

Rust Essentials

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Introduction

About AdaCore

The Company

- Founded in 1994
- Centered around helping programmers build **safe, secure and reliable** software
- Headquartered in New York and Paris
 - Representatives in countries around the globe
- Roots in Open Source software movement
 - Provides toolchains for Ada/SPARK, C/C++ and Rust
 - Focus on safety-critical and mission-critical systems

About This Training

Your Trainer

- Experience in software development
 - Languages
 - Methodology
- Experience teaching this class

Goals of the Training Session

- **Build Foundational Confidence:** Feel confident about your basic understanding of the language
- **Learn How to Learn:** Gain the skills to find information and solve new problems
- **Embrace the Process:** Understand that this course is one of many steps in your learning journey
- Syllabus overview
 - The syllabus is a guide, but we might stray off of it
 - ...and that's OK: we're here to cover **your needs**

Roundtable

- 5-minute exercise
- Your experience in software development
- Your personal goals for this training
 - What do you want to have coming out of this?
- Anecdotes, stories... feel free to share!
 - Most interesting or funny bug you've encountered?
 - Your own programming interests?

Course Presentation

- Slides
- Labs
 - Hands-on practice
 - Class reflection after some labs
- Recommended Setup
 - GNAT Pro for Rust
 - Visual Studio Code (VS Code)

Styles

- `This` is a definition
- `this/is/a.path`
- code is highlighted
- commands are emphasized --like-this
- This is an error message

⚠ Warning

This is a warning

📘 Note

This is an important piece of info

💡 Tip

This is a tip

This is an output message

This is an error message

Overview

What Is Rust?

What Is Rust?

- New(er) programming language
 - First stable release in 2015 (1.0)
 - Modern design to solve older language problems
- Statically compiled
 - RUSTC uses LLVM as its backend
- Supports many platforms and architectures
 - Linux, Windows, VxWorks...
 - x86, ARM ...

What Kind of Language Is Rust?

Fits in the same area as other systems languages (Ada, C++, ...)

- High flexibility
- High level of control
- Can be scaled down to very constrained devices
 - Such as microcontrollers
- No garbage collection
- Focuses on reliability and safety without sacrificing performance

Things to Consider About Rust

- Very much like other languages in the Ada/C++/Java tradition
 - Similar syntax
 - Statically typed
- Modern with full support for things like Unicode
- Macros provide powerful flexibility and safety
 - Varying numbers of arguments
 - Easy way to automate repetitive code
 - Checked at compile time
- Multi-paradigm
 - Imperative - instructs the compiler *how* to perform a task
 - Functional - describes *what* the result should be
 - Powerful OOP features

Benefits 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 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 other higher-level languages

- Enums and pattern matching
- Generics
- Zero-cost Foreign Function Interface (FFI)
- Zero-cost abstractions
- Helpful compilation errors
- Built-in dependency manager
- Built-in support for testing
- Excellent Language Server Protocol support
- OOP-style power without the class-hierarchy baggage

Rust in the Language Ecosystem

■ vs. Ada

- Similar goals: reliability, performance, low-level control
- Also enforces many safety guarantees at *compile* time
- Borrow checker enforces strict ownership and aliasing rules

■ vs. C/C++

- Memory safety by default
- C-like performance *without* manual memory management
- Modern conveniences missing in C/C++

■ vs. Java

- Memory safety *without* a garbage collector
- No null references
- Predictable performance and direct hardware access

Tooling

GNAT Pro for Rust

- **Stabilized** version of upstream Rust
 - Yearly updates for recent changes
 - Tested and secured
 - Reproducible (stable) build process
 - Vulnerability fixes backported
- AdaCore's Rust Development Toolsuite
 - CARGO - package manager
 - RUSTC - compiler
 - GDB - debugger
 - RUST-ANALYZER - language server/IDE integration tool
 - CLIPPY - linter
 - RUSTFMT - code formatter
 - GPRBUILD - AdaCore's multi-language build tool
- Tooling pairs seamlessly with VS CODE

Note

The Rust Playground (<https://play.rust-lang.org/>) provides an easy way to run short programs, quickly!

Hello World!

Hello World

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```
// Our first program!  
fn main () {  
    println!("Hello World!");  
}
```

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- `{ }` - curly braces enclose a **block**

Hello World

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- `//` - indicates a single-line **comment**
- `fn` - "introduces" a **function**
- `{ }` - curly braces enclose a **block**
- `main` - the entry point of the program

Hello World

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// Our first program!  
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    println!("Hello World!");  
}
```

- `//` - indicates a single-line **comment**
- `fn` - "introduces" a **function**
- `{ }` - curly braces enclose a **block**
- `main` - the entry point of the program
- `println!` - macro for printing a string followed by newline

File Naming Conventions

- File extension is `.rs`
- File name is the module name in *snake case*
 - All lower case, spaces replaced with underscore

Note

`fn` `main()` will be in file `main.rs`

Creating a Program

Creating a Project

- From a command prompt, execute the following

```
cargo new hello_world
```

- Package will be created for the executable program (*binary crate*)
- Directory will also be created (`hello_world/`)
- Noteworthy things automatically created at this step
 - `Cargo.toml` - the *manifest* used by CARGO
 - `src/main.rs` - the program source code
 - Open VS CODE to explore this file

Building Your First Program

- From a command prompt, ensure you are in the project directory (`hello_world/`)

- Execute the following command

```
cargo build
```

- You should see something like

```
Compiling hello v0.1.0 (C:\rust\hello_world)
Finished `dev` profile [unoptimized + debuginfo]
target(s) in 0.52s
```

Running Your First Program

- From a command prompt, ensure you are in the project directory (`hello_world/`)
- Execute the following command

```
cargo run
```

- You should see an output like the following

```
Finished `dev` profile [unoptimized + debuginfo]  
target(s) in 0.01s  
Running `target\debug\hello_world.exe`  
Hello world!
```

Summary

First Program: Done!

- **Congratulations!** You've completed your first program!
- We've touched on a few basic concepts
 - Comments
 - Functions
 - Macros
 - Program output
 - Code blocks
- On to the bigger concepts!

Types and Values

Introduction

Topics Covered

■ Variables

- How to create "boxes" to store data and give them names

■ Common Data Types

- What kind of data we can store

■ Arithmetic

- How to perform basic math operations

■ Type Inference

- How the compiler is smart enough to often guess the type of data

Variables

What Is a Variable?

- Like a **labeled box** that stores a single piece of information ("value")
 - **Label** - variable's name (e.g., score)
 - **Contents** - value (e.g., 100)
- Create a variable with the **let** keyword
 - This **binds** a name to a value

```
// Bind 'apples' to the value 5
```

```
let apples = 5;
```

```
// Bind 'person' to the value 'Alice'
```

```
let person = "Alice";
```

By Default, Variables Are Immutable

- **Immutable** = **unchangeable**
- This is a core concept
 - The **compiler** will generate errors on assignment
 - Safety and reliability principles are built into the language
 - Prevents accidental data assignment (especially in large programs!)
 - **let** creates an **immutable** binding

```
// This is OK!
```

```
let my_var = 10;
```

```
// This will cause an ERROR! We can't change the value
```

```
my_var = 20;
```

```
error[E0384]: cannot assign twice to immutable variable 'my_var'
```

Making Variables Mutable

- Sometimes, a value *needs* to change
- Variables are immutable unless mutability is declared **explicitly**
- **mut** - specifies the variable is **mutable**
 - Add it to the declaration
 - The keyword follows **let**

```
let mut change_me = 5;  
println!("change_me is: {change_me}");  
  
// This is now perfectly allowed!  
change_me = 6;  
println!("change_me is now: {change_me}");
```

```
change_me is: 5  
change_me is now: 6
```

Note

Mutability is an **opt-in** choice

Types

Rust Is Statically Typed

- One of the most important features
- Compiler **must** know the exact **type** of every variable at compile time
- Provides **type safety** (and prevents bugs!)

// We are explicitly stating:

// "this_var is a 32-bit signed integer with the value 10"

```
let this_var: i32 = 10;
```

Assigning Types

Two ways to specify what type a variable is

- Explicit Annotation

```
let explicit_var: i32 = 10;
```

- Type Inference

```
let infer_me = 10;
```

Type Inference Explained

- In most cases, there's no need to write the type
- Compiler **infers** it based on the provided value
 - This is why `let apples = 5` worked in our earlier example!
- **Default Rules**
 - Integers default to `i32`
 - Floating point (decimals) default to `f64`

```
// Compiler sees a whole number and infers 'i32'  
let inferred_int = 10;  
// This is the same as writing:  
// let explicit_int: i32 = 10;
```

```
// Compiler sees a decimal and infers 'f64'  
let inferred_float = 2.5;  
// This is the same as writing:  
// let explicit_float: f64 = 2.5;
```

Inference Is Smart

- Type inference isn't just about defaults
 - ...but also **how** a variable is used
- A variable's type might not be known until later in the function

```
// Compiler sees 10, but waits to decide the type...  
let inferred_var = 10;
```

```
// We declare 'unsigned_var' as an explicit 'u32'  
let unsigned_var: u32;
```

```
// Compiler decides 'inferred_var' MUST be 'u32'  
unsigned_var = inferred_var;
```

Common Types

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

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

Numeric Literal Formats

■ Numeric Readability

- Underscores can be used in numbers for legibility
- These are ignored by the compiler
- `1_000` is the same as `1000` (or `10_00`)

■ Type Suffixes

- Add type *directly* to the numeric literal
- Shorthand for full annotation

// These three bindings are identical:

```
let full: f64 = 10.0;           // Full annotation
```

```
let pretty_suffix = 10_f64;    // Type suffix
```

```
let suffix = 10.0f64;          // Suffix (no underscore)
```

Utilizing Different Bases

- Integers can be expressed in different bases
- They all represent the same value to the computer

Base	Syntax	Example
<i>Decimal</i>	Standard	98_222
<i>Hex</i>	0x	0xff
<i>Octal</i>	0o	0o77
<i>Binary</i>	0b	0b1111_0000
<i>Byte</i>	b (u8 only)	b'A'

Numeric Conversions

Types are not automatically converted

```
let my_int: i32 = 10;  
let my_float: f64 = 5.5;
```

```
// Will not compile!
```

```
let sum = my_int + my_float;
```

```
// 'as' tells the compiler to interpret 'my_int' as 'f64'
```

```
let sum = my_int as f64 + my_float;
```



Tip

- Forces the programmer to be **intentional**
 - Using **as** makes conversion explicit

The "char" Type Is Special

- **char** is **4 bytes** (as opposed to 1 byte in other languages)
- Holds almost *any* character from *any* language (including emojis!)
- Use single quotes for a **char**

```
let letter: char = 'a';  
let accented: char = 'é';
```

The Unit Type ()

- It *is* a type
 - Holds **no** meaningful data
 - Unlike traditional types, such as `i32`
- Represents "completion without a result"
- Written as `()` for both the **type** and **value**
 - When code seems to return *nothing*, it's actually `()`
 - It is the **only** possible value for this type

```
// This variable exists, but holds no data!  
let holds_no_data: () = ();
```



Note

Unlike `void`, `()` is a real value! It exists and can be assigned to variables

Recap: Anatomy of a Variable

*// A ***mutable***, ***explicitly typed*** variable binding*

```
let mut x: i32 = 10;
```

					+---	Value - numeric literal
				+-----	Type	- 32-bit signed integer
			+-----	Variable Name		
		+-----	mut	Keyword	- mutable	
+-----	let	Keyword	- declares a variable			

Key Takeaways:

- **mut** - *optional*, makes it changeable
- **:** **i32** - *optional* because can be inferred

Arithmetic

Standard Operators

Arithmetic operators, in order of precedence (highest to lowest)

<i>Multiplicative</i>	*	/	%
-----------------------	---	---	---

<i>Additive</i>	+	-
-----------------	---	---

```
let sum = 5 + 10;           // 15
let difference = 95.5 - 4.3; // 91.2
let product = 4 * 30;       // 120

// Integer division truncates (rounds down)
let quotient = 7 / 3;       // 2 (not 2.33...)

let remainder = 7 % 3;      // 1
```

The Exponent Trap

- **No** operator for exponent (i.e., power)!
- **Common Mistake:** using `^`
 - `^` is the **Bitwise XOR operator**
 - Code will compile, but math will be wrong!

```
let wrong = 5 ^ 2; // Result is 7 (binary 101 XOR 010)
```

- **Correct Way:** use methods
 - Must use a method specific to data type
 - `.pow(u32)` - integers
 - `.powf(f64)` - floats

```
5_i32.pow(2)           // Result = 25  
5.0_f64.powf(2.5)      // Result ~55.9
```

Note

Integer `pow()` requires a `u32` exponent to prevent negative exponents returning non-integers

Modifying Variables In-Place

- Increment (`++`) and decrement (`--`) operators don't exist
 - *Why?* - they can lead to confusing code, and Rust prefers *clarity*
- **The Alternative:** Compound Assignment
 - Use the standard "shortcut" operators to do math AND update at once!
 - This is the idiomatic way to increment counters

Operator	Expanded Meaning	Example	Result*
<code>+=</code>	<code>x = x + y</code>	<code>x += 1;</code>	11
<code>-=</code>	<code>x = x - y</code>	<code>x -= 5;</code>	5
<code>*=</code>	<code>x = x * y</code>	<code>x *= 2;</code>	20
<code>/=</code>	<code>x = x / y</code>	<code>x /= 2;</code>	5
<code>%=</code>	<code>x = x % y</code>	<code>x %= 3;</code>	1

* Assume `x` starts at 10

Arithmetic Nuance: Division

The `/` operator behaves differently depending on the type

■ Integer Division

- When dividing two **integers**, result is *always* an **integer**
- Decimal is **truncated** (cut off), not rounded

```
let truncated = 7 / 3;           // Result is 2 (not 2.33...)
let also_truncated = 1 / 2;     // Result is 0 (not 0.5)
```

■ Floating Point Division

- **Decimal** result requires **floating point** operands
- **f64**, **f32**

```
let precise = 7.0 / 3.0;       // Result is 2.333...
```

Integer Overflow

- What happens if a number gets too big for its type?

// 'u8' can only hold values from 0 to 255

```
let my_byte: u8 = 250;
```

```
let new_byte = my_byte + 10; // 260? This won't fit!
```

- Integer overflow has defined behavior

- **Debug Builds**

- Overflow is checked
- Program will **panic** (crash)
- An error will describe exactly what happened

- **Release Builds**

- Overflow checks are disabled by default
- Performs **two's complement wrapping**
- **Example:** For `u8`, `255 + 1` "wraps around" to `0`

Handling Overflow Explicitly

There are mechanisms to allow the code to control behavior

- `wrapping_add()`
 - Performs wrapping in all modules
- `saturating_add()`
 - Clamps the value at the type's *maximum* or *minimum*
- `overflowing_add()`
 - Returns the value AND a `bool` indicating if overflow happened

```
127_i8.wrapping_add(1)      // Results in -128
120_i8.saturating_add(20)   // Results in 127 (max 'i8' value)
100_i8.overflowing_add(50)  // Results in (-106, true)
```

- These methods make overflow behavior explicit and predictable
- Choose the method that matches the intended behavior
 - Checked
 - Wrapping
 - Saturating
 - Overflowing arithmetic

Note

Equivalent methods exist for subtraction (`*_sub`) and multiplication (`*_mul`)

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Immutability by Default

- Safety is the default
- Change is an opt-in choice using `mut`
- Prefer **immutable**, choose **mutable** with intention

■ Static Typing and Inference

- Compiler must know every type
- **Inference** can do the work

■ Numeric Conversions

- No "magic" conversions
- Be **intentional**
- Cast types using `as`

■ Arithmetic Safety

- Protects application from undefined behavior
- **Overflow** is detected (panic) or defined (wrap)

Control Flow Basics

Introduction

Topics Covered

■ Blocks

- Tail expression, unit type ()

■ Conditional Expressions

- `if` expressions
- `match` expressions

■ Loops

- `while` statement
- `for` statement
- `loop` expression

■ Loop Control

- `break` and `continue`
- Labels (`for` loops and arbitrary blocks)
- Returning a value with `loop` and `break`

■ Functions

- Parameters and return values
- Functions with no return value

■ Macros

- `println!`, `dbg!`, `todo!`, `unreachable!`

Blocks

Block

- Encloses a sequence of expressions and statements within `{}`
- Each block has a **value** and a **type**
 - Determined by the last expression of the block
- Result is `()` (the unit type) if the last line ends with an instruction

```
let bank = 13;  
let balance = {  
    let withdraw = 10;  
    println!("withdraw: {withdraw}");  
    bank - withdraw  
};  
println!("balance: {balance}");
```

```
withdraw: 10  
balance: 3
```

"if" Expressions

Using "if" as a Statement

- Evaluated top to bottom
- Condition tests if a boolean expression evaluates to `true`
- Blocks are **mandatory**, no shorthand!
- Parentheses around the condition are **optional**
 - Usage is considered unidiomatic
- May have either
 - Zero or more `else if`
 - Zero or one final `else`

```
let coins = 800;
if coins == 0 {
    println!("You have no gold. The dragon eats you.");
} else if coins < 700 {
    println!("A solid pouch! Buy a new sword!");
} else {
    println!("New graphics card acquired.");
}
```

New graphics card acquired.

Using "if" as an Expression

Every block is an expression that returns a value

```
let food = 80;  
let status = if food < 100 {  
    "Starving. Call the vet and the police."  
} else {  
    "Full. Now demanding fresh water."  
}; // Note the ; here to terminate the let statement  
println!("Pet Status: {}", status);
```

```
Pet Status: Starving. Call the vet and the police.
```

Return Type Consistency

- Returned values, from all branches, must have the same type

```
let size = if x < 20 {  
    "small"; // Note the ;  
} else {  
    "large" // Note the absence of ;  
};
```

error[E0308]: 'if' and 'else' have incompatible types

- "small" and "large" are both strings
 - Adding a ; after a value makes the types different

"match" Expressions

Using "match" as a Statement

- Checks a value against one or more options (*arms*)
- Evaluated top to bottom
 - First arm that matches has its corresponding body executed
- No fall-through between arms
 - Like `case` in Ada, but unlike `switch` in C/C++
- If an arm is a single expression, the `{ }` are **optional**

```
let belly_rubs = 2;
match belly_rubs {
  0 => {
    println!("Grumble");
    println!("Must protest");
  } // Comma is optional here, usually omitted
  1 => {
    println!("Tail wag engaged")
  } // Block is valid but unnecessary for one line
  2 => println!("Happiness!"), // Comma is REQUIRED here
  _ => println!("Suspicion"), // Trailing comma is allowed, idiomatic
}
```

Happiness!

The "match" Must Be Exhaustive

- Must cover all possibilities
 - Can have a default case `_`

```
let count = 3;
match count {
  1 => println!("One"),
  2 => println!("Two"),
  _ => println!("Other!"), // Catches all other possibilities
}
```

Other!

- Use `|` to match several values to one arm

```
let belly_rubs = 4;
match belly_rubs {
  1 | 2 => println!("Not enough."), // Matches 1 or 2
  3 | 4 | 5 => println!("Perfect!"), // Matches 3 or 4 or 5
  _ => println!("Suspicion."),
}
```

Perfect!

Using "match" as an Expression

- Entire match expression evaluates to a value
- Every arm must return the exact same type
- Inclusive and exclusive ranges

Range	From	Up To
<i>low..=high</i>	low	high (inclusive)
<i>low..high</i>	low	high (exclusive)
<i>..high</i>	minimum possible value	high (exclusive)
<i>low..</i>	low (inclusive)	maximum possible value

```
let temperature_c = 35;
let current_mood = match temperature_c {
    ..=0 => "Hibernation",
    1..10 => "Need a scarf",
    10..30 => "Perfect",
    30..40 => "Melting!",
    40.. => "This reading is impossible.",
};
println!("Current mood: {}", current_mood);
```

Current mood: Melting!

Loops

"while" Statement

- Condition is checked **before** each iteration
- Parentheses around the condition are **optional**
 - Usage is considered unidiomatic
- Executes the block while the condition is **true**

```
let mut countdown = 2;
while countdown > 0 {
    println!("T-minus {}", countdown);
    countdown = countdown - 1;
}
println!("LIFTOFF!");
```

```
T-minus 2...
T-minus 1...
LIFTOFF!
```

"for" Statement

Iterates over range of values or elements of a collection

```
for index in 1..5 {  
    // 4 iterations  
}
```

```
for index in 1..=5 {  
    // 5 iterations  
}
```

```
for element in [1, 2, 3, 4, 5] {  
    // 5 iterations  
}
```

"loop" Expression

Loops forever, or until a **break**

```
let mut count = 0;
loop {
    count += 1;
    println!("Count: {count}");
    if count > 2 {
        break;
    }
}
```

Count: 1

Count: 2

Count: 3

`"break"` and `"continue"`

"break" and "continue"

- Start immediately the next iteration with **continue**
- Exit any kind of loop early with **break**
- Both work with **while**, **for**, and **loop**

```
let mut count = 0;
loop {
    count += 1;
    if count < 3 { continue; }
    if count > 5 { break; }
    println!("Count: {}", count);
};
```

Count: 3

Count: 4

Count: 5

Returning a Value With "loop" and "break"

- `loop` is also an expression
- Can return a non-trivial value

```
let mut count = 0;  
let result = loop {  
    count += 1;  
    if count > 5 { break count; }  
};  
println!("Result: {}", result);
```

Result: 6

Labels

- **Optionally** attached to loops (`loop`, `while`, `for`)
- Denoted by a single quote (') followed by an identifier
- Both `continue` and `break` can optionally take a label argument
- Primarily used to break out of nested loops
 - Or to continue an outer loop from within an inner one

```
let mut eaten = 0;
'outer: for _box in 1..=5 {
    for _piece in 1..=5 {
        eaten += 1;
        if eaten == 13 {
            break 'outer;
        }
    } // Inner loop ends
} // Outer loop ends
println!("Sugar crash at: {}", eaten);
```

Sugar crash at: 13

Block Labels

Labeled break also works on arbitrary blocks

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

Before

After

Functions

What Is a Function?

- Primary way to organize code into reusable blocks
- Take inputs, process them, and return a result (even if empty)
- Declared using the **fn** keyword
 - Must be immediately followed by the body enclosed in { }
- Typically in **snake_case** (e.g., `calculate_area`)

```
fn function_name(parameter_1:Type) -> ReturnType {  
    // Function body (statements and expressions)  
}
```

Parameters and Type Signatures

- Function parameters must have their types **explicitly** declared
 - No inference, unlike variable bindings
- Function signature defines
 - Types of data the function accepts (parameters)
 - Type of data it produces ($\rightarrow$ ReturnType)

```
// We must specify the types of both 'first' and 'second'  
fn add(first: i32, second: i32)  $\rightarrow$  i32 {  
    first + second  
}
```

Return Values (Expression vs. Statement)

- Return type is specified after an arrow `->`
- No `->` syntax means function returns the unit type `()`
- Functions can return values by ending with either
 - **Statement:** ends with a semicolon `;` ; returns `()`
 - **Expression:** does **not** end in a semicolon
 - Last expression evaluated in the body is returned

```
fn get_forty_two() -> i32 {  
    // The automatically returned expression  
    42  
}
```

```
fn print_and_return_unit() {  
    // A statement (ends with ;), returns ()  
    println!("Hello!");  
}
```

Explicit Exit With "return"

Forces the function to exit immediately

- Bypassing the rest of the code
- Essential for early exits based on control flow

```
fn do_things(condition: bool) {  
    if condition {  
        println!("doing something else!");  
        return; // Exits, returns ()  
    }  
    println!("doing something!");  
}
```

- Returning a value for early exit

```
fn check_age(age: i32) -> bool {  
    if age < 0 {  
        return false; // Exits immediately  
    }  
    age >= 18 // Idiomatic way to return a value  
}
```

Design Philosophy: Clarity and Precision

- Overloading is not supported
 - No multiple same-name functions with different arguments
- No default arguments
 - Callers must provide a value for every parameter
 - All inputs must be explicitly specified
- Fixed number of arguments
 - Take a strict number of inputs
 - *Macros* (like `println!`) can take variable arguments
 - But *functions* cannot

Macros

What Is a Macro?

- Code that **generates** other code at **compile-time**
- Can take a **variable** number of arguments
- Is **not** a function
- Macro calls are required to end with !
 - E.g., `println!`, `dbg!`
- Custom macros are fully supported!

Note

Writing custom macros is an advanced, non-trivial topic

println!

Standard Library

`println!(format, ..)` prints a line to standard output

```
let name = "World";
```

```
let answer = 41;
```

```
println!("Hello!");
```

```
// Positional arguments
```

```
println!("Hello, {}, the answer is {}. ", name, answer + 1);
```

```
// Named argument, improves readability and refactoring
```

```
// Expressions not allowed inside the curly braces
```

```
println!("Hello {name}!");
```

```
Hello!
```

```
Hello, World, the answer is 42.
```

```
Hello World!
```

dbg!

Standard Library

- `dbg!(expression)` logs the value of the expression
- Returns the value itself
- Often used for quick, temporary debugging
 - Prints the file, line number, and the value
 - Can be used inside other expressions
- Works the same in both **debug** and **release** modes

```
fn factorial(n: u32) -> u32 {  
    let mut product = 1;  
    for i in 1..=n {  
        product *= dbg!(i);  
    }  
    product  
}  
  
let result = factorial(3);
```

```
[src/main.rs:5:20] i = 1
```

```
[src/main.rs:5:20] i = 2
```

```
[src/main.rs:5:20] i = 3
```

todo!

Standard Library

- `todo!()` marks a bit of code as not-yet-implemented
- When executed, it immediately causes a **panic**
 - Message indicates the un-implemented code
 - Useful for sketching out function signatures during development
- Works the same in both **debug** and **release** modes

```
fn fizzbuzz(n: u32) -> u32 {  
    todo!("Implement this") // Absence of ; is idiomatic here  
}  
  
fn main() {  
    fizzbuzz(10);  
}
```

```
thread 'main' (11) panicked at src/main.rs:4:5:  
not yet implemented: Implement this
```

unreachable!

Standard Library

- `unreachable!()` marks a bit of code as unreachable
- Marks a point in the code that should never be reached
- When reached, immediately causes a **panic** with a message
- Serves as a sanity check for the programmer
- Works the same in both **debug** and **release** modes

```
let number = 3;
match number {
    // The match is exhaustive for a 'i32', but in this context,
    // we logically know 'number' will only be 1 or 2.
    1 => println!("One"),
    2 => println!("Two"),

    // The underscore _ matches all other possible values.
    // If we assume 'number' is only ever 1 or 2, this arm
    // should logically be unreachable.
    _ => unreachable!("Number is outside the expected range!"),
}
```

```
thread 'main' (41) panicked at src/main.rs:12:14:
internal error: entered unreachable code: Number is outside the expected range!
```

Lab

Dragon Tamer's Trial

Objective: Fix the code to successfully tame the dragon

Goals

- Fix all compiler errors and runtime panics
- Get the program to print: "Success! You tamed the beast."

Guiding Questions

- **Blocks**
 - Why is the fire damage calculation failing to return a value?
- **Match**
 - How do we handle "every other" possibility?
- **Macros**
 - Can you identify the macros for *debugging*, *placeholders*, and *logic guards*?

The Saboteur Challenge

- After the code runs successfully
 - Change `is_brave` to `false`
 - Increase `fire_intensity`
- What happens with "impossible" logic?

Summary

What We Covered

■ Expressions and Blocks

- Blocks have a value and type defined by their last expression
- All branches of `if/match` expression must return same type
- `match` must be exhaustive

■ Loops

- Only the `loop` construct is both a loop and an expression
- Skip the rest of current iteration with `continue`
- Exit any loop type early with `break`
- Use labels with `break` and `continue`

■ Functions

- Last expression is the function return value
- No overloading, no default value for parameters

■ Macros

- Expand into code at compile-time, suffixed with `!`
- Allow variable number of arguments

Tuples and Arrays

Introduction

Topics Covered

■ Arrays

- Basics and initialization
- Safety (out-of-bound panic)
- Iteration and looping

■ Tuples

- Basics and heterogeneous types
- Accessing fields

■ Patterns and Destructuring

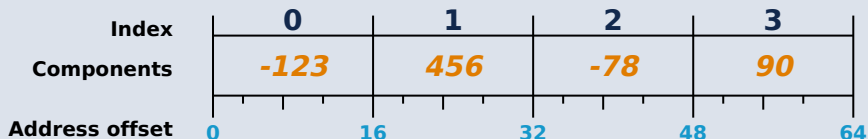
- Destructuring (tuples, arrays, (re)assignment)
- Ignoring elements (`_`, `..`)
- Nested destructuring

Arrays

What Is an Array?

■ Collection of elements

- ... of the **same type**
- ... stored in contiguous memory
- ... indexed using a discrete range



Basics

- Allocated on the stack - they're fast!
- *Length* is **fixed** and defined at **compile-time**
- *Length* of an array is part of its type
 - `[T;N]` holds `N` elements of type `T`
 - `[u8;3]` and `[u8;4]` are considered two different types
- Index starts at `0` (range is `0` to `N-1`)

// Array of 3 elements of type 'i8'

`let mut` values: `[i8; 3] = [2, 3, 4];`

`values[2] = 5; // Accessing and modifying an element`

Note

Remember, `mut` is required for modification

Safety and Initialization

Safety

- Compile-time and run-time **out-of-bounds** checks
- Accessing an element beyond the defined length will cause a **panic**

Initialization

- Can be assigned values either using *array literals*

```
let integers = [1, 2, 3, 4, 5];           // Integer literals
let floats   = [1.1, 2.2, 3.3];         // Float literals
let strings  = ["Hello", "World"];      // String literals
let bools    = [true, false, true];     // Boolean literals
```

- Or using *array repeat expression* [value; N]
 - With length N, known at compile-time
 - Where every element is *value*

```
let elements: [i8; 5] = [0; 5];
```

- Assignment is **not** limited to literals
 - Can use variables, function calls, or expressions

Iteration

- `for` statement natively supports iterating over arrays
- Given an array

```
let primes = [2, 3, 5, 7, 11, 13, 17];
```

- Iteration by value would look like

```
for prime in primes {  
    println!("{}", prime);  
}
```

- While index-based looping would look like

```
for ii in 0..primes.len() {  
    println!("{}", primes[ii]);  
}
```

Tuples

Basics

- Group together values of **different types**
- Like arrays, have a **fixed length**
- Elements are accessed via dot notation by their index
 - Starting from 0
 - Also referred to as *field* or *member*

```
// Tuple with an 'i8' and a 'bool'  
let alien_report: (i8, bool) = (3, false);  
println!("Number of tentacles: {}", alien_report.0);  
println!("Hostile? {}", alien_report.1);
```

```
Number of tentacles: 3  
Hostile? false
```

Patterns and Destructuring

What Is Destructuring?

- **Convenient** data access
- **Breaking down** a complex data structure into its inner parts
 - Like a tuple, an array, or other compound types
- **Assigning** those parts to individual variables
 - In a single step!

Destructuring a Tuple

- Extract multiple values in **single line**
- Assign **meaningful names** to improve readability
- Ignore specific elements that are **not needed**
 - With the wildcard pattern `_`

```
let person_data = ("Renoir", 33, "Painter");  
let (name, _, profession) = person_data;  
// 'name' is more meaningful than 'person_data.0'  
println!("Name: {name}, {profession}");
```

```
Name: Renoir, Painter
```

Irrefutable Patterns With Tuples

- Irrefutable tuple pattern = **guaranteed match**
- Used in **let** statements
 - **let** bindings must always succeed
 - Pattern must **always** match the data structure

```
let point: (i32, i32) = (10, 20);
```

```
// Pattern (xx, yy) is IRREFUTABLE  
// Perfectly matches the structure of that tuple  
let (xx, yy) = point;  
// Guaranteed to get an xx and a yy!
```

Destructuring Assignment

- Destructuring can be used as an assignment operation
- Assigned to variables that were already declared
- Target variables must be declared as **mutable**

```
let mut cat_snacks = 1;  
let mut dog_treats = 42;
```

```
// No temporary variable required!  
(cat_snacks, dog_treats) = (dog_treats, cat_snacks);
```

Destructuring an Array

- Assign the array to a pattern that specifies names for each element
- Pattern must **exactly** match the array's length and type
- Compile-time error occurs if it has fewer or more elements

// Destructuring an array into three separate variables

```
let bag: [i32; 3] = [10, 20, 30];  
let [shirts, pants, socks] = bag;  
println!("shirts: {}", shirts);  
println!("pants: {}", pants);  
println!("socks: {}", socks);
```

```
shirts: 10  
pants: 20  
socks: 30
```

Ignoring Specific Elements

Ignore specific elements using the underscore (`_`)

```
let colors = ["red", "green", "blue", "yellow"];  
// Destructuring only the second and fourth elements  
let [_, second, _, fourth] = colors;  
  
println!("Second color: {}", second); // green  
println!("Fourth color: {}", fourth); // yellow
```

```
Second color: green  
Fourth color: yellow
```

Ignoring Multiple Elements

- Ignore multiple elements using the **rest pattern** (`..`)
- Can only be used **once** per pattern
 - Anywhere within the element list

```
let data = [1, 22, 333, 44, 5, 66];
```

```
// Get first and last, skip everything in-between
```

```
let [first, .., last] = data;  
println!("First: {}", first);  
println!("Last: {}", last);
```

```
First: 1  
Last: 66
```

```
// Get first and second, skip everything after
```

```
let [one, two, ..] = data;  
println!("One: {}", one);  
println!("Two: {}", two);
```

```
One: 1  
Two: 22
```

```
// Get last two, skip everything before
```

```
let [.., fifth, sixth] = data;  
println!("Fifth: {}", fifth);  
println!("Sixth: {}", sixth);
```

```
Fifth: 5  
Sixth: 66
```

Nested Destructuring

Use a pattern within a pattern to destructure an array of arrays

```
let line_data = [[10, 20], [80, 90]];
let [[start_x, start_y], [end_x, end_y]] = line_data;

println!("Drawing line from ({}, {}) to ({}, {})",
        start_x, start_y, end_x, end_y);
```

```
Drawing line from (10, 20) to (80, 90)
```

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Arrays

- Group values of same type, fixed length
- Length is part of the type
- Initialization with literals (e.g., `[2, 3, 5]`)
- Looping over arrays with `for`

■ Tuples

- Group values of different types, fixed length
- Fields are accessed via dot notation followed by their index

■ Patterns and Destructuring

- Used for clarity, simplicity
- Irrefutable patterns are patterns guaranteed to match the structure
- Skip an element using `_` and multiple elements using `..`
- Destructuring can be used as an assignment operation
- Use a pattern within a pattern to destructure an array of arrays

References

Introduction

Topics Covered

■ Shared References

- Read-only access to data

■ Mutable References

- Read-write access to data

■ Reference Validity

- Null safety and scope

■ Slices

- View into collections
- `&str` vs. `String`

Shared References

Shared References

- Created with the `&` operator
- Provide a mechanism to access a value without taking ownership
- Strictly **read-only**
 - Referenced data **cannot change**
 - Even if the *original* variable was declared as `mut`
- Shared reference to type `T` has type `&T`

```
let first = 'A';  
let ref_1: &char = &first; // Refers to 'first'  
let ref_2: &char = &first; // Also refers to 'first'
```



Note

Unlimited shared references to the *same* data can exist at the *same* time

Using Reference (Accessing Data)

- The `*` operator **dereferences** the address to read the value

```
let first = 'A';  
let reference: &char = &first; // Refers to 'first'  
println!("reference: {}", *reference);
```

```
reference: A
```

Automatic Dereferencing for Field Access

- Use `.` for field access
 - No `->` operator (unlike C++)

```
let coordinates = (3, 5);  
let reference = &coordinates;
```

```
println!("x: {}, y: {}", coordinates.0, coordinates.1);  
println!("ref x: {}, ref y: {}", reference.0, reference.1);
```

```
x: 3, y: 5  
ref x: 3, ref y: 5
```

Reference Reassignment

```
let first = 'A';  
let second = 'B';  
let mut reference: &char = &first; // Refers to 'first'  
println!("reference: {}", *reference);  
reference = &second; // Now refers to 'second'  
println!("reference: {}", *reference);
```

```
reference: A
```

```
reference: B
```

Mutable References

Mutable References (AKA Exclusive References)

- Created with `&mut` operator
- Allow modifying value they point to
- Cannot coexist with any other reference
- Mutable reference to a type `T` has type `&mut T`

```
let mut two_plus_two = 4;  
let big_brother = &mut two_plus_two;  
*big_brother = 5;  
println!("Truth: {two_plus_two}");
```

Truth: 5

Note

A `&mut` reference cannot be created from an **immutable** variable

Binding vs. Reference

Rust's Reference System

Syntax	Binding	Reference
<code>let r = &x</code>	Immutable	Shared
<code>let mut r = &x</code>	Mutable	Shared
<code>let r = &mut x</code>	Immutable	Mutable
<code>let mut r = &mut x</code>	Mutable	Mutable

■ Binding

- Labeled slot that holds the address

■ Reference

- Access contract for data at that address

The "Observer" (`let r = &x`)

- *Cannot* point to something else
- *Cannot* change the value

```
let past = 1984;  
let future = 2048;  
let rf = &past;
```

```
*rf = 1776; // Error
```

```
error[E0594]: cannot assign to '*rf', which is behind a '&' reference
```

```
rf = &future; // Error
```

```
error[E0384]: cannot assign twice to immutable variable 'rf'
```

Note

The reference cannot be redirected, nor can the data be modified

The "Rebinder" (`let mut r = &x`)

- *Can* point to something else
- *Cannot* change value

```
let news_a = "War with the North";  
let news_b = "War with the South";  
let mut rf = &news_a;
```

```
rf = &news_b;  
*rf = "Peace"; // Error
```

```
error[E0594]: cannot assign to '*rf', which is behind a '&' reference
```

Note

The reference *can* be redirected, but the data *cannot* be modified

The "Modifier" (`let r = &mut x`)

- *Cannot* point to something else
- *Can* change value

```
let mut room_101 = 0;  
let mut room_102 = 0;  
let rf = &mut room_101;  
  
*rf = 1;  
rf = &mut room_102; // Error
```

```
error[E0384]: cannot assign twice to immutable variable 'rf'
```

Note

The reference *cannot* be redirected, but the data *can* be modified

The "Free Agent" (`let mut r = &mut x`)

- *Can* point to something else
- *Can* change value

```
let mut focus = 100;  
let mut shame = 0;  
let mut rf = &mut focus;
```

```
*rf = 0;  
rf = &mut shame;  
*rf = 999;
```

Note

The reference *can* be redirected, and the data *can* be modified

Reference Validity

References End at Their Last Use

```
let mut ego = 10;  
let ref_1 = &ego;  
println!("ref_1: {ref_1}"); // Last use of 'ref_1'  
let ref_2 = &mut ego;      // Allowed
```

- `ref_1` is no longer needed after `println!`
- `ref_2` creation is allowed
- `ref_1` and `ref_2` do not overlap

```
ref_1: 10
```



Note

References end at their **last use**, not necessarily at the end of the scope `{ }`

References Are Always Safe to Use

- Can **never** be null
- Cannot outlive data they point to
- Dangling references cannot occur

```
let rose = {  
    let jack = String::from("Jack");  
    &jack  
};  
println!("Jack screams: {rose}");
```

error[E0597]: 'jack' does not live long enough

Slices

What Are Slices?

- View into memory owned by another variable
 - Must be contiguous sequence (like an array)
- Refer to data stored elsewhere
- Use zero-based indexing
 - Are inclusive of the starting bound but exclusive of the end
 - Using `..`
 - Unless explicitly marked as inclusive
 - Using `..=`

```
let primes: [i32; 6] = [2, 3, 5, 7, 11, 13];  
let slice: &[i32] = &primes[2..4];
```

```
primes: [2, 3, 5, 7, 11, 13]  
slice: [5, 7]
```

Slice Creation

Created by referring to a collection, and specifying the range

Syntax	Range
<code>&a[start..]</code>	Explicit start to implicit end
<code>&a[..end]</code>	Implicit start to explicit end (<i>end</i> excluded)
<code>&a[..]</code>	Full range
<code>&a[start..end]</code>	Explicit start and end (<i>end</i> excluded)

Slice Examples

```
let terminator: [char; 4] = ['T', '8', '0', '0'];
```

```
terminator:      ['T', '8', '0', '0']
```

```
// Slicing the 'terminator' array
```

```
let version: &[char] = &terminator[1..];
```

```
let generation: &[char] = &version[..1];
```

```
let arnold: &[char] = &terminator[..];
```

```
let james: &[char] = &arnold[2..4];
```

```
let terminated = &terminator[0..0];
```

```
version:      ['8', '0', '0']
```

```
generation:   ['8']
```

```
arnold:       ['T', '8', '0', '0']
```

```
james:       ['0', '0']
```

```
terminated:   []
```

Note

Out-of-bounds slicing triggers a compile error if the range is static, or a *panic* if the range is dynamic

Fat Pointer

Slices are sometimes called "Fat Pointers"

- Carry **two** components
 - **Data Pointer** - memory address where data starts
 - **Length** - how many elements to look at

```
const ARRAY_SIZE: usize = 4_000_000;  
static HUGE_ARRAY: [i32; ARRAY_SIZE] = [0; ARRAY_SIZE];  
let first_five = &HUGE_ARRAY[0..5];
```

Note

Creating a slice is **O(1)** - it takes the same constant time whether the original array has 4 elements or 4 million

"&str" vs. "String"

■ &str

- **String slice** - immutable reference to UTF-8 encoded bytes
 - Fixed length (cannot grow or shrink)
 - String literals ("Hello") are &str

■ String

- Buffer of UTF-8 encoded bytes
 - Allocated on the heap, can grow or shrink

```
let message: &str = "Hello World";  
let preview: &str = &message[..5];  
println!("preview: {preview}");
```

```
preview: Hello
```

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

- **Shared References** (`&T`)
 - Allow read-only access to value
 - Implemented as safe pointers
- **Mutable References** (`&mut T`)
 - Allow read-write access
 - Only one reference allowed at a time
- **Safety**
 - References are never null and are always valid
- **Slices** (`&[T]`)
 - Efficient views into arrays or other collections
 - `&str` is a slice

Structs and Enums

Introduction

Topics Covered

■ Structs

- Group related data
- Initialization and update syntax
- Named-field vs. tuple forms

■ Enums

- Define distinct options
- Variants holding data
- State machines

Introduction

struct and **enum** create custom data structures

- Programmer-defined types
- Bundle related pieces of information together
- Programmer-defined behavior can be implemented

```
struct PlayerStats {  
    level: u16,  
    health: u32,  
    is_online: bool,  
    score: i64,  
}  
  
enum Direction {  
    North,  
    East,  
    South,  
    West,  
}
```

Structs

Basics

- **struct** creates a type that can hold multiple related values
 - Visually similar to **struct** in C/C++ or **record** in Ada
- Can hold any type that is **Sized**
 - Size is known at compile time
- Fields accessed via dot notation
- Called **named-field struct**

```
struct User {  
    age: u8,  
    number_of_messages: u32,  
}  
  
let myself = User {  
    age: 32,  
    number_of_messages: 275,  
}  
  
if myself.number_of_messages > 300 {  
    println!("You post too much!");  
}
```

Nesting Structs

```
struct Engine {  
    horsepower: u16,  
    fuel_type: String,  
}  
  
struct Car {  
    new: bool,  
    // 'Engine' struct inside 'Car' struct  
    power_plant: Engine,  
}
```

Beware of Recursion!

Structs cannot be recursive

- Type would not be **Sized**

```
// 'RussianDoll' size = size of u8 + size of itself  
// Size is infinite  
struct RussianDoll {  
    size: u8,  
    // ...another 'RussianDoll'! (Infinite recursion)  
    inner_doll: RussianDoll,  
}
```

```
error[E0072]: recursive type 'RussianDoll' has infinite size
```

Struct Initialization

No partial initialization possible

- No implicit default values

```
struct User {  
    active: bool,  
    sign_in_count: u64,  
    logged_in: bool,  
}  
  
let tic: User;  
let tac = User {  
    active: true,  
    sign_in_count: 1,  
    logged_in: true,  
};  
  
let toe = User {  
    active: true,  
    sign_in_count: 1  
};
```

error[E0063]: missing field 'logged_in' in initializer of 'User'

Shorthand for Field Initialization

- If field and variable have same name, it could be written only once
 - This is called *Field Init Shorthand*
 - Compiler automatically expands the variable
 - Can be mixed with explicit field assignments
- No positional association allowed

```
struct User {  
    active: bool,  
    sign_in_count: u64,  
    logged_in: bool,  
}  
  
let active = true;  
let sign_in_count = 1;  
  
let user_1 = User {  
    // Same as 'active: active'  
    // Field takes value of local variable  
    active,  
    // Name association is still possible  
    sign_in_count: sign_in_count,  
    logged_in: true;  
};
```

Struct Update Operator

- Creation of **struct** based on another instance via `..` operator
 - Specify values only for fields that need to change
 - Unspecified fields are *copied* or *moved* from the base instance
- Base instance can't be followed by a comma
 - Must be at the end of the declaration

```
struct Settings {  
    font_size: u8,  
    active: bool,  
}  
  
let default_set = Settings {  
    font_size: 14,  
    active: false,  
};  
  
// Only change 'active' to true in 'set_1'  
let set_1 = Settings {  
    active: true,    // Overridden field  
    ..default_set   // Copy all other fields ('font_size')  
};  
  
let set_2 = Settings {  
    ..default_set   // Copy all fields  
};
```

⚠ Warning

Fields are *moved* if their type doesn't implement the **Copy** trait

Mutable

Mutability applies to the entire instance

- No partial application for only some fields

```
struct CatStatus {  
    energy_level: u8,  
    is_napping: bool,  
}  
  
let mut active_cat = CatStatus {  
    energy_level: 80,  
    is_napping: false,  
};  
active_cat.is_napping = true;  
  
let new_cat = CatStatus {  
    mut energy_level: 80, // Error  
    is_napping: false,  
};
```

error: expected identifier, found keyword 'mut'

Tuple Structs

- Like named-field **struct**, can hold any type that is **Sized**
 - Useful to give a structure a specific name without naming any fields
- Tuple indexing starts at 0

```
struct Character(  
    u64,    // Power  
    i64,    // Money  
    bool,  // Is good?  
);  
  
let hero = Character(10000, -500, true);  
println!("Power level is : {}", hero.0);  
println!("Money is : {}", hero.1);  
  
println!("out of bound is : {}", hero.3);
```

```
error[E0609]: no field '3' on type 'Character'
```

Constructor Ambiguity

- Tuple struct type declaration defines both
 - Data type
 - Constructor function

```
struct Point(i32, i32);  
// Creates a binding to the constructor function  
let coord = Point; // 'Point' is the constructor function  
  
// Calls the 'Point' constructor function  
// Initializes the tuple  
let maximum = coord(1,2); // 'maximum' is a 'Point'  
  
// Calls the 'Point' constructor  
// No initialization because of missing fields  
let coord2 = Point();
```

```
error[E0061]: this struct takes 2 arguments but 0 arguments were supplied
```

Type Safety With Tuples

- **Name** differentiates types
 - Not their definition
- Tuple structs with the same definition are different types

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

```
struct Size(i32, i32);
```

```
let coordinates = Point(10, 20);
```

```
let mut dimension = Size(30, 40);
```

```
dimension = coordinates; // ERROR
```

```
error[E0308]: mismatched types
```

Idiom: Newtype

A **newtype** is a tuple **struct** with a single field

- Used to ensure type safety

```
struct Feet(i32);
```

```
struct Inches(i32);
```

```
let mut distance = Feet(12) + Inches(3);
```

```
error[E0369]: cannot add 'Inches' to 'Feet'
```

Enums

Basics

- **enum** can be one of several distinct **variants**
- **Variants** are accessed using the `::` notation
 - Called **path separator**
 - Commonly referred to as *scope resolution operator*

```
enum Direction {  
    Left,  
    Right,  
}  
  
let dir = Direction::Left;
```

Enums With Data

- **Variants** can optionally hold data
 - This is an **enum** superpower!
- Can't be recursive
 - Type would not be **Sized**
- Similar to *tagged unions* in C++
 - But Rust *enums* are a core language feature

```
enum PlayerMove {  
    Pass,                                // Simple variant  
    Run(Direction),                      // Tuple variant  
    Teleport { xx: u32, yy: u32 },       // Named-field struct variant  
}  
  
let action = PlayerMove::Run(Direction::Left);  
  
let teleport = PlayerMove::Teleport { xx: 10, yy: 10 };
```

Enum Initialization

- **Must** specify entire variant when creating `enum` variable
 - A variant must be selected
 - Data must be initialized if variant holds data

```
enum Message {  
    Quit,  
    Move { coord_x: i32, coord_y: i32 },  
    ChangeColor(i32, i32, i32),  
}
```

```
let white = Message::ChangeColor(255,255,255); // OK
```

```
// Error! Must provide the content of 'Move'
```

```
let no_color = Message::Move;
```

```
error[E0533]: expected value, found struct variant 'Message::Move'
```

Idiom: State Machine

Each variant is mutually exclusive

```
// Represent distinct states of a network connection
enum ConnectionState {
    // Unit variant (no data)
    Idle,
    // Struct variant (contains connection data)
    Connected {
        session_id: u64,
        curr_ip: IpAddressV4,
    },
    // Tuple variant (contains error data)
    Failed(u16),
}
```

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Structs

- Group related data into a single, named entity (*composition*)
- Full field initialization is mandatory
- Supplies *Struct Update Operator* (`. .`) to copy with minor modifications
- Includes named-field structs, tuple structs, and the *newtype* idiom

■ Enums

- Define a type that can be one of a fixed set of variants
- Variants can optionally carry specific data (tuple or struct-like)

Pattern Matching

Introduction

Topics Covered

■ Patterns as Bindings

- Variable assignments
- Implicit pattern matching

■ Destructuring

- Extracting data
- Works with structs and enums

■ Control Flow

- `match` statements
- `if let` and `while let` expressions

■ Exhaustiveness

- Compiler-checked safety
- Total case coverage

Patterns

What Is a Pattern?

- Core language feature
- Describes the **structure** of a value
- Used to *test* and *decompose* values
- Successful matching may introduce new bindings

Basic Pattern

```
let musketeers = 3;
```

```
// Pattern: Identifier (musketeers)
```

```
// Structure: Single, scalar value
```

```
// Binding: 'musketeers' is now bound to value '3'
```

Patterns Are Declarative

- Patterns describe *what* (shape) rather than *how* (steps)
- Matching is a structural check
 - Not a sequence of procedural field accesses
- Scale effectively as data structures grow in complexity

```
struct Point {  
    x: i64,  
    y: i64,  
}  
  
let point = Point { x: 0, y: 7 };  
  
// Declarative: Describing the 'stencil'  
match point {  
    Point { x: 0, y: ver } => println!("On Y axis at {ver} (using 'match')"),  
    _ => {}  
}  
  
// Procedural: Step-by-step instructions (what patterns avoid)  
if point.x == 0 {  
    let ver = point.y;  
    println!("On Y axis at {ver} (using 'if')");  
}
```

```
On Y axis at 7 (using 'match')  
On Y axis at 7 (using 'if')
```

Patterns as Bindings

- Every **let** binding uses a pattern
- Simple bindings use identifier patterns
- Complex patterns can destructure values

```
let number = 5;           // Identifier pattern
```

```
let (first, second) = (1, 2); // Tuple pattern
```

Literal Patterns

- Match exact values
- Commonly used in `match` expressions
- Useful for branching on specific cases

```
let choices = 3;
```

```
match choices {  
    0 => println!("zero"),  
    1 => println!("one"),  
    _ => println!("too many"),  
}
```

too many

Wildcard Pattern

- `_` matches any value
- Does not *bind* or *move* the value
- Often used to ignore irrelevant cases

```
enum Status {  
    Ok(i32),  
    Error,  
}  
  
let status = Status::Ok(10);  
  
match status {  
    Status::Ok(_) => println!("ok"),  
    Status::Error => println!("error"),  
}
```

ok

Binding With Patterns

- Identifier patterns bind matched values to names
- Bindings only exist when the pattern matches
- Commonly used with enums and tuples

```
let (first, second) = (10, 20);
```

```
println!("first is {}, second is {}", first, second);
```

```
first is 10, second is 20
```

Pattern Composition

- Patterns may be composed recursively
- Larger patterns are built from smaller ones
- Inner patterns describe substructure

```
1 let point = (0, 5);  
2  
3 match point {  
4     (0, y) => println!("on y-axis at {}", y),  
5     _ => {}  
6 }
```

on y-axis at 5

- If line 1 was `let point = (5, 0);`
 - Fails to match the first pattern because 5 does not equal 0
 - Matches the wildcard pattern (`_`)
 - Performs no action
 - Nothing is printed

Pattern Vocabulary

■ Literal Matching

- Patterns can match specific values like numbers or strings

■ Alternative Patterns

- Use the "pipe" (|) to handle multiple values in a single arm

■ Variable Bindings

- Use @ to give a name to a value while checking it against a range or pattern

■ The Rest Pattern

- A placeholder (..) that ignores "everything else" in a sequence or structure

```
let x = 5;

match x {
    // Matches 1, 2, or 3
    1 | 2 | 3 => println!("Small"),

    // Binds the value to 'n' AND checks the range
    n @ 4..=10 => println!("Value {n} is in range"),

    _ => println!("Other"),
}
```

Value 5 is in range

Patterns in Rust Constructs

Patterns are reused consistently across the language

- `let` bindings
- `match` expressions
- `if let` and `while let`
- Function parameters

Match

What Is "match"?

- Compares a value against a set of patterns
- At least one pattern must match
 - First matching arm is executed
- Selected arm determines the result



Note

`match` is an *expression*, not a *statement*

"match" as an Expression

- Every `match` evaluates to a value
- All arms must produce compatible types
- Result can be bound to a name

```
let choices = 2;
```

```
let description = match choices {  
    0 => "zero",  
    1 => "one",  
    _ => "too many",  
};
```

Match Arms

- Each arm consists of a pattern and an expression
- Patterns are tested top to bottom
- First matching arm is selected

```
let scoops = 5;
```

```
match scoops {  
    1 => println!("Single scoop!"),  
    2 => println!("Double scoop!!"),  
    _ => println!("Wow, that's a lot of ice cream!"),  
}
```

```
Wow, that's a lot of ice cream!
```

Exhaustiveness

- All possible cases must be handled
- Missing cases cause a *compile-time* error
- Applies to all `match` expressions

```
enum Direction {  
    North,  
    South,  
    East,  
    West,  
}
```

```
let travel_to = Direction::East;
```

```
match travel_to {  
    Direction::North => println!("Heading Up"),  
    Direction::South => println!("Heading Down"),  
}
```

```
error[E0004]: non-exhaustive patterns: 'Direction::East' and 'Direction::West' not covered
```

Matching With Bindings

- Patterns can bind values while matching
- Bound names are available in the arm body
- `_` ignores the matched value

```
let player_score = (10, 250);
```

```
match player_score {  
    (10, bonus) => println!("Level 10! Bonus: {}", bonus),  
    _ => println!("Keep playing!"),  
}
```

```
Level 10! Bonus: 250
```

Nested Patterns in "match"

- Nested patterns are checked within the selected arm
- Patterns are not ranked by specificity
- First matching arm is selected

```
let point = (0, 0);
```

```
match point {  
    (0, y) => println!("on y-axis at {}", y),  
    (x, 0) => println!("on x-axis at {}", x),  
    (x, y) => println!("{}", x, y),  
}
```

on y-axis at 0

Note

First matching arm is selected

Why "match" Matters

- Makes all cases explicit
- Each arm is independent and exclusive
 - No fallthrough between cases
- Enables compiler-checked completeness

Note

`match` is a powerful core construct to handle branching

Destructuring Structs

Struct Patterns

- Match values by field name
- Fields can be accessed without dot notation
- Patterns may *bind*, *ignore*, or *partially match* fields



Note

Destructuring works anywhere patterns are allowed

Destructuring: The Stencil Metaphor

- Think of a **pattern** as a *stencil* placed over a value
- **Field**
 - The "cutout" in the stencil that tells the compiler *where* to look
- **Binding**
 - Where the data "falls through" into your local scope
- **Result**
 - You "break open" the complex struct to get exactly the pieces you need

```
struct Point {  
    x: i64,  
    y: i64,  
}  
  
let point = Point { x: 12, y: -34 };  
  
// Placing the stencil (pattern) over 'point'  
// 'x' and 'y' are the cutouts; data fills new variables  
let Point { x, y } = point;  
  
println!("Coordinates ({x}, {y})")
```

```
Coordinates (12, -34)
```

Basic Destructuring

- The pattern mirrors the struct's shape to extract values
- **Order Independence**
 - Struct fields are matched by name, not position
- **Implicit Matching**
 - Patterns work anywhere a variable is introduced

```
let p = Point { x: 3, y: 4 };
```

```
// Pattern shape must match the struct shape
```

```
let Point { x, y } = p;
```

```
// Fields are found by name, so order doesn't matter
```

```
let Point { y, x } = p;
```

Shorthand Binding

- Field names can be reused as bindings
- Reduces repetition for common cases
- Shorthand is a syntactic shortcut for longhand renaming
- Most common way to destructure

```
// Shorthand
```

```
let Point { x, y } = p;
```

```
// ...is equivalent to explicit "rename" syntax:
```

```
let Point { x: x, y: y } = p;
```

Longhand and Renaming

- Use `field: variable` to rename data as it is extracted
- Useful when generic field names (like `x`) need descriptive local names
- New variables inherit the exact type (e.g., `i32`) from the struct

```
struct Point {  
    x: i32,  
    y: i32,  
}
```

```
// Renaming 'x' to 'new_x' to provide local context  
// Types are strictly preserved during the "binding"  
let Point { x: new_x, y: new_y } = p;  
  
// new_x: i32 = 3  
// new_y: i32 = 4
```

Ignoring Fields

- Unused fields may be ignored
- `..` matches remaining fields
- Useful when only part of a struct matters

```
struct PhysicsObject {  
    id: u32,  
    x: i32,  
    y: i32,  
    velocity: f64,  
}  
  
let obj = PhysicsObject { id: 1, x: 10, y: 20, velocity: 5.5 };  
  
// Capture 'x' and ignore all other fields  
let PhysicsObject { x, .. } = obj;  
  
// Ignore a specific field by name using '_'  
let PhysicsObject { id, velocity: _, .. } = obj;  
  
// Capturing multiple specific fields  
let PhysicsObject { id, velocity, .. } = obj;
```

Note
`..` captures specific named fields and *ignores* the rest

Destructuring Enums

Enums and Variants

- Enums represent a value that is exactly one of several possibilities
- Variant names *qualify* the pattern
 - Identify which specific structure is being matched
- Each variant can store different types and amounts of data

```
enum Message {  
    Quit,                                // No data  
    Move { x: i32, y: i32 },            // Named fields  
    Write(String),                       // Tuple data  
}
```

Note

Patterns are the **only** way to safely access the data inside these variants

Matching Enum Variants

- Enum patterns match specific variants
- Each variant is handled explicitly
- Variant names *qualify* patterns

```
enum Message {  
    Quit,  
    Write(String),  
}  
  
let msg = Message::Quit;  
  
match msg {  
    Message::Quit => println!("quit"),  
    Message::Write(text) => println!("write: {}", text),  
}
```

quit

Destructuring Variant Data

- Patterns can extract data from variants
- Payloads are bound directly in the pattern
- Binding occurs only when the variant matches
- Use `_` or `..` to ignore specific variant data

```
let msg = Message::Write(String::from("hello"));

match msg {
    // Capture: Binding the payload to 'text'
    Message::Write(text) => println!("text: {text}"),

    // Ignore: Using '_' because we don't need the string
    // Note: Must keep the parens for variants with data
    Message::Write(_) => println!("Received a message, but ignoring content"),

    // Ignore All: Using '..' for complex variants
    Message::Move { .. } => println!("System is moving"),

    Message::Quit => println!("quit"),
}
```

```
text: hello
```

Tuple Variants

- Contain unnamed fields
- Data is matched positionally
- Patterns mirror the variant structure

```
enum Event {  
    KeyPress(char),  
    MouseClick(i32, i32),  
}
```

```
let touch = Event::MouseClick(10, 20);
```

```
match touch {  
    Event::KeyPress(tap) => println!("key: {}", tap),  
    Event::MouseClick(x, y) => println!("click at {}, {}", x, y),  
}
```

click at 10, 20

Struct Variants

- Use named fields
- Patterns match fields by name
- Partial matching is supported

```
enum Shape {  
    Circle { radius: f64 },  
    Rectangle { width: f64, height: f64 },  
}  
  
let profile = Shape::Rectangle { width: 3.0, height: 4.0 };  
  
match profile {  
    Shape::Circle { radius } => {  
        println!("circle r={}", radius)  
    }  
    Shape::Rectangle {  
        width,  
        height,  
    } => {  
        println!("rect {} x {}", width, height);  
    }  
}
```

rect 3 x 4

Enums as Robust Data Models

■ Mutually Exclusive States

- Enums represent a value that is exactly *one* of several possibilities

■ Safety via Exhaustiveness

- *All* variants must be handled
- Missing cases cause a compile-time error

■ Future-Proofing

- If a new variant is added later, the compiler identifies every `match` that needs updating

■ Pattern Enforcement

- Pattern matching is the *only* way to safely access data inside a variant

```
enum Status {  
    Loading,  
    Success(String),  
    Failure(i32),  
}  
  
let current_status = Status::Loading;  
  
// Non-exhaustive pattern - 'Failure' not covered  
match current_status {  
    Status::Loading => println!("Please wait..."),  
    Status::Success(data) => println!("Got: {data}"),  
}
```

```
error[E0004]: non-exhaustive patterns: 'Status::Failure(_)' not covered
```

"Let" Control Flow

"let" as a Pattern

- Every **let** binding uses a pattern
- Simple bindings always match
- Complex patterns may fail to match

```
// ALWAYS matches. This is "irrefutable"
```

```
let x = 5;
```

```
// ERROR. This "refutable"
```

```
let 7 = x;
```

```
error[E0005]: refutable pattern in local binding
```

Conditional Matching

- Some patterns only match certain values
- `match` can always be used to handle this
- Shorthand forms available for common cases

Match Guards

- Use an **if** condition to filter a pattern based on its value
- Guard runs *after* the pattern matches
 - ...but *before* the arm's code block
- Guards are *dynamic*
 - Compiler usually requires a "catch-all" arm (`_`)

```
let pair = (2, -2);  
  
match pair {  
    (x, y) if x == y => println!("They match!"),  
    (x, y) if x + y == 0 => println!("They neutralize!"),  
    (x, _) if x % 2 == 0 => println!("The first is even"),  
    _ => println!("No special relationship"),  
}
```

They neutralize!

"if let"

- Matches a single pattern conditionally
- Follows assignment order
 - Pattern = value
 - Cannot be swapped
- All other cases are implicitly ignored

```
let value = Some(3);
```

```
if let Some(x) = value {  
    println!("x = {}", x);  
}
```

```
x = 3
```

"if let" vs. "match"

- `if let` is shorthand for a two-arm `match`
- Suited for logic where only one specific pattern is relevant
- `match` remains the standard for handling multiple distinct cases

```
let value = Some(3);
```

```
// Shorthand version:
```

```
if let Some(x) = value {  
    println!("x = {}", x);  
}
```

```
x = 3
```

```
// Equivalent 'match' version:
```

```
match value {  
    Some(x) => println!("x = {}", x),  
    _ => {} // Explicitly ignore all other cases  
}
```

```
x = 3
```

"while let"

- Commonly used for iterative extraction
- Repeats while a pattern continues to match
- Stops when the pattern no longer matches

```
enum Progress {  
    Step(i32),  
    Done,  
}  
  
let mut current = Progress::Step(3);  
  
// Loop continues as long as 'current' matches 'Step(val)'  
while let Progress::Step(val) = current {  
    println!("Steps remaining: {val}");  
  
    if val > 0 {  
        current = Progress::Step(val - 1);  
    } else {  
        current = Progress::Done; // Pattern will fail on next check  
    }  
}  
  
println!("Finished!");
```

```
Steps remaining: 3  
Steps remaining: 2  
Steps remaining: 1  
Steps remaining: 0  
Finished!
```

Pattern-Based Convenience

- `let`, `if let`, and `while let` all use patterns
 - Reduce boilerplate for common matches
- Same pattern rules apply everywhere

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Patterns as Bindings

- Every variable binding is a pattern match
- `match` compares values against patterns

■ Destructuring

- Extract data from structs and enums
- Use `..` to ignore fields

■ Pattern Matching Forms

- `match`, `if let`, and `while let`

■ Exhaustiveness

- Compiler-checked handling of all cases

Methods and Traits

Introduction

Topics Covered

■ **Methods**

- Attach behavior directly to a type

■ **Traits**

- Define shared behavior that multiple types can implement

■ **Deriving**

- Auto-generate common trait implementations at compile time

Methods

Methods in Rust

- What is a *method*?
 - Function *associated* with type via `impl` block
- Why use methods?
 - Organize behavior with the data it operates on

```
struct CarRace {  
    laps: Vec<i32>,  
}  
  
impl CarRace {  
    // Method: Modify data  
    fn record_lap(&mut self, time: i32) {  
        self.laps.push(time);  
    }  
}  
  
let mut race = CarRace::new();  
race.record_lap(114); // Data and logic live together
```

What Is a Method Receiver?

- First parameter of a **method**
 - Named **self**
- Specifies how the method accesses the value it is called on

```
fn method(&mut self, lap: i32) {  
    self.laps.push(lap);  
}
```

- Determines whether method
 - Takes ownership
 - Borrows immutably
 - Borrows mutably

Method Receiver - Shared Borrow

Definition

```
struct Counter {  
    value: i32,  
}  
  
impl Counter {  
    fn get(&self) -> i32 {  
        self.value  
    }  
}
```

Usage

```
let count = Counter { value: 5 };  
let val1 = count.get();  
  
// OK: multiple shared borrows  
let val2 = count.get();
```

Behavior

- Read-only access
- Value remains usable after calls

Method Receiver - Mutable Borrow

Definition

```
struct Counter {  
    value: i32,  
}  
  
impl Counter {  
    fn increment(&mut self) {  
        self.value += 1;  
    }  
}
```

Usage

```
let mut count = Counter { value: 0 };  
count.increment();
```

```
// OK, sequential mutable borrows  
count.increment();
```

```
let bad = Counter { value: 0 };  
bad.increment();
```

```
error[E0596]: cannot borrow "bad" as mutable, as it is not declared as mutable
```

Behavior

- Exclusive access
- Caller must declare the value `mut`

Method Receiver - Take Ownership

Definition

```
impl Counter {  
    // This consumes 'counter' and returns the final number  
    fn finalize(self) -> i32 {  
        println!("Shutting down counter...");  
        // Return the value, 'self' is dropped here  
        self.value  
    }  
}
```

Usage

```
let count = Counter { value: 10 };  
let total = count.finalize();  
  
count.get();
```

```
error[E0382]: borrow of moved value: "count"
```

Behavior

- Value is moved into the method
- Object cannot be reused afterward

Method Receiver - Mutable Ownership

Definition

```
struct Counter {  
    value: i32,  
}  
  
impl Counter {  
    fn reset(mut self) -> Self {  
        self.value = 0;  
        self  
    }  
}
```

Usage

```
let count = Counter { value: 5 };  
  
// Ownership moved, new value returned  
let count = count.reset();  
  
count.reset();  
// Because we do not capture the return value  
// It is moved to nowhere - 'count' is no longer the owner
```

Behavior

- Takes ownership and allows mutation
- Original value is consumed
- [Builder pattern](#)
 - Allows construction of complex objects
 - Chain multiple calls together

Method Receiver - No Receiver

Definition

```
struct Counter {  
    value: i32,  
}  
  
impl Counter {  
    fn new() -> Self {  
        Counter { value: 0 }  
    }  
}
```

Usage

```
// Call on the type, not an instance  
let count = Counter::new();  
  
// OK: 'count' is now a normal value  
println!("Value: {}", count.value);
```

```
Value: 0
```

Behavior

- Not called on an instance
- No access to existing fields (`self` is unavailable)

Note

This is usually called an *associated function*

Method Receivers at a Glance

- **&self** (**The Reader** - *shared, read-only borrow*)
 - *Power*: Can read data but cannot change it
 - *Usage*: Multiple parts of the code can call this at the same time
- **&mut self** (**The Writer** - *unique, mutable borrow*)
 - *Power*: Can modify the internal data of the object
 - *Usage*: Exclusive access; no one else has visibility while running
- **self** (**The Owner** - *takes full ownership*)
 - *Power*: Can destroy, move, or transform the object
 - *Usage*: Object is "consumed" - cannot be used again after the call
- **mut self** (**The Builder** - *takes ownership and allows mutation*)
 - *Power*: Can change an object before returning or discarding it
 - *Usage*: Common "Builder Pattern" for constructing complex objects
- **No Receiver** (**The Helper** - *associated function*)
 - *Power*: No access to a specific instance or its fields
 - *Usage*: Usually used for constructors, like `Counter::new()`

Traits

Traits - Rust's Interfaces

- What is a `trait`?
 - *Collection of method signatures* a type must implement
 - Similar to interfaces in other languages **but**
 - Typically compile-time resolution
 - Traits are *separate* from types
 - Traits can define associated types and constants
- Traits allow abstraction over types that share behavior

Simple Trait Example

```
trait Friend {  
    fn response(&self) -> String;  
    fn greet(&self);  
}
```

- Defines what methods types must provide
- Does **not** contain implementation

Implementing a Trait

Syntax

```
impl SomeTrait for TheType { ... }
```

Example

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

```
impl Friend for Dog {  
    fn response(&self) -> String { String::from("Wag!") }  
    fn greet(&self) { println!("Hello"); }  
}
```

Behavior

- Dog has the Friend capability (or behavior)
- Dog is **not** derived from Friend

Default Trait Methods

- Traits can provide **default implementations**
- Types implementing the trait can *use* or *override* them
- Defaults can call required methods

```
trait Friend {  
    fn response(&self) -> String;  
    // Default 'greet' will use 'response'  
    fn greet(&self) {  
        println!("Hello! {}", self.response());  
    }  
}  
  
impl Friend for Dog {  
    fn response(&self) -> String {  
        format!("I'm a dog, my name is {}!", self.name)  
    }  
    // Without defining 'greet', it would print  
    // Hello! I'm a dog my name is Fido  
}
```

Traits vs. Methods

Feature	Methods	Traits
<i>Identity</i>	What a Dog is	What a Dog can do
<i>Availability</i>	Only for Dog	Any type that is a Friend
<i>Example</i>	<code>fn wag_tail(&self)</code>	<code>fn response(&self)</code>

Real World Comparison

- Methods are *unique capabilities*
 - A dog knows how to wag its tail (but a cat doesn't)
 - Put `wag_tail` in `impl Dog`
- Traits are *shared behaviors*
 - Both dog and cat have a friendly response (but they do it differently)
 - Put the response in a trait, which focuses on *what an object can do*
 - Not what the object is

Deriving

Deriving Traits

- What is *deriving*?
 - Built-in macro to automatically generate code
- What does **deriving** do?
 - Automatically generates trait implementations
 - Uses `#[derive(...)]` attribute
 - Saves boilerplate for common behaviors

Commonly Derived Traits

Trait	Purpose
<code>Debug</code>	Enables <code>{:?}</code> formatting
<code>Clone</code>	Deep copy (everything it contains)
<code>Copy</code>	Shallow copy (just the bits)
<code>PartialEq</code> , <code>Eq</code>	Equality comparisons
<code>PartialOrd</code> , <code>Ord</code>	Ordering
<code>Hash</code>	Hash map/set keys
<code>Default</code>	Default value construction

Example of Deriving

```
#[derive(Debug, Clone, Default)]
struct Employee {
    name: String,
    age: u8,
}

fn main() {
    let human = Employee::default();
    // Default trait adds 'default' constructor

    let mut smith = human.clone();
    // Clone trait adds 'clone' method

    smith.name = String::from("Agent Smith");
    println!("{human:?} vs. {smith:?}");
    // Debug trait adds support for printing with '{:?}'
}
```

```
Employee { name: "", age: 0 } vs. Employee { name: "Agent Smith", age: 0 }
```

- Compiler generates implementations
- Works if all fields also implement the trait
- Zero runtime cost

Deriving in Complex Structures

Deriving a trait generally requires its inner types to implement the trait

```
struct Child {  
    x: i32,  
}  
  
#[derive(Clone)]  
struct Parent {  
    child: Child,  
}
```

```
error[E0277]: the trait bound "main::Child: Clone" is not satisfied
```

Limitations on Deriving

Cannot derive when

- Behavior depends on logic, not structure
- Implementation requires validation or other custom behavior
- Only part of the data should participate

Note

In these cases, use a manual `impl` Trait `for` Type instead

"Derive" vs. Manual "Impl"

Decision Factor	<code>#[derive(...)]</code>	Manual <code>impl</code>
<i>Logic Source</i>	Compiler-Generated Uses standard "one-size-fits-all" template	Programmer-Written Write code from scratch for total control
<i>Effort</i>	Minimal Single line above struct or enum	High Requires writing boilerplate and handling every field
<i>Customization</i>	None It's "all-or-nothing" for every field in the struct	Total Can hide fields, transform data, skip logic
<i>Compile-Time</i>	Checked Compiler ensures logic is safe	Checked Compiler ensures manual code is safe

- Derive is for Computers
 - Simple behaviors (clone, print) can be done by the compiler
- Manual is for Humans
 - More complicated behaviors should be done by the programmer

Advanced Trait Topics

Orphan Rule

- Implement a trait for a type only if the current crate defines
 - Either the trait
 - Or the type
- Why do we need this?
 - Prevents two libraries from defining conflicting behavior
 - Ensures trait implementations are globally unambiguous
- To implement trait `SomeTrait` for `SomeType`
 - `SomeTrait` or `SomeType` must be **defined** in the current crate
 - Otherwise, → compile error

Orphan Rule Examples

Define the type not the trait

```
struct MyType(i32);           // Defined type
impl Debug for MyType {}      // External trait
```

Define the trait not the type

```
trait Hello { // Defined trait
    fn hello(&self) -> &'static str;
}
impl Hello for String { // External type
    fn hello(&self) -> &'static str {
        "Hello!"
    }
}
```

Defined neither

```
impl Debug for Vec<i32> {}
```

error[E0117]: only traits defined in the current crate
can be implemented for types defined outside of the crate

Supertraits

A *supertrait* is a trait that requires another trait

- "If you implement this trait, you must also implement that one"

A "party animal" must be able to dance

- Base trait

```
trait Dance {  
    fn dance(&self);  
}
```

- Supertrait

```
trait PartyAnimal: Dance {  
    fn party(&self);  
}
```

Explanation

- A PartyAnimal must know how to Dance

Advanced Supertraits

A supertrait can depend on multiple traits

The "life of the party" must be able to sing AND dance

- New base trait

```
trait Sing {  
    fn Sing (&self);  
}
```

- New supertrait

```
trait LifeOfParty: Dance + Sing {  
    fn revel(&self);  
}
```

Explanation

- A LifeOfParty must know how to Dance and Sing

Associated Types

- An `associated type` is a type placeholder defined inside a trait
 - Chosen by the implementing type

```
trait Animal {  
    type Food; // Associated type  
    fn consume(&self, food: Self::Food);  
}  
  
struct Cat;  
struct Catnip;  
  
impl Animal for Cat {  
    // We associate 'Catnip' with 'Cat'  
    type Food = Catnip;  
    fn consume(&self, food: Catnip) {  
        println!("The cat purrs intensely over the catnip.");  
    }  
}
```

Note

- Implementer decides type once
 - Becomes "property" of implementation
- Use when only one logical choice for helper type per implementation

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Methods

- Functions tied directly to a specific type via `impl` blocks
- Use `self` receivers to define how data is accessed
 - Shared, mutable, or owned
- Associated functions (no `self`) act as constructors or helpers

■ Traits

- Act as *contracts* or interfaces for shared behavior across different types
- Can provide default implementations to reduce repetitive code

■ Deriving

- Uses `#[derive]` to auto-generate implementations for common traits
- Saves boilerplate for standard tasks
 - Debugging, cloning, and comparisons
- Functions based on the internal structure of the type

Generics

Introduction

Topics Covered

■ Generic Type Parameter

- Definition and instantiation
- Define multiple generic type

■ Constraints and Properties

- Traits add functionalities
 - And restrictions

■ Generic Traits and Constants

- Define generic constructs over traits and numbers

The Notion of a Pattern

- Sometimes algorithms can be abstracted from types and subprograms

```
fn swap_int(left: i32, right: i32) -> (i32, i32) {  
    (right, left)  
}
```

```
fn swap_float(left: f64, right: f64) -> (f64, f64) {  
    (right, left)  
}
```

- A common pattern could be extracted, with only some parts to replace

```
fn swap<T>(left: T, right: T) -> (T, T) {  
    (right, left)  
}
```

Generics

Generic Data Type

- Used to parameterize an object

- Declared using `<>`

- Can take any identifier name

- Conventionally called `T`

```
fn swap<T> (l: T, r: T) -> (T, T) {  
    (r, l)  
}
```

- `T` (*generic type parameter*) means `swap` can wrap any type
 - `swap<i32>`, `swap<MyOwnType>`, etc.

Be Generic

■ Items that can be made generic

Constructs	Example Syntax	Purpose
<i>Functions</i>	<code>fn</code> <code>logic</code> <T>(arg: T)	Logic that works on multiple types
<i>Structs</i>	<code>struct</code> <code>Container</code> <T>(T)	Data structures that hold any type
<i>Enums</i>	<code>enum</code> <code>Choice</code> <T> { A(T), B }	Variants that can wrap different data
<i>Traits</i>	<code>trait</code> <code>Behavior</code> <T>	Defining interfaces with generic inputs
<i>Impl Blocks</i>	<code>impl</code> <T> <code>Container</code> <T>	Implementing methods or traits for generic types
<i>Type Aliases</i>	<code>type</code> <code>Res</code> <T> = <code>Result</code> <T, <code>Error</code> >	Simplifying complex generic names

■ Examples

```
enum LaundryStatus<T> {  
    SoakingInWater(T),  
    SpinningViolently(T),  
}  
  
type Laundry<T> = LaundryStatus<T>;
```

Type Inference

- Any **Sized** type can be used as the type argument

// Definition: 'T' is a placeholder for ANY type

```
fn validate<T>(item: T) -> T {  
    println!("You're doing great, little value!");  
    item  
}
```

- Type is **inferred** at compile-time from the context

// With an integer

```
let points = validate(42);
```

// With a string

```
let name = validate("Rustacean");
```

```
You're doing great, little value!
```

```
You're doing great, little value!
```

Multiple Generic Type Parameters

Generic types can have multiple generic type parameters

```
struct Point<T, U> {  
    x: T,  
    y: U,  
}
```

```
let both_integer = Point { x: 5, y: 10 };  
let both_float = Point { x: 1.0, y: 4.0 };  
let integer_and_float = Point { x: 5, y: 4.0 };
```

Type Aliases

- Can be used to rename types and generic parameters

```
// 'Item' and 'Label' are generic parameters  
struct LargeShippingUnit<Item, Label>(Item, Label);  
type LargeCrate<T, U> = LargeShippingUnit<T, U>;
```

- Can *specify* the generic type

- **Partially**

```
struct Animal;  
type AnimalCrate<U> = LargeCrate<Animal, U>;
```

- **Totally**

```
struct Environment;  
type Biome = LargeCrate<Animal, Environment>;
```

Constraints and Properties

Trait Bounds

- Compiler will restrict what can be done with `<T>`
 - Doesn't know if it can do math, order or anything else
- Traits are the **fine print** on a generic **contract**
 - Ensure the logic only executes on types that "fit" the requirements
- Trait is specified with generic parameter type

```
fn smaller<T: PartialOrd>(item: T, max_v: T) -> bool {  
    item < max_v  
}
```

Adding Constraints

Adding a trait to a generic specifies what capabilities the type must have

```
// Compiler: "What if 'T' is a string? Is 'Bob' < 10?"  
fn smaller<T>(item: T) -> bool {  
    item < 10  
}
```

```
error[E0369]: binary operation '<' cannot be applied to type 'T'
```

```
fn smaller<T: PartialOrd>(item: T, max_v: T) -> bool {  
    item < max_v  
}
```

Meeting Constraints

Adding a trait restricts types that satisfy the generic contract

```
struct Vegetable;

fn smaller<T: PartialOrd>(item: T, threshold: T) -> bool {
    item < threshold
}

let potato : Vegetable;
let sweet_potato : Vegetable;
println!("{}", smaller(5, 10));
println!("{}", smaller(potato , sweet_potato));

error[E0277]: can't compare 'Vegetable' with 'Vegetable'
```

Programmer-Defined Traits as Constraints

Can be constraints for a generic function

```
trait Speak {  
    fn say_hello(&self);  
}  
  
struct Dog;  
  
impl Speak for Dog {  
    fn say_hello(&self) {  
        println!("Woof!");  
    }  
}  
  
// This function ONLY accepts types that can 'Speak'  
fn make_it_speak<T: Speak>(item: T) {  
    item.say_hello();  
}  
  
let pet = Dog;  
make_it_speak(pet);
```

Woof!

Turbofish "::<>"

- Compiler enforces the type to use from context
 - Sometimes there is *ambiguity*

```
// 'Vec<T>' is a generic struct  
// 'Vec' defines an associated function called 'new'  
// Compiler knows it's a 'Vec', but a 'Vec' of what?  
let x = Vec::new();
```

```
error[E0282]: type annotations needed for 'Vec<_>'
```

- Turbofish `::<>` syntax is used to remove ambiguity

```
// Turbofish dispels the mystery!  
let x = Vec::<i32>::new();
```

Multiple Traits

- Can have multiple trait bounds

- Uses the + to combine

```
fn complex_fn<T: Display + Clone,  
              U: Debug + PartialOrd>(t: T, u: U)  
{ ... }
```

- **where** clause can be used for better visibility

```
fn complex_fn<T, U>(t: T, u: U)  
  where  
    T: Display + Clone,  
    U: Debug + PartialOrd  
{ ... }
```

"derive" Macro and Generics

derive macro can be used on generic struct using standard traits

- Can't be used on generic traits

```
// Compiler enforces 'Debug' trait for 'T'
#[derive(Debug)]
struct Box<T> {
    content: T,
}
struct Secret; // Note: No 'Debug' here

let good_box = Box { content: 42 };
println!("{:?}", good_box); // Works ('i32' has 'Debug')

let bad_box = Box { content: Secret };
println!("{:?}", bad_box);
// 'Secret' doesn't implement 'Debug', 'derive' macro fails
```

```
error[E0277]: 'Secret' doesn't implement 'Debug'
```

Generic Traits and Constants

Generic Traits

Traits can be made generic

- Allows the same trait to behave differently with each type

```
// 'T' is the "target" type we want to turn into
trait Transform<T> {
    fn convert(&self) -> T;
}

struct Minutes(i32);
// Rule for converting 'Minutes' to 'Seconds'
impl Transform<i32> for Minutes {
    fn convert(&self) -> i32 { self.0 * 60 }
}

// Rule for converting 'Minutes' to a 'String'
impl Transform<String> for Minutes {
    fn convert(&self) -> String { format!("{} mins", self.0) }
```

Const Generics

- No generic constant declaration
- *Generic type parameter* can be made *constant*
 - *Const Generics* are generic over a **value** not a type

```
struct Buffer<const N: usize> {  
    data: [i32; N],  
}
```

```
let small_buffer = Buffer::<10> { data: [0; 10] };  
let large_buffer = Buffer::<1024> { data: [0; 1024] };
```

Note

`Buffer<10>` and `Buffer<1024>` are two different types

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Generic Data Types

■ Pattern

- Abstracts algorithms and structures from code reuse

■ Generic Objects

- Functions, structs, enums, and type aliases

■ Generics and Traits

■ Trait Bounds

- Act as a contract to add requirements and properties

■ Multiple Constraints

- Bounds can be combined using +

■ Generic Traits and Constants

■ Traits

- Traits can be generic, to interact with multiple types

■ Constants

- *Const Generics* are generic over values not types

Common Library Types

Introduction

Topics Covered

■ Standard Library

- Three tiers of dependence

■ Redefining Control Flow

- Eliminating hidden failures and null pointer crashes
- Handling absence and errors as first-class values

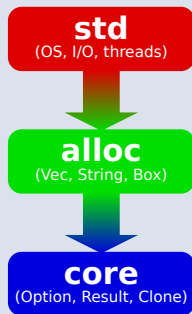
■ Dynamic Data Handling

- Transitioning from stack-allocated primitives to heap-allocated types

Overview

One Library, Three Tiers

- Standard Library is not a monolithic block
 - Layered stack designed to scale
- **core** (foundation)
 - No OS or memory allocator required
 - Basic types, primitive operations
- **alloc** (middle layer)
 - Depends on **core**
 - Requires heap allocator
 - Growable types
 - **Vec**, **String**, **Box**, etc.
- **std** (full suite)
 - Requires host environment
 - Contains everything in **core** and **alloc**
 - Adds OS abstractions
 - File I/O, networking, etc.



Introducing: The Prelude

- Small collection of items *automatically* imported into every module
 - No "with" or "include" - you get them for "free"
- In this module, that means items dealing with
 - **Logic:** `Option` and `Result` (Error handling)
 - **Data:** `String` and `Vec` (Dynamic storage)
- Why it matters
 - Types so essential that they're needed in every file

Without Prelude

```
let long: std::result::Result<i8, std::string::String> = std::result::Result::Ok(6);
```

With Prelude

```
let short: Result<i8, String> = Ok(5);
```

Option

Why Use "Option<T>"?

- In many languages, a variable can be a value or *unknown*
 - Null pointer
 - Uninitialized
- If we don't handle these cases, we can get bugs
 - Which can be difficult to find
- In Rust, a variable is *always* its type
 - So the value is always valid
 - To allow for *unknown* we wrap the type in **Option**
 - Requires explicit handling before accessing the value
 - Must determine if value is **None** or **Some**
 - Then extract value if **Some**

What Is "Option<T>"?

- `Option<T>` is defined as an `enum` with two variants

```
enum Option<T> {  
    Some(T),    // Contains a value of type 'T'  
    None,       // Represents the absence of a value  
}
```

- Typical usage

```
fn find_user(id: u32) -> Option<String>;  
  
fn main() {  
    let user_id = 1;  
  
    match find_user(user_id) {  
        Some(name) => println!("Found user: {}", name),  
        None => println!("User not found."),  
    }  
}
```

Found user: Waldo

Note

`Option` is useful when there is no resultant value

Benefits of "Option"

- Safety and clarity
 - No hidden null pointer
 - Must explicitly handle absence of value
- Type system enforces handling of missing values
 - Cannot just ignore them
 - Fewer runtime surprises

Common Use Cases

■ Optional arguments

- Configuration data where a value might not be specified

```
struct Arguments {  
    // Always there  
    source_file: String,  
    // Sometimes there  
    output_file: Option<String>,  
}
```

■ Collection lookups

- Looking for something in a database that might not be there

```
fn find_user(id: u32) -> Option<User> {  
    // Returns 'None' if 'User' doesn't exist  
}
```

■ Functions that may not return a result

- Popping from an empty stack

```
let value = stack.pop();
```

Result

Why Use "Result"?

- Provides explicit error handling
 - **Cannot** ignore errors silently
 - More error handling described later in the course
- Compiler warns if **Result** is unused
- Used pervasively for recoverable errors
 - I/O, parsing, etc.



Warning

Result is annotated with `#[must_use]` attribute - it **cannot** be ignored

What Is "Result<T, E>"?

- Mechanism to handle *recoverable* errors

```
enum Result<T, E> {  
    Ok(T),    // Success  
    Err(E),   // Failure  
}
```

- **Result** carries information about the success or failure
 - T - type returned on success
 - E - type returned on failure

Common Usage

```
fn divide(top: f64, bottom: f64) -> Result<f64, String> {  
    if bottom == 0.0 {  
        // Failure  
        Err("Cannot divide by zero!".to_string())  
    } else {  
        // Success  
        Ok(top / bottom)  
    }  
}  
  
let result = divide(10.0, 0.0);  
  
match result {  
    Ok(value) => println!("Result: {value}"),  
    Err(e)    => println!("Error: {e}"),  
}
```

Error: Cannot divide by zero!

String

What Is "String"?

String is an owned and growable UTF-8 encoded type

- Lives on the heap
- Grows as needed
- Ensures valid UTF-8
 - Length in bytes not necessarily number of characters



Note

- Functions often accept `&str`
- `&str` is a fixed view into text, so not modifiable like `String`

Creating Strings

- `String::new()` builds text manually

```
let simple_string = String::new();
```

- Traits/methods create from literals

```
let string_to_str = String::from("hello");  
let str_to_string = "world".to_string();
```

Modifying Strings

Strings support "append" methods (if mutable)

```
let mut my_text = String::new();
```

```
my_text.push('!');           // Append a char
```

```
my_text.push_str(" foo");    // Append a &str
```

Note

Because **String** owns its buffer, it may reallocate as it grows

Length vs. Characters

- `.chars()`
 - Iterator over actual characters
 - Characters are UTF-8, so may be multiple bytes
- `.len()`
 - Size of string in bytes (**not** characters)

```
fancy_string.push_str("Greek letters: λ ω π ");  
println!("Length = {}", fancy_string.len());  
println!("Chars = {}", fancy_string.chars().count());
```

```
Length = 23
```

```
Chars = 20
```

Note

To get number of characters in **String** use `.chars().count()`

Strings vs. Character Arrays

	Encoding	Size	Memory Type
<code>String</code>	UTF-8	1-4 bytes/char	Heap-allocated (growable)
<code>[char; N]</code>	UCS-4	4 bytes/char	Stack-allocated (fixed)

- `String` better for large ASCII text
 - `[char;N]` always requires 4 bytes per character
- `[char;N]` faster for random (direct) access
 - `String` needs to search content from the beginning

Vec

What Is "Vec<T>"?

- **Vec<T>** is a **growable heap-allocated** array
 - Holds a sequence of values of type T on the heap
 - Size can grow/shrink at runtime
 - Generic over element type: **Vec<i32>**, **Vec<String>**, etc.
 - Elements are contiguous in memory
- Dereferences to a slice (`[T]`)
 - All slice methods apply

Creating Vectors

- Creating a vector using `new()`

```
let mut simple_vector = Vec::new();  
simple_vector.push(1);
```

- Using the `vec!` macro

```
// Explicit list  
let list_of_values = vec![1, 2, 3];  
  
// Repeat expression  
let zeroes = vec![0; 10]; // Value "0" 10 times  
  
// List of 'i8'  
let bytes_1 = vec![1_i8, 2, 3];  
let bytes_2: Vec<i8> = vec![1, 2, 3];
```

Basic Operations

Accessing elements in the array

- **Safe access:** `v.get(idx)` returns `Option<&T>`
 - Use `Some/None` capability to handle `idx` out of bounds
- **Remove last:** `v.pop()` returns `Option<T>`
 - Also returns `Option<&T>`
- **Iterators:** iterate with `for x in &v`
 - Iterator is of actual type
- **Direct Indexing** `v[idx]` allowed but not recommended

```
let v = vec![1, 2, 3];  
println!("The sixth element is: {}", v[5]);
```

```
thread 'main' (14) panicked at src/main.rs:3:41:  
index out of bounds: the len is 3 but the index is 5
```

Working With "Vec"

```
let mut colors = vec!["Red", "Green", "Blue"];
```

```
// Iterate over 'colors'
```

```
println!("All colors");
```

```
for c in &colors { println!("{}", c); }
```

```
// Pop - remove and return the last element
```

```
let last = colors.pop();
```

```
println!("last: {last:?}");
```

```
// Get - safe indexing
```

```
let one = colors.get(1);
```

```
let five = colors.get(5);
```

```
println!("one: {one:?}");
```

```
println!("five: {five:?}");
```

```
All colors
```

```
Red
```

```
Green
```

```
Blue
```

```
last: Some("Blue")
```

```
one: Some("Green")
```

```
five: None
```

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Standard Library

- **core** - basic building blocks
- **alloc** - adding some memory management
- **std** - adding everything else, like file I/O, networking, etc.

■ Common library types

Option	Contains a value or None to indicate absence of value
Result	Contains one type of value on success and another on failure
String	UTF-8 string that can be mapped to default str
Vec	Growable sequence of values

Standard Library Traits

Introduction

Topics Covered

- **Comparing Objects**
 - Equality and ordering
- **Performing Mathematical Operations**
 - Math across types
- **Converting Between Types and Values**
 - Conversion vs. casting
- **Input/Output on Types**
 - Reading/writing to streams or files
- **Default Values for Types**
 - Method to create initial values

Overview

Review: What Is a Trait?

- Contract for behavior
 - Defines the set of methods a type must implement
- Abstraction tool
 - Allows for code that functions on many different types
 - As long as they provide the required behavior
- Similar to constructs in other languages
 - *Interfaces* in Java/C#
 - *Abstract Base Classes* in Python/C++
- Separates *interface* from *data*
 - Describes what a type **does**, not what it **is**
 - Adds functionality to types without modifying original code

What Is a Standard Library Trait?

- Predefined in Standard Library
 - Describes common behaviors
 - Integrates programmer types with language features and library API's
- Defines standardized capabilities
 - E.g., comparing, converting, formatting
- Allows programmer types to work with built-in syntax and functions

Comparisons

Comparison Traits

- Mechanism to define how types interact with comparison operators
 - **Equality:** `PartialEq`, `Eq`
 - Evaluate if two values are the same
 - **Ordering:** `PartialOrd`, `Ord`
 - Determine which value is "bigger"
 - Basis of Rust's comparison operators like `==`, `<`, etc.
- Compiler and Standard Library use these traits in many APIs
 - Sorting, matching, etc.
- Typically created via `#[derive]`
 - But can be implemented manually

Two Traits for Equality

■ `PartialEq`

- Enables `==` and `!=`
- **Symmetric:** If `a == b` then `b == a`
- **Transitive:** If `a == b` and `b == c` then `a == c`
- Objects are **considered** equal
 - Even if they are not identical
 - Think floating point numbers

■ `Eq`

- *Marker trait* - no actual methods
- Objects are **actually** equal
 - Trait guarantees that `a == a`

Deriving Equality

Most custom types do not need manual implementation

- Use derivation when structs/enums should be compared normally

```
#[derive(PartialEq, Eq)]  
struct MyData {  
    value_a: i32,  
    value_b: i32,  
}
```

- MyData objects will be equal if all fields are equal

Note

Can only derive if all fields already implement `PartialEq` and `Eq`

Custom Implementation of Equality

- **Example:** Type has a validity flag and a value

```
struct SensorData {  
    valid: bool,  
    value: i32,  
}
```

- Objects are equal when

- **EITHER** valid fields are False
 - Regardless of value contents
- **OR** all fields are equal
 - valid is True and value matches

```
impl PartialEq for SensorData {  
    fn eq(&self, other: &Self) -> bool {  
        if self.valid && other.valid {  
            self.value == other.value  
        } else {  
            self.valid == other.valid  
        }  
    }  
}
```

Note

Custom Equality: Two different objects can represent the same value

Ordering

- Similar to `Eq` (and `PartialEq`)
 - Automatic implementation (`derive`) does a lexicographical comparison
 - Programmer implementation allowed for **both** traits
- `Ord`
 - Built on `PartialOrd`
 - Returns `Ordering`

```
enum Ordering {Less, Equal, Greater};
```
- When using `derive`, fields compared *in order*
 - Changing list of fields can change `Ord` result

Note

`PartialEq` must be defined (either manual or derived)

Partial Ordering

PartialOrd

- Returns `Option<Ordering>`
 - `None` can be returned if two values cannot be compared

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

```
impl PartialOrd for MyData {  
    fn partial_cmp(&self, other: &Self) -> Option<Ordering> {  
        // If one is invalid and the other isn't, the valid one is "greater"  
        match (self.valid, other.valid) {  
            (true, true) => self.value.partial_cmp(&other.value),  
            (true, false) => Some(Ordering::Greater),  
            (false, true) => Some(Ordering::Less),  
            (false, false) => Some(Ordering::Equal),  
        }  
    }  
}
```

Ordering and Equality

- `PartialOrd` and `PartialEq` are *linked traits*
 - They must be **consistent**
- If `PartialOrd` returns `Ordering::Equal` for two objects
 - `PartialEq` **must** return `True` for those objects



Warning

If `PartialEq` returns `True` but `PartialOrd` does not return `Equal`, behavior is non-deterministic

Operators

Operator Overloading

Traits in `std::ops` are used to overload operators (e.g., `+`, `-`, `*`)

- E.g., `+`, `-`, `*`
- Operators are delegated to trait methods (`Add`, `Sub`, etc.)

Operator	Trait	Method Signature
<code>+</code>	<code>Add</code>	<code>fn add(self, rhs: Rhs) -> Self::Output</code>
<code>-</code>	<code>Sub</code>	<code>fn sub(self, rhs: Rhs) -> Self::Output</code>
<code>*</code>	<code>Mul</code>	<code>fn mul(self, rhs: Rhs) -> Self::Output</code>
<code>/</code>	<code>Div</code>	<code>fn div(self, rhs: Rhs) -> Self::Output</code>
<code>%=</code>	<code>RemAssign</code>	<code>fn rem_assign(&mut self, rhs: Rhs)</code>
<code>!</code>	<code>Not</code>	<code>fn not(self) -> Self::Output</code>

Note

`Self::Output` indicates return type defined by the implementation

Overload "Add" Example

```
struct Feet(f64);
struct Inches(f64);

impl std::ops::Add for Inches {
    type Output = Feet;

    fn add(self, rhs: Self) -> Self::Output {
        Feet((self.0 + rhs.0) / 12.0)
    }
}

let measure1 = Inches(10.0);
let measure2 = Inches(32.0);

println!("{}", inches + {} inches", measure1.0, measure2.0);

let feet = measure1 + measure2;
println!("= {} feet", feet.0);
```

10 inches + 32 inches
= 3.5 feet

Type Conversions

Type Conversion

■ Conversion traits

- `From<T>` - converts a value into `Self`
- `Into<T>` - converts `Self` into a value
- `Into` can be inferred when `From` implemented

■ Why it matters

- Standardized way to convert between types with consistent syntax
- Used extensively in APIs for ergonomic type transformations

■ These methods are transformative

- `.into()` consumes the source (unless it implements `Copy`)

Note

`From`/`Into` are intended for infallible conversions (cannot fail)

Conversion Examples

■ From

- Uses source type for conversion

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

■ Into

- Uses target type for conversion

```
let a_string: String = "hello".into();  
let addr: std::net::Ipv4Addr = [127, 0, 0, 1].into();  
let one: i16 = true.into();  
let bigger: i32 = 123_i16.into();
```

"From" vs. "Into"

- If **From** is implemented, **Into** is inferred
 - Good idea to always implement **From** for types
 - Common practice to just implement **From**

- **From** specifies both source and destination

```
let result = Feet::from(measure);
```

- result is in Feet

- **Into** is called on an object

- Compiler might not know the source
- Need to supply hints

```
// What do we want 'target' to be?
```

```
let target = source.into();
```

```
// Have to help it:
```

```
let target: Feet = source.into();
```

Note

Conversions become very powerful when writing generic functions

Casting Between Primitive Types

- Conversion (casting) between primitive types with **as**

`my_u8 as u32`

- No *implicit* casting
- Unlike **From**, casting does not use traits
 - It is a built-in language "force-move"
- Casting truncates using **bitmasking** - keeps the lower bits
 - Even for things like **enum** and pointers
 - **From** and **Into** are safer

Casting Examples

```
let value: i64 = 1000;  
println!("value as i16: {}", value as i16);  
println!("value as u8: {}", value as u8);  
let signed_value = -136;  
println!("signed_value as u16: {}", signed_value as u16);
```

value as i16: 1000 *no lost bits*

value as u8: 232 *lost higher order bits*

signed_value as u16: 65400 *lost sign bit!*

Safer Conversions

Use `TryFrom` (or `TryInto`) rather than `as`

- Returns error type
- Useful when input is not guaranteed
 - Such as user input

```
let big_number: i32 = 300;
```

```
let casted = big_number as u8;
```

```
println!("'as' result:    {} -> {}", big_number, casted);
```

```
let tried = u8::try_from(big_number);
```

```
match tried {
```

```
    Ok(num) => println!("'TryFrom' result: Success! {}", num),
```

```
    Err(_) => println!("'TryFrom' result: Error! {} is too big for u8", big_number),
```

```
}
```

```
}
```

```
'as' result:    300 -> 44
```

```
'TryFrom' result: Error! 300 is too big for u8
```

Conversion vs. Casting

Method	Safety Level	Best Use Case
<code>From/Into</code>	Guaranteed	Lossless conversion (e.g., <code>&str</code> to <code>String</code>)
<code>TryFrom/TryInto</code>	Checked	Conversions that might fail (e.g., <code>u32</code> to <code>u8</code>)
<code>as</code> (Widening)	Safe	Moving to a larger type (e.g., <code>u8</code> to <code>u32</code>)
<code>as</code> (Narrowing)	Dangerous	Only when truncating bits is intentional



Tip

- `Into` or `TryInto` for clarity and safety
- Don't use `as` to force a conversion

I/O Traits

Reading and Writing via Trait

■ `std::io::Read`

- Implemented by types from which bytes can be sourced
 - E.g., `File` or `&[u8]`
- **Key methods:** `read()`, `read_to_string()`

■ `std::io::Write`

- Implemented by types to which bytes can be sent
 - Such as `File`, `TcpStream`, or `Vec<u8>`
- **Key methods:** `write()`, `flush()`

■ Central to I/O ecosystem

- Many types can be read from/written to
- Allows function to accept any readable/writable source
 - I.e., files, network, memory, etc.

"Write" Then "Read" Example

```
use std::fs::File;
use std::io::{Read, Write};

// ----- Write -----
let mut file = File::create("example.txt"?);
file.write_all(b"Hello, Rust!\n"?);

// ----- Read -----
let mut file = File::open("example.txt"?);
let mut contents = String::new();
file.read_to_string(&mut contents)?;
```

Note

More on *try operator* (?) later

Practical Patterns

- Writers often implement `flush()` to ensure output is sent

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

fn main() -> std::io::Result<()> {
    let mut file = File::create("log.txt"?;

    // The OS receives this data, but might hold it in a 'page cache'
    file.write_all(b"Critical system event occurred.")?;

    // Ensures the OS moves data from its internal cache to the storage device
    file.flush()?;

    println!("Data is physically committed to disk.");
    Ok(())
}
```

Data is physically committed to disk.

Default Values

"Default" Trait

- `std::default::Default` trait
 - Defines a default value for a type
 - `fn default() -> Self`
 - Great for API ergonomics and fallback values
- Usage
 - Commonly derived with `#[derive(Default)]`
 - If every field implements `std::default::Default`

Default Values

Category	Type	Default Value
<i>Integers</i>	i8, u32, isize, etc.	0
<i>Floats</i>	f32, f64	0.0
<i>Boolean</i>	bool	false
<i>Characters</i>	char	'\0' (Nul)
<i>Strings</i>	String	"" (Empty)
<i>Collections</i>	Vec<T>, HashMap<K, V>	Empty (Size 0)
<i>Options</i>	Option<T>	None
<i>Smart Pointers</i>	Box<T>, Arc<T>	Pointer to T::default()
<i>Tuples</i>	(A, B)	(A::default(), B::default())

Default Values in a "struct"

```
#[derive(Debug, Default)]
struct Config {
    port: u16,
    host: String,
    debug: bool,
}
```

■ Usage

```
let example = Config::default();
println!("Defaults: {example:?}");
```

- `std::default::Default` uses sensible default values for each field

```
Defaults: Config { port: 0, host: "", debug: false }
```

■ Using struct update operator

```
let c2 = Config { port:123, ..Default::default() }
```

- Default values for host and debug
- New value for port

Default Values in "enum"

- `enum` can be one of multiple variants
 - How is the default specified?
- Default value specified by programmer when creating `enum`

```
#[derive(Default)]  
enum Status {  
    #[default]  
    Pending,  
    Active(i32),  
    Closed,  
}
```

- `Pending` becomes the default value
- Derived defaults only work for *unit variants*
 - `Active` would not be selectable



Tip

If `Active` should be default, manually implement `Default` trait

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Comparing Objects

- `PartialEq` and `Eq` for comparison
- `PartialOrd` and `Ord` for ordering

■ Performing Mathematical Operations

- Overloading operators to provide custom capabilities

■ Converting Between Types and Values

- Conversion using `From` and `Into`
- Casting using `as`

■ Input/Output on Types

- Implementing `Read` and `Write` for types

■ Default Values for Types

- Assigning default values to fields

Memory Management

Introduction

Topics Covered

- **Program Memory**
 - Stack and heap
- **Ownership**
 - Scope and single owner rule
- **Move Semantics**
 - Transferring ownership
- **Deep Copies vs. Bitwise Replication**
 - **Clone** vs. **Copy**
- **Clean-Up Logic**
 - **Drop** mechanism

Program Memory

Overview

Stack

- Continuous area of available memory
- Types must have a fixed size known at compile-time
- Extremely fast due to contiguous memory layout

Heap

- Allocation is requested at runtime
- Supports dynamic sizes and data that outlive function calls
- Slower due to pointer indirection and allocation overhead

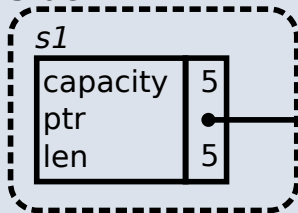
Memory Layout Example

Creating a `String` puts

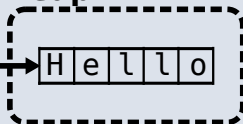
- Fixed-sized metadata on the **stack**
- String contents (UTF-8 bytes) on the **heap**

```
let s1 = String::from("Hello");
```

Stack



Heap



Approaches

Approaches to Memory Management

■ Manual Memory Management (e.g., C/C++)

■ *Full control*

- Programmer explicitly allocates/deallocates

■ *Higher risk*

- Programmer must ensure pointers are valid

■ Automatic Memory Management (e.g., Java, Python)

■ *Safety*

- Runtime ensures memory is not freed until unreferenced

■ *Higher cost*

- Runtime overhead for garbage collection

■ Ownership-based Memory Management (e.g., Rust, SPARK)

■ *Safety*

- Compile-time memory guarantees

■ *Control*

- Ownership, borrowing and lifetimes

Quick Comparison

Feature	Manual (C/C++)	Automatic (Java, Python)	Ownership (Rust, SPARK)
<i>Control</i>	Full	Low	High
<i>Safety</i>	High risk of error	High safety	Compile-time safety
<i>Mechanism</i>	<code>malloc/free</code>	Garbage collector	Borrow checker
<i>Runtime Overhead</i>	Minimal	<i>Stop-the-World</i> pauses	Zero
<i>Programmer Overhead</i>	Manual tracking	Low	Compilation time



Note

Rust offers memory safety, predictable performance, and zero runtime cost

Ownership

Scope and Validity

- Variable bindings are only accessible within their defined **scope**
- Out-of-scope variables are strictly caught at compile-time

```
struct Point(i32, i32);

{ // Outer scope starts
  { // Inner scope starts
    let pt = Point(3, 4); // 'pt' becomes valid
    println!("x: {}", pt.0);
  } // Inner scope ends, 'pt' is dropped
  println!("y: {}", pt.1); // Error
} // Outer scope ends
```

error[E0425]: cannot find value 'pt' in this scope

Ownership Principles

- Variable **owns** the value
- Every value has precisely **one owner** at all times
- When the owner goes **out of scope**, the value is **dropped**

```
{  
    let poodle = String::from("ball"); // 'poodle' owns the ball  
    let yorkie = poodle; // 'poodle' lets go, 'yorkie' picked it up  
  
    // println!("{}", poodle); // Error  
    println!("{}", yorkie);  
} // 'yorkie' drops the ball, and leaves  
// 'poodle' leaves quietly
```

ball

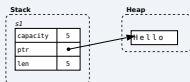
Move Semantics

Transferring Ownership

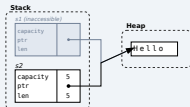
Assigning a value to a new variable transfers ownership

- Compiler treats a *moved* variable as uninitialized
- To ensure memory safety and prevent "double-free" errors
- And forbids any further use of it

Before move to s2:



After move to s2:



```
let s1 = String::from("Hello");  
let s2 = s1;
```

```
println!("{}", s1); // Error  
println!("s2: {}", s2);
```

error[E0382]: borrow of moved value: 's1'

Note

Applies to non-**Copy** types only: other types remain valid after assignment

Functions and Ownership

Passing by value moves data into function's scope

```
fn say_hello(name: String) {  
    println!("Hello {}", name);  
}  
  
let name = String::from("Alice");  
say_hello(name);  
say_hello(name); // Error
```

```
error[E0382]: use of moved value: 'name'
```

Note

`name` is *consumed* and can no longer be used

"Clone"

Explicit Duplication

Creates a "deep copy" of underlying data

- Typically duplicating heap-allocated resources

```
let poodle = String::from("ball");
```

```
let yorkie = poodle.clone();
```

```
println!("{}", poodle); // 'poodle' still has its ball
```

```
println!("{}", yorkie); // 'yorkie' has its own copy
```

```
ball
```

```
ball
```

Cost of Duplication

- Useful when original variable must remain valid after function call
- Significantly more expensive than a move
 - Requires new memory allocation and data migration

```
let t_rex_one = vec![0_u8; 10 * 1024 * 1024];  
let t_rex_two = t_rex_one.clone();  
println!("T-Rex One: {} bytes", t_rex_one.len());  
println!("T-Rex Two: {} bytes", t_rex_two.len());
```

T-Rex One: 10485760 bytes

T-Rex Two: 10485760 bytes

The "Clone Away" Strategy

During development, cloning can simplify ownership conflicts

- Optimize later when logic is stable
- Further refinements can substitute clones with references
 - `.clone()` serves as a clear visual marker of intentional heap allocation

```
let agent = String::from("Smith");
```

```
// Explicitly clone the data
```

```
say_hello(agent.clone());
```

```
say_hello(agent.clone());
```

```
say_hello(agent.clone());
```

```
say_hello(agent);
```

```
// 'agent' is no longer valid - its value was consumed
```

Note

Useful for rapid prototyping and getting code working early

"Copy" Semantics

"Copy" Types

- Usually live on the stack
- Utilize automatic *bitwise* duplication
- Cost of copying is negligible
- Implement `Copy` trait
 - Scalar types are `Copy`

Note

Saying a type is `Copy` means it implements the `Copy` trait

```
let gizmo = 1984;  
let gremlin = gizmo;  
  
println!("gizmo: {gizmo}"); // Valid: 'gizmo' was not moved  
println!("gremlin: {gremlin}");
```

```
gizmo: 1984  
gremlin: 1984
```

Custom "Copy" Types

- Programmer-defined types can opt-in to `Copy`
 - Via `#[derive]` macro or manually with `impl`

```
#[derive(Copy, Clone)]  
struct Point(i32, i32);
```

```
let p1 = Point(3, 4);  
let p2 = p1;
```

- `p1` and `p2` hold independent copies of data
- `let p2 = p1.clone();` produces the same result
 - But `Copy` makes it implicit

No "Copy" Without "Clone"

- `Copy` is a *subtrait* of `Clone`
 - Defined as `trait Copy: Clone`
- Using `#derive[Copy]` alone triggers a compile error

```
#[derive(Copy)]  
struct Point(i32, i32);
```

```
let p1 = Point(3, 4);  
let p2 = p1;
```

error[E0277]: the trait bound 'Point: Clone' is not satisfied

"Copy" Types and Field Constraints

- Programmer-defined types can only be `Copy` if all fields are also `Copy`
- Types that own heap memory cannot be `Copy`
 - Prevents memory issues

```
#[derive(Copy, Clone)]  
struct User(i32, String);
```

```
let user_a = User(42, String::from("Alice"));  
let user_b = user_a;
```

```
error[E0204]: the trait 'Copy' cannot be implemented for this type
```

"Copy" vs. Non-"Copy"

Property	Copy types	Non-Copy types
<i>Assignment logic</i>	Still usable	Invalid (compile error if used)
<i>Trait required</i>	<code>impl Copy</code>	None (default behavior)
<i>Examples</i>	<code>i32</code> , <code>bool</code> , <code>[f64, 4]</code>	<code>String</code> , <code>Vec<T></code>

"Drop"

Destructor ("Drop")

- Deterministic clean-up implemented with `Drop` trait
 - Occurs *implicitly*, and usually at the closing brace `}`
 - Calling `.drop()` manually results in a compile error
- Ideal for resource management, e.g, closing files or network sockets

```
struct Mic {  
    owner: String,  
}  
  
impl Drop for Mic {  
    fn drop(&mut self) {  
        println!("{}", self.owner);  
    }  
}
```

Note

Saying a type has a *destructor* means it implements the `Drop` trait

Variable Drop Order Example

```
struct Potato {  
    id: String,  
}  
  
impl Drop for Potato {  
    fn drop(&mut self) {  
        println!("Dropping {}", self.id);  
    }  
}  
  
fn main() {  
    let s1 = "tic".into();  
    let s2 = "tac".into();  
    let s3 = "toe".into();  
    let _tic = Potato { id: s1 };  
    {  
        let _tac = Potato { id: s2 };  
    }  
    let _toe = Potato { id: s3 };  
}
```

Dropping tac
Dropping toe
Dropping tic

Note

Variables are dropped in the *reverse order* of their declarations

Internal Field Drop Order Example

```
struct Eggs;
struct Bacon;

impl Drop for Eggs {
    fn drop(&mut self) {
        println!("Dropping eggs!");
    }
}

impl Drop for Bacon {
    fn drop(&mut self) {
        println!("Dropping bacon!");
    }
}

struct Breakfast {
    one: Eggs,
    two: Bacon,
}

fn main() {
    let _meal = Breakfast {
        one: Eggs,
        two: Bacon,
    };
}
```

Dropping eggs!
Dropping bacon!

Note

Fields of a struct are dropped in *declaration order*

Explicit Drop

- Early clean-up is possible by calling `std::mem::drop`
- `std::mem::drop` (in *prelude*) is an empty generic function that
 - Captures ownership of passed value
 - Triggers `Drop` mechanism as value goes out of scope

```
let my_precious = String::from("The One Ring");  
drop(my_precious); // 'my_precious' is moved then dropped
```

```
println!("{}", my_precious); // Error
```

```
error[E0382]: borrow of moved value: 'my_precious'
```

Note

`std::mem::drop` differs from `std::ops::Drop::drop`

Exclusivity of "Copy" and "Drop"

- Type cannot implement both **Copy** and **Drop** traits
 - Implementing **Drop** guarantees destructor runs *exactly once*
- **Copy** implies simple bitwise replication

```
#[derive(Copy, Clone)] // This line will not compile  
struct Highlander;
```

```
impl Drop for Highlander {  
    fn drop(&mut self) {  
        println!("There can be only one!");  
    }  
}
```

```
error[E0184]: the trait 'Copy' cannot be implemented for this type; the type has a destructor
```

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

Recap: Memory Semantics

Mechanism	Behavior	Impact	Trigger
<i>Move</i>	Ownership transfer	Zero	Default for non- Copy types
<i>Clone</i>	Explicit duplication	High	Manual <code>.clone()</code> call
<i>Copy</i>	Implicit duplication	Low	Automatic for Copy types

What We Covered

■ Ownership

- Single owner rule ensures safety at compile time
- Scopes determine when data is freed

■ Move

- Transfers ownership

■ Copy

- Implicit bitwise copy

■ Clone

- Explicit deep copy, required for non-**Copy** types

■ Clean-up

- Resources are freed the moment owner exits its scope
- **Drop** trait allows custom destructor logic
- Manually triggered destruction with `std::mem::drop`

Smart Pointers

Introduction

Topics Covered

■ Heap allocation

- Flexible sizing
- Bypassing Sized constraints

■ Dereferencing

- Overriding the operator
- Transparent data access via coercion

■ Shared Ownership

- Tracking references

Why Smart Pointers?

- Allow recursive types
 - Provide a fixed-size pointer on the stack
- Prevent stack overflows
 - Allocate data on the heap
- Allow multiple owners
 - Share ownership of data for complex architectures

`"Box<T>"`

What Is "Box<T>"

- Allocates data on the heap (via `Box::new`)
 - Stores a fixed-size pointer on the stack
 - Retains single ownership of heap data
- Deallocates memory automatically when object goes out of scope
- Defined in **prelude**

```
// 'Box::new()' is used to allocate data
```

```
let my_box = Box::new(5);
```

```
// Implicit dereference
```

```
println!("Box value is {}", my_box);
```

```
Box value is 5
```

Using "Box<T>" for Recursive Types

- Types must have a known size at compile time

- Recursive types don't have a known size

```
// FAILS: How big is an infinite doll?
```

```
enum Doll {  
    Inside(Doll),  
    Empty,  
}
```

```
error[E0072]: recursive type 'Doll' has infinite size
```

- `Box<T>` provides a pointer with known size

- Breaks direct recursion loop in memory

```
// WORKS: The 'Box' is just a pointer to the next doll
```

```
enum Doll {  
    Inside(Box<Doll>),  
    Empty,  
}
```

```
let a_doll = Doll::Inside(Box::new(Doll::Empty));
```

```
let last_doll = Doll::Empty;
```

Handling Large Data

- `Box<T>` allows transferring ownership of data
- Rather than copying data passed in parameters for function calls
 - Useful for large data

```
struct BigData {  
    samples: [u64; 1000000],  
    metadata: String,  
}  
  
let huge_chunk = Box::new(BigData {  
    samples: [0; 1000000],  
    metadata: String::from("Satellite Telemetry - Region A"),  
});  
  
// Only reference is moved to the function...  
// ...not the whole array  
process_data(huge_chunk);
```

Resource Management

- `Box<T>` implements `Drop` to ensure memory safety
 - Invokes `Drop` method automatically at end of scope
 - No need for manual intervention
 - Prevents memory leaks by ensuring deallocation
- Transferring ownership is an $O(1)$ operation
 - Regardless of what it points to

Dereferencing

"Deref" Trait

- Smart pointers behave like references
 - Because they implement `Deref`
- `Deref` returns a reference to the inner data
 - Data is accessed with dereference operator `*`
 - Avoids moving ownership

```
fn say_hello(name: i32) {  
    println!("Hello, 00{name}!");  
}
```

```
let agent = Box::new(7_i32);
```

```
say_hello(*agent);
```

Hello, 007!

Coercing Types With "Deref"

- Coercion allows conversion of a referenced type to a different type
 - If `Deref` is implemented between the types
- Performs multiple "steps" of coercion at compile time
 - Zero runtime performance penalty
- Accesses inner value of smart pointers transparently

```
fn hello(name: &str) {  
    println!("Hello, {name}!");  
}
```

```
let my_box = Box::new(String::from("Rust"));
```

```
hello(&my_box);
```

```
Hello, Rust!
```

Note

- `&my_box` is `&Box<String>`
- Compiler coerces: `&Box<String> -> &String -> &str`

"DerefMut"

- Subtrait of `Deref`
 - `Deref` must be implemented first
- Allows *mutable reference*

```
// 'my_box' is mutable and 'Box' implements 'DerefMut'  
let mut my_box = Box::new(0);  
*my_box = 10; // 'DerefMut' is used
```

Mutability and Coercion

■ From `&T` to `&U`

- Trait required T: `Deref<Target = U>`

```
fn hello(name: &str) { println!("Hello, {name}!"); }  
  
fn edit(name: &mut str) { println!("Hello, {name}!"); }
```

```
let my_box = Box::new(String::from("Rust"));  
hello(&my_box);
```

■ From `&T` to `&mut U`

- Not allowed

```
edit(&my_box); // Error
```

```
error[E0308]: mismatched types
```

```
let mut my_box2 = Box::new(String::from("Rust"));
```

■ From `&mut T` to `&mut U`

- Trait required T: `DerefMut<Target = U>`

```
edit(&mut my_box2);
```

■ From `&mut T` to `&U`

- Trait required T: `Deref<Target = U>`

```
hello(&mut my_box2);
```

`"Rc<T>"`

Multiple Ownership With "Rc<T>"

- Useful when *single* value is owned by *multiple* parts of a program
 - Only provides *immutable access* to the data
 - Tracks number of active references
 - Prevents data cleanup until last owner finishes
- Called *Reference Counted (Smart) Pointer*
 - included with `use std::rc::Rc`

"Rc<T>" Counts References

Shares ownership of value on the heap using `Clone`

- Creates a *shallow* copy not a deep copy
 - Only the *pointer* is copied
- Increments the internal counter

// Both 'var_a' and 'var_b' share ownership of the value

```
let var_a = Rc::new(5);  
println!("Count: {}", Rc::strong_count(&var_a));
```

```
let var_b = Rc::clone(&var_a);  
println!("Count: {}", Rc::strong_count(&var_a));
```

Count: 1

Count: 2

Immutable Access

Rc<T> allows multiple ownership but no mutable access

```
let tic = Rc::new(5);  
let tac = Rc::clone(&tic);  
let toe = Rc::clone(&tic);
```

```
*tic += 10; // Error: no mutable access
```

```
error[E0594]: cannot assign to data in an 'Rc'
```

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

Comparing "Rc<T>" and "Box<T>"

Properties	Box<T>	Rc<T>
<i>Ownership</i>	Single	Multiple
<i>Access</i>	Mutable	Immutable
<i>Memory location</i>	Heap	Heap
<i>Cloning</i>	Deep copy	Shallow copy
<i>Main Use Case</i>	Big data/recursive types	Complex architecture

What We Covered

- **Box<T>**
 - Allocates data on the heap
 - Enables recursive data structures
- **Deref**
 - Treats smart pointers like references
 - Uses coercion to access inner values
 - With no runtime cost
- **Rc<T>**
 - Allows multiple owners for the same data
 - Avoids expensive cloning by reusing the same heap allocation

Borrowing

Introduction

Topics Covered

■ Accessing Data Without Taking Ownership

- Local, function, and method borrows
- Compile-time safety and the *Borrow Checker*

■ Interior Mutability

- `Cell<T>` vs. `RefCell<T>`
- Bypassing strict compile-time rules safely

Borrowing a Value

Why Borrowing?

- Ownership transfer is not always practical
 - Because cloning is expensive
 - And moving data back and forth is cumbersome
- Borrowing allows access to data
 - Without taking ownership
 - Implemented using a reference
 - Denoted `&` or `&mut`

Note

Borrowed data is not dropped when a reference is no longer used

Local Borrows

- Multiple references (`&T`) can read the data simultaneously
- A single reference (`&mut T`) can change the data
 - Provided "readers" are gone

```
struct Sensor(i32);  
let mut scanner = Sensor(42);  
  
let r1 = &scanner; // First immutable borrow  
let r2 = &scanner; // Second immutable borrow  
println!("Reads: {} and {}", r1.0, r2.0);  
// 'r1' and 'r2' drop here  
  
let w1 = &mut scanner; // Mutable borrow  
w1.0 += 10;  
println!("Calibrated to: {}", w1.0);  
println!("Original      : {}", scanner.0);
```

```
Reads      : 42 and 42  
Calibrated to: 52  
Original   : 52
```

Mixing Mutable and Immutable Borrows

Guarantees memory safety at compile-time

```
struct Sensor(i32);  
let mut scanner = Sensor(42);  
  
// Immutable borrow starts  
let reader = &scanner;  
  
// Mutable borrow  
let writer = &mut scanner; // This won't compile  
  
println!("Read: {}, Write: {}", reader.0, writer.0);
```

```
error[E0502]: cannot borrow 'scanner' as mutable because it is also borrowed as immutable
```

Function Borrows

Functions can

- Access values safely without consuming them
- Update the original variable directly

```
struct Sensor(i32);

fn read(device: &Sensor) {
    println!("Read: {}", device.0);
}

fn calibrate(device: &mut Sensor) {
    device.0 += 10;
}

let mut scanner = Sensor(42);

read(&scanner);           // Read-only borrow starts and ends
calibrate(&mut scanner);  // Mutable borrow starts and ends
read(&scanner);           // Read-only borrow starts and ends
```

Read: 42

Read: 52

Note

As long as function calls do not overlap in their borrowing, compiler allows it

Overlapping Borrows

- Passing data to functions is still bound by the same rules
- Cannot call a function that requires a mutable reference
 - If an immutable reference is still used

```
struct Sensor(i32);

fn calibrate(device: &mut Sensor) {
    device.0 += 10;
}

let mut scanner = Sensor(42);
let active_reader = &scanner; // Immutable borrow starts

calibrate(&mut scanner); // Mutable borrow - this won't compile

println!("Reader sees: {}", active_reader.0);
```

```
[E0502]: cannot borrow 'scanner' as mutable because it is also borrowed as immutable
```

Multiple Mutable Borrows

Functions cannot receive multiple mutable references to the same data

- Prevented by the borrow checker at compile-time

```
struct Sensor(i32);
```

```
fn sync_sensors(s1: &mut Sensor, s2: &mut Sensor) {  
    s1.0 = s2.0;  
}
```

```
let mut scanner = Sensor(42);  
sync_sensors(&mut scanner, &mut scanner); // Error
```

```
error[E0499]: cannot borrow 'scanner' as mutable more than once at a time
```

Method Borrows

Methods can take

- Simultaneous immutable borrows using `&self`
- Exclusive mutable borrow using `&mut self`

```
struct Sensor(i32);

impl Sensor {
    fn read(&self) -> i32 { self.0 }
    fn calibrate(&mut self) { self.0 += 10; }
}

let mut scanner = Sensor(42);
let val = scanner.read(); // '&self' borrow, completes and drops

scanner.calibrate();      // '&mut self' borrow, exclusive
scanner.read();           // '&self' borrow
```

Note

`&` and `&mut` referencing handled **automatically** at the call site

Conflicting Self Borrows

- Same overlapping rules enforced for methods as for functions
- Immutable borrow prevents mutable method calls
- Immutable reference must reach final use before value can be modified

```
struct Sensor(i32);

impl Sensor {
    fn read(&self) -> i32 { self.0 }
    fn calibrate(&mut self) { self.0 += 10; }
}

let mut scanner = Sensor(42);

let snapshot = &scanner; // Immutable borrow starts
scanner.calibrate(); // This won't compile
println!("Reference sees: {}", snapshot.read());
```

```
error[E0502]: cannot borrow 'scanner' as mutable because it is also borrowed as immutable
```

Interior Mutability

Limitations of Strict Rules

- Immutable references strictly **forbid** data modification
- Certain patterns require updating hidden state
 - During a read-only `&self` method call
- Compile-time borrow checks are traded for runtime checks

Note

Interior mutability enables safe modification through shared references

"Cell<T>"

- Guarantees safe modification through a shared, read-only reference
- Designed for types that implement **Copy** trait
 - Such as integers or booleans
- References to the inner data are never exposed

"Cell<T>" Example

Values are exclusively copied in (set) and out (get)

```
use std::cell::Cell;

struct Sensor {
    data: i32,
    read_count: Cell<u32>, // Can be modified even if 'Sensor' is '&self'
}

impl Sensor {
    fn read(&self) -> i32 {
        self.read_count.set(self.read_count.get() + 1);
        self.data
    }
}

let scanner = Sensor { data: 42, read_count: Cell::new(0) };
scanner.read(); // Borrows immutably

println!("Sensor read {} time(s)", scanner.read_count.get());
```

```
Sensor read 1 time(s)
```

"RefCell<T>"

- Used for complex types, like `Vec` or `String`
 - Where copying isn't cheap or possible
- Enforces borrowing rules at runtime rather than compile-time
- `.borrow()` for a reader
- `.borrow_mut()` for a writer

```
use std::cell::RefCell;
```

```
let memory = RefCell::new(vec![42, 10]);
```

```
// Modify the vector through an immutable variable 'memory'
```

```
let mut writer = memory.borrow_mut();  
writer.push(99);
```

```
let reader = memory.borrow(); // This will panic
```

⚠ Warning

If rules are violated, program will immediately panic and crash

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Borrowing Rules

- Guarantee safety by enforcing strict access

■ Local, Function, and Method Borrows

- Same borrowing rules apply when
 - Assigning local variables
 - Passing arguments to functions
 - Calling methods via `&self` or `&mut self`

■ Compile-Time Safety

- Overlapping mutable or immutable references are strictly checked

■ Interior Mutability

- Allows safe data modification through shared immutable references

Lifetimes

Introduction

Topics Covered

■ Lifetimes

- What a lifetime represents
- Why references must maintain validity
- How the borrow checker enforces this

■ Annotations

- Explicit lifetime syntax
- Lifetimes in function signatures
- Lifetimes in structs and other data types

■ Elision

- Why lifetimes are often omitted
- Compiler rules for assigning lifetimes
- When elision is not sufficient

■ Structs and Enums

- Lifetimes in structs
- Borrowed vs. owned data
- When explicit lifetimes are required

Lifetimes

What Is a Lifetime?

- Span of code during which a reference is valid
 - Not to be confused with **scope** of variables!
- Ends the last time its reference is used
- Exists even when not written

```
1 {  
2   let treasure = "gold";  
3   let treasure_map = &treasure;  
4   println!("{treasure_map}");  
5   println!("{treasure}");  
6 }
```

```
gold  
gold
```

- `treasure` is in scope from lines 2 – 5
- `treasure_map` lifetime is from lines 3 – 4

Why Lifetimes Matter

References point to data owned elsewhere

- If data is dropped while a reference still exists...
 - ...the program would have a **dangling reference**
- A reference cannot outlive the value it refers to
 - Enforced at **compile time**

Lifetime Enforcement

- Borrow checker verifies references remain valid
 - Reference Lifetime $\leq$ Value Lifetime
- Prevents
 - Dangling references
 - Use-after-free
 - Invalid memory access
- No garbage collector required!

Lifetime Annotations

Lifetime Annotations

- Every reference has a lifetime
 - Usually, compiler determines it automatically
 - A *lifetime annotation* can name it explicitly
- Written using a leading `'`

```
&'a  
&'my_life  
&'some_really_long_name
```

- **Example:** Reference to `str` valid for at least lifetime `'a`

```
&'a str
```

Note

- Common to use short names (`'a`, `'b`, etc.)
- More descriptive names can be used (`'i_mean_something`)

Why Do We Need Lifetime Annotations?

- Describe relationships between references
 - Do not create *actual* lifetimes
- Only *required* when relationships are ambiguous

// This code won't compile!

```
fn choose(left: &str, right: &str) -> &str {  
    if left.len() > right.len() {  
        left  
    } else {  
        right  
    }  
}
```

error[E0106]: missing lifetime specifier

Note

- Rust includes some predefined lifetimes
- For this course, it's only important to know
 - `'static` - means data lives for the entire program
 - `'_` - placeholder for an inferred lifetime

Solving Ambiguity With Lifetimes

Previously, we encountered an error: a lifetime annotation solves it

```
// The return value could come from either input,  
// so they must share the same lifetime  
fn choose<'a>(left: &'a str, right: &'a str) -> &'a str {  
    // Return 'left' or 'right' depending on the condition  
    if left.len() > right.len() {  
        left // Return a reference to 'left'  
    } else {  
        right // Or return a reference to 'right'  
    }  
}
```



Note

Sometimes the term "lifetime" is used to indicate "lifetime annotation"

Lifetimes in Function Signatures

- Appear in reference types
- Describe relationships between inputs and outputs

```
// Returned reference comes from 'slice'  
fn first<'a>(slice: &'a [i32]) -> &'a i32 {  
    &slice[0]  
}
```

Note

First element of a slice cannot live longer than the slice itself

Lifetime Elision

Why Are Lifetimes Often Omitted?

- Writing lifetime (annotations) everywhere would be verbose
- Many lifetime patterns are predictable
- Would add unnecessary annotation in common cases

// Same lifetime repeated in multiple places

```
fn print<'a>(s: &'a str) {  
    println!("{}", s);  
}
```

// Input and output clearly share the same lifetime

// (but we still have to write it everywhere)

```
fn first<'a>(slice: &'a [i32]) -> &'a i32 {  
    &slice[0]  
}
```

// Lifetime doesn't even affect the return value

// (but we still have to write it on the parameter)

```
fn len<'a>(s: &'a str) -> usize {  
    s.len()  
}
```

Note

Rust reduces this repetition automatically

Lifetime Elision

- Most code omits explicit lifetime annotations
- **Lifetime elision** rules can be applied
 - Each reference parameter gets its own lifetime
 - If there is only one input lifetime, it is used for the return value
 - If first parameter is **self**, that lifetime is used
- Compiler automatically assigns lifetimes using these rules
- Essentially, syntactic shorthand (not inference)

```
fn length(s: &str) -> usize
```

// ...is interpreted as

```
fn length<'a>(s: &'a str) -> usize
```

Note

Compiler infers lifetimes even when they're not written

Lifetimes in Structs and Enums

Lifetimes in Structs

- If a struct stores references, it **must** specify a lifetime
- Instances of the struct cannot outlive the data they reference

```
// Missing lifetime - does not compile  
struct Scroll {  
    inscription: &str,  
}
```

```
error[E0106]: missing lifetime specifier
```

```
// Lifetime ties the struct to the referenced data  
struct Scroll<'a> {  
    inscription: &'a str,  
}
```

Note

We refer to structs here, but enums behave the same way

Borrowed Data vs. Owned Data

// Borrowed data (requires a lifetime)

```
struct Scroll<'a> {  
    inscription: &'a str,  
}
```

// Owned data (no lifetime needed)

```
struct Scroll {  
    inscription: String,  
}
```



Tip

Better to own data *unless* borrowing provides clear benefits

When to Use Explicit Lifetimes

- Returning references from functions
- Structs store references
- Multiple input references create ambiguity

Note

For most other cases, lifetime elision rules apply

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Lifetimes

- How long references are valid
- References cannot outlive data they refer to
- Borrow checker verifies this at compile time

■ Annotations

- Describe relationships between references
- Part of reference types
- Most are inferred automatically

■ Elision

- Lifetimes are still present even when not written
- Compiler applies fixed rules (not guesswork)
- Explicit lifetimes needed when relationships are ambiguous

■ Structs and Enums

- Storing references requires lifetimes
- Lifetimes follow same rules as functions
- Owning data is often simpler than borrowing

Iterators

Introduction

Topics Covered

■ What Is an Iterator

- Mechanics of loops over collections

■ Iterator as a Trait

- Looping over a collection

■ Iterator Trait Methods

- Mechanisms to work with collections

■ Collecting Data via Iterator

- Creating a new collection from an existing one

■ Converting to an Iterator

- Creating an iteration mechanism for a particular type

Defining an Iterator

What Is an Iteration?

- Simplest form of *iteration* is a "for loop"

```
let array = [2, 4, 6, 8];  
for idx in 0..4 {  
    println!("{}", array[idx]);  
}
```

- Iterations contain the following information

<i>Iteration State</i>	Current position in loop	<code>idx</code>
<i>Termination Condition</i>	When do we exit the loop	<code>idx < 4</code>
<i>State Update</i>	Moving to next item in loop	<code>idx = idx + 1</code>
<i>Data Retrieval</i>	Look at what is at the current position	<code>array[idx]</code>

What Is an Iterator?

- Provides standard way to access elements of a collection
 - One at a time
 - Typically in sequence
 - Without exposing collection's internal structure
 - Using types, traits, and methods
- Benefits include
 - Reduces "off-by-one" errors and index-out-of-bounds panics
 - Lightweight structs that hold iteration state
 - Compile to very efficient loops
- Simple iterator example

```
let numbers = vec![1, 2, 3];  
  
// '.iter()' creates the iterator  
let it = numbers.iter();  
for num in it {  
    println!("{}", num);  
}
```

```
1  
2  
3
```

Note

Iterators remove the need to worry about "how" to loop

Iterator Trait

What Is an Iterator Trait?

■ Definition

- Defines standard interface for producing sequence of values one at a time

■ Core Idea

- Yields elements lazily from some underlying data source
 - E.g., collection, range, computation

Describing an Iterator Trait

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

- **type** Item;
 - Type of value the iterator yields
- **next**
 - Called repeatedly to get "next" value
 - Only required method
 - Returns **Option**
 - **Some**(value) - next element
 - **None** - iteration complete

Common Use Case - Iterating Over Slice

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

- "for loop" uses an iterator behind the scenes
 - `for` is syntactic sugar over `IntoIterator` trait

Helper Methods

Iterator Toolbox

- `next` is only **required** method
 - *Many* more *can* be implemented
- Iterator Adapters
 - Transform iterator into a **new** iterator
 - E.g., `map`, `filter`
 - Useful in chaining
 - Consecutive iteration
- Consumers
 - Drive iterator to produce final value
 - E.g., `sum`, `collect`
 - End any chaining
 - Result is **not** an iterator

Getting an Iterator - ".iter()"

- Collections themselves are not iterators
- Call `.iter()` to create iterator
 - Does **not** consume collection
 - Allows use of iterator adapters

```
3 let numbers = vec![10, 20, 30];  
4 for n in numbers.iter() {  
5     println!("{n}");  
6 }
```

```
10  
20  
30
```

Note

`.iter()` returns an iterator over references

Common Iterator Adapters

■ map - transform values during iteration

```
let numbers = vec![10, 20, 30];  
for elem in numbers.iter().map(|n| n * 2) {  
    println!("{elem}");  
}
```

```
20  
40  
60
```

■ filter - select values matching condition

```
let numbers = vec![11, 12, 13, 14];  
for elem in numbers.iter().filter(|n| *n % 2 == 0) {  
    println!("{elem}");  
}
```

```
12  
14
```

Note

Adapters return a **new** iterator - they don't consume values

Common Consumers

- `sum` - adds all values and return a single value

```
let numbers = [1, 2, 3, 4, 5];  
// '.iter()' creates the stream of references  
// '.sum()' pulls them all off and adds them up  
let total: i32 = numbers.iter().sum();  
println!("The total is: {total}");
```

15

- `any` - return `True` if any value matches condition

```
fn is_freezing(t: &i32) -> bool { todo!() }  
let temperatures = [22, 28, -2, 15, 30];  
  
// '.iter()' creates the stream of references  
// '.any()' looks for the first item that satisfies the closure  
if temperatures.iter().any(is_freezing) {  
    println!("Warning: Freezing temperatures detected!");  
} else {  
    println!("All temperatures are above freezing.");  
}
```

Warning: Freezing temperatures detected!

Note

Consumers return a single result from the iteration

Declarative Data Processing

Can use "chaining" instead of loops and conditionals

- Easier to read

```
fn is_even(t: &i32) -> bool { todo!() }  
fn square(t: &i32) -> i32 { todo!() }  
let result: i32 = (1..=10) // Range: 1, 2, 3, ..., 10  
    .filter(is_even)       // Keep even: 2, 4, 6, 8, 10  
    .map(square)           // Square: 4, 16, 36, 64, 100  
    .sum();                // Total: 220  
  
println!("Sum of even squares: {}", result);
```

Sum of even squares: 220

- Chaining builds a pipeline that is evaluated when the iterator is consumed
 - Modify values (map)
 - Skip values (filter)
 - Etc.

Reliability and Maintenance

■ Lazy evaluation

- Adapters do nothing until a "consumer" is called
 - sum or count, etc.
- Pipeline runs only when needed

■ Imperative vs. iterator implementation

■ `for` loop

```
let mut sum = 0;
for x in 1..=10 {
    if x % 2 == 0 {
        sum += x * x;
    }
}
```

■ Chaining and collection

```
let sum: i32 = (1..=10)
    .filter(|x| x % 2 == 0) // Keep only even numbers
    .map(|x| x * x)         // Square them
    .sum();                // Add them all up
```

"collect" Method

The Ultimate Consumer

- Most iterator methods (like `map` and `filter`) are *lazy*
 - Describe transformations
 - Don't modify any data
- `collect()` is the "on switch"
 - Runs entire pipeline
 - Stores results in a collection (`Vec` or `HashMap`, etc.)
- Typically use *turbofish* syntax to tell compiler what to create

```
collect::
```

```
collect::
```

- The `_` placeholder lets the compiler infer the data type

One Method, Many Results

Same logic can build different structures

```
fn is_digit(c: &char) -> bool { c.is_numeric() }

let numbers = vec![1, 2, 2, 3];
let letters = "Value is 1234";

// Collect into a 'Vec' (keeps order and duplicates)
let my_vector: Vec<_> = numbers.iter().collect();

// Collect into a 'String' (only digits)
let my_string: String = letters.chars()
    .filter(is_digit)
    .collect();
```

Note

`my_vector` and `my_string` contain **references** to the elements in their sources

Collecting "Result"

- `collect()` combines many `Result<T, E>` values
 - Produces a single `Result<Vec<T>, E>`
- Stops on first `Err`
- Otherwise returns `Ok(Collection)`

```
let bad_strings = vec!["1", "2", "not_a_number"];
let good_strings = vec!["1", "2", "42"];

let bad_numbers: Result<Vec<i32>, _> = bad_strings
    .into_iter().map(|s| s.parse::<i32>())
    .collect();
println!("bad_numbers: {:?}", bad_numbers);

let good_numbers: Result<Vec<i32>, _> = good_strings
    .into_iter()
    .map(|s| s.parse::<i32>())
    .collect();
println!("good_numbers: {:?}", good_numbers);
```

```
bad_numbers: Err(ParseIntError { kind: InvalidDigit })
good_numbers: Ok([1, 2, 42])
```

"Intolterator"

Implicit Conversion

- `for` loop does not actually loop over `Vec` or `Array`

- Actually loops over an *iterator*

- When code looks like

```
let my_vector = vec![1, 2, 3];  
for elem in my_vector {  
    println!("{elem}");  
}
```

- Compiler sees

```
let my_vector = vec![1, 2, 3];  
// 'IntoIterator' trait provides this!  
let mut iter = my_vector.into_iter();  
while let Some(elem) = iter.next() {  
    println!("{elem}");  
}
```

Note

`.into_iter()` is the method defined by `IntoIterator` trait

The "IntoIterator" Trait

- Defines how type can be converted into an iterator
 - Used wherever something iterable is needed
 - Most commonly in `for` loops
- **Core method:** `into_iter(self)`
- Takes `self` as a parameter
 - **Not** `&self`
 - **Consumes** the collection
 - Original variable moved into iterator
 - Original variable can no longer be used

```
pub trait IntoIterator {  
    type Item;  
    type IntoIter: Iterator<Item = Self::Item>;  
  
    fn into_iter(self) -> Self::IntoIter;  
}
```

Note

`IntoIterator()` can also be used for references and mutable objects, where the source is **not** consumed

Making a Type Iterable

Implement `IntoIterator` for a custom collection type

```
struct MyCollection {  
    items: Vec<i32>,  
}  
  
impl IntoIterator for MyCollection {  
    type Item = i32;  
    type IntoIter = std::vec::IntoIter<i32>;  
  
    fn into_iter(self) -> Self::IntoIter {  
        self.items.into_iter()  
    }  
}  
  
let col = MyCollection { items: vec![10, 20] };  
for x in col { // This works because of the implementation above!  
    println!("{x}");  
}
```

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Defining an Iterator

- Mechanism used to span iterable content (like arrays)
- All languages have some iteration capability

■ Iterator as a Trait

- Trait-based mechanism to traverse any iterable type
- Only needs an associated type and a `next` method

■ Additional Iterator Trait Methods

- *Iterator Adapter* methods - e.g., `map`, `filter`
- *Consumer* methods - e.g., `sum`, `count`
 - `collect` is just a fancy consumer

■ Converting using `IntoIterator`

- Allows collection to be used directly in `for` loop

Modules

Introduction

Topics Covered

■ Modules

- Organizing code

■ Filesystem Hierarchy

- Mapping logical organization to physical organization

■ Visibility

- Providing limited access to functions and data

■ Encapsulation

- Providing safe access to data

■ Pathing

- Simplifying references to modules

Modules

Big Picture

- Most applications reside in more than one file
 - Rust uses *modules* to organize code
- Encapsulation
 - Groups related code together
 - Functions, structs, traits
 - Hides implementation details from programmer
- Namespacing
 - Prevents "name collisions"
- Unit of organization
 - Modules are the "folders" of your logic

Complete Picture

Code is made up of

Element	Description
<i>Item</i>	Function, struct, enum (Smallest unit)
<i>Module</i>	Folder for items (Privacy boundary)
<i>Crate</i>	Collection of modules (Binary or library)
<i>Package</i>	One or more crates (Managed by <code>Cargo.toml</code>)

"mod" Keyword

- **mod** - foundation of module system
 - Container for functions, structs, traits, modules
 - Like a "namespace" - helps prevent naming conflicts

```
mod cleaner {  
    pub fn perform_cleanup() {  
        println!("Cleaning up...");  
    }  
}  
  
fn main() {  
    cleaner::perform_cleanup();  
}
```

Cleaning up...

Note

Written as `module_name::function_name`

Filesystem Hierarchy

Using Modules From Other Files

- Each **file** is considered a **module**
 - Functions, structs, etc. are *potentially* visible to other files
 - File by definition is a module
 - Do not put `mod` at the top

`supplier.rs`

```
pub fn perform_cleanup() {  
    println!("Whistle while you work");  
}
```

- Calling file specifies module name

`client.rs`

```
mod supplier;  
  
fn main() {  
    supplier::perform_cleanup();  
}
```

Mapping Modules to Files

- How does Rust find `cleaner` module?
 - Module name must match filename
- Compiler looks for
 - `cleaner.rs`
 - `cleaner/mod.rs`
 - Legacy style but still common

Note

Filenames consist of module name and `.rs` extension

Directory-Based Modules

- For complex modules with their own sub-modules
 - If `cleaner.rs` contains `mod sweep`;
 - ... then sweep module can be in `cleaner/sweep.rs`
- This creates a clean tree structure that mirrors the file system

src/	
└ main.rs	<i>Needs "mod supplier;"</i>
└ supplier.rs	<i>'supplier' module root (has child 'service')</i>
└ supplier/	<i>Folder containing 'supplier' children</i>
└ └ supplier_utils.rs	<i>Some utility functions</i>
└ └ service.rs	<i>'service' module root (has child 'attributes')</i>
└ └ service/	<i>Folder containing 'service' children</i>
└ └ └ attributes.rs	<i>'attributes' module</i>

Visibility

Private by Default

- All items of a module are private (hidden)
 - Unless otherwise specified
- **pub** keyword makes item public (visible)
- Child module can see everything in its parent
 - Parent can only see **pub** items in its child
- Enforced by compiler

Module Visibility

parent.rs

```
pub mod child_pub;
mod child_priv;

fn parent_secret_handshake() {
    println!("Hello from the parent's private function!");
}

pub mod control {
    pub fn run_private_child() {
        // Use 'super' to refer to enclosing module ('parent')
        super::child_priv::secret_mission();
        // The following will generate an error
        super::child_priv::deeply_hidden();
    }
}
```

child_priv.rs

```
pub fn secret_mission() {
    println!("I am the private child module executing a task!");

    // Use 'super' to refer to enclosing module ('parent')
    super::parent_secret_handshake();
}

fn deeply_hidden() {
    println!("Not even the parent can see this.");
}
```

child_pub.rs

```
pub fn speak() {
    println!("I am the public child module!");

    // Accessing the parent's private function using 'super'
    super::parent_secret_handshake();
}
```

error[E0603]: function 'deeply_hidden' is private

Visibility at Every Level

- Making a struct **pub** allows client to know it exists
 - But does not make its fields public
- Each field needs its own **pub**
 - Client knows **pub** fields exist

```
pub struct MyType {  
    pub value: i32,      // Public  
    initialized: bool,  // Private  
}
```

- Making an enum **pub** makes **all** variants public

Example: Security Module

security.rs

```
// 'MasterKey' only visible in this file
struct MasterKey { level: u8, }

// 'KeyCard' is visible to caller
pub struct KeyCard { pub ident: u32, // Caller can see 'ident'
                    key: MasterKey, // But cannot see 'key'
}

// Caller can 'issue_card'
pub fn issue_card(ident: u32) -> KeyCard {
    KeyCard { ident,
              key: generate_master_key(),
            }
}

// Caller cannot 'generate_master_key'
fn generate_master_key() -> MasterKey {
    MasterKey { level: 255 }
}
```

main.rs

```
// Grant visibility to 'security' module
mod security;
fn main() {
    let mut my_card = security::issue_card(1234);
    my_card.ident = my_card.ident * 10; // Can see this field
    println!("{}", my_card.ident);
    my_card.key = my_card.key * 10;    // Error - field not visible
}
```

```
error[E0616]: field 'key' of struct 'KeyCard' is private
```

Encapsulation

Why Encapsulate?

- Protect internal state of a data structure
 - Ensure data is always valid
 - Typically implemented via getter/setter API's
- Decoupling
 - Hides implementation details
 - Can change code without breaking client
 - E.g., swapping an array for a **Vec**

Encapsulation in Structs

Gatekeeper pattern

- Keep fields private
 - Only supplier code can modify fields
- Provide **pub** getter and setter methods
 - Control how data is read or modified

```
pub struct Students {  
    names: Vec<String>, // Private!  
}  
  
impl Students {  
    pub fn new() -> Self {  
        Self { names: Vec::new() }  
    }  
    pub fn add(&mut self, name: String) {  
        if !name.is_empty() { self.names.push(name); }  
    }  
}
```

Breaking Encapsulation - Or, When to "pub"

Transparency vs. Control

- Use **pub** fields when struct is a simple "data collection"
 - No internal rules to protect

```
pub Point { pub x: i32, pub y: i32 }
```

"Crate-Internal" Compromise

- Use **pub(crate)** for items to be shared across project
- But remain hidden from external programmers



Note

- Encapsulation hides code to help guarantee correctness
- Private fields are only modifiable by supplier

"pub" vs. "pub(crate)"

```
// Some connection data
pub struct Client {
    pub url: String,
}

// Only this crate can see content
pub(crate) struct Connection {
    pub(crate) socket_id: u32,
}

// Programmers of this crate can connect
impl Client {
    pub fn connect(&self) -> Connection {
        // Logic to create a connection...
        Connection { socket_id: 101 }
    }
}
```

Why `pub(crate)`?

- Prevents clients from checking content
- Once published, changing it breaks users code

`"use", "super", "self"``"use", "super", "self"`

Dealing With Long Paths

```
mod greenhouse {  
    pub mod shelf {  
        pub mod cactus {  
            pub fn water_cactus() {  
                println!("Watering the cactus");  
            }  
            pub fn touch_spine() {  
                println!("Touching the prickly thing");  
            }  
        }  
    }  
}
```

Wouldn't it be nice to shorten these paths?

```
mod greenhouse;  
fn main() {  
    // This is repetitive and hard to read  
    greenhouse::shelf::cactus::water_cactus();  
    greenhouse::shelf::cactus::touch_spine();  
    greenhouse::shelf::cactus::water_cactus();  
    greenhouse::shelf::cactus::touch_spine();  
}
```

The "use" Shortcut

- **use** helps avoid typing long paths

```
mod greenhouse;  
use greenhouse::shelf::cactus;  
fn main() {  
    cactus::water_cactus();  
    cactus::touch_spine();  
    cactus::water_cactus();  
    cactus::touch_spine();  
}
```

- Code just needs to use `cactus`

- ... as if it was in scope

"use" With a Wildcard

- Use wildcard `**` (`glob import`) to get everything

- All public items in module get added to current scope

```
mod math_utils {  
    pub fn add(a: i32, b: i32) -> i32 { a + b }  
    pub fn subtract(a: i32, b: i32) -> i32 { a - b }  
    pub fn multiply(a: i32, b: i32) -> i32 { a * b }  
    pub fn divide(a: i32, b: i32) -> i32 { a / b }  
}  
  
use math_utils::*  
fn main() {  
    let sum = add(10, 5);  
}
```

- Benefits

- Used in preludes to load essential traits
- Speeds up prototyping

- Risks

- Makes it hard for programmer/autocomplete to find things
- Globbed modules with the same name cause compilation errors

Note

To reduce risks of *globbing*, use **nested imports**

```
use std::io::{self, Read, Write};
```

Name Collisions

```
mod two_dee_graphics {  
    pub fn render() { todo!() }  
}  
  
mod three_dee_graphics {  
    pub fn render() { todo!() }  
}  
  
// COLLISION!  
use two_dee_graphics::render;  
use three_dee_graphics::render;  
  
fn main() {  
    render(); // Error - which one should be called?  
}
```

error[E0252]: the name 'render' is defined multiple times

Solution: Rename with as

```
use two_dee_graphics::render as render2d;  
use three_dee_graphics::render as render3d;  
fn main() {  
    render3d();  
}
```

Relative Paths

- Use **self** when referring to current module

```
mod shelf {  
    pub mod cactus {  
        pub struct Pot;  
        pub fn water() {}  
    }  
}  
  
use shelf::cactus::{self, Pot};  
  
fn main() {  
    let my_pot = Pot; // Imported directly via 'Pot'  
    cactus::water(); // Imported via 'self' ('cactus' module)  
}
```

- Use **super** to refer to the enclosing module

- Useful for reaching "outside" the current module

```
mod parent {  
    pub fn hello() {}  
    mod child {  
        fn call_parent() {  
            super::hello(); // Reaches up to 'parent'  
        }  
    }  
}
```

Absolute Paths

- Use **crate** to refer to something from base directory of filesystem
 - Always starts from the root of the current crate
 - Path stays valid even if code is moved to a different module
- Example

```
use crate::network::server::start;
```

- Works from anywhere in the project

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Modules

- Creation of a hierarchy
- Use `mod` to group related code

■ Filesystem Hierarchy

- Physical organization of modules
- Mapping modules to files/directories
- Filesystem matches logical hierarchy

■ Visibility

- Items are hidden by default
- `pub` to allow clients access

■ Encapsulation

- Providing safe access to data
- Only supplier should (typically) modify data directly

■ Pathing

- Shortcuts/renaming to simplify module references
- `self`, `super`, `crate`

Error Handling

Introduction

Topics Covered

■ Errors

- Unrecoverable errors - `panic!`
- Recoverable errors - `Result`

■ Try Operator

- Error propagation
- Converting error traits

■ Error Trait

- Defining error implementations

■ Simplified Error Handling

- Creating errors through `derive` - `thiserror`
- `anyhow`

Overview

Rust Error Philosophy

- Errors are data, not drama!
 - Failures are explicit values
 - Not hidden control flow
- Errors are visible in function signatures
- Compiler ensures they are handled
 - No access to invalid data
- Failures do not show up mysteriously
 - Visible and enforced

Language Style	Error Visibility
<i>Exceptions</i>	Hidden control flow
<i>Error codes</i>	Easy to ignore
<i>Error wrappers (e.g., <code>Result</code>)</i>	Explicit and enforced

Expected Errors vs. Logic Violations

- Recoverable errors should be handled by the code
 - File not found
 - Network timeout
 - Invalid user input
- Unrecoverable errors mean we need to reboot the system
 - Impossible state reached
 - Violated assumptions/invariant
 - Logic error or other bug



Note

Rust separates bugs from expected failures

Panic

Unrecoverable Error

- System errors are **not** recoverable
 - Failed bounds checks
 - Accessing `v[42]` on 3-element vector
 - Logic problems
 - Failed `assert!` or `debug_assert!`
- Call `panic!` when logic indicates unrecoverable error
 - Triggers thread shut-down
 - Configurable
 - Unwind stack and exit thread
 - Abort immediately

Panic Strategies

■ Stack Unwinding (default)

- Walk back up the stack and "clean up"
 - Runs drop for all objects in scope
- Useful when working with hardware or multiple processes
 - Reset hardware flags
 - Release any locks
 - Exit thread

■ Aborting

- Instantly stops the program
- Results in smaller binary size
 - No cleanup code

Bounds Error Example

```
1 fn main() {  
2     let my_vector = vec![10, 20, 30];  
3  
4     println!("{}", my_vector[42]);  
5 }
```

```
thread 'main' (32) panicked at src/main.rs:4:21:  
index out of bounds: the len is 3 but the index is 42
```

Manual Panic Example

```
1 fn main() {  
2     let my_vector = Vec::<i32>::new();  
3  
4     if my_vector.is_empty() {  
5         panic!("Vector is empty!");  
6     }  
7 }
```

```
thread 'main' (12) panicked at src/main.rs:5:9:  
Vector is empty!
```

When to Panic?

■ Prototyping

- `unwrap()` or `expect()` for quick coding
 - Replace with proper error handling later

■ Infallible Logic (logic guarantees)

- State that should never occur

■ Library Boundaries

- Libraries should return `Result`
 - Programmer decides how to handle the error
- Panic if API **contract** is violated
 - E.g., passing an empty list to a function that requires at least one value

"Result"

Recoverable Error

- Operational issues should be recoverable
 - File not found
 - Network timeout
- **Result** allows safe handling of any outcome

```
enum Result<T, E> {  
    Ok(T), // Success - contains value of type 'T'  
    Err(E), // Failure - contains error of type 'E'  
}
```



Note

Both variants need to be handled

Handling Results

■ Pattern Matching (idiomatic)

```
match File::open("data.txt") {  
    Ok(file) => println!("File opened!"),  
    Err(e)   => eprintln!("Failed to open: {e}"),  
}
```

Failed to open: No such file or directory (os error 2)

Helper Methods

```
let good: Result<i32, &str> = Ok(42);  
let bad: Result<i32, &str> = Err("Problem");
```

`.unwrap()` returns the value or panics

```
println!("Good: {}", good.unwrap());  
println!("Bad: {}", bad.unwrap());
```

```
Good: 42
```

```
thread 'main' panicked at src/main.rs:5:27:  
called `Result::unwrap()` on an `Err` value: "Problem"
```

`.expect("Msg")` like `unwrap`, with custom panic message

```
println!("Good: {}", good.expect("Expected"));  
println!("Bad: {}", bad.expect("Expected"));
```

```
Good: 42
```

```
thread 'main' panicked at src/main.rs:5:27:  
Expected: "Problem"
```

`.unwrap_or(default)` fallback value on error

```
println!("Good: {}", good.unwrap_or(-1));  
println!("Bad: {}", bad.unwrap_or(-1));
```

```
Good: 42  
Bad: -1
```

Note

`eprintln!` outputs directly to `stderr` rather than `stdout`

Results vs. Exceptions

Feature	Result (Rust)	try / catch (other languages)
<i>Visibility</i>	Part of function signature	Not part of function definition
<i>Control Flow</i>	Explicitly handled	Bubbles up stack automatically
<i>Performance</i>	Low cost	Runtime overhead
<i>Safety</i>	Error must be handled	Easy to forget <code>catch</code> block

Propagating Errors

- Instead of handling error - return it to caller (manually)
- **Shortcut:** `?` operator makes propagation concise
 - Called the **Try Operator**

```
fn open_file(filename: &str) -> Result<File, io::Error> {  
    // 'open' returns 'Result'  
    // '?' returns to caller if 'Result' is 'Err'  
    let mut file = File::open("user.txt"?);  
    Ok(file)  
}
```

Note

Use `?` when current function wants caller to deal with error

Try Operator

What Is the Try Operator?

- *Try operator (?)* - syntax used to propagate errors by either
 - Unwrapping **Result** if it is the success variant
 - Immediately returning the failure variant
- Replaces repetitive match handling
- Keeps code focused on the "happy path"
- Automatically decodes **Result**
 - **Ok**(value) - **unwrap** value and continue execution
 - **Err**(E) - returns early
- Can only be used if function returns **Result**
 - Return must be compatible with error being raised

Clarity vs. Verbosity

Try Operator ?

```
fn get_data() -> Result<String, io::Error> {  
    let mut file = File::open("config.txt"?);  
    let mut text = String::new();  
    file.read_to_string(&mut text)?;  
    Ok(text)  
}
```

Manual match

```
fn get_data() -> Result<String, io::Error> {  
    let res = File::open("config.txt");  
    let mut file = match res {  
        Ok(f) => f,  
        Err(e) => return Err(e), // Explicit return  
    };  
    // ... repeat for every step ...  
}
```

Try Operator With "Option"

- `?` also works with `Some/None` from `Option`
- Behavior
 - `Some(value)` - evaluates to value
 - `None` - function returns `None` early



Warning

Cannot mix and match

Cannot use `?` on `Result` in function returning `Option`

Returning "Result" From "main"

- `main` can return `Result`
- If an error "bubbles up" to `main` and is returned
 - Prints `Debug` representation of error
 - Exits with a non-zero error code

```
use std::fs::File;
```

```
fn main() -> std::io::Result<()> {  
    let _file = File::open("essential_config.txt"?;  
    Ok::  
}
```

```
Error: Os { code: 2, kind: NotFound, message: "No such file or directory" }
```

Try Conversions

Automatic Error Type Conversion

? doesn't just return the error

- If error types match → returned directly
- If they differ → converted using `From`

```
enum Reason { TooYoung, TooOld, }
impl From<Reason> for String {
    fn from(Reason: Reason) -> Self {
        match Reason {
            Reason::TooYoung =>
                String::from("Too Young"),
            Reason::TooOld =>
                String::from("Too Old"),
        }
    }
}

// Error type is 'Reason'
fn check_age(age: i32) -> Result<i32, Reason> {
    if age < 18 {
        Err(Reason::TooYoung)
    } else if age > 65 {
        Err(Reason::TooOld)
    } else {
        Ok(age)
    }
}

// Error type is 'String'
fn register(age: i32) -> Result<i32, String> {
    // 'P' sees 'Reason', knows the return type is 'String'.
    // and converts it behind the scenes.
    check_age(age)?;
    Ok(age)
}

match register(10) {
    Ok(age) => println!("Good enough {age}"),
    Err(e) => eprintln!("Problem: {e}"),
}

match register(70) {
    Ok(age) => println!("Good enough {age}"),
    Err(e) => eprintln!("Problem: {e}"),
}
```

Problem: Too Young

Problem: Too Old

Note

Return error type (`String`) must implement `From<Reason>`

- Compiler verifies a valid path exists to convert the error
- If not, it throws a *trait bound not satisfied* error

One Return Type, Many Sources

```
fn initialize_system() -> Result<(), MyError> {  
    // Convert 'io::Error' to 'MyError'  
    let config = fs::read_to_string("config.json");  
  
    // Convert 'serde_json::Error' to 'MyError'  
    let val: Config = serde_json::from_str(&config);  
  
    // Convert 'ParseIntError' to 'MyError'  
    let port: u16 = val.port.parse();  
  
    Ok(())  
}
```

Note

- Main logic remains clean and focused on "happy path"
- ? operator handles heavy lifting of error translation

"Error" Trait

The "Error" Trait

- Common interface for all errors
 - Defined in `std::error`
 - Implemented by many standard and custom error types
- All errors should use `Error` trait
 - Without standard trait, libraries would have their own errors

Trait Prerequisites

To implement `Error` type must also implement

- `Display`
 - For user-facing error messages
- `Debug`
 - For programmer-facing details

Trait Definition

```
use std::fmt::{Debug, Display};

pub trait Error: Debug + Display {
    // Returns the lower-level cause of this error, if any
    fn source(&self) -> Option<&(dyn Error + 'static)> {
        None
    }
}
```

source() **method**

- Key to *Error Chaining*
- Allows peeling back layers of error to find root cause
- E.g., a "network error" caused by a "timeout"

Note

Source returns an **Option** type where **Error** is

- **dyn** - trait object (not a fixed-size type)
- **'static** - has no temporary references

Implementing the Trait

Manual implementation can be heavy

```
#[derive(Debug)]
enum MyError {
    Network(io::Error),
    BadInput,
}

impl Display for MyError {
    fn fmt(&self, f: &mut fmt::Formatter) -> fmt::Result {
        match self {
            Self::Network(e) => write!(f, "Network issue: {e}"),
            Self::BadInput => write!(f, "Invalid user input"),
        }
    }
}

// Finally, implement the Error trait itself
impl std::error::Error for MyError {
    fn source(&self) -> Option<&(dyn std::error::Error + 'static)> {
        match self {
            Self::Network(e) => Some(e),
            _ => None,
        }
    }
}
```



Tip

Instead, use crates like `thiserror`

Using the Trait

■ Return some kind of error

```
fn do_something(fail: bool) -> Result<(), Box<dyn Error>> {  
    if fail {  
        let err = MyError {  
            details: String::from("Something went wrong!"),  
        };  
        // We box the error to erase its specific type  
        return Err(Box::new(err));  
    }  
    Ok(())  
}
```

■ Receive error and check for a specific problem

```
2 match do_something(true) {  
3     Ok(_) => println!("Success!"),  
4     Err(e) => {  
5         // Attempt to downcast to our specific type  
6         if let Some(specific_err) = e.downcast_ref::<MyError>() {  
7             println!("Caught a specific error: {}", specific_err.details);  
8         } else {  
9             println!("Caught an unknown error type: {}", e);  
10        }  
11    }  
12 }
```

Note

Line 6 `.downcast_ref::<MyError>()` "unboxes" error using `Option`

Best Practices for Custom Errors

Implement methods for the following traits

- **Display**
 - Tell user what happened
- **Debug**
 - Tell programmer what happened and where
- **Error**
 - Allow everyone to know what happened

`"thiserror"`

"Macro Magic" for Custom Errors

- Implementing `Error` is tedious and error-prone
- `thiserror` crate provides a convenient **derive macro**
 - Generates all that code using simple attributes



Note

`thiserror` comes from a crate - needs to be installed

"error" Attribute

```
#[error("I/O error: {0}")]
```

```
#[error("Source {path}")]
```

- error attribute generates **Display** implementation
 - Displays error message
 - String interpolation for dynamic values
 - Index to fill from tuple data
 - Name to fill from struct data

Defining Errors With "thiserror" Crate

```
1 #[derive(Debug, Error)]
2 enum MyError {
3     #[error("I/O error: {0}")]
4     IoError(#[from] io::Error),
5     #[error("No text in {0}")]
6     EmptyText(String),
7 }
```

- Line 1: Generate `std::error::Error` implementation for `MyError`
- Line 3: Replace `fmt::Display` implementation
 - Uses this string with `IoError` value when printing error
- Line 5: Generate `impl From<io::Error>` for `MyError`
 - ? will convert error into `MyError::IoError`

More Attributes

- `#[source]`
 - Implement `source` trait
 - Describes where the original error came from
- `#[from]`
 - Implement `From` trait for error variant
 - Automatically implements `#[source]`
- `#[error(transparent)]`
 - Uses `Display` original error
 - No need to write custom string
 - Automatically implements `source()` method
 - Returns underlying error
 - Does not add new message

Why Use "thiserror"?

- **Main reason:** to avoid manual implementation!
- Structured data
 - Enums allow `match` to handle specific errors
 - Rather than checking error message string
- Type safety
 - Compiler ensures that error messages match enum fields
- Ecosystem compatibility
 - Generates `std::error::Error` implementation
 - Errors work with other tools
 - Like standard library traits

"thiserror" in Practice

```
use thiserror::Error;
use std::fs::File;

#[derive(Error, Debug)]
pub enum MyError {
    #[error("Environment variable {0} not set")]
    ConfigError(String),

    #[error("File system error")] // Automatically wraps 'io::Error'
    IoError(#[from] std::io::Error),
}

fn main() -> Result<(), MyError> {
    // 1. Manual error creation
    let _ = Err(MyError::ConfigError("PORT".into()))?;

    // 2. Automatic conversion using '?' (this returns 'IoError')
    let _f = File::open("missing.txt")?;

    Ok(())
}
```

Note

`_` and `_f` tell the compiler the objects are unused

`"anyhow"`

Flexible Error Handling

- Don't always want an enum for every error
 - Just want to propagate and report them
- `anyhow::Result<T>`
 - Available via **anyhow** crate
 - Wraps any error implementing `std::error::Error`
- Primarily used for applications (**not** libraries)
 - Effortless error propagation
 - But libraries should return specific errors

Note

`anyhow` comes from a crate - needs to be installed

One Type to Rule Them All

- One `anyhow::Result` can handle many different errors
 - Instead of writing

```
fn run_app() -> Result<(), MyCustomError>
```
 - Simpler to write

```
fn run_app() -> anyhow::Result<()>
```
- Type is compatible with any function that uses `?` operator

```
use anyhow::Result;
```

```
fn run_app() -> Result<()> {  
    let config = read_config()?;    // Could be 'io::Error'  
    let data = parse_data(config)?; // Could be 'ParseError'  
    Ok()  
}
```

Methods to Add Detail

- `.context()`
 - Attaches message to error
 - On failure, user sees *specified* message *plus* original error
- `.with_context()`
 - Only evaluates message if an error *actually* occurs
 - Better for performance with complex messages

```
use anyhow::Context;
```

```
fn main() -> Result<()> {  
    let path = "config.json";  
    let content = std::fs::read_to_string(path)  
        .with_context(|| format!("Failed config file {path}"))?;  
  
    Ok()  
}
```

Choosing the Right Tool

Feature	thiserror	anyhow
<i>Best For</i>	Libraries	Applications
<i>Error Type</i>	Strongly typed (enums)	General error (<code>anyhow::Error</code>)
<i>Goal</i>	Custom errors with no boilerplate	Simplifies propagation
<i>Matching</i>	Easy to <code>match</code>	Harder (requires <i>downcasting</i>)

Common Error Operations

■ `anyhow!`

- Create an error on the fly from a string
- Similar to `format!`

```
let my_error = anyhow!("Something bad happened");
```

■ `bail!`

- Shorthand for `return Err(anyhow!(...))`
- Great for early exits

```
if user.name.is_empty() {  
    bail!("User name cannot be empty!");  
}
```

■ Printing errors

- Top-level (outermost) error message

```
println!("{}", report);
```

- Error and every "source" (cause) underneath

```
println!("{:?}", report);
```

- Also called `developer view`

Lab

Lab Instructions

- Solve for compilation errors
- Follow the hints!
- Success is
 - Code that compiles
 - ...and that follows any behavior indicated within the hints!

Summary

What We Covered

■ Panics

- Unrecoverable errors
 - Impossible states where program should not continue

■ Result

- Enum-based way to handle recoverable errors
- Requires handling of success and failure

■ The ? Operator

- Syntax shortcut that keeps code clean
- Automatically unwraps success values
 - Or returns error early to caller

■ The Error Trait

- Interface to allow conversion of errors
- Standard way to show messages
 - Includes tracing back to the root cause

■ thiserror vs. anyhow

- thiserror
 - Used in libraries to create matchable error types
- anyhow
 - Used in applications to create human-readable errors

Annex - Reference Materials

General Rust Information

Useful Links

- Official Rust Learning Resources
 - Additional guides, docs, and learning paths
 - <https://rust-lang.org/learn/>
- GNAT Pro for Rust User's Guide
 - Tooling, workflows, mixed-language development
 - https://docs.adacore.com/live/wave/rust/html/rust_ug/index.html

AdaCore Support

Need More Help?

- If you have an AdaCore subscription:
 - Find out your customer number #XXXX
- Open a "Case" via the GNATtracker web interface and/or email
 - GNATtracker
 - Select "Create A New Case" from the main landing page
 - Email
 - Send to: support@adacore.com
 - Subject should read: #XXXX - (descriptive text)
- Not just for "bug reports"
 - Ask questions, make suggestions, etc.