RUSTikales Rust for advanced coders

Plan for today

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1. Recap

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1. Recap
2. Closures

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2. Closures
3. Iterators

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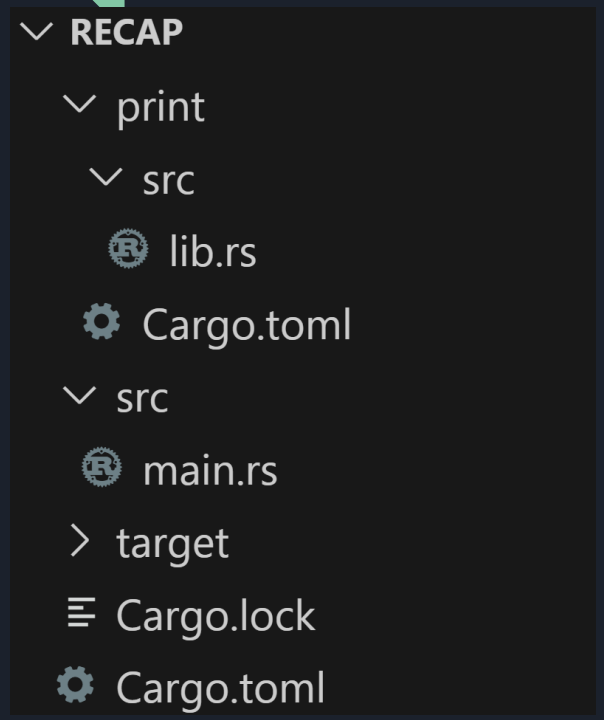
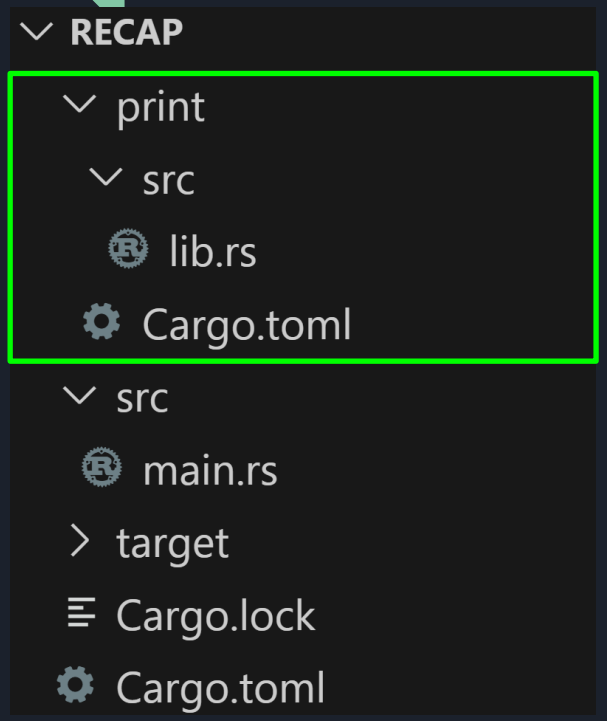
1. Recap

- Procedural Macros are powerful, but difficult to work with
- Because they are written in normal Rust, we can use crates
- syn and quote are popular crates that help us develop procedural macros
  - Thanks to them, writing powerful procedural macros becomes almost trivial
- syn is a Rust parser and converts TokenStreams into convenient data structures
- quote! uses Quasi-Quoting to generate code
  - We write code, the IDE can perform syntax-highlighting and auto-complete, but the macro uses it as data

1. Recap

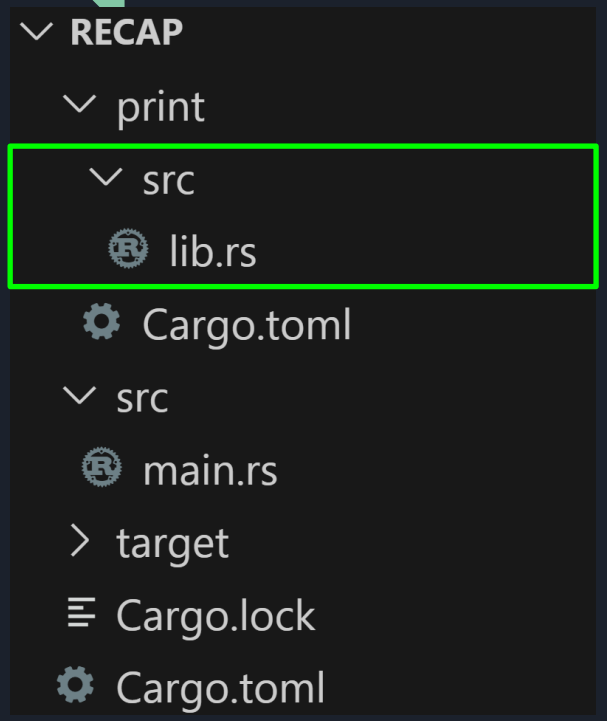

RECAP
print
src
lib.rs
Cargo.toml
src
main.rs
target
Cargo.lock
Cargo.toml

1. Recap



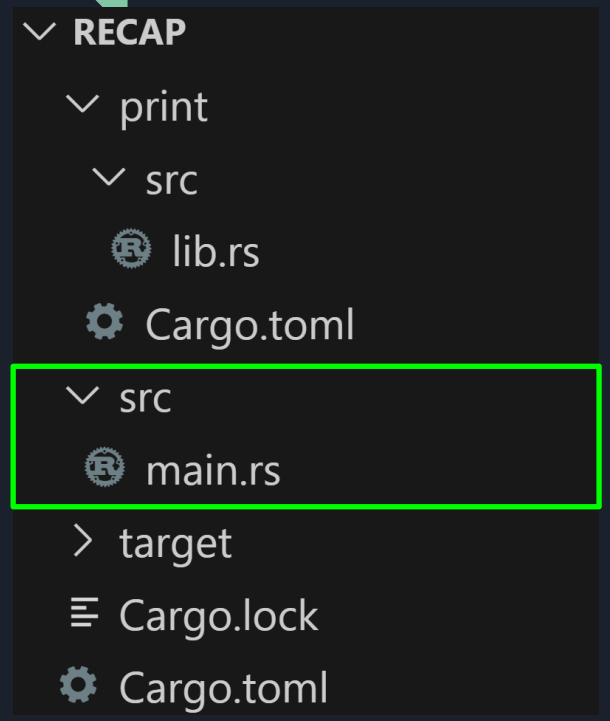
Idea:
→ print is a proc-macro crate

1. Recap



Idea:
→ print is a proc-macro crate
→ In there, we define a proc_macro_attribute which we want to use

1. Recap

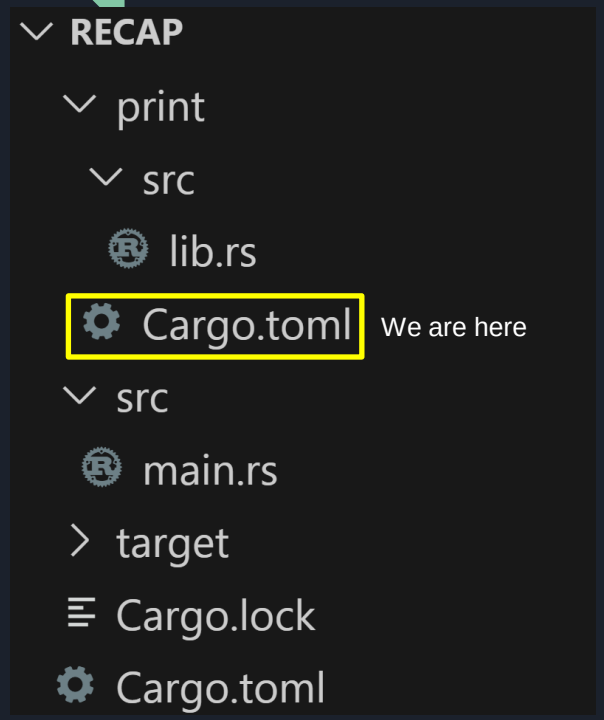


Idea:
→ print is a proc-macro crate
→ In there, we define a proc_macro_attribute which we want to use
→ We later use that macro in our main application

Usage: Annotate function, it then logs when we declare a variable using let

```
use print::log_variable;
#[log_variable]
▶ Run | Debug
fn main() {
```

1. Recap



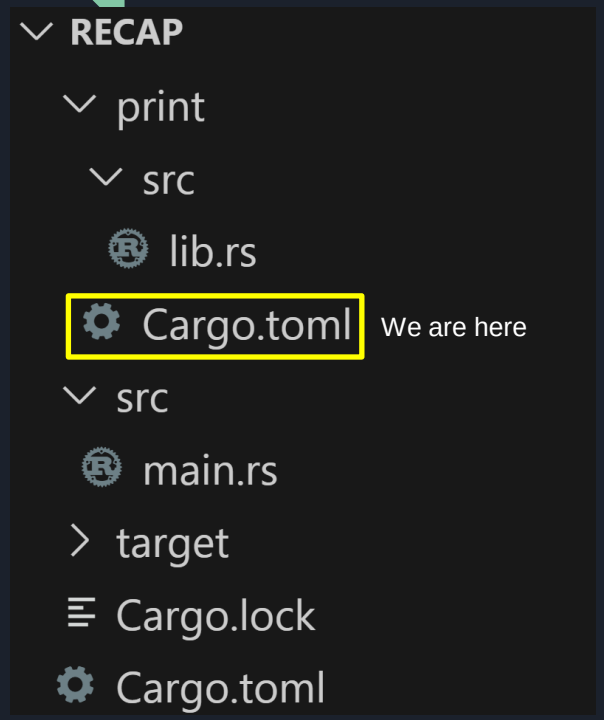

```
[package]
name = "print"
version = "0.1.0"
edition = "2021"

[lib]
proc-macro = true

[dependencies]
syn = { version="2.0.67", features=["full"] }
quote = "1.0.36"
```

Mark crate as proc-macro

1. Recap

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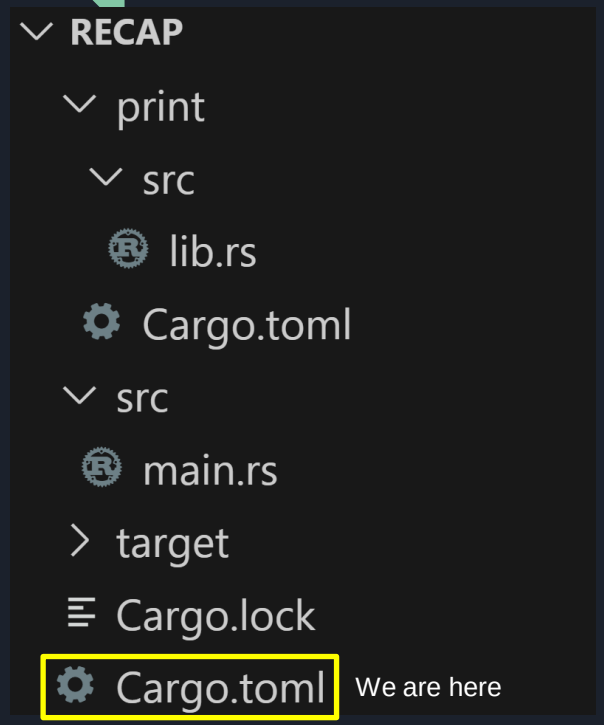
Use syn and quote like any other crate

1. Recap

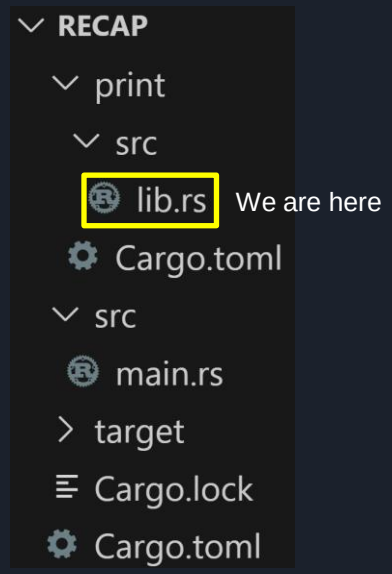



```
[package]
name = "recap"
version = "0.1.0"
edition = "2021"

[dependencies]
print = { path="./print" }
```

use proc-macro in our main application

1. Recap

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pub fn log_variable(_attr: TokenStream, item: TokenStream) -> TokenStream {
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        attrs: Vec<Attribute>,
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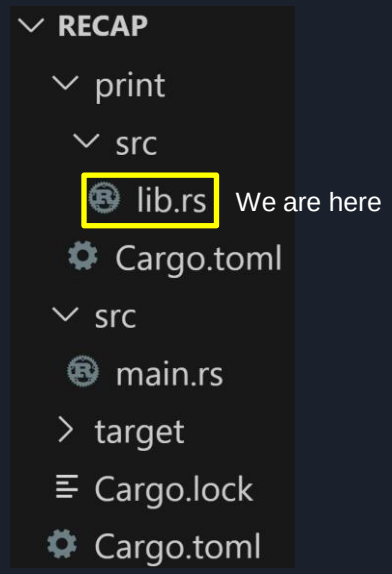
        sig: Signature,
        block: Box<Block>
    } = parse_macro_input!(item);
    let new_block: Block = replace_in_block(&block);
    quote! {
        #(#attrs)*
        #vis #sig #new_block
    }.into()
}
```

1. Recap

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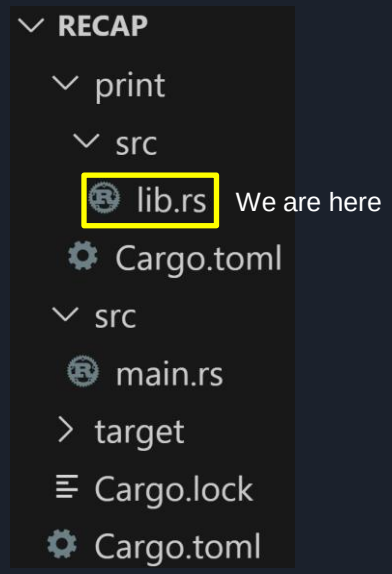
syn allows us to easily parse whatever input we have into any form we want

→ If the given input is not a function, we throw a compiler error

1. Recap

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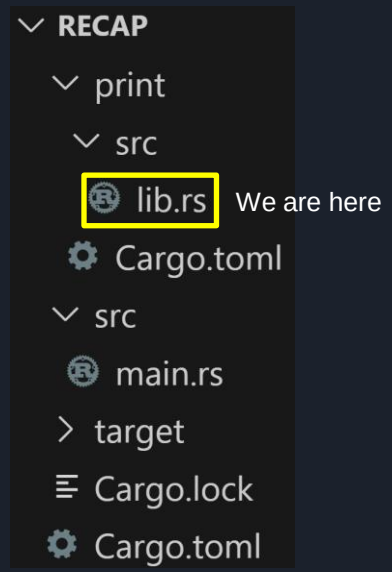
syn transforms the input into a data structure,
which we can now easily work with

1. Recap

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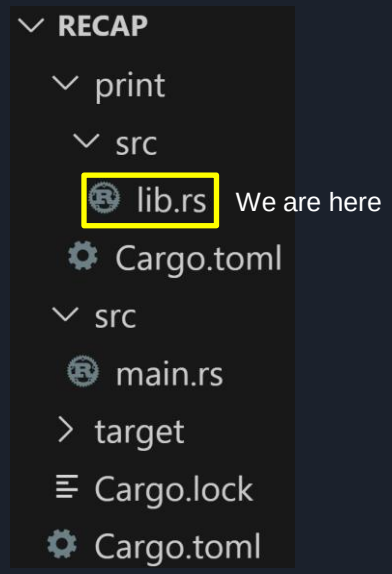
    }.into()
}
```

quote! allows us to easily generate code using Quasi-Quoting
→ # interpolates variables defined in the proc-macro and inserts its value into the TokenStream
→ This macro invocation generates a function for us

1. Recap

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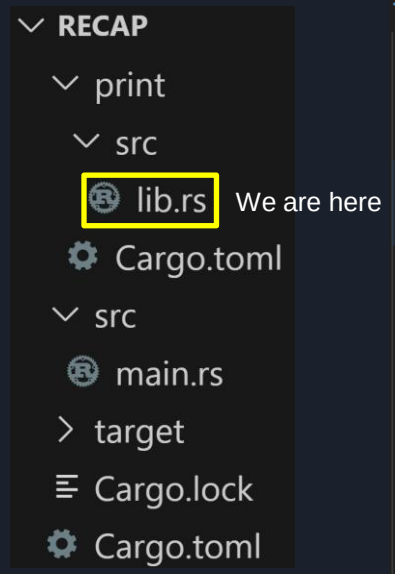
    }.into()
}
```

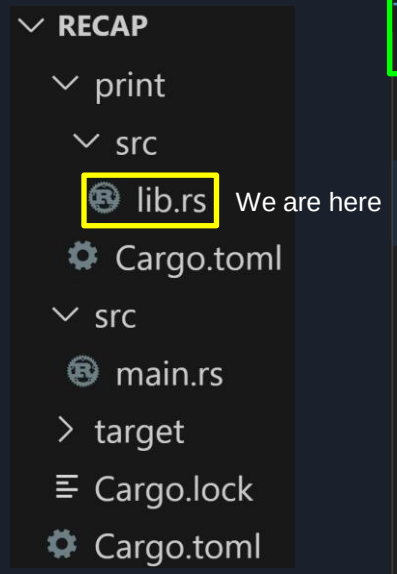
Combining both crates, we can now easily write macros

1. Recap




```rust
use syn::{parse_macro_input, Block, Expr, ExprBlock, ItemFn, Local, LocalInit, Pat, Stmt};
fn replace_in_block(block: &Block) -> Block {
    let mut new_stmts: Vec<Stmt> = vec![];
    for s: &Stmt in &block.stmts {
        match s {
            Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: Some(LocalInit { expr: &Box<E
            Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: None, .. }) => {…
            Stmt::Expr(Expr::Block(ExprBlock { attrs: a: &Vec<Attribute>, label: l: &Option<Label>,
                let new_inner: Block = replace_in_block(inner);
                new_stmts.push(Stmt::Expr(Expr::Block(ExprBlock { attrs: a.clone(), label: l.clone()
            }
            _ => new_stmts.push(s.clone()),
        }
    }
    Block { brace_token: block.brace_token, stmts: new_stmts }
} fn replace_in_block
```

1. Recap

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        }
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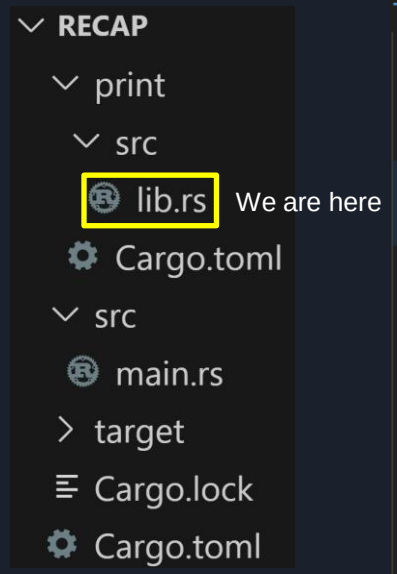
```

Idea: Build a new block out of the given input

1. Recap

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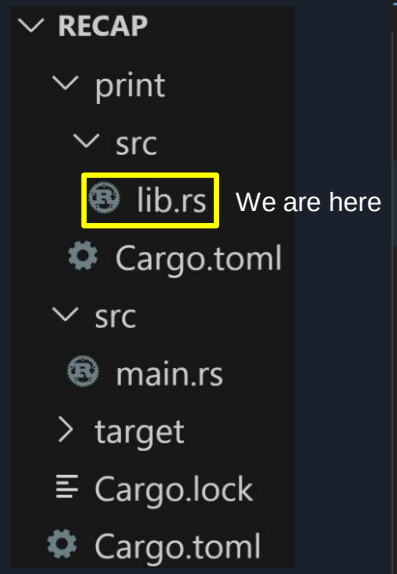
    }
    Block { brace_token: block.brace_token, stmts: new_stmts }
} fn replace_in_block
```

Iterate over all statements, and replace relevant statements with custom behavior

1. Recap

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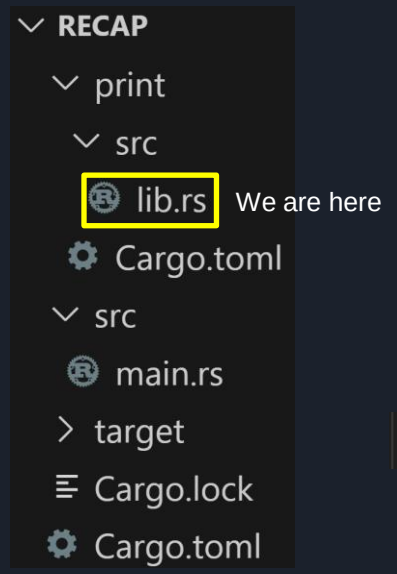
        }
    }
    Block { brace_token: block.brace_token, stmts: new_stmts }
} fn replace_in_block
```

Recursively replace all blocks we encounter

1. Recap



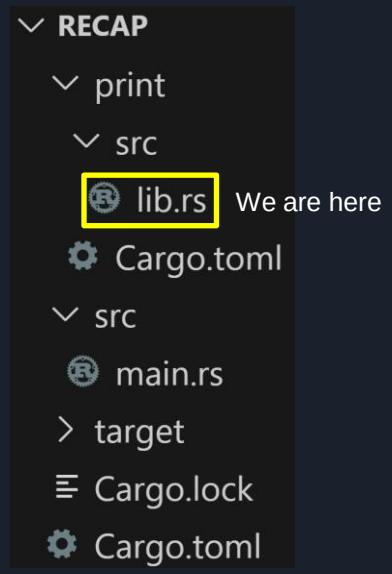

```
Stmt::
_ => n
brace_
```

- Expr(…)
- Item(…)
- Local(…)
- Macro(…)

```
_ => new_stmts.push(s.clone()),
```

Rust is expression-based:
→ Everything is an expression (except let)
→ We don‘t want to replace macros or items

1. Recap

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    // let <pat> = <expr>;
    // <pat> is a normal identifier like `a` or `b`
    let log: TokenStream = quote! {
        let #var = {
            let _e = #expr;
            let _print_green = |s: &str| -> String { format!("\x1b[92m{s}\x1b[0m") };
            let _print_yellow = |s: &str| -> String { format!("\x1b[93m{s}\x1b[0m") };
            println!("Setting {} to {}",
                _print_green(stringify!(#var)),
                _print_yellow(&format!("{} = {:?}", stringify!(#expr), _e))
            );
            _e
        };
    };
    let stmt: Stmt = syn::parse2::<Stmt>(tokens: log).unwrap();
    new_stmts.push(stmt);
}
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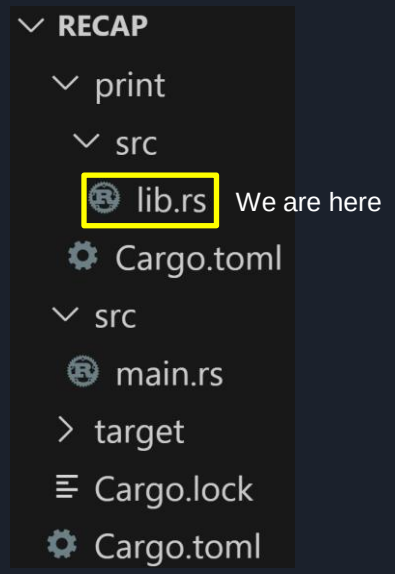
1. Recap

using syn and pattern matching makes developing procedural macros a breeze
→ If our input doesn‘t have this form, we simply don‘t match that case

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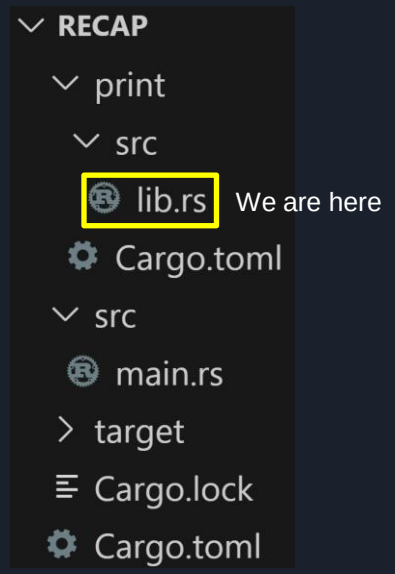


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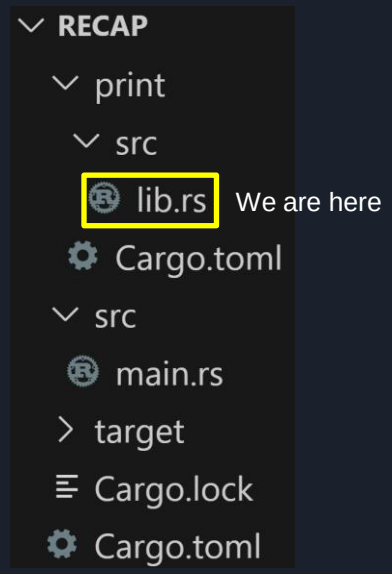
Using quote! also really helps, here:

→ Replace original <expr> with a big block, where we print our custom info

1. Recap

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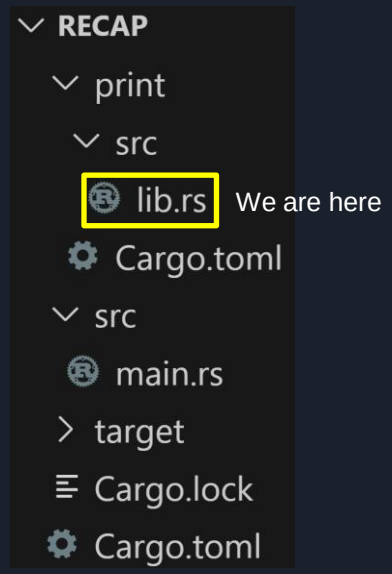
We declare local helper variables
→ Will be visible when using cargo expand

1. Recap

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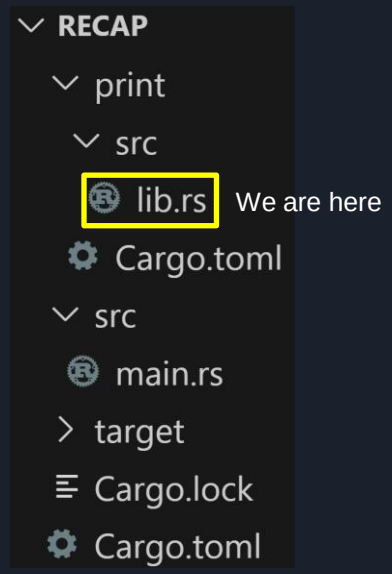
Convention: Prefix helper variables with _

→ Disables unused-warnings

→ Prevents name clashes and variable shadowing

1. Recap



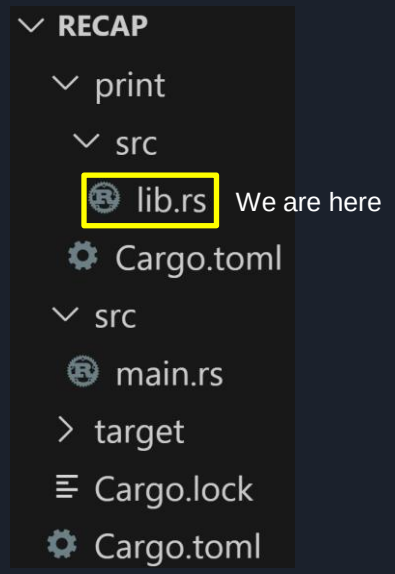
We are here

at runtime, we print this

```
Setting b to a + 4 = 9
Setting c to b.abs() = 9
```

```rust
let _print_green = |s: &str| -> String { format!("\x1b[92m{s}\x1b[0m") };
let _print_yellow = |s: &str| -> String { format!("\x1b[93m{s}\x1b[0m") };
println!("Setting {} to {}",
    _print_green(stringify!(#var)),
    _print_yellow(&format!("{} = {:?}", stringify!(#expr), _e))
);
```

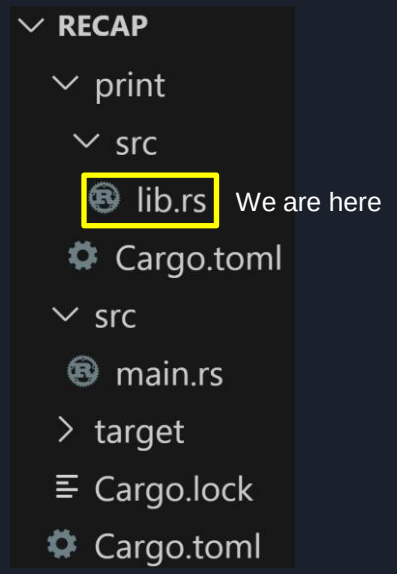
1. Recap




```rust
Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: Some(LocalInit { expr: &Box<Expr>, .. })
    // let <pat> = <expr>;
    // <pat> is a normal identifier like `a` or `b`
    let log: TokenStream = quote! {
        let #var = {
            let _e = #expr;
            let _print_green = |s: &str| -> String { format!("\x1b[92m{s}\x1b[0m") };
            let _print_yellow = |s: &str| -> String { format!("\x1b[93m{s}\x1b[0m") };
            println!("Setting {} to {}",
                _print_green(stringify!(#var)),
                _print_yellow(&format!("{} = {:?}", stringify!(#expr), _e))
            );
            _e
        };
    };
    let stmt: Stmt = syn::parse2::<Stmt>(tokens: log).unwrap();
    new_stmts.push(stmt);
}
```

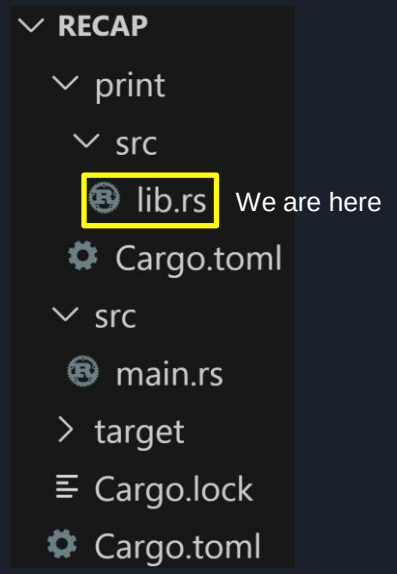
Parsing is a bit redundant, but we're building a vector of statements
→ Our generated code → We know it's correct → We can easily unwrap

1. Recap




```rust
Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: None, .. }) => {
    // let <pat>;
    // <pat> is a normal identifier like `a` or `b`
    new_stmts.push(s.clone());
    let log: TokenStream = quote! {
        {
            let _print_green = |s: &str| -> String { format!("\x1b[92m{s}\x1b[0m") };
            println!("Declaring {}", _print_green(stringify!(#var)));
        }
    };
    let stmt: Stmt = syn::parse2::<Stmt>(tokens: log).unwrap();
    new_stmts.push(stmt);
}
```

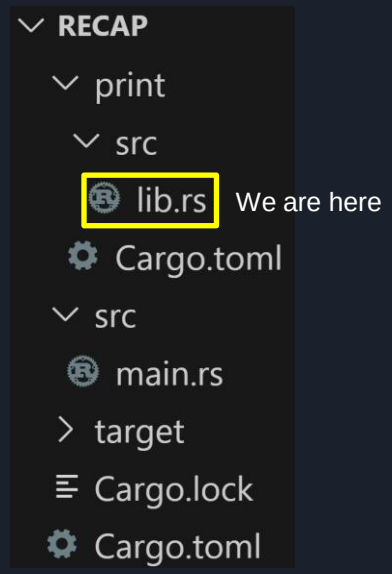
1. Recap




```rust
Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: None, .. }) => {
    // let <pat>;
    // <pat> is a normal identifier like `a` or `b`
    new_stmts.push(s.clone());
    let log: TokenStream = quote! {
        {
            let _print_green = |s: &str| -> String { format!("\x1b[92m{s}\x1b[0m") };
            println!("Declaring {}", _print_green(stringify!(#var)));
        }
    };
    let stmt: Stmt = syn::parse2::<Stmt>(tokens: log).unwrap();
    new_stmts.push(stmt);
}
```

Simpler this time, we just log that we declared a variable

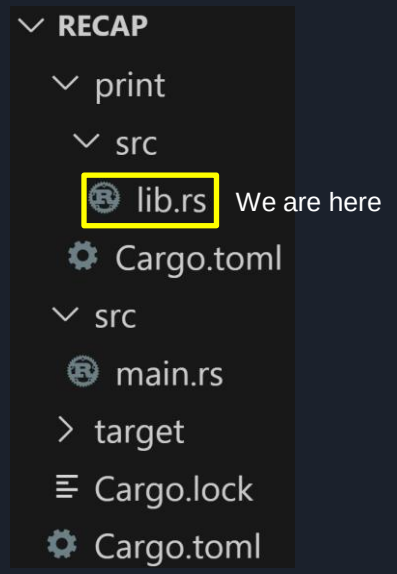
1. Recap




```
Declaring d
```

```
let _print_green = |s: &str| -> String { format!("\x1b[92m{s}\x1b[0m") };
println!("Declaring {}", _print_green(stringify!(#var)));
```

1. Recap




```rust
Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: None, .. }) => {
    // let <pat>;
    // <pat> is a normal identifier like `a` or `b`
    new_stmts.push(s.clone());
    let log: TokenStream = quote! {
        {
            let _print_green = |s: &str| -> String { format!("\x1b[92m{s}\x1b[0m") };
            println!("Declaring {}", _print_green(stringify!(#var)));
        }
    };
    let stmt: Stmt = syn::parse2::<Stmt>(tokens: log).unwrap();
    new_stmts.push(stmt);
}
```

Generate code

```rust
use proc_macro::TokenStream;
use quote::quote;
use syn::{parse_macro_input, Block, Expr, ExprBlock, ItemFn, Local, LocalInit, Pat, Stmt};

fn replace_in_block(block: &Block) -> Block {
    let mut new_stmts: Vec<Stmt> = vec![];
    for s: &Stmt in &block.stmts {
        match s {
            Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: Some(LocalInit { expr: &Box<Expr>, .. }), .. }) => {…
            Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: None, .. }) => {…
            Stmt::Expr(Expr::Block(ExprBlock { attrs: a: &Vec<Attribute>, label: l: &Option<Label>, block: inner: &Block, }), semi: …) => {…
            _ => new_stmts.push(s.clone()),
        }
    }
    Block { brace_token: block.brace_token, stmts: new_stmts }
} fn replace_in_block

#[proc_macro_attribute]
pub fn log_variable(_attr: TokenStream, item: TokenStream) -> TokenStream {
    let ItemFn {
        attrs: Vec<Attribute>,
        vis: Visibility,
        sig: Signature,
        block: Box<Block>
    } = parse_macro_input!(item);
    let new_block: Block = replace_in_block(&block);
    quote! {
        #(#attrs)*
        #vis #sig #new_block
    }.into()
}
```

And that‘s it!

```rust
use proc_macro::TokenStream;
use quote::quote;
use syn::{parse_macro_input, Block, Expr, ExprBlock, ItemFn, Local, LocalInit, Pat, Stmt};

fn replace_in_block(block: &Block) -> Block {
    let mut new_stmts: Vec<Stmt> = vec![];
    for s: &Stmt in &block.stmts {
        match s {
            Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: Some(LocalInit { expr: &Box<Expr>, .. }), .. }) => {…
            Stmt::Local(Local { pat: Pat::Ident(var: &PatIdent), init: None, .. }) => {…
            Stmt::Expr(Expr::Block(ExprBlock { attrs: a: &Vec<Attribute>, label: l: &Option<Label>, block: inner: &Block, }), semi: …) => {…
            _ => new_stmts.push(s.clone()),
        }
    }
    Block { brace_token: block.brace_token, stmts: new_stmts }
} fn replace_in_block

#[proc_macro_attribute]
pub fn log_variable(_attr: TokenStream, item: TokenStream) -> TokenStream {
    let ItemFn {
        attrs: Vec<Attribute>,
        vis: Visibility,
        sig: Signature,
        block: Box<Block>
    } = parse_macro_input!(item);
    let new_block: Block = replace_in_block(&block);
    quote! {
        #(#attrs)*
        #vis #sig #new_block
    }.into()
}
```

And that‘s it!

→ We only needed 60 lines of code to write this macro
→ We can now log every variable declaration in any function!

```rust
use print::log_variable;
#[derive(Debug)]
2 implementations
struct Foo;
impl Foo {
    #[log_variable]
    fn new() -> Self {
        let new_foo: Foo = Foo;
        new_foo
    }
}
#[log_variable]
▶ Run | Debug
fn main() {
    let a: i32 = 5;
    let b: i32 = a + 4;
    let c: i32= b.abs();
    let d: i32;
    d = 1;
    {
        let f: i32 = a + b + c;
    }
    let foo: Foo = Foo::new();
}
```

```rust
use print::log_variable;
#[derive(Debug)]
2 implementations
struct Foo;
impl Foo {
    #[log_variable]
    fn new() -> Self {
        let new_foo: Foo = Foo;
        new_foo
    }
}
#[log_variable]
▶ Run | Debug
fn main() {
    let a: i32 = 5;
    let b: i32 = a + 4;
    let c: i32= b.abs();
    let d: i32;
    d = 1;
    {
        let f: i32 = a + b + c;
    }
    let foo: Foo = Foo::new();
}
```

cargo expand

```rust
let c = {
    let _e = b.abs();
    let _print_green = |s: &str| -> String {
        {
            let res = ::alloc::fmt::format(
                format_args!("\u{1b}[92m{0}\u{1b}[0m", s),
            );
            res
        }
    };
    let _print_yellow = |s: &str| -> String {
        {
            let res = ::alloc::fmt::format(
                format_args!("\u{1b}[93m{0}\u{1b}[0m", s),
            );
            res
        }
    };
    {
        ::std::io::_print(
            format_args!(
                "Setting {0} to {1}\n",
                _print_green("c"),
                _print_yellow(
                    &{
                        let res = ::alloc::fmt::format(
                            format_args!("{0} = {1:?}", "b.abs()", _e),
                        );
                        res
                    },
                ),
            ),
        );
    };
    _e
};
let d;
{
    let _print_green = |s: &str| -> String {
        {
            let res = ::alloc::fmt::format(
                format_args!("\u{1b}[92m{0}\u{1b}[0m", s),
            );
            res
        }
    };
    {
        ::std::io::_print(format_args!("Declaring {0}\n", _print_green("d")));
    };
}
d = 1;
```

```rust
use print::log_variable;
#[derive(Debug)]
2 implementations
struct Foo;
impl Foo {
    #[log_variable]
    fn new() -> Self {
        let new_foo: Foo = Foo;
        new_foo
    }
}
#[log_variable]
▶ Run | Debug
fn main() {
    let a: i32 = 5;
    let b: i32 = a + 4;
    let c: i32= b.abs();
    let d: i32;
    d = 1;
    {
        let f: i32 = a + b + c;
    }
    let foo: Foo = Foo::new();
}
```

cargo expand

```rust
fn new() -> Self {
    let new_foo = {
        let _e = Foo;
        let _print_green = |s: &str| -> String {
            {
                let res = ::alloc::fmt::format(
                    format_args!("\u{1b}[92m{0}\u{1b}[0m", s),
                );
                res
            }
        };
        let _print_yellow = |s: &str| -> String {
            {
                let res = ::alloc::fmt::format(
                    format_args!("\u{1b}[93m{0}\u{1b}[0m", s),
                );
                res
            }
        };
        {
            ::std::io::_print(
                format_args!(
                    "Setting {0} to {1}\n",
                    _print_green("new_foo"),
                    _print_yellow(
                        &{
                            let res = ::alloc::fmt::format(
                                format_args!("{0} = {1:?}", "Foo", _e),
                            );
                            res
                        },
                    ),
                ),
            );
        };
        _e
    };
    new_foo
}
```

```rust
use print::log_variable;
#[derive(Debug)]
2 implementations
struct Foo;
impl Foo {
    #[log_variable]
    fn new() -> Self {
        let new_foo: Foo = Foo;
        new_foo
    }
}
#[log_variable]
▶ Run | Debug
fn main() {
    let a: i32 = 5;
    let b: i32 = a + 4;
    let c: i32= b.abs();
    let d: i32;
    d = 1;
    {
        let f: i32 = a + b + c;
    }
    let foo: Foo = Foo::new();
}
```

cargo run

```
     Running `target\debug\recap.exe`
Setting b to a + 4 = 9
Setting c to b.abs() = 9
Declaring d
Setting f to a + b + c = 23
Setting new_foo to Foo = Foo
Setting foo to Foo :: new() = Foo
```

```rust
use print::log_variable;
#[derive(Debug)]
2 implementations
struct Foo;
impl Foo {
    #[log_variable]
    fn new() -> Self {
        let new_foo: Foo = Foo;
        new_foo
    }
}
#[log_variable]
▶ Run | Debug
fn main() {
    let a: i32 = 5;
    let b: i32 = a + 4;
    let c: i32= b.abs();
    let d: i32;
    d = 1;
    {
        let f: i32 = a + b + c;
    }
    let foo: Foo = Foo::new();
}
```

cargo run

```
     Running `target\debug\recap.exe`
Setting b to a + 4 = 9
Setting c to b.abs() = 9
Declaring d
Setting f to a + b + c = 23
Setting new_foo to Foo = Foo
Setting foo to Foo :: new() = Foo
```

a: i32 is Pat::Type, not Pat::Ident, so we don‘t log that :^)

2. Closures

2. Closures

- Rust has various properties that make it a functional programming language

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- Functional programming:

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  - Programs are constructed by applying and composing functions

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- Rust has various properties that make it a functional programming language
- Functional programming:
  - Programs are constructed by applying and composing functions
  - Functions are first-class citizen

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
▶ Run | Debug
fn main() {
    let p: fn print(i32) = print;
    p(arg: 5);
    let mut lookup: HashMap<&'static str, fn(i32) -> ()> = HashMap::new();
    lookup.insert(k: "print", v: print);
    if let Some(func: &fn(i32)) = lookup.get("print") {
        func(12);
    }
}
```

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
▶ Run | Debug
fn main() {
    let p: fn print(i32) = print;
    p(arg: 5);
    let mut lookup: HashMap<&'static str, fn(i32) -> ()> = HashMap::new();
    lookup.insert(k: "print", v: print);
    if let Some(func: &fn(i32)) = lookup.get("print") {
        func(12);
    }
}
```

- Functions in Rust are first-class citizen
- → We can do everything with functions that we can do with normal variables

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
▶ Run | Debug
fn main() {
    let p: fn print(i32) = print;
    p(arg: 5);
    let mut lookup: HashMap<&'static str, fn(i32) -> ()> = HashMap::new();
    lookup.insert(k: "print", v: print);
    if let Some(func: &fn(i32)) = lookup.get("print") {
        func(12);
    }
}
```

- Functions in Rust are first-class citizen
- → We can do everything with functions that we can do with normal variables

We can assign functions to variables

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
▶ Run | Debug
fn main() {
    let p: fn print(i32) = print;
    p(arg: 5);
    let mut lookup: HashMap<&'static str, fn(i32) -> ()> = HashMap::new();
    lookup.insert(k: "print", v: print);
    if let Some(func: &fn(i32)) = lookup.get("print") {
        func(12);
    }
}
```

- Functions in Rust are first-class citizen
- → We can do everything with functions that we can do with normal variables

We can put functions into data structures

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
▶ Run | Debug
fn main() {
    let p: fn print(i32) = print;
    p(arg: 5);
    let mut lookup: HashMap<&'static str, fn(i32) -> ()> = HashMap::new();
    lookup.insert(k: "print", v: print);
    if let Some(func: &fn(i32)) = lookup.get("print") {
        func(12);
    }
}
```

- Functions in Rust are first-class citizen
  - → We can do everything with functions that we can do with normal variables

both p and func are pointers to the original function
→ Indirect function call

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
▶ Run | Debug
fn main() {
    let p: fn print(i32) = print;
    p(arg: 5);
    let mut lookup: HashMap<&'static str, fn(i32) -> ()> = HashMap::new();
    lookup.insert(k: "print", v: print);
    if let Some(func: &fn(i32)) = lookup.get("print") {
        func(12);
    }
}
```

- Functions in Rust are first-class citizen
- → We can do everything with functions that we can do with normal variables

Type signature for functions

2. Closures

Type signature for functions

```
let mut lookup: HashMap<&'static str, fn(i32) -> ()> = HashMap::new();
let mut lookup: HashMap<&'static str, fn(i32)> = HashMap::new();
```

Those types are the same

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
fn wrong_arg(arg: u8) {}
fn call_func(func: fn(i32), arg: i32) {
    func(arg);
}
▶ Run | Debug
fn main() {
    call_func(func: print, arg: 5);
    call_func(func: wrong_arg, arg: 5);
}
```

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
fn wrong_arg(arg: u8) {}
fn call_func(func: fn(i32), arg: i32) {
    func(arg);
}
▶ Run | Debug
fn main() {
    call_func(func: print, arg: 5);
    call_func(func: wrong_arg, arg: 5);
}
```

We can pass functions as arguments

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
fn wrong_arg(arg: u8) {}
fn call_func(func: fn(i32), arg: i32) {
    func(arg);
}
```

Everything is checked at compile time

```rust
▶ Run | Debug
fn main() {
    call_func(func: print, arg: 5);
    call_func(func: wrong_arg, arg: 5);
}
```

```
error[E0308]: mismatched types
  --> src\main.rs:10:15
   |
10 |     call_func(wrong_arg, 5);
   |     --------- ^^^^^^^^^ expected fn pointer, found fn item
   |     |
   |     arguments to this function are incorrect
   |
   = note: expected fn pointer `fn(i32)`
                 found fn item `fn(u8) {wrong_arg}`
note: function defined here
  --> src\main.rs:5:4
   |
5  | fn call_func(func: fn(i32), arg: i32) {
   |    ^^^^^^^^^ -------------
```

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
fn call_func(func: fn(i32), arg: i32) {
    func(arg);
}
▶ Run | Debug
fn main() {
    call_func(func: print, arg: 5);
    let p: fn print(i32) = print;
    p(arg: 10);
}
```

```
     Running
arg is 5
arg is 10
```

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
fn call_func(func: fn(i32), arg: i32) {
    func(arg);
}
▶ Run | Debug
fn main() {
    call_func(func: print, arg: 5);
    let p: fn print(i32) = print;
    p(arg: 10);
}
```

```
    Running
arg is 5
arg is 10
```

2. Closures

```rust
fn print(arg: i32) {
    println!("arg is {}", arg);
}
fn call_func(func: fn(i32), arg: i32) {
    func(arg);
}
▶ Run | Debug
fn main() {
    call_func(func: print, arg: 5);
    let p: fn print(i32) = print;
    p(arg: 10);
}
```

```
    Running
arg is 5
arg is 10
```

2. Closures

```rust
fn filter<T>(elems: Vec<T>, predicate: fn(&T) -> bool) -> Vec<T> {
    let mut new_elems: Vec<T> = vec![];
    for e: T in elems {
        if predicate(&e) {
            new_elems.push(e);
        }
    }
    new_elems
}
fn is_even(n: &i32) -> bool { n % 2 == 0 }
▶ Run | Debug
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let modified: Vec<i32> = filter(elems: vec, predicate: is_even);
    println!("modified: {:?}", modified);
}
```

2. Closures

```rust
fn filter<T>(elems: Vec<T>, predicate: fn(&T) -> bool) -> Vec<T> {
    let mut new_elems: Vec<T> = vec![];
    for e: T in elems {
        if predicate(&e) {
            new_elems.push(e);
        }
    }
    new_elems
}
fn is_even(n: &i32) -> bool { n % 2 == 0 }
▶ Run | Debug
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let modified: Vec<i32> = filter(elems: vec, predicate: is_even);
    println!("modified: {:?}", modified);
}
```

By accepting functions as parameters, we can now build higher-level functions
→ filter: Take a list, and collect all elements which satisfy a given predicate

2. Closures

```rust
fn filter<T>(elems: Vec<T>, predicate: fn(&T) -> bool) -> Vec<T> {
    let mut new_elems: Vec<T> = vec![];
    for e: T in elems {
        if predicate(&e) {
            new_elems.push(e);
        }
    }
    new_elems
}
fn is_even(n: &i32) -> bool { n % 2 == 0 }
▶ Run | Debug
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let modified: Vec<i32> = filter(elems: vec, predicate: is_even);
    println!("modified: {:?}", modified);
}
```

modified contains all even elements of vec

```
original: [1, 2, 3, 4, 5]
modified: [2, 4]
```

2. Closures

```rust
fn map<T, E>(elems: Vec<T>, func: fn(&T) -> E) -> Vec<E> {
    let mut new_elems: Vec<E> = Vec::with_capacity(elems.len());
    for e: T in elems {
        new_elems.push(func(&e));
    }
    new_elems
}
fn square(n: &i32) -> i32 { n * n }
▶ Run | Debug
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let modified: Vec<i32> = map(elems: vec, func: square);
    println!("modified: {:?}", modified);
}
```

2. Closures

```rust
fn map<T, E>(elems: Vec<T>, func: fn(&T) -> E) -> Vec<E> {
    let mut new_elems: Vec<E> = Vec::with_capacity(elems.len());
    for e: T in elems {
        new_elems.push(func(&e));
    }
    new_elems
}
fn square(n: &i32) -> i32 { n * n }
▶ Run | Debug
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let modified: Vec<i32> = map(elems: vec, func: square);
    println!("modified: {:?}", modified);
}
```

By accepting functions as parameters, we can now build higher-level functions:
→ map: Take a list, and apply a function to all elements

2. Closures

```rust
fn map<T, E>(elems: Vec<T>, func: fn(&T) -> E) -> Vec<E> {
    let mut new_elems: Vec<E> = Vec::with_capacity(elems.len());
    for e: T in elems {
        new_elems.push(func(&e));
    }
    new_elems
}
fn square(n: &i32) -> i32 { n * n }
▶ Run | Debug
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let modified: Vec<i32> = map(elems: vec, func: square);
    println!("modified: {:?}", modified);
}
```

modified contains the first five square numbers

```
original: [1, 2, 3, 4, 5]
modified: [1, 4, 9, 16, 25]
```

2. Closures

```rust
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let even_square: Vec<i32> = map(elems: filter(elems: vec, predicate: is_even), func: square);
    println!("modified: {:?}", even_square);
}
```

2. Closures

Composition means passing the output of one function directly to the next function
→ Filter our original vector, only keep the even numbers, which we square directly after

```rust
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let even_square: Vec<i32> = map(elems: filter(elems: vec, predicate: is_even), func: square);
    println!("modified: {:?}", even_square);
}
```

2. Closures

Composition means passing the output of one function directly to the next function
→ Filter our original vector, only keep the even numbers, which we square directly after

```rust
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let even_square: Vec<i32> = map(elems: filter(elems: vec, predicate: is_even), func: square);
    println!("modified: {:?}", even_square);
}
```

```
original: [1, 2, 3, 4, 5]
modified: [4, 16]
```

2. Closures

This is not ideal though, we need to think about function names for our predicates
→ Rust does not support function overloading, we can only have one is_even and one square
→ What if the actual square-function should serve a different purpose?

```
fn main() {
    let vec: Vec<i32> = vec![1, 2, 3, 4, 5];
    println!("original: {:?}", vec);
    let even_square: Vec<i32> = map(elems: filter(elems: vec, predicate: is_even), func: square);
    println!("modified: {:?}", even_square);
}
```

2. Closures

- Closures are special expressions that declare anonymous functions
  - Anonymous function → Closures have no name

2. Closures

- Closures are special expressions that declare anonymous functions
  - Anonymous function → Closures have no name

```
fn main() {
    let square: impl Fn(i32) -> i32 = |n: i32| n * n;
    let n: i32 = square(5);
    println!("n={}", n);
}
```

2. Closures

- Closures are special expressions that declare anonymous functions
  - Anonymous function → Closures have no name

```
fn main() {
    let square: impl Fn(i32) -> i32 = |n: i32| n * n;
    let n: i32 = square(5);
    println!("n={}", n);
}
```

This is a closure

2. Closures

- Closures are special expressions that declare anonymous functions
  - Anonymous function → Closures have no name

Parameters are declared between the pipes

```
fn main() {
    let square: impl Fn(i32) -> i32 = |n: i32| n * n;
    let n: i32 = square(5);
    println!("n={}", n);
}
```

2. Closures

- Closures are special expressions that declare anonymous functions
  - Anonymous function → Closures have no name

```
fn main() {
    let square: impl Fn(i32) -> i32 = |n: i32| n * n;
    let n: i32 = square(5);
    println!("n={}", n);
}
```

Closure body
→ Can also be a block {}

2. Closures

- Closures are special expressions that declare anonymous functions
  - Anonymous function → Closures have no name

We can now bind the closure to a variable, and call it like a normal function

```
fn main() {
    let square: impl Fn(i32) -> i32 = |n: i32| n * n;
    let n: i32 = square(5);
    println!("n={}", n);
}
```

2. Closures

- Closures are special expressions that declare anonymous functions
  - Anonymous function → Closures have no name

We can also directly call the closure

```
fn main() {
    let n: i32 = (|n: i32|n * n)(5);
    println!("n={}", n);
}
```

2. Closures

```rust
fn main() {
    let n: i32 = 7;
    let add_n: impl Fn(i32) -> i32 = |x: i32| x + n;
    let start: i32 = 3;
    let result: i32 = add_n(start);
    println!("{}+{}={}", start, n, result);
}
```

2. Closures

```rust
fn main() {
    let n: i32 = 7;
    let add_n: impl Fn(i32) -> i32 = |x: i32| x + n;
    let start: i32 = 3;
    let result: i32 = add_n(start);
    println!("{}+{}={}", start, n, result);
}
```

Closures are more powerful than function pointers
→ They allow us to capture and use local variables

2. Closures

```rust
fn main() {
    let n: i32 = 7;
    let add_n: impl Fn(i32) -> i32 = |x: i32| x + n;
    let start: i32 = 3;
    let result: i32 = add_n(start);
    println!("{}+{}={}", start, n, result);
}
```

Closure computes x + 7

```
3+7=10
```

2. Closures

Closures implement a special trait that defines their behavior

```
fn main() {
    let n: i32 = 7;
    let add_n: impl Fn(i32) -> i32 = |x: i32| x + n;
    let start: i32 = 3;
    let result: i32 = add_n(start);
    println!("{}+{}={}", start, n, result);
}
```

```
3+7=10
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let add_size_of_s: impl Fn(usize) -> usize = |x: usize| x + s.len();
    println!("{}", add_size_of_s(5));
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

If we only ever immutably borrow outer variables,
the closure implements Fn

```
fn main() {
    let mut s: String = String::from("Big Data");
    let add_size_of_s: impl Fn(usize) -> usize = |x: usize| x + s.len();
    println!("{}", add_size_of_s(5));
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

If we only ever immutably borrow outer variables, the closure implements Fn

```
fn main() {
    let mut s: String = String::from("Big Data");
    let add_size_of_s: impl Fn(usize) -> usize = |x: usize| x + s.len();
    println!("{}", add_size_of_s(5));
}
```

In this range we immutably borrow s

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let add_size_of_s: impl Fn(usize) -> usize = |x: usize| x + s.len();
    s.push(ch: 'c');
    println!("{}", add_size_of_s(5));
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```rust
fn main() {
    let mut s: String = String::from("Big Data");
    let add_size_of_s: impl Fn(usize) -> usize = |x: usize| x + s.len();
    s.push(ch: 'c');
    println!("{}", add_size_of_s(5));
}
```

Immutable borrow here

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let add_size_of_s: impl Fn(usize) -> usize = |x: usize| x + s.len();
    s.push(ch: 'c');
    println!("{}", add_size_of_s(5));
}
```

Mutable borrow here

Immutable borrow here

2. Closures

```
error[E0502]: cannot borrow `s` as mutable because it is also borrowed as immutable
  --> src\main.rs:49:5
   |
48 |     let add_size_of_s = |x| x + s.len();
   |                         ---     - first borrow occurs due to use of `s` in closure
   |                         |
   |                         immutable borrow occurs here
49 |     s.push('c');
   |     ^^^^^^^^^^ mutable borrow occurs here
50 |     println!("{}", add_size_of_s(5));
   |                    ------------- immutable borrow later used here
```

```rust
fn main() {
    let mut s: String = String::from("Big Data");
    let add_size_of_s: impl Fn(usize) -> usize = |x: usize| x + s.len();
    s.push(ch: 'c');
    println!("{}", add_size_of_s(5));
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```rust
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    push_to_str(what: ", now expanded!");
    println!("{}", s);
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```rust
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    push_to_str(what: ", now expanded!");
    println!("{}", s);
}
```

If we mutably borrow any outer variables, the closure implements FnMut

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    push_to_str(what: ", now expanded!");
    println!("{}", s);
}
```

We modify s → We mutably borrow s

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    push_to_str(what: ", now expanded!");
    println!("{}", s);
}
```

If we want to call a FnMut closure, the variable needs to be mutable

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    push_to_str(what: ", now expanded!");
    println!("{}", s);
}
```

In this range we mutably borrow s

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```rust
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    println!("{}", s);
    push_to_str(what: ", now expanded!");
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    println!("{}", s);
    push_to_str(what: ", now expanded!");
}
```

Mutable borrow here

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    println!("{}", s);
    push_to_str(what: ", now expanded!");
}
```

Immutable borrow here

Mutable borrow here

2. Closures

```
error[E0502]: cannot borrow `s` as immutable because it is also borrowed as mutable
  --> src\main.rs:56:20
   |
53 |     let mut push_to_str = |what: &str| {
   |                           ------------ mutable borrow occurs here
54 |         s.push_str(what)
   |         - first borrow occurs due to use of `s` in closure
55 |     };
56 |     println!("{}", s);
   |                    ^ immutable borrow occurs here
57 |     push_to_str(", now expanded!");
   |     ----------- mutable borrow later used here
   |
```

```rust
fn main() {
    let mut s: String = String::from("Big Data");
    let mut push_to_str: impl FnMut(&str) = |what: &str| {
        s.push_str(string: what)
    };
    println!("{}", s);
    push_to_str(what: ", now expanded!");
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
}
```

If we move any outer variables, the closure implements FnOnce

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
}
```

If we move any outer variables, the closure implements FnOnce

Because we move values, FnOnce closures can only be called once

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
}
```

String doesn‘t implement Copy, s is moved here

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```rust
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
    println!("{}", s);
}
```

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
    println!("{}", s);
}
```

s moved here

2. Closures

- There are three traits that a closure can implement → Fn, FnMut, FnOnce

```
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
    println!("{}", s);
}
```

s moved here

Can‘t use s here

2. Closures

```
error[E0382]: borrow of moved value: `s`
  --> src\main.rs:66:20
   |
60 |     let s = String::from("Big Data");
   |         - move occurs because `s` has type `String`, which does not implement the `Copy` trait
61 |     let move_str = || {
   |                    -- value moved into closure here
62 |         let x = s;
   |                 - variable moved due to use in closure
...
66 |     println!("{}", s);
   |                    ^ value borrowed here after move
   |
```

```rust
fn main() {
    let s: String = String::from("Big Data");
    let move_str: impl FnOnce() = || {
        let x: String = s;
        println!("{}", x);
    };
    move_str();
    println!("{}", s);
}
```

2. Closures

- Those traits have additional trait boundaries
  → FnMut: FnOnce → Every FnMut is also FnOnce
  → Fn: FnMut → Every Fn is also FnMut → Every Fn is also FnOnce

2. Closures

- Those traits have additional trait boundaries
  → FnMut: FnOnce → Every FnMut is also FnOnce
  → Fn: FnMut → Every Fn is also FnMut → Every Fn is also FnOnce

2. Closures

- Those traits have additional trait boundaries
  → FnMut: FnOnce → Every FnMut is also FnOnce
  → Fn: FnMut → Every Fn is also FnMut → Every Fn is also FnOnce
  → FnOnce is the most generic closure, every closure can be called at least once

2. Closures

- Those traits have additional trait boundaries
  → FnMut: FnOnce → Every FnMut is also FnOnce
  → Fn: FnMut → Every Fn is also FnMut → Every Fn is also FnOnce
  → FnOnce is the most generic closure, every closure can be called at least once
- When writing functions that accept closures, it's recommended to always use the most generic trait

2. Closures

- Those traits have additional trait boundaries
  → FnMut: FnOnce → Every FnMut is also FnOnce
  → Fn: FnMut → Every Fn is also FnMut → Every Fn is also FnOnce
  → FnOnce is the most generic closure, every closure can be called at least once
- When writing functions that accept closures, it's recommended to always use the most generic trait
  → Function only expects to call the closure once → Mark parameter as FnOnce → Can still pass FnMut

2. Closures

- Those traits have additional trait boundaries
  → FnMut: FnOnce → Every FnMut is also FnOnce
  → Fn: FnMut → Every Fn is also FnMut → Every Fn is also FnOnce
  → FnOnce is the most generic closure, every closure can be called at least once
- When writing functions that accept closures, it's recommended to always use the most generic trait
  → Function only expects to call the closure once → Mark parameter as FnOnce → Can still pass FnMut
  → Closure *might* mutate its environment → Mark parameter as FnMut → Can still pass Fn

2. Closures

```rust
fn filter_2<T, F>(elems: Vec<T>, mut predicate: F) -> Vec<T>
where F: FnMut(&T) -> bool {
    let mut new_elems: Vec<T> = vec![];
    for e: T in elems {
        if predicate(&e) {
            new_elems.push(e);
        }
    }
    new_elems
}
```

2. Closures

```rust
fn filter_2<T, F>(elems: Vec<T>, mut predicate: F) -> Vec<T>
where F: FnMut(&T) -> bool {
    let mut new_elems: Vec<T> = vec![];
    for e: T in elems {
        if predicate(&e) {
            new_elems.push(e);
        }
    }
    new_elems
}
```

We accept every closure that can be called multiple times
→ We don‘t care if it modifies its environment

2. Closures

```rust
fn filter_2<T, F>(elems: Vec<T>, mut predicate: F) -> Vec<T>
where F: FnMut(&T) -> bool {
    let mut new_elems: Vec<T> = vec![];
    for e: T in elems {
        if predicate(&e) {
            new_elems.push(e);
        }
    }
    new_elems
}
```

We accept every closure that can be called multiple times
→ We don‘t care if it modifies its environment
→ Can‘t accept FnOnce, because we call the closure more than once

2. Closures

```rust
fn main() {
    let vec: Vec<i32> = vec![6, 7, 8, 9, 10, 11, 12, 13, 14, 15];
    let evens: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 0);
    let odds: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 1);
    let mut not_prime: Vec<i32> = vec![];
    let primes: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| {
        for i: i32 in 2..*n {
            if n % i == 0 {
                not_prime.push(*n);
                return false;
            }
        }
        true
    });
    println!("original:  {:?}", vec);
    println!("even:      {:?}", evens);
    println!("odds:      {:?}", odds);
    println!("not_prime: {:?}", not_prime);
    println!("primes:    {:?}", primes);
}
```

2. Closures

```rust
fn main() {
    let vec: Vec<i32> = vec![6, 7, 8, 9, 10, 11, 12, 13, 14, 15];
    let evens: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 0);
    let odds: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 1);
    let mut not_prime: Vec<i32> = vec![];
    let primes: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| {
        for i: i32 in 2..*n {
            if n % i == 0 {
                not_prime.push(*n);
                return false;
            }
        }
        true
    });
    println!("original:  {:?}", vec);
    println!("even:      {:?}", evens);
    println!("odds:      {:?}", odds);
    println!("not_prime: {:?}", not_prime);
    println!("primes:    {:?}", primes);
}
```

We can now call our filter-function with any closure that‘s FnMut

2. Closures

```rust
fn main() {
    let vec: Vec<i32> = vec![6, 7, 8, 9, 10, 11, 12, 13, 14, 15];
    let evens: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 0);
    let odds: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 1);
    let mut not_prime: Vec<i32> = vec![];
    let primes: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| {
        for i: i32 in 2..*n {
            if n % i == 0 {
                not_prime.push(*n);
                return false;
            }
        }
        true
    });
    println!("original:  {:?}", vec);
    println!("even:      {:?}", evens);
    println!("odds:      {:?}", odds);
    println!("not_prime: {:?}", not_prime);
    println!("primes:    {:?}", primes);
}
```

Fn-closures

2. Closures

```rust
fn main() {
    let vec: Vec<i32> = vec![6, 7, 8, 9, 10, 11, 12, 13, 14, 15];
    let evens: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 0);
    let odds: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 1);
    let mut not_prime: Vec<i32> = vec![];
    let primes: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| {
        for i: i32 in 2..*n {
            if n % i == 0 {
                not_prime.push(*n);
                return false;
            }
        }
        true
    });
    println!("original:  {:?}", vec);
    println!("even:      {:?}", evens);
    println!("odds:      {:?}", odds);
    println!("not_prime: {:?}", not_prime);
    println!("primes:    {:?}", primes);
}
```

This closure modifies the environment (it pushes elements to not_prime), so it is FnMut

2. Closures

```rust
fn main() {
    let vec: Vec<i32> = vec![6, 7, 8, 9, 10, 11, 12, 13, 14, 15];
    let evens: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 0);
    let odds: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| n % 2 == 1);
    let mut not_prime: Vec<i32> = vec![];
    let primes: Vec<i32> = filter_2(elems: vec.clone(), predicate: |n: &i32| {
```

```
original:  [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]
even:      [6, 8, 10, 12, 14]
odds:      [7, 9, 11, 13, 15]
not_prime: [6, 8, 9, 10, 12, 14, 15]
primes:    [7, 11, 13]
```

```rust
    println!("original:  {:?}", vec);
    println!("even:      {:?}", evens);
    println!("odds:      {:?}", odds);
    println!("not_prime: {:?}", not_prime);
    println!("primes:    {:?}", primes);
}
```

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

We can also return closures from functions

2. Closures

```
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

However, Fn only borrows variables
→ Closure would outlive num

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    move |n: i32| n * num
}
```

Instead of borrowing, we explicitly move all variables into the closure

```rust
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    move |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

Composing functions

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    move |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

Those function calls return closures

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    move |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

n * 7

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    move |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

3 * 7

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    move |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

3 * 7 * 5

2. Closures

```rust
fn multiply_by(num: i32) -> impl Fn(i32) -> i32 {
    move |n: i32| n * num
}
▶ Run | Debug
fn main() {
    let result: i32 = multiply_by(num: 5)(multiply_by(num: 7)(3));
    println!("{}", result);
}
```

3 * 7 * 5

```
105
```

3. Iterators

3. Iterators

- The next step in making closures useful is implementing data structures that work with them

3. Iterators

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- Those data structures are called iterators

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- Those data structures are called iterators
- Iterators only serve one purpose → Repeatedly emit the next item of a collection, until it is exhausted

3. Iterators

- The next step in making closures useful is implementing data structures that work with them
- Those data structures are called iterators
- Iterators only serve one purpose → Repeatedly emit the next item of a collection, until it is exhausted
- Every iterator implements the Iterator trait in which they define how the next item is obtained

3. Iterators

There are three variations of iterators

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1, 2, 3];
    let ref_iter: Iter<i32> = collection.iter();
    let ref_mut_iter: IterMut<i32> = collection.iter_mut();
    let owned_iter: IntoIter<i32> = collection.into_iter();
}
```

3. Iterators

There are three variations of iterators
→ iter() creates an iterator over immutable references of the elements

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1, 2, 3];
    let ref_iter: Iter<i32> = collection.iter();
    let ref_mut_iter: IterMut<i32> = collection.iter_mut();
    let owned_iter: IntoIter<i32> = collection.into_iter();
}
```

3. Iterators

There are three variations of iterators
→ iter() creates an iterator over immutable references of the elements
→ iter_mut() creates an iterator over mutable references of the elements

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1, 2, 3];
    let ref_iter: Iter<i32> = collection.iter();
    let ref_mut_iter: IterMut<i32> = collection.iter_mut();
    let owned_iter: IntoIter<i32> = collection.into_iter();
}
```

3. Iterators

There are three variations of iterators
→ iter() creates an iterator over immutable references of the elements
→ iter_mut() creates an iterator over mutable references of the elements
→ into_iter() creates an iterator over owned elements

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1, 2, 3];
    let ref_iter: Iter<i32> = collection.iter();
    let ref_mut_iter: IterMut<i32> = collection.iter_mut();
    let owned_iter: IntoIter<i32> = collection.into_iter();
}
```

3. Iterators

Iterators are lazy → They only compute elements when you consume them

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1; 100_000_000];
    let ref_iter: Iter<i32> = collection.iter();
}
```

3. Iterators

Iterators are lazy → They only compute elements when you consume them

Creating an iterator over 100 million elements
→ Super fast because we're not doing anything with it

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1; 100_000_000];
    let ref_iter: Iter<i32> = collection.iter();
}
```

3. Iterators

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1; 100_000_000];
    let mut ref_iter: Iter<i32> = collection.iter();
    ref_iter.map(|n: &i32|n * n);
}
```

3. Iterators

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1; 100_000_000];
    let mut ref_iter: Iter<i32> = collection.iter();
    ref_iter.map(|n: &i32|n * n);
}
```

Iterators come with many different methods
→ map and filter are some of them

3. Iterators

```rust
fn main() {
    let mut collection: Vec<i32> = vec![1; 100_000_000];
    let mut ref_iter: Iter<i32> = collection.iter();
    ref_iter.map(|n: &i32|n * n);
}
```

Iterators come with many different methods
→ map and filter are some of them

map() returns an iterator over all elements of the original collection when applied to the given closure
→ map() is also lazy, it does not do anything until consumed

3. Iterators

```rust
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum();
    println!("{}", sum);
}
```

3. Iterators

```
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum();
    println!("{}", sum);
}
```

Because many iterator-methods are lazy and return iterators, we can easily chain those calls
→ Iterator adaptors
→ Function composition

3. Iterators

```
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum(); sum() consumes the iterator, now we start computing elements
    println!("{}", sum);
}
```

3. Iterators

```rust
fn main() {
    let mut sum: i128 = 0;
    for n in (1..100_000_000) {
        if n % 2 == 1 {
            sum += n * n;
        }
    }
    println!("{}", sum);
}
```

This iterator-chain is equivalent to this for-loop

```rust
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum();
    println!("{}", sum);
}
```

3. Iterators

```rust
fn main() {
    let mut sum: i128 = 0;
    for n in (1..100_000_000) {
        if n % 2 == 1 {
            sum += n * n;
        }
    }
    println!("{}", sum);
}
```

This iterator-chain is equivalent to this for-loop

```rust
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum();
    println!("{}", sum);
}
```

3. Iterators

```rust
fn main() {
    let mut sum: i128 = 0;
    for n in (1..100_000_000) {
        if n % 2 == 1 {
            sum += n * n;
        }
    }
    println!("{}", sum);
}
```

for also implicitly calls into_iter() for us
→ Moves the collection
→ That‘s why we need to borrow collections

This iterator-chain is equivalent to this for-loop

```rust
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum();
    println!("{}", sum);
}
```

3. Iterators

```rust
fn main() {
    let mut sum: i128 = 0;
    for n in (1..100_000_000) {
        if n % 2 == 1 {
            sum += n * n;
        }
    }
    println!("{}", sum);
}
```

This iterator-chain is equivalent to this for-loop

```rust
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        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum();
    println!("{}", sum);
}
```

3. Iterators

```rust
fn main() {
    let mut sum: i128 = 0;
    for n in (1..100_000_000) {
        if n % 2 == 1 {
            sum += n * n;
        }
    }
    println!("{}", sum);
}
```

This iterator-chain is equivalent to this for-loop

```rust
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
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        .map(|n: i128|n * n) impl Iterator<Item = i128>
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    println!("{}", sum);
}
```

3. Iterators

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fn main() {
    let mut sum: i128 = 0;
    for n in (1..100_000_000) {
        if n % 2 == 1 {
            sum += n * n;
        }
    }
    println!("{}", sum);
}
```

This iterator-chain is equivalent to this for-loop

```rust
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter() Range<i128>
        .filter(|n: &i128| n % 2 == 1) impl Iterator<Item = i128>
        .map(|n: i128|n * n) impl Iterator<Item = i128>
        .sum();
    println!("{}", sum);
}
```

3. Iterators

```rust
use rayon::iter::{IntoParallelIterator, ParallelIterator};
▶ Run | Debug
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_par_iter() Iter<i128>
        .filter(filter_op: |n: &i128| n % 2 == 1) Filter<It
        .map(map_op: |n: i128|n * n) Map<Filter<Iter<i128>,
        .sum();
    println!("{}", sum);
}
```

3. Iterators

```rust
use rayon::iter::{IntoParallelIterator, ParallelIterator};
▶ Run | Debug
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_par_iter() Iter<i128>
        .filter(filter_op: |n: &i128| n % 2 == 1) Filter<It
        .map(map_op: |n: i128|n * n) Map<Filter<Iter<i128>,
        .sum();
    println!("{}", sum);
}
```

Because all elements of iterators are decoupled, we can easily parallelize them

3. Iterators

```rust
use rayon::iter::{IntoParallelIterator, ParallelIterator};
▶ Run | Debug
fn main() {
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_par_iter() Iter<i128>
        .filter(filter_op: |n: &i128| n % 2 == 1) Filter<It
        .map(map_op: |n: i128|n * n) Map<Filter<Iter<i128>,
        .sum();
    println!("{}", sum);
}
```

The crate rayon makes it super easy to add parallelism to our iterators
→ Easy extra performance by just changing a single line

Because all elements of iterators are decoupled, we can easily parallelize them

3. Iterators

```rust
fn main() {
    let now: Instant = std::time::Instant::now();
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter().filter(|n: &i128| n % 2 == 1).map(|n: i128|n * n).sum();
    println!("{}", sum);
    println!("Normal: {}", now.elapsed().as_secs_f64());
    let now: Instant = std::time::Instant::now();
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_par_iter().filter(filter_op: |n: &i128| n % 2 == 1).map(map_op: |n: i128|n * n).sum();
    println!("{}", sum);
    println!("Parallel: {}", now.elapsed().as_secs_f64());
}
```

3. Iterators

```rust
fn main() {
    let now: Instant = std::time::Instant::now();
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter().filter(|n: &i128| n % 2 == 1).map(|n: i128|n * n).sum();
    println!("{}", sum);
    println!("Normal: {}", now.elapsed().as_secs_f64());
    let now: Instant = std::time::Instant::now();
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_par_iter().filter(filter_op: |n: &i128| n % 2 == 1).map(map_op: |n: i128|n * n).sum();
    println!("{}", sum);
    println!("Parallel: {}", now.elapsed().as_secs_f64());
}
```

The only difference in this iterator chain

3. Iterators

```
     Running `target\debug\
166666666666666650000000
Normal: 2.8685183
166666666666666650000000
Parallel: 0.8238326
```

```
     Running `target\release\
166666666666666650000000
Normal: 0.0467487
166666666666666650000000
Parallel: 0.008967
```

```rust
fn main() {
    let now: Instant = std::time::Instant::now();
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_iter().filter(|n: &i128| n % 2 == 1).map(|n: i128|n * n).sum();
    println!("{}", sum);
    println!("Normal: {}", now.elapsed().as_secs_f64());
    let now: Instant = std::time::Instant::now();
    let sum: i128 = (1..100_000_000) Range<i128>
        .into_par_iter().filter(filter_op: |n: &i128| n % 2 == 1).map(map_op: |n: i128|n * n).sum();
    println!("{}", sum);
    println!("Parallel: {}", now.elapsed().as_secs_f64());
}
```

3. Iterators

```rust
struct Container(i32);
▶ Run | Debug
fn main() {
    let collection: [Container; 3] = [Container(1), Container(2), Container(3)];
    let mut element: Option<&Container> = None;
    for c: &Container in &collection {
        if c.0 == 3 {
            element = Some(c);
            break;
        }
    }
    println!("Found container with a number of 3: {:?}", element);
}
```

3. Iterators

```rust
struct Container(i32);
▶ Run | Debug
fn main() {
    let collection: [Container; 3] = [Container(1), Container(2), Container(3)];
    let mut element: Option<&Container> = None;
    for c: &Container in &collection {
        if c.0 == 3 {
            element = Some(c);
            break;
        }
    }
    println!("Found container with a number of 3: {:?}", element);
}
```

Find the first element that has a value of 3

3. Iterators

```rust
struct Container(i32);
▶ Run | Debug
fn main() {
    let collection: [Container; 3] = [Container(1), Container(2), Container(3)];
    let element: Option<&Container> = collection.iter().find(|c: &&Container| c.0 == 3);
    println!("Found container with a number of 3: {:?}", element);
}
```

3. Iterators

```rust
struct Container(i32);
▶ Run | Debug
fn main() {
    let collection: [Container; 3] = [Container(1), Container(2), Container(3)];
    let element: Option<&Container> = collection.iter().find(|c: &&Container| c.0 == 3);
    println!("Found container with a number of 3: {:?}", element);
}
```

Find the first element that has a value of 3
→ Iterators allow us to write more concise and readable code

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}
▶ Run | Debug
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}
```

▶ Run | Debug

```rust
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

Iterators can go on forever, which means we can implement infinite data structures

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}
▶ Run | Debug
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

This iterator goes over every number that fits in an u128, and prints every prime

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}

▶ Run | Debug
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

To check if a number is prime:
Take all odd numbers

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}

▶ Run | Debug
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

To check if a number is prime:
Take all odd numbers that are smaller than the square root of the candidate

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}
```

To check if a number is prime:
Take all odd numbers that are smaller than the square root of the candidate and check that they don't divide the candidate

▶ Run | Debug

```rust
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}
▶ Run | Debug
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

all is short-circuiting
→ It stops iterating once it finds an element that returns false

3. Iterators

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}
▶ Run | Debug
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

If this iterator hits the end of u128, two things can happen

→ Debug mode: Panic

→ Release mode: Overflow and start at 0 again

3. Iterators

At the same time, iterators are memory efficient, at any point we only store two numbers:
The prime candidate, and the number we're currently checking against

```rust
fn is_prime(num: &u128) -> bool {
    if *num == 2 { return true; }
    else if num % 2 == 0 { return false; }
    (1..).map(|n: u128|2*n+1).take_while(|n: &u128|n*n<=*num).all(|n: u128|num % n != 0)
}
▶ Run | Debug
fn main() {
    let all_numbers: RangeFrom<u128> = 2..;
    all_numbers.filter(is_prime).for_each(|e: u128|println!("{e}"));
}
```

some prime numbers:

```
261775807
261775823
261775841
261775867
261775889
261775897
261775907
261775919
261775931
261775933
261775981
261775993
261776003
261776017
261776023
261776027
261776051
```

3. Iterators

```rust
struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
▶ Run | Debug
fn main() {
    let containers: Vec<Container> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i).unwrap()) impl Iterator<Item = Container>
        .collect::<Vec<_>>();
}
```

3. Iterators

```rust
struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
```

Implement Container::try_from(i32), which only accepts numbers above 10

```rust
▶ Run | Debug
fn main() {
    let containers: Vec<Container> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i).unwrap()) impl Iterator<Item = Container>
        .collect::<Vec<_>>();
}
```

3. Iterators

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struct Container(i32);
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        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
▶ Run | Debug
fn main() {
    let containers: Vec<Container> = (1..20)
        .map(|i: i32|Container::try_from(i).unwrap())
        .collect::<Vec<_>>();
}
```

Create an iterator to easily build a vector of containers

Range<i32>

impl Iterator<Item = Container>

3. Iterators

```rust
struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
▶ Run | Debug
fn main() {
    let containers: Vec<Container> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i).unwrap()) impl Iterator<Item = Container>
        .collect::<Vec<_>>();
}
```

Problem: .unwrap() is not good practice, we'd like to report the error

3. Iterators

```rust
struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
```

▶ Run | Debug

```rust
fn main() {
    let containers: Vec<Result<Container, String>> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i)) impl Iterator<Item = Result<…, …>>
        .collect::<Vec<_>>();
}
```

3. Iterators

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struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
```

.unwrap() is gone, but we now have a Vector of Results!

```rust
▶ Run | Debug
fn main() {
    let containers: Vec<Result<Container, String>> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i)) impl Iterator<Item = Result<…, …>>
        .collect::<Vec<_>>();
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```

3. Iterators

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struct Container(i32);
impl TryFrom<i32> for Container {
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▶ Run | Debug
fn main() {
    let containers: Vec<Result<Container, String>> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i)) impl Iterator<Item = Result<…, …>>
        .collect::<Vec<_>>();
}
```

.unwrap() is gone, but we now have a Vector of Results!
→ collect() comes with a lot of useful overloads

3. Iterators

```rust
struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
▶ Run | Debug
fn main() {
    let containers: Result<Vec<Container>, String> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i)) impl Iterator<Item = Result<…, …>>
        .collect::<Result<Vec<_>, _>>();
}
```

3. Iterators

```rust
struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
▶ Run | Debug
fn main() {
    let containers: Result<Vec<Container>, String> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i)) impl Iterator<Item = Result<…, …>>
        .collect::<Result<Vec<_>, _>>();
}
```

collect() can be called with any generic types that implement the FromIterator trait
→ Result<T, E> does implement that trait!

3. Iterators

```rust
struct Container(i32);
impl TryFrom<i32> for Container {
    type Error = String;
    fn try_from(value: i32) -> Result<Self, Self::Error> {
        if value < 10 { Err(format!("Numbers below 10 are reserved, got {}", value)) }
        else { Ok(Self(value)) }
    }
}
▶ Run | Debug
fn main() {
    let containers: Result<Vec<Container>, String> = (1..20) Range<i32>
        .map(|i: i32|Container::try_from(i)) impl Iterator<Item = Result<…, …>>
        .collect::<Result<Vec<_>, _>>();
}
```

collect() can be called with any generic types that implement the FromIterator trait

→ Result<T, E> does implement that trait!

→ If the iterator contains an Err()-element, we stop directly and return the Err()

→ If all elements are Ok(), we transform Vec<Ok> into Ok<Vec>

3. Iterators

```rust
fn main() -> Result<(), String> {
    let containers = (1..20) Range<i32>
        .inspect(|n|println!("Number: {}", n)) im
        .map(|i|Container::try_from(i)) impl Iter
        .inspect(|v|println!("Result: {:?}", v))
        .collect::<Result<Vec<_>, _>>()?;
    for c in &containers {
        println!("{:?}", c);
    }
    Ok(())
}
```

3. Iterators

```rust
fn main() -> Result<(), String> {
    let containers = (1..20) Range<i32>
        .inspect(|n|println!("Number: {}", n)) im
        .map(|i|Container::try_from(i)) impl Iter
        .inspect(|v|println!("Result: {:?}", v))
        .collect::<Result<Vec<_>, _>>()?;
    for c in &containers {
        println!("{:?}", c);
    }
    Ok(())
}
```

inspect() allows us to see what element the iterator is currently processing

3. Iterators

```rust
fn main() -> Result<(), String> {
    let containers = (1..20) Range<i32>
        .inspect(|n|println!("Number: {}", n)) im
        .map(|i|Container::try_from(i)) impl Iter
        .inspect(|v|println!("Result: {:?}", v))
        .collect::<Result<Vec<_>, _>>()?;
    for c in &containers {
        println!("{:?}", c);
    }
    Ok(())
}
```

Because we're now collecting into a Result, we can use the ?-operator

3. Iterators

```rust
fn main() -> Result<(), String> {
    let containers = (1..20) Range<i32>
        .inspect(|n|println!("Number: {}", n)) im
        .map(|i|Container::try_from(i)) impl Iter
        .inspect(|v|println!("Result: {:?}", v))
        .collect::<Result<Vec<_>, _>>()?;
    for c in &containers {
        println!("{:?}", c);
    }
    Ok(())
}
```

Our first element directly caused an error, so we did not advance the iterator further

```
     Running `target\debug\iterators.exe`
Number: 1
Result: Err("Numbers below 10 are reserved, got 1")
Error: "Numbers below 10 are reserved, got 1"
error: process didn't exit successfully: `target\deb
```

3. Iterators

Change range to something more reasonable

```rust
fn main() -> Result<(), String> {
    let containers = (15..20) Range<i32>
        .inspect(|n|println!("Number: {}", n)) ir
        .map(|i|Container::try_from(i)) impl Iter
        .inspect(|v|println!("Result: {:?}", v))
        .collect::<Result<Vec<_>, _>>()?;
    for c in &containers {
        println!("{:?}", c);
    }
    Ok(())
}
```

3. Iterators

```rust
fn main() -> Result<(), String> {
    let containers = (15..20) Range<i32>
        .inspect(|n|println!("Number: {}", n)) ir
        .map(|i|Container::try_from(i)) impl Iter
        .inspect(|v|println!("Result: {:?}", v))
        .collect::<Result<Vec<_>, _>>()?;
    for c in &containers {
        println!("{:?}", c);
    }
    Ok(())
}
```

We successfully iterate over all numbers and build containers!

```
Number: 15
Result: Ok(Container(15))
Number: 16
Result: Ok(Container(16))
Number: 17
Result: Ok(Container(17))
Number: 18
Result: Ok(Container(18))
Number: 19
Result: Ok(Container(19))
Container(15)
Container(16)
Container(17)
Container(18)
Container(19)
```

4. Next time

- Multithreading