031.rs:

```
#[repr(C, align(4))]
pub struct Registers {
    /// Data register
    dr: ReadPure<u32>,
    /// Match register
    mr: ReadPureWrite<u32>,
    /// Load register
    lr: ReadPureWrite<u32>,
    /// Control register
    cr: ReadPureWrite<u8>,
    _reserved0: [u8; 3],
    /// Interrupt Mask Set or Clear register
    imsc: ReadPureWrite<u8>,
    _reserved1: [u8; 3],
    /// Raw Interrupt Status
    ris: ReadPure<u8>,
    _reserved2: [u8; 3],
    /// Masked Interrupt Status
    mis: ReadPure<u8>,
    _reserved3: [u8; 3],
    /// Interrupt Clear Register
    icr: WriteOnly<u8>,
    _reserved4: [u8; 3],
}

/// Driver for a PL031 real-time clock.
#[derive(Debug)]
pub struct Rtc<'a> {
    registers: UniqueMmioPointer<'a, Registers>,
}

impl<'a> Rtc<'a> {
    /// Constructs a new instance of the RTC driver for a PL031 device with the
    /// given set of registers.
    pub fn new(registers: UniqueMmioPointer<'a, Registers>) -> Self {
        Self { registers }
    }

    /// Reads the current RTC value.
    pub fn read(&self) -> u32 {
        field_shared!(self.registers, dr).read()
    }

    /// Writes a match value. When the RTC value matches this then an interrupt
    /// will be generated (if it is enabled).
    pub fn set_match(&mut self, value: u32) {
        field!(self.registers, mr).write(value);
```

```rust
    }

    /// Returns whether the match register matches the RTC value, whether or not
    /// the interrupt is enabled.
    pub fn matched(&self) -> bool {
        let ris = field_shared!(self.registers, ris).read();
        (ris & 0x01) != 0
    }

    /// Returns whether there is currently an interrupt pending.
    ///
    /// This should be true if and only if `matched` returns true and the
    /// interrupt is masked.
    pub fn interrupt_pending(&self) -> bool {
        let mis = field_shared!(self.registers, mis).read();
        (mis & 0x01) != 0
    }

    /// Sets or clears the interrupt mask.
    ///
    /// When the mask is true the interrupt is enabled; when it is false the
    /// interrupt is disabled.
    pub fn enable_interrupt(&mut self, mask: bool) {
        let imsc = if mask { 0x01 } else { 0x00 };
        field!(self.registers, imsc).write(imsc);
    }

    /// Clears a pending interrupt, if any.
    pub fn clear_interrupt(&mut self) {
        field!(self.registers, icr).write(0x01);
    }
}
```

Part XIII

Concurrency: Morning

Chapter 57

Welcome to Concurrency in Rust

Rust has full support for concurrency using OS threads with mutexes and channels.

The Rust type system plays an important role in making many concurrency bugs compile time errors. This idea is known as *fearless concurrency* since you can rely on the compiler to ensure correctness at runtime.

Schedule

Including 10 minute breaks, this session should take about 3 hours and 20 minutes. It contains:

Segment	Duration
Threads	30 minutes
Channels	20 minutes
Send and Sync	15 minutes
Shared State	30 minutes
Exercises	1 hour and 10 minutes

- Rust lets us access OS concurrency toolkit: threads, sync. primitives, etc.
- The type system gives us safety for concurrency without any special features.
- The same tools that help with ”concurrent” access in a single thread (e.g., a called function that might mutate an argument or save references to it to read later) save us from multi-threading issues.

Chapter 58

Threads

This segment should take about 30 minutes. It contains:

Slide	Duration
Plain Threads	15 minutes
Scoped Threads	15 minutes

58.1 Plain Threads

Rust threads work similarly to threads in other languages:

```
use std::thread;
use std::time::Duration;

fn main() {
    thread::spawn(|| {
        for i in 0..10 {
            println!("Count in thread: {i}!");
            thread::sleep(Duration::from_millis(5));
        }
    });

    for i in 0..5 {
        println!("Main thread: {i}");
        thread::sleep(Duration::from_millis(5));
    }
}
```

- Spawning new threads does not automatically delay program termination at the end of `main`.
- Thread panics are independent of each other.
  - Panics can carry a payload, which can be unpacked with `Any::downcast_ref`.

This slide should take about 15 minutes.

- Run the example.
  - 5ms timing is loose enough that main and spawned threads stay mostly in lockstep.
  - Notice that the program ends before the spawned thread reaches 10!
  - This is because `main` ends the program and spawned threads do not make it persist.
    * Compare to pthreads/C++ `std::thread`/`boost::thread` if desired.
- How do we wait around for the spawned thread to complete?
- `thread::spawn` returns a `JoinHandle`. Look at the docs.
  - `JoinHandle` has a `.join()` method that blocks.
- Use `let handle = thread::spawn(...)` and later `handle.join()` to wait for the thread to finish and have the program count all the way to 10.
- Now what if we want to return a value?
- Look at docs again:
  - `thread::spawn`'s closure returns `T`
  - `JoinHandle` `.join()` returns `thread::Result<T>`
- Use the `Result` return value from `handle.join()` to get access to the returned value.
- Ok, what about the other case?
  - Trigger a panic in the thread. Note that this doesn't panic `main`.
  - Access the panic payload. This is a good time to talk about `Any`.
- Now we can return values from threads! What about taking inputs?
  - Capture something by reference in the thread closure.
  - An error message indicates we must move it.
  - Move it in, see we can compute and then return a derived value.
- If we want to borrow?
  - Main kills child threads when it returns, but another function would just return and leave them running.
  - That would be stack use-after-return, which violates memory safety!
  - How do we avoid this? See next slide.

58.2 Scoped Threads

Normal threads cannot borrow from their environment:

```rust
use std::thread;

fn foo() {
    let s = String::from("Hello");
    thread::spawn(|| {
        dbg!(s.len());
    });
}

fn main() {
```

```
    foo();
}
```

However, you can use a scoped thread for this:

```
use std::thread;

fn foo() {
    let s = String::from("Hello");
    thread::scope(|scope| {
        scope.spawn(|| {
            dbg!(s.len());
        });
    });
}

fn main() {
    foo();
}
```

This slide should take about 13 minutes.

- The reason for that is that when the `thread::scope` function completes, all the threads are guaranteed to be joined, so they can return borrowed data.
- Normal Rust borrowing rules apply: you can either borrow mutably by one thread, or immutably by any number of threads.

Chapter 59

Channels

This segment should take about 20 minutes. It contains:

Slide	Duration
Senders and Receivers	10 minutes
Unbounded Channels	2 minutes
Bounded Channels	10 minutes

59.1 Senders and Receivers

Rust channels have two parts: a `Sender<T>` and a `Receiver<T>`. The two parts are connected via the channel, but you only see the end-points.

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

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

    tx.send(10).unwrap();
    tx.send(20).unwrap();

    println!("Received: {:?}", rx.recv());
    println!("Received: {:?}", rx.recv());

    let tx2 = tx.clone();
    tx2.send(30).unwrap();
    println!("Received: {:?}", rx.recv());
}
```

This slide should take about 9 minutes.

- `mpsc` stands for Multi-Producer, Single-Consumer. `Sender` and `SyncSender` implement `Clone` (so you can make multiple producers) but `Receiver` does not.
- `send()` and `recv()` return `Result`. If they return `Err`, it means the counterpart `Sender` or `Receiver` is dropped and the channel is closed.

59.2 Unbounded Channels

You get an unbounded and asynchronous channel with `mpsc::channel()`:

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

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

    thread::spawn(move || {
        let thread_id = thread::current().id();
        for i in 0..10 {
            tx.send(format!("Message {i}")).unwrap();
            println!("{thread_id:?}: sent Message {i}");
        }
        println!("{thread_id:?}: done");
    });
    thread::sleep(Duration::from_millis(100));

    for msg in rx {
        println!("Main: got {msg}");
    }
}
```

This slide should take about 2 minutes.

- An unbounded channel will allocate as much space as is necessary to store pending messages. The `send()` method will not block the calling thread.
- A call to `send()` will abort with an error (that is why it returns `Result`) if the channel is closed. A channel is closed when the receiver is dropped.

59.3 Bounded Channels

With bounded (synchronous) channels, `send()` can block the current thread:

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

fn main() {
    let (tx, rx) = mpsc::sync_channel(3);

    thread::spawn(move || {
        let thread_id = thread::current().id();
        for i in 0..10 {
            tx.send(format!("Message {i}")).unwrap();
            println!("{thread_id:?}: sent Message {i}");
        }
        println!("{thread_id:?}: done");
    });
```

```
    thread::sleep(Duration::from_millis(100));

    for msg in rx {
        println!("Main: got {msg}");
    }
}
```

This slide should take about 8 minutes.

- Calling `send()` will block the current thread until there is space in the channel for the new message. The thread can be blocked indefinitely if there is nobody who reads from the channel.
- Like unbounded channels, a call to `send()` will abort with an error if the channel is closed.
- A bounded channel with a size of zero is called a ”rendezvous channel”. Every send will block the current thread until another thread calls `recv()`.

Chapter 60

Send and Sync

This segment should take about 15 minutes. It contains:

Slide	Duration
Marker Traits	2 minutes
Send	2 minutes
Sync	2 minutes
Examples	10 minutes

60.1 Marker Traits

How does Rust know to forbid shared access across threads? The answer is in two traits:

- Send: a type T is Send if it is safe to move a T across a thread boundary.
- Sync: a type T is Sync if it is safe to move a &T across a thread boundary.

Send and Sync are unsafe traits. The compiler will automatically derive them for your types as long as they only contain Send and Sync types. You can also implement them manually when you know it is valid.

This slide should take about 2 minutes.

- One can think of these traits as markers that the type has certain thread-safety properties.
- They can be used in the generic constraints as normal traits.

60.2 Send

> A type T is Send if it is safe to move a T value to another thread.

The effect of moving ownership to another thread is that *destructors* will run in that thread. So the question is when you can allocate a value in one thread and deallocate it in another.

This slide should take about 2 minutes.

As an example, a connection to the SQLite library must only be accessed from a single thread.

60.3 Sync

> A type T is Sync if it is safe to access a T value from multiple threads at the same time.

More precisely, the definition is:

> T is Sync if and only if &T is Send

This slide should take about 2 minutes.

This statement is essentially a shorthand way of saying that if a type is thread-safe for shared use, it is also thread-safe to pass references of it across threads.

This is because if a type is Sync it means that it can be shared across multiple threads without the risk of data races or other synchronization issues, so it is safe to move it to another thread. A reference to the type is also safe to move to another thread, because the data it references can be accessed from any thread safely.

60.4 Examples

Send + Sync

Most types you come across are Send + Sync:

- i8, f32, bool, char, &str, ...
- (T1, T2), [T; N], &[T], struct { x: T }, ...
- String, Option<T>, Vec<T>, Box<T>, ...
- Arc<T>: Explicitly thread-safe via atomic reference count.
- Mutex<T>: Explicitly thread-safe via internal locking.
- mpsc::Sender<T>: As of 1.72.0.
- AtomicBool, AtomicU8, ...: Uses special atomic instructions.

The generic types are typically Send + Sync when the type parameters are Send + Sync.

Send + !Sync

These types can be moved to other threads, but they're not thread-safe. Typically because of interior mutability:

- mpsc::Receiver<T>
- Cell<T>
- RefCell<T>

!Send + Sync

These types are safe to access (via shared references) from multiple threads, but they cannot be moved to another thread:

- MutexGuard<T>: Uses OS level primitives which must be deallocated on the thread which created them. However, an already-locked mutex can have its guarded variable read by any thread with which the guard is shared (unless T itself is !Sync).

!Send + !Sync

These types are not thread-safe and cannot be moved to other threads:

- Rc<T>: each Rc<T> has a reference to an RcBox<T>, which contains a non-atomic reference count.
- *const T, *mut T: Rust assumes raw pointers may have special concurrency considerations.

Chapter 61

Shared State

This segment should take about 30 minutes. It contains:

Slide	Duration
Arc	5 minutes
Mutex	15 minutes
Example	10 minutes

61.1 Arc

Arc<T> allows shared, read-only ownership via Arc::clone:

```
use std::sync::Arc;
use std::thread;

/// A struct that prints which thread drops it.
#[derive(Debug)]
struct WhereDropped(Vec<i32>);

impl Drop for WhereDropped {
    fn drop(&mut self) {
        println!("Dropped by {:?}", thread::current().id())
    }
}

fn main() {
    let v = Arc::new(WhereDropped(vec![10, 20, 30]));
    let mut handles = Vec::new();
    for i in 0..5 {
        let v = Arc::clone(&v);
        handles.push(thread::spawn(move || {
            // Sleep for 0-500ms.
            std::thread::sleep(std::time::Duration::from_millis(500 - i * 100));
            let thread_id = thread::current().id();
```

```
            println!("{thread_id:?}: {v:?}");
        }));
    }

    // Now only the spawned threads will hold clones of `v`.
    drop(v);

    // When the last spawned thread finishes, it will drop `v`'s contents.
    handles.into_iter().for_each(|h| h.join().unwrap());
}
```

This slide should take about 5 minutes.

- `Arc` stands for "Atomic Reference Counted", a thread safe version of `Rc` that uses atomic operations.
- `Arc<T>` implements `Clone` whether or not `T` does. It implements `Send` and `Sync` if and only if `T` implements them both.
- `Arc::clone()` has the cost of atomic operations that get executed, but after that the use of the `T` is free.
- Beware of reference cycles, `Arc` does not use a garbage collector to detect them.
  - `std::sync::Weak` can help.

61.2 Mutex

`Mutex<T>` ensures mutual exclusion *and* allows mutable access to `T` behind a read-only interface (another form of interior mutability):

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

fn main() {
    let v = Mutex::new(vec![10, 20, 30]);
    println!("v: {:?}", v.lock().unwrap());

    {
        let mut guard = v.lock().unwrap();
        guard.push(40);
    }

    println!("v: {:?}", v.lock().unwrap());
}
```

Notice how we have a `impl<T: Send> Sync for Mutex<T>` blanket implementation.

This slide should take about 14 minutes.

- `Mutex` in Rust looks like a collection with just one element --- the protected data.
  - It is not possible to forget to acquire the mutex before accessing the protected data.
- You can get an `&mut T` from an `&Mutex<T>` by taking the lock. The `MutexGuard` ensures that the `&mut T` doesn't outlive the lock being held.
- `Mutex<T>` implements both `Send` and `Sync` if and only if `T` implements `Send`.
- A read-write lock counterpart: `RwLock`.
- Why does `lock()` return a `Result`?

– If the thread that held the Mutex panicked, the Mutex becomes "poisoned" to signal that the data it protected might be in an inconsistent state. Calling lock() on a poisoned mutex fails with a PoisonError. You can call into_inner() on the error to recover the data regardless.

61.3 Example

Let us see Arc and Mutex in action:

```
use std::thread;
// use std::sync::{Arc, Mutex};

fn main() {
    let v = vec![10, 20, 30];
    let mut handles = Vec::new();
    for i in 0..5 {
        handles.push(thread::spawn(|| {
            v.push(10 * i);
            println!("v: {v:?}");
        }));
    }

    handles.into_iter().for_each(|h| h.join().unwrap());
}
```

This slide should take about 8 minutes.

Possible solution:

```
use std::sync::{Arc, Mutex};
use std::thread;

fn main() {
    let v = Arc::new(Mutex::new(vec![10, 20, 30]));
    let mut handles = Vec::new();
    for i in 0..5 {
        let v = Arc::clone(&v);
        handles.push(thread::spawn(move || {
            let mut v = v.lock().unwrap();
            v.push(10 * i);
            println!("v: {v:?}");
        }));
    }

    handles.into_iter().for_each(|h| h.join().unwrap());
}
```

Notable parts:

- v is wrapped in both Arc and Mutex, because their concerns are orthogonal.
  – Wrapping a Mutex in an Arc is a common pattern to share mutable state between threads.

- `v: Arc<_>` needs to be cloned to make a new reference for each new spawned thread. Note `move` was added to the lambda signature.
- Blocks are introduced to narrow the scope of the `LockGuard` as much as possible.

Chapter 62

Exercises

This segment should take about 1 hour and 10 minutes. It contains:

Slide	Duration
Dining Philosophers	20 minutes
Multi-threaded Link Checker	20 minutes
Solutions	30 minutes

62.1 Dining Philosophers

The dining philosophers problem is a classic problem in concurrency:

> Five philosophers dine together at the same table. Each philosopher has their own place at the table. There is a chopstick between each plate. The dish served is spaghetti which requires two chopsticks to eat. Each philosopher can only alternately think and eat. Moreover, a philosopher can only eat their spaghetti when they have both a left and right chopstick. Thus two chopsticks will only be available when their two nearest neighbors are thinking, not eating. After an individual philosopher finishes eating, they will put down both chopsticks.

You will need a local Cargo installation for this exercise. Copy the code below to a file called `src/main.rs`, fill out the blanks, and test that `cargo run` does not deadlock:

```
use std::sync::{Arc, Mutex, mpsc};
use std::thread;
use std::time::Duration;

struct Chopstick;

struct Philosopher {
    name: String,
    // left_chopstick: ...
    // right_chopstick: ...
    // thoughts: ...
}
```

```rust
impl Philosopher {
    fn think(&self) {
        self.thoughts
            .send(format!("Eureka! {} has a new idea!", &self.name))
            .unwrap();
    }

    fn eat(&self) {
        // Pick up chopsticks...
        println!("{} is eating...", &self.name);
        thread::sleep(Duration::from_millis(10));
    }
}

static PHILOSOPHERS: &[&str] =
    &["Socrates", "Hypatia", "Plato", "Aristotle", "Pythagoras"];

fn main() {
    // Create chopsticks

    // Create philosophers

    // Make each of them think and eat 100 times

    // Output their thoughts
}
```

You can use the following `Cargo.toml`:

```toml
[package]
name = "dining-philosophers"
version = "0.1.0"
edition = "2024"
```

This slide should take about 20 minutes.

- Encourage students to focus first on implementing a solution that "mostly" works.
- The deadlock in the simplest solution is a general concurrency problem and highlights that Rust does not automatically prevent this sort of bug.

62.2 Multi-threaded Link Checker

Let us use our new knowledge to create a multi-threaded link checker. It should start at a webpage and check that links on the page are valid. It should recursively check other pages on the same domain and keep doing this until all pages have been validated.

For this, you will need an HTTP client such as `reqwest`. You will also need a way to find links, we can use `scraper`. Finally, we'll need some way of handling errors, we will use `thiserror`.

Create a new Cargo project and `reqwest` it as a dependency with:

```
cargo new link-checker
```

```
cd link-checker
cargo add --features blocking reqwest
cargo add scraper
cargo add thiserror
```

> If `cargo add` fails with `error: no such subcommand`, then please edit the `Cargo.toml` file by hand. Add the dependencies listed below.

The `cargo add` calls will update the `Cargo.toml` file to look like this:

```toml
[package]
name = "link-checker"
version = "0.1.0"
edition = "2024"
publish = false

[dependencies]
reqwest = { version = "0.13.1", features = ["blocking"] }
scraper = "0.25.0"
thiserror = "2.0.18"
```

You can now download the start page. Try with a small site such as `https://www.google.org/`.

Your `src/main.rs` file should look something like this:

```rust
use reqwest::Url;
use reqwest::blocking::Client;
use scraper::{Html, Selector};
use thiserror::Error;

#[derive(Error, Debug)]
enum Error {
    #[error("request error: {0}")]
    ReqwestError(#[from] reqwest::Error),
    #[error("bad http response: {0}")]
    BadResponse(String),
}

#[derive(Debug)]
struct CrawlCommand {
    url: Url,
    extract_links: bool,
}

fn visit_page(client: &Client, command: &CrawlCommand) -> Result<Vec<Url>, Error> {
    println!("Checking {:#}", command.url);
    let response = client.get(command.url.clone()).send()?;
    if !response.status().is_success() {
        return Err(Error::BadResponse(response.status().to_string()));
    }

    let mut link_urls = Vec::new();
    if !command.extract_links {
        return Ok(link_urls);
```

```rust
    }

    let base_url = response.url().clone();
    let body_text = response.text()?;
    let document = Html::parse_document(&body_text);

    let selector = Selector::parse("a").unwrap();
    let href_values = document
        .select(&selector)
        .filter_map(|element| element.value().attr("href"));
    for href in href_values {
        match base_url.join(href) {
            Ok(link_url) => {
                link_urls.push(link_url);
            }
            Err(err) => {
                println!("On {base_url:#}: ignored unparsable {href:?}: {err}");
            }
        }
    }
    Ok(link_urls)
}

fn main() {
    let client = Client::new();
    let start_url = Url::parse("https://www.google.org").unwrap();
    let crawl_command = CrawlCommand{ url: start_url, extract_links: true };
    match visit_page(&client, &crawl_command) {
        Ok(links) => println!("Links: {links:#?}"),
        Err(err) => println!("Could not extract links: {err:#}"),
    }
}
```

Run the code in `src/main.rs` with

```
cargo run
```

Tasks

- Use threads to check the links in parallel: send the URLs to be checked to a channel and let a few threads check the URLs in parallel.
- Extend this to recursively extract links from all pages on the `www.google.org` domain. Put an upper limit of 100 pages or so so that you don't end up being blocked by the site.

This slide should take about 20 minutes.

- This is a complex exercise and intended to give students an opportunity to work on a larger project than others. A success condition for this exercise is to get stuck on some ”real” issue and work through it with the support of other students or the instructor.

62.3 Solutions

Dining Philosophers

```rust
use std::sync::{Arc, Mutex, mpsc};
use std::thread;
use std::time::Duration;

struct Chopstick;

struct Philosopher {
    name: String,
    left_chopstick: Arc<Mutex<Chopstick>>,
    right_chopstick: Arc<Mutex<Chopstick>>,
    thoughts: mpsc::SyncSender<String>,
}

impl Philosopher {
    fn think(&self) {
        self.thoughts
            .send(format!("Eureka! {} has a new idea!", &self.name))
            .unwrap();
    }

    fn eat(&self) {
        println!("{} is trying to eat", &self.name);
        let _left = self.left_chopstick.lock().unwrap();
        let _right = self.right_chopstick.lock().unwrap();

        println!("{} is eating...", &self.name);
        thread::sleep(Duration::from_millis(10));
    }
}

static PHILOSOPHERS: &[&str] =
    &["Socrates", "Hypatia", "Plato", "Aristotle", "Pythagoras"];

fn main() {
    let (tx, rx) = mpsc::sync_channel(10);

    let chopsticks = PHILOSOPHERS
        .iter()
        .map(|_| Arc::new(Mutex::new(Chopstick)))
        .collect::<Vec<_>>();

    for i in 0..chopsticks.len() {
        let tx = tx.clone();
        let mut left_chopstick = Arc::clone(&chopsticks[i]);
        let mut right_chopstick =
            Arc::clone(&chopsticks[(i + 1) % chopsticks.len()]);
```

```
        // To avoid a deadlock, we have to break the symmetry
        // somewhere. This will swap the chopsticks without deinitializing
        // either of them.
        if i == chopsticks.len() - 1 {
            std::mem::swap(&mut left_chopstick, &mut right_chopstick);
        }

        let philosopher = Philosopher {
            name: PHILOSOPHERS[i].to_string(),
            thoughts: tx,
            left_chopstick,
            right_chopstick,
        };

        thread::spawn(move || {
            for _ in 0..100 {
                philosopher.eat();
                philosopher.think();
            }
        });
    }

    drop(tx);
    for thought in rx {
        println!("{thought}");
    }
}
```

Link Checker

```
use std::sync::{Arc, Mutex, mpsc};
use std::thread;

use reqwest::Url;
use reqwest::blocking::Client;
use scraper::{Html, Selector};
use thiserror::Error;

#[derive(Error, Debug)]
enum Error {
    #[error("request error: {0}")]
    ReqwestError(#[from] reqwest::Error),
    #[error("bad http response: {0}")]
    BadResponse(String),
}

#[derive(Debug)]
struct CrawlCommand {
    url: Url,
    extract_links: bool,
}
```

```rust
fn visit_page(client: &Client, command: &CrawlCommand) -> Result<Vec<Url>, Error> {
    println!("Checking {:#}", command.url);
    let response = client.get(command.url.clone()).send()?;
    if !response.status().is_success() {
        return Err(Error::BadResponse(response.status().to_string()));
    }

    let mut link_urls = Vec::new();
    if !command.extract_links {
        return Ok(link_urls);
    }

    let base_url = response.url().clone();
    let body_text = response.text()?;
    let document = Html::parse_document(&body_text);

    let selector = Selector::parse("a").unwrap();
    let href_values = document
        .select(&selector)
        .filter_map(|element| element.value().attr("href"));
    for href in href_values {
        match base_url.join(href) {
            Ok(link_url) => {
                link_urls.push(link_url);
            }
            Err(err) => {
                println!("On {base_url:#}: ignored unparsable {href:?}: {err}");
            }
        }
    }
    Ok(link_urls)
}

struct CrawlState {
    domain: String,
    visited_pages: std::collections::HashSet<String>,
}

impl CrawlState {
    fn new(start_url: &Url) -> CrawlState {
        let mut visited_pages = std::collections::HashSet::new();
        visited_pages.insert(start_url.as_str().to_string());
        CrawlState { domain: start_url.domain().unwrap().to_string(), visited_pages }
    }

    /// Determine whether links within the given page should be extracted.
    fn should_extract_links(&self, url: &Url) -> bool {
        url.domain().is_some_and(|d| d == self.domain)
    }
```

```rust
    /// Mark the given page as visited, returning false if it had already
    /// been visited.
    fn mark_visited(&mut self, url: &Url) -> bool {
        self.visited_pages.insert(url.as_str().to_string())
    }
}

type CrawlResult = Result<Vec<Url>, (Url, Error)>;

fn spawn_crawler_threads(
    command_receiver: mpsc::Receiver<CrawlCommand>,
    result_sender: mpsc::Sender<CrawlResult>,
    thread_count: u32,
) {
    // To multiplex the non-cloneable Receiver, wrap it in Arc<Mutex<_>>.
    let command_receiver = Arc::new(Mutex::new(command_receiver));

    for _ in 0..thread_count {
        let result_sender = result_sender.clone();
        let command_receiver = Arc::clone(&command_receiver);
        thread::spawn(move || {
            let client = Client::new();
            loop {
                let command_result = {
                    let receiver_guard = command_receiver.lock().unwrap();
                    receiver_guard.recv()
                };
                let Ok(crawl_command) = command_result else {
                    // The sender got dropped. No more commands coming in.
                    break;
                };
                let crawl_result = match visit_page(&client, &crawl_command) {
                    Ok(link_urls) => Ok(link_urls),
                    Err(error) => Err((crawl_command.url, error)),
                };
                result_sender.send(crawl_result).unwrap();
            }
        });
    }
}

fn control_crawl(
    start_url: Url,
    command_sender: mpsc::Sender<CrawlCommand>,
    result_receiver: mpsc::Receiver<CrawlResult>,
) -> Vec<Url> {
    let mut crawl_state = CrawlState::new(&start_url);
    let start_command = CrawlCommand { url: start_url, extract_links: true };
    command_sender.send(start_command).unwrap();
    let mut pending_urls = 1;
```

```
    let mut bad_urls = Vec::new();
    while pending_urls > 0 {
        let crawl_result = result_receiver.recv().unwrap();
        pending_urls -= 1;

        match crawl_result {
            Ok(link_urls) => {
                for url in link_urls {
                    if crawl_state.mark_visited(&url) {
                        let extract_links = crawl_state.should_extract_links(&url);
                        let crawl_command = CrawlCommand { url, extract_links };
                        command_sender.send(crawl_command).unwrap();
                        pending_urls += 1;
                    }
                }
            }
            Err((url, error)) => {
                bad_urls.push(url);
                println!("Got crawling error: {:#}", error);
            }
        }
    }
    bad_urls
}

fn check_links(start_url: Url) -> Vec<Url> {
    let (result_sender, result_receiver) = mpsc::channel::<CrawlResult>();
    let (command_sender, command_receiver) = mpsc::channel::<CrawlCommand>();
    spawn_crawler_threads(command_receiver, result_sender, 16);
    control_crawl(start_url, command_sender, result_receiver)
}

fn main() {
    let start_url = reqwest::Url::parse("https://www.google.org").unwrap();
    let bad_urls = check_links(start_url);
    println!("Bad URLs: {:#?}", bad_urls);
}
```

Part XIV

Concurrency: Afternoon

Chapter 63

Welcome

”Async” is a concurrency model where multiple tasks are executed concurrently by executing each task until it would block, then switching to another task that is ready to make progress. The model allows running a larger number of tasks on a limited number of threads. This is because the per-task overhead is typically very low and operating systems provide primitives for efficiently identifying I/O that is able to proceed.

Rust's asynchronous operation is based on ”futures”, which represent work that may be completed in the future. Futures are ”polled” until they signal that they are complete.

Futures are polled by an async runtime, and several different runtimes are available.

Comparisons

- Python has a similar model in its `asyncio`. However, its `Future` type is callback-based, and not polled. Async Python programs require a ”loop”, similar to a runtime in Rust.
- JavaScript's `Promise` is similar, but again callback-based. The language runtime implements the event loop, so the majority of the details of Promise resolution are hidden.

Schedule

Including 10 minute breaks, this session should take about 3 hours and 30 minutes. It contains:

Segment	Duration
Async Basics	40 minutes
Channels and Control Flow	20 minutes
Pitfalls	55 minutes
Exercises	1 hour and 10 minutes

Chapter 64

Async Basics

This segment should take about 40 minutes. It contains:

Slide	Duration
async/await	10 minutes
Futures	4 minutes
State Machine	10 minutes
Runtimes	10 minutes
Tasks	10 minutes

64.1 async/await

At a high level, async Rust code looks very much like ”normal” sequential code:

```rust
use futures::executor::block_on;

async fn count_to(count: i32) {
    for i in 0..count {
        println!("Count is: {i}!");
    }
}

async fn async_main(count: i32) {
    count_to(count).await;
}

fn main() {
    block_on(async_main(10));
}
```

This slide should take about 6 minutes.

Key points:

- Note that this is a simplified example to show the syntax. There is no long running operation or any real concurrency in it!
- The ”async” keyword is syntactic sugar. The compiler replaces the return type with a future.
- You cannot make `main` async, without additional instructions to the compiler on how to use the returned future.
- You need an executor to run async code. `block_on` blocks the current thread until the provided future has run to completion.
- `.await` asynchronously waits for the completion of another operation. Unlike `block_on`, `.await` doesn't block the current thread.
- `.await` can only be used inside an `async` function (or block; these are introduced later).

64.2 Futures

`Future` is a trait, implemented by objects that represent an operation that may not be complete yet. A future can be polled, and `poll` returns a `Poll`.

```
use std::pin::Pin;
use std::task::Context;

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

pub enum Poll<T> {
    Ready(T),
    Pending,
}
```

An async function returns an `impl Future`. It's also possible (but uncommon) to implement `Future` for your own types. For example, the `JoinHandle` returned from `tokio::spawn` implements `Future` to allow joining to it.

The `.await` keyword, applied to a Future, causes the current async function to pause until that Future is ready, and then evaluates to its output.

This slide should take about 4 minutes.

- The `Future` and `Poll` types are implemented exactly as shown; click the links to show the implementations in the docs.
- `Context` allows a Future to schedule itself to be polled again when an event such as a timeout occurs.
- `Pin` ensures that the Future isn't moved in memory, so that pointers into that future remain valid. This is required to allow references to remain valid after an `.await`. We will address `Pin` in the ”Pitfalls” segment.

64.3 State Machine

Rust transforms an async function or block to a hidden type that implements `Future`, using a state machine to track the function's progress. The details of this transform are complex, but it is beneficial to have a schematic understanding of what is happening. The following function

```rust
/// Sum two D10 rolls plus a modifier.
async fn two_d10(modifier: u32) -> u32 {
    let first_roll = roll_d10().await;
    let second_roll = roll_d10().await;
    first_roll + second_roll + modifier
}
```

is transformed to something like

```rust
use std::future::Future;
use std::pin::Pin;
use std::task::{Context, Poll};

/// Sum two D10 rolls plus a modifier.
fn two_d10(modifier: u32) -> TwoD10 {
    TwoD10::Init { modifier }
}

enum TwoD10 {
    // Function has not begun yet.
    Init { modifier: u32 },
    // Waiting for first `.await` to complete.
    FirstRoll { modifier: u32, fut: RollD10Future },
    // Waiting for second `.await` to complete.
    SecondRoll { modifier: u32, first_roll: u32, fut: RollD10Future },
}

impl Future for TwoD10 {
    type Output = u32;
    fn poll(mut self: Pin<&mut Self>, ctx: &mut Context) -> Poll<Self::Output> {
        loop {
            match *self {
                TwoD10::Init { modifier } => {
                    // Create future for first dice roll.
                    let fut = roll_d10();
                    *self = TwoD10::FirstRoll { modifier, fut };
                }
                TwoD10::FirstRoll { modifier, ref mut fut } => {
                    // Poll sub-future for first dice roll.
                    if let Poll::Ready(first_roll) = fut.poll(ctx) {
                        // Create future for second roll.
                        let fut = roll_d10();
                        *self = TwoD10::SecondRoll { modifier, first_roll, fut };
                    } else {
                        return Poll::Pending;
```

```
                }
            }
            TwoD10::SecondRoll { modifier, first_roll, ref mut fut } => {
                // Poll sub-future for second dice roll.
                if let Poll::Ready(second_roll) = fut.poll(ctx) {
                    return Poll::Ready(first_roll + second_roll + modifier);
                } else {
                    return Poll::Pending;
                }
            }
        }
    }
}
}
```

This slide should take about 10 minutes.

This example is illustrative, and isn't an accurate representation of the Rust compiler's transformation. The important things to notice here are:

- Calling an async function does nothing but construct and return a future.
- All local variables are stored in the function's future, using an enum to identify where execution is currently suspended.
- An `.await` in the async function is translated into an a new state containing all live variables and the awaited future. The `loop` then handles that updated state, polling the future until it returns `Poll::Ready`.
- Execution continues eagerly until a `Poll::Pending` occurs. In this simple example, every future is ready immediately.
- `main` contains a naïve executor, which just busy-loops until the future is ready. We will discuss real executors shortly.

More to Explore

Imagine the `Future` data structure for a deeply nested stack of async functions. Each function's `Future` contains the `Future` structures for the functions it calls. This can result in unexpectedly large compiler-generated `Future` types.

This also means that recursive async functions are challenging. Compare to the common error of building recursive type, such as

```
enum LinkedList<T> {
    Node { value: T, next: LinkedList<T> },
    Nil,
}
```

The fix for a recursive type is to add a layer of indrection, such as with `Box`. Similarly, a recursive async function must box the recursive future:

```
async fn count_to(n: u32) {
    if n > 0 {
        Box::pin(count_to(n - 1)).await;
        println!("{n}");
```

```
    }
}
```

64.4 Runtimes

A *runtime* provides support for performing operations asynchronously (a *reactor*) and is responsible for executing futures (an *executor*). Rust does not have a ”built-in” runtime, but several options are available:

- Tokio: performant, with a well-developed ecosystem of functionality like Hyper for HTTP or Tonic for gRPC.
- smol: simple and lightweight

Several larger applications have their own runtimes. For example, Fuchsia already has one.

This slide and its sub-slides should take about 10 minutes.

- Note that of the listed runtimes, only Tokio is supported in the Rust playground. The playground also does not permit any I/O, so most interesting async things can't run in the playground.
- Futures are ”inert” in that they do not do anything (not even start an I/O operation) unless there is an executor polling them. This differs from JS Promises, for example, which will run to completion even if they are never used.

64.4.1 Tokio

Tokio provides:

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

```rust
use tokio::time;

async fn count_to(count: i32) {
    for i in 0..count {
        println!("Count in task: {i}!");
        time::sleep(time::Duration::from_millis(5)).await;
    }
}

#[tokio::main]
async fn main() {
    tokio::spawn(count_to(10));

    for i in 0..5 {
        println!("Main task: {i}");
        time::sleep(time::Duration::from_millis(5)).await;
    }
}
```

- With the `tokio::main` macro we can now make `main` async.

- The spawn function creates a new, concurrent ”task”.
- Note: `spawn` takes a `Future`, you don't call `.await` on `count_to`.

Further exploration:

- Why does `count_to` not get to 10? This is an example of async cancellation. `tokio::spawn` returns a handle which can be awaited to wait until it finishes.
- Try `count_to(10).await` instead of spawning.
- Try awaiting the task returned from `tokio::spawn`.

64.5 Tasks

Rust has a task system, which is a form of lightweight threading.

A task has a single top-level future which the executor polls to make progress. That future may have one or more nested futures that its `poll` method polls, corresponding loosely to a call stack. Concurrency within a task is possible by polling multiple child futures, such as racing a timer and an I/O operation.

```
use tokio::io::{self, AsyncReadExt, AsyncWriteExt};
use tokio::net::TcpListener;

#[tokio::main]
async fn main() -> io::Result<()> {
    let listener = TcpListener::bind("127.0.0.1:0").await?;
    println!("listening on port {}", listener.local_addr()?.port());

    loop {
        let (mut socket, addr) = listener.accept().await?;

        println!("connection from {addr:?}");

        tokio::spawn(async move {
            socket.write_all(b"Who are you?\n").await.expect("socket error");

            let mut buf = vec![0; 1024];
            let name_size = socket.read(&mut buf).await.expect("socket error");
            let name = std::str::from_utf8(&buf[..name_size]).unwrap().trim();
            let reply = format!("Thanks for dialing in, {name}!\n");
            socket.write_all(reply.as_bytes()).await.expect("socket error");
        });
    }
}
```

This slide should take about 6 minutes.

Copy this example into your prepared `src/main.rs` and run it from there.

Try connecting to it with a TCP connection tool like nc or telnet.

- Ask students to visualize what the state of the example server would be with a few connected clients. What tasks exist? What are their Futures?

- This is the first time we've seen an `async` block. This is similar to a closure, but does not take any arguments. Its return value is a Future, similar to an `async fn`.
- Refactor the async block into a function, and improve the error handling using `?`.

Chapter 65

Channels and Control Flow

This segment should take about 20 minutes. It contains:

Slide	Duration
Async Channels	10 minutes
Join	4 minutes
Select	5 minutes

65.1 Async Channels

Several crates have support for asynchronous channels. For instance `tokio`:

```
use tokio::sync::mpsc;

async fn ping_handler(mut input: mpsc::Receiver<()>) {
    let mut count: usize = 0;

    while let Some(_) = input.recv().await {
        count += 1;
        println!("Received {count} pings so far.");
    }

    println!("ping_handler complete");
}

#[tokio::main]
async fn main() {
    let (sender, receiver) = mpsc::channel(32);
    let ping_handler_task = tokio::spawn(ping_handler(receiver));
    for i in 0..10 {
        sender.send(()).await.expect("Failed to send ping.");
        println!("Sent {} pings so far.", i + 1);
    }
```

```
    drop(sender);
    ping_handler_task.await.expect("Something went wrong in ping handler task.");
}
```

This slide should take about 8 minutes.

- Change the channel size to 3 and see how it affects the execution.
- Overall, the interface is similar to the sync channels as seen in the morning class.
- Try removing the std::mem::drop call. What happens? Why?
- The Flume crate has channels that implement both sync and async send and recv. This can be convenient for complex applications with both IO and heavy CPU processing tasks.
- What makes working with async channels preferable is the ability to combine them with other futures to combine them and create complex control flow.

65.2 Join

A join operation waits until all of a set of futures are ready, and returns a collection of their results. This is similar to Promise.all in JavaScript or asyncio.gather in Python.

```
use anyhow::Result;
use futures::future;
use reqwest;
use std::collections::HashMap;

async fn size_of_page(url: &str) -> Result<usize> {
    let resp = reqwest::get(url).await?;
    Ok(resp.text().await?.len())
}

#[tokio::main]
async fn main() {
    let urls: [&str; 4] = [
        "https://google.com",
        "https://httpbin.org/ip",
        "https://play.rust-lang.org/",
        "BAD_URL",
    ];
    let futures_iter = urls.into_iter().map(size_of_page);
    let results = future::join_all(futures_iter).await;
    let page_sizes_dict: HashMap<&str, Result<usize>> =
        urls.into_iter().zip(results.into_iter()).collect();
    println!("{page_sizes_dict:?}");
}
```

This slide should take about 4 minutes.

Copy this example into your prepared src/main.rs and run it from there.

- For multiple futures of disjoint types, you can use std::future::join! but you must know how many futures you will have at compile time. This is currently in the futures crate, soon to be stabilised in `std::future`.

- The risk of `join` is that one of the futures may never resolve, this would cause your program to stall.
- You can also combine `join_all` with `join!` for instance to join all requests to an http service as well as a database query. Try adding a `tokio::time::sleep` to the future, using `futures::join!`. This is not a timeout (that requires `select!`, explained in the next chapter), but demonstrates `join!`.

65.3 Select

A select operation waits until any of a set of futures is ready, and responds to that future's result. In JavaScript, this is similar to `Promise.race`. In Python, it compares to `asyncio.wait(task_set, return_when=asyncio.FIRST_COMPLETED)`.

Similar to a match statement, the body of `select!` has a number of arms, each of the form `pattern = future => statement`. When a `future` is ready, its return value is destructured by the `pattern`. The `statement` is then run with the resulting variables. The `statement` result becomes the result of the `select!` macro.

```
use tokio::sync::mpsc;
use tokio::time::{Duration, sleep};

#[tokio::main]
async fn main() {
    let (tx, mut rx) = mpsc::channel(32);
    let listener = tokio::spawn(async move {
        tokio::select! {
            Some(msg) = rx.recv() => println!("got: {msg}"),
            _ = sleep(Duration::from_millis(50)) => println!("timeout"),
        };
    });
    sleep(Duration::from_millis(10)).await;
    tx.send(String::from("Hello!")).await.expect("Failed to send greeting");

    listener.await.expect("Listener failed");
}
```

This slide should take about 5 minutes.

- The `listener` async block here is a common form: wait for some async event, or for a timeout. Change the `sleep` to sleep longer to see it fail. Why does the `send` also fail in this situation?
- `select!` is also frequently used in a loop in ”actor” architectures, where a task reacts to events in a loop. That has some pitfalls, which will be discussed in the next segment.

Chapter 66

Pitfalls

Async / await provides convenient and efficient abstraction for concurrent asynchronous programming. However, the async/await model in Rust also comes with its share of pitfalls and footguns. We illustrate some of them in this chapter.

This segment should take about 55 minutes. It contains:

Slide	Duration
Blocking the Executor	10 minutes
Pin	20 minutes
Async Traits	5 minutes
Cancellation	20 minutes

66.1 Blocking the executor

Most async runtimes only allow IO tasks to run concurrently. This means that CPU blocking tasks will block the executor and prevent other tasks from being executed. An easy workaround is to use async equivalent methods where possible.

```
use futures::future::join_all;
use std::time::Instant;

async fn sleep_ms(start: &Instant, id: u64, duration_ms: u64) {
    std::thread::sleep(std::time::Duration::from_millis(duration_ms));
    println!(
        "future {id} slept for {duration_ms}ms, finished after {}ms",
        start.elapsed().as_millis()
    );
}

#[tokio::main(flavor = "current_thread")]
async fn main() {
    let start = Instant::now();
    let sleep_futures = (1..=10).map(|t| sleep_ms(&start, t, t * 10));
```

```
    join_all(sleep_futures).await;
}
```

This slide should take about 10 minutes.

- Run the code and see that the sleeps happen consecutively rather than concurrently.
- The "current_thread" flavor puts all tasks on a single thread. This makes the effect more obvious, but the bug is still present in the multi-threaded flavor.
- Switch the `std::thread::sleep` to `tokio::time::sleep` and await its result.
- Another fix would be to `tokio::task::spawn_blocking` which spawns an actual thread and transforms its handle into a future without blocking the executor.
- You should not think of tasks as OS threads. They do not map 1 to 1 and executors will allow multiple tasks to run on a single OS thread. This is particularly problematic when interacting with other libraries via FFI, where that library might depend on thread-local storage or map to specific OS threads (e.g., CUDA). Prefer `tokio::task::spawn_blocking` in such situations.
- Use sync mutexes with care. Holding a mutex over an `.await` may cause another task to block, and that task may be running on the same thread.

66.2 Pin

Recall an async function or block creates a type implementing `Future` and containing all of the local variables. Some of those variables can hold references (pointers) to other local variables. To ensure those remain valid, the future can never be moved to a different memory location.

To prevent moving the future type in memory, it can only be polled through a pinned pointer. `Pin` is a wrapper around a reference that disallows all operations that would move the instance it points to into a different memory location.

```
use tokio::sync::{mpsc, oneshot};
use tokio::task::spawn;
use tokio::time::{Duration, sleep};

// A work item. In this case, just sleep for the given time and respond
// with a message on the `respond_on` channel.
#[derive(Debug)]
struct Work {
    input: u32,
    respond_on: oneshot::Sender<u32>,
}

// A worker which listens for work on a queue and performs it.
async fn worker(mut work_queue: mpsc::Receiver<Work>) {
    let mut iterations = 0;
    loop {
        tokio::select! {
            Some(work) = work_queue.recv() => {
                sleep(Duration::from_millis(10)).await; // Pretend to work.
```

```
                work.respond_on
                    .send(work.input * 1000)
                    .expect("failed to send response");
                iterations += 1;
            }
            // TODO: report number of iterations every 100ms
        }
    }
}

// A requester which requests work and waits for it to complete.
async fn do_work(work_queue: &mpsc::Sender<Work>, input: u32) -> u32 {
    let (tx, rx) = oneshot::channel();
    work_queue
        .send(Work { input, respond_on: tx })
        .await
        .expect("failed to send on work queue");
    rx.await.expect("failed waiting for response")
}

#[tokio::main]
async fn main() {
    let (tx, rx) = mpsc::channel(10);
    spawn(worker(rx));
    for i in 0..100 {
        let resp = do_work(&tx, i).await;
        println!("work result for iteration {i}: {resp}");
    }
}
```

This slide should take about 20 minutes.

- You may recognize this as an example of the actor pattern. Actors typically call `select!` in a loop.
- This serves as a summation of a few of the previous lessons, so take your time with it.
  - Naively add a `_ = sleep(Duration::from_millis(100)) => { println!(..) }` to the `select!`. This will never execute. Why?
  - Instead, add a `timeout_fut` containing that future outside of the `loop`:

    ```
    let timeout_fut = sleep(Duration::from_millis(100));
    loop {
        select! {
            ..,
            _ = timeout_fut => { println!(..); },
        }
    }
    ```

  - This still doesn't work. Follow the compiler errors, adding `&mut` to the `timeout_fut` in the `select!` to work around the move, then using `Box::pin`:

    ```
    let mut timeout_fut = Box::pin(sleep(Duration::from_millis(100)));
    loop {
    ```

```
        select! {
            ..,
            _ = &mut timeout_fut => { println!(..); },
        }
    }
```

- This compiles, but once the timeout expires it is `Poll::Ready` on every iteration (a fused future would help with this). Update to reset `timeout_fut` every time it expires:

```
let mut timeout_fut = Box::pin(sleep(Duration::from_millis(100)));
loop {
    select! {
        _ = &mut timeout_fut => {
            println!(..);
            timeout_fut = Box::pin(sleep(Duration::from_millis(100)));
        },
    }
}
```

- Box allocates on the heap. In some cases, `std::pin::pin!` (only recently stabilized, with older code often using `tokio::pin!`) is also an option, but that is difficult to use for a future that is reassigned.
- Another alternative is to not use `pin` at all but spawn another task that will send to a `oneshot` channel every 100ms.
- Data that contains pointers to itself is called self-referential. Normally, the Rust borrow checker would prevent self-referential data from being moved, as the references cannot outlive the data they point to. However, the code transformation for async blocks and functions is not verified by the borrow checker.
- `Pin` is a wrapper around a reference. An object cannot be moved from its place using a pinned pointer. However, it can still be moved through an unpinned pointer.
- The `poll` method of the `Future` trait uses `Pin<&mut Self>` instead of `&mut Self` to refer to the instance. That's why it can only be called on a pinned pointer.

66.3 Async Traits

Async methods in traits were stabilized in the 1.75 release. This required support for using return-position `impl Trait` in traits, as the desugaring for `async fn` includes `-> impl Future<Output = ...>`.

However, even with the native support, there are specific pitfalls around `async fn`:

- Return-position `impl Trait` captures all in-scope lifetimes (so certain patterns of borrowing cannot be expressed).
- Async traits cannot be used with trait objects (`dyn Trait` support).

The async_trait crate provides a workaround for `dyn` support through a macro, with specific caveats:

```
use async_trait::async_trait;
use std::time::Instant;
```

```rust
use tokio::time::{Duration, sleep};

#[async_trait]
trait Sleeper {
    async fn sleep(&self);
}

struct FixedSleeper {
    sleep_ms: u64,
}

#[async_trait]
impl Sleeper for FixedSleeper {
    async fn sleep(&self) {
        sleep(Duration::from_millis(self.sleep_ms)).await;
    }
}

async fn run_all_sleepers_multiple_times(
    sleepers: Vec<Box<dyn Sleeper>>,
    n_times: usize,
) {
    for _ in 0..n_times {
        println!("Running all sleepers...");
        for sleeper in &sleepers {
            let start = Instant::now();
            sleeper.sleep().await;
            println!("Slept for {} ms", start.elapsed().as_millis());
        }
    }
}

#[tokio::main]
async fn main() {
    let sleepers: Vec<Box<dyn Sleeper>> = vec![
        Box::new(FixedSleeper { sleep_ms: 50 }),
        Box::new(FixedSleeper { sleep_ms: 100 }),
    ];
    run_all_sleepers_multiple_times(sleepers, 5).await;
}
```

This slide should take about 5 minutes.

- `async_trait` is easy to use, but note that it's using heap allocations to achieve this. This heap allocation has performance overhead.
- The challenges in language support for `async trait` are too deep to describe in-depth in this class. See this blog post by Niko Matsakis if you are interested in digging deeper. See also these keywords:
  - RPIT: short for return-position `impl Trait`.
  - RPITIT: short for return-position `impl Trait` in trait (RPIT in trait).

- Try creating a new sleeper struct that will sleep for a random amount of time and adding it to the Vec.

66.4 Cancellation

Dropping a future implies it can never be polled again. This is called *cancellation* and it can occur at any `await` point. Care is needed to ensure the system works correctly even when futures are cancelled. For example, it shouldn't deadlock or lose data.

```
use std::io;
use std::time::Duration;
use tokio::io::{AsyncReadExt, AsyncWriteExt, DuplexStream};

struct LinesReader {
    stream: DuplexStream,
}

impl LinesReader {
    fn new(stream: DuplexStream) -> Self {
        Self { stream }
    }

    async fn next(&mut self) -> io::Result<Option<String>> {
        let mut bytes = Vec::new();
        let mut buf = [0];
        while self.stream.read(&mut buf[..]).await? != 0 {
            bytes.push(buf[0]);
            if buf[0] == b'\n' {
                break;
            }
        }
        if bytes.is_empty() {
            return Ok(None);
        }
        let s = String::from_utf8(bytes)
            .map_err(|_| io::Error::new(io::ErrorKind::InvalidData, "not UTF-8"))?;
        Ok(Some(s))
    }
}

async fn slow_copy(source: String, mut dest: DuplexStream) -> io::Result<()> {
    for b in source.bytes() {
        dest.write_u8(b).await?;
        tokio::time::sleep(Duration::from_millis(10)).await
    }
    Ok(())
}

#[tokio::main]
async fn main() -> io::Result<()> {
```

```rust
    let (client, server) = tokio::io::duplex(5);
    let handle = tokio::spawn(slow_copy("hi\nthere\n".to_owned(), client));

    let mut lines = LinesReader::new(server);
    let mut interval = tokio::time::interval(Duration::from_millis(60));
    loop {
        tokio::select! {
            _ = interval.tick() => println!("tick!"),
            line = lines.next() => if let Some(l) = line? {
                print!("{}", l)
            } else {
                break
            },
        }
    }
    handle.await.unwrap()?;
    Ok(())
}
```

This slide should take about 18 minutes.

- The compiler doesn't help with cancellation-safety. You need to read API documentation and consider what state your `async fn` holds.
- Unlike `panic` and `?`, cancellation is part of normal control flow (vs error-handling).
- The example loses parts of the string.
  - Whenever the `tick()` branch finishes first, `next()` and its `buf` are dropped.
  - `LinesReader` can be made cancellation-safe by making `buf` part of the struct:

```rust
struct LinesReader {
    stream: DuplexStream,
    bytes: Vec<u8>,
    buf: [u8; 1],
}

impl LinesReader {
    fn new(stream: DuplexStream) -> Self {
        Self { stream, bytes: Vec::new(), buf: [0] }
    }
    async fn next(&mut self) -> io::Result<Option<String>> {
        // prefix buf and bytes with self.
        // ...
        let raw = std::mem::take(&mut self.bytes);
        let s = String::from_utf8(raw)
            .map_err(|_| io::Error::new(io::ErrorKind::InvalidData, "not UTF-8")
        // ...
    }
}
```

- `Interval::tick` is cancellation-safe because it keeps track of whether a tick has been 'delivered'.

- `AsyncReadExt::read` is cancellation-safe because it either returns or doesn't read data.
- `AsyncBufReadExt::read_line` is similar to the example and *isn't* cancellation-safe. See its documentation for details and alternatives.

Chapter 67

Exercises

This segment should take about 1 hour and 10 minutes. It contains:

Slide	Duration
Dining Philosophers	20 minutes
Broadcast Chat Application	30 minutes
Solutions	20 minutes

67.1 Dining Philosophers --- Async

See dining philosophers for a description of the problem.

As before, you will need a local Cargo installation for this exercise. Copy the code below to a file called `src/main.rs`, fill out the blanks, and test that `cargo run` does not deadlock:

```
use std::sync::Arc;
use tokio::sync::{Mutex, mpsc};
use tokio::time;

struct Chopstick;

struct Philosopher {
    name: String,
    // left_chopstick: ...
    // right_chopstick: ...
    // thoughts: ...
}

impl Philosopher {
    async fn think(&self) {
        self.thoughts
            .send(format!("Eureka! {} has a new idea!", &self.name))
            .await
            .unwrap();
```

```rust
    }

    async fn eat(&self) {
        // Keep trying until we have both chopsticks
        println!("{} is eating...", &self.name);
        time::sleep(time::Duration::from_millis(5)).await;
    }
}

// tokio scheduler doesn't deadlock with 5 philosophers, so have 2.
static PHILOSOPHERS: &[&str] = &["Socrates", "Hypatia"];

#[tokio::main]
async fn main() {
    // Create chopsticks

    // Create philosophers

    // Make them think and eat

    // Output their thoughts
}
```

Since this time you are using Async Rust, you'll need a `tokio` dependency. You can use the following `Cargo.toml`:

```toml
[package]
name = "dining-philosophers-async-dine"
version = "0.1.0"
edition = "2024"

[dependencies]
tokio = { version = "1.26.0", features = ["sync", "time", "macros", "rt-multi-thread"] }
```

Also note that this time you have to use the `Mutex` and the `mpsc` module from the `tokio` crate.

This slide should take about 20 minutes.

- Can you make your implementation single-threaded?

67.2 Broadcast Chat Application

In this exercise, we want to use our new knowledge to implement a broadcast chat application. We have a chat server that the clients connect to and publish their messages. The client reads user messages from the standard input, and sends them to the server. The chat server broadcasts each message that it receives to all the clients.

For this, we use a broadcast channel on the server, and `tokio_websockets` for the communication between the client and the server.

Create a new Cargo project and add the following dependencies:

Cargo.toml:

```toml
[package]
name = "chat-async"
version = "0.1.0"
edition = "2024"

[dependencies]
futures-util = { version = "0.3.32", features = ["sink"] }
http = "1.4.0"
tokio = { version = "1.49.0", features = ["full"] }
tokio-websockets = { version = "0.13.1", features = ["client", "fastrand", "server", "sl
```

The required APIs

You are going to need the following functions from `tokio` and `tokio_websockets`. Take time to familiarize yourself with the API.

- StreamExt::next() implemented by `WebSocketStream`: for asynchronously reading messages from a Websocket Stream.
- SinkExt::send() implemented by `WebSocketStream`: for asynchronously sending messages on a Websocket Stream.
- Lines::next_line(): for asynchronously reading user messages from the standard input.
- Sender::subscribe(): for subscribing to a broadcast channel.

Two binaries

Normally in a Cargo project, you can have only one binary, and one `src/main.rs` file. In this project, we need two binaries. One for the client, and one for the server. You could potentially make them two separate Cargo projects, but we are going to put them in a single Cargo project with two binaries. For this to work, the client and the server code should go under `src/bin` (see the documentation).

Copy the following server and client code into `src/bin/server.rs` and `src/bin/client.rs`, respectively. Your task is to complete these files as described below.

src/bin/server.rs:

```rust
use futures_util::sink::SinkExt;
use futures_util::stream::StreamExt;
use std::error::Error;
use std::net::SocketAddr;
use tokio::net::{TcpListener, TcpStream};
use tokio::sync::broadcast::{Sender, channel};
use tokio_websockets::{Message, ServerBuilder, WebSocketStream};

async fn handle_connection(
    addr: SocketAddr,
    mut ws_stream: WebSocketStream<TcpStream>,
    bcast_tx: Sender<String>,
) -> Result<(), Box<dyn Error + Send + Sync>> {

    // TODO: For a hint, see the description of the task below.
```

```
}

#[tokio::main]
async fn main() -> Result<(), Box<dyn Error + Send + Sync>> {
    let (bcast_tx, _) = channel(16);

    let listener = TcpListener::bind("127.0.0.1:2000").await?;
    println!("listening on port 2000");

    loop {
        let (socket, addr) = listener.accept().await?;
        println!("New connection from {addr:?}");
        let bcast_tx = bcast_tx.clone();
        tokio::spawn(async move {
            // Wrap the raw TCP stream into a websocket.
            let (_req, ws_stream) = ServerBuilder::new().accept(socket).await?;

            handle_connection(addr, ws_stream, bcast_tx).await
        });
    }
}
```

src/bin/client.rs:

```
use futures_util::SinkExt;
use futures_util::stream::StreamExt;
use http::Uri;
use tokio::io::{AsyncBufReadExt, BufReader};
use tokio_websockets::{ClientBuilder, Message};

#[tokio::main]
async fn main() -> Result<(), tokio_websockets::Error> {
    let (mut ws_stream, _) =
        ClientBuilder::from_uri(Uri::from_static("ws://127.0.0.1:2000"))
            .connect()
            .await?;

    let stdin = tokio::io::stdin();
    let mut stdin = BufReader::new(stdin).lines();


    // TODO: For a hint, see the description of the task below.

}
```

Running the binaries

Run the server with:

```
cargo run --bin server
```

and the client with:

```
cargo run --bin client
```

Tasks

- Implement the handle_connection function in `src/bin/server.rs`.
  - Hint: Use `tokio::select!` for concurrently performing two tasks in a continuous loop. One task receives messages from the client and broadcasts them. The other sends messages received by the server to the client.
- Complete the main function in `src/bin/client.rs`.
  - Hint: As before, use `tokio::select!` in a continuous loop for concurrently performing two tasks: (1) reading user messages from standard input and sending them to the server, and (2) receiving messages from the server, and displaying them for the user.
- Optional: Once you are done, change the code to broadcast messages to all clients, but the sender of the message.

67.3 Solutions

Dining Philosophers --- Async

```rust
use std::sync::Arc;
use tokio::sync::{Mutex, mpsc};
use tokio::time;

struct Chopstick;

struct Philosopher {
    name: String,
    left_chopstick: Arc<Mutex<Chopstick>>,
    right_chopstick: Arc<Mutex<Chopstick>>,
    thoughts: mpsc::Sender<String>,
}

impl Philosopher {
    async fn think(&self) {
        self.thoughts
            .send(format!("Eureka! {} has a new idea!", &self.name))
            .await
            .unwrap();
    }

    async fn eat(&self) {
        // Keep trying until we have both chopsticks
        // Pick up chopsticks...
        let _left_chopstick = self.left_chopstick.lock().await;
        let _right_chopstick = self.right_chopstick.lock().await;

        println!("{} is eating...", &self.name);
        time::sleep(time::Duration::from_millis(5)).await;
```

```rust
            // The locks are dropped here
        }
    }

    // tokio scheduler doesn't deadlock with 5 philosophers, so have 2.
    static PHILOSOPHERS: &[&str] = &["Socrates", "Hypatia"];

    #[tokio::main]
    async fn main() {
        // Create chopsticks
        let mut chopsticks = vec![];
        PHILOSOPHERS
            .iter()
            .for_each(|_| chopsticks.push(Arc::new(Mutex::new(Chopstick))));

        // Create philosophers
        let (philosophers, mut rx) = {
            let mut philosophers = vec![];
            let (tx, rx) = mpsc::channel(10);
            for (i, name) in PHILOSOPHERS.iter().enumerate() {
                let mut left_chopstick = Arc::clone(&chopsticks[i]);
                let mut right_chopstick =
                    Arc::clone(&chopsticks[(i + 1) % PHILOSOPHERS.len()]);
                if i == PHILOSOPHERS.len() - 1 {
                    std::mem::swap(&mut left_chopstick, &mut right_chopstick);
                }
                philosophers.push(Philosopher {
                    name: name.to_string(),
                    left_chopstick,
                    right_chopstick,
                    thoughts: tx.clone(),
                });
            }
            (philosophers, rx)
            // tx is dropped here, so we don't need to explicitly drop it later
        };

        // Make them think and eat
        for phil in philosophers {
            tokio::spawn(async move {
                for _ in 0..100 {
                    phil.think().await;
                    phil.eat().await;
                }
            });
        }

        // Output their thoughts
        while let Some(thought) = rx.recv().await {
            println!("Here is a thought: {thought}");
        }
```

```
}
```

Broadcast Chat Application

src/bin/server.rs:

```rust
use futures_util::sink::SinkExt;
use futures_util::stream::StreamExt;
use std::error::Error;
use std::net::SocketAddr;
use tokio::net::{TcpListener, TcpStream};
use tokio::sync::broadcast::{Sender, channel};
use tokio_websockets::{Message, ServerBuilder, WebSocketStream};

async fn handle_connection(
    addr: SocketAddr,
    mut ws_stream: WebSocketStream<TcpStream>,
    bcast_tx: Sender<String>,
) -> Result<(), Box<dyn Error + Send + Sync>> {

    ws_stream
        .send(Message::text("Welcome to chat! Type a message".to_string()))
        .await?;
    let mut bcast_rx = bcast_tx.subscribe();

    // A continuous loop for concurrently performing two tasks: (1) receiving
    // messages from `ws_stream` and broadcasting them, and (2) receiving
    // messages on `bcast_rx` and sending them to the client.
    loop {
        tokio::select! {
            incoming = ws_stream.next() => {
                match incoming {
                    Some(Ok(msg)) => {
                        if let Some(text) = msg.as_text() {
                            println!("From client {addr:?} {text:?}");
                            bcast_tx.send(text.into())?;
                        }
                    }
                    Some(Err(err)) => return Err(err.into()),
                    None => return Ok(()),
                }
            }
            msg = bcast_rx.recv() => {
                ws_stream.send(Message::text(msg?)).await?;
            }
        }
    }
}

#[tokio::main]
async fn main() -> Result<(), Box<dyn Error + Send + Sync>> {
```

```
    let (bcast_tx, _) = channel(16);

    let listener = TcpListener::bind("127.0.0.1:2000").await?;
    println!("listening on port 2000");

    loop {
        let (socket, addr) = listener.accept().await?;
        println!("New connection from {addr:?}");
        let bcast_tx = bcast_tx.clone();
        tokio::spawn(async move {
            // Wrap the raw TCP stream into a websocket.
            let (_req, ws_stream) = ServerBuilder::new().accept(socket).await?;

            handle_connection(addr, ws_stream, bcast_tx).await
        });
    }
}
```

src/bin/client.rs:

```
use futures_util::SinkExt;
use futures_util::stream::StreamExt;
use http::Uri;
use tokio::io::{AsyncBufReadExt, BufReader};
use tokio_websockets::{ClientBuilder, Message};

#[tokio::main]
async fn main() -> Result<(), tokio_websockets::Error> {
    let (mut ws_stream, _) =
        ClientBuilder::from_uri(Uri::from_static("ws://127.0.0.1:2000"))
            .connect()
            .await?;

    let stdin = tokio::io::stdin();
    let mut stdin = BufReader::new(stdin).lines();

    // Continuous loop for concurrently sending and receiving messages.
    loop {
        tokio::select! {
            incoming = ws_stream.next() => {
                match incoming {
                    Some(Ok(msg)) => {
                        if let Some(text) = msg.as_text() {
                            println!("From server: {}", text);
                        }
                    },
                    Some(Err(err)) => return Err(err),
                    None => return Ok(()),
                }
            }
            res = stdin.next_line() => {
                match res {
```

```
                    Ok(None) => return Ok(()),
                    Ok(Some(line)) => ws_stream.send(Message::text(line.to_string())).aw
                    Err(err) => return Err(err.into()),
                }
            }

        }
    }
}
```

Part XV

Idiomatic Rust

Chapter 68

Welcome to Idiomatic Rust

Rust Fundamentals introduced Rust syntax and core concepts. We now want to go one step further: how do you use Rust *effectively* in your projects? What does *idiomatic* Rust look like?

This course is opinionated: we will nudge you towards some patterns, and away from others. Nonetheless, we do recognize that some projects may have different needs. We always provide the necessary information to help you make informed decisions within the context and constraints of your own projects.

> ⚠️ This course is under **active development**.
>
> The material may change frequently and there might be errors that have not yet been spotted. Nonetheless, we encourage you to browse through and provide early feedback!

Schedule

Including 10 minute breaks, this session should take about 14 hours and 25 minutes. It contains:

Segment	Duration
Foundations of API Design	3 hours and 30 minutes
Leveraging the Type System	7 hours and 30 minutes
Polymorphism	3 hours and 5 minutes

The course will cover the topics listed below. Each topic may be covered in one or more slides, depending on its complexity and relevance.

Target Audience

Engineers with at least 2-3 years of coding experience in C, C++11 or newer, Java 7 or newer, Python 2 or 3, Go or any other similar imperative programming language. We have no expectation of experience with more modern or feature-rich languages like Swift, Kotlin, C#, or TypeScript.

Foundations of API design

- Golden rule: prioritize clarity and readability at the callsite. People will spend much more time reading the call sites than declarations of the functions being called.
- Make your API predictable
  - Follow naming conventions (case conventions, prefer vocabulary precedented in the standard library - e.g., methods should be called ”push” not ”push_back”, ”is_empty” not ”empty” etc.)
  - Know the vocabulary types and traits in the standard library, and use them in your APIs. If something feels like a basic type/algorithm, check in the standard library first.
  - Use well-established API design patterns that we will discuss later in this class (e.g., newtype, owned/view type pairs, error handling)
- Write meaningful and effective doc comments (e.g., don't merely repeat the method name with spaces instead of underscores, don't repeat the same information just to fill out every markdown tag, provide usage examples)

Leveraging the type system

- Short recap on enums, structs and type aliases
- Newtype pattern and encapsulation: parse, don't validate
- Extension traits: avoid the newtype pattern when you want to provide additional behaviour
- RAII, scope guards and drop bombs: using `Drop` to clean up resources, trigger actions or enforce invariants
- ”Token” types: force users to prove they've performed a specific action
- The typestate pattern: enforce correct state transitions at compile-time
- Using the borrow checker to enforce invariants that have nothing to do with memory ownership
  - OwnedFd/BorrowedFd in the standard library
  - Branded types

Don't fight the borrow checker

- ”Owned” types and ”view” types: `&str` and `String`, `Path` and `PathBuf`, etc.
- Don't hide ownership requirements: avoid hidden `.clone()`, learn to love `Cow`
- Split types along ownership boundaries
- Structure your ownership hierarchy like a tree
- Strategies to manage circular dependencies: reference counting, using indexes instead of references
- Interior mutability (Cell, RefCell)
- Working with lifetime parameters on user-defined data types

Polymorphism in Rust

- A quick refresher on traits and generic functions
- Rust has no inheritance: what are the implications?
  - Using enums for polymorphism
  - Using traits for polymorphism
  - Using composition

    - How do I pick the most appropriate pattern?
- Working with generics
    - Generic type parameter in a function or trait object as an argument?
    - Trait bounds don't have to refer to the generic parameter
    - Type parameters in traits: should it be a generic parameter or an associated type?
- Macros: a valuable tool to DRY up code when traits are not enough (or too complex)

Error Handling

- What is the purpose of errors? Recovery vs. reporting.
- Result vs. Option
- Designing good errors:
    - Determine the error scope.
    - Capture additional context as the error flows upwards, crossing scope boundaries.
    - Leverage the `Error` trait to keep track of the full error chain.
    - Leverage `thiserror` to reduce boilerplate when defining error types.
    - `anyhow`
- Distinguish fatal errors from recoverable errors using `Result<Result<T, RecoverableError>, FatalError>`.

Chapter 69

Foundations of API Design

This segment should take about 3 hours and 30 minutes. It contains:

Slide	Duration
Foundations of API Design	2 minutes
Meaningful Doc Comments	1 hour and 25 minutes
Predictable API	2 hours and 5 minutes

69.1 Meaningful Doc Comments

```rust
/// API for the client // ❌ Lacks detail
pub mod client {}

/// Function from A to B // ❌ Redundant
fn a_to_b(a: A) -> B {...}

/// Connects to the database. // ❌ Lacks detail
fn connect() -> Result<(), Error> {...}
```

This slide and its sub-slides should take about 85 minutes.

- Doc comments are the most common form of documentation developers engage with.
- Good doc comments provide information that the code, names, and types cannot, without restating the obvious information.

69.1.1 Who are you writing for?

Colleagues, collaborators, largely-silent API users, or just yourself?

```rust
// expert writes for experts
/// Canonicalizes the MIR for the borrow checker.
///
/// This pass ensures that all borrows conform to the NLL-Polonius constraints
/// before we proceed to MIR-to-LLVM-IR translation.
```

```rust
pub fn canonicalize_mir(mir: &mut Mir) {
    // ...
}

// expert writes for newcomers
/// Prepares the Mid-level IR (MIR) for borrow checking.
///
/// The borrow checker operates on a simplified, "canonical" form of the MIR.
/// This function performs that transformation. It is a prerequisite for the
/// final stages of code generation.
///
/// For more about Rust's intermediate representations, see the
/// [rustc-dev-guide](https://rustc-dev-guide.rust-lang.org/mir/index.html).
pub fn canonicalize_mir(mir: &mut Mir) {
    // ...
}
```

- Background: The curse of knowledge is a cognitive bias where experts assume that others have the same level of expertise and perspective.
- Motivation: Your reader does not have the same level of expertise and the same perspective as you. Don't write for people like yourself, write for others.
- Unintentionally writing for yourself can lead to people not understanding a point you're trying to make or the concept you're trying to articulate.
- Imagine a version of you, or others you've known, struggling to find practical information while going through documentation.

  Keep this idea of a person in mind when thinking about what areas of a codebase need attention for doc comments.
- Who are you writing for?
- Also imagine a version of you, or others you've known, who is struggling to find the important details in winding, extensive doc comments. Don't give too much information.
- Always ask: Is this documentation making it difficult for the API user? Are they able to quickly grasp what they need or find out where they could need it?
- Always consider: Experts also read API level documentation. Doc comments might not be the right place to educate your audience about the basics of your domain. In that case, signpost and name-drop. Divert people to long-form documentation.

69.1.2 Library vs application docs

You might see elaborate documentation for fundamental APIs that repeats the names and type signatures. Stable and highly reusable code can afford this with a positive RoI.

- Library code:
  - has a high number of users,
  - solves a whole range of related problems,
  - often has stable APIs.
- Application code is the opposite:

  - few users,
  - solves a specific problem,
  - changes often.

- You might have seen elaborate documentation that repeats code, looks at the same API multiple times with many examples and case studies. Context is key: who wrote it, for whom, and what material it is covering, and what resources did they have.

- Fundamental library code often has Elaborate documentation, for example, the standard library, highly reusable frameworks like serde and tokio. Teams responsible for this code often have appropriate resources to write and maintain elaborate documentation.

- Library code is often stable, so the community is going to extract a significant benefit from elaborate documentation before it needs to be reworked.

- Application code has the opposite traits: it has few users, solves a specific problem, and changes often. For application code elaborate documentation quickly becomes outdated and misleading. It is also difficult to extract a positive RoI from boilerplate docs even while they are up to date, because there are only a few users.

69.1.3 The Anatomy of a Doc Comment

1. A brief, one-sentence summary.
2. A more detailed explanation.
3. Special sections: code examples, panics, errors, safety preconditions.

```rust
/// Parses a key-value pair from a string.
///
/// The input string must be in the format `key=value`. Everything before the
/// first '=' is treated as the key, and everything after is the value.
///
/// # Examples
///
/// ```
/// use my_crate::parse_key_value;
/// let (key, value) = parse_key_value("lang=rust").unwrap();
/// assert_eq!(key, "lang");
/// assert_eq!(value, "rust");
/// ```
///
/// # Panics
///
/// Panics if the input is empty.
///
/// # Errors
///
/// Returns a `ParseError::Malformed` if the string does not contain `=`.
///
/// # Safety
///
/// Triggers undefined behavior if...
unsafe fn parse_key_value(s: &str) -> Result<(String, String), ParseError>
```

```rust
enum ParseError {
    Empty,
    Malformed,
}
```

- Idiomatic Rust doc comments follow a conventional structure that makes them easier for developers to read.
- The first line of a doc comment is a single-sentence summary of the function. Keep it concise. `rustdoc` and other tools have a strong expectation about that: it is used as a short summary in module-level documentation and search results.
- Next, you can provide a long, multi-paragraph description of the ”why” and ”what” of the function. Use Markdown.
- Finally, you can use top-level section headers to organize your content. Doc comments commonly use `# Examples`, `# Panics`, `# Errors`, and `# Safety` as section titles. The Rust community expects to see relevant aspects of your API documented in these sections.
- Rust heavily focuses on safety and correctness. Documenting behavior of your code in case of errors is critical for writing reliable software.
- `# Panics`: If your function may panic, you must document the specific conditions when that might happen. Callers need to know what to avoid.
- `# Errors`: For functions returning a `Result`, this section explains what kind of errors can occur and under what circumstances. Callers need this information to write robust error handling logic.
- **Question:** Ask the class why documenting panics is so important in a language that prefers returning `Result`.
  - **Answer:** Panics are for unrecoverable, programming errors. A library should not panic unless a contract is violated by the caller. Documenting these contracts is essential.
- `# Safety` comments document safety preconditions on unsafe functions that must be satisfied, or else undefined behavior might result. They are discussed in detail in the Unsafe Rust deep dive.

69.1.4 Name-dropping keywords and signposting topics

```rust
/// A parsed representation of a MARC 21 record
/// [leader](//www.loc.gov/marc/bibliographic/bdleader.html).
/// A MARC leader contains metadata that dictates how to interpret the rest
/// of the record.
pub struct Leader {
    /// Determines the schema and the set of valid subsequent data fields.
    ///
    /// Encoded in byte 6 of the leader.
    pub type_of_record: char,

    /// Indicates whether to parse relationship fields, such as a "773 Host
    /// Item Entry" for an article within a larger work.
    ///
    /// Encoded in byte 7 of the leader.
```

```rust
    pub bibliographic_level: char,
    // ... other fields
}

/// Parses the [leader of a MARC 21 record](https://www.loc.gov/marc/bibliographic/bdlea
///
/// The leader is encoded as a fixed-length 24-byte field, containing metadata
/// that determines the semantic interpretation of the rest of the record.
pub fn parse_leader(leader_bytes: &[u8; 24]) -> Result<Leader, MarcError> {
    todo!()
}

#[derive(Debug)]
pub enum MarcError {}
```

- Motivation: Readers of documentation will not be closely reading most of your doc comments like they would dialogue in a novel they love.

Users will most likely be skimming and scan-reading to find the part of the documentation that is relevant to whatever problem they're trying to solve in the moment.

Once a user has found a keyword or potential signpost that's relevant to them they will begin to search for context surrounding what is being documented.

- Ask the class: What do you look for in documentation? Focus on the moment-to-moment searching for information here, not general values in documentation.
- Name-drop keywords close to the beginning of a paragraph.

  This aids skimming and scanning, as the first few words of a paragraph stand out the most.

  Skimming and scanning lets users quickly navigate a text, keeping keywords as close to the beginning of a paragraph as possible lets a user determine if they've found relevant information faster.
- Signpost, but don't over-explain.

  Users will not necessarily have the same domain expertise as an API designer.

  If a tangential, specialist term or acronym is mentioned try to bring in enough context such that a novice could quickly do more research.
- Signposting often happens organically, consider a networking library that mentions various protocols. But when it doesn't happen organically, it can be difficult to choose what to mention.

  Rule of thumb: API developers should be asking themselves ”if a novice ran into what they are documenting, what sources would they look up and are there any red herrings they might end up following”?

  Users should be given enough information to look up subjects on their own.
- What we've already covered, predictability of an API including the naming conventions, is a form of signposting.

69.1.5 Avoiding Redundancy

Names and type signatures communicate a lot of information, don't repeat it in comments!

```rust
// Repeats name/type information. Can omit!
/// Parses an ipv4 from a str. Returns an option for failure modes.
fn parse_ip_addr_v4(input: &str) -> Option<IpAddrV4> { ... }

// Repeats information obvious from the field name. Can omit!
struct BusinessAsset {
  /// The customer id.
  let customer_id: u64,
}

// Mentions the type name first thing, don't do this!
/// `ServerSynchronizer` is an orchestrator that sends local edits [...]
struct ServerSynchronizer { ... }

// Better! Focuses on purpose.
/// Sends local edits [...]
struct ServerSynchronizer { ... }

// Mentions the function name first thing, don't do this!
/// `sync_to_server` sends local edits [...]
fn sync_to_server(...)

// Better! Focuses on function.
/// Sends local edits [...]
fn sync_to_server(...)
```

- Motivation: Documentation that merely repeats name/signature information provides nothing new to the API user.

Additionally, signature information may change over time without the documentation being updated accordingly!

- This is an understandable pattern to fall into!

  Naive approach to "always document your code," follows this advice literally but does not follow the intent.

  Some tools might enforce documentation coverage, this kind of documentation is an easy fix.

- Be aware of the purpose of different modes of documentation:
  - Library code will need to be documented in ways that understand the scope of what it is used for and the breadth of people who are trying to use it.
  - Application code has a more narrow purpose, it can afford to be more simple and direct.

- The name of an item is part of the documentation of that item.

  Similarly, the signature of a function is part of the documentation of that function.

Therefore: Some aspects of the item are already covered when you start writing doc comments!

Do not repeat information for the sake of an itemized list.

- Many areas of the standard library have minimal documentation because the name and types do give enough information.

  Rule of Thumb: What information is missing from a user's perspective? Other than name, signature, and irrelevant details of the implementation.

- Don't explain the basics of Rust or the standard library. Assume the reader of doc comments has an intermediate understanding of the language itself. Focus on documenting your API.

  For example, if your function returns `Result`, you don't need to explain how `Result` or the question mark operators work.

- If there is a complex topic involved with the functions and types you're documenting, signpost to a "source of truth" if one exists such as an internal document, a paper, a blog post etc.

- Collaborate with Students: Go through the methods in the slide and discuss what might be relevant to an API user.

More to Explore

- The `#![warn(missing_docs)]` lint can be helpful for enforcing the existence of doc comments, but puts a large burden on developers that could lead to leaning onto these patterns of writing low-quality comments.

  This kind of lint should only be enabled if the people maintaining a project can afford to keep up with its demands, and usually only for library-style crates rather than application code.

69.1.6 Names and Signatures are not full documentation

```rust
// bad
/// Returns a future that resolves when operation completes.
fn sync_to_server() -> Future<Bool>;

// good
/// Sends local edits to the server, overwriting concurrent edits
/// if any happened.
fn sync_to_server() -> Future<Bool>;
// bad
/// Returns an error if sending the email fails.
fn send(&self, email: Email) -> Result<(), Error>;

// good
/// Queues the email for background delivery and returns immediately.
/// Returns an error immediately if the email is malformed.
fn send(&self, email: Email) -> Result<(), Error>;
```

- Motivation: API designers can over-commit to the idea that a function name and signature is enough documentation.

It's better than nothing, but it's worse than good documentation.

- Again, names and types are *part* of the documentation. They are not always the full story!
- Consider the behavior of functions that are not covered by the name, parameter names, or signature of that function.

  In the example on the slide it is not obvious that `sync_to_server()` could overwrite something (leading to a data loss), so document that.

  In the email example, it is not obvious that the function can return success and still fail to deliver the email.
- Use comments to disambiguate. Nuanced behaviors, behaviors that users of an API could trip up on, should be documented.

  For example, consider a remove() method on a business entity: There are many ways to remove an entity!

  Is it removing the entity from the database? From the parent collection in memory (unlink vs erase)?

  If it is removing the data in the database, is the data actually being deleted, or merely marked as deleted, but still recoverable (soft vs hard delete)?

69.1.7 Why and What, not How and Where

Avoid documenting irrelevant details that may frequently change.

```
/// Sorts a slice. Implemented using recursive quicksort.

fn sort_quickly<T: Ord>(to_sort: &mut [T]) { /* ... */
}

// bad
/// Saves a `User` record to the Postgres database.
///
/// This function opens a new connection and begins a transaction. It checks
/// if a user with the given ID exists with a `SELECT` query. If a user is
/// not found, performs an `INSERT`.
///
/// # Errors
///
/// Returns an error if any database operation fails.
pub fn save_user(user: &User) -> Result<(), db::Error> {
    // ...
}

// good
/// Atomically saves a user record.
///
/// # Errors
```

```rust
///
/// Returns a `db::Error::DuplicateUsername` error if the user (keyed by
/// `user.username` field) already exists.
pub fn save_user(user: &User) -> Result<(), db::Error> {
    // ...
}
```

- Motivation: Users want to know the contract of the API (what is guaranteed about this function), rather than implementation details.
- Motivation: Doc comments that explain implementation details become outdated faster than comments that explain the contract.

  Internal information is likely irrelevant to a user. Imagine explaining in a doc comment for a function that you're using for loops to solve a problem, what is the point of this information?
- Consider the `sort_quickly` function above. Its documentation calls out that it uses quicksort, but is this necessary?

  It could be that another sorting function is used in the future, if that were the case then this comment would need to be updated too. This is a point of failure in documentation.
- It could be that the implementation is necessary to explain, but this is likely due to whatever effects or invariants the user of that API needs to be aware of instead.

  Focus on those effects and invariants instead of instead of the implementation details themselves.

  Reiterate: Implementation details can and will change, so do not explain these details.
- Don't talk about where something is used for the sake of it.

  This is another instance where this information can become stale quickly.
- Focus on what the function does (not how it is implemented) for a user trying to reach this practical information as quickly as possible.

69.1.8 Exercise: Dialog on Details

Unnecessary details can sometimes be indicative of something that does need documentation.

```rust
/// Sorts a slice. Implemented using recursive quicksort.
fn sort_quickly<T: Ord>(to_sort: &mut [T]) { ... }
```

- Consider the example here, we discussed in what and why, not how and where that internal details are unlikely relevant to someone reading documentation.

  Here we're discussing a counterexample.
- Ask the class: Is this comment necessary for this function?
- Narrative: Playing the part of an intermediary between the class and the author, such as a PM, manager, etc. tell the class that the author of this function is pushing back.
- Ask the class: Why would an author of this kind of comment push back?

  If the class asks why the author is pushing back, do not give details yet.
- Ask the class: Why would the caller need to know the sorting algorithm in use?

- Narrative: "Come back" from a meeting with the original author, explain to the class that this function is application code that is called on untrusted data that could be crafted maliciously to cause quadratic behavior during sorting.
- Ask the class: Now we have more detail, how should we comment this function?

  The point being implementation detail vs not depends a lot on what the public contract is (e.g., can you supply untrusted data or not), and this requires careful judgement.

  Consider if a comment is explaining that a for-loop is used (unnecessary detail) or if it is explaining that the algorithms used internally have known exploits (documentation draws attention to the wrong thing).

69.2 Predictable API

Keep your APIs predictable through naming conventions and implementing common traits.

```
/* What traits should this implement? */
pub struct ApiToken(String);

impl ApiToken {
    // What should this method be called?
    pub unsafe fn ____(String) -> ApiToken;
}
```

This slide and its sub-slides should take about 122 minutes.

- A predictable API is one where a user's can make assumptions about a part of the API based on surface-level details like names, types, and signatures.
- We'll be looking at common naming conventions in Rust, which allow users to search for methods that fit their needs quickly and be able to understand existing code quickly.
- We will also be looking at common traits that types implement, and when to implement them for types you define.

69.2.1 Naming Conventions

- One core component of readability and predictability is the way function names are composed.

A formal and consistently-applied naming convention lets developers treat names like a domain-specific language and quickly understand the functionality and use cases of a method.

Rust's community developed naming conventions early, making them mostly consistent in places like the standard library.

- Here we'll learn common components of Rust method names, giving examples from the standard library and some context to go with them.

69.2.1.1 `new`: Constructor functions

Rust does not have a `new` keyword, instead `new` is a common prefix or whole method name.

```rust
impl <T> Vec<T> {
    // Creates an empty vec.
    fn new() -> Vec<T>;
}

impl <T> Box<T> {
    fn new(T) -> Box<T>;
}
```

- There's no `new` keyword for Rust to initialize a new value, only functions you call or values you directly populate.

  `new` is conventional for the ”default” constructor function for a type. It holds no special syntactic meaning.

  This is sometimes a prefix, it sometimes takes arguments.

69.2.1.2 `get`: Borrow an Element

Getting an element from a collection or container.

```rust
impl <T> Vec<T> {
    fn get(&self, index: usize) -> Option<&T> {...}
}

impl <T> OnceCell {
    fn get(&self) -> Option<&T> {...}
}
```

- Gets are trivial, they get a value!

Immutable by default, for the most part.

Should not panic. May return an option or result, depending on the framework.

- Not for fields!

  For private fields you don't want users to have direct, assign a method with a more descriptive name (or the same name as the field) is preferred.

69.2.1.3 `push`

Common on array-like structures.

```rust
impl<T> Vec<T> {
    fn push(&mut self, value: T);
}

impl<T> VecDeque<T> {
    fn push_back(&mut self, value: T);
    fn push_front(&mut self, value: T);
}
```

- Modifies a sequential collection by adding an element.

- Takes `self` by mutable reference.

69.2.1.4 is_[condition]: Boolean Check

Check a condition about a datatype.

```
impl <T> Vec<T> {
    is_empty(&self) -> bool;
}

impl f32 {
    is_nan(self) -> bool;
}

impl u32 {
    is_power_of_two(self) -> bool;
}
```

- A boolean condition on a value.

  - `is` prefix is preferred over methods with `not` in the name.

    There are no instances of `is_not_` in standard library methods, just use `!value.is_[condition]`.

69.2.1.5 [method]_mut: Mutable reference access

Suffix for access-style methods.

```
impl<T> Vec<T> {
    // Simplified
    fn get_mut(&mut self, index: usize) -> Option<&mut T>;
}

impl<T> [T] {
    // Simplified
    fn iter_mut(&mut self) -> impl Iterator<Item = &mut T>;
}

impl str {
    fn from_utf8_mut(v: &mut [u8]) -> Result<&mut str, Utf8Error>;
}
```

- Mut for Mutability

  - Suffix that signifies the method gives access to a mutable reference.

    Requires mutable access to the value you're calling this method on.

69.2.1.6 with as constructor

`with` as a constructor sets one value among a type while using default values for the rest.

`with` as in ”<Type> with specific setting.”

```
impl<T> Vec<T> {
    // Initializes memory for at least N elements, len is still 0.
    fn with_capacity(capacity: usize) -> Vec<T>;
}
```

- with can appear as a constructor prefix, most commonly when initializing heap memory for container types.

  In this case, it's distinct from new constructors because it specifies the value for something that is not usually cared about by API users.

- Ask the class: Why not from_capacity?

  Answer: Vec::with_capacity as a method call scans well as creating a ”Vec with capacity”. Consider how Vec::new_capacity or Vec::from_capacity scan when written down, they do not communicate what's going on well.

69.2.1.7 with as copy-and-set

with appears when a value is being copied, but also changed in a specific way.

with as in ”like <value>, but with something different.”

```
impl Path {
    // Simplified. "/home/me/mortgage.pdf".with_extension("mov") =>
    // "/home/me/mortgage.mov"
    fn with_extension(&self, ext: &OsStr) -> PathBuf;
}
```

- with can be used for methods that copy a value, but then change a specific part of that value.

  In the example here, with_extension copies the data of a &Path into a new PathBuf, but changes the extension to something else.

  The original Path is unchanged.

69.2.1.8 with: Working with Closures

with as in ”do X, but with this specific way of computing things.”

```
impl<T> Vec<T> {
    // Simplified. If the resize is larger than the current vec size, use the
    // closure to populate elements.
    pub fn resize_with(&mut self, new_len: usize, f: impl FnMut() -> T);
}

mod iter {
    // Create an infinite, lazy iterator using a closure.
    pub fn repeat_with<A, F: FnMut() -> A>(repeater: F) -> RepeatWith<F>;
}
```

- with can appear as a suffix to communicate there is a specific function or closure that can be used instead of a ”sensible default” for a computation.

  Similar to by.

69.2.1.9 with in normal use

Sometimes a with is just a with.

with when used in common English contexts.

```rust
// impl block for slices
impl <T> [T] {
    // A condition, but doesn't start with `is`, and uses `with` as a normal word.
    fn starts_with(&self, &[T]) -> bool;
}
```

- Name fragments are not hard rules, they are guidance. Sometimes a method's name will include words that break its pattern.
- In this example with have `starts_with`, which is a boolean condition that does not start with "is" and is suffixed by "with".

  If naming conventions were to be treated as hard rules, this would fail as a case.

  This is a good name for understanding what is going on at the callsite. We end up writing `<variable>.starts_with(<sequence>)` which scans well for authors and readers of code.
- Remember: the point of naming conventions is predictability, and how predictability is in service of callsite clarity and readability.

69.2.1.10 `try_[method]`: Fallible methods with Specific Errors

Prefix for fallible methods that return a `Result`.

```rust
impl TryFrom<i32> for u32 {
    type Error = TryFromIntError;
    fn try_from(value: i32) -> Result<i64, TryFromIntError>;
}

impl<T> Receiver<T> {
    try_recv(&self) -> Result<T, TryRecvError>;
}
```

- Prefix for methods that can fail, returning a 'Result'.

- `TryFrom` is a `From`-like trait for types whose single-value constructors might fail in some way.
- Ask: Why aren't `Vec::get` and other similar methods called `try_get`?

  Methods are named `get` if they return a reference to an existing value and return an `Option` instead of `Result` because there is only one failure mode. For example, only "index out of bounds" for `Vec::get`, and "key does not exist" for `HashMap::get`.

69.2.1.11 `from`

A constructor function, strongly implying "type conversion".

```rust
impl CStr {
    unsafe fn from_ptr<'a>(ptr: *const i8) -> &'a CStr;
}

impl Duration {
    fn from_days(days: u64) -> Duration;
}
```

```rust
impl<T> Vec<T> {
    fn from_raw_parts(ptr: *mut T, length: usize, capacity: usize) -> Vec<T>;
}

impl i32 {
    fn from_ascii(src: &[u8]) -> Result<i32, ParseIntError>;
}

impl u32 {
    fn from_le_bytes(bytes: [u8; 4]) -> u32;
}
```

- Prefix for constructor-style, 'From'-trait-style functions.

- These functions can take multiple arguments, but usually imply the user is doing more of the work than a usual constructor would.

  `new` is still preferred for most constructor-style functions, the implication for `from` is transformation of one data type to another.

- Ask: Without looking at the standard library documentation, what would the argument type of `u32::from_be` be?

  Answer guidance: we already see `u32::from_le_bytes` on the slide, it takes a slice of bytes. So from_le must be simpler, taking not bytes. Think about the contrast between `u32` and be. The argument must be a big-endian `u32`!

  Follow-up question: How about `str::from_utf8`?

  Answer guidance: `str` vs `utf8`. The argument can't be a `str` because every `str` is valid UTF-8. So what is the simplest way to provide UTF-8 data? A slice of bytes.

  Follow-up: Why not `str::from_utf8_bytes`?

  Answer: It could be in theory. However, the "omit needless words" principle applies, the word "bytes" would merely repeat the obvious - could a UTF-8 sequence ever be non-bytes?

69.2.1.12 `into`

- Prefix for methods that convert `self` into another type.

Consumes `self`, returns an owned value.

```rust
impl<T> Vec<T> {
    fn into_parts(self) -> (NonNull<T>, usize, usize);
}

impl<T> Cell<T> {
    fn into_inner(self) -> T;
}
```

- Prefix for a function that consumes an owned value and transforms it into a value of another type.

Not reinterpret cast! The data can be rearranged, reallocated, changed in any way, including losing information.

- corollary to `From`
- `into_iter` consumes a collection (like a vec, or a btreeset, or a hashmap) and produces an iterator over owned values, unlike `iter` and `iter_mut` which produce iterators over reference values.
- Ask the class: what will `Vec::into_raw_parts` do?

69.2.1.13 Aside: `into_inner`

Special case of `into`: for exclusive pointer types or newtypes, extract the internal value.

```
pub struct Wrapper<T>(T);

impl<T> Wrapper<T> {
    fn into_inner(self) -> T;
}

pub struct NonZeroU32(u32);

impl NonZeroU32 {
    fn into_inner(self) -> u32;
}

impl<T> Cell<T> {
    fn into_inner(self) -> T;
}
```

- `into_inner` is a method usually found on newtypes: types whose main purpose is to wrap around an existing type and be semantically distinct from other uses of that inner type.

This kind of method is also found on types like `Cell`, which exclusively own the internal data.

The purpose of this kind of method is to consume the "wrapper" type and return the "contained" value.

- When defining a type with exactly one field, consider if it makes sense to implement an `into_inner` method that consumes `self` and returns the field as an owned value.

  Don't write a method like this if more fields will be added in the future.

69.2.1.14 by: custom comparator or projection

Component for methods that take a custom projection or comparison function.

```
impl<T> [T] {
    // Simplified
    fn sort_by(&mut self, compare: impl FnMut(&T, &T) -> Ordering);

    // Uses a predicate to determine what items end up in non-overlapping chunks.
    fn chunk_by_mut<F: FnMut(&T, &T) -> bool>(
        &mut self,
```

```
        pred: F,
    ) -> ChunkByMut<'_, T, F>;
}

trait Iterator {
    // Provided method of Iterator. Simplified.
    fn min_by<F>(
        self,
        compare: impl FnMut(&Self::Item, &Self::Item) -> Ordering,
    ) -> Option<Self::Item>;
}
```

- Method will take a comparison or projection function.

A projection function here being a function that, given a reference to a value that exists in the data structure, will compute a value to perform the principle computation with.

Methods like `sort_by_key` allow us to sort by *the hash function I've passed to the method* or sort by *this specific field of the data in the slice.*

For example, if you have a slice of values of some data structure you might want to sort them by a field of that data structure, or even a hash value of that data.

`sort_by` takes a comparator function directly.

- Most often seen in methods that sort or otherwise manipulate a slice with a custom sort or comparison function rather than by the `Ord` implementation of the type itself.
- Sometimes the ”by” preposition is simply a preposition.

  ”by”, like some other name components, may end up in a method name for normal linguistic reasons rather than holding specific naming convention semantic weight.

  – `Read::by_ref()`
  – `Iterator::advance_by()` iterator method (nightly feature)

69.2.1.15 unchecked: Unsafe

unchecked distinguishes the unsafe function in a safe/unsafe pair.

Don't add ”unchecked” to the name of every unsafe function.

```
impl <T> NonNull<T> {
    // A checked version of the constructor, `None` on null.
    fn new(ptr: *mut T) -> Option<NonNull<T>>

    // Unchecked constructor, you can violate the non-null invariant!
    unsafe fn new_unchecked(ptr: *mut T) -> NonNull<T>
}

impl <T> Vec<T> {
    // Panics on OOB, old API design.
    fn split_at(&self, mid: usize) -> (&[T], &[T])

    // Newer method, returns `None` if mid > len
    fn split_at_checked(&self, mid: usize) -> Option<(&[T], &[T])>
```

```
    // Unchecked split function, splitting out of bounds is undefined behavior!
    unsafe fn split_at_unchecked(&self, mid: usize) -> (&[T], &[T])
}
```

- Sometimes we need to define a pair of functions that have very similar behavior, but one is safe, and the other one is unsafe.

- Please take the Unsafe Rust deep dive if you want to learn more about unsafe code. Briefly, unsafe functions transfer the responsibility for memory safety from the compiler to the programmer. If misused, they can trigger undefined behavior.
- Rust does not overload functions on safety, so we use different names for the functions in the pair. To make the names predictable for users, we use a naming convention.
- The safe function gets the short name. We add "unchecked" to the name of the unsafe function.
- We don't add "unchecked" to the name of every unsafe function.
  - In Rust we don't need a naming convention to highlight the danger of unsafe code at the callsite: Rust already requires the caller to write an `unsafe {}` block. This is different from other languages that don't have unsafe blocks, for example, Swift naming convention is to add the word "unsafe" to the type and function names.
  - We only use this naming convention when we want to provide a function pair, and therefore must use different names.

69.2.1.16 `to`: Non-consuming Conversion

Prefix to a function that takes a borrowed value and creates an owned value

```
impl str {
    // &str is not consumed.
    fn to_owned(&str) -> String;

    fn to_uppercase(&self) -> String;
}

impl u32 {
    // take an owned self because `u32` implements `Copy`
    to_be(self) -> u32;
}
```

- Methods that create a new owned value without consuming ‘self‘, and imply a type conversion, are named starting with ‘to‘.

- This is not a borrow checker escape hatch, or an instance of unsafe code. A new value is created, the original data is left alone.
- Methods that start with "to" return a different type, and strongly imply a non-trivial type conversion, or even a data transformation. For example, `str::to_uppercase`.
- "to" methods most commonly take `&self`. However they can take `self` by value if the type implements `Copy`: this also ensures that the conversion method call does not consume `self`.

- If you simply want to define a method that takes `&self` and returns an owned value of the same type, implement the `Clone` trait.

Example: to_uppercase creates a version of a string with all uppercase letters.

- If you want to define a method that consumes the source value, use the ”into” naming pattern.
- Also seen in functions that convert the endianness of primitives, or copy and expose the value of a newtype.

More to Explore

- Ask the class: What's the difference between `to_owned` and `into_owned`?

  Answer: `to_owned` appears on reference values like `&str`, whereas `into_owned` appears on owned values that hold reference types, like `Cow` (copy-on-write).

  Types like `Cow` can be owned while containing references that are borrowed, so the owned value of `Cow` is consumed to create an owned value of the reference type it was holding onto.

69.2.1.17 `as_` and `_ref`: reference conversions

`as` is a prefix for methods that convert references. `ref` is a suffix (but prefer `as`.)

`as` methods borrow out the primary piece of data contained in `&self`.

Most commonly return references, but can also return a custom borrowing type or an unsafe pointer.

```
impl<T> Rc<T> {
    fn as_ptr(&self) -> *const T;

    // Very common on container types, see how it's also on Option.
    fn as_ref(&self) -> &T;
}

impl<T> Option<T> {
    fn as_ref(&self) -> Option<&T>;
    // Slices can be empty! So this is 0 or 1 elements.
    fn as_slice(&self) -> &[T];
}

impl OwnedFd {
    // Covered later.
    fn as_fd(&'a self) -> BorrowedFd<'a>;
}
```

- Method that returns a borrow of the primary piece of contained data.
- The borrowing relationship is most often straightforward: the return value is a reference that borrows `self`.
- Borrowing can also be subtle, and merely implied.

- The returned value could be a custom borrowing type, fore example, `BorrowedFd` borrows `OwnedFd` through an explicit lifetime.
- We cover custom borrowing types later in this deep dive, PhantomData: OwnedFd & BorrowedFd.
- The returned value could borrow `self` only logically, for example, `as_ptr()` methods return an unsafe pointer. The borrow checker does not track borrowing for pointers.

- The type implementing an "as" method should contain one primary piece of data that is being borrowed out.
  - The "as" naming convention does not work if the data type is an aggregate of many fields without an obvious primary one. Think about the call site:

```
my_vec.as_ptr() // OK
my_person.as_first_name() // does not read right, don't use "as_"
my_person.first_name() // OK
```

  - If you want to have two getters that you need to distinguish, one that returns first name by value, and another one that returns it by reference, use `_ref` suffix:

```
impl Person {
  fn first_name(&self) -> String
  fn first_name_ref() -> &str
  fn first_name_mut() -> &mut String
}
```

69.2.1.18 `raw_parts`

Peeling back safe abstractions on heap data.

```
impl<T> Vec<T> {
    // Note how this is an unsafe function
    unsafe fn from_raw_parts(ptr: *mut T, length: usize, capacity: usize) -> Vec<T>;

    fn into_raw_parts(self) -> (*mut T, usize, usize);
}
```

- `raw_parts` denotes methods that construct items from or decompose items into underlying pointer data and its relevant layout information (capacity, etc.).
- These kinds of methods can be marked as `unsafe` if constructing new values as trust is placed on the user to avoid conditions that might lead to undefined behavior.

  Such a case might be passing a pointer of `sizeof T * 10` to `Vec::from_raw_parts` but also passing `20` as the capacity argument, which would lead to writing or accessing values 10 through 19 in the vector being undefined behavior.

69.2.1.19 Exercise

1. What do these names imply they do?
2. What should we name these signatures?

```
// What are the types of these methods?
Option::is_some // ?
```

```
slice::get // ?
slice::get_unchecked_mut // ?
Option::as_ref // ?
str::from_utf8_unchecked_mut // ?
Rc::get_mut // ?
Vec::dedup_by_key // ?

// What should we name methods with these types?
fn ____(String) -> Self;
fn ____(&self) -> Option<&InnerType>; // details for InnerType do not matter.
fn ____(self, String) -> Self;
fn ____(&mut self) -> Option<&mut InnerType>;
```

- Go through the methods in the example with the class and discuss what the types of the functions should be.
- Go through the unnamed methods and brainstorm what names those methods should have.

  Answers for missing types:

  - `Option::is_some(&self) -> bool`
  - `slice::get(&self /* &[T] */, usize) -> Option<&T>`
  - `slice::get_unchecked_mut(&self /* &[T] */, usize) -> &T` (unsafe and simplified)
  - `Option::as_ref(&self /* &Option<T> */) -> Option<&T>`
  - `str::from_utf8_unchecked_mut(v: &mut [u8]) -> &mut str` (unsafe)
  - `Rc::get_mut(&mut self /* &mut Rc<T> */) -> Option<&mut T>` (simplified)
  - `Vec::dedup_by_key<K: PartialEq>(&mut self /* &mut Vec<T> */, key: impl FnMut(&mut T) -> K)` (simplified)

  Answers for missing names:

  - `fn from_string(String) -> Self`
  - `fn inner(&self) -> Option<&InnerType>` or `as_ref`, depending on context
  - `fn with_string(self, String) -> Self`
  - `fn inner_mut(&mut self) -> Option<&mut InnerType>` or `as_ref_mut`, depending on context

69.2.2 Common Traits to Implement

```
#[derive(Debug, PartialEq, Eq, PartialOrd, Ord, Hash, Clone /* ... */)]
pub struct MyData {
    pub name: String,
    pub number: usize,
    pub data: [u8; 64],
}
```

- Traits are one of the most potent tools in the Rust language. The language and ecosystem expects you to use them, and so a big part of _predictability_ is what traits are implemented for a type!

- Traits should be liberally implemented on types you author, but there are caveats!

- Remember, many traits have the ability to be *derived*: to have a compiler plugin (macro) write the implementation for you!
- Authors of ecosystem traits (like De/Serialize) have made derive implementations for traits available to users, leading to very little commitment needed on the developer side for implementing these kinds of traits!

69.2.2.1 Debug

"Write to string" trait, for debug purposes.

Derivable: ✅

When to implement: Almost always

```
// pub trait Debug {
//     fn fmt(&self, f: &mut Formatter<'_>) -> Result<(), Error>;
// }

#[derive(Debug)]
pub struct Date {
    day: u8,
    month: u8,
    year: i64,
}

#[derive(Debug)]
pub struct User {
    name: String,
    date_of_birth: Date,
}

pub struct PlainTextPassword {
    password: String,
    hint: String,
}

impl std::fmt::Debug for PlainTextPassword {
    fn fmt(&self, f: &mut std::fmt::Formatter<'_>) -> std::fmt::Result {
        f.debug_struct("PlainTextPassword")
            .field("hint", &self.hint)
            .field("password", &"[omitted]")
            .finish()
    }
}

fn main() {
    let user = User {
        name: "Alice".to_string(),
        date_of_birth: Date { day: 31, month: 10, year: 2002 },
    };

    println!("{user:?}");
```

```
    println!(
        "{:?}",
        PlainTextPassword {
            password: "Password123".to_string(),
            hint: "Used it for years".to_string()
        }
    );
}
```

- Provides trivial ”write to string” functionality.

- Formatting for *debug information* for programmers during , not appearance or serialization.
- Allows for use of `{:?}` and `{#?}` interpolation in string formatting macros.
- When to not derive/implement: If a struct holds sensitive data, investigate if you should implement Debug for it.

  If Debug is needed, consider manually implementing Debug rather than deriving it. Omit the sensitive data from the implementation.

PartialEq and Eq

Partial equality & Total equality.

Derivable: ✅

When to implement: Almost always.

```
// pub trait PartialEq<Rhs = Self>
//{
//    // Required method
//     fn eq(&self, other: &Rhs) -> bool;
//
//     // Provided method
//     fn ne(&self, other: &Rhs) -> bool { ... }
// }
//
// pub trait Eq: PartialEq { }

#[derive(PartialEq, Eq)]
pub struct User { name: String, favorite_number: i32 }

let alice = User { name: "alice".to_string(), favorite_number: 1_000_042 };
let bob = User { name: "bob".to_string(), favorite_number: 42 };

dbg!(alice == alice);
dbg!(alice == bob);
```

- Equality-related methods. If a type implements ‘PartialEq‘/‘Eq‘ then you can use the ‘==‘ operator with that type.

- A type can't implement Eq without implementing `PartialEq`.
- Reminder: Partial means ”there are invalid members of this set for this function.”

This doesn't mean that equality will panic, or that it returns a result, just that there may be values that may not behave as you expect equality to behave.

For example, with floating point values `NaN` is an outlier: `NaN == NaN` is false, despite bitwise equality.

`PartialEq` exists to separate types like f32/f64 from types with Total Equality.

- You can implement `PartialEq` between different types, but this is mostly useful for reference/smart pointer types.

69.2.2.2 PartialOrd and Ord

Partial ordering & Total ordering.

Derivable: ✅

When to implement: Almost always.

```
// pub trait PartialOrd<Rhs = Self>: PartialEq<Rhs>
// {
//     // Required method
//     fn partial_cmp(&self, other: &Rhs) -> Option<Ordering>;
//
//     /* Provided methods omitted */
// }
// pub trait Ord: Eq + PartialOrd {
//     // Required method
//     fn cmp(&self, other: &Self) -> Ordering;
//
//     /* Provided methods omitted */
// }

#[derive(PartialEq, PartialOrd)]
pub struct Partially(f32);

#[derive(PartialEq, Eq, PartialOrd, Ord)]
pub struct Totally {
    id: u32,
    name: String,
}
```

- Comparison-related methods. If a type implements ‘PartialOrd‘/‘Ord‘ then you can use comparison operators (‘<‘, ‘<=‘, ‘>‘, ‘>=‘) with that type.

`Ord` gives access to `min`, `max`, and `clamp` methods.

- When derived, compares things in the order they are defined.

  For enums this means each variant is considered ”greater than” the last as they are written.

  For structs this means fields are compared as they are written, so `id` fields are compared before `name` fields in `Totally`.

- Prerequisites: `PartialEq` for `PartialOrd`, `Eq` for `Ord`.

To implement Ord, a type must also implement PartialEq, Eq, and PartialOrd.

- Like with PartialEq and Eq, a type cannot implement Ord without implementing PartialOrd.

  Like those equality traits, PartialOrd exists to separate types with non-total ordering (particularly floating-point numbers) from types with total ordering.

- Used for sorting/searching algorithms and maintaining the ordering of BTreeMap/BTreeSet style data types.

69.2.2.3 Hash

Performing a hash on a type.

Derivable: ✅

When to implement: Almost always.

```
// pub trait Hash {
//     // Required method
//     fn hash<H>(&self, state: &mut H)
//        where H: Hasher;
//
//     // Provided method
//     fn hash_slice<H>(data: &[Self], state: &mut H)
//        where H: Hasher,
//              Self: Sized { ... }
// }

#[derive(Hash)]
pub struct User {
    id: u32,
    name: String,
    friends: Vec<u32>,
}
```

- Allows a type to be used in hash algorithms.

  - Most commonly used with data structures like HashMap.

69.2.2.4 Clone

Deep-copy a type or duplicate a smart, shareable pointer.

Derivable: ✅

When to implement: If duplicating doesn't break invariants.

```
// pub trait Clone: Sized {
//     // Required method
//     fn clone(&self) -> Self;
//
//     // Provided methods omitted
// }
```

```rust
use std::collections::BTreeSet;
use std::rc::Rc;

#[derive(Clone)]
pub struct LotsOfData {
    string: String,
    vec: Vec<u8>,
    set: BTreeSet<u8>,
}

let lots_of_data = LotsOfData {
    string: "String".to_string(),
    vec: vec![1; 255],
    set: BTreeSet::from_iter([1, 2, 3, 4, 5, 6, 7, 8]),
};

let lots_of_data_cloned = lots_of_data.clone();

let reference_counted = Rc::new(lots_of_data);
// Copies the reference-counted pointer, not the value.
let reference_copied = reference_counted.clone();
```

- ”Deep copy” a value, or in the case of reference counting pointers like `Rc`/`Arc` create a new instance of that pointer.
- When to not implement/derive: For types that, to maintain an invariant, the value should not be duplicated. We'll touch on this later in Idiomatic Rust.

69.2.2.5 Copy

Like `Clone`, but indicates the type is can be bitwise copied.

Derivable: ✅

When to implement: If possible, but with caveats.

```rust
// Copy is just a marker trait with Clone as a supertrait.
// pub trait Copy: Clone { }

#[derive(Clone, Copy)]
pub struct Copyable(u8, u16, u32, u64);
```

- Clone represents a deep clone, and so does copy, but copy suggests to the compiler that a value can be copied bitwise.

- When not to implement/derive: If you do not want to implicitly create copies when dereferencing values of a type, do not implement this trait.

  Copy enables implicit duplication, so be careful about what types you're implementing this on.

- Ask the class: Can a type with heap data (`Vec`, `BTreeMap`, `Rc`, etc.) be copy? Should it be?

  It both cannot and should not, this is a misuse of this trait.

Bitwise copying on these types would mean types with heap data would no longer have exclusive ownership of a pointer, breaking the invariants usually upheld by Rust and its ecosystem.

Multiple `Vec`s would point to the same data in memory. Adding and removing data would only update individual `Vec`s length and capacity values. The same for `BTreeMap`.

Bitwise copying of `Rc`s would not update the reference counting value within the pointers, meaning there could be two instances of a `Rc` value that believe themselves to be the only `Rc` for that pointer. Once one of them is destroyed, the reference count will become 0 on one of them and the inner value dropped despite there being another `Rc` still alive.

Serialize/Deserialize style traits

Crates like `serde` can implement serialization automatically.

Derivable: ✅

When to implement: Almost always.

```rust
#[derive(Serialize, Deserialize)]
struct ExtraData {
    fav_color: String,
    name_of_dog: String,
}

#[derive(Serialize, Deserialize)]
struct Data {
    name: String,
    age: usize,
    extra_data: ExtraData,
}
```

- Provides serialization and deserialization functionality for a type.

- When not to implement: If a type contains sensitive data that should not be erroneously saved to disk or sent over a network, consider not implementing Serialize/Deserialize for that type.

  Shares security concerns with `Debug`, but given serialization is often used in networking there can be higher stakes.

69.2.2.6 From & Into

Conversion from one type to another.

Derivable: ❌, without crates like `derive_more`.

When to implement: As-needed and convenient.

```rust
pub struct ObviousImplementation(String);

impl From<String> for ObviousImplementation {
    fn from(value: String) -> Self {
        ObviousImplementation(value)
    }
```

```rust
}

impl From<&str> for ObviousImplementation {
    fn from(value: &str) -> Self {
        ObviousImplementation(value.to_owned())
    }
}

fn main() {
    // From String
    let obvious1 = ObviousImplementation::from("Hello, obvious!".to_string());
    // From &str
    let obvious2 = ObviousImplementation::from("Hello, obvious!");
    // A From implementation implies an Into implementation, &str.into() ->
    // ObviousImplementation
    let obvious3: ObviousImplementation = "Hello, implementation!".into();
}
```

- Provides conversion functionality to types.

- The two traits exist to express different areas you'll find conversion in codebases.
- `From` provides a constructor-style function, whereas `into` provides a method on an existing value.
- Prefer writing `From<T>` implementations for a type you're authoring instead of `Into<T>`.

  The `Into` trait is implemented for any type that implements `From` automatically.

  `Into` is preferred as a trait bound for arguments to functions for clarity of intent for what the function can take.

  `T: Into<String>` has clearer intent than `String: From<T>`.

69.2.2.7 TryFrom/TryInto

Fallible conversion from one type to another.

Derivable: ❌

When to implement: As-needed.

```rust
#[derive(Debug)]
pub struct InvalidNumber;

#[derive(Debug)]
pub struct DivisibleByTwo(usize);

impl TryFrom<usize> for DivisibleByTwo {
    type Error = InvalidNumber;
    fn try_from(value: usize) -> Result<Self, InvalidNumber> {
        if value.rem_euclid(2) == 0 {
            Ok(DivisibleByTwo(value))
        } else {
            Err(InvalidNumber)
        }
```

```
    }
}

fn main() {
    let success: Result<DivisibleByTwo, _> = 4.try_into();
    dbg!(success);
    let fail: Result<DivisibleByTwo, _> = 5.try_into();
    dbg!(fail);
}
```

- Provides conversion that can fail, returning a result type.

- Like `From`/`Into`, prefer implementing `TryFrom` for types rather than `TryInto`.
- Implementations can specify what the error type of the `Result`.

69.2.2.8 Display

"Write to string" trait, prioritizing readability for an end user.

Derivable: ❌, without crates like `derive_more`.

When to implement: As-needed, for errors and other types that an end-user will see.

```
#[derive(Debug)]
pub enum NetworkError {
    HttpCode(u16),
    WhaleBitTheUnderseaCable,
}

impl std::fmt::Display for NetworkError {
    fn fmt(&self, f: &mut std::fmt::Formatter<'_>) -> std::fmt::Result {
        match self {
            NetworkError::HttpCode(code) => write!(f, "HTTP Error code {code}"),
            NetworkError::WhaleBitTheUnderseaCable => {
                write!(f, "Whale attack detected - call Ishmael")
            }
        }
    }
}

impl std::error::Error for NetworkError {}
```

- A trait similar to 'Debug', but with a focus on end-user readability.

- Prerequisite for the `Error` trait.

  If implementing for an error type, focus on providing a descriptive error for users and programmers other than you.
- Same security considerations as Debug, consider the ways that sensitive data could be exposed in UI or logs.
- Types that implement `Display` automatically have `ToString` implemented for them.

Chapter 70

Leveraging the Type System

Rust's type system is *expressive*: you can use types and traits to build abstractions that make your code harder to misuse.

In some cases, you can go as far as enforcing correctness at *compile-time*, with no runtime overhead.

Types and traits can model concepts and constraints from your business domain. With careful design, you can improve the clarity and maintainability of the entire codebase.

This slide should take about 5 minutes.

Additional items speaker may mention:

- Rust's type system borrows a lot of ideas from functional programming languages.

  For example, Rust's enums are known as "algebraic data types" in languages like Haskell and OCaml. You can take inspiration from learning material geared towards functional languages when looking for guidance on how to design with types. "Domain Modeling Made Functional" is a great resource on the topic, with examples written in F#.

- Despite Rust's functional roots, not all functional design patterns can be easily translated to Rust.

  For example, you must have a solid grasp on a broad selection of advanced topics to design APIs that leverage higher-order functions and higher-kinded types in Rust.

  Evaluate, on a case-by-case basis, whether a more imperative approach may be easier to implement. Consider using in-place mutation, relying on Rust's borrow-checker and type system to control what can be mutated, and where.

- The same caution should be applied to object-oriented design patterns. Rust doesn't support inheritance, and object decomposition should take into account the constraints introduced by the borrow checker.

- Mention that type-level programming can be often used to create "zero-cost abstractions", although the label can be misleading: the impact on compile times and code complexity may be significant.

This segment should take about 7 hours and 30 minutes. It contains:

Slide	Duration
Leveraging the Type System	5 minutes
Newtype Pattern	20 minutes
RAII	1 hour and 50 minutes
Extension Traits	1 hour and 5 minutes
Typestate Pattern	1 hour and 5 minutes
Borrow checking invariants	1 hour and 30 minutes
Token Types	1 hour and 35 minutes

70.1 Newtype Pattern

A *newtype* is a wrapper around an existing type, often a primitive:

```
/// A unique user identifier, implemented as a newtype around `u64`.
pub struct UserId(u64);
```

Unlike type aliases, newtypes aren't interchangeable with the wrapped type:

```
fn triple(n: u64) -> u64 {
    n * 3
}

triple(UserId(1)); // 🛠️❌
```

The Rust compiler won't let you use methods or operators defined on the underlying type either:

```
assert_ne!(UserId(1), UserId(2)); // 🛠️❌
```

This slide and its sub-slides should take about 20 minutes.

- Students should have encountered the newtype pattern in the ”Fundamentals” course, when they learned about tuple structs.
- Run the example to show students the error message from the compiler.
- Modify the example to use a typealias instead of a newtype, such as `type MessageId = u64`. The modified example should compile, thus highlighting the differences between the two approaches.
- Stress that newtypes, out of the box, have no behaviour attached to them. You need to be intentional about which methods and operators you are willing to forward from the underlying type. In our `UserId` example, it is reasonable to allow comparisons between `UserId`s, but it wouldn't make sense to allow arithmetic operations like addition or subtraction.

70.1.1 Semantic Confusion

When a function takes multiple arguments of the same type, call sites are unclear:

```
pub fn login(username: &str, password: &str) -> Result<(), LoginError> {
    // [...]
}
```

```rust
// In another part of the codebase, we swap arguments by mistake.
// Bug (best case), security vulnerability (worst case)
login(password, username);
```

The newtype pattern can prevent this class of errors at compile time:

```rust
pub struct Username(String);
pub struct Password(String);

pub fn login(username: &Username, password: &Password) -> Result<(), LoginError> {
    // [...]
}

login(password, username); // 🛠️❌
```

- Run both examples to show students the successful compilation for the original example, and the compiler error returned by the modified example.
- Stress the *semantic* angle. The newtype pattern should be leveraged to use distinct types for distinct concepts, thus ruling out this class of errors entirely.
- Nonetheless, note that there are legitimate scenarios where a function may take multiple arguments of the same type. In those scenarios, if correctness is of paramount importance, consider using a struct with named fields as input:

  ```rust
  pub struct LoginArguments<'a> {
      pub username: &'a str,
      pub password: &'a str,
  }

  // No need to check the definition of the `login` function to spot the issue.
  login(LoginArguments {
      username: password,
      password: username,
  })
  ```

  Users are forced, at the callsite, to assign values to each field, thus increasing the likelihood of spotting bugs.

70.1.2 Parse, Don't Validate

The newtype pattern can be leveraged to enforce *invariants*.

```rust
pub struct Username(String);

impl Username {
    pub fn new(username: String) -> Result<Self, InvalidUsername> {
        if username.is_empty() {
            return Err(InvalidUsername::CannotBeEmpty)
        }
        if username.len() > 32 {
            return Err(InvalidUsername::TooLong { len: username.len() })
        }
        // Other validation checks...
        Ok(Self(username))
```

```rust
    }

    pub fn as_str(&self) -> &str {
        &self.0
    }
}
```

- The newtype pattern, combined with Rust's module and visibility system, can be used to *guarantee* that instances of a given type satisfy a set of invariants.

  In the example above, the raw `String` stored inside the `Username` struct can't be accessed directly from other modules or crates, since it's not marked as pub or `pub(in ...)`. Consumers of the `Username` type are forced to use the new method to create instances. In turn, new performs validation, thus ensuring that all instances of `Username` satisfy those checks.

- The `as_str` method allows consumers to access the raw string representation (e.g., to store it in a database). However, consumers can't modify the underlying value since `&str`, the returned type, restricts them to read-only access.

- Type-level invariants have second-order benefits.

  The input is validated once, at the boundary, and the rest of the program can rely on the invariants being upheld. We can avoid redundant validation and ”defensive programming” checks throughout the program, reducing noise and improving performance.

70.1.3 Is It Truly Encapsulated?

You must evaluate *the entire API surface* exposed by a newtype to determine if invariants are indeed bullet-proof. It is crucial to consider all possible interactions, including trait implementations, that may allow users to bypass validation checks.

```rust
pub struct Username(String);

impl Username {
    pub fn new(username: String) -> Result<Self, InvalidUsername> {
        // Validation checks...
        Ok(Self(username))
    }
}

impl std::ops::DerefMut for Username { // ‼
    fn deref_mut(&mut self) -> &mut Self::Target {
        &mut self.0
    }
}
```

- `DerefMut` allows users to get a mutable reference to the wrapped value.

  The mutable reference can be used to modify the underlying data in ways that may violate the invariants enforced by `Username::new`!

- When auditing the API surface of a newtype, you can narrow down the review scope to methods and traits that provide mutable access to the underlying data.

- Remind students of privacy boundaries.

  In particular, functions and methods defined in the same module of the newtype can access its underlying data directly. If possible, move the newtype definition to its own separate module to reduce the scope of the audit.

70.2 RAII: Drop trait

RAII (**R**esource **A**cquisition **I**s **I**nitialization) ties the lifetime of a resource to the lifetime of a value.

Rust uses RAII to manage memory, and the `Drop` trait allows you to extend this to other resources, such as file descriptors or locks.

```rust
pub struct File(std::os::fd::RawFd);

impl File {
    pub fn open(path: &str) -> Result<Self, std::io::Error> {
        // [...]
        Ok(Self(0))
    }

    pub fn read_to_end(&mut self) -> Result<Vec<u8>, std::io::Error> {
        // [...]
        Ok(b"example".to_vec())
    }

    pub fn close(self) -> Result<(), std::io::Error> {
        // [...]
        Ok(())
    }
}

fn main() -> Result<(), std::io::Error> {
    let mut file = File::open("example.txt")?;
    println!("content: {:?}", file.read_to_end()?);
    Ok(())
}
```

This slide and its sub-slides should take about 110 minutes.

- Easy to miss: `file.close()` is never called. Ask the class if they noticed.
- To release the file descriptor correctly, `file.close()` must be called after the last use — and also in early-return paths in case of errors.
- Instead of relying on the user to call `close()`, we can implement the `Drop` trait to release the resource automatically. This ties cleanup to the lifetime of the `File` value.

  ```rust
  impl Drop for File {
      fn drop(&mut self) {
          // libc::close(...);
          println!("file descriptor was closed");
  ```

```
        }
    }
```

- Note that `Drop::drop()` cannot return a `Result`. Any failures must be handled internally or ignored. In the standard library, errors during FD closure inside `Drop` are silently discarded. See the implementation: https://doc.rust-lang.org/src/std/os/fd/owned.rs.html#169-196
- When is `Drop::drop` called?

  Normally, when the `file` variable in `main()` goes out of scope (either on return or due to a panic), `drop()` is called automatically.

  If the file is moved into another function (as is this case with `File::close()`), the value is dropped when that function returns — not in `main`.

  In contrast, C++ runs destructors in the original scope even for moved-from values.
- Demo: insert `panic!("oops")` at the start of `read_to_end()` and run it. `drop()` still runs during unwinding.

More to Explore

The `Drop` trait has another important limitation: it is not `async`.

This means you cannot `await` inside a destructor, which is often needed when cleaning up asynchronous resources like sockets, database connections, or tasks that must signal completion to another system.

- Learn more: https://rust-lang.github.io/async-fundamentals-initiative/roadmap/async_drop.html
- There is an experimental `AsyncDrop` trait available on nightly: https://doc.rust-lang.org/nightly/std/future/trait.AsyncDrop.html

70.2.1 Drop can be skipped

There are cases where destructors will not run.

```rust
#[derive(Debug)]
struct OwnedFd(i32);

impl Drop for OwnedFd {
    fn drop(&mut self) {
        println!("OwnedFd::drop() called with raw fd: {:?}", self.0);
    }
}

impl Drop for TmpFile {
    fn drop(&mut self) {
        println!("TmpFile::drop() called with owned fd: {:?}", self.0);
        // libc::unlink("/tmp/file")
        // panic!("TmpFile::drop() panics");
    }
}
```

```rust
#[derive(Debug)]
struct TmpFile(OwnedFd);

impl TmpFile {
    fn open() -> Self {
        Self(OwnedFd(2))
    }

    fn close(&self) {
        panic!("TmpFile::close(): not implemented yet");
    }
}

fn main() {
    let owned_fd = OwnedFd(1);

    let file = TmpFile::open();

    std::process::exit(0);

    // std::mem::forget(file);

    // file.close();

    let _ = owned_fd;
}
```

- Drop is not guaranteed to always run. There is a number of cases when drop is skipped: the program can crash or exit, the value with the drop implementation can be leaked etc.
- In the version that calls `std::process::exit`, `TmpFile::drop()` is never run because `exit()` terminates the process immediately without any opportunity for a `drop()` method to be called.
  - You can prevent accidental use of `exit` by denying the `clippy::exit` lint.
- If you remove the `std::process::exit(0)` line, each `drop()` method in this simple case will run in turn.
- Try uncommenting the `std::mem::forget` call. What do you think will happen?

  `mem::forget()` takes ownership and "forgets" about the value `file` without running its **destructor** `Drop::drop()`. The destructor of `owned_fd` is still run.
- Remove the `mem::forget()` call, then uncomment the `file.close()` call below it. What do you expect now?

  With the default `panic = "unwind"` setting, the stack still unwinds and destructors run, even when the panic starts in `main`.
  - With `panic = "abort"` no destructors are run.
- As a last step, uncomment the `panic!` inside `TmpFile::drop()` and run it. Ask the class: which destructors run before the abort?

After a double panic, Rust no longer guarantees that remaining destructors will run:

- Some cleanup that was already in progress may still complete (for example, field destructors of the value currently being dropped),
- but anything scheduled later in the unwind path might be skipped entirely.
- This is why we say you cannot rely solely on `drop()` for critical external cleanup, nor assume that a double panic aborts without running any further destructors.

- Some languages forbid or restrict exceptions in destructors. Rust allows panicking in `Drop::drop`, but it is almost never a good idea, since it can disrupt unwinding and lead to unpredictable cleanup. It is best avoided unless there is a very specific need, such as in the case of a **drop bomb**.
- Drop is suitable for cleaning up resources within the scope of a process, but it is not the right tool for providing hard guarantees that something happens outside of the process (e.g., on local disk, or in another service in a distributed system).
- For example, deleting a temporary file in `drop()` is fine in a toy example, but in a real program you would still need an external cleanup mechanism such as a temp file reaper.
- In contrast, we can rely on `drop()` to unlock a mutex, since it is a process-local resource. If `drop()` is skipped and the mutex is left locked, it has no lasting effects outside the process.

70.2.2 Mutex and MutexGuard

In earlier examples, RAII was used to manage concrete resources like file descriptors. With a `Mutex`, the "resource" is mutable access to a value. You access the value by calling `lock`, which then returns a `MutexGuard` which will unlock the `Mutex` automatically when dropped.

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

fn main() {
    let m = Mutex::new(vec![1, 2, 3]);

    let mut guard = m.lock().unwrap();
    guard.push(4);
    guard.push(5);
    println!("{guard:?}");
}
```

- A `Mutex` controls exclusive access to a value. Unlike earlier RAII examples, the resource here is logical: temporary exclusive access to the data inside.
- This right is represented by a `MutexGuard`. Only one guard for this mutex can exist at a time. While it lives, it provides `&mut T` access.
- Although `lock()` takes `&self`, it returns a `MutexGuard` with mutable access. This works through *interior mutability*, where a type manages its own borrowing rules internally to allow mutation through `&self`.
- `MutexGuard` implements `Deref` and `DerefMut`, making access ergonomic. You lock the mutex and use the guard like a `&mut T`.
- The mutex is released by `MutexGuard::drop()`. You never call an explicit unlock function.

70.2.3 Drop Guards

A **drop guard** in Rust is a temporary object that performs some kind of cleanup when it goes out of scope. In the case of `Mutex`, the `lock` method returns a `MutexGuard` that automatically unlocks the mutex on `drop`:

```rust
struct Mutex {
    is_locked: bool,
}

struct MutexGuard<'a> {
    mutex: &'a mut Mutex,
}

impl Mutex {
    fn new() -> Self {
        Self { is_locked: false }
    }

    fn lock(&mut self) -> MutexGuard<'_> {
        self.is_locked = true;
        MutexGuard { mutex: self }
    }
}

impl Drop for MutexGuard<'_> {
    fn drop(&mut self) {
        self.mutex.is_locked = false;
    }
}
```

- The example above shows a simplified `Mutex` and its associated guard.
- Even though it is not a production-ready implementation, it illustrates the core idea:
  - the guard represents exclusive access,
  - and its `Drop` implementation releases the lock when it goes out of scope.

More to Explore

This example shows a C++ style mutex that does not contain the data it protects. While this is non-idiomatic in Rust, the goal here is only to illustrate the core idea of a drop guard, not to demonstrate a proper Rust mutex design.

For brevity, several features are omitted:

- A real `Mutex<T>` stores the protected value inside the mutex.
  This toy example omits the value entirely to focus only on the drop guard mechanism.
- Ergonomic access via `Deref` and `DerefMut` on `MutexGuard` (letting the guard behave like a `&T` or `&mut T`).
- A fully blocking `.lock()` method and a non-blocking `try_lock` variant.

You can explore the Mutex implementation in Rust's std library as an example of a production-ready mutex. The Mutex from the parking_lot crate is another worthwhile reference.

70.2.4 Drop Bombs: Enforcing API Correctness

Use Drop to enforce invariants and detect incorrect API usage. A "drop bomb" panics if a value is dropped without being explicitly finalized.

This pattern is often used when the finalizing operation (like `commit()` or `rollback()`) needs to return a `Result`, which cannot be done from `Drop`.

```rust
use std::io::{self, Write};

struct Transaction {
    active: bool,
}

impl Transaction {
    fn start() -> Self {
        Self { active: true }
    }

    fn commit(mut self) -> io::Result<()> {
        writeln!(io::stdout(), "COMMIT")?;
        self.active = false;
        Ok(())
    }
}

impl Drop for Transaction {
    fn drop(&mut self) {
        if self.active {
            panic!("Transaction dropped without commit!");
        }
    }
}

fn main() -> io::Result<()> {
    let tx = Transaction::start();
    // Use `tx` to build the transaction, then commit it.
    // Comment out the call to `commit` to see the panic.
    tx.commit()?;
    Ok(())
}
```

- In some systems, a value must be finalized by a specific API before it is dropped.

  For example, a `Transaction` might need to be committed or rolled back.

- A drop bomb ensures that a value like `Transaction` cannot be silently dropped in an unfinished state. The destructor panics if the transaction has not been explicitly finalized (for example, with `commit()`).

- The finalizing operation (such as `commit()`) usually takes `self` by value. This ensures that once the transaction is finalized, the original object can no longer be used.

- A common reason to use this pattern is when cleanup cannot be done in `Drop`, either because it is fallible or asynchronous.

- This pattern is appropriate even in public APIs. It can help users catch bugs early when they forget to explicitly finalize a transactional object.
- If cleanup can safely happen in Drop, some APIs choose to panic only in debug builds. Whether this is appropriate depends on the guarantees your API must enforce.
- Panicking in release builds is reasonable when silent misuse would cause major correctness or security problems.
- Question: Why do we need an `active` flag inside `Transaction`? Why can't `drop()` panic unconditionally?

  Expected answer: `commit()` takes `self` by value and runs `drop()`, which would panic.

More to explore

Several related patterns help enforce correct teardown or prevent accidental drops.

- The drop_bomb crate: A small utility that panics if dropped unless explicitly defused with `.defuse()`. Comes with a DebugDropBomb variant that only activates in debug builds.

70.2.5 Drop Bombs: using `std::mem::forget`

```
use std::io::{self, Write};

struct Transaction;

impl Transaction {
    fn start() -> Self {
        Transaction
    }

    fn commit(self) -> io::Result<()> {
        writeln!(io::stdout(), "COMMIT")?;

        // Defuse the drop bomb by preventing Drop from ever running.
        std::mem::forget(self);

        Ok(())
    }
}

impl Drop for Transaction {
    fn drop(&mut self) {
        // This is the "drop bomb"
        panic!("Transaction dropped without commit!");
    }
}

fn main() -> io::Result<()> {
    let tx = Transaction::start();
    // Use `tx` to build the transaction, then commit it.
```

```rust
    // Comment out the call to `commit` to see the panic.
    tx.commit()?;
    Ok(())
}
```

This example removes the flag from the previous slide and makes the drop method panic unconditionally. To avoid that panic on a successful commit, the commit method now takes ownership of the transaction and calls `std::mem::forget`, which prevents the `Drop::drop()` method from running.

If the forgotten value owned heap allocated memory that would normally be freed in its `drop()` implementation, one consequence is a memory leak. That is not the case for the `Transaction` in the example above, since it does not own any heap memory.

We can avoid needing a runtime flag by using `mem::forget()` in a tactical way. When the transaction commits successfully, we can defuse the drop bomb by calling `std::mem::forget` on the value, which prevents its `Drop` implementation from running.

70.2.6 forget and drop functions

Below are the signatures for the `drop()` and `forget()` functions:

```rust
// std::mem::forget
fn forget<T>(t: T) {
    let _ = std::mem::ManuallyDrop::new(t);
}

// std::mem::drop
fn drop<T>(_x: T) {}
```

- Both `mem::forget()` and `mem::drop()` take ownership of the value `t`.
- Despite having the same function signature, they have opposite effects:
  - `forget()` uses `ManuallyDrop` to prevent the destructor `Drop::drop()` from being invoked.

    This is useful for scenarios such as implementing a drop bomb or otherwise opting out of destructor behavior.

    Be careful though, since any resources the value exclusively owns such as heap allocated memory or file handles will remain in an unreachable state.
  - `drop()` is a convenience function for disposing of a value. Because `t` is moved into the function, it is automatically dropped which triggers its `Drop::drop()` implementation before the parent function returns.

70.2.7 Scope Guards

A scope guard uses the `Drop` trait to run cleanup code automatically when a scope exits, even during unwinding.

```rust
use scopeguard::{ScopeGuard, guard};
use std::fs::{self, File};
use std::io::Write;
```

```rust
fn download_successful() -> bool {
    // [...]
    true
}

fn main() {
    let path = "download.tmp";
    let mut file = File::create(path).expect("cannot create temporary file");

    // Set up cleanup immediately after file creation
    let cleanup = guard(path, |path| {
        println!("download failed, deleting: {:?}", path);
        let _ = fs::remove_file(path);
    });

    writeln!(file, "partial data...").unwrap();

    if download_successful() {
        // Download succeeded, keep the file
        let path = ScopeGuard::into_inner(cleanup);
        println!("Download '{path}' complete!");
    }
    // Otherwise, the guard runs and deletes the file
}
```

- This example models a download workflow. We create a temporary file first, then use a scope guard to ensure that the file is deleted if the download fails.
- The `scopeguard` crate allows you to conveniently define a single-use `Drop`-based cleanup without defining a custom type with a custom `Drop` implementation.
- The guard is created directly after creating the file, so even if `writeln!()` fails, the file will still be cleaned up. This ordering is essential for correctness.
- The `guard()` creates a `ScopeGuard` instance. It a user-defined value (in this case, `path`) and the cleanup closure that later receives this value.
- The guard's closure runs on scope exit unless it is *defused* with `ScopeGuard::into_inner` (removing the value so the guard does nothing on drop). In the success path, we call `into_inner` so the guard will not delete the file.
- A scope guard is similar to the `defer` feature in Go.
- This pattern is ideal for ”cleanup on failure” scenarios, where a cleanup should run by default unless a success path is explicitly taken.
- This pattern is also useful when you don't control the cleanup strategy of the resource object. In this example, `File::drop()` closes the file but does not delete it, and we can't change the standard library to delete the file instead (nor should we, it is not a good idea anyway).
- The `scopeguard` crate also supports cleanup strategies via the `Strategy` trait. You can choose to run the guard on unwind only, or on success only, not just always.

70.2.8 Drop: Option

```rust
struct File(Option<Handle>);

impl File {
    fn open(path: &'static str) -> std::io::Result<Self> {
        Ok(Self(Some(Handle { path })))
    }

    fn write(&mut self, data: &str) -> std::io::Result<()> {
        let handle = self.0.as_ref().unwrap();
        println!("write '{data}' to file '{}'", handle.path);
        Ok(())
    }

    fn close(mut self) -> std::io::Result<&'static str> {
        Ok(self.0.take().unwrap().path)
    }
}

impl Drop for File {
    fn drop(&mut self) {
        if let Some(handle) = self.0.take() {
            println!("automatically closing handle for file: {}", handle.path);
        }
    }
}

struct Handle {
    path: &'static str,
}
impl Drop for Handle {
    fn drop(&mut self) {
        println!("closed handle for file: {}", self.path)
    }
}

fn main() -> std::io::Result<()> {
    let mut file = File::open("foo.txt")?;
    file.write("hello")?;
    println!("manually closed file: {}", file.close()?);
    Ok(())
}
```

- In this example we want to let the user call `close()` manually so that errors from closing the file can be reported explicitly.
- At the same time we still want RAII semantics: if the user forgets to call `close()`, the handle must be cleaned up automatically in `Drop`.
- Wrapping the handle in an `Option` gives us both behaviors. `close()` extracts the handle with `take()`, and `Drop` only runs cleanup if a handle is still present.

Demo: remove the `.close()` call and run the code — `Drop` now prints the automatic cleanup.

- The main downside is ergonomics. `Option` forces us to handle both the `Some` and `None` case even in places where, logically, `None` cannot occur. Rust's type system cannot express that relationship between `File` and its `Handle`, so we handle both cases manually.

More to explore

Instead of `Option` we could use `ManuallyDrop`, which suppresses automatic destruction by preventing Rust from calling `Drop` for the value; you must handle teardown yourself.

The *scopeguard* example on the previous slide shows how `ManuallyDrop` can replace `Option` to avoid handling `None` in places where the value should always exist.

In such designs we typically track the drop state with a separate flag next to the `ManuallyDrop<Handle>`, which lets us track whether the handle has already been manually consumed.

70.3 Extension Traits

It may desirable to **extend** foreign types with new inherent methods. For example, allow your code to check if a string is a palindrome using method-calling syntax: `s.is_palindrome()`.

It might feel natural to reach out for an `impl` block:

```
// 🛠️❌
impl str {
    pub fn is_palindrome(&self) -> bool {
        self.chars().eq(self.chars().rev())
    }
}
```

The Rust compiler won't allow it, though. But you can use the **extension trait pattern** to work around this limitation.

This slide and its sub-slides should take about 65 minutes.

- A Rust item (be it a trait or a type) is referred to as:
  - **foreign**, if it isn't defined in the current crate
  - **local**, if it is defined in the current crate

  The distinction has significant implications for coherence and orphan rules, as we'll get a chance to explore in this section of the course.

- Compile the example to show the compiler error that's emitted.

  Highlight how the compiler error message nudges you towards the extension trait pattern.

- Explain how many type-system restrictions in Rust aim to prevent *ambiguity*.

  What would happen if you were allowed to define new inherent methods on foreign types? Different crates in your dependency tree might end up defining different methods on the same foreign type with the same name.

As soon as there is room for ambiguity, there must be a way to disambiguate. If disambiguation happens implicitly, it can lead to surprising or otherwise unexpected behavior. If disambiguation happens explicitly, it can increase the cognitive load on developers who are reading your code.

Furthermore, every time a crate defines a new inherent method on a foreign type, it may cause compilation errors in *your* code, as you may be forced to introduce explicit disambiguation.

Rust has decided to avoid the issue altogether by forbidding the definition of new inherent methods on foreign types.

- Other languages (e.g, Kotlin, C#, Swift) allow adding methods to existing types, often called "extension methods." This leads to different trade-offs in terms of potential ambiguities and the need for global reasoning.

70.3.1 Extending Foreign Types

An **extension trait** is a local trait definition whose primary purpose is to attach new methods to foreign types.

```rust
mod ext {
    pub trait StrExt {
        fn is_palindrome(&self) -> bool;
    }

    impl StrExt for str {
        fn is_palindrome(&self) -> bool {
            self.chars().eq(self.chars().rev())
        }
    }
}

fn main() {
    // Bring the extension trait into scope...
    pub use ext::StrExt as _;
    // ...then invoke its methods as if they were inherent methods
    assert!("dad".is_palindrome());
    assert!(!"grandma".is_palindrome());
}
```

- The `Ext` suffix is conventionally attached to the name of extension traits.

  It communicates that the trait is primarily used for extension purposes, and it is therefore not intended to be implemented outside the crate that defines it.

  Refer to the "Extension Trait" RFC as the authoritative source for naming conventions.

- The extension trait implementation for a foreign type must be in the same crate as the trait itself, otherwise you'll be blocked by Rust's *orphan rule*.

- The extension trait must be in scope when its methods are invoked.

  Comment out the `use` statement in the example to show the compiler error that's emitted if you try to invoke an extension method without having the corresponding extension trait in scope.

- The example above uses an *underscore import* (`use ext::StringExt as _`) to minimize the likelihood of a naming conflict with other imported traits.

  With an underscore import, the trait is considered to be in scope and you're allowed to invoke its methods on types that implement the trait. Its *symbol*, instead, is not directly accessible. This prevents you, for example, from using that trait in a `where` clause.

  Since extension traits aren't meant to be used in `where` clauses, they are conventionally imported via an underscore import.

70.3.2 Method Resolution Conflicts

What happens when you have a name conflict between an inherent method and an extension method?

```
mod ext {
    pub trait CountOnesExt {
        fn count_ones(&self) -> u32;
    }

    impl CountOnesExt for i32 {
        fn count_ones(&self) -> u32 {
            let value = *self;
            (0..32).filter(|i| ((value >> i) & 1i32) == 1).count() as u32
        }
    }
}
fn main() {
    pub use ext::CountOnesExt;
    // Which `count_ones` method is invoked?
    // The one from `CountOnesExt`? Or the inherent one from `i32`?
    assert_eq!((-1i32).count_ones(), 32);
}
```

- A foreign type may, in a newer version, add a new inherent method with the same name as our extension method.

  Ask: What will happen in the example above? Will there be a compiler error? Will one of the two methods be given higher priority? Which one?

  Add a `panic!("Extension trait");` in the body of `CountOnesExt::count_ones` to clarify which method is being invoked.

- To prevent users of the Rust language from having to manually specify which method to use in all cases, there is a priority ordering system for how methods get ”picked” first:

  - Immutable (`&self`) first
    - Inherent (method defined in the type's `impl` block) before Trait (method added by a trait impl).
  - Mutable (`&mut self`) Second
    - Inherent before Trait.

  If every method with the same name has different mutability and was either defined in as an inherent method or trait method, with no overlap, this makes the job easy for the compiler.

This does introduce some ambiguity for the user, who may be confused as to why a method they're relying on is not producing expected behavior. Avoid name conflicts instead of relying on this mechanism if you can.

Demonstrate: Change the signature and implementation of `CountOnesExt::count_ones` to `fn count_ones(&mut self) -> u32` and modify the invocation accordingly:

```
assert_eq!((&mut -1i32).count_ones(), 32);
```

`CountOnesExt::count_ones` is invoked, rather than the inherent method, since `&mut self` has a higher priority than `&self`, the one used by the inherent method.

If an immutable inherent method and a mutable trait method exist for the same type, we can specify which one to use at the call site by using `(&<value>).count_ones()` to get the immutable (higher priority) method or `(&mut <value>).count_ones()`

Point the students to the Rust reference for more information on method resolution.

- Avoid naming conflicts between extension trait methods and inherent methods. Rust's method resolution algorithm is complex and may surprise users of your code.

More to explore

- The interaction between the priority search used by Rust's method resolution algorithm and automatic `Deref`ing can be used to emulate specialization on the stable toolchain, primarily in the context of macro-generated code. Check out "Autoref Specialization" for the specific details.

70.3.3 Trait Method Conflicts

What happens when you have a name conflict between two different trait methods implemented for the same type?

```
mod ext {
    pub trait Ext1 {
        fn is_palindrome(&self) -> bool;
    }

    pub trait Ext2 {
        fn is_palindrome(&self) -> bool;
    }

    impl Ext1 for str {
        fn is_palindrome(&self) -> bool {
            self.chars().eq(self.chars().rev())
        }
    }

    impl Ext2 for str {
        fn is_palindrome(&self) -> bool {
            self.chars().eq(self.chars().rev())
        }
    }
}
```

```rust
pub use ext::{Ext1, Ext2};

// Which method is invoked?
// The one from `Ext1`? Or the one from `Ext2`?
fn main() {
    assert!("dad".is_palindrome());
}
```

- The trait you are extending may, in a newer version, add a new trait method with the same name as your extension method. Or another extension trait for the same type may define a method with a name that conflicts with your own extension method.

  Ask: what will happen in the example above? Will there be a compiler error? Will one of the two methods be given higher priority? Which one?

- The compiler rejects the code because it cannot determine which method to invoke. Neither `Ext1` nor `Ext2` has a higher priority than the other.

  To resolve this conflict, you must specify which trait you want to use.

  Demonstrate: call `Ext1::is_palindrome("dad")` or `Ext2::is_palindrome("dad")` instead of `"dad".is_palindrome()`.

  For methods with more complex signatures, you may need to use a more explicit fully-qualified syntax.

- Demonstrate: replace `"dad".is_palindrome()` with `<str as Ext1>::is_palindrome("dad")` or `<str as Ext2>::is_palindrome("dad")`.

70.3.4 Extending Other Traits

As with types, it may be desirable to **extend foreign traits**. In particular, to attach new methods to *all* implementors of a given trait.

```rust
mod ext {
    use std::fmt::Display;

    pub trait DisplayExt {
        fn quoted(&self) -> String;
    }

    impl<T: Display> DisplayExt for T {
        fn quoted(&self) -> String {
            format!("'{}'", self)
        }
    }
}

pub use ext::DisplayExt as _;

assert_eq!("dad".quoted(), "'dad'");
assert_eq!(4.quoted(), "'4'");
assert_eq!(true.quoted(), "'true'");
```

- Highlight how we added new behavior to *multiple* types at once. `.quoted()` can be called on string slices, numbers, and booleans since they all implement the `Display` trait.

  This flavor of the extension trait pattern uses *blanket implementations*.

  A blanket implementation implements a trait for all types `T` that satisfy the trait bounds specified in the `impl` block. In this case, the only requirement is that `T` implements the `Display` trait.

- Draw the students' attention to the implementation of `DisplayExt::quoted`: we can't make any assumptions about `T` other than that it implements `Display`. All our logic must either use methods from `Display` or functions/macros that don't require other traits.

  For example, we can call `format!` with `T`, but can't call `.to_uppercase()` because it is not necessarily a `String`.

  We could introduce additional trait bounds on `T`, but it would restrict the set of types that can leverage the extension trait.

- Conventionally, the extension trait is named after the trait it extends, followed by the `Ext` suffix. In the example above, `DisplayExt`.

- There are entire crates that extend standard library traits with new functionality.

  – `itertools` crate provides the `Itertools` trait that extends `Iterator`. It adds many iterator adapters, such as `interleave` and `unique`. It provides new algorithmic building blocks for iterator pipelines built with method chaining.

  – `futures` crate provides the `FutureExt` trait, which extends the `Future` trait with new combinators and helper methods.

More To Explore

- Extension traits can be used by libraries to distinguish between stable and experimental methods.

  Stable methods are part of the trait definition.

  Experimental methods are provided via an extension trait defined in a different library, with a less restrictive stability policy. Some utility methods are then "promoted" to the core trait definition once they have been proven useful and their design has been refined.

- Extension traits can be used to split a dyn-incompatible trait in two:

  – A **dyn-compatible core**, restricted to the methods that satisfy dyn-compatibility requirements.
  – An **extension trait**, containing the remaining methods that are not dyn-compatible (e.g., methods with a generic parameter).

- Concrete types that implement the core trait will be able to invoke all methods, thanks to the blanket impl for the extension trait. Trait objects (`dyn CoreTrait`) will be able to invoke all methods on the core trait as well as those on the extension trait that don't require `Self: Sized`.

70.3.5 Should I Define An Extension Trait?

In what scenarios should you prefer an extension trait over a free function?

```rust
pub trait StrExt {
    fn is_palindrome(&self) -> bool;
}

impl StrExt for &str {
    fn is_palindrome(&self) -> bool {
        self.chars().eq(self.chars().rev())
    }
}

// vs

fn is_palindrome(s: &str) -> bool {
    s.chars().eq(s.chars().rev())
}
```

The main advantage of extension traits is **ease of discovery**.

- Extension methods can be easier to discover than free functions. Language servers (e.g., `rust-analyzer`) will suggest them if you type `.` after an instance of the foreign type.
- However, a bespoke extension trait might be overkill for a single method. Both approaches require an additional import, and the familiar method syntax may not justify the boilerplate of a full trait definition.
- **Discoverability:** Extension methods are easier to discover than free functions. Language servers (e.g., `rust-analyzer`) will suggest them if you type `.` after an instance of the foreign type.
- **Method Chaining:** A major ergonomic win for extension traits is method chaining. This is the foundation of the `Iterator` trait, allowing for fluent calls like `data.iter().filter(...).map(...)`. Achieving this with free functions would be far more cumbersome (`map(filter(iter(data), ...), ...)`).
- **API Cohesion:** Extension traits help create a cohesive API. If you have several related functions for a foreign type (e.g., `is_palindrome`, `word_count`, `to_kebab_case`), grouping them in a single `StrExt` trait is often cleaner than having multiple free functions for a user to import.
- **Trade-offs:** Despite these advantages, a bespoke extension trait might be overkill for a single, simple function. Both approaches require an additional import, and the familiar method syntax may not justify the boilerplate of a full trait definition.

70.4 Typestate Pattern: Problem

How can we ensure that only valid operations are allowed on a value based on its current state?

```rust
use std::fmt::Write as _;

#[derive(Default)]
```

```rust
struct Serializer {
    output: String,
}

impl Serializer {
    fn serialize_struct_start(&mut self, name: &str) {
        let _ = writeln!(&mut self.output, "{name} {{");
    }

    fn serialize_struct_field(&mut self, key: &str, value: &str) {
        let _ = writeln!(&mut self.output, "  {key}={value};");
    }

    fn serialize_struct_end(&mut self) {
        self.output.push_str("}\n");
    }

    fn finish(self) -> String {
        self.output
    }
}

fn main() {
    let mut serializer = Serializer::default();
    serializer.serialize_struct_start("User");
    serializer.serialize_struct_field("id", "42");
    serializer.serialize_struct_field("name", "Alice");

    // serializer.serialize_struct_end(); // ← Oops! Forgotten

    println!("{}", serializer.finish());
}
```

This slide and its sub-slides should take about 65 minutes.

- This `Serializer` is meant to write a structured value.
- However, in this example we forgot to call `serialize_struct_end()` before `finish()`. As a result, the serialized output is incomplete or syntactically incorrect.
- One approach to fix this would be to track internal state manually, and return a `Result` from methods like `serialize_struct_field()` or `finish()` if the current state is invalid.
- But this has downsides:
  - It is easy to get wrong as an implementer. Rust's type system cannot help enforce the correctness of our state transitions.
  - It also adds unnecessary burden on the user, who must handle `Result` values for operations that are misused in source code rather than at runtime.
- A better solution is to model the valid state transitions directly in the type system.

  In the next slide, we will apply the **typestate pattern** to enforce correct usage at compile time and make it impossible to call incompatible methods or forget to do a required action.

70.4.1 Typestate Pattern: Example

The typestate pattern encodes part of a value's runtime state into its type. This allows us to prevent invalid or inapplicable operations at compile time.

```rust
use std::fmt::Write as _;

#[derive(Default)]
struct Serializer {
    output: String,
}

struct SerializeStruct {
    serializer: Serializer,
}

impl Serializer {
    fn serialize_struct(mut self, name: &str) -> SerializeStruct {
        writeln!(&mut self.output, "{name} {{").unwrap();
        SerializeStruct { serializer: self }
    }

    fn finish(self) -> String {
        self.output
    }
}

impl SerializeStruct {
    fn serialize_field(mut self, key: &str, value: &str) -> Self {
        writeln!(&mut self.serializer.output, "  {key}={value};").unwrap();
        self
    }

    fn finish_struct(mut self) -> Serializer {
        self.serializer.output.push_str("}\n");
        self.serializer
    }
}

fn main() {
    let serializer = Serializer::default()
        .serialize_struct("User")
        .serialize_field("id", "42")
        .serialize_field("name", "Alice")
        .finish_struct();

    println!("{}", serializer.finish());
}
```

Serializer usage flowchart:

```
+------------+  serialize struct   +-----------------+
| Serializer | ------------------> | SerializeStruct | <------+
+------------+                     +-----------------+        |
                                                              |
   |   ^                              |      |                |
   |   |     finish struct            |      | serialize field |
   |   +------------------------------+      +----------------+
   |
   +---> finish
```

- This example is inspired by Serde's `Serializer` trait. Serde uses typestates internally to ensure serialization follows a valid structure. For more, see: https://serde.rs/impl-serializer.html
- The key idea behind typestate is that state transitions happen by consuming a value and producing a new one. At each step, only operations valid for that state are available.
- In this example:
  - We begin with a `Serializer`, which only allows us to start serializing a struct.
  - Once we call `.serialize_struct(...)`, ownership moves into a `SerializeStruct` value. From that point on, we can only call methods related to serializing struct fields.
  - The original `Serializer` is no longer accessible — preventing us from mixing modes (such as starting another *struct* mid-struct) or calling `finish()` too early.
  - Only after calling `.finish_struct()` do we receive the `Serializer` back. At that point, the output can be finalized or reused.
- If we forget to call `finish_struct()` and drop the `SerializeStruct` early, the `Serializer` is also dropped. This ensures incomplete output cannot leak into the system.
- By contrast, if we had implemented everything on `Serializer` directly — as seen on the previous slide, nothing would stop someone from skipping important steps or mixing serialization flows.

70.4.2 Beyond Simple Typestate

How do we manage increasingly complex configuration flows with many possible states and transitions, while still preventing incompatible operations?

```
struct Serializer {/* [...] */}
struct SerializeStruct {/* [...] */}
struct SerializeStructProperty {/* [...] */}
struct SerializeList {/* [...] */}

impl Serializer {
    // TODO, implement:
    //
    // fn serialize_struct(self, name: &str) -> SerializeStruct
    // fn finish(self) -> String
```

```
}

impl SerializeStruct {
    // TODO, implement:
    //
    // fn serialize_property(mut self, name: &str) -> SerializeStructProperty

    // TODO,
    // How should we finish this struct? This depends on where it appears:
    // - At the root level: return `Serializer`
    // - As a property inside another struct: return `SerializeStruct`
    // - As a value inside a list: return `SerializeList`
    //
    // fn finish(self) -> ???
}

impl SerializeStructProperty {
    // TODO, implement:
    //
    // fn serialize_string(self, value: &str) -> SerializeStruct
    // fn serialize_struct(self, name: &str) -> SerializeStruct
    // fn serialize_list(self) -> SerializeList
    // fn finish(self) -> SerializeStruct
}

impl SerializeList {
    // TODO, implement:
    //
    // fn serialize_string(mut self, value: &str) -> Self
    // fn serialize_struct(mut self, value: &str) -> SerializeStruct
    // fn serialize_list(mut self) -> SerializeList

    // TODO:
    // Like `SerializeStruct::finish`, the return type depends on nesting.
    //
    // fn finish(mut self) -> ???
}
```

Diagram of valid transitions:

```
    +-----------+   +---------+------------+-----+
    |           |   |         |            |     |
    V           |   V         |            V     |
                +                                |
serializer --> structure --> property --> list +-+

    |           |   ^           |          ^
    V           |   |           |          |
                |   +-----------+          |
  String        |                          |
                +--------------------------+
```

- Building on our previous serializer, we now want to support **nested structures** and **lists**.
- However, this introduces both **duplication** and **structural complexity**.
- Even more critically, we now hit a **type system limitation**: we cannot cleanly express what `finish()` should return without duplicating variants for every nesting context (e.g. root, struct, list).
- From the diagram of valid transitions, we can observe:
  - The transitions are recursive
  - The return types depend on *where* a substructure or list appears
  - Each context requires a return path to its parent
- With only concrete types, this becomes unmanageable. Our current approach leads to an explosion of types and manual wiring.
- In the next chapter, we'll see how **generics** let us model recursive flows with less boilerplate, while still enforcing valid operations at compile time.

70.4.3 Typestate Pattern with Generics

By combining typestate modeling with generics, we can express a wider range of valid states and transitions without duplicating logic. This approach is especially useful when the number of states grows or when multiple states share behavior but differ in structure.

```
struct Serializer<S> {
    // [...]
    indent: usize,
    buffer: String,
    state: S,
}

struct Root;
struct Struct<S>(S);
struct Property<S>(S);
struct List<S>(S);
```

We now have all the tools needed to implement the methods for the `Serializer` and its state type definitions. This ensures that our API only permits valid transitions, as illustrated in the following diagram:

Diagram of valid transitions:

```
    +-----------+   +---------+-----------+-----+
    |           |   |         |           |     |
    V           |   V         |           V     |
                +                               |
serializer --> structure --> property --> list +-+

    |           |   ^           |          ^
    V           |   |           |          |
                |   +-----------+          |
  String        |                          |
                +--------------------------+
```

- By leveraging generics to track the parent context, we can construct arbitrarily nested serializers that enforce valid transitions between struct, list, and property states.
- This enables us to build a recursive structure while maintaining strict control over which methods are accessible in each state.
- Methods common to all states can be defined for any `S` in `Serializer<S>`.
- Marker types (e.g., `List<S>`) introduce no memory or runtime overhead, as they contain no data other than a possible Zero-Sized Type. Their only role is to enforce correct API usage through the type system.

70.4.3.1 Serializer: implement Root

```rust
struct Serializer<S> {
    // [...]
    indent: usize,
    buffer: String,
    state: S,
}

struct Root;
struct Struct<S>(S);

impl Serializer<Root> {
    fn new() -> Self {
        // [...]
        Self { indent: 0, buffer: String::new(), state: Root }
    }

    fn serialize_struct(mut self, name: &str) -> Serializer<Struct<Root>> {
        // [...]
        writeln!(self.buffer, "{name} {{").unwrap();
        Serializer {
            indent: self.indent + 1,
            buffer: self.buffer,
            state: Struct(self.state),
        }
    }

    fn finish(self) -> String {
        // [...]
        self.buffer
    }
}
```

Referring back to our original diagram of valid transitions, we can visualize the beginning of our implementation as follows:

```
                          serialize
                          struct
+--------------------+ --------------> +-----------------------------+
| "Serializer<Root>" |                 | "Serializer<Struct<Root>>" |
```

```
+--------------------+ <-------------- +----------------------------+
                          finish struct
         |
         |
         |
finish   |
         V

     +--------+
     | String |
     +--------+
```

- At the ”root” of our `Serializer`, the only construct allowed is a `Struct`.
- The `Serializer` can only be finalized into a `String` from this root level.

70.4.3.2 Serializer: implement Struct

```rust
struct Serializer<S> {
    // [...]
    indent: usize,
    buffer: String,
    state: S,
}

struct Struct<S>(S);
struct Property<S>(S);

impl<S> Serializer<Struct<S>> {
    fn serialize_property(mut self, name: &str) -> Serializer<Property<Struct<S>>> {
        // [...]
        write!(self.buffer, "{}{name}: ", " ".repeat(self.indent * 2)).unwrap();
        Serializer {
            indent: self.indent,
            buffer: self.buffer,
            state: Property(self.state),
        }
    }

    fn finish_struct(mut self) -> Serializer<S> {
        // [...]
        self.indent -= 1;
        writeln!(self.buffer, "{}}}", " ".repeat(self.indent * 2)).unwrap();
        Serializer { indent: self.indent, buffer: self.buffer, state: self.state.0 }
    }
}
```

The diagram can now be expanded as follows:

```
                                                +------+
                                  finish        |      |
                    serialize     struct        V      |
                    struct
```

```
+--------------------+ --------------> +-------------------------+
| "Serializer<Root>" |                 | "Serializer<Struct<S>>" |
+--------------------+ <-------------- +-------------------------+
                          finish struct
         |                                    serialize    |
         |                                    property     V
         |
finish   |                           +-----------------------------------+
         V                           | "Serializer<Property<Struct<S>>>" |
                                     +-----------------------------------+
     +--------+
     | String |
     +--------+
```

- A `Struct` can only contain a `Property`;
- Finishing a `Struct` returns control back to its parent, which in our previous slide was assumed the `Root`, but in reality however it can be also something else such as `Struct` in case of nested "structs".

70.4.3.3 Serializer: implement Property

```rust
struct Serializer<S> {
    // [...]
    indent: usize,
    buffer: String,
    state: S,
}

struct Struct<S>(S);
struct Property<S>(S);
struct List<S>(S);

impl<S> Serializer<Property<Struct<S>>> {
    fn serialize_struct(mut self, name: &str) -> Serializer<Struct<Struct<S>>> {
        // [...]
        writeln!(self.buffer, "{name} {{").unwrap();
        Serializer {
            indent: self.indent + 1,
            buffer: self.buffer,
            state: Struct(self.state.0),
        }
    }

    fn serialize_list(mut self) -> Serializer<List<Struct<S>>> {
        // [...]
        writeln!(self.buffer, "[").unwrap();
        Serializer {
            indent: self.indent + 1,
            buffer: self.buffer,
            state: List(self.state.0),
        }
```

```
    }

    fn serialize_string(mut self, value: &str) -> Serializer<Struct<S>> {
        // [...]
        writeln!(self.buffer, "{value},").unwrap();
        Serializer { indent: self.indent, buffer: self.buffer, state: self.state.0 }
    }
}
```

With the addition of the Property state methods, our diagram is now nearly complete:

```
                                                     +------+
                                             finish  |      |
                          serialize          struct  V      |
                          struct
+--------------------+ --------------> +-------------------------+
| "Serializer<Root>" |                 | "Serializer<Struct<S>>" |
+--------------------+ <-------------- +-------------------------+ <-----------+
                         finish struct                                         |
         |                                     serialize   |                   |
         |                                     property    V        serialize  |
         |                                                          string or  |
finish   |                            +---------------------------+ struct     |
         V                            | "Serializer<Property<S>>" | ------------+
                                      +---------------------------+
     +--------+
     | String |                                serialize   |
     +--------+                                list        V

                                         +-----------------------+
                                         | "Serializer<List<S>>" |
                                         +-----------------------+
```

- A property can be defined as a `String`, `Struct<S>`, or `List<S>`, enabling the representation of nested structures.
- This concludes the step-by-step implementation. The full implementation, including support for `List<S>`, is shown in the next slide.

70.4.3.4 Serializer: complete implementation

Looking back at our original desired flow:

```
    +-----------+   +---------+------------+-----+
    |           |   |         |            |     |
    V           |   V         |            V     |
                +                                |
serializer --> structure --> property --> list +-+

    |           |   ^           |          ^
    V           |   |           |          |
                |   +-----------+          |
  String        |                          |
```

```
                +--------------------------+
```

We can now see this reflected directly in the types of our serializer:

```
                                                     +------+
                                             finish  |      |
                          serialize          struct  V      |
                          struct
+--------------------+ --------------> +-------------------------+ <----------------+
| "Serializer<Root>" |                 | "Serializer<Struct<S>>" |                  |
+--------------------+ <-------------- +-------------------------+ <------------+   |
                         finish struct                                          |   |
         |                                  |  serialize    |                   |   |
         |                       +----------+  property     V       serialize   |   |
         |                       |                                  string or   |   |
finish   |                       |   +---------------------------+  struct      |   |
         V                       |   | "Serializer<Property<S>>" | -------------+   |
                         finish  |   +---------------------------+                  |
     +--------+          struct  |                                                  |
     | String |                  |             serialize    |                       |
     +--------+                  |             list         V                       |
                                 |                                    finish        |
                                 |       +-----------------------+    list          |
                                 +-----> | "Serializer<List<S>>" | -----------------+
                                         +-----------------------+
                                              serialize
                                            | list or string  ^
                                            | or finish list  |
                                            +-----------------+
```

The code for the full implementation of the `Serializer` and all its states can be found in this Rust playground.

- This pattern isn't a silver bullet. It still allows issues like:
  - Empty or invalid property names (which can be fixed using the newtype pattern)
  - Duplicate property names (which could be tracked in `Struct<S>` and handled via `Result`)
- If validation failures occur, we can also change method signatures to return a `Result`, allowing recovery:

```rust
struct PropertySerializeError<S> {
    kind: PropertyError,
    serializer: Serializer<Struct<S>>,
}

impl<S> Serializer<Struct<S>> {
    fn serialize_property(
        self,
        name: &str,
    ) -> Result<Serializer<Property<Struct<S>>>, PropertySerializeError<S>> {
        /* ... */
    }
```

```
}
```

- While this API is powerful, it's not always ergonomic. Production serializers typically favor simpler APIs and reserve the typestate pattern for enforcing critical invariants.
- One excellent real-world example is `rustls::ClientConfig`, which uses typestate with generics to guide the user through safe and correct configuration steps.

70.5 Using the Borrow checker to enforce Invariants

The borrow checker, while added to enforce memory ownership, can model other problems and prevent API misuse.

```rust
/// Doors can be open or closed, and you need the right key to lock or unlock
/// one. Modelled with a Shared key and Owned door.
pub struct DoorKey {
    pub key_shape: u32,
}
pub struct LockedDoor {
    lock_shape: u32,
}
pub struct OpenDoor {
    lock_shape: u32,
}

fn open_door(key: &DoorKey, door: LockedDoor) -> Result<OpenDoor, LockedDoor> {
    if door.lock_shape == key.key_shape {
        Ok(OpenDoor { lock_shape: door.lock_shape })
    } else {
        Err(door)
    }
}

fn close_door(key: &DoorKey, door: OpenDoor) -> Result<LockedDoor, OpenDoor> {
    if door.lock_shape == key.key_shape {
        Ok(LockedDoor { lock_shape: door.lock_shape })
    } else {
        Err(door)
    }
}

fn main() {
    let key = DoorKey { key_shape: 7 };
    let closed_door = LockedDoor { lock_shape: 7 };
    let opened_door = open_door(&key, closed_door);
    if let Ok(opened_door) = opened_door {
        println!("Opened the door with key shape '{}'", key.key_shape);
    } else {
        eprintln!(
            "Door wasn't opened! Your key only opens locks with shape '{}'",
            key.key_shape
```

```
        );
    }
}
```

This slide and its sub-slides should take about 90 minutes.

- We've seen the borrow checker prevent memory safety bugs (use-after-free, data races).
- We've also used types to shape and restrict APIs already using the Typestate pattern.
- Language features are often introduced for a specific purpose.

  Over time, users may develop ways of using a feature in ways that were not predicted when they were introduced.

  Java 5 introduced Generics in 2004 with the main stated purpose of enabling type-safe collections.

  Adoption was slow at first, but some new projects began designing their APIs around generics from the beginning.

  Since then, users and developers of the language expanded the use of generics to other areas of type-safe API design:

  - Class information can be held onto via Java's `Class<T>` or Guava's `TypeToken<T>`.
  - The Builder pattern can be implemented using Recursive Generics.

  We aim to do something similar here: Even though the borrow checker was introduced to prevent use-after-free and data races, we treat it as just another API design tool.

  It can be used to model program properties that have nothing to do with preventing memory safety bugs.

- To use the borrow checker as a problem solving tool, we will need to "forget" that the original purpose of it is to prevent mutable aliasing in the context of preventing use-after-frees and data races.

  We should imagine working within situations where the rules are the same but the meaning is slightly different.

- This example uses ownership and borrowing are used to model the state of a physical door.

  `open_door` **consumes** a `LockedDoor` and returns a new `OpenDoor`. The old `LockedDoor` value is no longer available.

  If the wrong key is used, the door is left locked. It is returned as an `Err` case of the `Result`.

  It is a compile-time error to try and use a door that has already been opened.

- Similarly, `lock_door` consumes an `OpenDoor`, preventing closing the door twice at compile time.
- The rules of the borrow checker exist to prevent memory safety bugs, but the underlying logical system does not "know" what memory is.

  All the borrow checker does is enforce a specific set of rules of how users can order operations.

This is just one case of piggy-backing onto the rules of the borrow checker to design APIs to be harder or impossible to misuse.

70.5.1 Lifetimes and Borrows: the Abstract Rules

```
// An internal data type to have something to hold onto.
pub struct Internal;
// The "outer" data.
pub struct Data(Internal);

fn shared_use(value: &Data) -> &Internal {
    &value.0
}
fn exclusive_use(value: &mut Data) -> &mut Internal {
    &mut value.0
}
fn deny_future_use(value: Data) {}

fn demo_exclusive() {
    let mut value = Data(Internal);
    let shared = shared_use(&value);
    // let exclusive = exclusive_use(&mut value); // ❌🔨
    let shared_again = shared;
}

fn demo_denied() {
    let value = Data(Internal);
    deny_future_use(value);
    // let shared = shared_use(&value); // ❌🔨
}
```

- This example re-frames the borrow checker rules away from references and towards semantic meaning in non-memory-safety settings.

  Nothing is being mutated, nothing is being sent across threads.
- In Rust's borrow checker we have access to three different ways of "taking" a value:
  - Owned value `T`. Value is dropped when the scope ends, unless it is not returned to another scope.
  - Shared Reference `&T`. Allows aliasing but prevents mutable access while shared references are in use.
  - Mutable Reference `&mut T`. Only one of these is allowed to exist for a value at any one point, but can be used to create shared references.
- Ask: The two commented-out lines in the demo functions would cause compilation errors, Why?

  `demo_exclusive`: Because the `shared` value is still aliased after the `exclusive` reference is taken.

demo_denied: Because `value` is consumed the line before the `shared_again_again` reference is taken from `&value`.

- Remember that every `&T` and `&mut T` has a lifetime, just one the user doesn't have to annotate or think about most of the time.

  We rarely specify lifetimes because the Rust compiler allows us to *elide* them in most cases. See: Lifetime Elision

70.5.2 Single-use values

Sometimes we want values that *can only be used once*. One critical example of this is in cryptography: A "Nonce."

```
pub struct Key(/* specifics omitted */);
/// A single-use number suitable for cryptographic purposes.
pub struct Nonce(u32);
/// A cryptographically sound random generator function.
pub fn new_nonce() -> Nonce {
    Nonce(4) // chosen by a fair dice roll, https://xkcd.com/221/
}
/// Consume a nonce, but not the key or the data.
pub fn encrypt(nonce: Nonce, key: &Key, data: &[u8]) {}

fn main() {
    let nonce = new_nonce();
    let data_1: [u8; 4] = [1, 2, 3, 4];
    let data_2: [u8; 4] = [4, 3, 2, 1];
    let key = Key(/* specifics omitted */);

    // The key and data can be re-used, copied, etc. but the nonce cannot.
    encrypt(nonce, &key, &data_1);
    // encrypt(nonce, &key, &data_2); // 🛠️❌
}
```

- Problem: How can we guarantee a value is used only once?
- Motivation: A nonce is a piece of random, unique data used in cryptographic protocols to prevent replay attacks.

  Background: In practice people have ended up accidentally re-using nonces. Most commonly, this causes the cryptographic protocol to completely break down and stop fulfilling its function.

  Depending on the specifics of nonce reuse and cryptography at hand, private keys can also become computable by attackers.

- Rust has an obvious tool for achieving the invariant "Once you use this, you can't use it again": passing a value as an *owned argument*.
- Highlight: the `encrypt` function takes `nonce` by value (an owned argument), but `key` and `data` by reference.
- The technique for single-use values is as follows:

  - Keep constructors private, so a user can't construct values with the same inner value twice.
  - Don't implement `Clone`/`Copy` traits or equivalent methods, so a user can't duplicate data we want to keep unique.
  - Make the interior type opaque (like with the newtype pattern), so the user cannot modify an existing value on their own.
- Ask: What are we missing from the newtype pattern in the slide's code?

  Expect: Module boundary.

  Demonstrate: Without a module boundary a user can construct a nonce on their own.

  Fix: Put `Key`, `Nonce`, and `new_nonce` behind a module.

More to Explore

- Cryptography Nuance: A nonce might still be used twice if it was created through pseudo-random process with no actual randomness. That can't be prevented through this method. This API design prevents one nonce duplication, but not all logic bugs.

70.5.3 Mutually Exclusive References / "Aliasing XOR Mutability"

We can use the mutual exclusion of `&T` and `&mut T` references to prevent data from being used before it is ready.

```
pub struct QueryResult;
pub struct DatabaseConnection {/* fields omitted */}

impl DatabaseConnection {
    pub fn new() -> Self {
        Self {}
    }
    pub fn results(&self) -> &[QueryResult] {
        &[] // fake results
    }
}

pub struct Transaction<'a> {
    connection: &'a mut DatabaseConnection,
}

impl<'a> Transaction<'a> {
    pub fn new(connection: &'a mut DatabaseConnection) -> Self {
        Self { connection }
    }
    pub fn query(&mut self, _query: &str) {
        // Send the query over, but don't wait for results.
    }
    pub fn commit(self) {
        // Finish executing the transaction and retrieve the results.
    }
```

```rust
}

fn main() {
    let mut db = DatabaseConnection::new();

    // The transaction `tx` mutably borrows `db`.
    let mut tx = Transaction::new(&mut db);
    tx.query("SELECT * FROM users");

    // This won't compile because `db` is already mutably borrowed by `tx`.
    // let results = db.results(); // ❌🔨

    // The borrow of `db` ends when `tx` is consumed by `commit()`.
    tx.commit();

    // Now it is possible to borrow `db` again.
    let results = db.results();
}
```

- Motivation: In this database API queries are kicked off for asynchronous execution and the results are only available once the whole transaction is finished.

  A user might think that queries are executed immediately, and try to read results before they are made available. This API misuse could make the app read incomplete or incorrect data.

  While an obvious misunderstanding, situations such as this can happen in practice.

  Ask: Has anyone misunderstood an API by not reading the docs for proper use?

  Expect: Examples of early-career or in-university mistakes and misunderstandings.

  As an API grows in size and user base, a smaller percentage of users has deep knowledge of the system the API represents.

- This example shows how we can use Aliasing XOR Mutability to prevent this kind of misuse.
- The code might read results before they are ready if the programmer assumes that the queries execute immediately rather than kicked off for asynchronous execution.
- The constructor for the `Transaction` type takes a mutable reference to the database connection, and stores it in the returned `Transaction` value.

  The explicit lifetime here doesn't have to be intimidating, it just means ”`Transaction` is outlived by the `DatabaseConnection` that was passed to it” in this case.

  The reference is mutable to completely lock out the `DatabaseConnection` from other usage, such as starting further transactions or reading the results.

- While a `Transaction` exists, we can't touch the `DatabaseConnection` variable that was created from it.

  Demonstrate: uncomment the `db.results()` line. Doing so will result in a compile error, as db is already mutably borrowed.

- Note: The query results not being public and placed behind a getter function lets us enforce the invariant ”users can only look at query results if there is no active transactions.”

If the query results were placed in a public struct field, this invariant could be violated.

70.5.4 PhantomData 1/4: De-duplicating Same Data & Semantics

The newtype pattern can sometimes come up against the DRY principle, how do we solve this?

```
pub struct UserId(u64);
impl ChatUser for UserId { /* ... */ }

pub struct PatronId(u64);
impl ChatUser for PatronId { /* ... */ }

pub struct ModeratorId(u64);
impl ChatUser for ModeratorId { /* ... */ }
impl ChatModerator for ModeratorId { /* ... */ }

pub struct AdminId(u64);
impl ChatUser for AdminId { /* ... */ }
impl ChatModerator for AdminId { /* ... */ }
impl ChatAdmin for AdminId { /* ... */ }

// And so on ...
fn main() {}
```

- Problem: We want to use the newtype pattern to differentiate permissions, but we're having to implement the same traits over and over again for the same data.
- Ask: Assume the details of each implementation here are the same between types, what are ways we can avoid repeating ourselves?

  Expect:

  - Make this an enum, not distinct data types.
  - Bundle the user ID with permission tokens like `struct Admin(u64, UserPermission, ModeratorPermission, AdminPermission);`
  - Adding a type parameter which encodes permissions.
  - Mentioning `PhantomData` ahead of schedule (it's in the title).

70.5.5 PhantomData 2/4: Type-level tagging

Let's solve the problem from the previous slide by adding a type parameter.

```
// use std::marker::PhantomData;

pub struct ChatId<T> { id: u64, tag: T }

pub struct UserTag;
pub struct AdminTag;

pub trait ChatUser {/* ... */}
pub trait ChatAdmin {/* ... */}
```

```rust
impl ChatUser for UserTag {/* ... */}
impl ChatUser for AdminTag {/* ... */} // Admins are users
impl ChatAdmin for AdminTag {/* ... */}

// impl <T> Debug for UserTag<T> {/* ... */}
// impl <T> PartialEq for UserTag<T> {/* ... */}
// impl <T> Eq for UserTag<T> {/* ... */}
// And so on ...

impl <T: ChatUser> ChatId<T> {/* All functionality for users and above */}
impl <T: ChatAdmin> ChatId<T> {/* All functionality for only admins */}

fn main() {}
```

- Here we're using a type parameter and gating permissions behind "tag" types that implement different permission traits.

  Tag types, or marker types, are zero-sized types that have some semantic meaning to users and API designers.

- Ask: What issues does having it be an actual instance of that type pose?

  Answer: If it's not a zero-sized type (like `()` or `struct MyTag;`), then we're allocating more memory than we need to when all we care for is type information that is only relevant at compile-time.

- Demonstrate: remove the `tag` value entirely, then compile!

  This won't compile, as there's an unused (phantom) type parameter.

  This is where `PhantomData` comes in!

- Demonstrate: Uncomment the `PhantomData` import, and make `ChatId<T>` the following:

  ```rust
  pub struct ChatId<T> {
      id: u64,
      tag: PhantomData<T>,
  }
  ```

- `PhantomData<T>` is a zero-sized type with a type parameter. We can construct values of it like other ZSTs with `let phantom: PhantomData<UserTag> = PhantomData;` or with the `PhantomData::default()` implementation.

  Demonstrate: implement `From<u64>` for `ChatId<T>`, emphasizing the construction of `PhantomData`

  ```rust
  impl<T> From<u64> for ChatId<T> {
      fn from(value: u64) -> Self {
          ChatId {
              id: value,
              // Or `PhantomData::default()`
              tag: PhantomData,
          }
      }
  }
  ```

- PhantomData can be used as part of the Typestate pattern to have data with the same structure but different methods, e.g., have TaggedData<Start> implement methods or trait implementations that TaggedData<End> doesn't.

70.5.6 PhantomData 3/4: Lifetimes for External Resources

The invariants of external resources often match what we can do with lifetime rules.

```
// use std::marker::PhantomData;

/// Direct FFI to a database library in C.
/// We got this API as is, we have no influence over it.
mod ffi {
    pub type DatabaseHandle = u8; // maximum 255 databases open at the same time

    fn database_open(name: *const std::os::raw::c_char) -> DatabaseHandle {
        unimplemented!()
    }
    // ... etc.
}

struct DatabaseConnection(ffi::DatabaseHandle);

struct Transaction<'a>(&'a mut DatabaseConnection);

impl DatabaseConnection {
    fn new_transaction(&mut self) -> Transaction<'_> {
        Transaction(self)
    }
}

fn main() {}
```

- Remember the transaction API from the Aliasing XOR Mutability example.

  We held onto a mutable reference to the database connection within the transaction type to lock out the database while a transaction is active.

  In this example, we want to implement a Transaction API on top of an external, non-Rust API.

  We start by defining a Transaction type that holds onto &mut DatabaseConnection.

- Ask: What are the limits of this implementation? Assume the u8 is accurate implementation-wise and enough information for us to use the external API.

  Expect:

  - Indirection takes up 7 bytes more than we need to on a 64-bit platform, as well as costing a pointer dereference at runtime.

- Problem: We want the transaction to borrow the database connection that created it, but we don't want the Transaction object to store a real reference.

- Ask: What happens when we remove the mutable reference in Transaction while keeping the lifetime parameter?

Expect: Unused lifetime parameter!

- Like with the type tagging from the previous slides, we can bring in PhantomData to capture this unused lifetime parameter for us.

  The difference is that we will need to use the lifetime alongside another type, but that other type does not matter too much.

- Demonstrate: change Transaction to the following:

```
struct Transaction<'a> {
    connection: DatabaseConnection,
    _phantom: PhantomData<&'a mut DatabaseConnection>,
}
```

  Update the DatabaseConnection::new_transaction() method:

```
impl DatabaseConnection {
    fn new_transaction<'a>(&'a mut self) -> Transaction<'a> {
        Transaction { connection: DatabaseConnection(self.0), _phantom: PhantomData
    }
}
```

  This gives an owned database connection that is tied to the DatabaseConnection that created it, but with less runtime memory footprint that the store-a-reference version did.

  Because PhantomData is a zero-sized type (like () or struct MyZeroSizedType;), the size of Transaction is now the same as u8.

  The implementation that held onto a reference instead was as large as a usize.

More to Explore

- This way of encoding relationships between types and values is very powerful when combined with unsafe, as the ways one can manipulate lifetimes becomes almost arbitrary. This is also dangerous, but when combined with tools like external, mechanically-verified proofs we can safely encode cyclic/self-referential types while encoding lifetime & safety expectations in the relevant data types.
- The GhostCell (2021) paper and its relevant implementation show this kind of work off. While the borrow checker is restrictive, there are still ways to use escape hatches and then *show that the ways you used those escape hatches are consistent and safe.*

70.5.7 PhantomData 4/4: OwnedFd & BorrowedFd

BorrowedFd is a prime example of PhantomData in action.

```
use std::marker::PhantomData;
use std::os::raw::c_int;

mod libc_ffi {
    use std::os::raw::{c_char, c_int};
    pub unsafe fn open(path: *const c_char, oflag: c_int) -> c_int {
        3
    }
```

```rust
    pub unsafe fn close(fd: c_int) {}
}

struct OwnedFd {
    fd: c_int,
}

impl OwnedFd {
    fn try_from_fd(fd: c_int) -> Option<Self> {
        if fd < 0 {
            return None;
        }
        Some(OwnedFd { fd })
    }

    fn as_fd<'a>(&'a self) -> BorrowedFd<'a> {
        BorrowedFd { fd: self.fd, _phantom: PhantomData }
    }
}

impl Drop for OwnedFd {
    fn drop(&mut self) {
        unsafe { libc_ffi::close(self.fd) };
    }
}

struct BorrowedFd<'a> {
    fd: c_int,
    _phantom: PhantomData<&'a ()>,
}

fn main() {
    // Create a file with a raw syscall with write-only and create permissions.
    let fd = unsafe { libc_ffi::open(c"c_str.txt".as_ptr(), 065) };
    // Pass the ownership of an integer file descriptor to an `OwnedFd`.
    // `OwnedFd::drop()` closes the file descriptor.
    let owned_fd =
        OwnedFd::try_from_fd(fd).expect("Could not open file with syscall!");

    // Create a `BorrowedFd` from an `OwnedFd`.
    // `BorrowedFd::drop()` does not close the file because it doesn't own it!
    let borrowed_fd: BorrowedFd<'_> = owned_fd.as_fd();
    // std::mem::drop(owned_fd); // ❌🔨
    std::mem::drop(borrowed_fd);
    let second_borrowed = owned_fd.as_fd();
    // owned_fd will be dropped here, and the file will be closed.
}
```

- A file descriptor represents a specific process's access to a file.

  Reminder: Device and OS-specific features are exposed as if they were files on unix-style systems.

- OwnedFd is an owned wrapper type for a file descriptor. It *owns* the file descriptor, and closes it when dropped.

  Note: We have our own implementation of it here, draw attention to the explicit Drop implementation.

  BorrowedFd is its borrowed counterpart, it does not need to close the file when it is dropped.

  Note: We have not explicitly implemented Drop for BorrowedFd.

- BorrowedFd uses a lifetime captured with a PhantomData to enforce the invariant "if this file descriptor exists, the OS file descriptor is still open even though it is not responsible for closing that file descriptor."

  The lifetime parameter of BorrowedFd demands that there exists another value in your program that lasts as long as that specific BorrowedFd or outlives it (in this case an OwnedFd).

  Demonstrate: Uncomment the std::mem::drop(owned_fd) line and try to compile to show that borrowed_fd relies on the lifetime of owned_fd.

  This has been encoded by the API designers to mean *that other value is what keeps the access to the file open*.

  Because Rust's borrow checker enforces this relationship where one value must last at least as long as another, users of this API do not need to worry about handling this correct file descriptor aliasing and closing logic themselves.

70.6 Token Types

Types with private constructors can be used to act as proof of invariants.

```rust
pub mod token {
    // A public type with private fields behind a module boundary.
    pub struct Token { proof: () }

    pub fn get_token() -> Option<Token> {
        Some(Token { proof: () })
    }
}

pub fn protected_work(token: token::Token) {
    println!("We have a token, so we can make assumptions.")
}

fn main() {
    if let Some(token) = token::get_token() {
        // We have a token, so we can do this work.
        protected_work(token);
    } else {
        // We could not get a token, so we can't call `protected_work`.
    }
}
```

This slide and its sub-slides should take about 95 minutes.

- Motivation: We want to be able to restrict user's access to functionality until they've performed a specific task.

  We can do this by defining a type the API consumer cannot construct on their own, through the privacy rules of structs and modules.

  Newtypes use the privacy rules in a similar way, to restrict construction unless a value is guaranteed to hold up an invariant at runtime.

- Ask: What is the purpose of the `proof: ()` field here?

  Without `proof: ()`, `Token` would have no private fields and users would be able to construct values of `Token` arbitrarily.

  Demonstrate: Try to construct the token manually in `main` and show the compilation error. Demonstrate: Remove the `proof` field from `Token` to show how users would be able to construct `Token` if it had no private fields.

- By putting the `Token` type behind a module boundary (`token`), users outside that module can't construct the value on their own as they don't have permission to access the `proof` field.

  The API developer gets to define methods and functions that produce these tokens. The user does not.

  The token becomes a proof that one has met the API developer's conditions of access for those tokens.

- Ask: How might an API developer accidentally introduce ways to circumvent this?

  Expect answers like "serialization implementations", other parser/"from string" implementations, or an implementation of `Default`.

70.6.1 Permission Tokens

Token types work well as a proof of checked permission.

```
mod admin {
    pub struct AdminToken(());

    pub fn get_admin(password: &str) -> Option<AdminToken> {
        if password == "Password123" { Some(AdminToken(())) } else { None }
    }
}

// We don't have to check that we have permissions, because
// the AdminToken argument is equivalent to such a check.
pub fn add_moderator(_: &admin::AdminToken, user: &str) {}

fn main() {
    if let Some(token) = admin::get_admin("Password123") {
        add_moderator(&token, "CoolUser");
    } else {
        eprintln!("Incorrect password! Could not prove privileges.")
```

```
    }
}
```

- This example shows modelling gaining administrator privileges for a chat client with a password and giving a user a moderator rank once those privileges are gained. The `AdminToken` type acts as "proof of correct user privileges."

  The user asked for a password in-code and if we get the password correct, we get a `AdminToken` to perform administrator actions within a specific environment (here, a chat client).

  Once the permissions are gained, we can call the `add_moderator` function.

  We can't call that function without the token type, so by being able to call it at all all we can assume we have permissions.

- Demonstrate: Try to construct the `AdminToken` in `main` again to reiterate that the foundation of useful tokens is preventing their arbitrary construction.

70.6.2 Token Types with Data: Mutex Guards

Sometimes, a token type needs additional data. A mutex guard is an example of a token that represents permission + data.

```
use std::sync::{Arc, Mutex, MutexGuard};

fn main() {
    let mutex = Arc::new(Mutex::new(42));
    let try_mutex_guard: Result<MutexGuard<'_, _>, _> = mutex.lock();
    if let Ok(mut guarded) = try_mutex_guard {
        // The acquired MutexGuard is proof of exclusive access.
        *guarded = 451;
    }
}
```

- Mutexes enforce mutual exclusion of read/write access to a value. We've covered Mutexes earlier in this course already (See: RAII/Mutex), but here we're looking at `MutexGuard` specifically.

- `MutexGuard` is a value generated by a `Mutex` that proves you have read/write access at that point in time.

  `MutexGuard` also holds onto a reference to the `Mutex` that generated it, with `Deref` and `DerefMut` implementations that give access to the data of `Mutex` while the underlying `Mutex` keeps that data private from the user.

- If `mutex.lock()` does not return a `MutexGuard`, you don't have permission to change the value within the mutex.

  Not only do you have no permission, but you have no means to access the mutex data unless you gain a `MutexGuard`.

  This contrasts with C++, where mutexes and lock guards do not control access to the data itself, acting only as a flag that a user must remember to check every time they read or manipulate data.

- Demonstrate: make the `mutex` variable mutable then try to dereference it to change its value. Show how there's no deref implementation for it, and no other way to get to the data held by it other than getting a mutex guard.

70.6.3 Variable-Specific Tokens (Branding 1/4)

What if we want to tie a token to a specific variable?

```rust
struct Bytes {
    bytes: Vec<u8>,
}
struct ProvenIndex(usize);

impl Bytes {
    fn get_index(&self, ix: usize) -> Option<ProvenIndex> {
        if ix < self.bytes.len() { Some(ProvenIndex(ix)) } else { None }
    }
    fn get_proven(&self, token: &ProvenIndex) -> u8 {
        unsafe { *self.bytes.get_unchecked(token.0) }
    }
}

fn main() {
    let data_1 = Bytes { bytes: vec![0, 1, 2] };
    if let Some(token_1) = data_1.get_index(2) {
        data_1.get_proven(&token_1); // Works fine!

        // let data_2 = Bytes { bytes: vec![0, 1] };
        // data_2.get_proven(&token_1); // Panics! Can we prevent this?
    }
}
```

- What if we want to tie a token to a *specific variable* in our code? Can we do this in Rust's type system?
- Motivation: We want to have a Token Type that represents a known, valid index into a byte array.

  Once we have these proven indexes we would be able to avoid bounds checks entirely, as the tokens would act as the *proof of an existing index*.

  Since the index is known to be valid, `get_proven()` can skip the bounds check.

  In this example there's nothing stopping the proven index of one array being used on a different array. If an index is out of bounds in this case, it is undefined behavior.
- Demonstrate: Uncomment the `data_2.get_proven(&token_1);` line.

  The code here panics! We want to prevent this "crossover" of token types for indexes at compile time.
- Ask: How might we try to do this?

  Expect students to not reach a good implementation from this, but be willing to experiment and follow through on suggestions.

- Ask: What are the alternatives, why are they not good enough?

  Expect runtime checking of index bounds, especially as both `Vec::get` and `Bytes::get_index` already uses runtime checking.

  Runtime bounds checking does not prevent the erroneous crossover in the first place, it only guarantees a panic.

- The kind of token-association we will be doing here is called Branding. This is an advanced technique that expands applicability of token types to more API designs.

- `GhostCell` is a prominent user of this, later slides will touch on it.

70.6.4 PhantomData and Lifetime Subtyping (Branding 2/4)

Idea:

- Use a lifetime as a unique brand for each token.
- Make lifetimes sufficiently distinct so that they don't implicitly convert into each other.

```rust
use std::marker::PhantomData;

#[derive(Default)]
struct InvariantLifetime<'id>(PhantomData<&'id ()>); // The main focus

struct Wrapper<'a> { value: u8, invariant: InvariantLifetime<'a> }

fn lifetime_separator<T>(value: u8, f: impl for<'a> FnOnce(Wrapper<'a>) -> T) -> T {
    f(Wrapper { value, invariant: InvariantLifetime::default() })
}

fn try_coerce_lifetimes<'a>(left: Wrapper<'a>, right: Wrapper<'a>) {}

fn main() {
    lifetime_separator(1, |wrapped_1| {
        lifetime_separator(2, |wrapped_2| {
            // We want this to NOT compile
            try_coerce_lifetimes(wrapped_1, wrapped_2);
        });
    });
}
```

- In Rust, lifetimes can have subtyping relations between one another.

  This kind of relation allows the compiler to determine if one lifetime outlives another.

  Determining if a lifetime outlives another also allows us to say *the shortest common lifetime is the one that ends first.*

  This is useful in many cases, as it means two different lifetimes can be treated as if they were the same in the regions they do overlap.

  This is usually what we want. But here we want to use lifetimes as a way to distinguish values so we say that a token only applies to a single variable without having to create a newtype for every single variable we declare.

- **Goal**: We want two lifetimes that the Rust compiler cannot determine if one outlives the other.

  We are using `try_coerce_lifetimes` as a compile-time check to see if the lifetimes have a common shorter lifetime (AKA being subtyped).

- Note: This slide compiles, by the end of this slide it should only compile when `subtyped_lifetimes` is commented out.

- There are two important parts of this code:

  - The `impl for<'a>` bound on the closure passed to `lifetime_separator`.
  - The way lifetimes are used in the parameter for `PhantomData`.

`for<'a>` bound on a Closure

- We are using `for<'a>` as a way of introducing a lifetime generic parameter to a function type and asking that the body of the function to work for all possible lifetimes.

  What this also does is remove some ability of the compiler to make assumptions about that specific lifetime for the function argument, as it must meet Rust's borrow checking rules regardless of the "real" lifetime its arguments are going to have. The caller is substituting in actual lifetime, the function itself cannot.

  This is analogous to a forall (∀) quantifier in mathematics, or the way we introduce `<T>` as type variables, but only for lifetimes in trait bounds.

  When we write a function generic over a type `T`, we can't determine that type from within the function itself. Even if we call a function `fn foo<T, U>(first: T, second: U)` with two arguments of the same type, the body of this function cannot determine if `T` and `U` are the same type.

  This also prevents *the API consumer* from defining a lifetime themselves, which would allow them to circumvent the restrictions we want to impose.

PhantomData and Lifetime Variance

- We already know `PhantomData`, which can introduce a formal no-op usage of an otherwise unused type or a lifetime parameter.

- Ask: What can we do with `PhantomData`?

  Expect mentions of the Typestate pattern, tying together the lifetimes of owned values.

- Ask: In other languages, what is subtyping?

  Expect mentions of inheritance, being able to use a value of type `B` when a asked for a value of type `A` because `B` is a "subtype" of `A`.

- Rust does have Subtyping! But only for lifetimes.

  Ask: If one lifetime is a subtype of another lifetime, what might that mean?

  A lifetime is a "subtype" of another lifetime when it *outlives* that other lifetime.

- The way that lifetimes used by `PhantomData` behave depends not only on where the lifetime "comes from" but on how the reference is defined too.

The reason this compiles is that the **Variance** of the lifetime inside of `InvariantLifetime` is too lenient.

Note: Do not expect to get students to understand variance entirely here, just treat it as a kind of ladder of restrictiveness on the ability of lifetimes to establish subtyping relations.

- Ask: How can we make it more restrictive? How do we make a reference type more restrictive in Rust?

  Expect or demonstrate: Making it `&'id mut ()` instead. This will not be enough!

  We need to use a **Variance** on lifetimes where subtyping cannot be inferred except on *identical lifetimes*. That is, the only subtype of `'a` the compiler can know is `'a` itself.

  Note: Again, do not try to get the whole class to understand variance. Treat it as a ladder of restrictiveness for now.

  Demonstrate: Move from `&'id ()` (covariant in lifetime and type), `&'id mut ()` (covariant in lifetime, invariant in type), `*mut &'id mut ()` (invariant in lifetime and type), and finally `*mut &'id ()` (invariant in lifetime but not type).

  Those last two should not compile, which means we've finally found candidates for how to bind lifetimes to `PhantomData` so they can't be compared to one another in this context.

  Reason: `*mut` means mutable raw pointer. Rust has mutable pointers! But you cannot reason about them in safe Rust. Making this a mutable raw pointer to a reference that has a lifetime complicates the compiler's ability subtype because it cannot reason about mutable raw pointers within the borrow checker.

- Wrap up: We've introduced ways to stop the compiler from deciding that lifetimes are "similar enough" by choosing a Variance for a lifetime in `PhantomData` that is restrictive enough to prevent this slide from compiling.

  That is, we can now create variables that can exist in the same scope as each other, but whose types are automatically made different from one another per-variable without much boilerplate.

More to Explore

- The `for<'a>` quantifier is not just for function types. It is a **Higher-ranked trait bound**.

70.6.5 Implementing Branded Types (Branding 3/4)

Constructing branded types is different to how we construct non-branded types.

```
struct ProvenIndex<'id>(usize, InvariantLifetime<'id>);

struct Bytes<'id>(Vec<u8>, InvariantLifetime<'id>);

impl<'id> Bytes<'id> {
    fn new<T>(
        // The data we want to modify in this context.
        bytes: Vec<u8>,
        // The function that uniquely brands the lifetime of a `Bytes`
```

```
        f: impl for<'a> FnOnce(Bytes<'a>) -> T,
    ) -> T {
        f(Bytes(bytes, InvariantLifetime::default()),)
    }

    fn get_index(&self, ix: usize) -> Option<ProvenIndex<'id>> {
        if ix < self.0.len() { Some(ProvenIndex(ix, InvariantLifetime::default())) }
        else { None }
    }

    fn get_proven(&self, ix: &ProvenIndex<'id>) -> u8 {
        debug_assert!(ix.0 < self.0.len());
        unsafe { *self.0.get_unchecked(ix.0) }
    }
}
```

- Motivation: We want to have "proven indexes" for a type, and we don't want those indexes to be usable by different variables of the same type. We also don't want those indexes to escape a scope.

  Our Branded Type will be `Bytes`: a byte array.

  Our Branded Token will be `ProvenIndex`: an index known to be in range.

- There are several notable parts to this implementation:
  - `new` does not return a `Bytes`, instead asking for "starting data" and a use-once Closure that is passed a `Bytes` when it is called.
  - That `new` function has a `for<'a>` on its trait bound.
  - We have both a getter for an index and a getter for a values with a proven index.

- Ask: Why does `new` not return a `Bytes`?

  Answer: Because we need `Bytes` to have a unique lifetime controlled by the API.

- Ask: So what if `new()` returned `Bytes`, what is the specific harm that it would cause?

  Answer: Think about the signature of that hypothetical `new()` method:

  `fn new<'a>() -> Bytes<'a> { ... }`

  This would allow the API user to choose what the lifetime `'a` is, removing our ability to guarantee that the lifetimes between different instances of `Bytes` are unique and unable to be subtyped to one another.

- Ask: Why do we need both a `get_index` and a `get_proven`?

  Expect "Because we can't know if an index is occupied at compile time"

  Ask: Then what's the point of the proven indexes?

  Answer: Avoiding bounds checking while keeping knowledge of what indexes are occupied specific to individual variables, unable to erroneously be used on the wrong one.

  Note: The focus is not on only on avoiding overuse of bounds checks, but also on preventing that "cross over" of indexes.

70.6.6 Branded Types in Action (Branding 4/4)

```rust
use std::marker::PhantomData;

#[derive(Default)]
struct InvariantLifetime<'id>(PhantomData<*mut &'id ()>);
struct ProvenIndex<'id>(usize, InvariantLifetime<'id>);

struct Bytes<'id>(Vec<u8>, InvariantLifetime<'id>);

impl<'id> Bytes<'id> {
    fn new<T>(
        // The data we want to modify in this context.
        bytes: Vec<u8>,
        // The function that uniquely brands the lifetime of a `Bytes`
        f: impl for<'a> FnOnce(Bytes<'a>) -> T,
    ) -> T {
        f(Bytes(bytes, InvariantLifetime::default()))
    }

    fn get_index(&self, ix: usize) -> Option<ProvenIndex<'id>> {
        if ix < self.0.len() {
            Some(ProvenIndex(ix, InvariantLifetime::default()))
        } else {
            None
        }
    }

    fn get_proven(&self, ix: &ProvenIndex<'id>) -> u8 {
        self.0[ix.0]
    }
}

fn main() {
    let result = Bytes::new(vec![4, 5, 1], |mut bytes_1| {
        Bytes::new(vec![4, 2], |mut bytes_2| {
            let index_1 = bytes_1.get_index(2).unwrap();
            let index_2 = bytes_2.get_index(1).unwrap();
            bytes_1.get_proven(&index_1);
            bytes_2.get_proven(&index_2);
            // bytes_2.get_proven(&index_1); // ❌🔨
            "Computations done!"
        })
    });
    println!("{result}");
}
```

- We now have the implementation ready, we can now write a program where token types that are proofs of existing indexes cannot be shared between variables.
- Demonstration: Uncomment the `bytes_2.get_proven(&index_1);` line and show that it does not compile when we use indexes from different variables.

- Ask: What operations can we perform that we can guarantee would produce a proven index?

  Expect a ”push” implementation, suggested demo:

  ```
  fn push(&mut self, value: u8) -> ProvenIndex<'id> {
      self.0.push(value);
      ProvenIndex(self.0.len() - 1, InvariantLifetime::default())
  }
  ```

- Ask: Can we make this not just about a byte array, but as a general wrapper on `Vec<T>`?

  Trivial: Yes!

  Maybe demonstrate: Generalising `Bytes<'id>` into `BrandedVec<'id, T>`

- Ask: What other areas could we use something like this?
- The resulting token API is **highly restrictive**, but the things that it makes possible to prove as safe within the Rust type system are meaningful.

More to Explore

- GhostCell, a structure that allows for safe cyclic data structures in Rust (among other previously difficult to represent data structures), uses this kind of token type to make sure cells can't ”escape” a context where we know where operations similar to those shown in these examples are safe.

  This ”Branded Types” sequence of slides is based off their `BrandedVec` implementation in the paper, which covers many of the implementation details of this use case in more depth as a gentle introduction to how `GhostCell` itself is implemented and used in practice.

  GhostCell also uses formal checks outside of Rust's type system to prove that the things it allows within this kind of context (lifetime branding) are safe.

Chapter 71

Polymorphism

```
pub trait Trait {}

pub struct HasGeneric<T>(T);

pub enum Either<A, B> {
    Left(A),
    Right(B),
}

fn takes_generic<T: Trait>(value: &T) {}

fn takes_dyn(value: &dyn Trait) {}
```

This slide should take about 2 minutes.

- Rust has plenty of mechanisms for writing and using polymorphic code, but they're somewhat different from other popular languages!
- This chapter will cover the details of Rust's polymorphism and how it's similar, or different to, other languages.

71.1 Refresher

Basic features of Rust's generics and polymorphism.

```
pub struct HasGenerics<T>(...);

pub fn uses_traits<T: Debug>(input: T) {...}

pub trait TraitBounds: Clone {...}
```

This slide and its sub-slides should take about 74 minutes.

- In this section we'll be going through the core concepts of Rust's approach to polymorphism, the things you'll run into the most in day-to-day usage.

71.1.1 Traits, Protocols, Interfaces

```
trait Receiver {
    fn send(&self, message: &str);
}

struct EmailAddress(String);

impl Receiver for EmailAddress {
    fn send(&self, message: &str) {
        println!("Email to {}: {}", self.0, message);
    }
}

struct ChatId {
    uuid: [u8; 16],
}

impl Receiver for ChatId {
    fn send(&self, message: &str) {
        println!("Chat message sent to {:?}: {}", self.uuid, message);
    }
}
```

- Rust's concept of polymorphism and generics is heavily built around traits.
- Traits are requirements on a type in a generic context.
- Requirements function much like a compile-time checked duck typing.

  Duck typing is a concept from the practice of dynamic, untyped languages like Python, ”if it walks like a duck and quacks like a duck, it's a duck.”

  That is, types with the methods and fields expected by a function are all valid inputs for that function. If a type implements methods, it is that type in a duck-typing context.

  Traits behave like a static duck typing mechanism, in that we specify behavior rather than type. But we get the compile-time checks on if that behavior does really exist.
- Alternatively: Traits are like collections of propositions, and implementing a trait for a type is a proof that the type can be used wherever the trait is asked for.

  Traits have required methods, implementing those methods is the proof that a type has the required behavior.

reference:

- https://doc.rust-lang.org/reference/items/traits.html

71.1.2 Trait Bounds on Generics

```
use std::fmt::Display;

fn print_with_length<T: Display>(item: T) {
    println!("Item: {}", item);
    println!("Length: {}", item.to_string().len());
```

```
}

fn main() {
    let number = 42;
    let text = "Hello, Rust!";

    print_with_length(number); // Works with integers
    print_with_length(text); // Works with strings
}
```

- Traits are most commonly used as bounds on generic type parameters for a function or method.

  Without a trait bound on a generic type parameter, we don't have access to any behavior to write functions and methods with.

  Trait bounds allow us to specify the minimum viable behavior of a type for it to work in generic code.

ref:

- https://doc.rust-lang.org/reference/trait-bounds.html

71.1.3 Deriving Traits

```
#[derive(Debug, PartialEq, Eq, PartialOrd, Ord)]
struct BufferId([u8; 16]);

#[derive(Debug, PartialEq, Eq, PartialOrd, Ord)]
struct DrawingBuffer {
    target: [u8; 16],
    commands: Vec<String>,
}
```

- Many traits, protocols, interfaces, have trivial implementations that would be easy to mechanically write.
- Definitions of types (their syntax trees) can be fed to procedural macros (compiler plugins) to automatically generate implementations of traits.

  These macros have to be authored by someone, the compiler cannot figure out everything by itself.
- Many traits have a naive, obvious implementation. Mostly implementations that depend on all fields or variants already implementing the trait.

  `PartialEq`/`Eq` can be derived on types whose fields / variants all implement those traits fairly easily: line up the fields / variants, if any of them don't match then the equality check returns false.
- Derives let us avoid boilerplate mechanically and predictably, the authors of a derive implementation likely authored the trait the derive was implemented with the proper semantics of a trait in mind.
- Ask the class: Have the students had to deal with a codebase where most of the code was trivial boilerplate?

- This is similar to Haskell's `deriving` system.

references:

- https://doc.rust-lang.org/reference/attributes/derive.html#r-attributes.derive

71.1.4 Default Method Implementations

```
pub trait CollectLeaves {
    type Leaf;

    // Required Method
    fn collect_leaves_buffered(&self, buf: &mut Vec<Self::Leaf>);

    // Default implementation
    fn collect_leaves(&self) -> Vec<Self::Leaf> {
        let mut buf = vec![];
        self.collect_leaves_buffered(&mut buf);
        buf
    }
}
```

- Traits often have methods that are implemented for you already, once you implement the required methods.
- A trait method has a default implementation if the function body is present. This implementation can be written in terms of other methods available, such as other methods in the trait or methods of a supertrait.
- Often you'll see methods that provide the broad functionality that is necessary to implement (like `Ord`'s `compare`) with default implementations for functions that can be implemented in terms of those methods (like `Ord`'s `max`/`min`/`clamp`).
- Default methods can be overridden by derive macros, as derive macros produce arbitrary ASTs in the implementation.

ref:

- https://doc.rust-lang.org/reference/items/traits.html#r-items.traits.associated-item-decls

71.1.5 Supertraits / Trait Dependencies

Traits can be extended by new traits.

```
pub trait Animal {
    /* methods common to all animals */
}

pub trait Mammal: Animal {
    /* methods only for mammals */
}

// From stdlib

pub trait Ord: Eq + PartialOrd {
```

```
    /* methods for Ord */
}
```

- When authoring a trait, you can specify traits that a type must also. These are called *supertraits*.

  For the example above, any type that implements `Mammal` must also implement `Animal`.
- These hierarchies of traits let us design systems around the behavior of complex real-world taxonomies (like fauna, machine hardware, operating system specifics, etc).
- This is distinct from object inheritance! But it looks similar.
  - Object inheritance allows for overrides and brings in the behavior of the inherited types by default.
  - A trait having a supertrait doesn't mean that trait can override method implementations as default implementations.

ref:

- https://doc.rust-lang.org/reference/items/traits.html?highlight=supertrait#r-items.traits.supertraits

71.1.6 Blanket Trait Implementations

When a trait is local, we can implement it for as many types as we like. How far can we take this?

```
pub trait PrettyPrint {
    fn pretty_print(&self);
}

// A blanket implementation! If something implements Display, it implements
// PrettyPrint.
impl<T> PrettyPrint for T
where
    T: std::fmt::Display,
{
    fn pretty_print(&self) {
        println!("{self}")
    }
}
```

- The subject of a trait implementation at the definition site of a trait can be anything, including `T` with no bounds.

  We can't do anything with a `T` we don't know nothing about, so this is uncommon.
- Conditional blanket implementations are much more useful and you are more likely to see and author them.

  These implementations will have a bound on the trait, like `impl <T: Display> ToString for T {...}`

  In the example above we have a blanket implementation for all types that implement Display, the implementation has one piece of information available to it from the trait bounds: it implements `Display::fmt`.

This is enough to write an implementation for pretty printing to console.

- Do be careful with these kinds of implementations, as it may end up preventing users downstream from implementing a more meaningful.

  The above isn't written for `Debug` as that would mean almost all types end up implementing `PrettyPrint`, and `Debug` is not semantically similar to `Display`: It's meant for debug output instead of something more human-readable.

ref:

- https://doc.rust-lang.org/reference/glossary.html#blanket-implementation

71.1.7 Conditional Method Implementations

```
// No trait bounds on the type definition.
pub struct Value<T>(T);

// Instead bounds are put on the implementations for the type.
impl<T: std::fmt::Display> Value<T> {
    fn log(&self) {
        println!("{}", self.0);
    }
}

// alternatively
impl<T> Value<T> {
    // Specifies the trait bound in a where expression
    fn log_error(&self)
    where
        T: std::error::Error,
    {
        eprintln!("{}", self.0);
    }
}
```

- When authoring a type with generic parameters, we can write implementations for that type that depend on what the parameters are or what traits they implement.
- These methods are only available when the type meets those conditions.
- For things like ordered sets, where you'd want the inner type to always be `Ord`, this is the preferred way of putting a trait bound on a parameter of a type.

  We don't put the definition on the type itself as this would cause downstream issues for everywhere the type is mentioned with a generic parameter.

  We can maintain invariants just fine with conditional method implementations.

71.1.8 Orphan Rule

What prevents users from writing arbitrary trait implementations for any type?

```
// Crate `postgresql-bindings`
```

```rust
pub struct PostgresqlConn(/* details */);

// Crate `database-traits`, depends on `postgresql-bindings`

pub trait DbConnection {
    /* methods */
}

impl DbConnection for PostgresqlConn {} // ✅, `DbConnection` is local.

// Crate `mycoolnewdb` depends on `database-traits`

pub struct MyCoolNewDbConn(/* details */);

impl DbConnection for MyCoolNewDbConn {} // ✅, `MyCoolNewDbConn` is local.

// Neither `PostgresqlConn` or `DbConnection` are local to `mycoolnewdb`.
// This would lead to two implementations of `DbConnection` for PostgresqlConn!
impl DbConnection for PostgresqlConn {} // ❌🔨
```

- Rust traits should never be able to be implemented twice in its ecosystem. Two implementations of the same trait for the same type is a conflict with no solution.
- We can prevent this within a crate by detecting if there are multiple definitions and disallowing it, but what about between crates in the entire Rust ecosystem?
- Types are either *local* to a crate, they are defined there, or they're not.

  In the example's ”crates”, `PostgresqlConn` is local to `postgresql-bindings`, `MyCoolNewDbConn` is local to `mycoolnewdb`.
- Traits are also either *local* to a crate, they are defined there, or they're not.

  Again in the example, the `DbConnection` trait is local to `database-traits`.
- If something is local, you can write trait implementations for it.

  If the trait is local, you can write implementations of that trait for any type.

  If the type is local, you can write any trait implementations for that type.
- Outside of these boundaries, trait implementations cannot be written.

  This keeps implementations ”coherent”: Only one implementation of a trait for a type can exist across crates.

ref:

- https://doc.rust-lang.org/stable/reference/items/implementations.html#r-items.impl.trait.orphan-rule

71.1.9 Statically Sized and Dynamically Sized Types

```rust
use std::fmt::Debug;

pub struct AlwaysSized<T /* : Sized */>(T);
```

```rust
pub struct OptionallySized<T: ?Sized>(T);

type Dyn1 = OptionallySized<dyn Debug>;
```

- Motivation: Being able to specify between types whose size are known and compile time and types whose size are known at runtime is useful for
- The Sized trait is automatically implemented by types with a known size at compile-time.

  This trait is also automatically added to any type parameter that doesn't opt-out of being sized.
- Most types implement `Sized`: they have a compile-time known size.

  Types like `[T]`, `str` and `dyn Trait` are all dynamically sized types. Their size is stored as part of the reference to the value of that type.
- Type parameters automatically implement `Sized` unless specified.

ref:

- https://doc.rust-lang.org/stable/reference/dynamically-sized-types.html#r-dynamic-sized

71.1.10 Monomorphization and Binary Size

```rust
fn print_vec<T: std::fmt::Debug>(debug_vec: &Vec<T>) {
    for item in debug_vec {
        println!("{:?}", item);
    }
}

fn main() {
    let ints = vec![1u32, 2, 3];
    let floats = vec![1.1f32, 2.2, 3.3];

    // instance one, &Vec<u32> -> ()
    print_vec(&ints);
    // instance two, &Vec<f32> -> ()
    print_vec(&floats);
}
```

- Each instance of a function or type with generics gets transformed into a unique, concrete version of that function at compile time. Generics do not exist at runtime, only specific types.
- This comes with a strong baseline performance and capacity for optimization, but at a cost of binary size and compile time.
- There are plenty of ways to trim binary size and compilation times, but we're not covering them here.
- Pay for what you use: Binary size increase of monomorphization is only incurred for instances of a type or functions on a type used in the final program or dynamic library.

- When to care: Monomorphization impacts compile times and binary size. In circumstances like WebAssembly in-browser or embedded systems development, you may want to be mindful about designing with generics in mind.

71.2 From OOP to Rust: Composition, Not Inheritance

- Inheritance is key to OOP's success as a paradigm. Decades of successful software engineering has been done with Inheritance as a core part of business logic.
- So why did Rust avoid inheritance?
- How do we move from inheritance-based problem solving to Rust's approach?
- How do you represent heterogeneous collections in Rust?

This slide and its sub-slides should take about 106 minutes.

- In this section we'll be looking at how to move from thinking about polymorphic problem solving with types in OOP languages like java, C++ etc. to Rust's trait-based approach to Polymorphism.
- There will be differences, but there are also plenty of areas in common – especially with modern standards of OOP development. Remember to keep an open mind.

71.2.1 Inheritance in OOP languages

```cpp
// Base class
class Vehicle {
public:
    void accelerate() { }
    void brake() { }
};

// Inheriting class
class Car : public Vehicle {
public:
    void honk() { }
};

int main() {
    Car myCar;                  // Create a Car object
    myCar.accelerate();         // Inherited method
    myCar.honk();               // Car's own method
    myCar.brake();              // Inherited method
    return 0;
}
```

- This should be a short reminder for students about what inheritance is in other languages.
- Inheritance is a mechanism where a ”child” type gains the fields and methods of the ”parent” types it is inheriting from.
- Methods are able to be overridden as-needed by the inheriting type.

- Can call methods of inherited-from classes with `super`.

71.2.2 Why no Inheritance in Rust?

```rust
pub struct Id {
    pub id: u32
}

impl Id {
    // methods
}

// 🔨❌, Rust does not have inheritance!
pub struct Data: Id {
    // Inherited "id" field
    pub name: String,
}

impl Data {
    // methods, but also includes Id's methods, or maybe overrides to
    // those methods.
}

// ✅
pub struct Data {
    pub id: Id,
    pub name: String,
}

impl Data {
    // All of data's methods that aren't from traits.
}

impl SomeTrait for Data {
    // Implementations for traits in separate impl blocks.
}
```

- Inheritance comes with a number of downsides.
- Heterogeneous by default:

  Class inheritance implicitly allows types of different classes to be used interchangeably, without being able to specify a concrete type or if a type is identical to another.

  For operations like equality, comparison this allows for comparison and equality that throws and error or otherwise panics.
- Multiple sources of truth for what makes up a data structure and how it behaves:

  A type's fields are obscured by the inheritance hierarchy.

  A type's methods could be overriding a parent type or be overridden by a child type, it's hard to tell what the behavior of a type is in complex codebases maintained by multiple parties.

- Dynamic dispatch as default adds overhead from vtable lookups:

  For dynamic dispatch to work, there needs to be somewhere to store information on what methods to call and other pieces of runtime-known pieces of information on the type.

  This store is the `vtable` for a value. Method calls will require more dereferences than calling a method for a type that is known at compile time.

71.2.3 Inheritance from Rust's Perspective

```rust
// Data
pub struct Data {
    id: usize,
    name: String,
}

// Concrete behavior
impl Data {
    fn new(id: usize, name: impl Into<String>) -> Self {
        Self { id, name: name.into() }
    }
}

// Abstract behavior
trait Named {
    fn name(&self) -> &str;
}

// Instanced behavior
impl Named for Data {
    fn name(&self) -> &str {
        &self.name
    }
}
```

- From Rust's perspective, one where Inheritance was never there, introducing inheritance would look like muddying the water between types and traits.
- A type is a concrete piece of data and its associated behavior.

  A trait is abstract behavior that must be implemented by a type.

  A class is a combination of data, behavior, and overrides to that behavior.
- Coming from Rust, an inheritable class looks like a type that is also a trait.
- This is not an upside, as we can no longer reason about concrete types.
- Without being able to separate the two, it becomes difficult to reason about generic behavior vs concrete specifics, because in OOP these two concepts are tied up in each other.
- The convenience of flat field access and DRY in type definitions is not worth the loss in specificity between writing code that delineates between behavior and data.

71.2.4 "Inheritance" in Rust: Supertraits

```
pub trait SuperTrait {}

pub trait Trait: SuperTrait {}
```

- In Rust, traits can depend on other traits. We're already familiar with Traits being able to have Supertraits.
- This looks superficially similar to inheritance.
- This is a mechanism like inheritance, but separates the data from the behavior.
- Keeps behavior in a state where it's easy to reason about.
- Makes what we aim to achieve with "multiple inheritance" easier too:

  We only care about what behavior a type is capable of at the point where we clarify we want that behavior (when bounding a generic by traits).

  By specifying multiple traits on a generic, we know that the type has the methods of all those traits.
- Does not involve inheritance of fields. A trait doesn't expose fields, only methods and associated types / constants.

71.2.5 Composition over Inheritance

```
pub struct Uuid([u8; 16]);

pub struct Address {
    street: String,
    city_or_province: String,
    code: String,
    country: String,
}

pub struct User {
    id: Uuid,
    address: Address,
}
```

- Rather than mixins or inheritance, we compose types by creating fields of different types.

  This has downsides, largely in ergonomics of field access, but gives developers a lot of control and clarity over what a type does and it has access to.
- When deriving traits, make sure all the field types of a struct or variant types of an enum implement that trait. Derive macros often assume all types that compose a new type implement that trait already.

71.2.6 `dyn Trait` for Dynamic Dispatch in Rust

```
pub trait Trait {}
```

```rust
impl Trait for i32 {}
impl Trait for String {}

fn main() {
    let int: &dyn Trait = &42i32;
    let string: &dyn Trait = &String::from("Hello dyn!");;
}
```

- Dynamic Dispatch is a tool in Object Oriented Programming that is often used in places where one needs to care more about the behavior of a type than what the type is.

  In OOP languages, dynamic dispatch is often an *implicit* process and not something you can opt out of.

  In Rust, we use `dyn Trait`: an opt-in form of dynamic dispatch.

- For any trait that is *dyn compatible* we can coerce a reference to a value of that trait into a `dyn Trait` value.
- We call these *trait objects*. Their type is not known at compile time, but their behavior is: what is implemented by the trait itself.
- When you *need* OOP-style heterogeneous data structures, you can reach for `Box<dyn Trait>`, but try to keep it homogeneous and generic-based first!

71.2.7 Dyn-compatible traits

```rust
pub trait Trait {
    // dyn compatible
    fn takes_self(&self);

    // dyn compatible, but you can't use this method when it's dyn
    fn takes_self_and_param<T>(&self, input: &T);

    // no longer dyn compatible
    const ASSOC_CONST: i32;

    // no longer dyn compatible
    fn clone(&self) -> Self;
}
```

- Not all traits are able to be invoked as trait objects. A trait that can be invoked is referred to as a *dyn compatible* trait.
- This was previously called *object safe traits* or *object safety*.
- Dynamic dispatch offloads a lot of compile-time type information into runtime vtable information.

  If a concept is incompatible with what we can meaningfully store in a vtable, either the trait stops being dyn compatible or those methods are excluded from being able to be used in a dyn context.

- A trait is dyn-compatible when all its supertraits are dyn-compatible and when it has no associated constants/types, and no methods that depend on generics.

- You'll most frequently run into dyn incompatible traits when they have associated types/constants or return values of `Self` (i.e. the Clone trait is not dyn compatible.)

  This is because the associated data would have to be stored in vtables, taking up extra memory.

  For methods like `clone`, this disqualifies dyn compatibility because the output type depends on the concrete type of `self`.

ref:

- https://doc.rust-lang.org/1.91.1/reference/items/traits.html#r-items.traits.dyn-compatible

71.2.8 Generic Function Parameters vs dyn Trait

We have two means of writing polymorphic functions, how do they compare?

```rust
fn print_display<T: std::fmt::Display>(t: &T) {
    println!("{}", t);
}

fn print_display_dyn(t: &dyn std::fmt::Display) {
    println!("{}", t);
}

fn main() {
    let int = 42i32;
    // Monomorphized to a unique function for i32 inputs.
    print_display(&int);
    // One per
    print_display_dyn(&int);
}
```

- We can write polymorphic functions over generics or over trait objects.
- When writing functions with generic parameters, for each unique type that substitutes a parameter a new version of that function is generated.

  We went over this in monomorphization: in exchange for binary size, we gain a greater capacity for optimization.
- When writing functions that take a trait object, only one version of that function will exist in the final binary (not counting inlining.)
- Generic parameters are zero-cost other than binary size. Types must be homogenous (all instances of T can only be the same type).

71.2.9 Limits of Trait Objects

```rust
use std::any::Any;

pub trait Trait: Any {}

impl Trait for i32 {}
```

```rust
fn main() {
    dbg!(size_of::<i32>()); // 4 bytes, owned value
    dbg!(size_of::<&i32>()); // 8 bytes, reference
    dbg!(size_of::<&dyn Trait>()); // 16 bytes, wide pointer
}
```

- Trait objects are a limited way of solving problems.
- If you want to downcast to a concrete type from a trait object, you will need to specify that the trait in question has Any as a supertrait or that the trait object is over the main trait and Any.

  Even then, you will still need to cast a `dyn MyTrait` to `dyn Any`
- Trait objects have overhead in memory, they are "wide pointers" that need to hold not just the pointer to the data itself but another pointer for the vtable.
- Trait objects, being dynamically sized types, can only be used practically via reference or pointer types.

  There is a baseline overhead of dereferencing the value and relevant trait methods when using trait objects.

71.2.10 Heterogeneous data with `dyn trait`

```rust
use std::fmt::Display;

pub struct Lambda;

impl Display for Lambda {
    fn fmt(&self, f: &mut std::fmt::Formatter<'_>) -> std::fmt::Result {
        write!(f, "λ")
    }
}

fn main() {
    let heterogeneous: Vec<Box<dyn Display>> = vec![
        Box::new(42u32),
        Box::new(String::from("Woah")),
        Box::new(Lambda),
    ];
    for item in heterogeneous {
        // We know "item" implements Display, but we know nothing else!
        println!("Display output: {}", item);
    }
}
```

- `dyn Trait`, being a dynamic dispatch tool, lets us store heterogeneous data in collections.
- In this example, we're storing types that all implement `std::fmt::Display` and printing all items in that collection to screen.

71.2.11 Any Trait and Downcasting

```
use std::any::Any;

#[derive(Debug)]
pub struct ThisImplementsAny;

fn take_any<T: Any>(t: &T) {}

fn main() {
    let is_an_any = ThisImplementsAny;
    take_any(&is_an_any);

    let dyn_any: &dyn Any = &is_an_any;
    dbg!(dyn_any.type_id());
    dbg!(dyn_any.is::<ThisImplementsAny>());
    let is_downcast: Option<&ThisImplementsAny> = dyn_any.downcast_ref();
    dbg!(is_downcast);
}
```

- The Any trait allows us to downcast values back from dyn values into concrete values.
- This is an auto trait: like Send/Sync/Sized, it is automatically implemented for any type that meets specific criteria.
- The criteria for Any is that a type is `'static`. That is, the type does not contain any non-`'static` lifetimes within it.
- Any offers two related behaviors: downcasting, and runtime checking of types being the same.

  In the example above, we see the ability to downcast from Any into `ThisImplementsAny` automatically.

  We also see `Any::is` being used to check to see what type the value is.
- Any does not implement reflection for a type, this is all you can do with Any.

71.2.12 Pitfall: Reaching too quickly for dyn `Trait`

```
use std::any::Any;

pub trait AddDyn: Any {
    fn add_dyn(&self, rhs: &dyn AddDyn) -> Box<dyn AddDyn>;
}

impl AddDyn for i32 {
    fn add_dyn(&self, rhs: &dyn AddDyn) -> Box<dyn AddDyn> {
        if let Some(downcast) = (rhs as &dyn Any).downcast_ref::<Self>() {
            Box::new(self + downcast)
        } else {
            Box::new(*self)
        }
    }
```

```
}

fn main() {
    let i: &dyn AddDyn = &42;
    let j: &dyn AddDyn = &64;
    let k: Box<dyn AddDyn> = i.add_dyn(j);
    dbg!((k.as_ref() as &dyn Any).is::<i32>());
    dbg!((k.as_ref() as &dyn Any).downcast_ref::<i32>());
}
```

- Coming from an OOP background, it's understandable to reach for this dynamic dispatch tool as early as possible.
- This is not the preferred way of doing things, trait objects put us in a situation where we're exchanging knowledge of a type that both the developer and compiler has for flexibility.
- The above example takes things to the absurd: If adding numbers were tied up in the dynamic dispatch process, it would be difficult to do anything at all.

  But dynamic dispatch is often hidden in a lot of programming languages: here's it is more explicit.

  In the `i32` implementation of `AddDyn`, first we need to attempt to downcast the `rhs` argument to the same type as `i32`, silently failing if this isn't the case.

  Then we need to allocate the new value on the heap, because if we're keeping this in the world of dynamic dispatch then we need to do this.

  Once we've added two values together, if we want to view them we must downcast them again into a ”real” type we can print out given the trait bounds tied up in the operation so far.
- Ask the class: Why can't we just add Display bounds in `main` to be able to print things as-is?

  Answer: Because add_dyn returns only a `dyn AddDyn`, we lose information about what the type implements between the argument type and return type. Even if the inputs implement `Display`, the return type does not.
- This leads to less performant code which is harder to understand

71.2.13 Sealed traits for Polymorphism users cannot extend

```
// crate can access the "sealed" module and its trait, but projects that
// depend on it cannot.
mod sealed {
    pub trait Sealed {}
    impl Sealed for String {}
    impl Sealed for Vec<u8> {}
    //...
}

pub trait APITrait: sealed::Sealed {
    /* methods */
}
```

```rust
impl APITrait for String {}
impl APITrait for Vec<u8> {}
```

- Motivation: We want trait-driven code in a crate, but we don't want projects that depend on this crate to be able to implement a trait.

Why?

The trait could be considered unstable for downstream-implementations at this point in time.

Alternatively: Domain is high-risk for naive implementations of a trait (such as cryptography).

- The mechanism we use to do this is restricting access to a supertrait, preventing downstream users from being able to implement that trait for their types.
- Why not just use enums?
  - Enums expose implementation details – ”this works for these types”.
  - Users need to use variant constructors of an enum to use the API.
  - Users can use the enum as a type in their own code, and when the enum changes users need to update their code to match those changes.
  - Enums require branching on variants, whereas sealed traits lets the compile specify monomorphized functions for each type.

71.2.14 Sealing with Enums

```rust
use std::collections::BTreeMap;
pub enum GetSource {
    WebUrl(String),
    BytesMap(BTreeMap<String, Vec<u8>>),
}

impl GetSource {
    fn get(&self, url: &str) -> Option<&Vec<u8>> {
        match self {
            Self::WebUrl(source) => unimplemented!(),
            Self::BytesMap(map) => map.get(url),
        }
    }
}
```

- Motivation: API is designed around a specific list of types that are valid for it, users of the API are not expected to extend it.
- Enums in Rust are *algebraic data types*, we can define different structures for each variant.

  For some domains, this might be enough polymorphism for the problem. Experiment and see what works, what solutions seem to make more sense.
- By having the user-facing part of the API refer to an enum, users know what types are valid inputs and can construct those types using the available methods to do so.
  - If the types that make up the enum have invariants that the API internally upholds, and the only way users can construct those types is through constructors that build

  and maintain those invariants, then you can be sure that inputs to a generic method uphold their invariants.
  - If the types that make up the enum instead are types the user can freely construct, then sanitisation and interpretation may need to be taken into consideration.

71.2.15 Traits for Polymorphism users can extend

```rust
// Crate A

pub trait Trait {
    fn use_trait(&self) {}
}

// Crate B, depends on A

pub struct Data(u8);

impl Trait for Data {}

fn main() {
    let data = Data(7u8);
    data.use_trait();
}
```

- We've already covered normal traits at length, but compared to enums and sealed traits they allow users to extend an API by implementing the behavior that API asks of them.

This ability for users to extend is powerful for a number of domains, from serialization to abstract representations of hardware and type safe linear algebra.

- If a trait is exposed publicly in a crate, a user depending on that crate can implement that trait for types they define.

71.2.16 Problem solving: Break Down the Problem

```rust
// Problem: implementing a GUI API

// Question: What's the minimum useful behavior for a drawing API?
pub trait DrawApi {
    fn arc(&self, center: [f32; 2], radius: f32, start_angle: f32, end_angle: f32);
    fn line(&self, start: [f32; 2], end: [f32; 2]);
}

pub struct TextDraw;

impl DrawApi for TextDraw {
    fn arc(&self, center: [f32; 2], radius: f32, start_angle: f32, end_angle: f32) {
        println!("arc of radius ")
    }

    fn line(&self, start: [f32; 2], end: [f32; 2]) { /* ... */
```

```rust
    }
}

// Question: What's a good API for users?

pub trait Draw {
    fn draw<T: DrawApi>(&self, surface: &mut T);
}

pub struct Rect {
    start: [f32; 2],
    end: [f32; 2],
}

impl Draw for Rect {
    fn draw<T: DrawApi>(&self, surface: &mut T) {
        surface.line([self.start[0], self.start[1]], [self.end[0], self.start[1]]);
        surface.line([self.end[0], self.start[1]], [self.end[0], self.end[1]]);
        surface.line([self.end[0], self.end[1]], [self.start[0], self.end[1]]);
        surface.line([self.start[0], self.end[1]], [self.start[0], self.start[1]]);
    }
}
```

- You're already adept at breaking down problems, but you're likely used to reaching for OOP-style methods.

This isn't a drastic change, it just requires re-ordering the way you approach things.

- Try to solve the problem with either Generics & Traits or Enums first.

  Does the problem require a specific set of types? An enum may be the cleanest way of solving this problem.

  Does the problem really care about the specifics of the types involved, or can behavior be focused on?

- Organize your problem solving around finding a minimum viable amount of knowledge to implement something.

  Does a trait already exist for this use case? If so, use it!

- If you really do need heterogeneous collections, use them! They exist in Rust as a tool for a reason.

  Be aware of the XY problem: a problem may seem most easily addressable by one solution, but it might not tackle the root cause and could lead to new difficult problems popping up in the future.

  That is, be certain that dynamic dispatch with trait objects is what you need before you commit to using them.

  Be certain that traits are what you need before you commit to using them.

Part XVI

Unsafe

IMPORTANT: THIS MODULE IS IN AN EARLY STAGE OF DEVELOPMENT

Please do not consider this module of Comprehensive Rust to be complete. With that in mind, your feedback, comments, and especially your concerns, are very welcome.

To comment on this module's development, please use the GitHub issue tracker.

Chapter 72

Welcome to the Unsafe Rust Deep Dive

This deep dive aims to enable you to work productively with Unsafe Rust.

We'll work on three areas:

- establishing a mental model of Unsafe Rust
- practicing reading & writing Unsafe Rust
- practicing code review for Unsafe Rust

The goal of this class is to teach you enough Unsafe Rust for you to be able to review easy cases yourself, and distinguish difficult cases that need to be reviewed by more experienced Unsafe Rust engineers.

- Establishing a mental model of Unsafe Rust
  - what the `unsafe` keyword means
  - a shared vocabulary for talking about safety
  - a mental model of how memory works
  - common patterns
  - expectations for code that uses `unsafe`
- Practicing working with unsafe
  - reading and writing both code and documentation
  - using unsafe APIs
  - designing and implementing them
- Reviewing code
  - the confidence to self-review easy cases
  - the knowledge to detect difficult cases

"We'll be using a spiral model of teaching. This means that we revisit the same topic multiple times with increasing depth."

A round of introductions is useful, particularly if the class participants don't know each other well. Ask everyone to introduce themselves, noting down any particular goals for the class.

- Who are you?

- What are you working on?
- What are your goals for this class?

Chapter 73

Setting Up

Local Rust installation

You should have a Rust compiler installed that supports the 2024 edition of the language, which is any version of rustc higher than 1.84.

```
$ rustc --version
rustc 1.87
```

(Optional) Create a local instance of the course

```
$ git clone --depth=1 https://github.com/google/comprehensive-rust.git
Cloning into 'comprehensive-rust'...
...
$ cd comprehensive-rust
$ cargo install-tools
...
$ cargo serve # then open http://127.0.0.1:3000/ in a browser
```

This slide should take about 2 minutes.

Ask everyone to confirm that everyone is able to execute `rustc` with a version newer than 1.87.

For those people who do not, tell them that we'll resolve that in the break.

Chapter 74

Introduction

We'll start our course by creating a shared understanding of what Unsafe Rust is and what the `unsafe` keyword does.

Outline

This segment should take about 1 hour and 10 minutes. It contains:

Slide	Duration
Defining Unsafe Rust	5 minutes
Purpose of the unsafe keyword	5 minutes
Two roles of the unsafe keyword	5 minutes
Warm Up Examples	25 minutes
Characteristics of Unsafe Rust	15 minutes
Responsibility shift	3 minutes
Stronger development workflow required	5 minutes
Example: may_overflow	10 minutes

74.1 Defining Unsafe Rust

This slide should take about 5 minutes.

"Unsafe Rust is a superset of Safe Rust."

"Unsafe Rust adds extra capabilities, such as allowing you to dereference raw pointers and call functions that can break Rust's safety guarantees if called incorrectly."

"These extra capabilities are referred to as *unsafe operations*."

"Unsafe operations provide the foundation that the Rust standard library is built on. For example, without the ability to dereference a raw pointer, it would be impossible to implement `Vec` or `Box`."

"The compiler will still assist you while writing Unsafe Rust. Borrow checking and type safety still apply. Unsafe operations have their own rules, which we'll learn about in this class."

The unsafe operations from the Rust Reference (Avoid spending too much time):

> The following language level features cannot be used in the safe subset of Rust:
>
> - Dereferencing a raw pointer.
> - Reading or writing a mutable or unsafe external static variable.
> - Accessing a field of a union, other than to assign to it.
> - Calling an `unsafe` function.
> - Calling a safe function marked with a <target_feature> from a function that does not have a <target_feature> attribute enabling the same features.
> - Implementing an unsafe trait.
> - Declaring an extern block.
> - Applying an unsafe attribute to an item.

74.2 Why the unsafe keyword exists

- Rust ensures safety
- But there are limits to what the compiler can do
- The unsafe keyword allows programmers to assume responsibility for Rust's rules

This slide should take about 5 minutes.

"A fundamental goal of Rust is to ensure memory safety."

"But, there are limits. Some safety considerations cannot be expressed in a programming language. Even if they could be, there are limits to what the Rust compiler can control."

"The `unsafe` keyword shifts the burden of upholding Rust's rules from the compiler to the programmer."

"When you see the `unsafe` keyword, you are seeing responsibility shift from the compiler to the programmer.

74.3 The unsafe keyword has two roles

1. *Creating* APIs with safety considerations

    - unsafe functions: `unsafe fn get_unchecked(&self) { ... }`
    - unsafe traits: `unsafe trait Send {}`

2. *Using* APIs with safety considerations

    - invoking built-in unsafe operators: `unsafe { *ptr }`
    - calling unsafe functions: `unsafe { x.get_unchecked() }`
    - implementing unsafe traits: `unsafe impl Send for Counter {}`

This slide should take about 5 minutes.

Two roles:

1. **Creating** APIs with safety considerations and defining what needs to be considered
2. **Using** APIs with safety considerations and confirming that the consideration has been made

Creating APIs with safety considerations

"First, the unsafe keyword enables you to create APIs that can break Rust's safety guarantees. Specifically, you need to use the unsafe keyword when defining unsafe functions and unsafe traits.

"When used in this role, you're informing users of your API that they need to be careful."

"The creator of the API should communicate what care needs to be taken. Unsafe APIs are not complete without documentation about safety requirements. Callers need to know that they have satisfied any requirements, and that's impossible if they're not written down."

Using APIs with safety considerations

"The unsafe keyword adopts its other role, using APIs, when it is used nearby to a curly brace.

"When used in this role, the unsafe keyword means that the author has been careful. They have verified that the code is safe and is providing an assurance to others."

"Unsafe blocks are most common. They allow you to invoke unsafe functions that have been defined using the first role.

"Unsafe blocks also allow you to perform operations which the compiler knows are unsafe, such as dereferencing a raw pointer."

"You might also see the unsafe keyword being used to implement unsafe traits.

74.4 Warm-up examples

Examples to demonstrate:

- using an unsafe block (`unsafe { ... }`)
- defining an unsafe function (`unsafe fn`)
- implementing an unsafe trait (`unsafe impl { ... }`)
- defining an unsafe trait (`unsafe trait`)

74.4.1 Using an unsafe block

```
fn main() {
    let numbers = vec![0, 1, 2, 3, 4];
    let i = numbers.len() / 2;

    let x = *numbers.get_unchecked(i);
    assert_eq!(i, x);
}
```

Walk through the code. Confirm that the audience is familiar with the dereference operator.

Attempt to compile the code, trigger the compiler error.

Add the unsafe block:

```
 let x = unsafe { *numbers.get_unchecked(i) };
```

Prompt audience for a code review. Guide learners towards adding a safety comment.

Add the safety comment:

```
// SAFETY: `i` must be within 0..numbers.len()
```

Suggested Solution

```
fn main() {
    let numbers = vec![0, 1, 2, 3, 4];
    let i = numbers.len() / 2;

    let x = unsafe { *numbers.get_unchecked(i) };
    assert_eq!(i, x);
}
```

74.4.2 Defining an unsafe function

```
/// Convert a nullable pointer to a reference.
///
/// Returns `None` when `p` is null, otherwise wraps `val` in `Some`.
fn ptr_to_ref<'a, T>(ptr: *mut T) -> Option<&'a mut T> {
    if ptr.is_null() {
        None
    } else {
        // SAFETY: `ptr` is non-null
        unsafe { Some(&mut *ptr) }
    }
}
```

"This looks as though it's safe code, however it actually requires an unsafe block."

Highlight the dereference operation, i.e. `*p` within the unsafe block.

"Callers must ensure that the `ptr` is null, or that it may be converted to a reference.

"It may be counter-intuitive, but many pointers cannot be converted to references.

"Among other issues, a pointer could be created that points to some arbitrary bits rather than a valid value. That's not something that Rust allows and something that this function needs to protect itself against.

"So we, as API designers, have two paths. We can either try to assume responsibility for guarding against invalid inputs, or we can shift that responsibility to the caller with the unsafe keyword."

"The first path is a difficult one. We're accepting a generic type T, which is all possible types that implement Sized. That's a lot of types!

"Therefore, the second path makes more sense.

Extra content (time permitting)

"By the way, if you're interested in the details of pointers and what the rules of converting them to references are, the standard library has a lot of useful documentation. You should also look into the source code of many of the methods on std::pointer.

"For example, the `ptr_to_ref` function on this slide actually exists in the standard library as the `as_mut` method on pointers."

Open the documentation for std::pointer.as_mut and highlight the Safety section.

74.4.3 Implementing an unsafe trait

```
pub struct LogicalClock {
    inner: std::sync::Arc<std::sync::atomic::AtomicUsize>,
}

// ...

impl Send for LogicalClock {}
impl Sync for LogicalClock {}
```

"Before we take a look at the code, we should double check that everyone knows what a trait is. Is anyone able to explain traits for the rest of the class?

- "Traits are often described as a way to create shared behavior. Thinking about traits as shared behavior focuses on the syntax of methods and their signatures.
- "There's also a deeper way to think of traits: as sets of requirements. This emphasizes the shared semantics of the implementing types.

"Can anyone explain what the Send and Sync traits are?

- If no
  - "Send and Sync relate to concurrency. There are many details, but broadly speaking, Send types can be shared between threads by value. Sync types must be shared by reference.
  - There are many rules to follow to ensure that it's safe to share data across thread boundaries. Those rules cannot be checked by the compiler, and therefore the code author must take responsibility for upholding them.
  - Arc implements Send and Sync, therefore it's safe for our clock to as well.
  - It may be useful to point out that the word *atomic* has the meaning of "indivisible" or "whole" from Ancient Greek, rather than the contemporary English sense of "tiny particle".

74.4.4 Defining an unsafe trait

```
/// Indicates that the type uses 32 bits of memory.
pub trait Size32 {}
```

“Now let’s define our own unsafe trait.”

Add the unsafe keyword and compile the code.

“If the requirements of the trait are semantic, then your trait may not need any methods at all. The documentation is essential, however.”

“Traits without methods are called marker traits. When implementing them for types, you are adding information to the type system. You have now given the compiler the ability to talk about types that meet the requirements described in the documentation.”

74.5 Characteristics of unsafe

- Dangerous
- Sometimes necessary
- Sometimes useful

74.5.1 Unsafe is dangerous

> “Use-after-free (UAF), integer overflows, and out of bounds (OOB) reads/writes comprise 90% of vulnerabilities with OOB being the most common.”
>
> --- **Jeff Vander Stoep and Chong Zang**, Google. ”Queue the Hardening Enhancements”

“The software industry has gathered lots of evidence that unsafe code is difficult to write correctly and creates very serious problems.”

“The issues in this list are eliminated by Rust. The unsafe keyword lets them back into your source code.”

“Be careful.”

74.5.2 Unsafe is sometimes necessary

The Rust compiler can only enforce its rules for code that it has compiled.

```
fn main() {
    let pid = unsafe { libc::getpid() };
    println!("{pid}");
}
```

“There are some activities that *require* unsafe.

“The Rust compiler cannot verify that external functions comply with Rust's memory guarantees. Therefore, invoking external functions requires an unsafe block.”

Optional:

“Working with the external environment often involves sharing memory. The interface that computers provide is a memory address (a pointer).”

“Here's an example that asks the Linux kernel to write to memory that we control:

```
fn main() {
    let mut buf = [0u8; 8];
    let ptr = buf.as_mut_ptr() as *mut libc::c_void;

    let status = unsafe { libc::getrandom(ptr, buf.len(), 0) };
    if status > 0 {
        println!("{buf:?}");
    }
}
```

“This FFI call reaches into the operating system to fill our buffer (`buf`). As well as calling an external function, we must mark the boundary as `unsafe` because the compiler cannot verify how the OS touches that memory.”

74.5.3 Unsafe is sometimes useful

Your code can go faster!

```
fn iter_sum(xs: &[u64]) -> u64 {
    xs.iter().sum()
}

fn fast_sum(xs: &[u64]) -> u64 {
    let mut acc = 0;
    let mut i = 0;
    unsafe {
        while i < xs.len() {
            acc += *xs.get_unchecked(i);
            i += 1;
        }
    }
    acc
}

fn main() {
    let data: Vec<_> = (0..1_000_000).collect();

    let baseline = iter_sum(&data);
    let unchecked = fast_sum(&data);

    assert_eq!(baseline, unchecked);
}
```

Code using `unsafe` *might* be faster.

`fast_sum()` skips bounds checks. However, benchmarking is necessary to validate performance claims. For cases like this, Rust's iterators can usually elide bounds checks anyway.

Optional: show identical generated assembly for the two functions.

74.6 Unsafe keyword shifts responsibility

Is Memory Safe?	Responsibility for Memory Safety	
Safe Rust	Yes	Compiler
Unsafe Rust	Yes	Programmer

This slide should take about 3 minutes.

Who has responsibility for memory safety?

- Safe Rust □ compiler
- Unsafe Rust □ programmer

"While writing safe Rust, you cannot create memory safety problems. The compiler will ensure that a program with mistakes will not build."

"The `unsafe` keyword shifts responsibility for maintaining memory safety from the compiler to programmers. It signals that there are preconditions that must be satisfied.

"To uphold that responsibility, programmers must ensure that they've understood what the preconditions are and that their code will always satisfy them.

"Throughout this course, we'll use the term *safety preconditions* to describe this situation."

74.7 Impact on workflow

While writing code

- Verify that you understand the preconditions of any `unsafe` functions/traits
- Check that the preconditions are satisfied
- Document your reasoning in safety comments

Enhanced code review

- Self-review □ peer reviewer □ unsafe Rust expert (when needed)
- Escalate to a person who is comfortable with your code and reasoning

This slide should take about 5 minutes.

"The unsafe keyword places more responsibility on the programmer; therefore it requires a stronger development workflow.

"This class assumes a specific software development workflow where code review is mandatory, and where the author and primary reviewer have access to an unsafe Rust expert."

"The author and primary reviewer will verify simple unsafe Rust code themselves, and punt to an unsafe expert when necessary."

"There are only a few unsafe Rust experts, and they are very busy, so we need to optimally use their time."

74.8 Example: may_overflow function

```
/// Adds 2^31 - 1 to negative numbers.
unsafe fn may_overflow(a: i32) -> i32 {
    a + i32::MAX
}

fn main() {
    let x = unsafe { may_overflow(123) };
    println!("{x}");
}
```

This slide should take about 10 minutes.

“The `unsafe` keyword may have a subtly different meaning than what some people assume.”

“The code author believes that the code is correct. In principle, the code is safe.”

“In this toy example, the `may_overflow` function is only intended to be called with negative numbers.

Ask learners if they can explain why `may_overflow` requires the unsafe keyword.

“In case you’re unsure what the problem is, let’s pause briefly to explain. An `i32` only has 31 bits available for positive numbers. When an operation produces a result that requires more than 31 bits, then the program is put into an invalid state. And it’s not just a numerical problem. Compilers optimize code on the basis that invalid states are impossible. This causes code paths to be deleted, producing erratic runtime behavior while also introducing security vulnerabilities.

Compile and run the code, producing a panic. Then run the example in the playground to run under `--release` mode to trigger UB.

“This code can be used correctly, however, improper usage is highly dangerous.”

“And it's impossible for the compiler to verify that the usage is correct.”

This is what we mean when we say that the `unsafe` keyword marks the location where responsibility for memory safety shifts from the compiler to the programmer.

Chapter 75

Safety Preconditions

Safety preconditions are conditions on an action that must be satisfied before that action will be safe.

“Safety preconditions are conditions on code that must be satisfied to maintain Rust's safety guarantees

“You're likely to see a strong affinity between safety preconditions and the rules of Safe Rust.”

Q: Can you list any?

(Fuller list in the next slide)

75.1 Common safety preconditions

- Aliasing and Mutability
- Alignment
- Array access is in-bound
- Initialization
- Lifetimes
- Pointer provenance
- Validity
- Memory

This slide and its sub-slides should take about 6 minutes.

Avoid spending too much time explaining every precondition: we will be working through the details during the course. The intent is to show that there are several.

”An incomplete list, but these are a few of the major safety preconditions to get us thinking.”

- Validity. Values must be valid values of the type that they represent. Rust's references may not be null. Creating one with `unsafe` causes the.
- Alignment. References to values must be well-aligned, which means th
- Aliasing. All Rust code must uphold Rust's borrowing rules. If you are manually creating mutable references (`&mut T`) from pointers, then you may only create one
- Initialization. All instances of Rust types must be fully initialized. To create a value from raw memory, we need to make sure that we've written

- Pointer provenance. The origin of a pointer is important. Casting a `usize` to a raw pointer is no longer allowed.
- Lifetimes. References must not outlive their referent.

Some conditions are even more subtle than they first seem.

Consider ”in-bounds array access”. Reading from the memory location, i.e. dereferencing, is not required to break the program. Creating an out-of-bounds reference already breaks the compiler's assumptions, leading to erratic behavior.

Rust tells LLVM to use its `getelementptr inbounds` assumption. That assumption will cause later optimization passes within the compiler to misbehave (because out-of-bounds memory access cannot occur).

Optional: open the playground, which shows the code below. Explain that this is essentially a C function written in Rust syntax that gets items from an array. Generate the LLVM IR with the **Show LLVM IR** button. Highlight `getelementptr inbounds i32, ptr %array, i64 %offset`.

```
#[unsafe(no_mangle)]
pub unsafe fn get(array: *const i32, offset: isize) -> i32 {
    unsafe { *array.offset(offset) }
}
```

Expected output (the line to highlight starts with ‘%_3):

```
define noundef i32 @get(ptr noundef readonly captures(none) %array, i64 noundef %offset)
start:
  %_3 = getelementptr inbounds i32, ptr %array, i64 %offset
  %_0 = load i32, ptr %_3, align 4, !noundef !3
  ret i32 %_0
}
```

Bounds: You correctly noted that creating an out-of-bounds pointer (beyond the ”one-past-the-end” rule) is UB, even without dereferencing, due to LLVM's inbounds assumptions.

75.1.1 Getter example

```
/// Return the element at `index` from `arr`
unsafe fn get(arr: *const i32, index: usize) -> i32 {
    unsafe { *arr.add(index) }
}
```

“Safety preconditions are conditions on code that must be satisfied to maintain Rust's safety guarantees

“You're likely to see a strong affinity between safety preconditions and the rules of Safe Rust.”

Ask: “What are the safety preconditions of `get`?”

- The pointer `arr` is non-null, well-aligned and refers to an array of `i32`
- `index` is in-bounds

Add safety comments:

```
/// Return the element at `index` from `arr`
///
/// # Safety
```

```
///
/// - `arr` is non-null, correctly aligned and points to a valid `i32`
/// - `index` is in-bounds for the array
unsafe fn get(arr: *const i32, index: usize) -> i32 {
    // SAFETY: Caller guarantees that index is inbounds
    unsafe { *arr.add(index) }
}
```

Optional: Add runtime checks can be added in debug builds to provide some extra robustness.

```
debug_assert!(!arr.is_null());
debug_assert_eq!(arr as usize % std::mem::align_of::<i32>(), 0);
```

75.2 Semantic preconditions

75.2.1 Example: u8 to bool

75.3 Determining Preconditions

Where do you find the safety preconditions?

```
fn main() {
    let b: *mut i32 = std::ptr::null_mut();
    println!("{:?}", b.as_mut());
}
```

This slide and its sub-slides should take about 10 minutes.

Attempt to compile the program to trigger the compiler error ("error[E0133]: call to unsafe function ...").

Ask: "Where would you look if you wanted to know the preconditions for a function? Here we need to understand when it's safe to convert from a null pointer to a mutable reference."

Locations to look:

- A function's API documentation, especially its safety section
- The source code and its internal safety comments
- Module documentation
- Rust Reference

Consult the documentation for the `as_mut` method.

Highlight Safety section.

> **Safety**
>
> When calling this method, you have to ensure that either the pointer is null or the pointer is convertible to a reference.

Click the "convertible to a reference" hyperlink to the "Pointer to reference conversion"

Track down the rules for converting a pointer to a reference, i.e., whether it is "dereferenceable".

Consider the implications of this excerpt (Rust 1.90.0) "You must enforce Rust's aliasing rules. The exact aliasing rules are not decided yet, ..."

75.3.1 Example: References

```rust
fn main() {
    let mut boxed = Box::new(123);
    let a: *mut i32 = &mut *boxed as *mut i32;
    let b: *mut i32 = std::ptr::null_mut();

    println!("{:?}", *a);
    println!("{:?}", b.as_mut());
}
```

Confirm understanding of the syntax

- Box<i32> type is a reference to an integer on the heap that is owned by the box.
- *mut i32 type is a so-called raw pointer to an integer that the compiler does not know the ownership of. Programmers need to ensure the rules are enforced without assistance from the compiler.
  - Note: raw pointers do not provide ownership info to Rust. A pointer can be semantically owning the data, or semantically borrowing, but that information only exists in the programmer's mind.
- &mut *boxed as *mut _ expression:
  - *boxed is ...
  - &mut *boxed is ...
  - finally, as *mut i32 casts the reference to a pointer.
- References, such as &mut i32, "borrow" their referent. This is Rust's ownership system.

Confirm understanding of ownership

- Step through code:
  - (Line 3) Creates raw pointer to the 123 by dereferencing the box, creating a new reference and casting the new reference as a pointer.
  - (Line 4) Creates raw pointer with a NULL value
  - (Line 7) Converts the raw pointer to an Option with .as_mut()
- Highlight that pointers are nullable in Rust (unlike references).
- Compile to reveal the error messages.
- Discuss
  - (Line 6) println!("{:?}", *a);
    - Prefix star dereferences a raw pointer.
    - It is an explicit operation. Whereas regular references have implicit dereferencing most of the time thanks to the Deref trait. This is referred to as "auto-deref".
    - Dereferencing a raw pointer is an unsafe operation.
    - Requires an unsafe block.
  - (Line 7) println!("{:?}", b.as_mut());
    - as_mut() is an unsafe function.
    - Calling an unsafe function requires an unsafe block.
- Demonstrate: Fix the code (add unsafe blocks) and compile again to show the working program.

- Demonstrate: Replace `as *mut i32` with `as *mut _`, show that it compiles.
  - We can partially omit the target type in the cast. The Rust compiler knows that the source of the cast is a `&mut i32`. This reference type can only be converted to one pointer type, `*mut i32`.
- Add safety comments:
  - We said that the unsafe code marks the responsibility shift from the compiler to the programmer.
  - How do we convey that we thought about our unusual responsibilities while writing unsafe code? Safety comments.
  - Safety comments explain why unsafe code is correct.
  - Without a safety comment, unsafe code is not safe.
- Discuss: Whether to use one large unsafe block or two smaller ones:
  - Possibility of using a single unsafe block rather than multiple.
  - Using more allows safety comments as specific as possible.

Suggested Solution

```rust
fn main() {
    let mut boxed = Box::new(123);
    let a: *mut i32 = &mut *boxed as *mut i32;
    let b: *mut i32 = std::ptr::null_mut();

    // SAFETY: `a` is a non-null pointer to i32, it is initialized and still
    // allocated.
    println!("{:?}", unsafe { *a });

    // SAFETY: `b` is a null pointer, which `as_mut()` converts to `None`.
    println!("{:?}", unsafe { b.as_mut() });
}
```

75.4 Defining your own preconditions

- User-defined types are entitled to have their own safety preconditions
- Include documentation so that they can later be determined and satisfied

75.4.1 Example: ASCII Type

```rust
/// Text that is guaranteed to be encoded within 7-bit ASCII.
pub struct Ascii<'a>(&'a mut [u8]);

impl<'a> Ascii<'a> {
    pub fn new(bytes: &'a mut [u8]) -> Option<Self> {
        bytes.iter().all(|&b| b.is_ascii()).then(|| Ascii(bytes))
    }

    /// Creates a new `Ascii` from a byte slice without checking for ASCII
    /// validity.
    ///
```

```rust
    /// # Safety
    ///
    /// Providing non-ASCII bytes results in undefined behavior.
    pub unsafe fn new_unchecked(bytes: &'a mut [u8]) -> Self {
        Ascii(bytes)
    }
}
```

”The `Ascii` type is a minimal wrapper around a byte slice. Internally, they share the same representation. However, `Ascii` requires that the high bit must not be used.”

Optional: Extend the example to mention that it's possible to use `debug_assert!` to test the preconditions during tests without impacting release builds.

```rust
unsafe fn new_unchecked(bytes: &mut [u8]) -> Self {
    debug_assert!(bytes.iter().all(|&b| b.is_ascii()))
    Ascii(bytes)
}
```

Chapter 76

Rules of the game

“We've seen many examples of code that has problems in the class, but we lack consistent terminology.

“The goal of the next section is to introduce some terms that describe many of the concepts that we have been thinking about.

- undefined behavior
- sound
- unsound

“Given that many safety preconditions are semantic rather than syntactic, it's important to use a shared vocabulary. That way we can agree on semantics.

“The overarching goal is to develop a mental framework of what soundness is and ensure that Rust code that contains unsafe remains sound.”

76.1 Rust is sound

- Soundness is fundamental to Rust
- Soundness □ impossible to cause memory safety problems
- Sound functions have common “shapes”

This slide should take about 5 minutes.

“A fundamental principle of Rust code is that it is sound.

“We’ll create a formal definition of the term soundness shortly. In the meantime, think of sound code as code that cannot trigger memory safety problems.

“Sound code is made up of *sound functions* and *sound operations*.

“A sound function is a function where none of its possible inputs could provoke soundness problems.

Sound functions have common shapes.

Those shapes are what we’ll look at now.

"We'll start with one that's implemented in Safe Rust, and then see what could happen when we introduce `unsafe` to different parts.

76.2 Copying memory - Introduction

```rust
/// Reads bytes from `source` and writes them to `dest`
pub fn copy(dest: &mut [u8], source: &[u8]) { ... }
```

This slide and its sub-slides should take about 28 minutes.

"Here is our initial function prototype."

"`copy` accepts two slices as arguments. `dest` (destination) is mutable, whereas `source` is not."

"Let's see the shapes of sound Rust code."

76.2.1 Safe Rust

```rust
pub fn copy(dest: &mut [u8], source: &[u8]) {
    for (dest, src) in dest.iter_mut().zip(source) {
        *dest = *src;
    }
}

fn main() {
    let a = &[114, 117, 115, 116];
    let b = &mut [82, 85, 83, 84];

    println!("{}", String::from_utf8_lossy(b));
    copy(b, a);
    println!("{}", String::from_utf8_lossy(b));
}
```

"The implementation only uses safe Rust.

What can we learn from this?

"It is impossible for `copy` to trigger memory safety issues when implemented in Safe Rust. This is true for all possible input arguments."

"For example, by using Rust's iterators, we can ensure that we'll never trigger errors relating to handling pointers directly, such as needing null pointer or bounds checks."

Ask: "Can you think of any others?"

- No aliasing issues
- Dangling pointers are impossible
- Alignment will be correct
- Cannot accidentally read from uninitialized memory

"We can say that the `copy` function is *sound* because Rust ensures that all of the safety preconditions are satisfied."

"From the point of view of the programmer, as this function is implemented in safe Rust, we can think of it as having no safety preconditions."

"This does not mean that copy will always do what the caller might want. If there is insufficient space available in the dest slice, then data will not be copied across."

76.2.2 Encapsulated Unsafe Rust

```
pub fn copy(dest: &mut [u8], source: &[u8]) {
    let len = dest.len().min(source.len());
    let mut i = 0;
    while i < len {
        // SAFETY: `i` must be in-bounds as it was produced by source.len()
        let new = unsafe { source.get_unchecked(i) };

        // SAFETY: `i` must be in-bounds as it was produced by dest.len()
        let old = unsafe { dest.get_unchecked_mut(i) };

        *old = *new;
        i += 1;
    }

    for (dest, src) in dest.iter_mut().zip(source) {
        *dest = *src;
    }
}

fn main() {
    let a = &[114, 117, 115, 116];
    let b = &mut [82, 85, 83, 84];

    println!("{}", String::from_utf8_lossy(b));
    copy(b, a);
    println!("{}", String::from_utf8_lossy(b));
}
```

"Here we have a safe function that encapsulates unsafe blocks that are used internally.

"This implementation avoids iterators. Instead, the implementor is accessing memory manually."

"Is this correct?" "Are there any problems?"

"Who has responsibility for ensuring that correctness? The author of the function.

"A Safe Rust function that contains unsafe blocks remains sound if it's impossible for an input to cause memory safety issues.

76.2.3 Exposed Unsafe Rust

```
pub fn copy(dest: &mut [u8], source: *const u8) {
    let source = {
        let mut len = 0;

        let mut end = source;
        while unsafe { *end != 0 } {
```

```
            len += 1;
            end = unsafe { end.add(1) };
        }

        unsafe { std::slice::from_raw_parts(source, len + 1) }
    };

    for (dest, src) in dest.iter_mut().zip(source) {
        *dest = *src;
    }
}

fn main() {
    let a = [114, 117, 115, 116].as_ptr();
    let b = &mut [82, 85, 83, 84, 0];

    println!("{}", String::from_utf8_lossy(b));
    copy(b, a);
    println!("{}", String::from_utf8_lossy(b));
}
```

The functionality of copying bytes from one place to the next remains the same.

"However, we need to manually create a slice. To do that, we first need to find the end of the data.

"As we're working with text, we'll use the C convention of a null-terminated string.

Compile the code. See that the output remains the same.

"An unsound function can still work correctly for some inputs. Just because your tests pass, does not mean that you have a sound function."

"Can anyone spot any issues?"

- Readability: difficult to quickly scan code
- `source` pointer might be null
- `source` pointer might be dangling, i.e. point to freed or uninitialized memory
- `source` might not be null-terminated

"Assume that we cannot change the function signature, what improvements could we make to the code to address these issues?"

- Null pointer: Add null check with early return (`if source.is_null() { return; }`)
- Readability: Use a well-tested library rather than implementing "find first null byte" ourselves

"Some safety requirements are impossible to defensively check for, however, i.e.:"

- dangling pointer
- no null termination byte

"How can we make this function sound?"

- Either
  - Change the type of the `source` input argument to something that has a known length, i.e. use a slice like the previous example.

- Or
  - Mark the function as unsafe
  - Document the safety preconditions

76.2.4 Documented safety preconditions

```
/// ...
///
/// # Safety
///
/// This function can easily trigger undefined behavior. Ensure that:
///
///  - `source` pointer is non-null and non-dangling
///  - `source` data ends with a null byte within its memory allocation
///  - `source` data is not freed (its lifetime invariants are preserved)
///  - `source` data contains fewer than `isize::MAX` bytes
pub unsafe fn copy(dest: &mut [u8], source: *const u8) {
    let source = {
        let mut len = 0;

        let mut end = source;
        // SAFETY: Caller has provided a non-null pointer
        while unsafe { *end != 0 } {
            len += 1;
            // SAFETY: Caller has provided a data with length < isize:MAX
            end = unsafe { end.add(1) };
        }

        // SAFETY: Caller maintains lifetime and aliasing requirements
        unsafe { std::slice::from_raw_parts(source, len + 1) }
    };

    for (dest, src) in dest.iter_mut().zip(source) {
        *dest = *src;
    }
}

fn main() {
    let a = [114, 117, 115, 116].as_ptr();
    let b = &mut [82, 85, 83, 84, 0];

    println!("{}", String::from_utf8_lossy(b));
    unsafe {
        copy(b, a);
    }
    println!("{}", String::from_utf8_lossy(b));
}
```

Changes to previous iterations:

- copy marked as unsafe
- Safety preconditions are documented

- inline safety comments

An unsafe function is sound when both its safety preconditions and its internal unsafe blocks are documented.

Fixes needed in `main`.

- `a` does not satisfy one of the preconditions of `copy` (source‘ data ends with a null byte within its memory allocation)
- SAFETY comment needed

76.2.5 Crying Wolf

```
pub unsafe fn copy(dest: &mut [u8], source: &[u8]) {
    for (dest, src) in dest.iter_mut().zip(source) {
        *dest = *src;
    }
}

fn main() {
    let a = &[114, 117, 115, 116];
    let b = &mut [82, 85, 83, 84];

    println!("{}", String::from_utf8_lossy(b));
    unsafe { copy(b, a) };
    println!("{}", String::from_utf8_lossy(b));
}
```

“It is also possible to create so-called crying wolf functions.

“These are functions which are tagged as unsafe, but which have no safety preconditions that programmers need to check.

76.3 3 Shapes of Sound Rust

- Functions written only in Safe Rust
- Functions that contain `unsafe` blocks which are impossible to misuse
- Unsafe functions that have their safety preconditions documented

This slide should take about 5 minutes.

- We want to write sound code.
- Sound code can only have the following shapes:
  - safe functions that contain no unsafe blocks
  - safe functions that completely encapsulate unsafe blocks, meaning that the caller does not need to know about them
  - unsafe functions that contain unsafe blocks but don't encapsulate them, and pass the proof burden to their caller
- Burden of proof
  - safe functions with only Safe Rust -> compiler
  - safe functions with unsafe blocks -> function author
  - unsafe functions -> function caller

76.4 Soundness Proof

76.4.1 Soundness

A sound function is one that can't trigger UB if its safety preconditions are satisfied.

- Read the definition of sound functions.
- Remind the students that the programmer who implements the caller is responsible for satisfying the safety precondition; the compiler is not helping.
- Translate into informal terms. Soundness means that the function is nice and plays by the rules. It documents its safety preconditions, and when the caller satisfies them, the function behaves well (no UB).

76.4.2 Soundness Proof (Part 2)

A sound function is one that can't trigger UB if its safety preconditions are satisfied.

Corollary: All functions implemented in pure safe Rust are sound.

Proof:

- Safe Rust code has no safety preconditions.
- Therefore, callers of functions implemented in pure safe Rust always trivially satisfy the empty set of preconditions.
- Safe Rust code can't trigger UB.

QED.

- Read the corollary.
- Explain the proof.
- Translate into informal terms: all safe Rust code is nice. It does not have safety preconditions that the programmer has to think of, always plays by the rules, and never triggers UB.

76.4.3 Unsoundness

A sound function is one that can't trigger UB if its safety preconditions are satisfied.

An unsound function can trigger UB even if you satisfy the documented safety preconditions.

Unsound code is *bad*.

- Read the definition of unsound functions.
- Translate into informal terms: unsound code is not nice. No, that's an understatement. Unsound code is BAD. Even if you play by the documented rules, unsound code can still trigger UB!
- We don't want any unsound code in our repositories.
- Finding unsound code is the **primary** goal of the code review.

Chapter 77

Memory Lifecycle

Memory moves through different phases as objects (values) are created and destroyed.

Memory State	Readable from Safe Rust?
Available	No
Allocated	No
Initialized	Yes

This section discusses what happens as memory from the operating system becomes a valid variable in the program.

When memory is available, the operating system has provided our program with it.

When memory is allocated, it is reserved for values to be written to it. We call this uninitialized memory.

When memory is initialized, it is safe to read from.

Chapter 78

Initialization

78.1 MaybeUninit

`MaybeUninit<T>` allows Rust to refer to uninitialized memory.

```
use std::mem::MaybeUninit;

fn main() {
    let uninit = MaybeUninit::<&i32>::uninit();
    println!("{uninit:?}");
}
```

This slide and its sub-slides should take about 16 minutes.

"Safe Rust is unable to refer to data that's potentially uninitialized"

"Yet, all data arrives at the program as uninitialized."

"Therefore, we need some bridge in the type system to allow memory to transition. `MaybeUninit<T>` is that type."

"`MaybeUninit<T>` is very similar to the `Option<T>` type, although its semantics are very different. The equivalent of `Option::None` for `MaybeUninit<T>` is uninitialized memory, which is only safe to write to."

"Reading from memory that may be uninitialized is extremely dangerous."

78.1.1 MaybeUninit and arrays

```
use std::mem::MaybeUninit;
use std::ptr;

fn main() {
    let input = b"RUST";

    let mut buf = [const { MaybeUninit::<u8>::uninit() }; 2048];

    // Initialize elements by writing values to the memory
```

```
    for (i, input_byte) in input.iter().enumerate() {
        unsafe {
            let dst = buf.as_mut_ptr().add(i);
            ptr::write((*dst).as_mut_ptr(), *input_byte);
        }
    }

    // When a portion of an array is initialized, one can
    // use unsafe to isolate it
    let ptr_to_init_subslice = buf.as_ptr() as *const u8;
    let init =
        unsafe { std::slice::from_raw_parts(ptr_to_init_subslice, input.len()) };
    let text = std::str::from_utf8(init).unwrap();
    println!("{text}");

    // We must manually drop the initialized elements
    for element in &mut buf[0..input.len()] {
        unsafe {
            element.assume_init_drop();
        }
    }
}
```

To create an array of uninitialized memory, the `::uninit()` constructor can be used within a `const` context.

Use `ptr::write` to initialize values as per normal.

`.assume_init()` does not work as easily for arrays. It requires every value to be initialized, which may not occur when reusing a buffer. This example uses a pointer to isolate the initialized bytes to create a string slice.

When creating a sub-slice of a partially-initialized array, be careful with ownership and correctly implementing drop. Reminder: `MaybeUninit<T>` will not call drop on its `T`.

`MaybeUninit<[u8;2048]>` is distinct from `[MaybeUninit::<u8>; 2048]`. This is the difference between an array of uninitialized memory and an array that contains uninitialized elements.

- `MaybeUninit<[u8;2048]>` is "all or nothing". You either fully initialize the whole array and then call `assume_init`, or you must keep it as `MaybeUninit<[u8; 2048]>` and avoid touching it as `[u8; 2048]`.
- `[MaybeUninit<u8>; 2048]` lets you initialize elements one at a time, then take a subslice of just the initialized prefix and treat it as `[u8]` via `std::slice::from_raw_parts`.
- `slice_assume_init_ref` is safe only when every element in the slice is initialized. For this example, we only pass `&buf[..input.len()]` after writing exactly those bytes.
- When `T` needs drop, you must manually call `assume_init_drop()` for the initialized elements. Skipping this leaks memory. However, calling it on an uninitialized element is undefined behavior.

78.1.2 MaybeUninit::zeroed()

```
use std::mem::{MaybeUninit, transmute};
```

```rust
fn main() {
    let mut x = [const { MaybeUninit::<u32>::zeroed() }; 10];

    x[6].write(7);

    // SAFETY: All values of `x` have been written to
    let x: [u32; 10] = unsafe { transmute(x) };
    println!("{x:?}")
}
```

"MaybeUninit::zeroed() is an alternative constructor to MaybeUninit::uninit(). It instructs the compiler to fill the bits of T with zeros."

Q: "Although the memory has been written to, the type remains `MaybeUninit<T>`. Can anyone think of why?"

A: Some types require their values to be non-zero or non-null. The classic case is references, but this applies to many other types as well. Consider the `NonZeroUsize` integer type and others in its family.

78.1.3 MaybeUninit.write() vs assignment

```rust
use std::mem::MaybeUninit;

fn main() {
    let mut buf = MaybeUninit::<String>::uninit();

    // Initialize
    buf.write(String::from("Hello, Rust!"));

    // Overwrite
    buf.write(String::from("Hi again"));

    // Assignment replaces the whole MaybeUninit value.
    buf = MaybeUninit::new(String::from("Goodbye"));

    // Ensure inner value is dropped
    let _ = unsafe { buf.assume_init() };
}
```

Replacing inner values can cause memory leaks because the drop semantics differ from most types. `MaybeUninit<T>` does not call the destructor on its `T`.

`MaybeUninit::write()` uses `ptr::write`: it initializes the memory in place without reading or dropping the old contents. That is exactly what you want when the memory might be uninitialized, but it also means you will leak if there was already a live value there.

Assignment, e.g. `buf = MaybeUninit::new(value)`, replaces the whole `MaybeUninit`. The old `MaybeUninit` is moved and then dropped, but `MaybeUninit` has no destructor for `T`, so the inner value is not dropped. If the old slot held an initialized value, it is leaked just like with `write()`.

If you need normal drop behavior, you need to tell Rust that the value is initialized with `assume_init` or one of the related methods.

78.2 How to Initialize Memory

Steps:

1. Create `MaybeUninit<T>`
2. Write a value to it
3. Notify Rust that the memory is initialized

```
use std::mem::MaybeUninit;

fn main() {
    // Step 1: Create MaybeUninit
    let mut uninit = MaybeUninit::uninit();

    // Step 2: Write a valid value to the memory
    uninit.write(1);

    // Step 3: Inform the type system that the memory location is valid
    let init = unsafe { uninit.assume_init() };

    println!("{init}");
}
```

This slide should take about 8 minutes.

To work with uninitialized memory, follow this general workflow: create, write, confirm.

1. Create `MaybeUninit<T>`. The `::uninit()` constructor is the most general-purpose one, but there are others which perform a write as well.

2. Write a value of T. Notice that this is available from safe Rust. Staying in safe Rust is useful because you must ensure that the value you write is valid.

3. Confirm to the type system that the memory is now initialized with the `.assume_init()` method.

78.3 Partial Initialization

```
use std::mem::MaybeUninit;

fn main() {
    // let mut buf = [0u8; 2048];
    let mut buf = [const { MaybeUninit::<u8>::uninit() }; 2048];

    let external_data = b"Hello, Rust!";
    let len = external_data.len();

    for (dest, src) in buf.iter_mut().zip(external_data) {
        dest.write(*src);
    }

    // SAFETY: We initialized exactly 'len' bytes of `buf` with UTF-8 text
    let text: &str = unsafe {
```

```
        let ptr: *const u8 = buf.as_ptr().cast::<u8>();
        let init: &[u8] = std::slice::from_raw_parts(ptr, len);
        std::str::from_utf8_unchecked(init)
    };

    println!("{text}");
}
```

This code simulates receiving data from some external source.

When reading bytes from an external source into a buffer, you typically don't know how many bytes you'll receive. Using `MaybeUninit<T>` lets you allocate the buffer once without paying for a redundant initialization pass.

If we were to create the array with the standard syntax (`buf = [0u8; 2048]`), the whole buffer would be flushed with zeroes. `MaybeUninit<T>` tells the compiler to reserve space, but not to touch the memory yet.

Q: Which part of the code snippet is performing a similar role to `.assume_init()`? A: The pointer cast and the implicit read.

We cannot call `assume_init()` on the whole array. That would be unsound because most elements remain uninitialized. Instead, we cast the pointer from `*const MaybeUninit<u8>` to `*const u8` and build a slice covering only the initialised portion.

Chapter 79

Pinning

This segment of the course covers:

- What ”pinning” is
- Why it is necessary
- How Rust implements it
- How it interacts with unsafe and FFI

Outline

This segment should take about 1 hour and 20 minutes. It contains:

Slide	Duration
What pinning is	5 minutes
Definition of Pin	5 minutes
PhantomPinned	5 minutes
Self-Referential Buffer Example	50 minutes
Pin and Drop	15 minutes

”Pinning, or holding a value's memory address in a fixed location,is one of the more challenging concepts in Rust.”

”Normally only seen within async code, i.e. `poll(self: Pin<&mut Self>)`, pinning has wider applicability.”

Some data structures that are difficult or impossible to write without the unsafe keyword, including self-referential structs and intrusive data structures.

FFI with C++ is a prominent use case that's related to this. Rust must assume that any C++ with a reference might be a self-referential data structure.

”To understand this conflict in more detail, we'll first need to make sure that we have a strong understanding of Rust's move semantics.”

79.1 What pinning is

- A pinned type cannot change its memory address (move)
- The pointed-to value cannot be moved by safe code

`Pin<Ptr>` makes use of the ownership system to control how the pinned value is accessed. Rather than changing the language, Rust's ownership system is used to enforce pinning. `Pin` owns its contents and nothing in its safe API triggers a move.

This is explained in

This slide should take about 5 minutes.

Conceptually, pinning prevents the default movement behavior.

This appears to be a change in the language itself.

However, the `Pin` wrapper doesn't actually change anything fundamental about the language.

`Pin` doesn't expose safe APIs that would allow a move. Thus, it can prevent bitwise copy.

Unsafe APIs allow library authors to wrap types that do not implement `Unpin`, but they must uphold the same guarantees.

The documentation of `Pin` uses the term "pointer types".

The term "pointer type" is much more broad than the pointer primitive type in the language.

A "pointer type" wraps every type that implements `Deref` with a target that implements `Unpin`.

Rust style note: This trait bound is enforced through trait bounds on the `::new()` constructor, rather than on the type itself.

79.2 What a move is in Rust

Always a bitwise copy, even for types that do not implement `Copy`:

```rust
#[derive(Debug, Default)]
pub struct DynamicBuffer {
    data: Vec<u8>,
    position: usize,
};

pub fn move_and_inspect(x: DynamicBuffer) { println!("{x:?}"); }

pub fn main() {
   let a = DynamicBuffer::default();
   let mut b = a;
   b.data.push(b'R');
   b.data.push(b'U');
   b.data.push(b'S');
   b.data.push(b'T');
   move_and_inspect(b);
}
```

Generated LLVM IR for calling `move_and_expect()`:

```
call void @llvm.memcpy.p0.p0.i64(ptr align 8 %_12, ptr align 8 %b, i64 32, i1 false)
invoke void @move_and_inspect(ptr align 8 %_12)
```

- memcpy from variable %b to %_12
- Call to move_and_inspect with %_12 (the copy)

Note that DynamicBuffer does not implement Copy.

Implication: a value's memory address is not stable.

To show movement as a bitwise copy, either open the code in the playground and look at the or the Compiler Explorer.

Optional for those who prefer assembly output:

The Compiler Explorer is useful for discussing the generated assembly and focus the cursor assembly output in the main function on lines 128-136 (should be highlighted in pink).

Relevant code generated output move_and_inspect:

```
mov     rax, qword ptr [rsp + 16]
mov     qword ptr [rsp + 48], rax
mov     rax, qword ptr [rsp + 24]
mov     qword ptr [rsp + 56], rax
movups  xmm0, xmmword ptr [rsp]
movaps  xmmword ptr [rsp + 32], xmm0
lea     rdi, [rsp + 32]
call    qword ptr [rip + move_and_inspect@GOTPCREL]
```

79.3 Definition of Pin

```
#[repr(transparent)]
pub struct Pin<Ptr> {
    pointer: Ptr,
}

impl<Ptr: Deref<Target: Unpin>> Pin<Ptr> {
    pub fn new(pointer: Ptr) -> Pin<Ptr> { ... }
}

impl<Ptr: Deref> Pin<Ptr> {
    pub unsafe fn new_unchecked(pointer: Ptr) -> Pin<Ptr> { ... }
}
```

This slide should take about 5 minutes.

Pin is a minimal wrapper around a *pointer type*, which is defined as a type that implements Deref.

However, Pin::new() only accepts types that dereference into a target that implements Unpin (Deref<Target: Unpin>). This allows Pin to rely on the type system to enforce its guarantees.

Types that do not implement Unpin, i.e., types that require pinning, must create a Pin via the unsafe Pin::new_unchecked().

Aside: Unlike other `new()`/`new_unchecked()` method pairs, `new` does not do any runtime checking. The check is a zero-cost compile-time check.

79.4 Why Pin is difficult to use

- `Pin<Ptr>` is "just" a type defined in the standard library
- This satisfied the needs of its original audience, the creators of async runtimes, without needing to extending the core language
- That audience could accept some of its ergonomic downsides, as users of `async` would rarely interact with `Pin` directly

"You might wonder why Pin is so awkward to use. The answer is largely historical."

"`Pin<Ptr>` offered a simpler implementation for the Rust project than alternatives".

"Pin was designed primarily for the ~100 people in the world who write async runtimes. The Rust team chose a simpler (for the compiler) but less ergonomic design."

"More user-friendly proposals existed but were rejected as too complex for the primary audience, who could handle the complexity."

79.5 Unpin trait

- `Unpin` type allows types to move freely, even when they're wrapped by a `Pin`
- Most types implement `Unpin`, because it is an "`auto trait`"
- `auto trait` behavior can be changed:
  - `!Unpin` types must never move
  - Types containing a `PhantomPinned` field do not implement `Unpin` by default

Explain that when a trait implements `Unpin`, the pinning behavior of `Pin<Ptr>` does not get invoked. The value is free to move.

Explain that almost all types implement `Unpin`; automatically implemented by the compiler.

Types implementing `Unpin` are saying: 'I promise I have no self-references, so moving me is always safe.'

Ask: What types might be `!Unpin`?

- Compiler-generated futures
- Types containing a `PhantomPinned` field
- Some types wrapping C++ objects

`!Unpin` types cannot be moved once pinned

79.6 PhantomPinned

Definition

```
pub struct PhantomPinned;

impl !Unpin for PhantomPinned {}
```

Usage

```rust
pub struct DynamicBuffer {
    data: Vec<u8>,
    cursor: std::ptr::NonNull<u8>,
    _pin: std::marker::PhantomPinned,
}
```

This slide should take about 5 minutes.

`PhantomPinned` is a marker type.

If a type contains a `PhantomPinned`, it will not implement `Unpin` by default.

This has the effect of enforcing pinning when `DynamicBuffer` is wrapped by `Pin`.

79.7 Self-Referential Buffer Example

A ”self-referential buffer” is a type that has a reference to one of its own fields:

```rust
pub struct SelfReferentialBuffer {
    data: [u8; 1024],
    cursor: *mut u8,
}
```

This kind of structure is not typical in Rust, because there's no way to update the cursor's address when instances of `SelfReferentialBuffer` move.

However, this kind of setup is more natural in other languages that provide garbage collection, and also C++ that allows users to define their own behavior during moves and copies.

Outline

This segment should take about 1 hour and 20 minutes. It contains:

Slide	Duration
What pinning is	5 minutes
Definition of Pin	5 minutes
PhantomPinned	5 minutes
Self-Referential Buffer Example	50 minutes
Pin and Drop	15 minutes

79.7.1 Modelled in C++

```cpp
#include <cstddef>
#include <cstring>

class SelfReferentialBuffer {
    std::byte data[1024];
    std::byte* cursor = data;

public:
```

```
    SelfReferentialBuffer(SelfReferentialBuffer&& other)
        : cursor{data + (other.cursor - other.data)}
    {
        std::memcpy(data, other.data, 1024);
    }
};
```

Investigate on Compiler Explorer

The `SelfReferentialBuffer` contains two members, `data` is a kilobyte of memory and `cursor` is a pointer into the former.

Its move constructor ensures that cursor is updated to the new memory address.

This type can't be expressed easily in Rust.

79.7.2 Modeled in Rust

```rust
/// Raw pointers
pub struct SelfReferentialBuffer {
    data: [u8; 1024],
    cursor: *mut u8,
}

/// Integer offsets
pub struct SelfReferentialBuffer {
    data: [u8; 1024],
    cursor: usize,
}

/// Pinning
pub struct SelfReferentialBuffer {
    data: [u8; 1024],
    cursor: *mut u8,
    _pin: std::marker::PhantomPinned,
}
```

Original C++ class definition for reference

```cpp
class SelfReferentialBuffer {
    char data[1024];
    char* cursor;
};
```

The next few slides show three approaches to creating a Rust type with the same semantics as the original C++.

- Using raw pointers: matches C++ very closely, but using the resulting type is extremely hazardous
- Storing integer offsets: more natural in Rust, but references need to be created manually
- Pinning: allows raw pointers with fewer `unsafe` blocks

79.7.2.1 With a raw pointer

```rust
#[derive(Debug)]
pub struct SelfReferentialBuffer {
    data: [u8; 1024],
    cursor: *mut u8,
}

impl SelfReferentialBuffer {
    pub fn new() -> Self {
        let mut buffer =
            SelfReferentialBuffer { data: [0; 1024], cursor: std::ptr::null_mut() };

        buffer.update_cursor();
        buffer
    }

    // Danger: must be called after every move
    pub fn update_cursor(&mut self) {
        self.cursor = self.data.as_mut_ptr();
    }

    pub fn read(&self, n_bytes: usize) -> &[u8] {
        unsafe {
            let start = self.data.as_ptr();
            let end = start.add(1024);
            let cursor = self.cursor as *const u8;

            assert!((start..=end).contains(&cursor), "cursor is out of bounds");

            let available = end.offset_from(cursor) as usize;
            let len = n_bytes.min(available);
            std::slice::from_raw_parts(cursor, len)
        }
    }

    pub fn write(&mut self, bytes: &[u8]) {
        unsafe {
            let start = self.data.as_mut_ptr();
            let end = start.add(1024);

            assert!((start..=end).contains(&self.cursor), "cursor is out of bounds");
            let available = end.offset_from(self.cursor) as usize;
            let len = bytes.len().min(available);

            std::ptr::copy_nonoverlapping(bytes.as_ptr(), self.cursor, len);
            self.cursor = self.cursor.add(len);
        }
    }
}
```

Avoid spending too much time here.

Talking points:

- Emphasize that `unsafe` appears frequently. This is a hint that another design may be more appropriate.
- `unsafe` blocks lack safety comments. Therefore, this code is unsound.
- `unsafe` blocks are too broad. Good practice uses smaller `unsafe` blocks with specific behavior, specific preconditions and specific safety comments.

Questions:

Q: Should the `read()` and `write()` methods be marked as unsafe?
A: Yes, because `self.cursor` will be a null pointer unless written to.

79.7.2.2 With Offset

```rust
#[derive(Debug)]
pub struct SelfReferentialBuffer {
    data: [u8; 1024],
    position: usize,
}

impl SelfReferentialBuffer {
    pub fn new() -> Self {
        SelfReferentialBuffer { data: [0; 1024], position: 0 }
    }

    pub fn read(&self, n_bytes: usize) -> &[u8] {
        let available = self.data.len().saturating_sub(self.position);
        let len = n_bytes.min(available);
        &self.data[self.position..self.position + len]
    }

    pub fn write(&mut self, bytes: &[u8]) {
        let available = self.data.len().saturating_sub(self.position);
        let len = bytes.len().min(available);
        self.data[self.position..self.position + len].copy_from_slice(&bytes[..len]);
        self.position += len;
    }
}
```

In Rust, it's more idiomatic to use an offset variable and to create references on-demand.

79.7.2.3 With `Pin<Ptr>`

Pinning allows Rust programmers to create a type which is much more similar to C++ classes.

```rust
use std::marker::PhantomPinned;
use std::pin::Pin;

/// A self-referential buffer that cannot be moved.
#[derive(Debug)]
pub struct SelfReferentialBuffer {
    data: [u8; 1024],
```

```rust
    cursor: *mut u8,
    _pin: PhantomPinned,
}

impl SelfReferentialBuffer {
    pub fn new() -> Pin<Box<Self>> {
        let buffer = SelfReferentialBuffer {
            data: [0; 1024],
            cursor: std::ptr::null_mut(),
            _pin: PhantomPinned,
        };
        let mut pinned = Box::pin(buffer);

        unsafe {
            let mut_ref = Pin::get_unchecked_mut(pinned.as_mut());
            mut_ref.cursor = mut_ref.data.as_mut_ptr();
        }

        pinned
    }

    pub fn read(&self, n_bytes: usize) -> &[u8] {
        unsafe {
            let start = self.data.as_ptr();
            let end = start.add(self.data.len());
            let cursor = self.cursor as *const u8;

            assert!((start..=end).contains(&cursor), "cursor is out of bounds");

            let offset = cursor.offset_from(start) as usize;
            let available = self.data.len().saturating_sub(offset);
            let len = n_bytes.min(available);

            &self.data[offset..offset + len]
        }
    }

    pub fn write(mut self: Pin<&mut Self>, bytes: &[u8]) {
        let this = unsafe { self.as_mut().get_unchecked_mut() };
        unsafe {
            let start = this.data.as_mut_ptr();
            let end = start.add(1024);

            assert!((start..=end).contains(&this.cursor), "cursor is out of bounds");
            let available = end.offset_from(this.cursor) as usize;
            let len = bytes.len().min(available);

            std::ptr::copy_nonoverlapping(bytes.as_ptr(), this.cursor, len);
            this.cursor = this.cursor.add(len);
        }
    }
```

```
}
```

Note that the function signatures have now changed. For example, `::new()` returns `Pin<Box<Self>>` rather than `Self`. This incurs a heap allocation because `Pin<Ptr>` must work with a pointer type like `Box`.

In `::new()`, we use `Pin::get_unchecked_mut()` to get a mutable reference to the buffer *after* it has been pinned. This is `unsafe` because we are breaking the pinning guarantee for a moment to initialize the `cursor`. We must make sure not to move the `SelfReferentialBuffer` after this point. The safety contract of `Pin` is that once a value is pinned, its memory location is fixed until it is dropped.

79.8 Pin<Ptr> and Drop

A key challenge with pinned, `!Unpin` types is implementing the `Drop` trait. The `drop` method takes `&mut self`, which allows moving the value. However, pinned values must not be moved.

An Incorrect Drop Implementation

It's easy to accidentally move a value inside `drop`. Operations like assignment, `ptr::read`, and `mem::replace` can silently break the pinning guarantee.

```rust
struct SelfRef {
    data: String,
    ptr: *const String,
}

impl Drop for SelfRef {
    fn drop(&mut self) {
        // BAD: `ptr::read` moves `self.data` out of `self`.
        // When `_dupe` is dropped at the end of the function, it's a double free!
        let _dupe = unsafe { std::ptr::read(&self.data) };
    }
}
```

This slide and its sub-slides should take about 15 minutes. '!Unpin' types can make it difficult to safely implement 'Drop'. Implementations must not move pinned values.

Pinned types make guarantees about memory stability. Operations like `ptr::read` and `mem::replace` can silently break these guarantees by moving or duplicating data, invalidating internal pointers without the type system's knowledge.

In this `drop()` method, _dupe is a bitwise copy of `self.data`. At the end of the method, it will be dropped along with `self`. This double drop is undefined behavior.

A Correct Drop Implementation

To implement `Drop` correctly for a `!Unpin` type, you must ensure that the value is not moved. A common pattern is to create a helper function that operates on `Pin<&mut T>`.

```rust
use std::marker::PhantomPinned;
use std::pin::Pin;
```

```rust
struct SelfRef {
    data: String,
    ptr: *const String,
    _pin: PhantomPinned,
}

impl SelfRef {
    fn new(data: impl Into<String>) -> Pin<Box<SelfRef>> {
        let mut this = Box::pin(SelfRef {
            data: data.into(),
            ptr: std::ptr::null(),
            _pin: PhantomPinned,
        });
        let ptr: *const String = &this.data;
        // SAFETY: `this` is pinned before we create the self-reference.
        unsafe {
            Pin::as_mut(&mut this).get_unchecked_mut().ptr = ptr;
        }
        this
    }

    // This function can only be called on a pinned `SelfRef`.
    unsafe fn drop_pinned(self: Pin<&mut SelfRef>) {
        // `self` is pinned, so we must not move out of it.
        println!("dropping {}", self.data);
    }
}

impl Drop for SelfRef {
    fn drop(&mut self) {
        // We can safely call `drop_pinned` because `drop` is the last time
        // the value is used. We use `new_unchecked` because we know `self`
        // will not be moved again.
        unsafe {
            SelfRef::drop_pinned(Pin::new_unchecked(self));
        }
    }
}

fn main() {
    let _pinned = SelfRef::new("Hello, ");
} // `Drop` runs without moving the pinned value
```

79.8.1 Worked Example: Implementing `Drop` for `!Unpin` types

```rust
use std::cell::RefCell;
use std::marker::PhantomPinned;
use std::mem;
use std::pin::Pin;
```

```rust
thread_local! {
    static BATCH_FOR_PROCESSING: RefCell<Vec<String>> = RefCell::new(Vec::new());
}

#[derive(Debug)]
struct CustomString(String);

#[derive(Debug)]
struct SelfRef {
    data: CustomString,
    ptr: *const CustomString,
    _pin: PhantomPinned,
}

impl SelfRef {
    fn new(data: &str) -> Pin<Box<SelfRef>> {
        let mut boxed = Box::pin(SelfRef {
            data: CustomString(data.to_owned()),
            ptr: std::ptr::null(),
            _pin: PhantomPinned,
        });

        let ptr: *const CustomString = &boxed.data;
        unsafe {
            Pin::get_unchecked_mut(Pin::as_mut(&mut boxed)).ptr = ptr;
        }
        boxed
    }
}

impl Drop for SelfRef {
    fn drop(&mut self) {
        // SAFETY: Safe because we are reading bytes from a String
        let payload = unsafe { std::ptr::read(&self.data) };
        BATCH_FOR_PROCESSING.with(|log| log.borrow_mut().push(payload.0));
    }
}

fn main() {
    let pinned = SelfRef::new("Rust 🦀");
    drop(pinned);

    BATCH_FOR_PROCESSING.with(|batch| {
        println!("Batch: {:?}", batch.borrow());
    });
}
```

This example uses the Drop trait to add data for some post-processing, such as telemetry or logging.

The Safety comment is incorrect. `ptr::read` creates a bitwise copy, leaving `self.data` in an invalid state. `self.data` will be dropped again at the end of the method, which is a double free.

Ask the class to fix the code.

Suggestion 0: Redesign

Redesign the post-processing system to work without `Drop`.

Suggestion 1: Clone

Using `.clone()` is an obvious first choice, but it allocates memory.

```
impl Drop for SelfRef {
    fn drop(&mut self) {
        let payload = self.data.0.clone();
        BATCH_FOR_PROCESSING.with(|log| log.borrow_mut().push(payload));
    }
}
```

Suggestion 2: ManuallyDrop

Wrapping `CustomString` in `ManuallyDrop` prevents the (second) automatic drop at the end of the `Drop` impl.

```
struct SelfRef {
    data: ManuallyDrop<CustomString>,
    ptr: *const CustomString,
    _pin: PhantomPinned,
}

// ...

impl Drop for SelfRef {
    fn drop(&mut self) {
        // SAFETY: self.data
        let payload = unsafe { ManuallyDrop::take(&mut self.data) };
        BATCH_FOR_PROCESSING.with(|log| log.borrow_mut().push(payload.0));
    }
}
```

Chapter 80

FFI

80.1 Language Interop

Ideal scenario:

```
╭────────────╮                                       ╭────────────╮
│            │                                       │            │
│            │  <----------------------------------> │            │
│            │                                       │            │
╰────────────╯                                       ╰────────────╯
     Rust                                                 "C++"
```

This section of the course covers interacting with Rust and external languages via its foreign-function interface (FFI), with a special focus on interoperability with C++.

Ideally, users of Rust and the external language (in this case C++) could call each others' methods directly.

This ideal scenario is very difficult to achieve:

Different languages have different semantics and mapping between them implies trade-offs Neither Rust nor C++ offer ABI stability[1], making it difficult to build from a stable foundation

80.2 Strategies of interop

Sharing data structures and symbols directly is very difficult:

```
╭────────────╮                                       ╭────────────╮
│            │                                       │            │
│            │  <----------------------------------> │            │
│            │                                       │            │
╰────────────╯                                       ╰────────────╯
     Rust                                                 "C++"
```

FFI through the C ABI is much more feasible:

[1] Some C++ compiler vendors provide support for ABI stability within their toolchain.

```
 ┌──────────────┐         ┌────┐           ┌────┐          ┌──────────────┐
 │              │         │    │           │    │          │              │
 │              │ <-----> │    │ <~~~~~~~> │    │ <------> │              │
 │              │         │    │           │    │          │              │
 └──────────────┘         └────┘           └────┘          └──────────────┘
       Rust                 C                C                  "C++"
```

Other strategies:

- Distributed system (RPC)
- Custom ABI (i.e. WebAssembly Interface Types)

This slide should take about 5 minutes.

High-fidelity interop

The ideal scenario is currently experimental.

Two projects exploring this are crubit and Zngur. The first provides glue code on each side for enabling compatible types to work seamlessly across domains. The second relies on dynamic dispatch and imports C++ objects into Rust as trait objects.

Low-fidelity interop work through a C API

The typical strategy for interop is to use the C language as the interface. C is a lossy codec. This strategy typically results in complicated code on both sides.

Other strategies are less viable in a zero cost environment.

Distributed systems impose runtime costs.

They incur significant overhead as calling a method in a foreign library incurs a round trip of serialization/transport/deserialization. Generally speaking, a transparent RPC is not a good idea. There's network in the middle.

Custom ABI, such as wasm require a runtime or significant implementation cost.

80.3 Consideration: Type Safety

80.4 Language differences

```
 ┌──────────────┐         ┌────┐           ┌────┐          ┌──────────────┐
 │              │         │    │           │    │          │              │
 │              │ <-----> │    │ <~~~~~~~> │    │ <------> │              │
 │              │         │    │           │    │          │              │
 └──────────────┘         └────┘           └────┘          └──────────────┘
       Rust                 C                C                  "C++"
```

This slide and its sub-slides should take about 29 minutes.

Using C as the lowest common denominator means that lots of the richness available to Rust and C++ is lost.

Each translation has the potential for semantic loss, runtime overhead, and subtle bugs.

80.4.1 Different representations

```
fn main() {
    let c_repr = b"Hello, C\0";
    let cc_repr = (b"Hello, C++\0", 10u32);
    let rust_repr = (b"Hello, Rust", 11);
}
```

Each language has its own opinion about how to implement things, which can lead to confusion and bugs. Consider three ways to represent text.

Show how to convert the raw representations to a Rust string slice:

```
// C representation to Rust
unsafe {
    let ptr = c_repr.as_ptr() as *const i8;
    let c: &str = std::ffi::CStr::from_ptr(ptr).to_str().unwrap();
    println!("{c}");
};

// C++ representation to Rust
unsafe {
    let ptr = cc_repr.0.as_ptr();
    let bytes = std::slice::from_raw_parts(ptr, cc_repr.1);
    let cc: &str = std::str::from_utf8_unchecked(bytes);
    println!("{cc}");
};

// Rust representation (bytes) to string slice
unsafe {
    let ptr = rust_repr.0.as_ptr();
    let bytes = std::slice::from_raw_parts(ptr, rust_repr.1);
    let rust: &str = std::str::from_utf8_unchecked(bytes);
    println!("{rust}");
};
```

Aside: Rust has a c-prefixed string literal. It appends a null byte at the end, e.g. `c"Rust" == b"Rust\0"`.

80.4.2 Different semantics

```
use std::ffi::{CStr, c_char};
use std::time::{SystemTime, SystemTimeError, UNIX_EPOCH};

unsafe extern "C" {
    /// Create a formatted time based on timestamp `t`.
    fn ctime(t: *const libc::time_t) -> *const c_char;
}

fn now_formatted() -> Result<String, SystemTimeError> {
    let now = SystemTime::now().duration_since(UNIX_EPOCH)?;
    let seconds = now.as_secs() as i64;
```

```rust
    // SAFETY: `seconds` is generated by the system clock and will not cause
    // overflow
    let ptr = unsafe { ctime(&seconds) };

    // SAFETY: ctime returns a pointer to a preallocated (non-null) buffer
    let ptr = unsafe { CStr::from_ptr(ptr) };

    // SAFETY: ctime uses valid UTF-8
    let fmt = ptr.to_str().unwrap();

    Ok(fmt.trim_end().to_string())
}

fn main() {
    let t = now_formatted();
    println!("{t:?}");
}
```

Some constructs that other languages allow cannot be expressed in the Rust language.

The `ctime` function modifies an internal buffer shared between calls. This cannot be represented as Rust's lifetimes.

- `'static` does not apply, as the semantics are different
- `'a` does not apply, as the buffer outlives each call

80.4.3 Rust ↔️ C

Concern	Rust	C
Errors	`Result<T, E>`, `Option<T>`	Magic return values, out-parameters, global `errno`
Strings	`&str`/`String` (UTF-8, length-known)	Null-terminated `char*`, encoding undefined
Nullability	Explicit via `Option<T>`	Any pointer may be null
Ownership	Affine types, lifetimes	Conventions
Callbacks	`Fn`/`FnMut`/`FnOnce` closures	Function pointer + `void* userdata`
Panics	Stack unwinding (or abort)	Abort

Errors: Must convert `Result` to abide by C conventions; easy to forget to check errors on C side.

Strings: Conversion cost; null bytes in Rust strings cause truncation; UTF-8 validation on ingress.

Nullability: Every pointer from C must be checked to create an `Option<NonNull<T>>`, implying unsafe blocks or runtime cost.

Ownership: Must document and enforce object lifetimes manually.

Callbacks: Must decompose closures into fn pointer + context; lifetime of context is manual.

Panics: Panic across FFI boundary is undefined behavior; must catch at boundary with `catch_unwind`.

80.4.4 C++ ↔️ C

Concern	C	C++
Overloading	Manual/ad-hoc	Automatic
Exceptions	-	Stack unwinding
Destructors	Manual cleanup	Automatic via destructors (RAII)
Non-POD types	-	Objects with constructors, vtables, virtual bases
Templates	-	Compile-time code generation

C++ includes a number of features that don't exist in C with an FFI impact:

Overloading: Overloads become impossible to express because of name mangling

Exceptions: Must catch exceptions at the FFI boundary and convert them to error codes, as escaping exceptions in `extern "C"` functions constitute undefined behavior

Destructors: C callers won't run destructors; must expose explicit `*_destroy()` functions

Non-POD types: Must use opaque pointers across the FFI boundary as pass by value does not make sense

Templates: Cannot expose directly; must instantiate explicitly and wrap each specialization

80.4.5 Rust ↔️ C++

Concern	Rust	C++
Trivial relocatability	All moves are `memcpy`	Self-referential types, move constructors can have side effects
Destruction safety	`Drop::drop()` on original location only	Destructor may run on moved-from objects
Exception safety	Panics (abort or unwind)	Exceptions (unwind)
ABI stability	Explicitly unstable	Vendor-specific

Even if it were possible to avoid interop via C, there are still some areas of the languages that impact FFI:

Trivial relocatability

Cannot safely move C++ objects on the Rust side; must pin or keep in C++ heap.

In Rust, object movement, which occurs during assignment or by being passed by value, always copies values bit by bit.

C++ allows users to define their own semantics by allowing them to overload the assignment operator and create move and copy constructors.

This impacts interop because self-referential types become natural in high-performance C++. Custom constructors can uphold safety invariants even when the object moves its position in memory.

Objects with the same semantics are impossible to define in Rust.

Destruction safety

Moved-from C++ object semantics don't map; must prevent Rust from ”moving” C++ types.

Exception safety

Neither can cross into the other safely; both must catch at the boundary.

80.5 Wrapping abs(3)

```rust
fn abs(x: i32) -> i32;

fn main() {
    let x = -42;
    let abs_x = abs(x);
    println!("{x}, {abs_x}");
}
```

This slide should take about 15 minutes.

In this slide, we're establishing a pattern for writing wrappers.

Find the external definition of a function's signature Write a matching function in Rust within an `extern` block Confirm which safety invariants need to be upheld Decide whether it's possible to mark the function as safe

Note that this doesn't work *yet*.

Add the extern block:

```rust
unsafe extern "C" {
    fn abs(x: i32) -> i32;
}
```

Explain that many POSIX functions are available in Rust because Cargo links against the C standard library (libc) by default, which brings its symbols into the program's scope.

Show `man 3 abs` in the terminal or a webpage.

Explain that our function signature must match its definition: `int abs(int j);`.

Update the code block to use the C types.

```rust
use std::ffi::c_int;

unsafe extern "C" {
    fn abs(x: c_int) -> c_int;
}
```

Discuss rationale: using `ffi::c_int` increases the portability of our code. When the standard library is compiled for the target platform, the platform can determine the widths. According to the C standard, a `c_int` may be defined as an `i16` rather than the much more common `i32`.

(Optional) Show the documentation for c_int to reveal that it is a type alias for `i32`.

Attempt to compile to trigger "error: extern blocks must be unsafe" error message.

Add the unsafe keyword to the block:

```rust
use std::ffi::c_int;

unsafe extern "C" {
    fn abs(x: c_int) -> c_int;
}
```

Check that learners understand the significance of this change. We are required to uphold type safety and other safety preconditions.

Recompile.

Add safe keyword to the abs function:

```rust
use std::ffi::c_int;

unsafe extern "C" {
    safe fn abs(x: c_int) -> c_int;
}
```

Explain that the `safe fn` marks `abs` as safe to call without an `unsafe` block.

Completed program for reference:

```rust
use std::ffi::c_int;

unsafe extern "C" {
    safe fn abs(x: c_int) -> c_int;
}

fn main() {
    let x = -42;
    let abs_x = abs(x);
    println!("{x}, {abs_x}");
}
```

80.6 Wrapping `srand(3)` and `rand(3)`

```rust
use libc::{rand, srand};

// unsafe extern "C" {
//     /// Seed the rng
//     fn srand(seed: std::ffi::c_uint);

//     fn rand() -> std::ffi::c_int;
// }

fn main() {
    unsafe { srand(12345) };

    let a = unsafe { rand() as i32 };
    println!("{a:?}");
}
```

This slide should take about 15 minutes.

This slide attempts to demonstrate that it is very easy for wrappers to trigger undefined behavior if they are written incorrectly. We'll see how easy it is to trigger type safety problems.

Explain that `rand` and `srand` functions are provided by the C standard library (libc).

Explain that the functions are exported by the libc crate, but we can also write an FFI wrapper for them manually.

Show calling the functions from the exported.

Code compiles because libc is linked to Rust programs by default.

Explain that Rust will trust you if you use the wrong type(s).

Modify `fn rand() -> std::ffi::c_int;` to return `char`.

Avoiding type safety issues is a reason for using tools for generating wrappers, rather than doing it by hand.

80.7 C Library Example

```c
#ifndef TEXT_ANALYSIS_H
#define TEXT_ANALYSIS_H

#include <stddef.h>
#include <stdbool.h>

typedef struct TextAnalyst TextAnalyst;

typedef struct {
    const char* start;
    size_t length;
    size_t index;
} Token;

typedef enum {
    TA_OK = 0,
    TA_ERR_NULL_POINTER,
    TA_ERR_OUT_OF_MEMORY,
    TA_ERR_OTHER,
} TAError;

/* Return `false` to indicate that no token was found. */
typedef bool (*Tokenizer)(Token* token, void* extra_context);


typedef bool (*TokenCallback)(void* user_context, Token* token, void* result);

/* TextAnalyst constructor */
TextAnalyst* ta_new(void);

/* TextAnalyst destructor */
void ta_free(TextAnalyst* ta);
```

```c
/* Resets state to clear the current document */
void ta_reset(TextAnalyst* ta);

/* Use custom tokenizer (defaults to whitespace) */
void ta_set_tokenizer(TextAnalyst* ta, Tokenizer* func);

TAError ta_set_text(TextAnalyst* ta, const char* text, size_t len, bool make_copy);

/* Apply `callback` to each token */
size_t ta_foreach_token(const TextAnalyst* ta, const TokenCallback* callback, void* use

/* Get human-readable error message */
const char* ta_error_string(TAError error);

#endif /* TEXT_ANALYSIS_H */
```

C libraries will hide their implementation details with a `void*` argument.

Consider this header file of a natural language processing library that hides the `TextAnalyst` and `Analysis` types.

This can be emulated in Rust with a type similar to this:

```rust
#[repr(C)]
pub struct TextAnalyst {
    _private: [u8; 0],
}
```

Exercise: Ask learners to wrap this library.

Suggested Solution

```rust
// ffi.rs
use std::ffi::c_char;
use std::os::raw::c_void;

#[repr(C)]
pub struct TextAnalyst {
    _private: [u8; 0],
}

#[repr(C)]
#[derive(Debug, Clone, Copy)]
pub struct Token {
    pub start: *const c_char,
    pub length: usize,
    pub index: usize,
}

#[repr(C)]
#[derive(Debug, Clone, Copy, PartialEq, Eq)]
pub enum TAError {
    Ok = 0,
```

```
    NullPointer = 1,
    OutOfMemory = 2,
    Other = 3,
}

pub type Tokenizer = Option<
    unsafe extern "C" fn(token: *mut Token, extra_context: *mut c_void) -> bool,
>;

pub type TokenCallback = Option<
    unsafe extern "C" fn(
        user_context: *mut c_void,
        token: *mut Token,
        result: *mut c_void,
    ) -> bool,
>;

unsafe extern "C" {
    pub fn ta_new() -> *mut TextAnalyst;

    pub fn ta_free(ta: *mut TextAnalyst);

    pub fn ta_reset(ta: *mut TextAnalyst);

    pub fn ta_set_tokenizer(ta: *mut TextAnalyst, func: *const Tokenizer);

    pub fn ta_set_text(
        ta: *mut TextAnalyst,
        text: *const c_char,
        len: usize,
        make_copy: bool,
    ) -> TAError;

    pub fn ta_foreach_token(
        ta: *const TextAnalyst,
        callback: *const TokenCallback,
        user_context: *mut c_void,
    ) -> usize;

    pub fn ta_error_string(error: TAError) -> *const c_char;
}
```

80.8 Example: String interning library

C++ Header: interner.hpp

```
#ifndef INTERNER_HPP
#define INTERNER_HPP

#include <string>
```

```cpp
#include <unordered_set>

class StringInterner {
    std::unordered_set<std::string> strings;

public:
    // Returns a pointer to the interned string (valid for lifetime of interner)
    const char* intern(const char* s) {
        auto [it, _] = strings.emplace(s);
        return it->c_str();
    }

    size_t count() const {
        return strings.size();
    }
};

#endif
```

C header file: interner.h

```c
// interner.h (C API for FFI)
#ifndef INTERNER_H
#define INTERNER_H

#include <stddef.h>

#ifdef __cplusplus
extern "C" {
#endif

typedef struct StringInterner StringInterner;

StringInterner* interner_new(void);
void interner_free(StringInterner* interner);
const char* interner_intern(StringInterner* interner, const char* s);
size_t interner_count(const StringInterner* interner);

#ifdef __cplusplus
}
#endif
```

C++ implementation (interner.cpp)

```cpp
#include "interner.hpp"
#include "interner.h"

extern "C" {

StringInterner* interner_new(void) {
    return new StringInterner();
}
```

```
void interner_free(StringInterner* interner) {
    delete interner;
}

const char* interner_intern(StringInterner* interner, const char* s) {
    return interner->intern(s);
}

size_t interner_count(const StringInterner* interner) {
    return interner->count();
}

}
```

This slide should take about 30 minutes.

This is a larger example. Write a wrapper for the string interner. You will need to guide learners on how to create an opaque pointer, either directly by explaining the code below or asking learners to do further research.

Suggested Solution

```
use std::ffi::{CStr, CString};
use std::marker::PhantomData;
use std::os::raw::c_char;

#[repr(C)]
pub struct StringInternerRaw {
    _opaque: [u8; 0],
    _pin: PhantomData<(*mut u8, std::marker::PhantomPinned)>,
}

unsafe extern "C" {
    fn interner_new() -> *mut StringInternerRaw;

    fn interner_free(interner: *mut StringInternerRaw);

    fn interner_intern(
        interner: *mut StringInternerRaw,
        s: *const c_char,
    ) -> *const c_char;

    fn interner_count(interner: *const StringInternerRaw) -> usize;
}
```

Once the raw wrapper is written, ask learners to create a safe wrapper.

Part XVII

Final Words

Chapter 81

Thanks!

Thank you for taking Comprehensive Rust 🦀! We hope you enjoyed it and that it was useful.

We have enjoyed putting the course together. The course is not perfect, so if you spotted any mistakes or have ideas for improvements, please get in contact with us on GitHub. We would love to hear from you.

- Thank you for reading the speaker notes! We hope they have been useful. If you find pages without notes, please send us a PR and link it to issue #1083. We are also very grateful for fixes and improvements to the existing notes.

Chapter 82

Glossary

The following is a glossary which aims to give a short definition of many Rust terms. For translations, this also serves to connect the term back to the English original.

h1#glossary ~ ul { list-style: none; padding-inline-start: 0; }

h1#glossary ~ ul > li { /* Simplify with "text-indent: 2em hanging" when supported: https://caniuse.com/mdn-css_properties_text-indent_hanging */ padding-left: 2em; text-indent: -2em; }

h1#glossary ~ ul > li:first-line { font-weight: bold; }

- allocate:
  Dynamic memory allocation on the heap.
- array:
  A fixed-size collection of elements of the same type, stored contiguously in memory. See Arrays.
- associated type:
  A type associated with a specific trait. Useful for defining the relationship between types.
- Bare-metal Rust:
  Low-level Rust development, often deployed to a system without an operating system. See Bare-metal Rust.
- block:
  See Blocks and *scope*.
- borrow:
  See Borrowing.
- borrow checker:
  The part of the Rust compiler which checks that all borrows are valid.
- brace:
  `{` and `}`. Also called *curly brace*, they delimit *blocks*.
- channel:
  Used to safely pass messages between threads.
- concurrency:
  The execution of multiple tasks or processes at the same time. See Welcome to Concurrency in Rust.
- constant:

A value that does not change during the execution of a program. See const.

- control flow:
  The order in which the individual statements or instructions are executed in a program. See Control Flow Basics.
- crash:
  An unexpected and unhandled failure or termination of a program. See panic.
- enumeration:
  A data type that holds one of several named constants, possibly with an associated tuple or struct. See enum.
- error:
  An unexpected condition or result that deviates from the expected behavior. See Error Handling.
- error handling:
  The process of managing and responding to errors that occur during program execution.
- function:
  A reusable block of code that performs a specific task. See Functions.
- garbage collector:
  A mechanism that automatically frees up memory occupied by objects that are no longer in use. See Approaches to Memory Management.
- generics:
  A feature that allows writing code with placeholders for types, enabling code reuse with different data types. See Generics.
- immutable:
  Unable to be changed after creation. See Variables.
- integration test:
  A type of test that verifies the interactions between different parts or components of a system. See Other Types of Tests.
- library:
  A collection of precompiled routines or code that can be used by programs. See Modules.
- macro:
  Rust macros can be recognized by a `!` in the name. Macros are used when normal functions are not enough. A typical example is `format!`, which takes a variable number of arguments, which isn't supported by Rust functions.
- `main` function:
  Rust programs start executing with the `main` function.
- match:
  A control flow construct in Rust that allows for pattern matching on the value of an expression.
- memory leak:
  A situation where a program fails to release memory that is no longer needed, leading to a gradual increase in memory usage. See Approaches to Memory Management.
- method:
  A function associated with an object or a type in Rust. See Methods.
- module:
  A namespace that contains definitions, such as functions, types, or traits, to organize code in Rust. See Modules.
- move:
  The transfer of ownership of a value from one variable to another in Rust. See Move Semantics.
- mutable:
  A property in Rust that allows variables to be modified after they have been declared.

- ownership:
  The concept in Rust that defines which part of the code is responsible for managing the memory associated with a value. See Ownership.
- panic:
  An unrecoverable error condition in Rust that results in the termination of the program. See Panics.
- pattern:
  A combination of values, literals, or structures that can be matched against an expression in Rust. See Pattern Matching.
- payload:
  The data or information carried by a message, event, or data structure.
- receiver:
  The first parameter in a Rust method that represents the instance on which the method is called.
- reference:
  A non-owning pointer to a value that borrows it without transferring ownership. References can be shared (immutable) or exclusive (mutable).
- reference counting:
  A memory management technique in which the number of references to an object is tracked, and the object is deallocated when the count reaches zero. See Rc.
- Rust:
  A systems programming language that focuses on safety, performance, and concurrency. See What is Rust?.
- safe:
  Refers to code that adheres to Rust's ownership and borrowing rules, preventing memory-related errors. See Unsafe Rust.
- slice:
  A dynamically-sized view into a contiguous sequence, such as an array or vector. Unlike arrays, slices have a size determined at runtime. See Slices.
- scope:
  The region of a program where a variable is valid and can be used. See Blocks and Scopes.
- standard library:
  A collection of modules providing essential functionality in Rust. See Standard Library.
- static:
  A keyword in Rust used to define static variables or items with a `'static` lifetime. See static.
- string:
  A data type storing textual data. See Strings.
- struct:
  A composite data type in Rust that groups together variables of different types under a single name. See Structs.
- test:
  A function that tests the correctness of other code. Rust has a built-in test runner. See Testing.
- thread:
  A separate sequence of execution in a program, allowing concurrent execution. See Threads.
- thread safety:
  The property of a program that ensures correct behavior in a multithreaded environment. See Send and Sync.

- trait:
  A collection of methods defined for an unknown type, providing a way to achieve polymorphism in Rust. See Traits.
- trait bound:
  An abstraction where you can require types to implement some traits of your interest. See Trait Bounds.
- tuple:
  A composite data type that contains variables of different types. Tuple fields have no names, and are accessed by their ordinal numbers. See Tuples.
- type:
  A classification that specifies which operations can be performed on values of a particular kind in Rust. See Types and Values.
- type inference:
  The ability of the Rust compiler to deduce the type of a variable or expression. See Type Inference.
- undefined behavior:
  Actions or conditions in Rust that have no specified result, often leading to unpredictable program behavior. See Unsafe Rust.
- union:
  A data type that can hold values of different types but only one at a time. See Unions.
- unit test:
  Rust comes with built-in support for running small unit tests and larger integration tests. See Unit Tests.
- unit type:
  Type that holds no data, written as a tuple with no members. See speaker notes on Functions.
- unsafe:
  The subset of Rust which allows you to trigger *undefined behavior*. See Unsafe Rust.
- variable:
  A memory location storing data. Variables are valid in a *scope*. See Variables.

Chapter 83

Other Rust Resources

The Rust community has created a wealth of high-quality and free resources online.

Official Documentation

The Rust project hosts many resources. These cover Rust in general:

- The Rust Programming Language: the canonical free book about Rust. Covers the language in detail and includes a few projects for people to build.
- Rust By Example: covers the Rust syntax via a series of examples which showcase different constructs. Sometimes includes small exercises where you are asked to expand on the code in the examples.
- Rust Standard Library: full documentation of the standard library for Rust.
- The Rust Reference: an incomplete book which describes the Rust grammar and memory model.
- Rust API Guidelines: recommendations on how to design APIs.

More specialized guides hosted on the official Rust site:

- The Rustonomicon: covers unsafe Rust, including working with raw pointers and interfacing with other languages (FFI).
- Asynchronous Programming in Rust: covers the new asynchronous programming model which was introduced after the Rust Book was written.
- The Embedded Rust Book: an introduction to using Rust on embedded devices without an operating system.

Unofficial Learning Material

A small selection of other guides and tutorial for Rust:

- Learn Rust the Dangerous Way: covers Rust from the perspective of low-level C programmers.
- Rust for Embedded C Programmers: covers Rust from the perspective of developers who write firmware in C.
- Rust for professionals: covers the syntax of Rust using side-by-side comparisons with other languages such as C, C++, Java, JavaScript, and Python.

- Rust on Exercism: 100+ exercises to help you learn Rust.
- Ferrous Teaching Material: a series of small presentations covering both basic and advanced part of the Rust language. Other topics such as WebAssembly, and async/await are also covered.
- Advanced testing for Rust applications: a self-paced workshop that goes beyond Rust's built-in testing framework. It covers `googletest`, snapshot testing, mocking as well as how to write your own custom test harness.
- Beginner's Series to Rust and Take your first steps with Rust: two Rust guides aimed at new developers. The first is a set of 35 videos and the second is a set of 11 modules which covers Rust syntax and basic constructs.
- Learn Rust With Entirely Too Many Linked Lists: in-depth exploration of Rust's memory management rules, through implementing a few different types of list structures.
- The Little Book of Rust Macros: covers many details on Rust macros with practical examples.

Please see the Little Book of Rust Books for even more Rust books.

Chapter 84

Credits

The material here builds on top of the many great sources of Rust documentation. See the page on other resources for a full list of useful resources.

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CXX

The Interoperability with C++ section uses an image from CXX. Please see the `third_party/cxx/` directory for details, including the license terms.