

# Lecture 2: Traits

Methods, traits, functional programming and standard library

Willem Vanhulle

**DevLab Rust 2025**

Tuesday November 11, 2025

[github.com/wvhulle/rust-course-ghent](https://github.com/wvhulle/rust-course-ghent)

<b>1. Quiz about last lecture .....</b>	<b>1</b>
1.1. Comparing pointers .....	2
1.2. Patterns .....	4
1.3. Bool .....	6
2. Pattern matching .....	8
3. Tooling intermezzo .....	23
4. Methods and traits .....	27
5. Generics .....	43
6. Closures .....	63
7. Standard library types .....	76
8. Conclusion .....	99



# 1.1. Comparing pointers

## 1.1.1. Question

```
1 struct S;  
2  
3 fn main() {  
4     let [x, y] = &mut [S, S];  
5  
6     let eq = x as *mut S == y as *mut S;  
7     print!("{}", eq as u8);  
8 }
```

(playground link)

What does this program print?

# 1.1. Comparing pointers

## 1. Quiz about last lecture

### 1.1.1. Question

```
1 struct S;  
2  
3 fn main() {  
4     let [x, y] = &mut [S, S];  
5  
6     let eq = x as *mut S == y as *mut S;  
7     print!("{}", eq as u8);  
8 }
```

(playground link)

What does this program print?

...

# 1.1. Comparing pointers

1. Quiz about last lecture

## 1.1.2. Explanation

What are zero-sized types?

# 1. Comparing pointers

## 1.1.2. Explanation

What are zero-sized types?

Types that occupy no space at runtime.

```
1 struct S;
2 fn main() {
3     let [x, y] = &mut [S, S];
4     let eq = x as *mut S == y as *mut S;
5     print!("{}", eq as u8);
6 }
```

(playground link)

# 1. Comparing pointers

## 1. Quiz about last lecture

### 1.1.2. Explanation

What are zero-sized types?

Types that occupy no space at runtime.

```
1 struct S;
2 fn main() {
3     let [x, y] = &mut [S, S];
4     let eq = x as *mut S == y as *mut S;
5     print!("{}", eq as u8);
6 }
```

(playground link)

Desugaring array  
pattern match

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let eq = x as *mut S == y as *mut S;
6     print!("{}", eq as u8);
7 }
```

(playground link)

# 1. Comparing pointers

## 1. Quiz about last lecture

### 1.1.2. Explanation

What are zero-sized types?

Types that occupy no space at runtime.

```
1 struct S;
2 fn main() {
3     let [x, y] = &mut [S, S];
4     let eq = x as *mut S == y as *mut S;
5     print!("{}", eq as u8);
6 }
```

(playground link)

Desugaring array  
pattern match

Operator == precedence  
above cast with as

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let eq = x as *mut S == y as *mut S;
6     print!("{}", eq as u8);
7 }
```

(playground link)

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let eq = (x as *mut S) == (y as *mut S);
6     print!("{}", eq as u8);
7 }
```

(playground link)

# 1. Comparing pointers

## 1. Quiz about last lecture

### 1.1.2. Explanation

What are zero-sized types?

Types that occupy no space at runtime.

```
1 struct S;
2 fn main() {
3     let [x, y] = &mut [S, S];
4     let eq = x as *mut S == y as *mut S;
5     print!("{}", eq as u8);
6 }
```

(playground link)

Desugaring array pattern match

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let eq = x as *mut S == y as *mut S;
6     print!("{}", eq as u8);
7 }
```

(playground link)

Operator == precedence above cast with as

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let eq = (x as *mut S) == (y as *mut S);
6     print!("{}", eq as u8);
7 }
```

(playground link)

Explicit casts

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let x_ptr: *mut S = x;
6     let y_ptr: *mut S = y;
7     let eq = x_ptr == y_ptr;
8     print!("{}", eq as u8);
9 }
```

(playground link)

Are x\_ptr and y\_ptr equal?

# 1. Comparing pointers

## 1.1.2. Explanation

What are zero-sized types?

Types that occupy no space at runtime.

```
1 struct S;
2 fn main() {
3     let [x, y] = &mut [S, S];
4     let eq = x as *mut S == y as *mut S;
5     print!("{}", eq as u8);
6 }
```

(playground link)

Desugaring array pattern match

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let eq = x as *mut S == y as *mut S;
6     print!("{}", eq as u8);
7 }
```

(playground link)

Operator == precedence above cast with as

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let eq = (x as *mut S) == (y as *mut S);
6     print!("{}", eq as u8);
7 }
```

(playground link)

Explicit casts

```
1 fn main() {
2     let tmp: [S; 2] = [S, S];
3     let x = &mut tmp[0];
4     let y = &mut tmp[1];
5     let x_ptr: *mut S = x;
6     let y_ptr: *mut S = y;
7     let eq = x_ptr == y_ptr;
8     print!("{}", eq as u8);
9 }
```

(playground link)

Are x\_ptr and y\_ptr equal?

Yes, since the compiler can see that S is a zero-sized type.

## 1.2. Patterns

### 1.2.1. Question

Last session I mentioned that variable assignments are actually patterns.

```
1 fn main() {  
2     let (.., x, y) = (0, 1, ..);  
3     print!("{}" , b"066"[y][x]);  
4 }
```

(playground link)

What does this program print?

## 1.2. Patterns

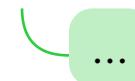
### 1.2.1. Question

Last session I mentioned that variable assignments are actually patterns.

```
1 fn main() {  
2     let (.., x, y) = (0, 1, ..);  
3     print!("{} ", b"066"[y][x]);  
4 }
```

(playground link)

What does this program print?



## 1.2.2. Explanation

```
1 fn main() {  
2     let (.., x, y) = (0,  
3     1, ..);  
4     print!("{}" , b"066"[y][x]);  
5 }
```

*(playground link)*

## 1.2. Patterns

1. Quiz about last lecture

### 1.2.2. Explanation

```
1 fn main() {  
2     let (.., x, y) = (0,  
3         1, ..);  
4     print!("{}" , b"066"[y][x]);  
5 }
```

(playground link)

Desugaring . . .  
as a range

```
1 fn main() {  
2     let x = 1;  
3     let y: RangeFull = ..;  
4     print!("{}" , b"066"[y][x]);  
5 }
```

(playground link)

## 1.2. Patterns

### 1.2.2. Explanation

```

1 fn main() {
2     let (.., x, y) = (0,
3         1, ..);
4     print!("{}", b"066"[y][x]);
5 }           (playground link)

```

Desugaring .  
as a range

```

1 fn main() {
2     let x = 1;
3     let y: RangeFull = ...;
4     print!("{}", b"066"[y][x]);
5 }           (playground link)

```

Explicit type  
binary literal

```

1 fn main() {
2     let x = 1;
3     let y = ...;
4     let bytes: &'static [u8; 3] =
5         b"066";
6     print!("{}", bytes[..][x]);
7 }           (playground link)

```

## 1.2. Patterns

1. Quiz about last lecture

### 1.2.2. Explanation

```
1 fn main() {  
2     let (.., x, y) = (0,  
3     1, ..);  
4     print!("{}", b"066"[y][x]);  
5 }
```

(playground link)

Desugaring ..  
as a range

```
1 fn main() {  
2     let x = 1;  
3     let y: RangeFull = ...;  
4     print!("{}", b"066"[y][x]);  
5 }
```

(playground link)

Explicit type  
binary literal

```
1 fn main() {  
2     let x = 1;  
3     let y = ...;  
4     let bytes: &'static [u8; 3] =  
5         b"066";  
6     print!("{}", bytes[..][x]);  
7 }
```

(playground link)

Slice  
indexing

```
1 fn main() {  
2     let x = 1;  
3     let bytes = b"066";  
4     print!("{}", bytes[x]);  
5 }
```

(playground link)

What is the decimal representation of the ASCII character '6'?

## 1.2.2. Explanation

```

1 fn main() {
2     let (.., x, y) = (0,
3         1, ..);
4     print!("{}", b"066"[y][x]);
5 }           (playground link)

```

Desugaring .  
as a range

```

1 fn main() {
2     let x = 1;
3     let y: RangeFull = ...;
4     print!("{}", b"066"[y][x]);
5 }           (playground link)

```

Explicit type  
binary literal

Slice  
indexing

```

1 fn main() {
2     let x = 1;
3     let y = ...;
4     let bytes: &'static [u8; 3] =
5         b"066";
6     print!("{}", bytes[..][x]);
7 }           (playground link)

```

```

1 fn main() {
2     let x = 1;
3     let bytes = b"066";
4     print!("{}", bytes[x]);
5 }           (playground link)

```

What is the decimal representation of the ASCII character '6'?

54

## 1.3. Bool

1. Quiz about last lecture

### 1.3.1. Question

```
1 fn check(x: i32) -> bool {
2     print!("{}", x);
3     false
4 }
5
6 fn main() {
7     match (1, 2) {
8         (x, _) | (_, x) if check(x) => {
9             print!("3")
10        }
11        _ => print!("4"),
12    }
13 }
```

(playground link)

What does this program print?

## 1.3. Bool

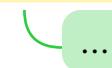
1. Quiz about last lecture

### 1.3.1. Question

```
1 fn check(x: i32) -> bool {
2     print!("{}", x);
3     false
4 }
5
6 fn main() {
7     match (1, 2) {
8         (x, _) | (_, x) if check(x) => {
9             print!("3")
10        }
11        _ => print!("4"),
12    }
13 }
```

(playground link)

What does this program print?



## 1.3. Bool

1. Quiz about last lecture

### 1.3.2. Explanation

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }
```

(playground link)

## 1.3. Bool

### 1.3.2. Explanation

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }  
                                (playground link)
```



```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x) =>  
4             print!("3")  
5         _ => print!("4"),  
6     }  
7 }  
                                (playground link)
```

# 1.3. Bool

## 1.3.2. Explanation

```
1 fn check(x: i32) -> bool {
2     print!("{}" , x);
3     false
4 }
```

(playground link)



```
1 fn main() {
2     match (1, 2) {
3         (x, _) | (_, x) if check(x) =>
4             print!("3")
5         }
6         _ => print!("4"),
7     }
8 }
```

(playground link)



```
1 fn main() {
2     match (1, 2) {
3         (x, _) | (_, x) if check(x)
4             => {
5                 print!("3")
6             }
7         _ => print!("4"),
8     }
9 }
```

(playground link)

# 1.3. Bool

## 1.3.2. Explanation

1. Quiz about last lecture

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }
```



```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x) =>  
4             print!("3")  
5         }  
6         _ => print!("4"),  
7     }  
8 }
```



```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x)  
4             => {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8     }  
9 }
```



```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }
```

# 1.3. Bool

# 1. Quiz about last lecture

## 1.3.2. Explanation

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }  
(playground link)
```



```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x) =>  
4             print!("3")  
5         }  
6         _ => print!("4"),  
7     }  
8 }  
(playground link)
```



```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x)  
4             => {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }  
(playground link)
```



```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x)  
4             => {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

# 1.3. Bool

## 1.3.2. Explanation

1. Quiz about last lecture

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x) =>  
4             print!("3")  
5         }  
6         _ => print!("4"),  
7     }  
8 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x)  
4             => {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x)  
4             => {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x) =>  
4             {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

What is going on here?

# 1.3. Bool

## 1.3.2. Explanation

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x) =>  
4             print!("3")  
5         }  
6         _ => print!("4"),  
7     }  
8 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x)  
4             => {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

```
1 fn check(x: i32) -> bool {  
2     print!("{}", x);  
3     false  
4 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x)  
4             => {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

```
1 fn main() {  
2     match (1, 2) {  
3         (x, _) | (_, x) if check(x) =>  
4             {  
5                 print!("3")  
6             }  
7             _ => print!("4"),  
8         }  
9 }  
(playground link)
```

What is going on here?

the guard is being run multiple times, once per |-separated alternative in the match-arm.

1.	Quiz about last lecture .....	1
<b>2.</b>	<b>Pattern matching .....</b>	<b>8</b>
2.1.	Irrefutable patterns .....	9
2.2.	Matching values .....	11
2.3.	Structs .....	15
2.4.	Enums .....	20
2.5.	Let control flow .....	21
2.6.	Exercise: Expression evaluation .....	22
3.	Tooling intermezzo .....	23
4.	Methods and traits .....	27
5.	Generics .....	43
6.	Closures .....	63
7.	Standard library types .....	76
8.	Conclusion .....	99

## Info

An **irrefutable pattern** is a pattern that always matches.

```
1 fn takes_tuple(tuple: (char, i32, bool)) {  
2     let a = tuple.0;  
3     let b = tuple.1;  
4     let c = tuple.2;  
5  
6     // This does the same thing as above.  
7     let (a, b, c) = tuple;  
8  
9     // Ignore the first element, only bind the  
10    second and third.  
11    let (_, b, c) = tuple;  
12  
13    // Ignore everything but the last element.  
14    let (.., c) = tuple;  
15 }
```

*(playground link)*

## Info

An **irrefutable pattern** is a pattern that always matches.

```
1 fn takes_tuple(tuple: (char, i32, bool)) {  
2     let a = tuple.0;  
3     let b = tuple.1;  
4     let c = tuple.2;  
5  
6     // This does the same thing as above.  
7     let (a, b, c) = tuple;  
8  
9     // Ignore the first element, only bind the  
10    second and third.  
11    let (_, b, c) = tuple;  
12  
13    // Ignore everything but the last element.  
14    let (.., c) = tuple;  
15 }
```

*(playground link)*

What happens when adding or removing an element to the tuple and look at the resulting compiler errors

## Info

An **irrefutable pattern** is a pattern that always matches.

```
1 fn takes_tuple(tuple: (char, i32, bool)) {  
2     let a = tuple.0;  
3     let b = tuple.1;  
4     let c = tuple.2;  
5  
6     // This does the same thing as above.  
7     let (a, b, c) = tuple;  
8  
9     // Ignore the first element, only bind the  
10    second and third.  
11    let (_, b, c) = tuple;  
12  
13    // Ignore everything but the last element.  
14    let (.., c) = tuple;  
15 }
```

*(playground link)*

What happens when adding or removing an element to the tuple and look at the resulting compiler errors

The destructuring pattern must match the structure of the value exactly.

**Info**

An **irrefutable pattern** is a pattern that always matches.

```
1 fn takes_tuple(tuple: (char, i32, bool)) {  
2     let a = tuple.0;  
3     let b = tuple.1;  
4     let c = tuple.2;  
5  
6     // This does the same thing as above.  
7     let (a, b, c) = tuple;  
8  
9     // Ignore the first element, only bind the  
10    second and third.  
11    let (_, b, c) = tuple;  
12  
13    // Ignore everything but the last element.  
14    let (.., c) = tuple;  
15 }
```

*(playground link)*

What happens when adding or removing an element to the tuple and look at the resulting compiler errors

The destructuring pattern must match the structure of the value exactly.

**Info**

A variable binding is actually a pattern itself!

The `_` pattern matches anything.

## 2.1. Irrefutable patterns

### 2.1.1. Advanced usage of ..

Ignoring middle element:

```
1 fn takes_tuple(tuple: (char, i32, bool, u8)) {  
2     let (first, ..., last) = tuple;  
3 }
```

(playground link)

## 2.1. Irrefutable patterns

## 2. Pattern matching

### 2.1.1. Advanced usage of ..

Ignoring middle element:

```
1 fn takes_tuple(tuple: (char, i32, bool, u8)) {  
2     let (first, ..., last) = tuple;  
3 }
```

(playground link)

Works with arrays as well:

```
1 fn takes_array(array: [u8; 5]) {  
2     let [first, ..., last] = array;  
3 }
```

(playground link)

## 2.1. Irrefutable patterns

### 2.1.1. Advanced usage of ..

Ignoring middle element:

```
1 fn takes_tuple(tuple: (char, i32, bool, u8)) {  
2     let (first, ..., last) = tuple;  
3 }
```

(playground link)

Works with arrays as well:

```
1 fn takes_array(array: [u8; 5]) {  
2     let [first, ..., last] = array;  
3 }
```

(playground link)

#### Warning

Pattern matching works on all data types in Rust!

## 2.2. Matching values

## 2. Pattern matching

Patterns can also be simple values like characters:

```
1 #[rustfmt::skip]
2 fn main() {
3     let input = 'x';
4     match input {
5         'q'                      => println!("Quitting"),
6         'a' | 's' | 'w' | 'd'   => println!("Moving around"),
7         '0'..='9'               => println!("Number input"),
8         key if key.is_lowercase() => println!("Lowercase: {}", key),
9         _                       => println!("Something else"),
10    }
11 }
```

(playground link)

A variable in the pattern (key in this example) will create a binding that can be used within the match arm.

## 2.2. Matching values

## 2. Pattern matching

A **match guard**:

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

```
1 #[rustfmt::skip]
2 fn main() {
3     let input = 'a';
4     match input {
5         key if key.is_uppercase() => println!("Uppercase"),
6         key => if input == 'q' { println!("Quitting") },
7         _    => println!("Lowercase"),
8     }
9 }
```

(playground link)

What is the bug in this program?

A **match guard**:

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

```
1 #[rustfmt::skip]
2 fn main() {
3     let input = 'a';
4     match input {
5         key if key.is_uppercase() => println!("Uppercase"),
6         key => if input == 'q' { println!("Quitting") },
7         _   => println!("Lowercase"),
8     }
9 }
```

(playground link)

What is the bug in this program?

The second arm will always match, so the third arm is unreachable. Write match guard in front of the second arm: `key if key == 'q' => ...`

**Warning**

**Can't use an existing variable** as the condition in a match arm, as it will instead be interpreted as a variable name pattern, which creates a new variable that will shadow the existing one.

```
1 let expected = 5;
2 match 123 {
3     expected => println!("Expected value is 5, actual is {expected}"),
4     _ => println!("Value was something else"),
5 }
```

(playground link)

What is the output of this program?

**Warning**

**Can't use an existing variable** as the condition in a match arm, as it will instead be interpreted as a variable name pattern, which creates a new variable that will shadow the existing one.

```
1 let expected = 5;  
2 match 123 {  
3     expected => println!("Expected value is 5, actual is {expected}"),  
4     _ => println!("Value was something else"),  
5 }
```

(playground link)

What is the output of this program?

Will always print “Expected value is 5, actual is 123”.

## 2.2. Matching values

## 2. Pattern matching

Use @ to bind to a value while also testing it:

```
1 let expected = 5;
2 match 123 {
3     val @ 1..=10 => println!("Value {val} is between 1 and 10"),
4     val @ 11..=20 => println!("Value {val} is between 11 and 20"),
5     val => println!("Value {val} is something else"),
6 }
```

(playground link)

Like tuples, structs can also be destructured by matching:

```
1 struct Foo {  
2     x: (u32, u32),  
3     y: u32,  
4 }  
5  
6 #[rustfmt::skip]  
7 fn main() {  
8     let foo = Foo { x: (1, 2), y: 3 };  
9     match foo {  
10         Foo { y: 2, x: i } => println!("y = 2, x = {i:?}"),  
11         Foo { x: (1, b), y } => println!("x.0 = 1, b = {b}, y = {y}"),  
12         Foo { y, .. }        => println!("y = {y}, other fields were ignored"),  
13     }  
14 }
```

(playground link)

Add or remove fields to Foo and see what happens!

### 2.3.1. Reference patterns

When matching on a reference, Rust **automatically dereferences** it for you:

```
1 fn main() {  
2     let foo = Foo { x: (1, 2), y: 3 };  
3     match &foo { // `foo` is turned into a reference  
4         Foo { y: 2, x: i } => println!("y = 2, x = {i:?}"),  
5         Foo { x: (1, b), y } => println!("x.0 = 1, b = {b}, y = {y}"),  
6         Foo { y, .. }          => println!("y = {y}, other fields were ignored"),  
7     }  
8 }
```

(playground link)

#### Info

The pattern `Foo { ... }` works on `&foo` because Rust automatically dereferences. You could also write `&Foo { ... }` explicitly, but it's not required.

Two equivalent ways to match on a reference:

```
1 match &foo {  
2     Foo { y, ... } => println!("y = {}", y), // Implicit dereference  
3 }  
4  
5 match &foo {  
6     &Foo { y, ... } => println!("y = {}", y), // Explicit dereference pattern  
7 }
```

(playground link)

Pick the one you like best!

### Warning

In the implicit version, bound variables like `y` will be references. In the explicit version with `&Foo`, `y` will be a value (copied from the struct).

### 2.3.2. Mutable reference patterns

When matching on `&mut`, bound variables are mutable references:

```
1 struct Foo {  
2     x: (u32, u32),  
3     y: u32,  
4 }  
5 fn main() {  
6     let mut foo = Foo { x: (1, 2), y: 3 };  
7     match &mut foo {  
8         Foo { x: (1, 2), y } => *y = 4, // y is &mut u32, need * to assign  
9         Foo { y, .. }           => println!("y = {}", y),  
10    }  
11 }
```

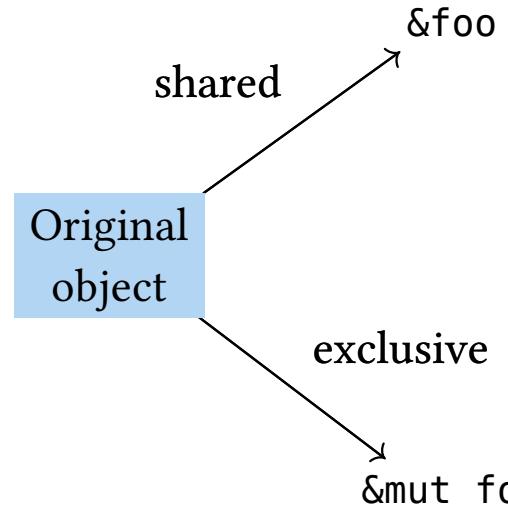
(playground link)

#### Warning

Bound variables like `y` are `&mut u32`, not `u32`. You must dereference with `*` to assign values.

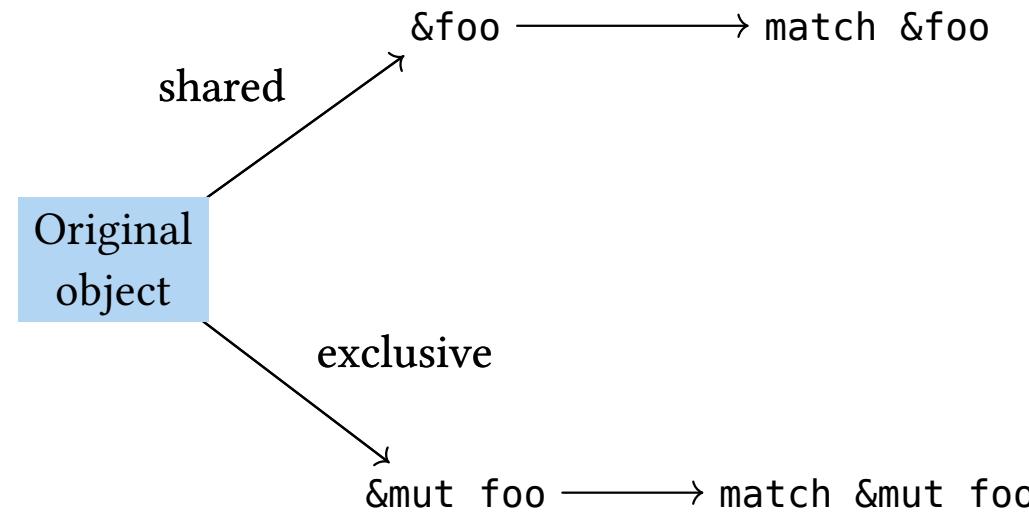
## 2.3. Structs

### 2.3.3. Intuition

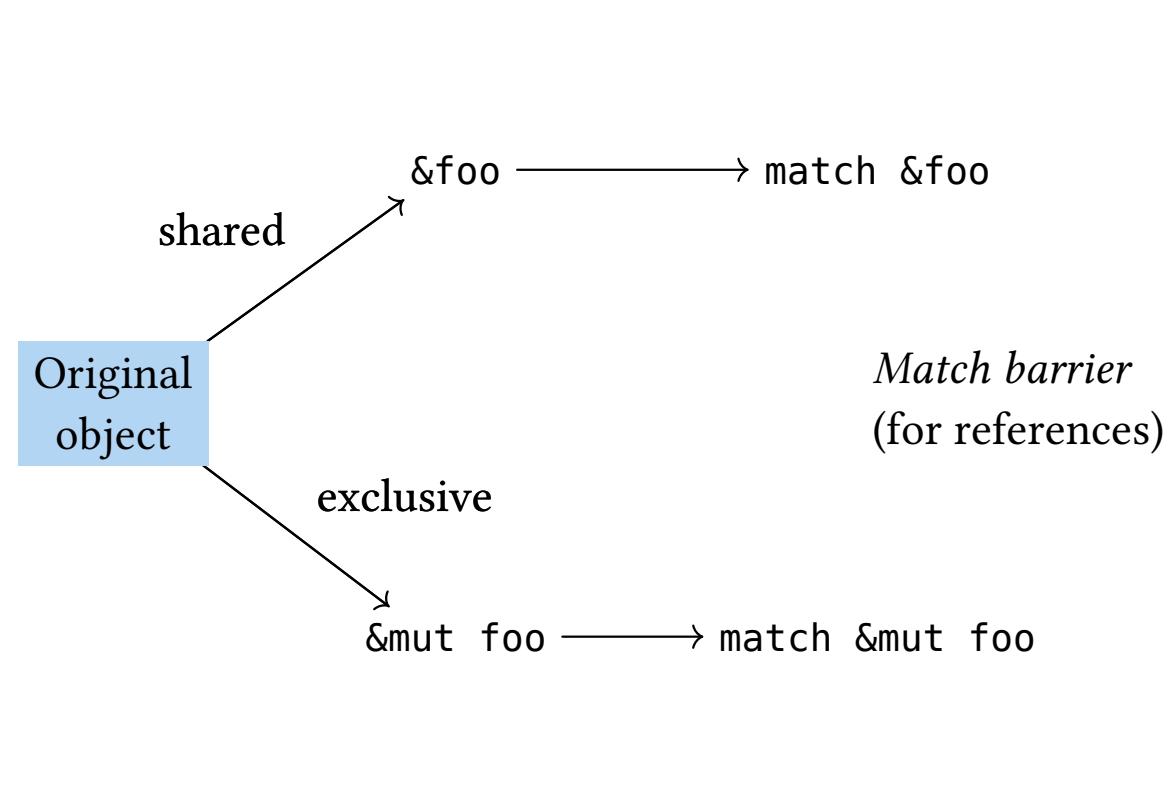


## 2.3. Structs

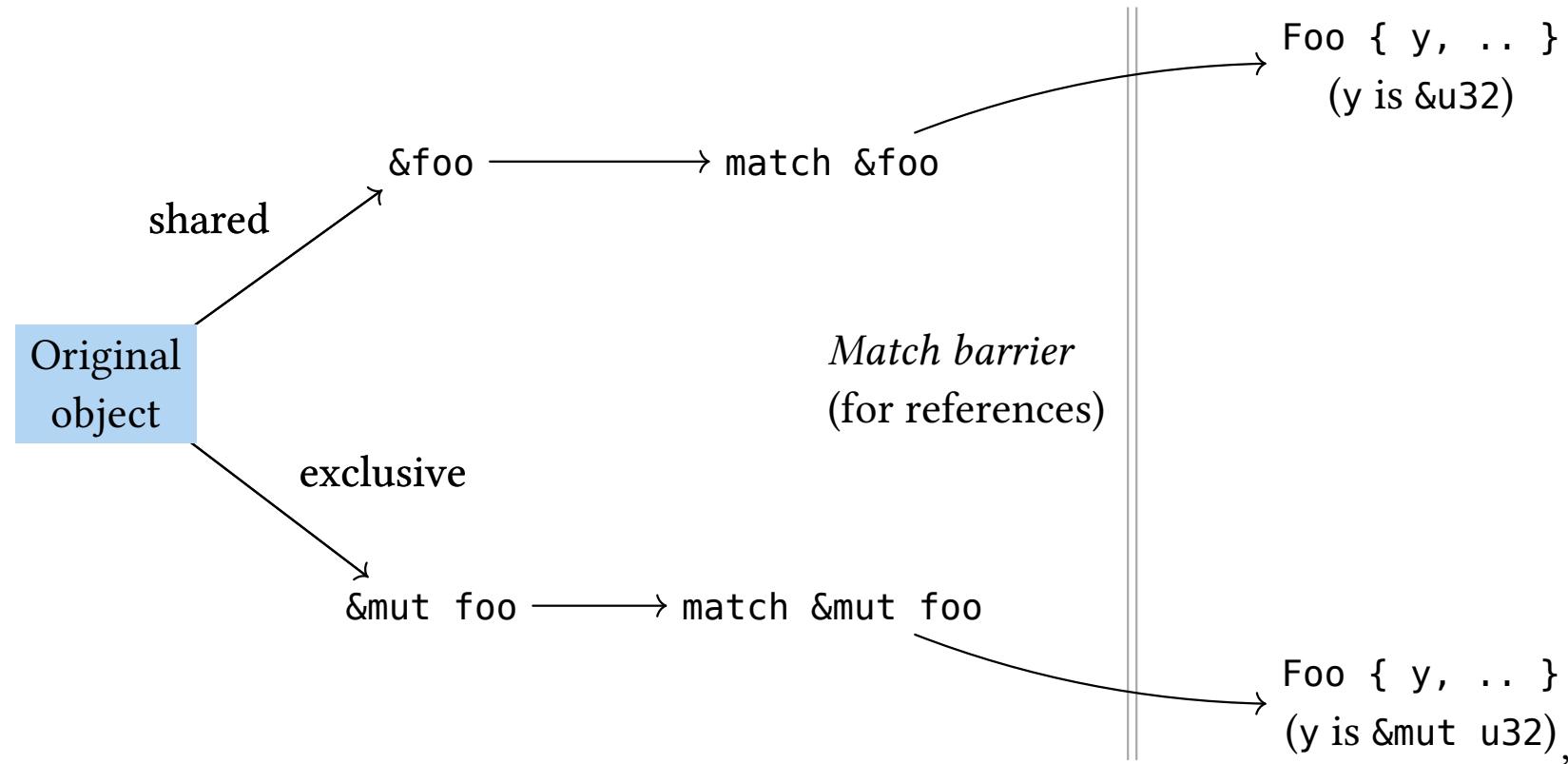
### 2.3.3. Intuition



## 2.3.3. Intuition



## 2.3.3. Intuition



## 2.4. Enums

## 2. Pattern matching

Like tuples, enums can also be destructured by matching:

```
1 enum Result {  
2     Ok(i32),  
3     Err(String),  
4 }  
5  
6 fn divide_in_two(n: i32) -> Result {  
7     if n % 2 == 0 {  
8         Result::Ok(n / 2)  
9     } else {  
10        Result::Err(format!("cannot divide {} into two equal parts"))  
11    }  
12 }
```

(playground link)

## 2.4. Enums

## 2. Pattern matching

Like tuples, enums can also be destructured by matching:

```
1 enum Result {  
2     Ok(i32),  
3     Err(String),  
4 }  
5  
6 fn divide_in_two(n: i32) -> Result {  
7     if n % 2 == 0 {  
8         Result::Ok(n / 2)  
9     } else {  
10        Result::Err(format!("cannot divide {} into two equal parts"))  
11    }  
12 }
```

(playground link)

```
1 fn main() {  
2     let n = 100;  
3     match divide_in_two(n) {  
4         Result::Ok(half) => println!("{} divided in two is {}", n, half),  
5         Result::Err(msg) => println!("sorry, an error happened: {}", msg),  
6     }  
7 }
```

(playground link)

### Warning

Rust does not allow non-exhaustive matches

```
1 use std::time::Duration;
2
3 fn sleep_for(secs: f32) {
4     let result = Duration::try_from_secs_f32(secs);
5
6     if let Ok(duration) = result {
7         std::thread::sleep(duration);
8         println!("slept for {duration:?}");
9     }
10 }
11
12 fn main() {
13     sleep_for(-10.0);
14     sleep_for(0.8);
15 }
```

(playground link)

When to use `if let` over `match`?

```
1 use std::time::Duration;
2
3 fn sleep_for(secs: f32) {
4     let result = Duration::try_from_secs_f32(secs);
5
6     if let Ok(duration) = result {
7         std::thread::sleep(duration);
8         println!("slept for {duration:?}");
9     }
10 }
11
12 fn main() {
13     sleep_for(-10.0);
14     sleep_for(0.8);
15 }
```

(playground link)

When to use `if let` over `match`?

Use `if let` when you only care about one specific pattern and want to ignore all others.

## 2.6. Exercise: Expression evaluation

## 2. Pattern matching

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

Complete the eval function in the file `session-2/tests/s2e2-evaluation.rs`.

Run tests with `cargo test --test s2e2-evaluation`.

1.	Quiz about last lecture .....	1
2.	Pattern matching .....	8
<b>3.</b>	<b>Tooling intermezzo .....</b>	<b>23</b>
3.1.	Debugger .....	23
3.2.	Clippy .....	24
3.3.	Summary .....	26
4.	Methods and traits .....	27
5.	Generics .....	43
6.	Closures .....	63
7.	Standard library types .....	76
8.	Conclusion .....	99

mod.rs - nu-lint - Visual Studio Code

RUN AND DEBUG | Debug unit tests | ⚙ ...

VARIABLES

- Local
- Static
- Global
- Registers

WATCH

CALL STACK

BREAKPOINTS

- Rust: on panic
- mod.rs src/rules/error\_make\_met... 203

MODULES

EXCLUDED CALLERS

mod.rs .../error\_make\_metadata

ignore\_good.rs .../error\_make\_metadata

src > rules > error\_make\_metadata > mod.rs > check

```
194 fn check_error_make_call(call: &Call, c: &ExpressionExt) {
195     call.is_call_to_command(command_name, "ERROR MAKE", context).boot()
196     .then_some(())
197     .and_then(|()| call.get_first_positional_arg()).ok()
198     .and_then(extract_record_from_expr).ok()
199     .and_then(|record: &RecordItem| check_error_make_metadata(record, context,
200         call.span()))
201 }
202
203 fn check(context: &LintContext) -> Vec<RuleViolation> {
204     context.collect_ruleViolations(collector: &expr::Expr, ctx: &
205         LintContext).match &expr.expr {
206         Expr::Call(call: &Box<Call>) => check_error_make_call(call, context: ctx).
207             into_iter().collect(),
208         _ => vec![],
209     }
210 }
```

PROBLEMS 4 | OUTPUT | DEBUG CONSOLE | TERMINAL | PORTS | Filter | Debug | ...

nu-lint organise-rules\* 4 ▲ 0 Debug unit tests in library 'nu-lint' (nu-lint) Live Share rust-analyzer Format: auto Disasm: auto Deref: on Console: cmd nu-lint Rust Prettier



## Clippy Lints

Total number: 795

Lint levels 4 ▾

Lint groups 2 ▾

Version 0 ▾

Filter:

Keywords or search string (~S~ or `~ to focus)

Clear



Applicability 4 ▾

All

Default

None

absurd\_extreme

- Cargo
- Complexity
- Correctness
- Nursery
- Pedantic
- Perf
- Restriction
- Style
- Suspicious
- Deprecated

almost\_swapped

approx\_constant

async\_yields\_asy

bad\_bit\_mask

bind\_instead\_of\_map

bool\_comparison

borrow\_deref\_mut

correctness

deny



correctness

deny



correctness

deny



correctness

deny



correctness

deny



complexity

warn



complexity

warn



## 3.2. Clippy

Most useful lints:

- complexity
- style
- correctness

Place clippy rules in your `Cargo.toml` like this:

```
1 [lints.clippy]
2 complexity = { level = "deny", priority = -1 }
3 pedantic = { level = "deny", priority = -1 }
4 style = { level = "deny", priority = -1 }
5
6 absolute_paths = "deny"
7 allow_attributes_without_reason = "deny"
8 ...
```

*(playground link)*

Find more lint rules at [rust-lang.github.io/rust-clippy.](https://rust-lang.github.io/rust-clippy/)

### 3.3. Summary

Typical development workflow in Rust:

1. Debug with GDB / LLDB or VS Code
2. Format with `cargo fmt`
3. Lint with `cargo clippy`
4. Test with `cargo test`
5. Build with `cargo build` or `cargo build --release`

1.	Quiz about last lecture .....	1
2.	Pattern matching .....	8
3.	Tooling intermezzo .....	23
<b>4.</b>	<b>Methods and traits .....</b>	<b>27</b>
4.1.	Methods .....	28
4.2.	Receivers .....	31
4.3.	Traits .....	32
4.4.	Implementing traits .....	33
4.5.	Contracts .....	34
4.6.	Super-trait .....	36
4.7.	Associated Types .....	37
4.8.	Deriving .....	40
4.9.	Exercise: Logger trait .....	42
5.	Generics .....	43
6.	Closures .....	63
7.	Standard library types .....	76
8.	Conclusion .....	99

## 4.1. Methods

## 4. Methods and traits

In Rust, methods are separated from fields:

```
1 #[derive(Debug)]
2 struct CarRace {
3     name: String,
4     laps: Vec<i32>,
5 }
6
7 impl CarRace {
8     // No receiver, a static method
9     fn new(name: &str) -> Self {
10         Self { name: String::from(name), laps: Vec::new() }
11     }
12     // Exclusive borrowed read-write access to self
13     fn add_lap(&mut self, lap: i32) {
14         self.laps.push(lap);
15     }
16 }
17
18 fn main() {
19     let mut race = CarRace::new("Monaco Grand Prix");
20     race.add_lap(70);
21 }
```

(playground link)

## 4.1. Methods

Like in other languages, methods group functionality around *acting* data types, types that *do* related things.

How are methods in Rust different from methods in other languages?

## 4.1. Methods

Like in other languages, methods group functionality around *acting* data types, types that *do* related things.

How are methods in Rust different from methods in other languages?

Methods cannot be overridden.

```
1 impl CarRace {  
2     fn add_lap(&mut self, lap: i32) {  
3         self.laps.push(lap);  
4     }  
5 }
```

(playground link)

What is the `&mut self` parameter syntax sugar for?

## 4.1. Methods

Like in other languages, methods group functionality around *acting* data types, types that *do* related things.

How are methods in Rust different from methods in other languages?

Methods cannot be overridden.

```
1 impl CarRace {
2     fn add_lap(&mut self, lap: i32) {
3         self.laps.push(lap);
4     }
5 }
```

(playground link)

What is the `&mut self` parameter syntax sugar for?

For `self: &mut Self`.

```
1 impl CarRace {
2     fn add_lap(self: &mut Self, lap: i32) {
3         self.laps.push(lap);
4     }
5 }
```

(playground link)

## 4.1. Methods

## 4. Methods and traits

Methods can **consume** self:

```
1 #[derive(Debug)]
2 struct CarRace {
3     name: String,
4     laps: Vec<i32>,
5 }
6
7 impl CarRace {
8     // Exclusive ownership of self (covered later)
9     fn finish(self) {
10         let total: i32 = self.laps.iter().sum();
11         println!("Race {} is finished, total lap time:
12             {}", self.name, total);
13     }
14
15 fn main() {
16     let mut race = CarRace::new("Monaco Grand Prix");
17     race.add_lap(70);
18     race.finish();
19     // race.add_lap(42);
20 }
```

(playground link)

## 4.1. Methods

Methods can **consume** self:

```
1 #[derive(Debug)]
2 struct CarRace {
3     name: String,
4     laps: Vec<i32>,
5 }
6
7 impl CarRace {
8     // Exclusive ownership of self (covered later)
9     fn finish(self) {
10         let total: i32 = self.laps.iter().sum();
11         println!("Race {} is finished, total lap time:
12             {}", self.name, total);
13     }
14
15 fn main() {
16     let mut race = CarRace::new("Monaco Grand Prix");
17     race.add_lap(70);
18     race.finish();
19     // race.add_lap(42);
20 }
```

(playground link)

What is the name given to the **self** parameter in methods?

## 4.1. Methods

Methods can **consume** self:

```

1 #[derive(Debug)]
2 struct CarRace {
3     name: String,
4     laps: Vec<i32>,
5 }
6
7 impl CarRace {
8     // Exclusive ownership of self (covered later)
9     fn finish(self) {
10         let total: i32 = self.laps.iter().sum();
11         println!("Race {} is finished, total lap time: {}", self.name, total);
12     }
13 }
14
15 fn main() {
16     let mut race = CarRace::new("Monaco Grand Prix");
17     race.add_lap(70);
18     race.finish();
19     // race.add_lap(42);
20 }
```

*(playground link)*

What is the name given to the **self** parameter in methods?

**self** is called the **receiver**.

After calling a method with `object.finish(self)`, you can no longer use `object`. It has been *consumed*.

### Warning

Use the **self** receiver to define destructors or functionality that should happen only once at the end.

## 4.2. Receivers

Rust allows receivers to be one of the following:

- `self`, consuming `self`
- any kind of reference to `self`: `&self`, `&mut self`
- exceptions (covered later)

Name a few reference types in Rust.

## 4.2. Receivers

Rust allows receivers to be one of the following:

- `self`, consuming `self`
- any kind of reference to `self`: `&self`, `&mut self`
- exceptions (covered later)

Name a few reference types in Rust.

`&T`, `&mut T`, `Box<T>`, `Rc<T>`, `Arc<T>`, ...

### Info

Reference types are also called **wrappers** and some are **smart pointers**.

Rust lets you abstract over types with traits. Similar to interfaces:

```
1 trait Pet {  
2     /// Return a sentence from this pet.  
3     fn talk(&self) -> String;  
4  
5     /// Print a string to the terminal greeting this pet.  
6     fn greet(&self);  
7 }
```

*(playground link)*

Properties of traits:

Rust lets you abstract over types with traits. Similar to interfaces:

```
1 trait Pet {  
2     /// Return a sentence from this pet.  
3     fn talk(&self) -> String;  
4  
5     /// Print a string to the terminal greeting this pet.  
6     fn greet(&self);  
7 }
```

*(playground link)*

Properties of traits:

- A trait is a list of methods that a type **must implement**

Rust lets you abstract over types with traits. Similar to interfaces:

```
1 trait Pet {  
2     /// Return a sentence from this pet.  
3     fn talk(&self) -> String;  
4  
5     /// Print a string to the terminal greeting this pet.  
6     fn greet(&self);  
7 }
```

(playground link)

Properties of traits:

- A trait is a list of methods that a type **must implement**
- The **signatures** of the type's methods **must be identical** to the trait's method signatures

Rust lets you abstract over types with traits. Similar to interfaces:

```
1 trait Pet {  
2     /// Return a sentence from this pet.  
3     fn talk(&self) -> String;  
4  
5     /// Print a string to the terminal greeting this pet.  
6     fn greet(&self);  
7 }
```

(playground link)

Properties of traits:

- A trait is a list of methods that a type **must implement**
- The **signatures** of the type's methods **must be identical** to the trait's method signatures

Info

Default implementations can be provided

## 4.4. Implementing traits

## 4. Methods and traits

```
1 trait Pet {  
2     fn talk(&self) -> String;  
3  
4     fn greet(&self) {  
5         println!("Oh you're a cutie!  
6         What's your name? {}",  
7             self.talk());  
8     }  
9 }  
10 struct Dog {  
11     name: String,  
12 }  
(playground link)
```

## 4.4. Implementing traits

## 4. Methods and traits

```
1 trait Pet {  
2     fn talk(&self) -> String;  
3  
4     fn greet(&self) {  
5         println!("Oh you're a cutie!  
6         What's your name? {}",  
7             self.talk());  
8     }  
9 }  
10  
11 struct Dog {  
12     name: String,  
13     age: i8,  
14 }
```

*(playground link)*

```
1 impl Pet for Dog {  
2     fn talk(&self) -> String {  
3         format!("Woof, my name is {}!", self.name)  
4     }  
5 }  
6  
7 fn main() {  
8     let fido = Dog { name: String::from("Fido"),  
9                     age: 5 };  
10    dbg!(fido.talk());  
11    fido.greet();  
12 }
```

*(playground link)*

## 4.4. Implementing traits

## 4. Methods and traits

```
1 trait Pet {  
2     fn talk(&self) -> String;  
3  
4     fn greet(&self) {  
5         println!("Oh you're a cutie!  
6         What's your name? {}",  
7             self.talk());  
8     }  
9 }  
10  
11 struct Dog {  
12     name: String,  
13     age: i8,  
14 }  
15  
(playground link)
```

```
1 impl Pet for Dog {  
2     fn talk(&self) -> String {  
3         format!("Woof, my name is {}!", self.name)  
4     }  
5 }  
6  
7 fn main() {  
8     let fido = Dog { name: String::from("Fido"),  
9                     age: 5 };  
10    dbg!(fido.talk());  
11    fido.greet();  
12 }
```

(playground link)

### Warning

a Cat type with a `talk()` method would not automatically satisfy Pet unless it is in an `impl Pet` block

## 4.4. Implementing traits

## 4. Methods and traits

You can:

- split trait implementation blocks
- override default method implementations

```
1  impl Pet for Dog {  
2      fn talk(&self) -> String {  
3          format!("Woof, my name is {}!", self.name)  
4      }  
5  }  
6  
7  impl Pet for Dog {  
8      fn greet(&self) -> String {  
9          format!("Woof, my name is {}!", self.name)  
10     }  
11 }
```

(playground link)

vec

write

writeln

## Keywords

SelfTy

as

async

await

become

break

const

continue

crate

dyn

else

enum

extern

false

fn

level of pointer indirection each time a new object is added to the mix (and, practically, a heap allocation).

Although there were other reasons as well, this issue of expensive composition is the key thing that drove Rust towards adopting a different model. It is particularly a problem when one considers, for example, the implications of composing together the [Future](#)s which will eventually make up an asynchronous task (including address-sensitive `async fn` state machines). It is plausible that there could be many layers of [Future](#)s composed together, including multiple layers of `async fn`s handling different parts of a task. It was deemed unacceptable to force indirection and allocation for each layer of composition in this case.

`Pin<Ptr>` is an implementation of the third option. It allows us to solve the issues discussed with the second option by building a *shared contractual language* around the guarantees of “pinning” data.

## Using `Pin<Ptr>` to pin values

In order to pin a value, we wrap a *pointer to that value* (of some type `Ptr`) in a `Pin<Ptr>`. `Pin<Ptr>` can wrap any pointer type, forming a promise that the **pointee** will not be *moved* or *otherwise invalidated*.

We call such a `Pin`-wrapped pointer a **pinning pointer**, (or pinning reference, or pinning Box, etc.) because its existence is the thing that is conceptually pinning the underlying pointee in place: it is the metaphorical “pin” securing the data in place on the pinboard (in memory).

Notice that the thing wrapped by `Pin` is not the value which we want to pin itself, but rather a pointer to that value! A `Pin<Ptr>` does not pin the `Ptr`; instead, it pins the pointer’s *pointee value*.

## Pinning as a library contract

Pinning does not require nor make use of any compiler “magic”<sup>2</sup>, only a specific contract between the `unsafe` parts of a library API and its users.

It is important to stress this point as a user of the `unsafe` parts of the `Pin` API. Practically, this means that performing the

## 4.5. Contracts

Rust, being a systems programming language, focuses on safety.

Rust, being a systems programming language, focuses on safety.

In Rust documentation, you will often encounter the word **contract**.

**Info**

A contract is an agreement between two parties. There are mainly two kinds of contracts in Rust:

- Contracts between **two pieces of code**
- Contracts between **the programmer and the compiler**

Rust, being a systems programming language, focuses on safety.

In Rust documentation, you will often encounter the word **contract**.

**Info**

A contract is an agreement between two parties. There are mainly two kinds of contracts in Rust:

- Contracts between **two pieces of code**
- Contracts between **the programmer and the compiler**

Contracts between two pieces of code are generally safe (can be enforced automatically).

Rust, being a systems programming language, focuses on safety.

In Rust documentation, you will often encounter the word **contract**.

### Info

A contract is an agreement between two parties. There are mainly two kinds of contracts in Rust:

- Contracts between **two pieces of code**
- Contracts between **the programmer and the compiler**

Contracts between two pieces of code are generally safe (can be enforced automatically).

### Warning

... but contracts between the programmer and the compiler can be unsafe or **may have to be checked by the programmer**.

Examples of such contracts: Pin, Send, Sync traits (advanced topic).

## 4.6. Super-trait

## 4. Methods and traits

```
1 trait Animal {  
2     fn leg_count(&self) -> u32;  
3 }  
4  
5 trait Pet: Animal {  
6     fn name(&self) -> String;  
7 }  
8  
9 struct Dog(String);  
10  
11 impl Animal for Dog {  
12     fn leg_count(&self) -> u32 {  
13         4  
14     }  
15 }  
16  
17 impl Pet for Dog {  
18     fn name(&self) -> String {  
19         self.0.clone()  
20     }  
21 }
```

(playground link)

**Super-trait** are an extra constraint on traits that say: “to implement this trait, you must also implement that other trait”.

## 4.6. Super-trait

## 4. Methods and traits

```
1 trait Animal {  
2     fn leg_count(&self) -> u32;  
3 }  
4  
5 trait Pet: Animal {  
6     fn name(&self) -> String;  
7 }  
8  
9 struct Dog(String);  
10  
11 impl Animal for Dog {  
12     fn leg_count(&self) -> u32 {  
13         4  
14     }  
15 }  
16  
17 impl Pet for Dog {  
18     fn name(&self) -> String {  
19         self.0.clone()  
20     }  
21 }
```

(playground link)

**Super-trait** are an extra constraint on traits that say: “to implement this trait, you must also implement that other trait”.

### Warning

Super traits are the kind of language feature you should **avoid as long as you are stuck with the OOP mindset.**

Once you are willing to forget OOP, you can see super-trait are actually easy.

## 4.6. Super-trait

## 4. Methods and traits

```
1 trait Animal {  
2     fn leg_count(&self) -> u32;  
3 }  
4  
5 trait Pet: Animal {  
6     fn name(&self) -> String;  
7 }  
8  
9 struct Dog(String);  
10  
11 impl Animal for Dog {  
12     fn leg_count(&self) -> u32 {  
13         4  
14     }  
15 }  
16  
17 impl Pet for Dog {  
18     fn name(&self) -> String {  
19         self.0.clone()  
20     }  
21 }
```

(playground link)

**Super-trait**s are an extra constraint on traits that say: “to implement this trait, you must also implement that other trait”.

### Warning

Super traits are the kind of language feature you should **avoid as long as you are stuck with the OOP mindset**.

Once you are willing to forget OOP, you can see super-trait are actually easy.

### Advanced

... at least as long as you don't constrain **associated types** of super traits in subtraits

## 4.7. Associated Types

## 4. Methods and traits

```
1 #[derive(Debug)]
2 struct Meters(i32);
3 #[derive(Debug)]
4 struct MetersSquared(i32);
5
6 trait Multiply {
7     type Output;
8     fn multiply(&self, other: &Self) -> Self::Output;
9 }
10
11 impl Multiply for Meters {
12     type Output = MetersSquared;
13     fn multiply(&self, other: &Self) -> Self::Output {
14         MetersSquared(self.0 * other.0)
15     }
16 }
17
18 fn main() {
19     println!("{:?}", Meters(10).multiply(&Meters(20)));
20 }
```

*(playground link)*

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

## 4.7. Associated Types

## 4. Methods and traits

```
1 #[derive(Debug)]
2 struct Meters(i32);
3 #[derive(Debug)]
4 struct MetersSquared(i32);
5
6 trait Multiply {
7     type Output;
8     fn multiply(&self, other: &Self) -> Self::Output;
9 }
10
11 impl Multiply for Meters {
12     type Output = MetersSquared;
13     fn multiply(&self, other: &Self) -> Self::Output {
14         MetersSquared(self.0 * other.0)
15     }
16 }
17
18 fn main() {
19     println!("{}?", Meters(10).multiply(&Meters(20)));
20 }
```

*(playground link)*

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

Why are associated types sometimes also called “output types”

## 4.7. Associated Types

## 4. Methods and traits

```
1 #[derive(Debug)]
2 struct Meters(i32);
3 #[derive(Debug)]
4 struct MetersSquared(i32);
5
6 trait Multiply {
7     type Output;
8     fn multiply(&self, other: &Self) -> Self::Output;
9 }
10
11 impl Multiply for Meters {
12     type Output = MetersSquared;
13     fn multiply(&self, other: &Self) -> Self::Output {
14         MetersSquared(self.0 * other.0)
15     }
16 }
17
18 fn main() {
19     println!("{}?", Meters(10).multiply(&Meters(20)));
20 }
```

*(playground link)*

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

Why are associated types sometimes also called “output types”

The implementer, not the caller, chooses the concrete associated type.

## 4.7. Associated Types

## 4. Methods and traits

```
1 #[derive(Debug)]
2 struct Meters(i32);
3 #[derive(Debug)]
4 struct MetersSquared(i32);
5
6 trait Multiply {
7     type Output;
8     fn multiply(&self, other: &Self) -> Self::Output;
9 }
10
11 impl Multiply for Meters {
12     type Output = MetersSquared;
13     fn multiply(&self, other: &Self) -> Self::Output {
14         MetersSquared(self.0 * other.0)
15     }
16 }
17
18 fn main() {
19     println!("{}?", Meters(10).multiply(&Meters(20)));
20 }
```

(playground link)

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

Why are associated types sometimes also called “output types”

The implementer, not the caller, chooses the concrete associated type.

Iterators from the standard library have an associated type `Item`:

```
1 pub trait Iterator {
2     type Item;
3     fn next(&mut self) ->
4         Option<Self::Item>;
5 }
```

(playground link)

## 4.7. Associated Types

Use cases for associated types: implementing  
(network) **protocols**.

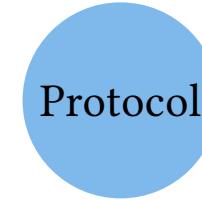
## 4.7. Associated Types

## 4. Methods and traits

```
1 trait Protocol {  
2     type Message;  
3     fn send(&self, msg: Self::Message);  
4     fn receive(&self) -> Self::Message;  
5 }  
6  
7 impl Protocol for Tcp {  
8     type Message = TcpPacket;  
9     fn send(&self, msg: Self::Message)  
10    {  
11        // Send the TCP packet  
12    }  
13    fn receive(&self) -> Self::Message  
14    {  
15        // Receive a TCP packet  
16    }  
17 }  
18 (playground link)
```

## 4.7. Associated Types

Use cases for associated types: implementing  
(network) **protocols**.



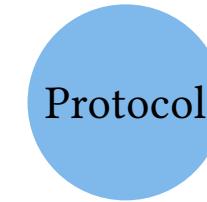
## 4.7. Associated Types

## 4. Methods and traits

```
1 trait Protocol {  
2     type Message;  
3     fn send(&self, msg: Self::Message);  
4     fn receive(&self) -> Self::Message;  
5 }  
6  
7 impl Protocol for Tcp {  
8     type Message = TcpPacket;  
9     fn send(&self, msg: Self::Message)  
10    {  
11        // Send the TCP packet  
12    }  
13    fn receive(&self) -> Self::Message  
14    {  
15        // Receive a TCP packet  
16    }  
17 }  
18 (playground link)
```

## 4.7. Associated Types

Use cases for associated types: implementing  
(network) **protocols**.



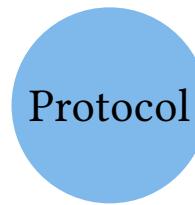
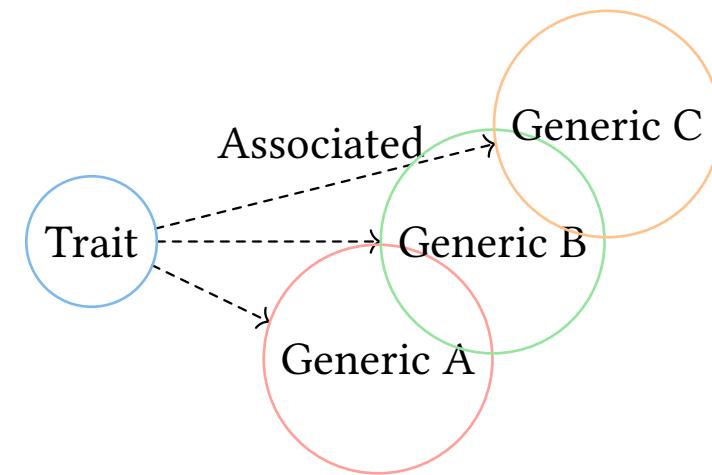
## 4.7. Associated Types

## 4. Methods and traits

```
1 trait Protocol {  
2     type Message;  
3     fn send(&self, msg: Self::Message);  
4     fn receive(&self) -> Self::Message;  
5 }  
6  
7 impl Protocol for Tcp {  
8     type Message = TcpPacket;  
9     fn send(&self, msg: Self::Message)  
10    {  
11        // Send the TCP packet  
12    }  
13    fn receive(&self) -> Self::Message  
14    {  
15        // Receive a TCP packet  
16    }  
17 }  
18 (playground link)
```

## 4.7. Associated Types

Use cases for associated types: implementing (network) **protocols**.



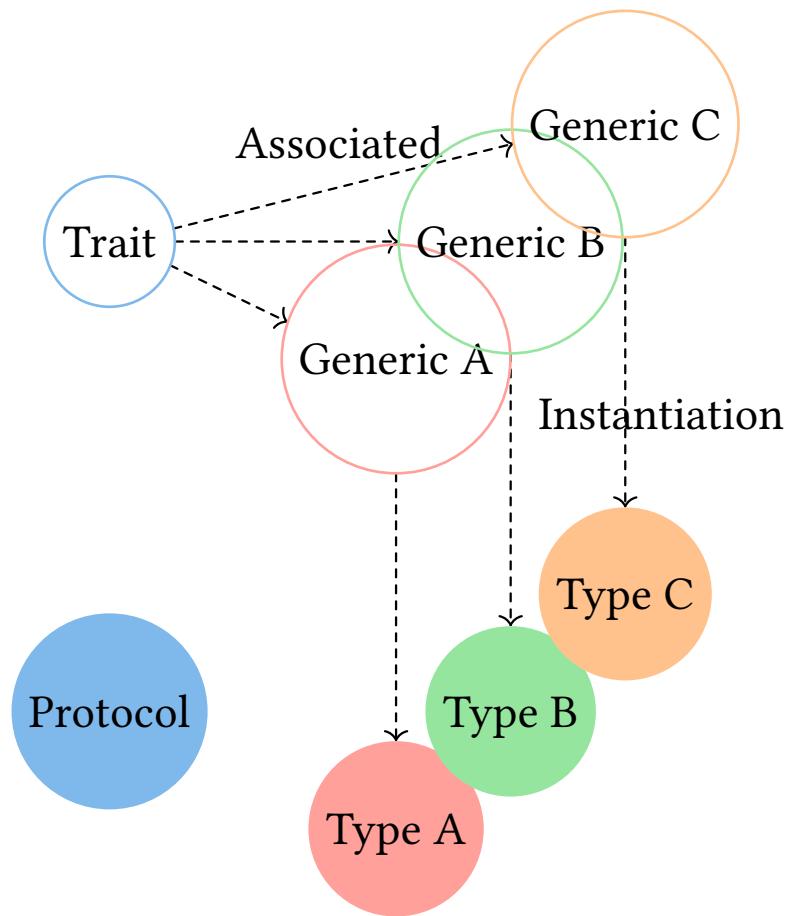
## 4.7. Associated Types

## 4. Methods and traits

```
1 trait Protocol {  
2     type Message;  
3     fn send(&self, msg: Self::Message);  
4     fn receive(&self) -> Self::Message;  
5 }  
6  
7 impl Protocol for Tcp {  
8     type Message = TcpPacket;  
9     fn send(&self, msg: Self::Message)  
10    {  
11        // Send the TCP packet  
12    }  
13    fn receive(&self) -> Self::Message  
14    {  
15        // Receive a TCP packet  
16    }  
17 }  
18 (playground link)
```

## 4.7. Associated Types

Use cases for associated types: implementing (network) **protocols**.



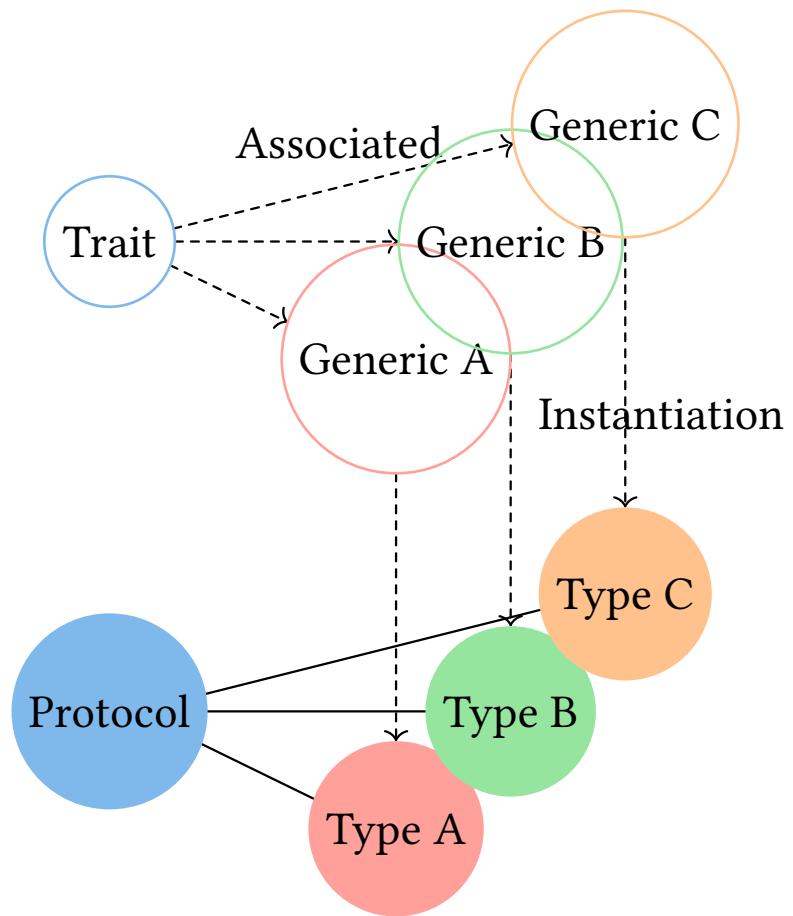
## 4.7. Associated Types

## 4. Methods and traits

```
1 trait Protocol {  
2     type Message;  
3     fn send(&self, msg: Self::Message);  
4     fn receive(&self) -> Self::Message;  
5 }  
6  
7 impl Protocol for Tcp {  
8     type Message = TcpPacket;  
9     fn send(&self, msg: Self::Message)  
10    {  
11        // Send the TCP packet  
12    }  
13    fn receive(&self) -> Self::Message  
14    {  
15        // Receive a TCP packet  
16    }  
17 }  
18 (playground link)
```

## 4.7. Associated Types

Use cases for associated types: implementing (network) **protocols**.



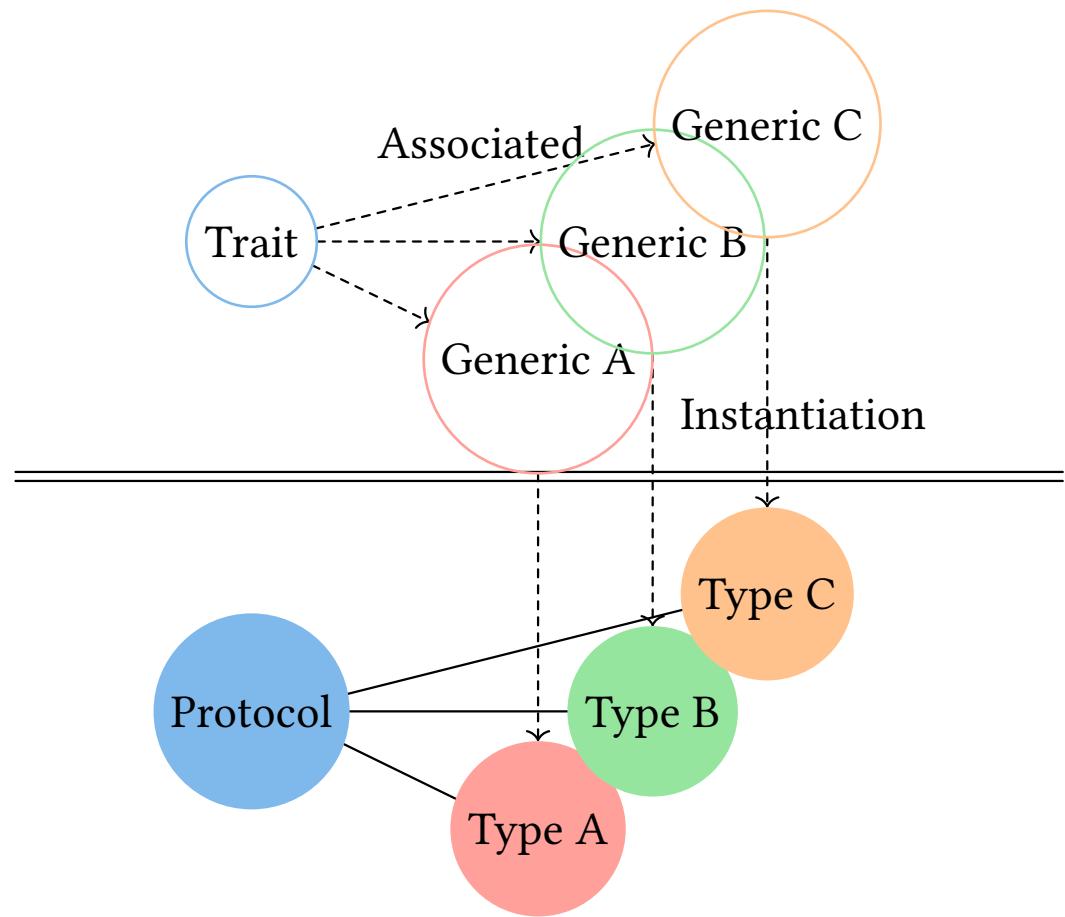
## 4.7. Associated Types

## 4. Methods and traits

```
1 trait Protocol {  
2     type Message;  
3     fn send(&self, msg: Self::Message);  
4     fn receive(&self) -> Self::Message;  
5 }  
6  
7 impl Protocol for Tcp {  
8     type Message = TcpPacket;  
9     fn send(&self, msg: Self::Message)  
10    {  
11        // Send the TCP packet  
12    }  
13    fn receive(&self) -> Self::Message  
14    {  
15        // Receive a TCP packet  
16    }  
17 }  
18 (playground link)
```

## 4.7. Associated Types

Use cases for associated types: implementing (network) **protocols**.



## 4.7. Associated Types

## 4. Methods and traits

```
1 trait Protocol {  
2     type Message;  
3     fn send(&self, msg: Self::Message);  
4     fn receive(&self) -> Self::Message;  
5 }  
6  
7 impl Protocol for Tcp {  
8     type Message = TcpPacket;  
9     fn send(&self, msg: Self::Message)  
10    {  
11        // Send the TCP packet  
12    }  
13    fn receive(&self) -> Self::Message  
14    {  
15        // Receive a TCP packet  
16    }  
17 }  
18 (playground link)
```

## 4.8. Deriving

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

```
1 #[derive(Debug, Clone, Default)]
2 struct Player {
3     name: String,
4     strength: u8,
5     hit_points: u8,
6 }
7
8 fn main() {
9     let p1 = Player::default(); // Default trait adds `default` constructor.
10    let mut p2 = p1.clone(); // Clone trait adds `clone` method.
11    p2.name = String::from("EldurScrollz");
12    // Debug trait adds support for printing with `{:?}`.
13    println!("{} vs. {}", p1, p2);
14 }
```

(playground link)

How is the derive functionality implemented in Rust?

## 4.8. Deriving

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

```
1 #[derive(Debug, Clone, Default)]
2 struct Player {
3     name: String,
4     strength: u8,
5     hit_points: u8,
6 }
7
8 fn main() {
9     let p1 = Player::default(); // Default trait adds `default` constructor.
10    let mut p2 = p1.clone(); // Clone trait adds `clone` method.
11    p2.name = String::from("EldurScrollz");
12    // Debug trait adds support for printing with `{:?}`.
13    println!("{} vs. {}", p1, p2);
14 }
```

(playground link)

How is the derive functionality implemented in Rust?

With **procedural macros**, and many crates provide useful derive macros to add useful functionality.

## 4.8. Deriving

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

```
1 #[derive(Debug, Clone, Default)]
2 struct Player {
3     name: String,
4     strength: u8,
5     hit_points: u8,
6 }
7
8 fn main() {
9     let p1 = Player::default(); // Default trait adds `default` constructor.
10    let mut p2 = p1.clone(); // Clone trait adds `clone` method.
11    p2.name = String::from("EldurScrollz");
12    // Debug trait adds support for printing with `{:?}`.
13    println!("{} vs. {}", p1, p2);
14 }
```

(playground link)

How is the derive functionality implemented in Rust?

With **procedural macros**, and many crates provide useful derive macros to add useful functionality.

For example, `serde` can derive serialization support for a struct using `#[derive(Serialize)]`.

### 4.8.1. Why is deriving useful?

A manual implementation of the `Clone` trait for the `Player` struct would look like this:

```
1 impl Clone for Player {  
2     fn clone(&self) -> Self {  
3         Player {  
4             name: self.name.clone(),  
5             strength: self.strength.clone(),  
6             hit_points: self.hit_points.clone(),  
7         }  
8     }  
9 }
```

(playground link)

It is easier to just write `#[derive(Clone)]`

#### Info

The derive attribute is similar to deriving in Haskell.

## 4.9. Exercise: Logger trait

## 4. Methods and traits

Complete the test code in `session-2/examples/s2e3-logger.rs`.

Run code with `cargo run --example s2e3-logger`.

1.	Quiz about last lecture .....	1
2.	Pattern matching .....	8
3.	Tooling intermezzo .....	23
4.	Methods and traits .....	27
<b>5.</b>	<b>Generics .....</b>	<b>43</b>
5.1.	Generic functions .....	45
5.2.	Monomorphisation .....	46
5.3.	Trait bounds .....	47
5.4.	Combining traits .....	48
5.5.	Composition over inheritance .....	49
5.6.	<code>where</code> clauses .....	50
5.7.	Feature of <code>where</code> clauses .....	51
5.8.	Generic datatypes .....	52
5.9.	Generic traits .....	56
5.10.	Associated types vs. generic type parameters .....	58
5.11.	Multiple generic <code>impl</code> blocks .....	59
5.12.	<code>impl Trait</code> .....	60
5.13.	Exercise .....	62

6.	Closures .....	63
7.	Standard library types .....	76
8.	Conclusion .....	99

## 5.1. Generic functions

## 5. Generics

```
1 fn pick<T>(cond: bool, left: T, right: T) -> T {  
2     if cond { left } else { right }  
3 }  
4  
5 fn main() {  
6     println!("picked a number: {:?}", pick(true, 222, 333));  
7     println!("picked a string: {:?}", pick(false, 'L', 'R'));  
8 }
```

*(playground link)*

Bodies of generic functions need to be well-defined for all possible types T.

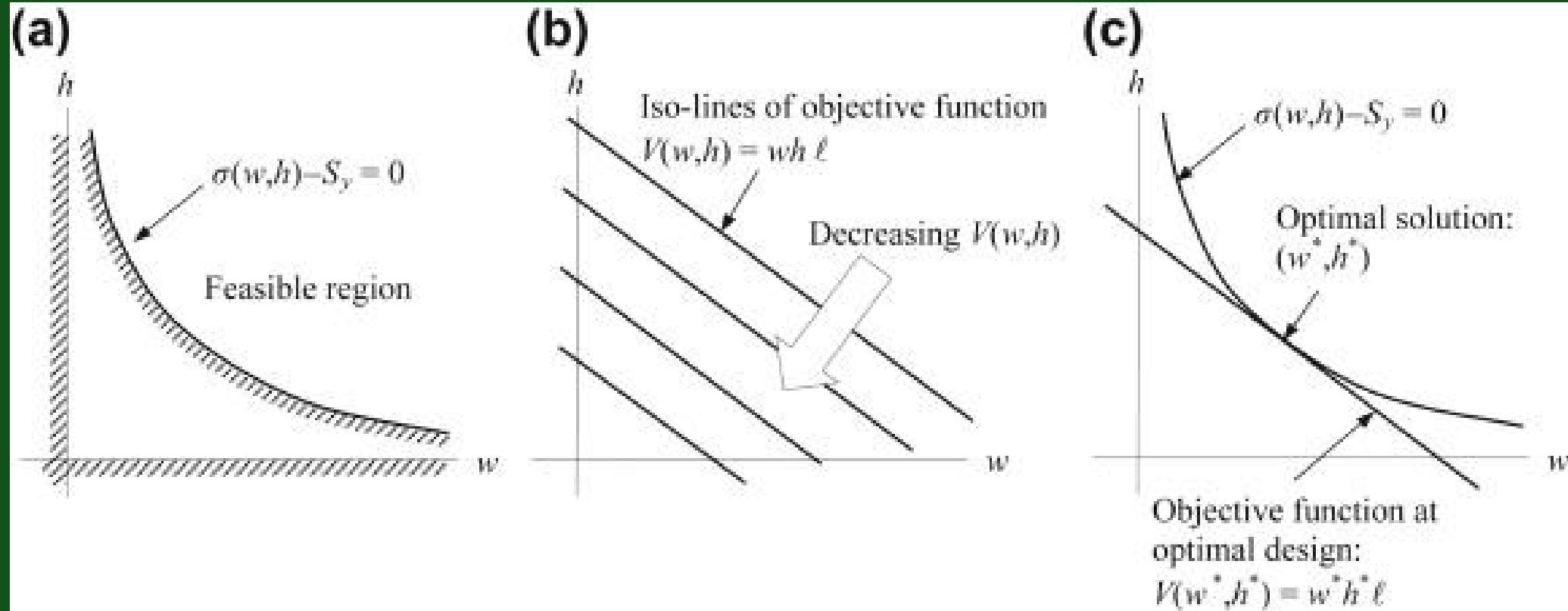
## 5.2. Monomorphisation

The compiler **generates concrete versions** of generic functions for each used type.

```
1 fn pick_i32(cond: bool, left: i32, right: i32) -> i32 {  
2     if cond { left } else { right }  
3 }  
4  
5 fn pick_char(cond: bool, left: char, right: char) -> char {  
6     if cond { left } else { right }  
7 }
```

*(playground link)*

Generics are a zero-cost abstraction.



## 5.3. Trait bounds

Require the types to implement some trait, so that you can call this trait's methods

```
1 fn duplicate<T: Clone>(a: T) -> (T, T) {  
2     (a.clone(), a.clone())  
3 }  
4  
5 struct NotCloneable;  
6  
7 fn main() {  
8     let foo = String::from("foo");  
9     let pair = duplicate(foo);  
10    println!("{}{:?}{}", pair.0, pair.1);  
11 }
```

(playground link)

What happens if we pass `NotCloneable` to `duplicate`? (Try in playground!)

## 5.3. Trait bounds

Require the types to implement some trait, so that you can call this trait's methods

```
1 fn duplicate<T: Clone>(a: T) -> (T, T) {  
2     (a.clone(), a.clone())  
3 }  
4  
5 struct NotCloneable;  
6  
7 fn main() {  
8     let foo = String::from("foo");  
9     let pair = duplicate(foo);  
10    println!("{}{:?}{}", pair.0, pair.1);  
11 }
```

(playground link)

What happens if we pass NotCloneable to `duplicate`? (Try in playground!)

A compile-time error, because `NotCloneable` does not implement the `Clone` trait.

## 5.4. Combining traits

## 5. Generics

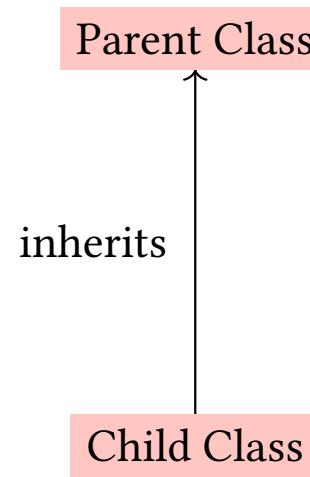
When multiple traits are necessary, use + to join them.

```
1 fn compare_and_print<T: PartialOrd + Display>(a: T, b: T) {  
2     if a < b {  
3         println!("{} is less than {}", a, b);  
4     } else {  
5         println!("{} is not less than {}", a, b);  
6     }  
7 }
```

(playground link)

Rust forbids object inheritance completely.

### Class inheritance

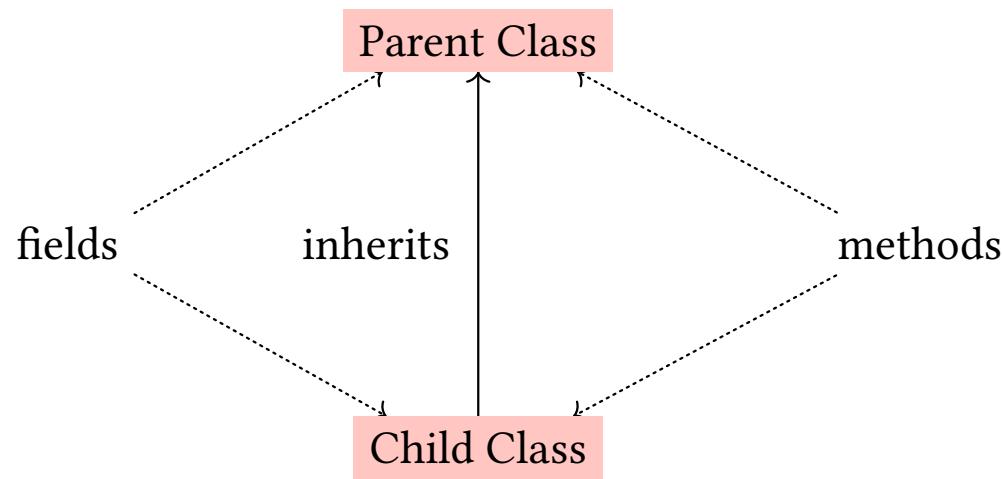


## 5.5. Composition over inheritance

## 5. Generics

Rust forbids object inheritance completely.

### Class inheritance

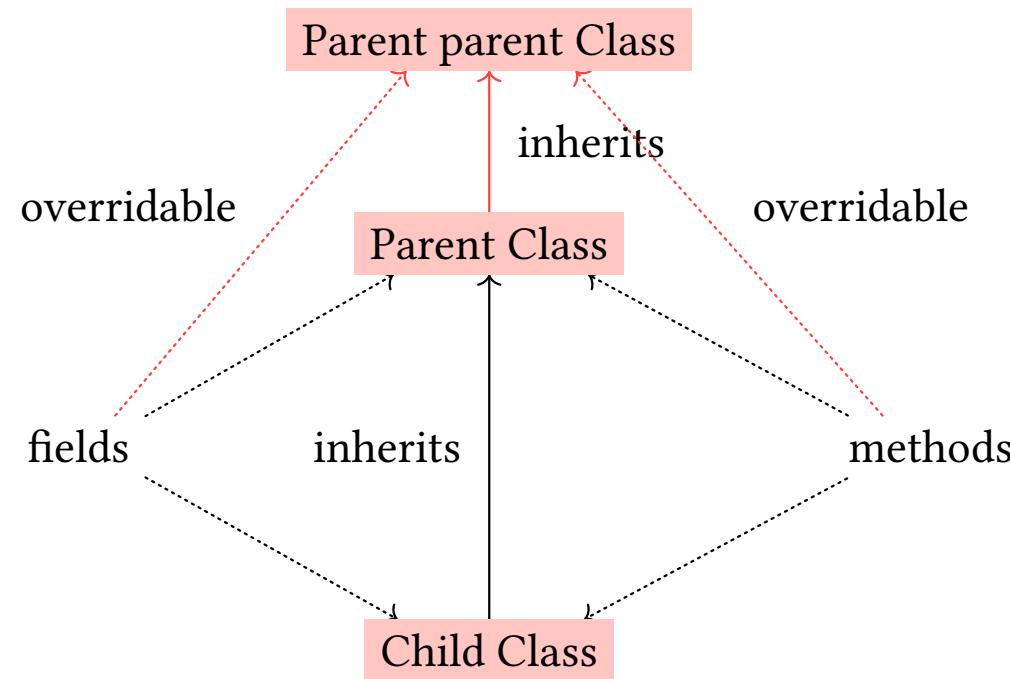


## 5.5. Composition over inheritance

## 5. Generics

Rust forbids object inheritance completely.

### Class inheritance

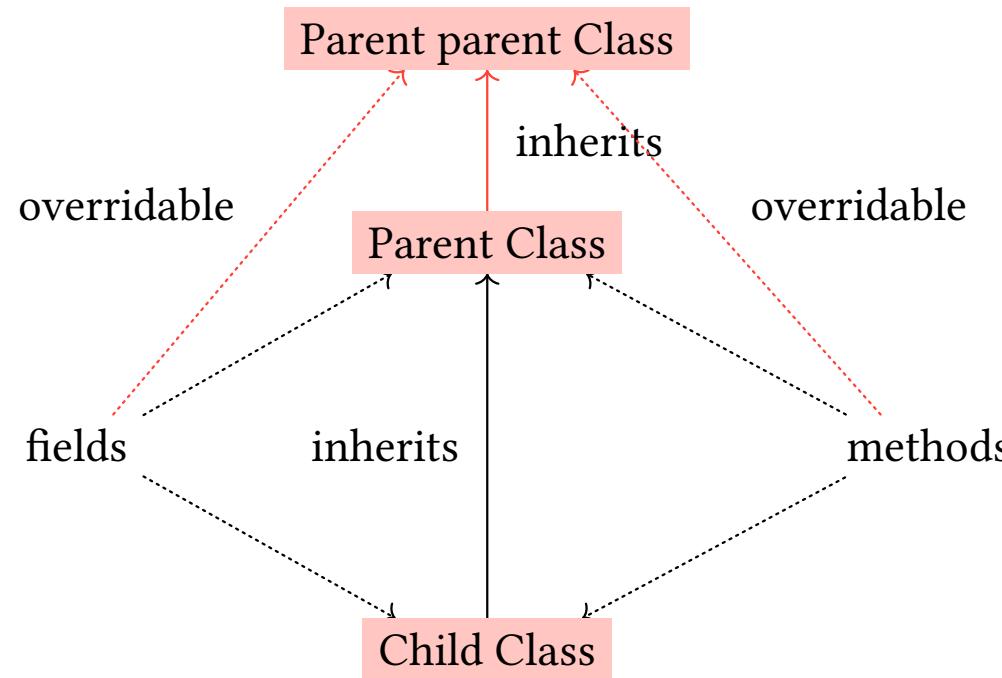


## 5.5. Composition over inheritance

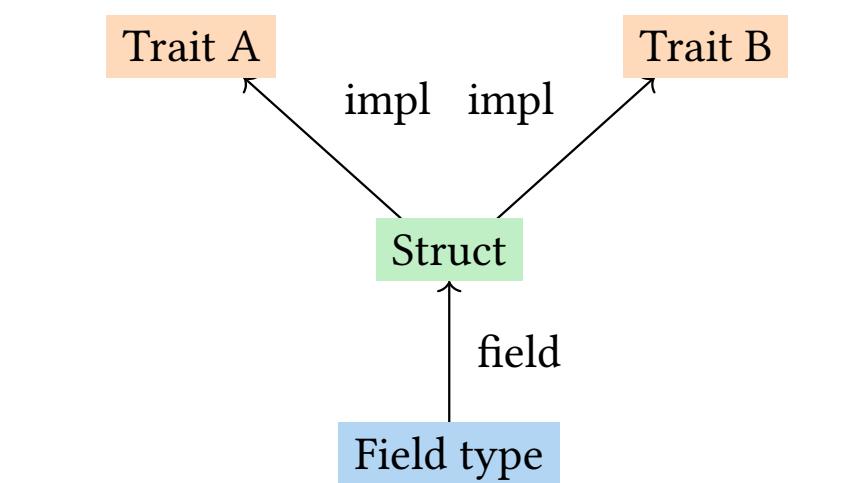
## 5. Generics

Rust forbids object inheritance completely.

### Class inheritance



### Composition with traits

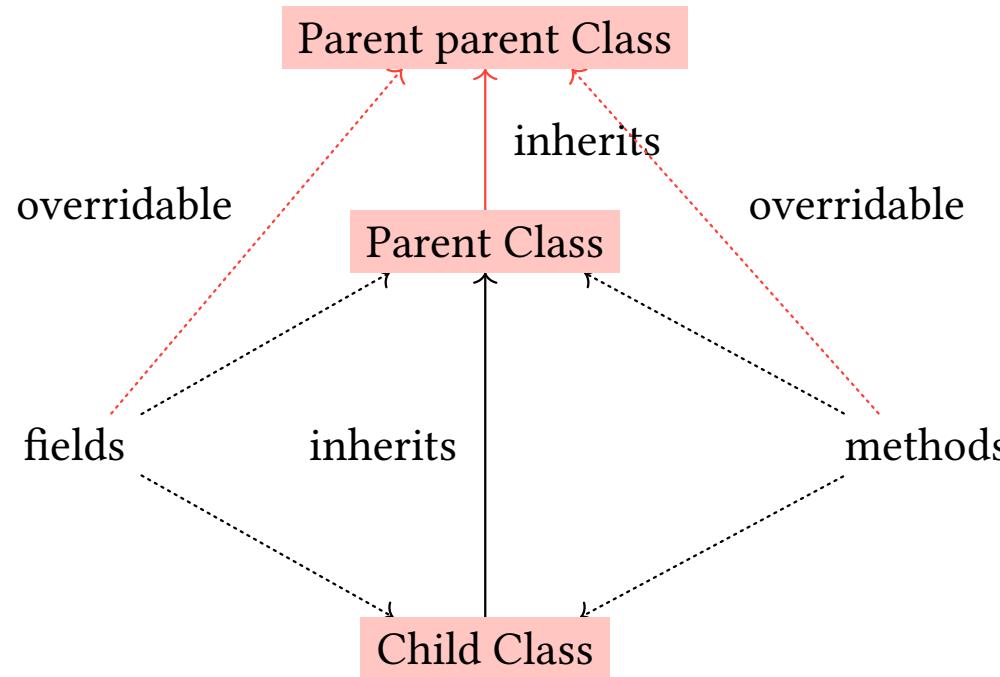


## 5.5. Composition over inheritance

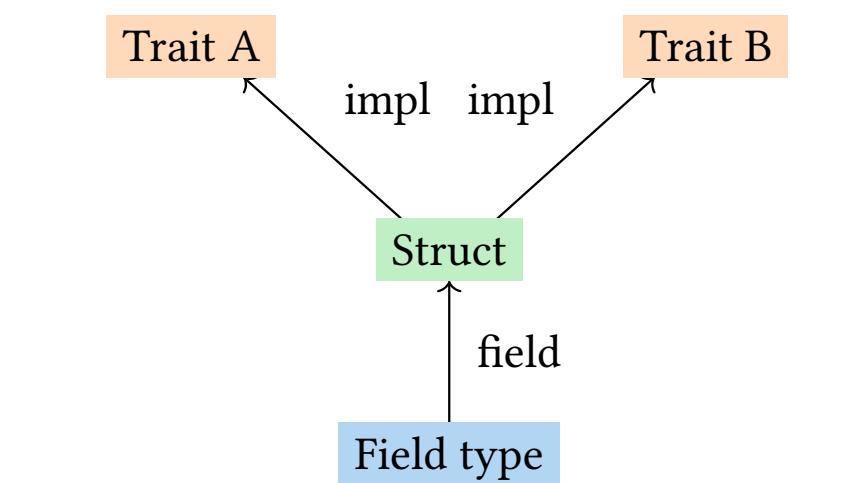
## 5. Generics

Rust forbids object inheritance completely.

### Class inheritance



### Composition with traits

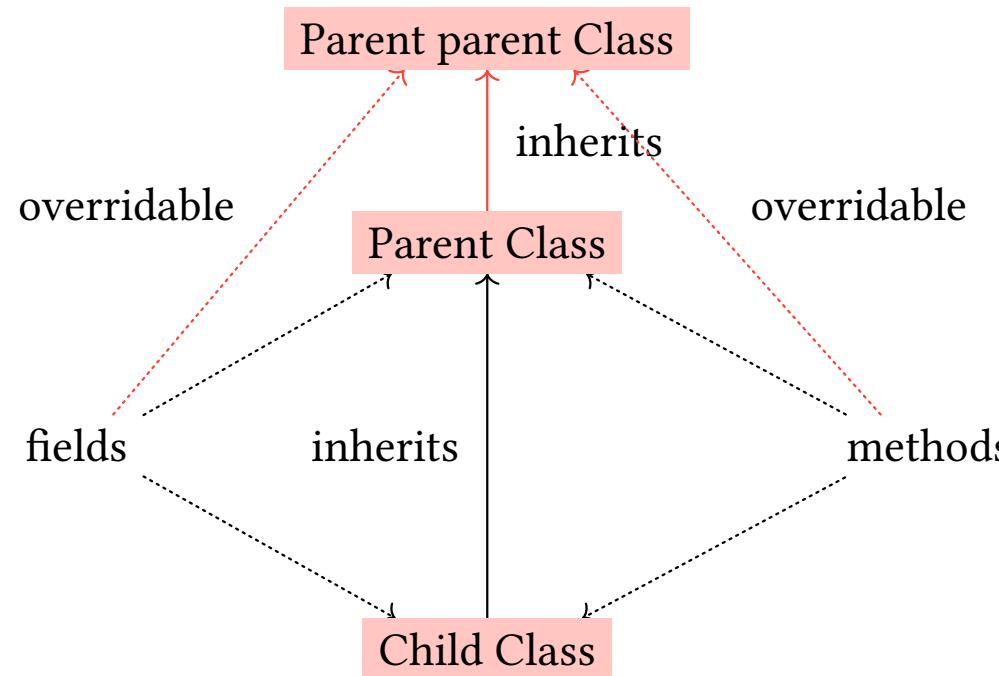


Are traits in Rust a kind of multiple inheritance?

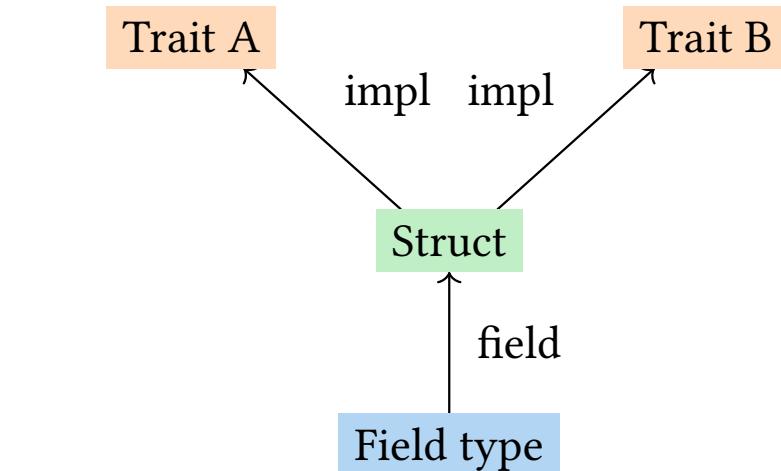
## 5.5. Composition over inheritance

Rust forbids object inheritance completely.

### Class inheritance



### Composition with traits



Are traits in Rust a kind of multiple inheritance?

Yes, but no data inheritance. No diamond problem (see example `diamond-problem`).

## 5.6. where clauses

## 5. Generics

Declutters the function signature if you have many parameters

```
1 fn duplicate<T>(a: T) -> (T, T)
2 where
3     T: Clone,
4 {
5     (a.clone(), a.clone())
6 }
```

*(playground link)*

## 5.7. Feature of where clauses

## 5. Generics

With where clauses you can put **trait bounds on composite types**:

```
1 fn duplicate_option<T>(a: Option<T>) -> (Option<T>, Option<T>)
2 where
3     Option<T>: Clone,
4 {
5     (a.clone(), a.clone())
6 }
7
8 fn main() {
9     let s = Some(String::from("hello"));
10    let pair = duplicate_option(s);
11    println!("{}{:?}{}", pair);
12 }
```

(playground link)

Info

Powerful feature of generic programming in Rust!

## 5.8. Generic datatypes

## 5. Generics

```
1 pub trait Logger {  
2     /// Log a message at the given verbosity level.  
3     fn log(&self, verbosity: u8, message: &str);  
4 }  
5  
6 struct StderrLogger;  
7  
8 impl Logger for StderrLogger {  
9     fn log(&self, verbosity: u8, message: &str) {  
10         eprintln!("verbosity={verbosity}: {message}");  
11     }  
12 }
```

(playground link)

## 5.8. Generic datatypes

```

1 pub trait Logger {
2     /// Log a message at the given verbosity level.
3     fn log(&self, verbosity: u8, message: &str);
4 }
5
6 struct StderrLogger;
7
8 impl Logger for StderrLogger {
9     fn log(&self, verbosity: u8, message: &str) {
10         eprintln!("verbosity={verbosity}: {message}");
11     }
12 }
```

(playground link)

You can implement a trait for a generic datatype **if you provide template type parameters.**

Only log messages up to the given verbosity level:

```

1 struct VerbosityFilter<L> {
2     max_verbosity: u8,
3     inner: L,
4 }
5
6 impl<L: Logger> Logger for VerbosityFilter<L> {
7     fn log(&self, verbosity: u8, message: &str) {
8         if verbosity <= self.max_verbosity {
9             self.inner.log(verbosity, message);
10        }
11    }
12 }
```

(playground link)

Why is L specified twice in `impl<L: Logger> .. VerbosityFilter<L>`?  
Isn't that redundant?

## 5.8. Generic datatypes

```

1 pub trait Logger {
2     /// Log a message at the given verbosity level.
3     fn log(&self, verbosity: u8, message: &str);
4 }
5
6 struct StderrLogger;
7
8 impl Logger for StderrLogger {
9     fn log(&self, verbosity: u8, message: &str) {
10         eprintln!("verbosity={verbosity}: {message}");
11     }
12 }
```

(playground link)

You can implement a trait for a generic datatype **if you provide template type parameters.**

Only log messages up to the given verbosity level:

```

1 struct VerbosityFilter<L> {
2     max_verbosity: u8,
3     inner: L,
4 }
5
6 impl<L: Logger> Logger for VerbosityFilter<L> {
7     fn log(&self, verbosity: u8, message: &str) {
8         if verbosity <= self.max_verbosity {
9             self.inner.log(verbosity, message);
10        }
11    }
12 }
```

(playground link)

Why is L specified twice in `impl<L: Logger> .. VerbosityFilter<L>`?  
Isn't that redundant?

↳ `impl` parameters are separate and usually carries trait bounds (not the datatype).

What happens if you would just use a concrete type as in `impl VerbosityFilter<StderrLogger> { .. }`

## 5.8. Generic datatypes

```

1 pub trait Logger {
2     /// Log a message at the given verbosity level.
3     fn log(&self, verbosity: u8, message: &str);
4 }
5
6 struct StderrLogger;
7
8 impl Logger for StderrLogger {
9     fn log(&self, verbosity: u8, message: &str) {
10         eprintln!("verbosity={verbosity}: {message}");
11     }
12 }
```

(playground link)

You can implement a trait for a generic datatype **if you provide template type parameters.**

Only log messages up to the given verbosity level:

```

1 struct VerbosityFilter<L> {
2     max_verbosity: u8,
3     inner: L,
4 }
5
6 impl<L: Logger> Logger for VerbosityFilter<L> {
7     fn log(&self, verbosity: u8, message: &str) {
8         if verbosity <= self.max_verbosity {
9             self.inner.log(verbosity, message);
10        }
11    }
12 }
```

(playground link)

Why is L specified twice in `impl<L: Logger> .. VerbosityFilter<L>`?  
Isn't that redundant?

↳ `impl` parameters are separate and usually carries trait bounds (not the datatype).

What happens if you would just use a concrete type as in `impl VerbosityFilter<StderrLogger> { .. }`

↳ Would only work with `StderrLogger` instances, not with any other type that implements `Logger`.

## 5.8. Generic datatypes

### 5.8.1. Blanket `impl` blocks

A blanket implementation is an `impl` block that applies to **all types** that satisfy the trait bounds.

```

1  struct VerboseFilter<L> {
2      max_verbosity: u8,
3      inner: L,
4  }
5
6  impl<L: Logger> Logger for VerboseFilter<L> {
7      fn log(&self, verbosity: u8, message: &str) {
8          if verbosity <= self.max_verbosity {
9              self.inner.log(verbosity, message);
10         }
11     }
12 }
```

(playground link)

It is a bit like in mathematics:

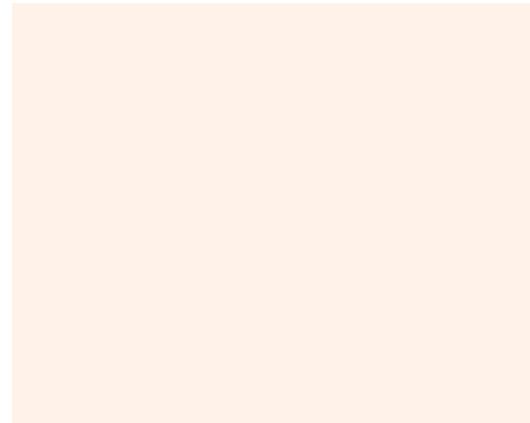
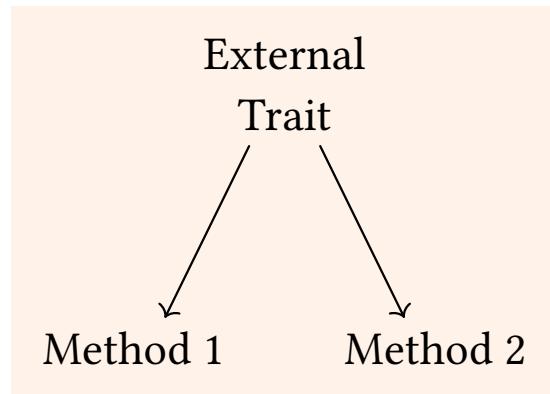
$$\forall l \in \text{Logger} : \text{VerboseFilter}(l) \rightarrow \text{Logger}(l)$$

### 5.8.2. Visualisation

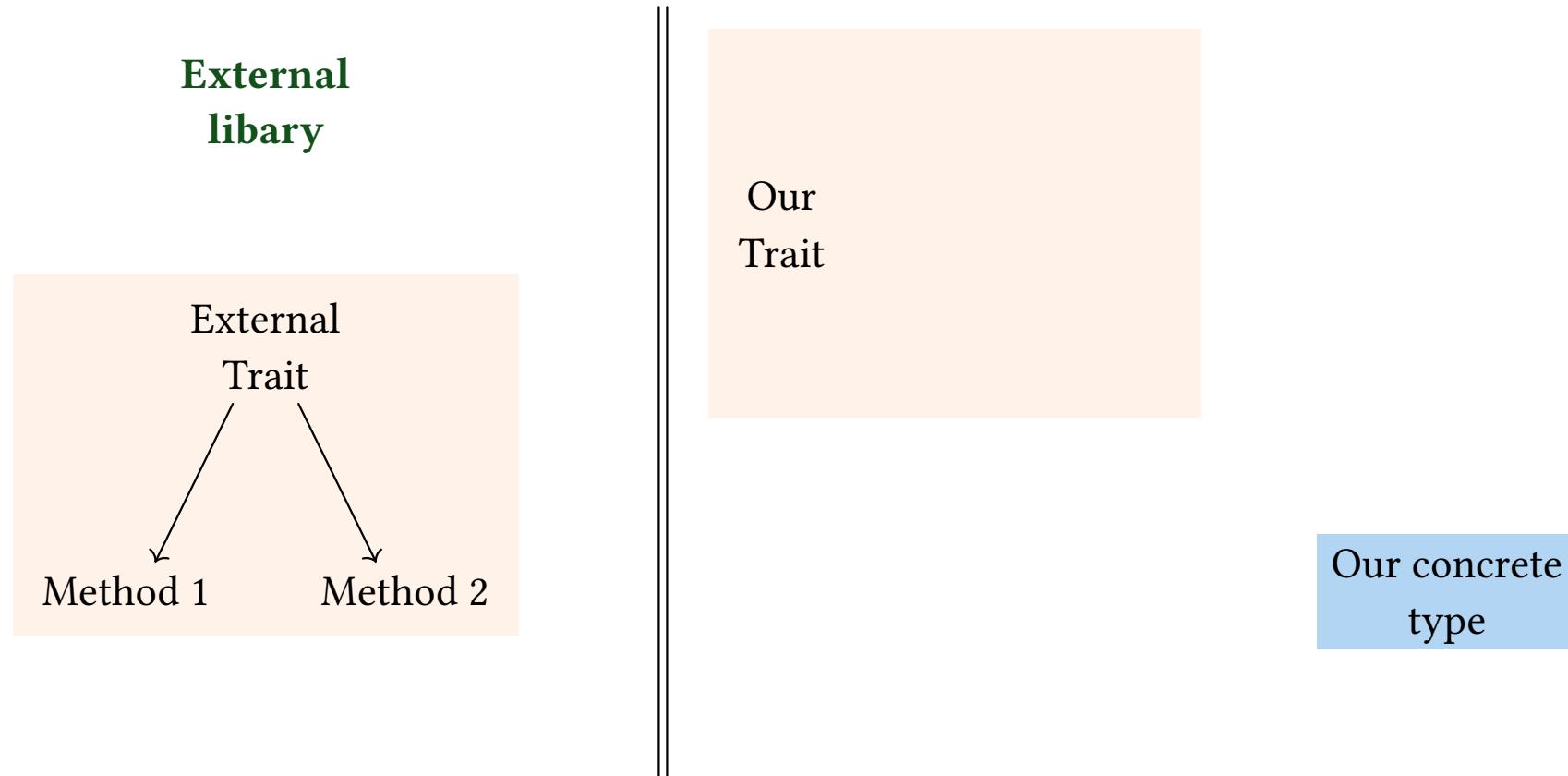
External  
library

External  
Trait

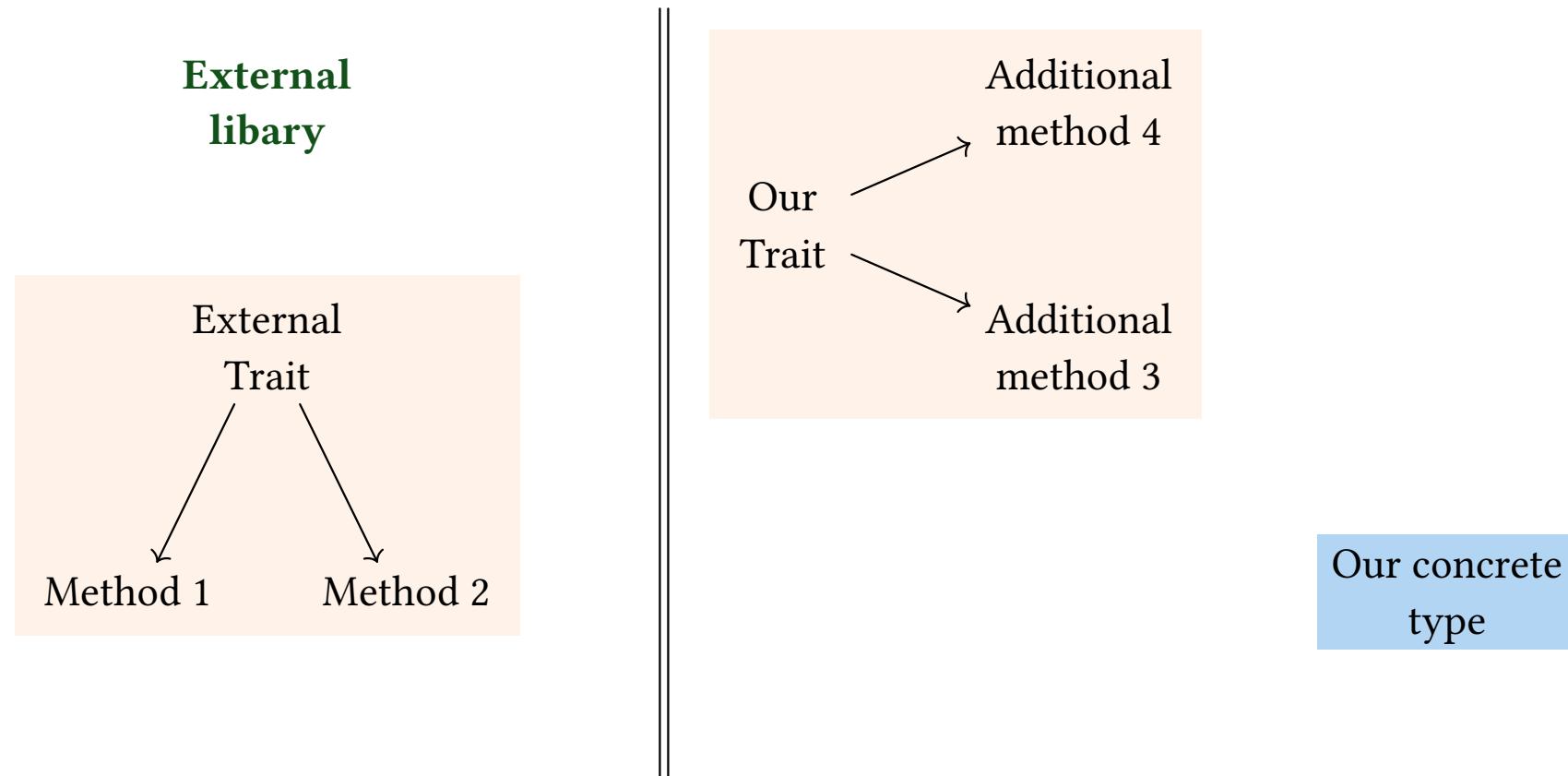
### 5.8.2. Visualisation



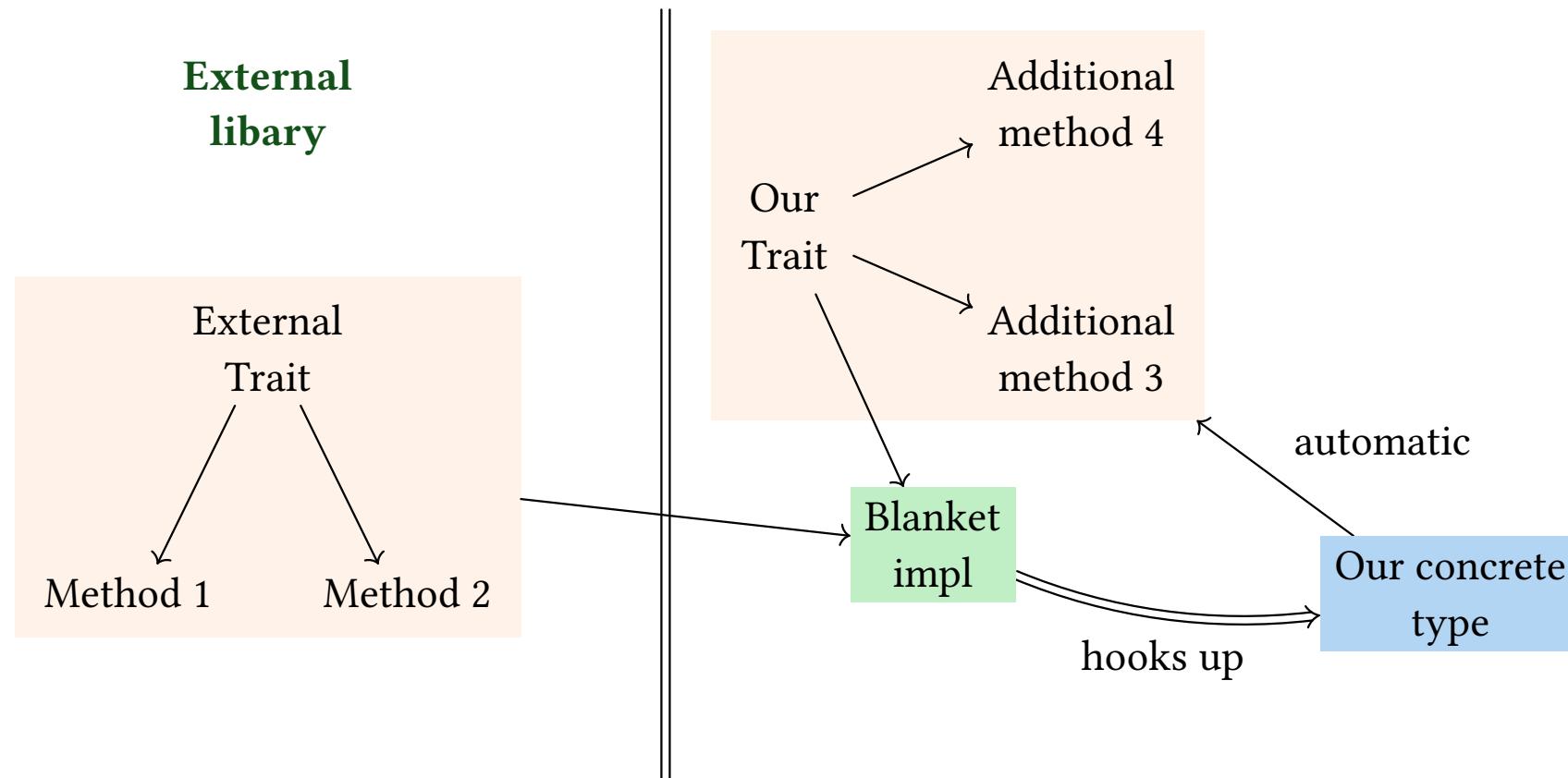
### 5.8.2. Visualisation



### 5.8.2. Visualisation



## 5.8.2. Visualisation



## 5.8. Generic datatypes

### 5.8.3. Putting constraints on super-trait (advanced)

A subtrait can add constraints on the associated types of its supertrait.

```

1 trait Container {
2     type Item;
3     fn get(&self) -> &Self::Item;
4 }
5
6 trait PrintableContainer: Container
7 where
8     Self::Item: Display,
9 {
10     fn print_item(&self) {
11         println!("Item: {}", self.get());
12     }
13 }
14
15 struct Box<T> {
16     value: T,
17 }                                         (playground link)

```

```

1 impl<T> Container for Box<T> {
2     type Item = T;
3     fn get(&self) -> &Self::Item {
4         &self.value
5     }
6 }
7
8 impl<T: Display> PrintableContainer for Box<T> {}
9
10 fn main() {
11     let b = Box { value: 42 };
12     b.print_item();
13 }                                         (playground link)

```

Why does `PrintableContainer` require `Self::Item: Display`?

## 5.8. Generic datatypes

### 5.8.3. Putting constraints on super-trait (advanced)

A subtrait can add constraints on the associated types of its supertrait.

```

1 trait Container {
2     type Item;
3     fn get(&self) -> &Self::Item;
4 }
5
6 trait PrintableContainer: Container
7 where
8     Self::Item: Display,
9 {
10     fn print_item(&self) {
11         println!("Item: {}", self.get());
12     }
13 }
14
15 struct Box<T> {
16     value: T,
17 }                                         (playground link)

```

```

1 impl<T> Container for Box<T> {
2     type Item = T;
3     fn get(&self) -> &Self::Item {
4         &self.value
5     }
6 }
7
8 impl<T: Display> PrintableContainer for Box<T> {}
9
10 fn main() {
11     let b = Box { value: 42 };
12     b.print_item();
13 }                                         (playground link)

```

Why does `PrintableContainer` require `Self::Item: Display`?

It constrains the supertrait's associated type so that `print_item` can use the `Display` trait.

The `From` trait is a standard library trait for type conversion.

```
1 pub trait From<T>: Sized {  
2     fn from(value: T) -> Self;  
3 }  
4  
5 #[derive(Debug)]  
6 struct Foo(String);
```

(playground link)

**Info**

Common traits in the standard library will be covered later on.

## 5.9. Generic traits

### 5.9.1. Example From

```
1  impl From<u32> for Foo {  
2      fn from(from: u32) -> Foo {  
3          Foo(format!("Converted from integer: {from}"))  
4      }  
5  }  
6  
7  impl From<bool> for Foo {  
8      fn from(from: bool) -> Foo {  
9          Foo(format!("Converted from bool: {from}"))  
10     }  
11 }  
12 fn main() {  
13     dbg!(Foo::from(123));  
14     dbg!(Foo::from(true));  
15 }
```

(playground link)

#### Warning

Notice that a **generic trait can be implemented multiple times** for the same type!

## 5.10. Associated types vs. generic type parameters

It may not always be clear when to pick an associated type or a generic type.

### Associated types

(chosen by the implementer)

Generic  
datatype

Non-generic  
trait

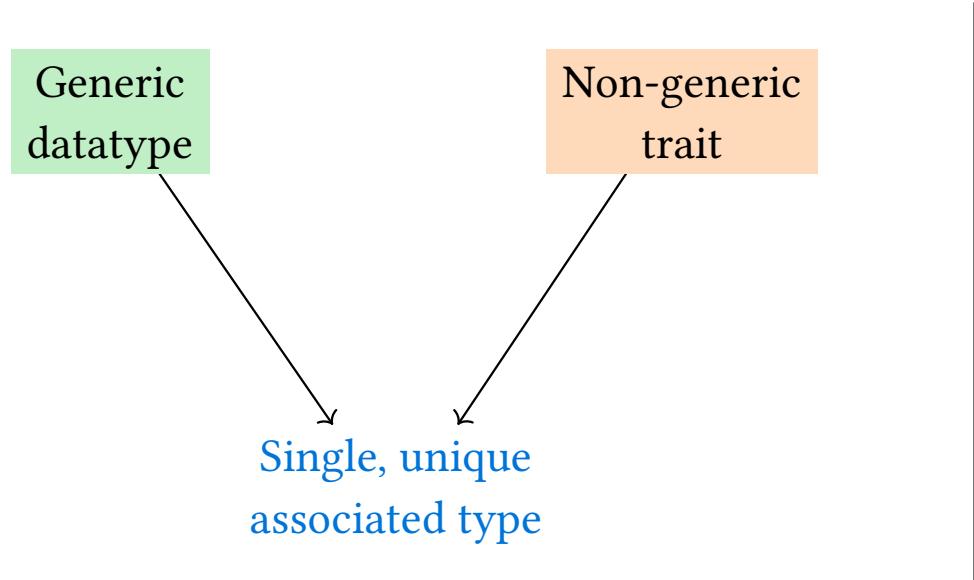
## 5.10. Associated types vs. generic type parameters

### 5. Generics

It may not always be clear when to pick an associated type or a generic type.

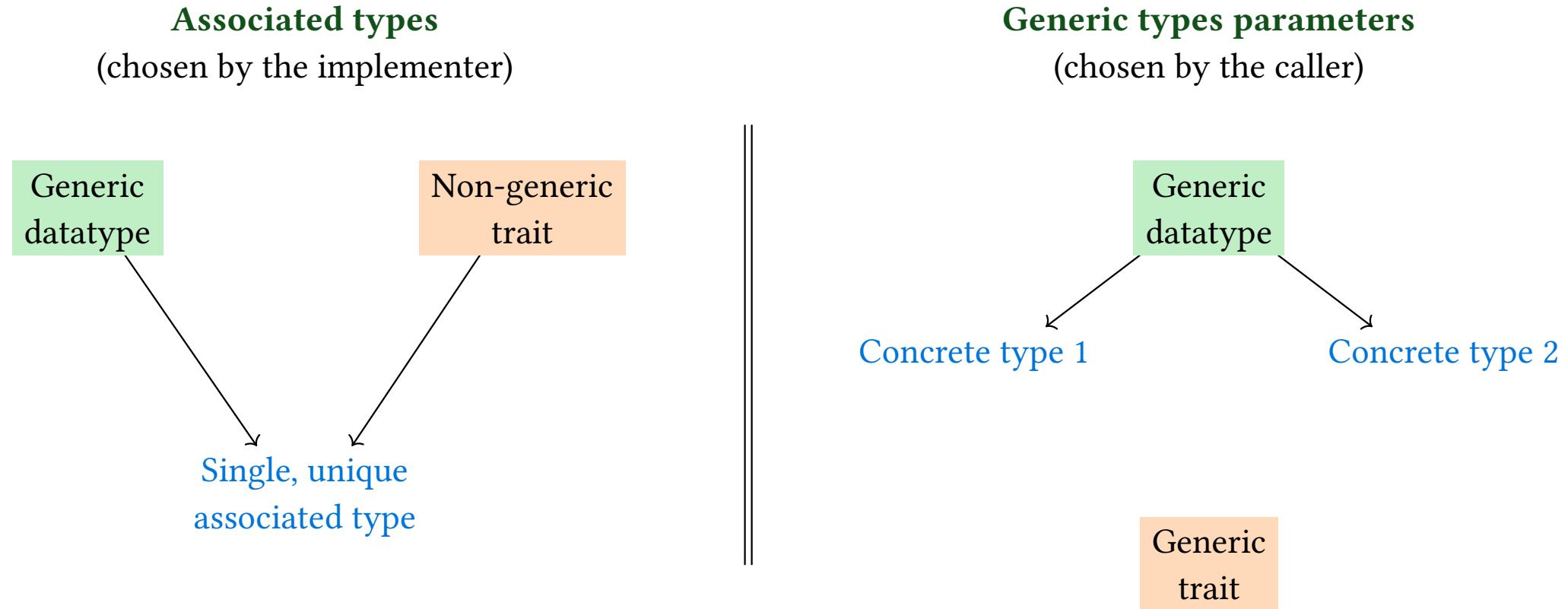
#### Associated types

(chosen by the implementer)



## 5.10. Associated types vs. generic type parameters

It may not always be clear when to pick an associated type or a generic type.

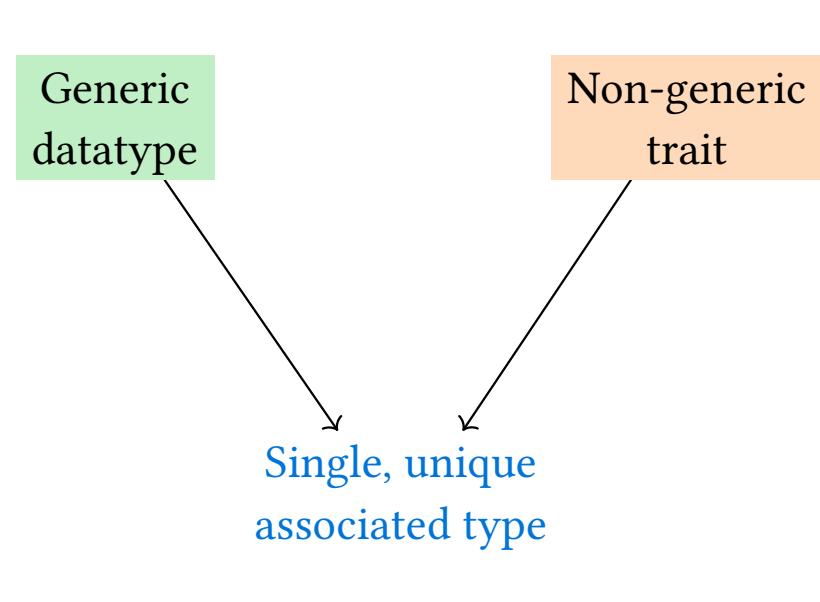


## 5.10. Associated types vs. generic type parameters

It may not always be clear when to pick an associated type or a generic type.

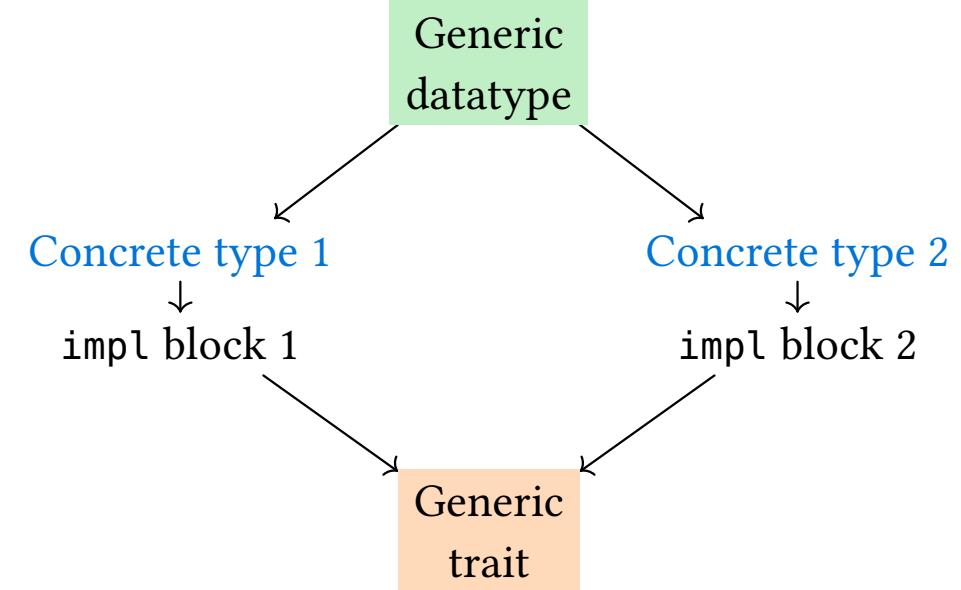
### Associated types

(chosen by the implementer)



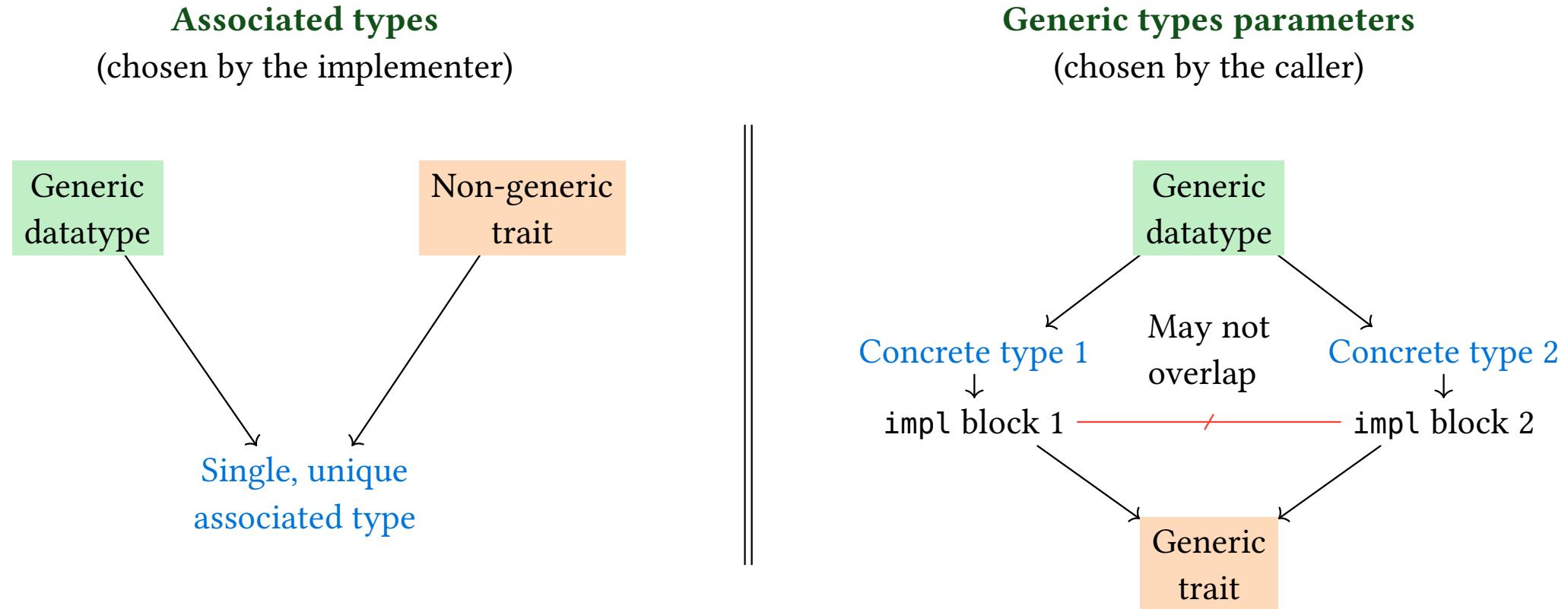
### Generic types parameters

(chosen by the caller)



## 5.10. Associated types vs. generic type parameters

It may not always be clear when to pick an associated type or a generic type parameter.



- Associated types behave like output (first choice).
- Generic type parameters behave like input.

## 5.11. Multiple generic `impl` blocks

## 5. Generics

```
1 struct Container<T> {
2     value: T,
3 }
4
5 impl<T> Container<T> {
6     fn process(&self) -> &'static str { "generic implementation" }
7 }
8
9 impl Container<i32> {
10    fn process(&self) -> &'static str { "specialized implementation for i32" }
11 }
```

(playground link)

Will this code compile?

## 5.11. Multiple generic `impl` blocks

## 5. Generics

```
1 struct Container<T> {  
2     value: T,  
3 }  
4  
5 impl<T> Container<T> {  
6     fn process(&self) -> &'static str { "generic implementation" }  
7 }  
8  
9 impl Container<i32> {  
10    fn process(&self) -> &'static str { "specialized implementation for i32" }  
11 }
```

(playground link)

Will this code compile?

No. Rust does not allow overlapping implementations.

## Info

`impl Into<i32>` is syntactic sugar for: `fn add_42_millions<T: Into<i32>>(x: T) -> i32.`  
`T` is an anonymous and **hidden generic type**.

```
1 fn add_42_millions(x: impl Into<i32>) -> i32 {  
2     x.into() + 42_000_000  
3 }  
4  
5 fn pair_of(x: u32) -> impl Debug {  
6     (x + 1, x - 1)  
7 }  
8  
9 fn main() {  
10    let many = add_42_millions(42_i8);  
11    dbg!(many);  
12    let many_more = add_42_millions(10_000_000);  
13    dbg!(many_more);  
14    let debuggable = pair_of(27);  
15    dbg!(debuggable);  
16 }
```

(playground link)

5.12.1. Inference for return type `impl Trait`

```
1 fn returns_impl_trait(x: i32) -> impl Display {  
2     if x > 0 {  
3         x  
4     } else {  
5         -x  
6     }  
7 }  
8  
9 fn main() {  
10    let result = returns_impl_trait(-5);  
11    println!("{}", result);  
12 }
```

(playground link)

What is the return type of `returns_impl_trait`?

5.12.1. Inference for return type `impl Trait`

```
1 fn returns_impl_trait(x: i32) -> impl Display {  
2     if x > 0 {  
3         x  
4     } else {  
5         -x  
6     }  
7 }  
8  
9 fn main() {  
10    let result = returns_impl_trait(-5);  
11    println!("{}", result);  
12 }
```

(playground link)

What is the return type of `returns_impl_trait`?



i32, because both branches return an i32.

## 5.13. Exercise

Please find the exercise in `./session-2/tests/s2e4-min.rs`.

Test using the command: `cargo test --test s2e4-min -- --nocapture`

1.	Quiz about last lecture .....	1
2.	Pattern matching .....	8
3.	Tooling intermezzo .....	23
4.	Methods and traits .....	27
5.	Generics .....	43
<b>6.</b>	<b>Closures .....</b>	<b>63</b>
6.1.	Syntax .....	64
6.2.	Capturing .....	65
6.3.	Moving .....	67
6.4.	Internal representation of closures .....	68
6.5.	Datastructures containing functions .....	69
6.6.	Closure traits .....	70
6.7.	Picking the right closure trait .....	72
6.8.	Auto-trait of closures .....	73
6.9.	Exercise .....	75
7.	Standard library types .....	76
8.	Conclusion .....	99

**Structure and  
Interpretation  
of Computer  
Programs**

Second Edition



**Harold Abelson and  
Gerald Jay Sussman  
with Julie Sussman**

**Closures**

Anonymous functions that can capture variables from their surrounding scope.

```
1 fn main() {  
2     // Argument and return type can be inferred for lightweight syntax:  
3     let double_it = |n| n * 2;  
4     dbg!(double_it(50));  
5  
6     // Or we can specify types and bracket the body to be fully explicit:  
7     let add_1f32 = |x: f32| -> f32 { x + 1.0 };  
8     dbg!(add_1f32(50.));  
9 }
```

(playground link)

**Closures**

Anonymous functions that can capture variables from their surrounding scope.

```
1 fn main() {  
2     // Argument and return type can be inferred for lightweight syntax:  
3     let double_it = |n| n * 2;  
4     dbg!(double_it(50));  
5  
6     // Or we can specify types and bracket the body to be fully explicit:  
7     let add_1f32 = |x: f32| -> f32 { x + 1.0 };  
8     dbg!(add_1f32(50.));  
9 }
```

(playground link)

- The body may be surrounded by { . . }

**Closures**

Anonymous functions that can capture variables from their surrounding scope.

```
1 fn main() {  
2     // Argument and return type can be inferred for lightweight syntax:  
3     let double_it = |n| n * 2;  
4     dbg!(double_it(50));  
5  
6     // Or we can specify types and bracket the body to be fully explicit:  
7     let add_1f32 = |x: f32| -> f32 { x + 1.0 };  
8     dbg!(add_1f32(50.));  
9 }
```

(playground link)

- The body may be surrounded by { .. }
- Argument and return types are optional, and are inferred if not given.

## 6.2. Capturing

### 6.2.1. Immutable capture

```
1 fn main() {  
2     let max_value = 5;  
3     let clamp = |v| {  
4         if v > max_value  
5             { max_value } else { v }  
6     };  
7     dbg!(clamp(1));  
8     dbg!(clamp(3));  
9     dbg!(clamp(5));  
10    dbg!(clamp(7));  
11 }
```

*(playground link)*

By default, a closure captures values by immutable reference. Here `max_value` is captured by `clamp`, but still available to `main` for printing.

Try making `max_value` mutable, changing it, and printing the clamped values again. Why doesn't this work?

## 6.2. Capturing

### 6.2.1. Immutable capture

```
1 fn main() {  
2     let max_value = 5;  
3     let clamp = |v| {  
4         if v > max_value  
5             { max_value } else { v }  
6     };  
7     dbg!(clamp(1));  
8     dbg!(clamp(3));  
9     dbg!(clamp(5));  
10    dbg!(clamp(7));  
11 }
```

(playground link)

By default, a closure captures values by immutable reference. Here `max_value` is captured by `clamp`, but still available to `main` for printing.

Try making `max_value` mutable, changing it, and printing the clamped values again. Why doesn't this work?

The closure captures by reference. No mutable borrow may coexist with an immutable borrow.

## 6.2. Capturing

### 6.2.2. Mutable capture

```
1 fn main() {  
2     let mut max_value = 5;  
3     let mut clamp = |v| {  
4         max_value += 1;  
5         if v > max_value  
6             { max_value } else { v }  
7     };  
8     dbg!(clamp(1));  
9     dbg!(clamp(3));  
10    dbg!(clamp(5));  
11    dbg!(clamp(7));  
12    dbg!(clamp(10));  
13 }
```

*(playground link)*

If a closure mutates captured values, it captures them by mutable reference.

## 6.2. Capturing

### 6.2.2. Mutable capture

```
1 fn main() {  
2     let mut max_value = 5;  
3     let mut clamp = |v| {  
4         max_value += 1;  
5         if v > max_value  
6             { max_value } else { v }  
7     };  
8     dbg!(clamp(1));  
9     dbg!(clamp(3));  
10    dbg!(clamp(5));  
11    dbg!(clamp(7));  
12    dbg!(clamp(10));  
13 }
```

*(playground link)*

If a closure mutates captured values, it captures them by mutable reference.

Why does the closure need to be `mut`?

## 6.2. Capturing

### 6.2.2. Mutable capture

```
1 fn main() {  
2     let mut max_value = 5;  
3     let mut clamp = |v| {  
4         max_value += 1;  
5         if v > max_value  
6             { max_value } else { v }  
7     };  
8     dbg!(clamp(1));  
9     dbg!(clamp(3));  
10    dbg!(clamp(5));  
11    dbg!(clamp(7));  
12    dbg!(clamp(10));  
13 }
```

*(playground link)*

If a closure mutates captured values, it captures them by mutable reference.

Why does the closure need to be `mut`?

The closure's internal state changes, so it must be declared mutable.

## 6.2. Capturing

### 6.2.2. Mutable capture

```

1 fn main() {
2     let mut max_value = 5;
3     let mut clamp = |v| {
4         max_value += 1;
5         if v > max_value
6             { max_value } else { v }
7     };
8     dbg!(clamp(1));
9     dbg!(clamp(3));
10    dbg!(clamp(5));
11    dbg!(clamp(7));
12    dbg!(clamp(10));
13 }
```

*(playground link)*

If a closure mutates captured values, it captures them by mutable reference.

Why does the closure need to be `mut`?

The closure's internal state changes, so it must be declared mutable.

What happens if you try to access `max_value` directly while the closure exists?

## 6.2. Capturing

### 6.2.2. Mutable capture

```

1 fn main() {
2     let mut max_value = 5;
3     let mut clamp = |v| {
4         max_value += 1;
5         if v > max_value
6             { max_value } else { v }
7     };
8     dbg!(clamp(1));
9     dbg!(clamp(3));
10    dbg!(clamp(5));
11    dbg!(clamp(7));
12    dbg!(clamp(10));
13 }
```

*(playground link)*

If a closure mutates captured values, it captures them by mutable reference.

Why does the closure need to be `mut`?

The closure's internal state changes, so it must be declared mutable.

What happens if you try to access `max_value` directly while the closure exists?

Compile error: the closure holds a mutable borrow, preventing other accesses.

## 6.3. Moving

### 6.3.1. Move closures

```
1 fn main() {  
2     let name =  
3         String::from("Alice");  
4     let greet = move || {  
5         println!("Hello, {}", name);  
6     };  
7     greet();  
8     greet();  
9  
10    // println!("{}", name); //  
11    Error!  
11 }  
                           (playground link)
```

The `move` keyword forces a closure to take ownership of captured values.

## 6.3. Moving

### 6.3.1. Move closures

```
1 fn main() {  
2     let name =  
3         String::from("Alice");  
4     let greet = move || {  
5         println!("Hello, {}", name);  
6     };  
7     greet();  
8     greet();  
9  
10    // println!("{}", name); //  
11    Error!  
11 }  
                                (playground link)
```

The `move` keyword forces a closure to take ownership of captured values.

What happens if you uncomment the last line?

# 6.3. Moving

## 6.3.1. Move closures

```
1 fn main() {  
2     let name =  
3         String::from("Alice");  
4     let greet = move || {  
5         println!("Hello, {}", name);  
6     };  
7     greet();  
8     greet();  
9  
10    // println!("{}", name); //  
11    Error!  
11 }  
                           (playground link)
```

The `move` keyword forces a closure to take ownership of captured values.

What happens if you uncomment the last line?

Compile error: `name` was moved into the closure and can no longer be used.

## 6.3. Moving

## 6. Closures

### 6.3.1. Move closures

```
1 fn main() {  
2     let name =  
3         String::from("Alice");  
4     let greet = move || {  
5         println!("Hello, {}", name);  
6     };  
7     greet();  
8     greet();  
9  
10    // println!("{}", name); //  
11    Error!  
11 }          (playground link)
```

The `move` keyword forces a closure to take ownership of captured values.

What happens if you uncomment the last line?

Compile error: `name` was moved into the closure and can no longer be used.

Why can we call `greet()` multiple times?

# 6.3. Moving

## 6.3.1. Move closures

```
1 fn main() {  
2     let name =  
3         String::from("Alice");  
4     let greet = move || {  
5         println!("Hello, {}", name);  
6     };  
7     greet();  
8     greet();  
9  
10    // println!("{}", name); //  
11    Error!  
11 }  
                                (playground link)
```

The `move` keyword forces a closure to take ownership of captured values.

What happens if you uncomment the last line?

Compile error: `name` was moved into the closure and can no longer be used.

Why can we call `greet()` multiple times?

The closure owns `name`, which implements `Clone`, so it can be called repeatedly.

# 6.3. Moving

## 6.3.1. Move closures

```

1 fn main() {
2     let name =
3         String::from("Alice");
4     let greet = move || {
5         println!("Hello, {}", name);
6     };
7     greet();
8     greet();
9
10    // println!("{}", name); // Error!
11 }
```

*(playground link)*

The `move` keyword forces a closure to take ownership of captured values.

What happens if you uncomment the last line?

Compile error: `name` was moved into the closure and can no longer be used.

Why can we call `greet()` multiple times?

The closure owns `name`, which implements `Clone`, so it can be called repeatedly.

Common use case: passing closures to threads or async tasks that must outlive their parent scope.

## 6.4. Internal representation of closures

## 6. Closures

What category of types do closures belong to?

## 6.4. Internal representation of closures

What category of types do closures belong to?

anonymous types. Each closure has a unique, unnamed type generated by the compiler.

Closures are like structs with a function field:

1. Each captured variable is a reference field.
2. The closure body is a method that uses these fields.

For example, the closure `|x| x + offset` where `offset` is captured from the environment is represented as:

```
1 struct Closure {  
2     offset: &i32,  
3 }  
4  
5 impl Closure {  
6     fn call(&self, x: i32) -> i32 {  
7         x + *self.offset  
8     }  
9 }
```

(playground link)

## 6.4. Internal representation of closures

What category of types do closures belong to?

**anonymous types.** Each closure has a unique, unnamed type generated by the compiler.

Closures are like structs with a function field:

1. Each captured variable is a reference field.
2. The closure body is a method that uses these fields.

For example, the closure `|x| x + offset` where `offset` is captured from the environment is represented as:

```

1 struct Closure {
2     offset: &i32,
3 }
4
5 impl Closure {
6     fn call(&self, x: i32) -> i32 {
7         x + *self.offset
8     }
9 }
```

(playground link)

### Warning

The thing that sets closures apart is the hidden signature of the `call` method (whether it takes `&self` or not).

## 6.5. Datastructures containing functions

To store a closure in a data structure, we need to turn the anonymous closure type into generic type variable.

```
1 struct Processor<F> {
2     field: i32
3     func: F,
4 }
5
6 impl<F> Processor<F>
7 where
8     F: Fn(i32) -> i32,
9 {
10    fn process(&self) -> i32 {
11        (self.func)(self.field)
12    }
13 }
```

*(playground link)*

What does `Fn(i32) -> i32` mean here?

## 6.5. Datastructures containing functions

To store a closure in a data structure, we need to turn the anonymous closure type into generic type variable.

```
1 struct Processor<F> {
2     field: i32
3     func: F,
4 }
5
6 impl<F> Processor<F>
7 where
8     F: Fn(i32) -> i32,
9 {
10    fn process(&self) -> i32 {
11        (self.func)(self.field)
12    }
13 }
```

*(playground link)*

What does `Fn(i32) -> i32` mean here?

It's an **Fn-trait bound** (function trait bound) indicating that `F` must be a type that implements the `Fn` trait.

Always use generic **Fn trait bounds** for structs containing functions.

## 6.5. Datastructures containing functions

To store a closure in a data structure, we need to turn the anonymous closure type into generic type variable.

```

1 struct Processor<F> {
2     field: i32
3     func: F,
4 }
5
6 impl<F> Processor<F>
7 where
8     F: Fn(i32) -> i32,
9 {
10    fn process(&self) -> i32 {
11        (self.func)(self.field)
12    }
13 }                                (playground link)

```

What does `Fn(i32) -> i32` mean here?

It's an **Fn-trait bound** (function trait bound) indicating that `F` must be a type that implements the `Fn` trait.

**Always use generic Fn trait bounds for structs containing functions.**

### Warning

Do not turn your closure into a **function pointer** (`fn` type), even when the compiler suggests it!

Why are function pointers bad?

## 6.5. Datastructures containing functions

To store a closure in a data structure, we need to turn the anonymous closure type into generic type variable.

```

1 struct Processor<F> {
2     field: i32
3     func: F,
4 }
5
6 impl<F> Processor<F>
7 where
8     F: Fn(i32) -> i32,
9 {
10    fn process(&self) -> i32 {
11        (self.func)(self.field)
12    }
13 }                                (playground link)

```

What does `Fn(i32) -> i32` mean here?

It's an **Fn-trait bound** (function trait bound) indicating that `F` must be a type that implements the `Fn` trait.

**Always use generic Fn trait bounds for structs containing functions.**

### Warning

Do not turn your closure into a **function pointer** (`fn` type), even when the compiler suggests it!

Why are function pointers bad?

May need heap allocation. Cannot capture variables.



## 6.6. Closure traits

Please open demo file `session-2/examples/s2e5-closure-traits.rs` and play around with the code.

## 6.6. Closure traits

Closures have anonymous types that implement one or more of these traits:

## 6.6. Closure traits

Closures have anonymous types that implement one or more of these traits:

`FnOnce`

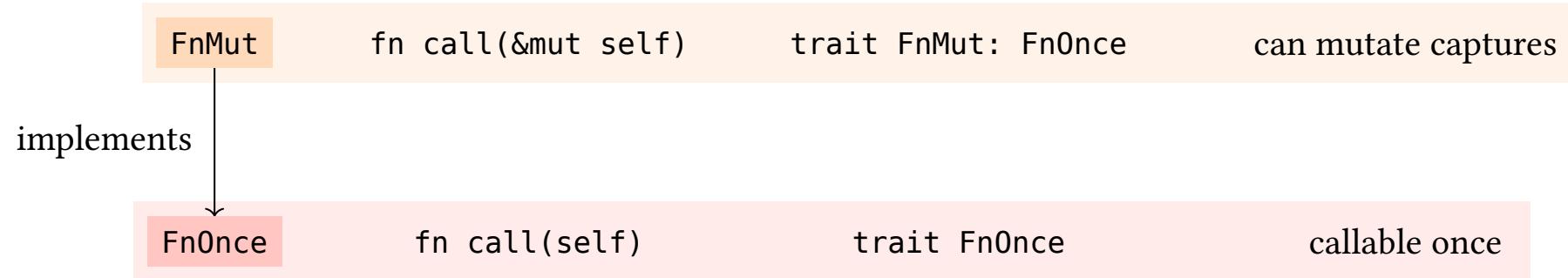
`fn call(self)`

`trait FnOnce`

`callable once`

## 6.6. Closure traits

Closures have anonymous types that implement one or more of these traits:



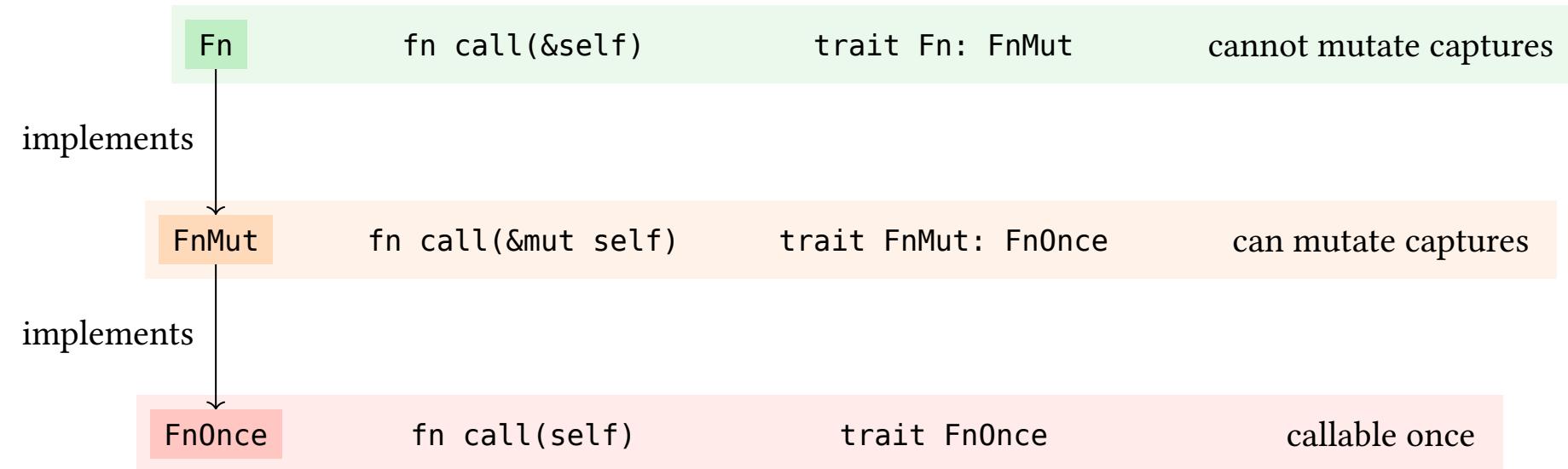
## 6.6. Closure traits

Closures have anonymous types that implement one or more of these traits:



## 6.6. Closure traits

Closures have anonymous types that implement one or more of these traits:

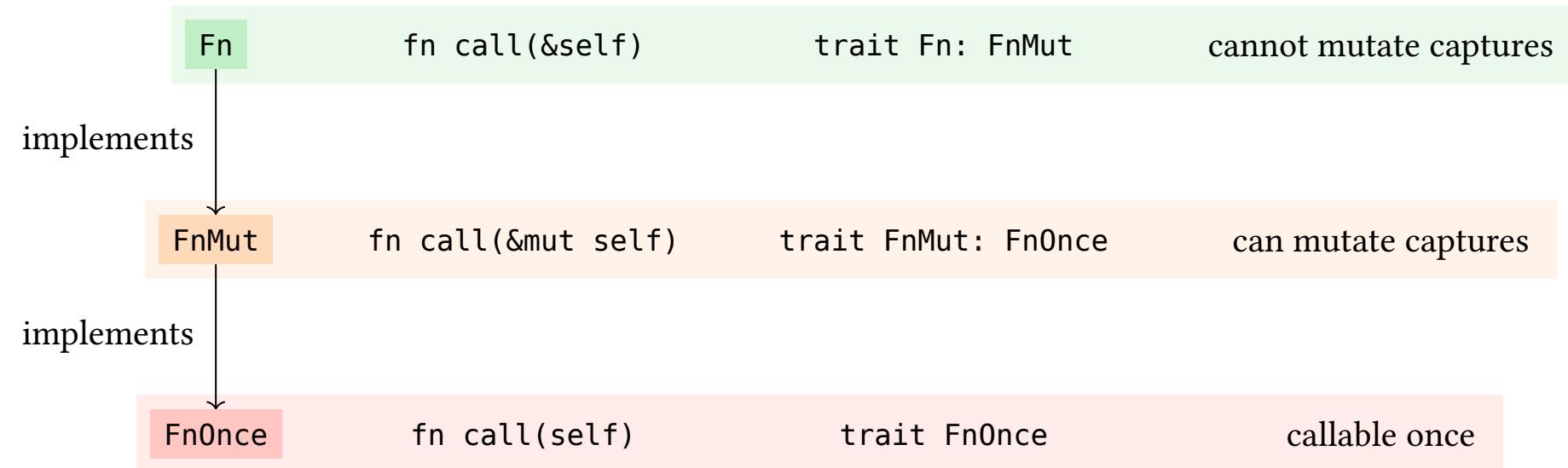


### Info

Trait hierarchy: Fn implements FnMut, FnMut implements FnOnce. A closure callable with &self can also be called with &mut self or self.

## 6.6. Closure traits

Closures have anonymous types that implement one or more of these traits:



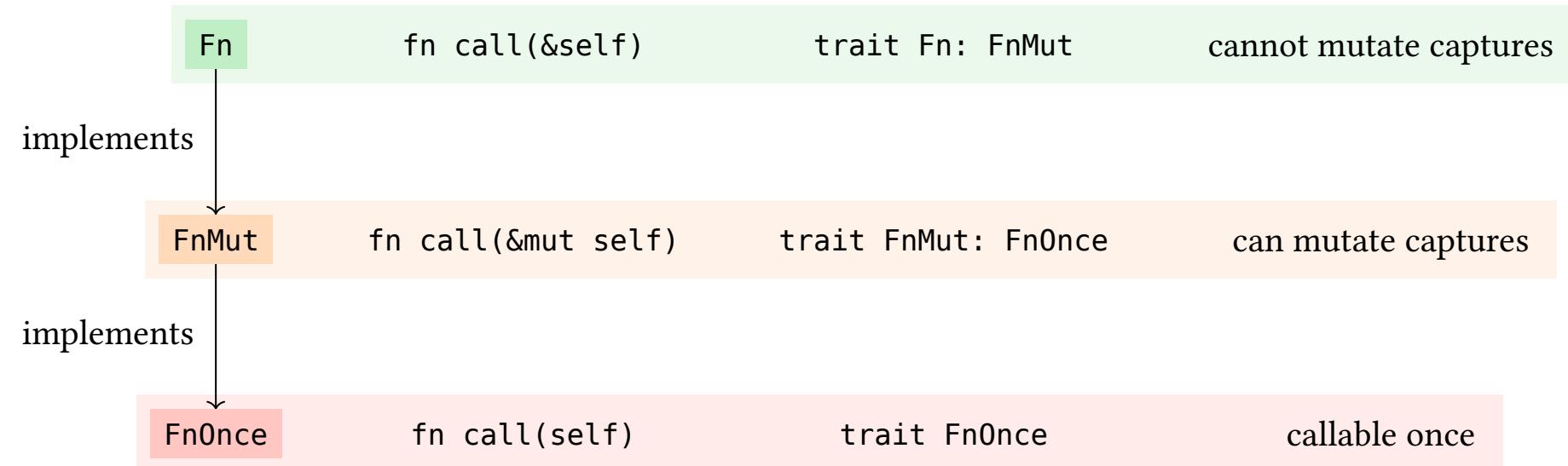
### Info

Trait hierarchy: Fn implements FnMut, FnMut implements FnOnce. A closure callable with &self can also be called with &mut self or self.

Can a closure implementing Fn be used where FnOnce is required?

## 6.6. Closure traits

Closures have anonymous types that implement one or more of these traits:



### Info

Trait hierarchy: Fn implements FnMut, FnMut implements FnOnce. A closure callable with &self can also be called with &mut self or self.

Can a closure implementing Fn be used where FnOnce is required?

Yes. Fn is a subtrait of FnMut, which is a subtrait of FnOnce.



## 6.7. Picking the right closure trait

You define a function accepting a closure (a higher-order function)

Which closure trait should use as a generic type trait bound?

## 6.7. Picking the right closure trait

You define a function accepting a closure (a higher-order function)

Which closure trait should use as a generic type trait bound?

Prefer FnOnce (accepts any closure type).

Why?

## 6.7. Picking the right closure trait

You define a function accepting a closure (a higher-order function)

Which closure trait should use as a generic type trait bound?

Prefer FnOnce (accepts any closure type).

Why?

Fn and FnMut both implement FnOnce, so all closures can be passed. Most flexible for callers.

## 6.7. Picking the right closure trait

You define a function accepting a closure (a higher-order function)

Which closure trait should use as a generic type trait bound?

Prefer FnOnce (accepts any closure type).

Why?

Fn and FnMut both implement FnOnce, so all closures can be passed. Most flexible for callers.

```
1 fn apply_once<F: FnOnce(i32) -> i32>(f: F, value: i32) -> i32 {  
2     f(value)  
3 }  
4  
5 fn main() {  
6     apply_once(|n| n + 1, 5);          // Fn works  
7     apply_once(move |n| n * 2, 5);    // FnOnce works  
8 }
```

(playground link)

## 6.7. Picking the right closure trait

You have to provide a closure for someone else's higher-order function

Which closure trait should your closure implement?

## 6.7. Picking the right closure trait

You have to provide a closure for someone else's higher-order function

Which closure trait should your closure implement?

Aim for Fn if possible, fall back to FnMut or FnOnce if needed.

Why?

## 6.7. Picking the right closure trait

You have to provide a closure for someone else's higher-order function

Which closure trait should your closure implement?

Aim for Fn if possible, fall back to FnMut or FnOnce if needed.

Why?

Fn closures work wherever FnMut or FnOnce is required, giving maximum usability.

Think of receiver types: &self (Fn) works where &mut self (FnMut) or self (FnOnce) is needed.

## 6.7. Picking the right closure trait

You have to provide a closure for someone else's higher-order function

Which closure trait should your closure implement?

Aim for Fn if possible, fall back to FnMut or FnOnce if needed.

Why?

Fn closures work wherever FnMut or FnOnce is required, giving maximum usability.

Think of receiver types: &self (Fn) works where &mut self (FnMut) or self (FnOnce) is needed.

```

1 fn process<F: Fn(i32) -> i32>(items: &[i32], f: F) {
2     for item in items {
3         println!("{}", f(*item)); // Requires Fn: called multiple times
4     }
5 }
6
7 fn main() {
8     process(&[1, 2, 3], |x| x * 2); // Fn: OK (no mutation)
9     // let mut c = 0;
10    // process(&[1, 2, 3], |x| { c += 1; x }); // FnMut: Error!
11 }
```

(playground link)



What are auto-traits?

What are auto-trait?

Traits that the compiler can automatically implement for types based on their structure.

Closures automatically implement `Copy` and `Clone` based on captured values:

What are auto-traits?

Traits that the compiler can automatically implement for types based on their structure.

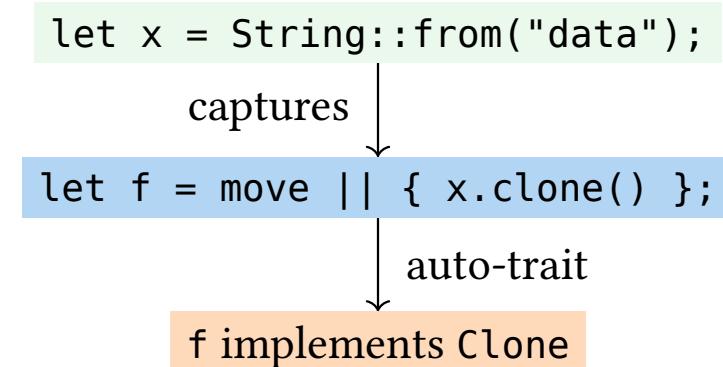
Closures automatically implement `Copy` and `Clone` based on captured values:

```
let x = String::from("data");
      captures ↓
let f = move || { x.clone() };
```

What are auto-traits?

Traits that the compiler can automatically implement for types based on their structure.

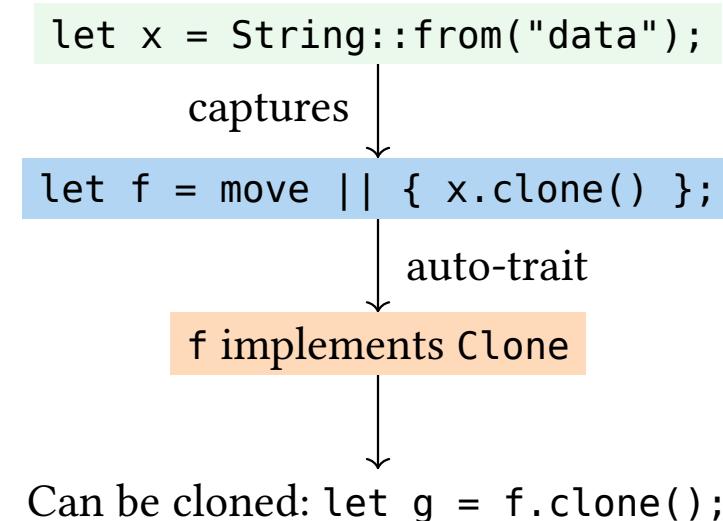
Closures automatically implement `Copy` and `Clone` based on captured values:



What are auto-traits?

Traits that the compiler can automatically implement for types based on their structure.

Closures automatically implement `Copy` and `Clone` based on captured values:

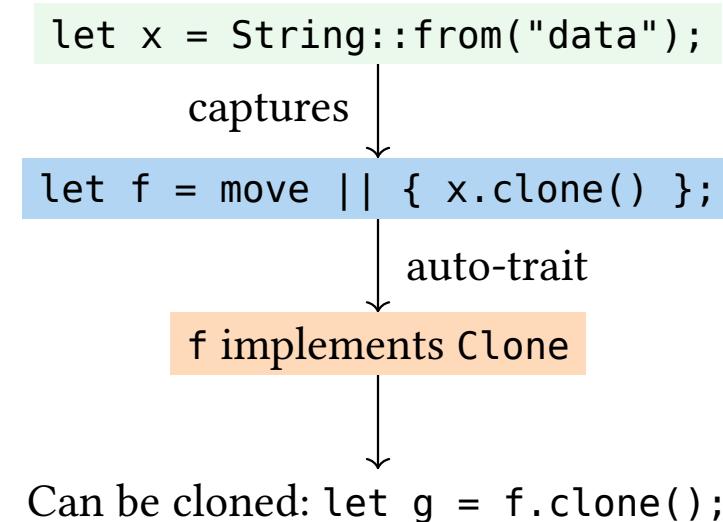


## 6.8. Auto-traits of closures

What are auto-traits?

Traits that the compiler can automatically implement for types based on their structure.

Closures automatically implement `Copy` and `Clone` based on captured values:



Info

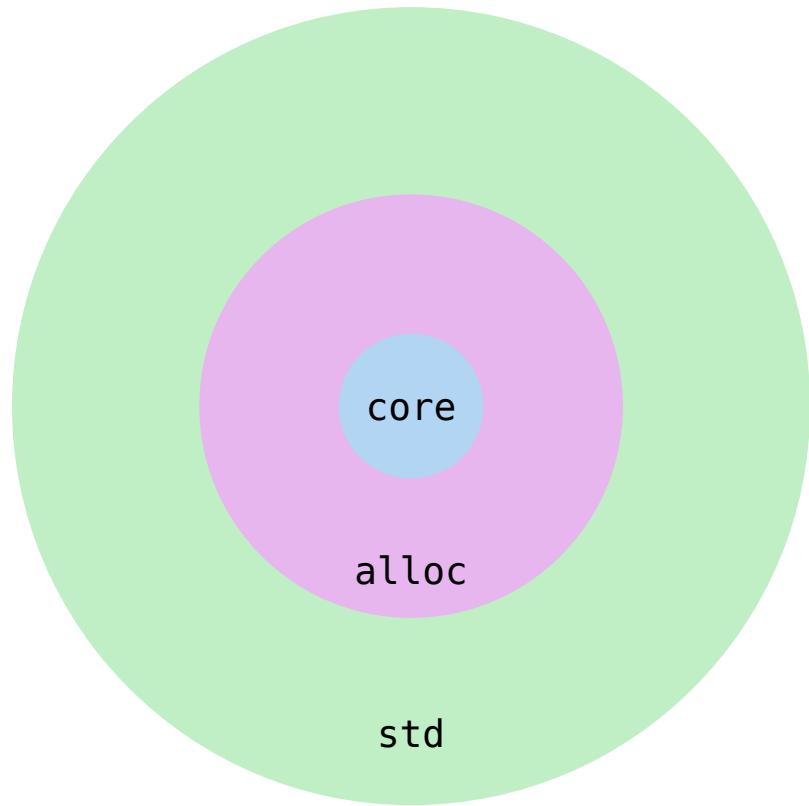
Closures inherit properties from the values they capture.

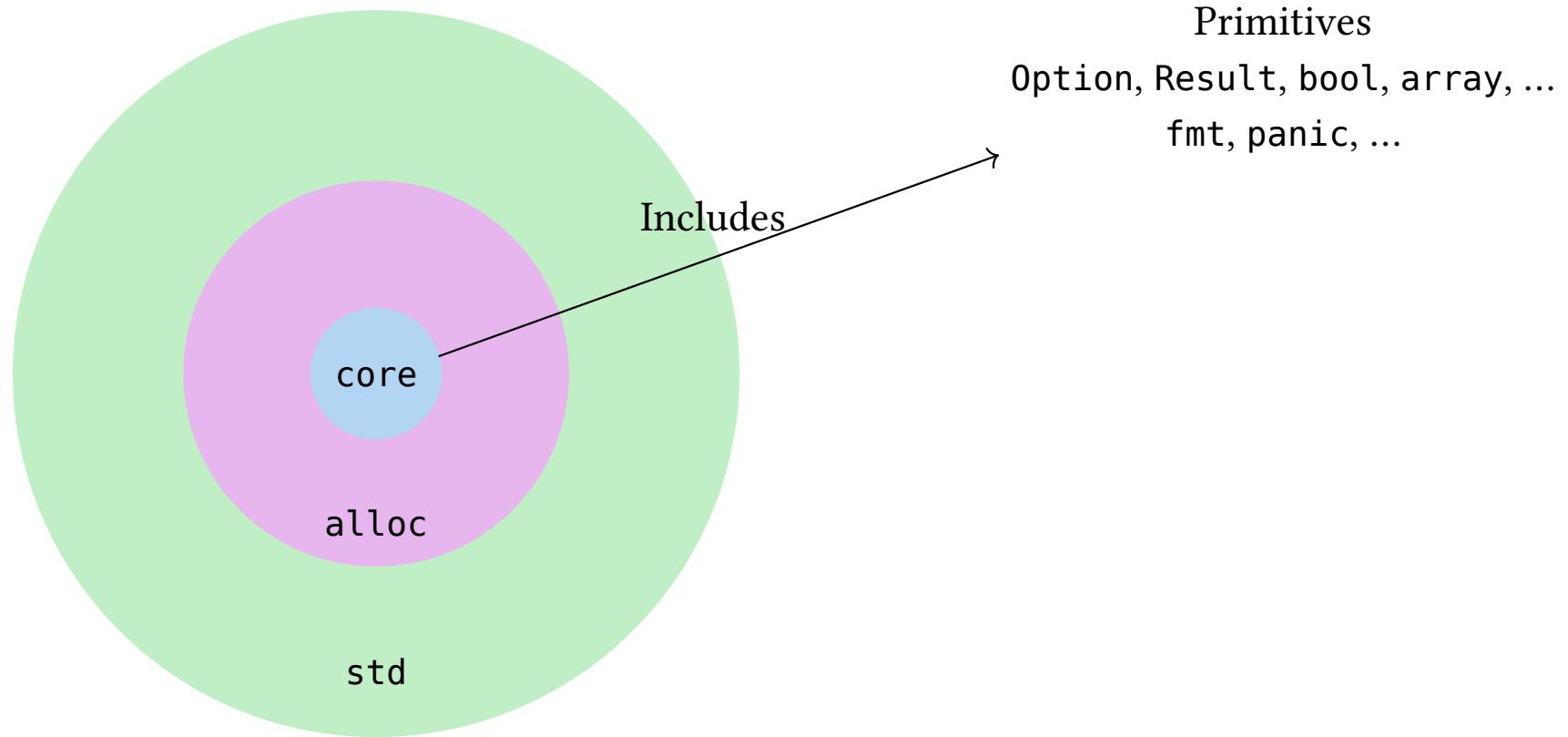
## 6.9. Exercise

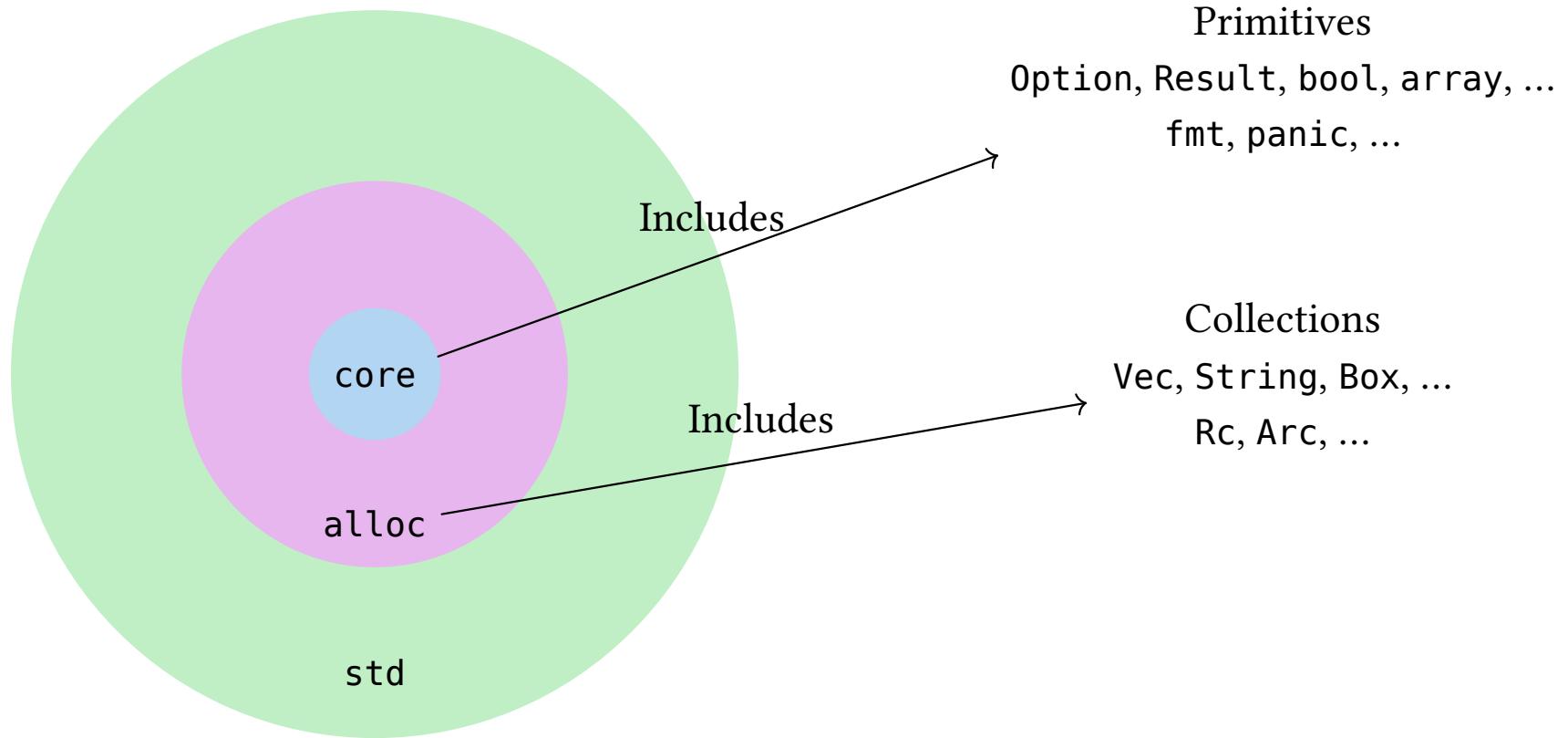
Please find the statement of the exercise at `session-2/examples/s2d6-closures.rs` in this repo.

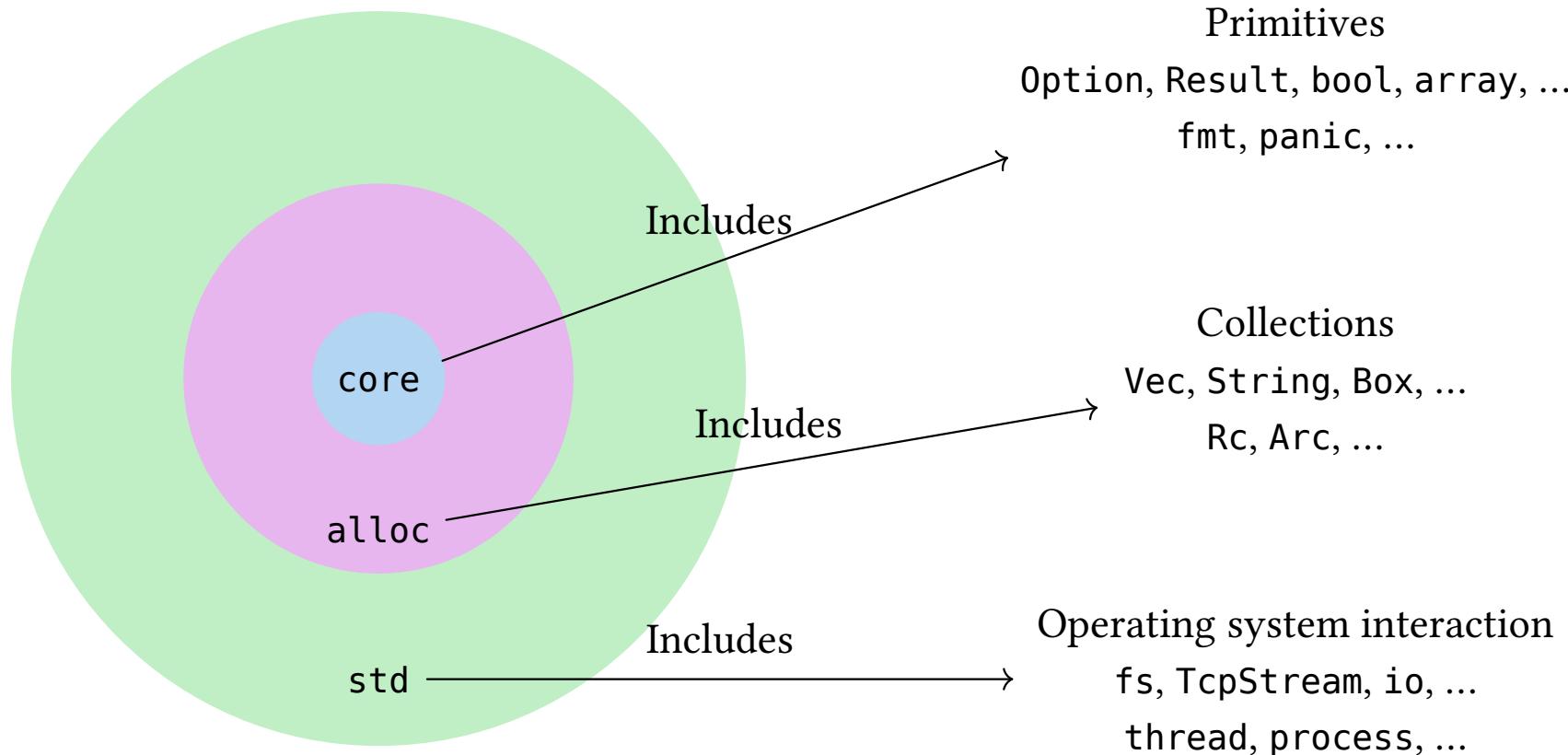
Run it with `cargo run --example s2d6-closures`.

1.	Quiz about last lecture .....	1
2.	Pattern matching .....	8
3.	Tooling intermezzo .....	23
4.	Methods and traits .....	27
5.	Generics .....	43
6.	Closures .....	63
<b>7.</b>	<b>Standard library types .....</b>	<b>76</b>
7.1.	Overview .....	77
7.2.	Documentation resources .....	79
7.3.	Creating documentation .....	80
7.4.	The Option type .....	84
7.5.	Result type .....	91
7.6.	Heap allocation .....	93
7.7.	String .....	94
7.8.	Vec type .....	97
7.9.	Exercise .....	98
8.	Conclusion .....	99









It is good style to prefer the minimal amount of imports:

- If it is available in `core`, use that
- Else, if it is available in `alloc`, use that
- Else, use `std`

It is good style to prefer the minimal amount of imports:

- If it is available in `core`, use that
- Else, if it is available in `alloc`, use that
- Else, use `std`

What would be a practical way to enforce this?

## 7.1. Overview

It is good style to prefer the minimal amount of imports:

- If it is available in `core`, use that
- Else, if it is available in `alloc`, use that
- Else, use `std`

What would be a practical way to enforce this?

Forbid certain lints in your `Cargo.toml` file.

```
1 [lints.clippy]
2 alloc_instead_of_core = "deny"
3 std_instead_of_alloc = "deny"
4 std_instead_of_core = "deny"
```

*(playground link)*

Locally:

- `rustup doc --std` (opens standard library docs)
- `cargo doc --open`
- `cargo doc --open --no-deps` (only your code)

Try these commands out!

Locally:

- `rustup doc --std` (opens standard library docs)
- `cargo doc --open`
- `cargo doc --open --no-deps` (only your code)

Try these commands out!

Online:

- <https://doc.rust-lang.org/stable/std/>
- <https://std.rs>

### 7.3.1. Function documentation

You can add “doc-comments” to your code using triple slashes `///`:

```
1 /// Determine whether the first argument is divisible by the second argument.  
2 ///  
3 /// If the second argument is zero, the result is false.  
4 fn is_divisible_by(lhs: u32, rhs: u32) -> bool {  
5     if rhs == 0 {  
6         return false;  
7     }  
8     lhs % rhs == 0  
9 }
```

(playground link)

Will be shown when you run `cargo doc --open` (or hover over the function in your editor).

### 7.3.2. More doc-comment positions

Enum variants and struct fields can be documented too:

```
1 /// A simple enum.  
2 enum MyEnum {  
3     /// The first variant.  
4     VariantA,  
5     /// The second variant.  
6     VariantB,  
7 }
```

(playground link)

### 7.3.3. Documenting modules

To document the module containing the current definition, use `//!` comments at the top of the file:

```
1 //! This module contains utility functions for mathematical operations.  
2 pub fn add(a: i32, b: i32) -> i32 {  
3     a + b  
4 }
```

(playground link)

All text in `///` or `//!` comments supports Markdown.

You can even **write unit tests in doc-comments** that are checked when you run `cargo test`!

```
1 /// Adds two numbers together.  
2 ///  
3 /// # Examples  
4 /// ``  
5 /// let sum = add(2, 3);  
6 /// assert_eq!(sum, 5);  
7 /// ``
```

(playground link)

### 7.3.4. Demonstration

Every library that you publish receive automatic documentation on `docs.rs`.

See for example:

- [https://docs.rs/clone-stream/0.4.0/clone\\_stream/](https://docs.rs/clone-stream/0.4.0/clone_stream/)
- <https://docs.rs/rand/latest/rand/>

Every public crate has a link to the documentation.

## 7.4. The Option type

## 7. Standard library types

Option is part of core and represents an optional value:

```
1 fn main() {  
2     let name = "Löwe 老虎 Léopard Gepardi";  
3     let mut position: Option<usize> = name.find('é');  
4     dbg!(position);  
5     assert_eq!(position.unwrap(), 14);  
6     position = name.find('Z');  
7     dbg!(position);  
8     assert_eq!(position.expect("Character not found"), 0);  
9 }
```

(playground link)

`String::find` returns `Option`. Unwrapping an `Option` that is `None` **will cause a panic**.

Is it possible to forget handling a `None` case?

## 7.4. The Option type

## 7. Standard library types

Option is part of core and represents an optional value:

```
1 fn main() {  
2     let name = "Löwe 老虎 Léopard Gepardi";  
3     let mut position: Option<usize> = name.find('é');  
4     dbg!(position);  
5     assert_eq!(position.unwrap(), 14);  
6     position = name.find('Z');  
7     dbg!(position);  
8     assert_eq!(position.expect("Character not found"), 0);  
9 }
```

(playground link)

`String::find` returns `Option`. Unwrapping an `Option` that is `None` **will cause a panic**.

Is it possible to forget handling a `None` case?

No, the compiler forces you to handle both cases.

## 7.4.1. Use cases for Option

Option is really about data or information that might be absent.

**Warning**

The `Option::None` variant should **not replace every null value in other languages!**

In most cases, you should declare a custom enum:

```
1 enum LoginResult {  
2     Success(UserData),  
3     InvalidPassword,  
4     UserNotFound,  
5 }
```

(playground link)

Why would it be better to use a custom enum instead of `Option<UserData>`?

## 7.4. The Option type

### 7.4.1. Use cases for Option

Option is really about data or information that might be absent.

#### Warning

The `Option::None` variant should **not replace every null value in other languages!**

In most cases, you should declare a custom enum:

```
1 enum LoginResult {  
2     Success(UserData),  
3     InvalidPassword,  
4     UserNotFound,  
5 }
```

(playground link)

Why would it be better to use a custom enum instead of `Option<UserData>`?

A custom enum can provide more context about why the data is absent

### 7.4.2. Relationship bool and Option

The standard library API entangles `bool` and `Option` in interesting ways.

## 7.4.2. Relationship bool and Option

The standard library API entangles bool and Option in interesting ways.

bool::then() converts a boolean to an Option:

```
1 let is_valid = true;
2 assert_eq!(is_valid.then(|| 42), Some(42));
3
4 let is_invalid = false;
5 assert_eq!(is_invalid.then(|| 42), None);
```

(playground link)

## 7.4.2. Relationship bool and Option

The standard library API entangles bool and Option in interesting ways.

bool::then() converts a boolean to an Option:

```
1 let is_valid = true;
2 assert_eq!(is_valid.then(|| 42), Some(42));
3
4 let is_invalid = false;
5 assert_eq!(is_invalid.then(|| 42), None);
```

(playground link)

and() combines Options like boolean AND (&&):

```
1 let x = Some(2);
2 let y: Option<i32> = None;
3 assert_eq!(x.and(y), None); // Returns None if either is None
```

(playground link)

What is the “niche optimisation” in the context of Option?

What is the “niche optimisation” in the context of Option?

Certain types have unused bit patterns (niches) that can be used to represent None without extra space.

### 7.4.3. The actual machine representation

We'll use `transmute` to peek at the internal bit representation:

```
1 use std::mem::transmute;
2 macro_rules! dbg_bits {
3     ($e:expr, $bit_type:ty) => {
4         println!("- {}: {:#x}", stringify!($e), transmute::<_, $bit_type>($e));
5     };
6 }
```

(playground link)

For every expression, what is its bit representation (as a hexadecimal number)?

What is the “niche optimisation” in the context of Option?

Certain types have unused bit patterns (niches) that can be used to represent None without extra space.

### 7.4.3. The actual machine representation

We'll use `transmute` to peek at the internal bit representation:

```
1 use std::mem::transmute;
2 macro_rules! dbg_bits {
3     ($e:expr, $bit_type:ty) => {
4         println!("- {}: {:?}", stringify!($e), transmute::<_, $bit_type>($e));
5     };
6 }
```

(playground link)

For every expression, what is its bit representation (as a hexadecimal number)?

#### Warning

`transmute` is unsafe and reinterprets memory.

## 7.4. The Option type

### 7.4.4. Representation of bool and Option<bool>

```

1 unsafe {
2     println!("bool:");
3     dbg_bits!(false, u8);
4     dbg_bits!(true, u8);
5
6     println!("Option<bool>:");
7     dbg_bits!(None::<bool>, u8);
8     dbg_bits!(Some(false), u8);
9     dbg_bits!(Some(true), u8);
10 }                                (playground link)

```

Expected output:

```

1 bool:
2 - false: 0x0
3 - true: 0x1
4 Option<bool>:
5 - None::<bool>: 0x2
6 - Some(false): 0x0
7 - Some(true): 0x1      (playground link)

```

#### Info

Option<bool> uses 0x2 for None, allowing all three states in 1 byte!

## 7.4. The Option type

## 7. Standard library types

### 7.4.5. Representation of Option<Option<bool>>

```
1 unsafe {
2     println!("Option<Option<bool>>:");
3     dbg_bits!(Some(Some(false)), u8);
4     dbg_bits!(Some(Some(true)), u8);
5     dbg_bits!(Some(None::<bool>), u8);
6     dbg_bits!(None::<Option<bool>>, u8);
7 }
8
9
10 (playground link)
```

Expected output:

```
1 Option<Option<bool>>:
2 - Some(Some(false)): 0x0
3 - Some(Some(true)): 0x1
4 - Some(None::<bool>): 0x2
5 - None::<Option<bool>>: (0x3 playground link)
```

Info

Four distinct states, still fitting in just 1 byte!

## 7.4. The Option type

### 7.4.6. Option<&i32> and null pointer optimization

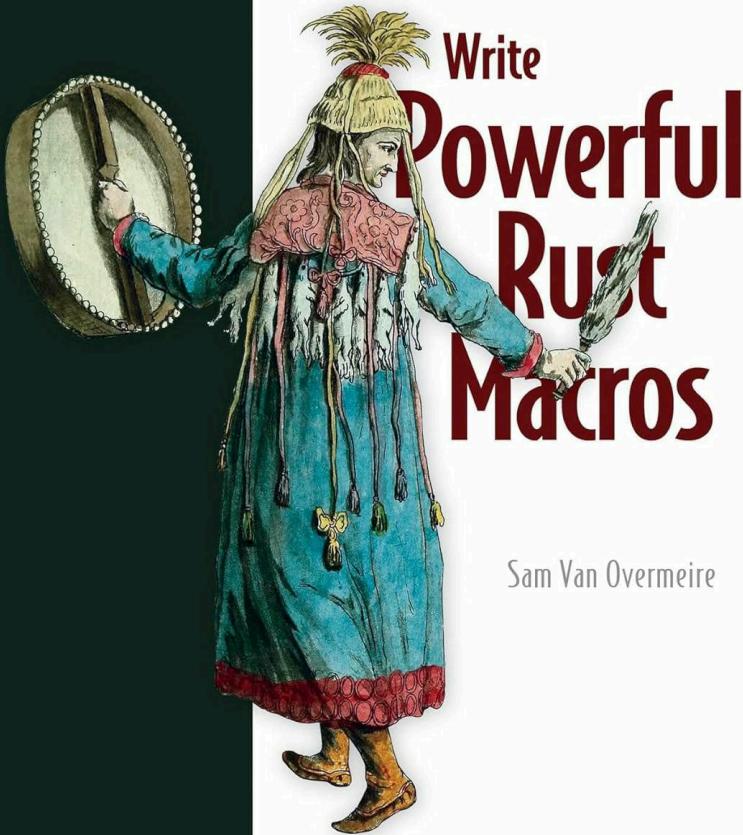
```
1 unsafe {
2     println!("Option<&i32>:");
3     dbg_bits!(None::<&i32>, usize);
4     dbg_bits!(Some(&0i32), usize);
5 }
6
7
8 (playground link)
```

Expected output (on 64-bit):

```
1 Option<&i32>:
2 - None::<&i32>: 0x0
3 - Some(&0i32): 0x7ffc8e4a1b2cground link)
```

**Info**

None is represented as null pointer (0x0), while Some contains the actual memory address. No extra space needed for the discriminant!



Write  
**Powerful  
Rust  
Macros**

Sam Van Overmeire

MANNING

```
1  use std::fs::File;
2  use std::io::Read;
3
4  fn main() {
5      let file: Result<File, std::io::Error> = File::open("diary.txt");
6      match file {
7          Ok(mut file) => {
8              let mut contents = String::new();
9              if let Ok(bytes) = file.read_to_string(&mut contents) {
10                  println!("Dear diary: {contents} ({bytes} bytes)");
11              } else {
12                  println!("Could not read file content");
13              }
14          }
15          Err(err) => {
16              println!("The diary could not be opened: {err}");
17          }
18      }
19 }
```

(playground link)

### 7.5.1. Interpretation

Result is similar to Option, but indicates the success or failure of an operation.

## 7.5. Result type

### 7.5.1. Interpretation

Result is similar to Option, but indicates the success or failure of an operation.

Result is generic: `Result<T, E>` where:

- T is used in the `Ok` variant and
- E appears in the `Err` variant.

#### Rule of thumb

Use `Result` instead of `Option` when the reason of failure needs different handling.

What do `Result` and `Option` have in common?

## 7.5. Result type

### 7.5.1. Interpretation

Result is similar to Option, but indicates the success or failure of an operation.

Result is generic: `Result<T, E>` where:

- T is used in the `Ok` variant and
- E appears in the `Err` variant.

#### Rule of thumb

Use `Result` instead of `Option` when the reason of failure needs different handling.

What do `Result` and `Option` have in common?

They **may short-circuit** the execution of a function.

What is the name for a object that has short-circuiting behaviour?

## 7.5. Result type

### 7.5.1. Interpretation

Result is similar to Option, but indicates the success or failure of an operation.

Result is generic: `Result<T, E>` where:

- T is used in the `Ok` variant and
- E appears in the `Err` variant.

#### Rule of thumb

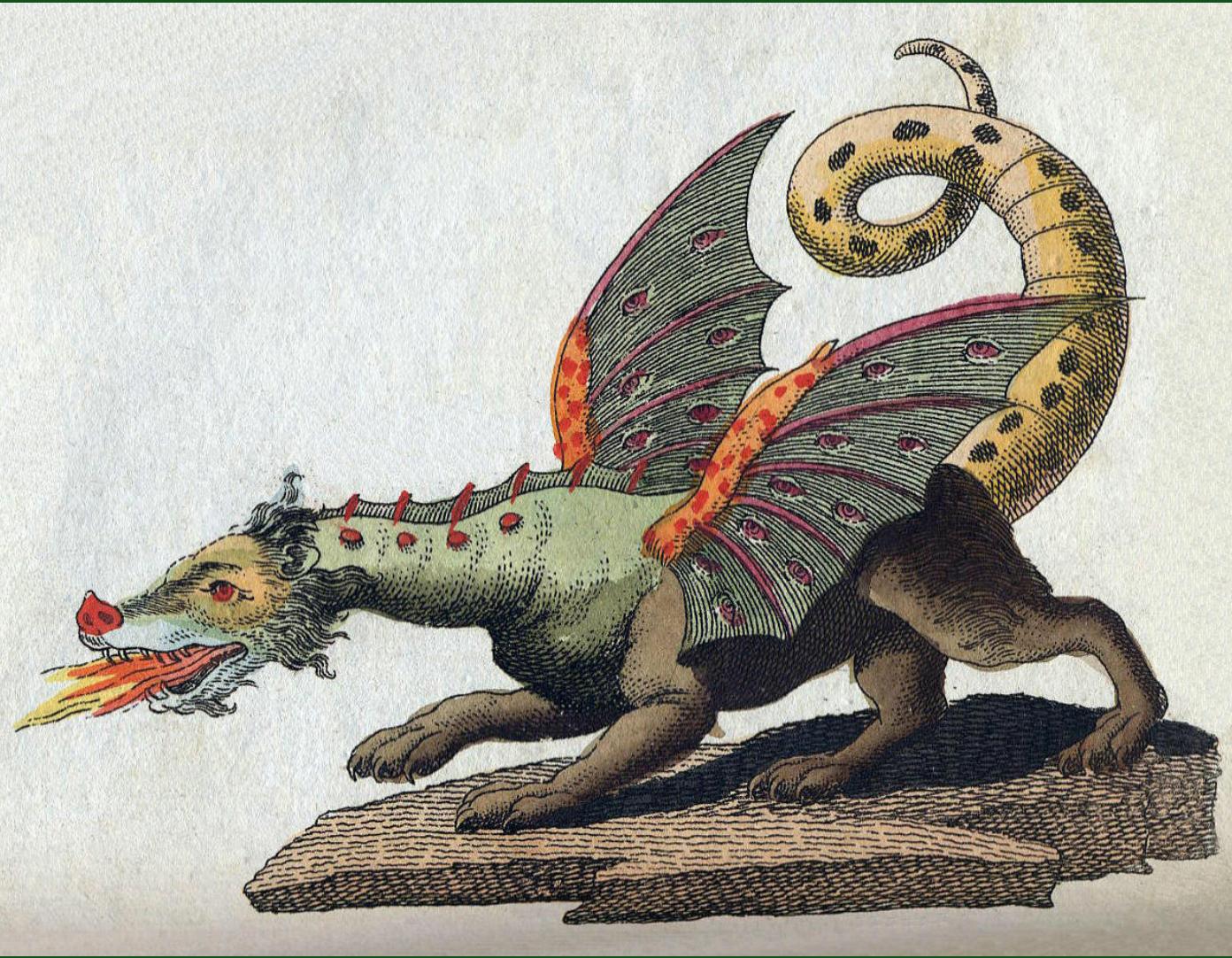
Use `Result` instead of `Option` when the reason of failure needs different handling.

What do `Result` and `Option` have in common?

They **may short-circuit** the execution of a function.

What is the name for a object that has short-circuiting behaviour?

A Monad.



## 7.6. Heap allocation

## 7. Standard library types

We have not yet done any heap allocation!

Why is stack allocation better than heap allocation?

## 7.6. Heap allocation

## 7. Standard library types

We have not yet done any heap allocation!

Why is stack allocation better than heap allocation?

Stack allocation is just a pointer increment (one CPU instruction), while heap allocation must search for free blocks and maintain bookkeeping data structures.

## 7.6. Heap allocation

## 7. Standard library types

We have not yet done any heap allocation!

Why is stack allocation better than heap allocation?

Stack allocation is just a pointer increment (one CPU instruction), while heap allocation must search for free blocks and maintain bookkeeping data structures.

### Warning

Heap allocation is not strictly required. In embedded, you would often use the heapless library crate.

String is a growable UTF-8 encoded string:

```
1 fn main() {  
2     let mut s1 = String::new();  
3     s1.push_str("Hello");  
4     println!("s1: len = {}, capacity = {}", s1.len(), s1.capacity());  
5  
6     let mut s2 = String::with_capacity(s1.len() + 1);  
7     s2.push_str(&s1);  
8     s2.push('!');  
9     println!("s2: len = {}, capacity = {}", s2.len(), s2.capacity());  
10  
11    let s3 = String::from("⊕");  
12    println!("s3: len = {}, number of chars = {}", s3.len(), s3.chars().count());  
13 }
```

(playground link)

How is `String` stored internally?

How is `String` stored internally?

Just a safe wrapper around a vector of bytes on the heap.

- `String::new` returns a new empty string, use `String::with_capacity` when you know how much data you want to push to the string.

How is `String` stored internally?

Just a safe wrapper around a vector of bytes on the heap.

- `String::new` returns a new empty string, use `String::with_capacity` when you know how much data you want to push to the string.
- `String::len` returns byte length (which can be different from its length in characters).

How is `String` stored internally?

Just a safe wrapper around a vector of bytes on the heap.

- `String::new` returns a new empty string, use `String::with_capacity` when you know how much data you want to push to the string.
- `String::len` returns byte length (which can be different from its length in characters).
- `String::chars` returns an iterator over the actual characters.

**Warning**

Note that a `char` can be different from what a human will consider a “character” due to grapheme clusters.

Most `String` methods are actually defined on the thing `String` “dereferences” to: `&str!`

Do you remember what `&str` is?

How is `String` stored internally?

Just a safe wrapper around a vector of bytes on the heap.

- `String::new` returns a new empty string, use `String::with_capacity` when you know how much data you want to push to the string.
- `String::len` returns byte length (which can be different from its length in characters).
- `String::chars` returns an iterator over the actual characters.

**Warning**

Note that a `char` can be different from what a human will consider a “character” due to grapheme clusters.

Most `String` methods are actually defined on the thing `String` “dereferences” to: `&str!`

Do you remember what `&str` is?

A string slice, a view into a UTF-8 encoded string stored elsewhere.

### 7.7.1. Creating strings

In practice, `String` instances are generated with the `to_string` or `into` method from compile-time static string slices:

```
1 let s1: String = "Hello, world!".to_string();
```

*(playground link)*

### 7.7.1. Creating strings

In practice, `String` instances are generated with the `to_string` or `into` method from compile-time static string slices:

```
1 let s1: String = "Hello, world!".to_string();
```

(playground link)

### 7.7.2. String interpolation

Always done with macros:

```
1 println!("s3: len = {}, number of chars = {}", s3.len(), s3.chars().count());
```

(playground link)

### 7.7.1. Creating strings

In practice, `String` instances are generated with the `to_string` or `into` method from compile-time static string slices:

```
1 let s1: String = "Hello, world!".to_string();
```

(playground link)

### 7.7.2. String interpolation

Always done with macros:

```
1 println!("s3: len = {}, number of chars = {}", s3.len(), s3.chars().count());
```

(playground link)

Try to use macros that do not allocate new string buffers like `write!`:

```
1 use std::fmt::Write;
2 let mut buffer = String::with_capacity(50);
3 write!(&mut buffer, "s3: len = {}, number of chars = {}", s3.len(),
       s3.chars().count()).unwrap();
```

(playground link)

The `Display` trait uses `write!` to display printable data. (A bit like `repr` in Python.)

## 7.8. Vec type

This is **heap allocated** and almost the same as `String` but:

- without UTF grapheme cluster limitations
- with arbitrary data types

## 7.8. Vec type

This is **heap allocated** and almost the same as `String` but:

- without UTF grapheme cluster limitations
- with arbitrary data types

Example of the heapless version (not essential for this course):

```
1 use heapless::Vec; // fixed capacity `std::Vec`  
2  
3 // on the stack  
4 let mut xs: Vec<u8, 8> = Vec::new(); // can hold up to 8 elements  
5 xs.push(42)?;  
6 assert_eq!(xs.pop(), Some(42));
```

(playground link)

Note that we need a compile-time `const` upper-bound on the storage size (8).

## 7.9. Exercise

## 7. Standard library types

Please solve exercise session-2/examples/s2d8-counter.rs

1.	Quiz about last lecture .....	1
2.	Pattern matching .....	8
3.	Tooling intermezzo .....	23
4.	Methods and traits .....	27
5.	Generics .....	43
6.	Closures .....	63
7.	Standard library types .....	76
<b>8.</b>	<b>Conclusion .....</b>	<b>99</b>

## Homework:

- study the standard library API and helper functions of `Result`
- study standard library traits
- (optional) read the `unsafe` chapter of Blandy and discussion about making safe buffer

## Questions?

Feel free to contact me:

- Video meeting / email: [willemvanhulle@protonmail.com](mailto:willemvanhulle@protonmail.com)
- Phone: +32 479 080 252