Lecture 06

Lifetimes, Closures

PLQ Questions

Enforcing Invariants

How can we guarantee that a `String` always represents valid UTF-8?

The compiler cannot enforce “everything” at compile time (due to Rice’s thm.), therefore we must “trust” library developers to write correct code (in this case, we can trust the standard library developers).

Correct ≠ “Safe” (many examples)

We guarantee that **invariants** are upheld by using private members for the purposes of encapsulation.

Many APIs expose “unsafe” methods which potentially break these invariants.

UTF-8 String Example

Strings are “actually” stored as a `Vec<u8>`, but that’s hidden to the user. Each “character” is **variable width**.

character	encoding	bits
A	UTF-8	01000001
A	UTF-16	00000000 01000001
A	UTF-32	00000000 00000000 00000000 01000001
あ	UTF-8	11100011 10000001 10000010
あ	UTF-16	00110000 01000010
あ	UTF-32	00000000 00000000 00110000 01000010

```rust
/// ... a bunch of documentation ...
#[derive(PartialEq, PartialOrd, Eq, Ord)]
#[stable(feature = "rust1", since = "1.0.0")]
#[lang = "String"]
pub struct String {
    vec: Vec<u8>,
}
```


Standard library: string.rs

Notably Rust doesn’t support indexing into a string, since the i^{th} index doesn’t necessarily correspond to the i^{th} character (or even a *valid* character).

Randomized Testing?

Yes! There is actually a Rust version of the QuickCheck library.

The proptest crate also offers similar functionality.

```
fn reverse<T: Clone>(xs: &[T]) -> Vec<T> {
    let mut rev = vec![];
    for x in xs.iter() {
        rev.insert(0, x.clone())
    }
    rev
}

#[cfg(test)]
mod tests {
    use quickcheck::quickcheck;
    use super::reverse;

    quickcheck! {
        fn prop(xs: Vec<u32>) -> bool {
            xs == reverse(&reverse(&xs))
        }
    }
}
```

Working around the Orphan Trait Rule

A common way to “work around” the Orphan Trait Rule is by a design pattern known as “extension traits”.

In this example, we implement new functionality for `i32`, which is not allowed directly.

Often times you will see the trait name suffixed by `Ext`, meaning “extension”.

The orphan issue is solved. Why?

```
mod example {
    pub trait NumericConstantsExt {
        fn zero() -> Self;
        fn one() -> Self;
    }

    impl NumericConstantsExt for i32 {
        fn zero() -> Self { 0 }
        fn one() -> Self { 1 }
    }
}

mod user {
    use crate::example::NumericConstantsExt;

    fn test() {
        let zero = i32::zero();
    }
}
```

Working around the Orphan Trait Rule

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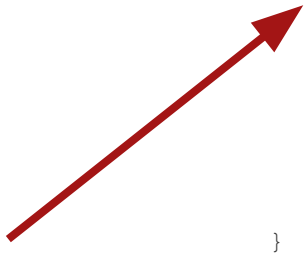
The orphan issue is solved. Why?

The user must explicitly import the trait…



```
mod example {
    pub trait NumericConstantsExt {
        fn zero() -> Self;
        fn one() -> Self;
    }

    impl NumericConstantsExt for i32 {
        fn zero() -> Self { 0 }
        fn one() -> Self { 1 }
    }
}

mod user {
    use crate::example::NumericConstantsExt;

    fn test() {
        let zero = i32::zero();
    }
}
```

How does `.iter()` work?

The Iterator type is actually a **trait**, which requires a single method. Each different "kind" of iterator is actually a **struct** which implements that trait.

This trait is implemented + optimized differently for every type that supports iteration.

```
// core/src/slice/iter.rs
pub struct Iter<'a, T: 'a> {
    ptr: NonNull<T>,
    end_or_len: *const T,
    _marker: PhantomData<&'a T>,
}
```

```
pub trait Iterator {
    type Item;

    // Required method
    fn next(&mut self) -> Option<Self::Item>;

    // A bunch of provided "helper" methods...
}
```

The actual implementations often make use of "unsafe" code for performance reasons. But generally, **no copy** is performed. Instead, the iterator struct *references* the base collection and stores some *metadata* (e.g. iteration index).

How does `.iter()` work?

The Iterator type is actually a **trait**, which requires a single method. Each different "kind" of iterator is actually a **struct** which implements that trait.

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    ptr: NonNull<T>,
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}
```

```
pub trait Iterator {
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Today: safety and performance

Why care about this?

Performance:

- Spend lots of time running user code
- Run it quickly

If we don't have this?

Safety:

None of

- null pointer deref
- use after free
- double free

Performance is only hard...

if you have to maintain safety

How to make safety easy?

Imagine Rust but without references

- All values are owned
- Every value is
  a. returned from a function, OR
  b. freed at the end of the function

At compile time, know exactly where to insert calls to `malloc()` and `free()`

- impossible to have dangling references

```rust
fn make_list() -> Vec<i32> {
    vec![0, 1, 2, 3]
    // vec is not deallocated, it's returned
}

fn main() {
    let l = make_list();
    // l is deallocated here
}
```

References are what make safety hard!

How to make safety hard?

Now consider references

- Regardless of language!

```c
void main() {
    // "owned" string
    char* name = malloc(8);
    memcpy(name, "cis1905", 8);

    // reference into string
    char* number = name + 3;
}
```

```rust
fn main() {
    let s = String::from("hello");
    let as_ref = &s;
    println!("{}", as_ref);
}
```

```java
public static void main(String[] args) {
    // "Owned" list of strings
    List<String> stringList = new ArrayList<>();
    stringList.add("Hello");
    stringList.add("World");

    // Reference to element of list
    String s = stringList.get(0);
}
```

How to make safety hard?

Now consider references

- Regardless of language!

```c
void main() {
    // "owned" string
    char* name = malloc(8);
    memcpy(name, "cis1905", 8);

    // reference into string
    char* number = name + 3;
}
```

What happens when a reference outlives the value it references?

- **Let the reference dangle**
- **Extend the life of the referenced value**

How to deal with reference outliving value?

Let the reference dangle

- Approach taken by C/C++
- Performance but no safety!

Extend the life of the referenced value

- Approach taken by Java/Python
- Safety but poor performance!
- (garbage collection)

Brief primer on garbage collection

Used in all languages that don't have `malloc/free`

Does `clients` get returned in the `db` or can it be freed at the end of setup? Impossible to know

How to know how long values live?

```
public static Database setup() {
    List<String> clients = new ArrayList<>{}
    clients.add("ClientA");
    clients.add("ClientB");

    List<Client> client_list = makeClients(clients);
    List<Orders> orders = makeOrders(client_list, orders);
    List<Invoice> invoices = makeInvoices(clients, orders);

    Database db = makeDatabase(orders, invoices, clients);

    return db;
}
```

Brief primer on garbage collection

Garbage collection:

1. Just put every value on the heap and don’t worry about freeing it
2. When you get low on memory, walk through every alive variable to find values that are still reachable.
3. Free any value that isn’t reachable

Brief primer on garbage collection

Garbage collection guarantees

- An in-use value will never be freed
- When a value is no longer accessible, it will *eventually* be freed

Developer never needs to free values 😊

Program periodically **stops** and all unused values are freed 😢

Modern garbage collectors are fast...

But manually managing your memory is (usually) faster

How to deal with reference outliving value?

Let the reference dangle

- Approach taken by C/C++
- Performance but no safety!

Extend the life of the referenced value

- Approach taken by Java/Python
- Safety but poor performance!
- (garbage collection)

Disallow compilation of program with dangling reference?

- All programs that compile are performant and safe
- But how?

Why can references dangle?

Where could the returned pointer point to?

- input argument `name`
- input argument `job`
- a local variable created during the function
- a global variable

Some of these make a dangling reference, some don't

- If the compiler is going to detect dangling references, it needs more information...

```
char* foo(char *name, char *job) {
    // implementation omitted
}
```

The same function but in Rust

Where could the returned pointer point to?

- input argument `name`
- input argument `job`
- a local variable created during the function
- a global variable

```rust
fn foo(name: &str, job: &str) -> &str {
    // implementation omitted
}
```

Need to tell compiler

```
error[E0106]: missing lifetime specifier
--> lecture.rs:1:34
  |
1 | fn foo(name: &str, job: &str) -> &str {
  |              ----       ----     ^ expected named lifetime parameter
  |
  = help: this function's return type contains a borrowed value, but the
signature does not say whether it is borrowed from `name` or `job`
```

The same function but in Rust

Where could the returned pointer point to?

- input argument `name`
- input argument `job`
- a local variable created during the function
- a global variable

Need to tell compiler

```
fn foo0<'a, 'b>(name: &'a str, job: &'b str) -> &'a str
```

```
fn foo1<'a, 'b>(name: &'a str, job: &'b str) -> &'b str
```

```
fn foo2(name: &str, job: &str) -> &'static str
```

```
fn foo3<'a>(name: &'a str, job: &'a str) -> &'a str
```

The same function but in Rust

Where could the returned pointer point to?

- input argument `name`
- input argument `job`
- a local variable created during the function
- a global variable

```
fn foo0<'a, 'b>(name: &'a str, job: &'b str) -> &'a str
```

```
fn foo1<'a, 'b>(name: &'a str, job: &'b str) -> &'b str
```

```
fn foo2(name: &str, job: &str) -> &'static str
```

Need to tell compiler

```
fn foo3<'a>(name: &'a str, job: &'a str) -> &'a str
```

Could be from `name` or `job`
(e.g. conditional)

The same function but in Rust

Where could the returned pointer point to?

- input argument `name`
- input argument `job`
- a local variable created during the function
- a global variable

```
fn foo0<'a, 'b>(name: &'a str, job: &'b str) -> &'a str
```

```
fn foo1<'a, 'b>(name: &'a str, job: &'b str) -> &'b str
```

```
fn foo2(name: &str, job: &str) -> &'static str
```

Need to tell compiler

```
fn foo3<'a>(name: &'a str, job: &'a str) -> &'a str
```

Types allow reasoning about how **functions** compose

Lifetimes allow reasoning about how **references** compose

How to read lifetimes

```
fn main() {
    let substring;
    if read_from_file {
        let s = read_to_string(file_path);
        substring = find(&s, "fn main");
    } else {
        substring = "no file provided";
    }
    println!("{}", substring)
}
```

```
// find substring `target` in `s`
fn find<'a, 'b>(s: &'a str, target: &'b str)
  -> &'a str
```

`find` takes

- a str `s` that lives for duration `'a`
- a str `target` that lives for duration `'b`

It returns a str that can live for up to duration `'a`

Is this program valid?
How do you know?

How to read lifetimes

```
fn main() {
    let substring;
    if read_from_file {
        let s = read_to_string(file_path);
        substring = find(&s, "fn main");
    } else {
        substring = "no file provided";
    }
    println!("{}", substring)
}
```

```
// find substring `target` in `s`
fn find<'a, 'b>(s: &'a str, target: &'b str)
  -> &'a str
```

`find` takes

- a str `s` that lives for duration `'a`
- a str `target` that lives for duration `'b`

```
error[E0597]: `s` does not live long enough
  |
4 |         let s = read_to_string(file_path);
  |             - binding `s` declared here
5 |         substring = find(&s, "fn main");
  |                          ^^ borrowed value does not live long enough
6 |     } else {
  |   - `s` dropped here while still borrowed
...
9 |     println!("{}", substring)
  |                    --------- borrow later used here
```

Appendix: find implementation

```
fn find<'a, 'b>(s: &'a str, target: &'b str) -> &'a str {
    for i in 0..s.len() {
        let snippet = &s[i..(i + target.len())];
        if snippet == target {
            return snippet;
        }
    }
    panic!("Not found");
}
```

Where do lifetimes come from?

```
fn main() {
    let substring;
    if read_from_file {
        let s = read_to_string(file_path);
        substring = find(&s, "fn main");
    } else {
        substring = "no file provided";
    }
    println!("{}", substring)
}
```

Lifetime:

- starts when a value can first be referred to*
- ends when a value can not be referred to*

Lifetimes are implicit

- Never explicitly declared by programmer

*variable lifetimes are complicated and usually you don't need to think too hard. As a rule of thumb, a variable's lifetime is equal to its scope.

Another lifetime example

```
fn main() {
    let s1 = String::from("foobar");
    let mut longest = s1.as_str();
    for i in 0..100 {
        let s2 = i.to_string();
        longest = longer(&s1, &s2);
    }
    println!("{}", longest);
}
```

```
fn longer<'a>(s1: &'a str, s2: &'a str)
  -> &'a str {
    if s1.len() > s2.len() {
        s1
    } else {
        s2
    }
}
```

Is it valid to call `longer` with s1 and s2 as arguments?

Another lifetime example

```
fn main() {
    let s1 = String::from("foobar");
    let mut longest = s1.as_str();
    for i in 0..100 {
        let s2 = i.to_string();
        longest = longer(&s1, &s2);
    }
    println!("{}", longest);
}
```

```
fn longer<'a>(s1: &'a str, s2: &'a str)
  -> &'a str {
    if s1.len() > s2.len() {
        s1
    } else {
        s2
    }
}
```

s1 lives *at least* duration ‘a
s2 lives *at least* duration ‘a
return value lives *at most* duration ‘a

One more lifetime example

```
const program_name: &str = "Theseus";

fn get_program_name() -> &str {
    program_name
}
```

Ok… but we don't have any lifetimes to use

```
error[E0106]: missing lifetime specifier
--> lecture.rs:3:26
  |
3 | fn get_program_name() -> &str {
  |                          ^ expected named lifetime parameter
```

One more lifetime example

```
const program_name: &str = "Theseus";

fn get_program_name() -> &'static str {
    program_name
}
```

Ok... but we don't have any lifetimes to use

`'static` lifetime: the lifetime of the entire program duration

Back to safety and performance

Safety goal: never have dangling references

Performance goal: avoid using garbage collection

Lifetime annotations enable the compiler to disallow programs that cause dangling references

- avoid garbage collection
- maintain safety

Advanced usage: lifetimes in structs

```
struct BookPage {
    number: u32,
    content: &str,
}
```

```
error[E0106]: missing lifetime specifier
--> lecture.rs:3:14
  |
3 |     content: &str,
  |              ^ expected named lifetime parameter
  |
```

Advanced usage: lifetimes in structs

Structs with references need to expose their lifetime parameter

```
struct BookPage<'a> {
    number: u32,
    content: &'a str,
}
```

```
fn later_page<'a>(p1: BookPage<'a>, p2: BookPage<'a>) -> BookPage<'a>
{
    if p1.number > p2.number {
        return p1;
    } else {
        return p2;
    }
}
```

References in structs are tricky: if you find yourself doing this make sure there isn't a better way

Final notes: lifetime elision

We've previously seen code like this. Why no lifetime annotations required?

```
fn prefix(s: &str) -> &str {
    &s[0..3]
}
```

In simple cases, the Rust compiler will infer lifetimes to make things easier

- If the return type is not a reference
- If the return type is a reference and only one input is a reference

https://doc.rust-lang.org/nomicon/lifetime-elision.html

Quiz

```
struct Foo<'a> {
   bar: &'a i32
}
fn baz(f: &Foo) -> &i32
{
    /* omitted */
}
```

Will this compile? If so, what lifetime annotations will be inferred?

Quiz

```
struct Foo<'a> {
   bar: &'a i32
}
fn baz<'a, 'b>(f: &'a Foo<'b>) -> &’??? i32
{
    /* omitted */
}
```

Will this compile? If so, what lifetime annotations will be inferred?

Two separate lifetimes in the input

- can’t infer output lifetime without ambiguity

Yes but… what if my code is too complicated?

What if I need mutable and immutable references at the same time?

What if I need to express reference logic but the compiler won't accept my lifetime annotations?

Rust does it's analysis at compile time when possible.
If you can't fit within those bounds, use built-in types that offload safety checks to run-time

Topic of next lecture

Anonymous Functions/Closures

Another side to performance

Can we allow high level programming patterns while maintaining performance?

```
let rainfall nums =
 nums |>
 take_while (fun x -> x != -999) |>
 filter (fun x -> x >= 0) |>
 mean
```

As a case study: higher-order list functions vs. loops

Iterators and lambdas

```rust
fn rainfall(nums: Vec<i32>) -> Option<f64> {
    let valid_nums: Vec<i32> = nums
        .into_iter()
        .take_while(|&x| x != -999)
        .filter(|&x| x >= 0)
        .collect();
    mean(valid_nums);
}
```

```
let rainfall nums =
 nums |>
 take_while (fun x -> x != -999) |>
 filter (fun x -> x >= 0) |>
 mean
```

How do we translate this to Rust?

- need iterator functions
- need anonymous functions

Iterators and lambdas

```
fn rainfall(nums: Vec<i32>) -> Option<f64> {
    let valid_nums: Vec<i32> = nums
        .into_iter()
        .take_while(|&x| x != -999)
        .filter(|&x| x >= 0)
        .collect();
    mean(valid_nums);
}
```

Anonymous functions

Iterator functions

```
let rainfall nums =
 nums |>
 take_while (fun x -> x != -999) |>
 filter (fun x -> x >= 0) |>
 mean
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How do we translate this to Rust?

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Iterators and lambdas

```
fn rainfall(nums: Vec<i32>) -> Option<f64> {
    let valid_nums: Vec<i32> = nums
        .into_iter()
        .take_while(|&x| x != -999)
        .filter(|&x| x >= 0)
        .collect();
    mean(valid_nums);
}
```

Anonymous functions

Iterator functions

Once you've called `iter`/`into_iter`/`iter_mut`, many iterator functions are available

- map
- filter
- fold
- take_while
- flat_map
- filter_map
- zip
- https://doc.rust-lang.org/std/iter/trait.Iterator.html

Iterators and lambdas

```
fn rainfall(nums: Vec<i32>) -> Option<f64> {
    let valid_nums: Vec<i32> = nums
        .into_iter()
        .take_while(|&x| x != -999)
        .filter(|&x| x >= 0)
        .collect();
    mean(valid_nums);
}
```

Anonymous functions

Iterator functions

What about these?

Once you've called `iter`/`into_iter`/`iter_mut`, many iterator functions are available

- map
- filter
- fold
- take_while
- flat_map
- filter_map
- zip
- https://doc.rust-lang.org/std/iter/trait.Iterator.html

Anonymous Functions

Allows defining short-lived functions

- Type annotations optional
- Abbreviated syntax
- Used frequently in iterator functions

```
fn  add_one_v1    (x: u32) -> u32 { x + 1 }
let add_one_v2 = |x: u32| -> u32 { x + 1 };
let add_one_v3 = |x|             { x + 1 };
let add_one_v4 = |x|               x + 1  ;
```

Closures

More than just a function

- can access values that are in scope when they're defined
- function + environment

```
fn add_num(v: &mut Vec<i32>, value: i32) {
  let my_fn = |x| {*x += value};
   v.iter_mut().for_each(my_fn);
}
```

Quiz(?)

Does this code compile?

```
fn take(v: Vec<i32>) {}

fn main() {
    let v = Vec::new();
    let my_fun = || { take(v) };
    my_fun();
    my_fun();
}
```

Quiz(?)

Does this code compile?

```
fn take(v: Vec<i32>) {}

fn main() {
    let v = Vec::new();
    let my_fun = || { take(v) };
    my_fun();
    my_fun();
}
```

function

```
note: closure cannot be invoked more than once because it moves
the variable `v` out of its environment
  |
5 |     let my_fun = || take(v);
  |
```

Tricky closures

Three different traits that govern functions

- `Fn` -> immutable access to environment
- `FnMut` -> mutable access to environment
- `FnOnce` -> moves values out of environment

```
fn main() {
    let mut v = Vec::new();
    let impls_fn = || { println!("{}", v)
};

    let impls_fnmut = || { v.push(1)   }

    let impls_fnonce = || { take(v) };
}
```

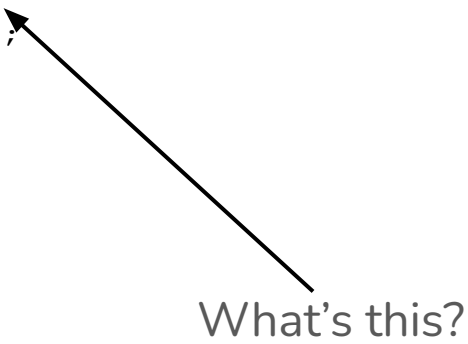
Noticing a pattern? Behavior changes based on

- reference
- mutable reference
- owned value

Keeping these cases separate gives the Rust compiler enough info to check many things at compile time

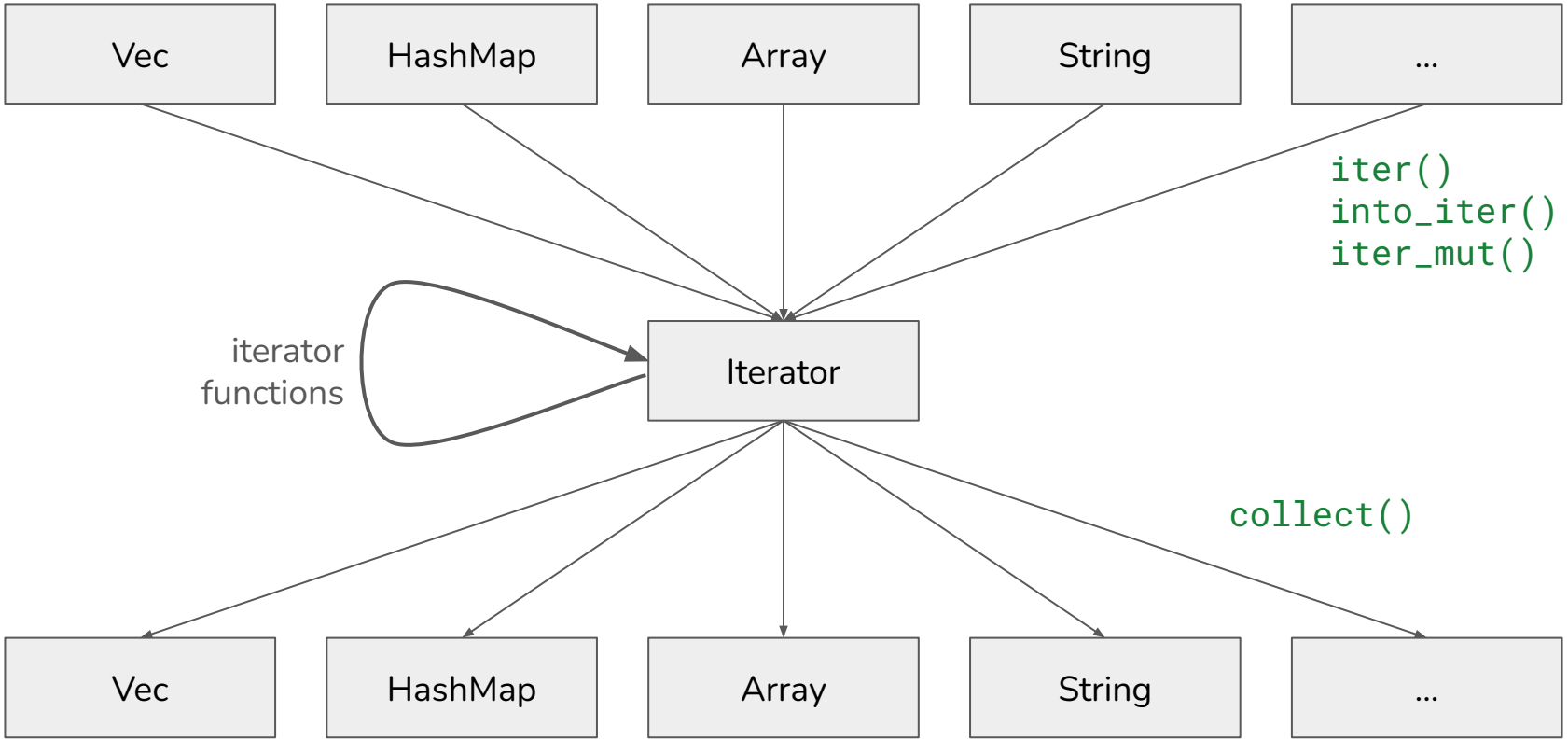
Iterators and lambdas

```
fn rainfall(nums: Vec<i32>) -> Option<f64> {
    let valid_nums: Vec<i32> = nums
        .into_iter()
        .take_while(|&x| x != -999)
        .filter(|&x| x >= 0)
        .collect();
    mean(valid_nums);
}
```



What's this?

Collect: turning iterators back to collections



Loops vs. Iterators: rainfall performance

```rust
fn iter(v: &Vec<i32>) -> f32 {
    let valid_nums: Vec<i32> = v
        .iter()
        .take_while(|&&x| x != -999)
        .cloned()
        .filter(|&x| x >= 0)
        .collect();
    if valid_nums.len() == 0 {
        0.0
    } else {
        valid_nums.iter().fold(0, |n, &a| n + a)
as f32 / valid_nums.len() as f32
    }
}
```

```rust
fn loops(v: &Vec<i32>) -> f32 {
    let mut valid_nums = Vec::new();
    for x in v {
        match x {
            -999 => break,
            &x if x >= 0 => valid_nums.push(x),
            _ => {}
        };
    }
    if valid_nums.len() == 0 {
        0.0
    } else {
        valid_nums.iter().fold(0, |n, &a| n + a)
as f32 / valid_nums.len() as f32
    }
}
```

https://doc.rust-lang.org/book/ch13-04-performance.html

Appendix: comparing generated code

Comparing generated code when using loops vs iterators

https://godbolt.org/z/qePhnhzvY