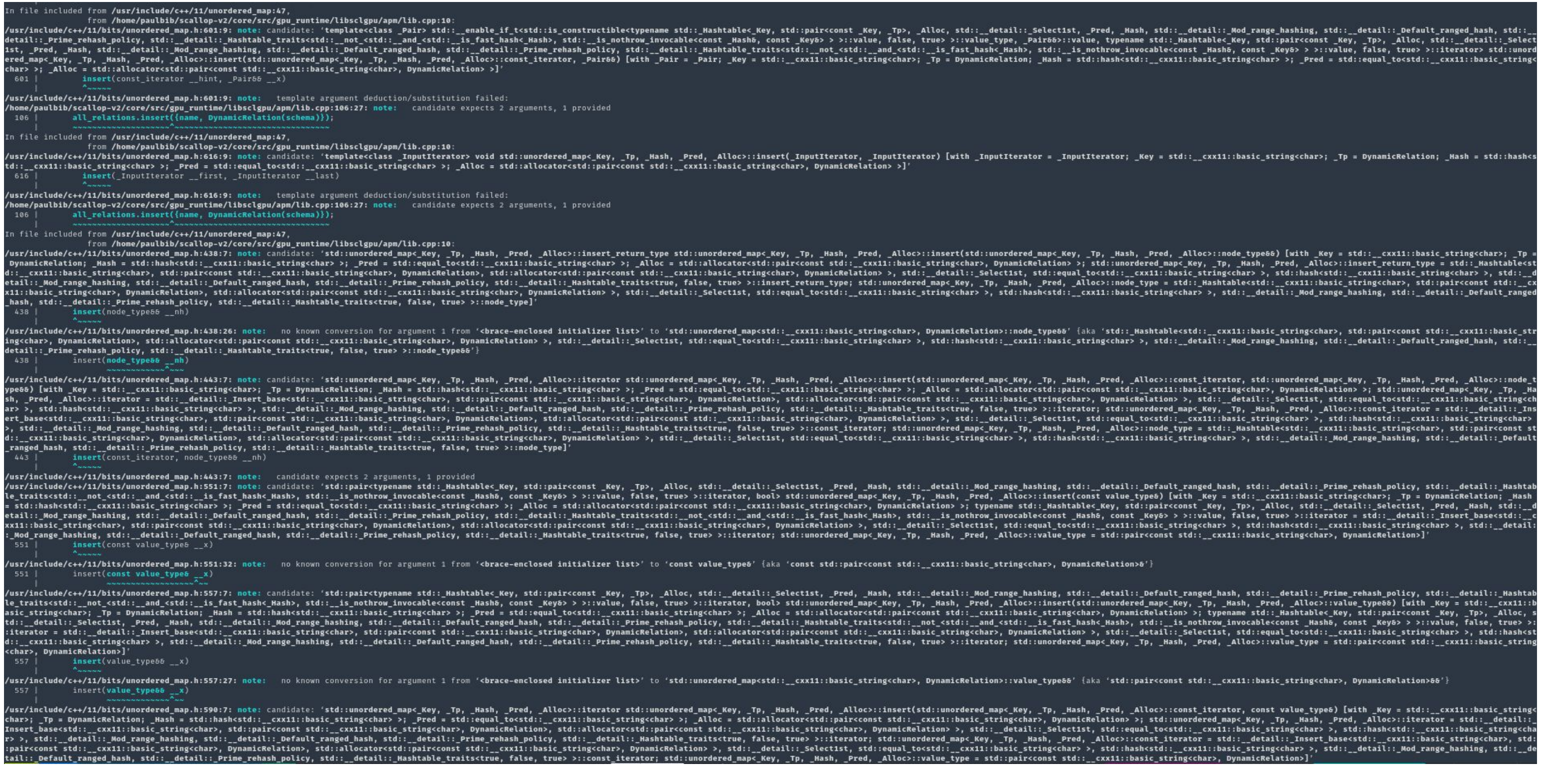
# Lecture 5

Potpourri

# Why no overloading?



*C++ template overloading function call error (2025) (colorized)*

# Why no overloading?

Suppose you have a function name overloaded. When a function call fails did you…

- Pass the wrong number of arguments?
- Pass the right number of arguments but of the wrong types?
- Pass the right number of arguments and types but the types don't satisfy the right traits?

Error messages are abysmal

`insert(key: K, value: V)`

`insert(key: K)` // insert with default value

`insert(key: K, args*: T…)` // construct in place

`insert(key_value_pair: Pair<K,V>)` // insert pair

# Overloading workarounds

You can "overload" `default` by having it be a trait method

```
fn main() {
    let x: u32 = Default::default();
    let o: Option<String> = Default::default();
}
```

You can "overload" `write_to_file` by having it accept `Into<...>`

```
fn write_to_file<T: Into<Vec<u8>>>(data: T) {
   let data = data.into();
   ...
}
```

# Overriding arithmetic operators

User can’t define their own new operators

Built-in operators like `+`, `*`, `-`, `/` are magically linked to `Add`, `Mul`, `Sub`, `Div` traits by compiler

# More macros

a `Macro` looks at your code as text and generates new code at compile time

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

```
use inline_python::python;

fn main() {
  let who = "world";
  let n = 5;
  python! {
    for i in range('n):
      print(i, "Hello", 'who)
    print("Goodbye")
  }
}
```

# Important trait: `Drop`

```rust
struct MyType {
    s: String
}

impl Drop for MyType {
    fn drop(&mut self) {
        println("Dropping...");
    }
}
```

Destructor behavior

- Closing files
- Logging data

Never need to worry about freeing `struct`/`enum` members: always automatic

Find this at https://doc.rust-lang.org/std/ops/trait.Drop.html

# Generic trait vs trait associated type

A generic trait defines a template for a trait

```
trait Into<T> {
   into(self) -> T
}
```

stands in for

```
trait IntoInt {
   into(self) -> u32
}
trait IntoFloat {
   into(self) -> f32
}
trait IntoString {
   into(self) -> String
}
```

Associated types describe a type related to a trait implementation

```
impl Iterator {
   type Item;
   fn next(&mut self) -> Item;
}

impl Iterator for Counter {
   type Item = u32;
   ...
}
impl Iterator for File {
   type Item = String;
   ...
}
impl Iterator for Calendar {
   type Item = Day;
   ...
}
```

# PLQ review

```
trait Mul<Rhs> {
    type Out;
    fn mul(self, rhs: Rhs) -> Self::Out;
}
```

Why is `Output` an associated type, but `Rhs` is a type parameter?

Standard library takes the opinion that given two input types, the output type is fixed

```
trait Mul<Rhs> { type Output; }
impl Mul<u32> for u32 { type Output = u32 }
impl Mul<u32> for u32 { type Output = f32 }
```

Tow `impl`s with different output types do collide (doesn't compile)

```
trait Mul<Rhs, Out> { ... }
impl Mul<Rhs=u32, Out=u32> for u32 { ... }
impl Mul<Rhs=u32, Out=f32> for u32 { ... }
```

Tow `impl`s with different output types don't collide (does compile)

# Managing complexity

*“All of these traits and things add a lot of "boilerplate". are there ways to simplify this or is having complex method and function headers just a downside of rust.”*

Rust trades **up-front complexity** for **eventual complexity**

- Explicitly annotate trait requirements -> avoids terrible errors later (like in C++)
  - but takes more up-front work
- Prototyping, don’t care about performance? Rust **may not be the right language**

**Goal of type system: make requirements checkable by compiler, instead of written in English**

Rust

```rust
pub fn write<P: AsRef<Path>, C: AsRef<[u8]>>(path: P, contents: C) -> Result<()>
```

Python

```python
write(s, /)
```

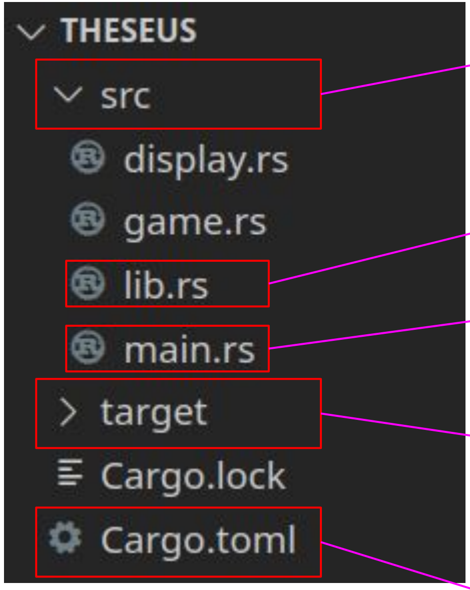
Write the string *s* to the stream and return the number of characters written.

# Project 1 retrospective

What worked well? What didn't? Rust growing pains?

# Modules

# Anatomy of a crate




All code goes here

Crate root

Program entrypoint

Build artifacts

Metadata and dependencies

- Project name
- Version
- Compilation options

# Modules

At the top level is a “crate” (package)

Crates contain modules

Modules contain modules and items

Items are

- types (struct/enum)
- traits
- functions
- impl blocks
- constants

`main.rs` and `lib.rs` are optional, but must have at least one

- No main.rs -> can’t `cargo run`
- No `lib.rs` -> can’t be depended on by another crate

# Using exported items

In `main.rs` we can write

```rust
let game = theseus::game::Game::new();
```

From package `theseus`

and module `game`

the struct `Game`

the function `new`

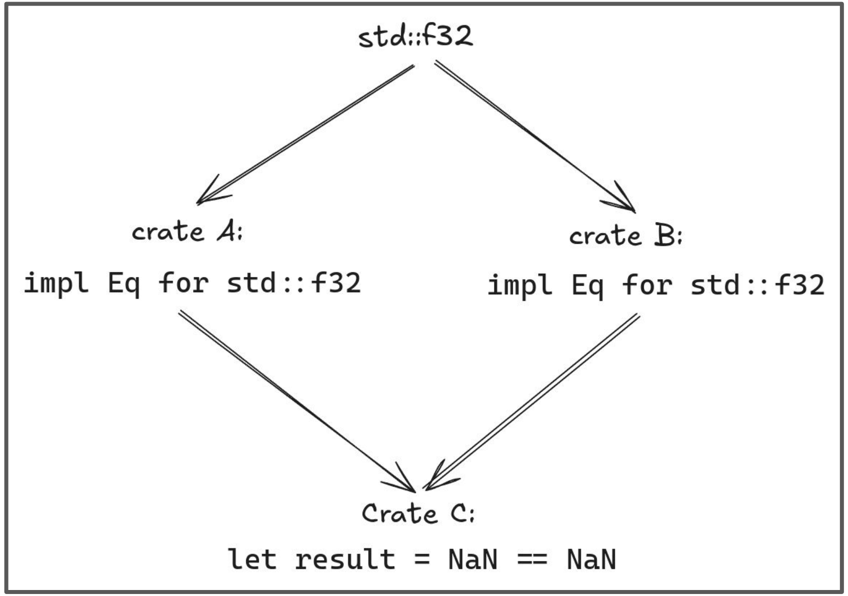
# Using exported items

```
use theseus::game::Game;
let game =                          Game::new();
```

# The prelude

```rust
use std::marker::Copy
use std::ops::{Drop, Fn}
use std::mem::drop
use std::boxed::Box
use std::clone::Clone
use std::cmp::{PartialEq, PartialOrd, Eq, Ord}
use std::convert::{Into, From}
use std::default::Default
use std::iter::Iterator
use std::option::Option::{self, Some, None}
use std::result::Result::{self, Ok, Err}
use std::string::{String, ToString}
use std::vec::Vec
// <5 items omitted>
```

# Orphan trait rule: why?




Which `impl` to use?

# Orphan trait rule

```
impl SomeTrait for SomeType {
    ...
}
```

One must be true

- `SomeTrait` is part of this module
- `SomeType` is part of this module
- Both are part of this module

# Adjacent problem: conflicting method names

What gets printed?

```rust
trait Paint  { fn draw(&self) }
trait Cowboy { fn draw(&self) }

impl Paint for String {
    fn draw(&self) { println!("🎨"); }
}
impl Cowboy for String {
    fn draw(&self) { println!("🤠"); }
}

fn main() {
  String::from("cis1905").draw();
}
```

# Adjacent problem: conflicting method names

What gets printed?

Need to explicitly disambiguate

```rust
trait Paint  { fn draw(&self) }
trait Cowboy { fn draw(&self) }

impl Paint for String {
    fn draw(&self) { println!("🎨"); }
}
impl Cowboy for String {
    fn draw(&self) { println!("🤠"); }
}

fn main() {
  Paint::draw(&String::from("cis1905"));
}
```

# In summary

Code comes from three places

- Your own package
- An external package
- The standard library

These are all treated the same by the language

At the top level is a “crate” (package)

Crates contain modules

Modules contain modules and items

Items are

- types (struct/enum)
- traits
- functions
- impl blocks
- constants

# Containers

# Two bread-and-butter containers

`Vec<T>` ordered collection of values

- `ArrayList<T>` in Java
- `std::vector` in C++
- `list` Python

`HashMap<K,V>` unordered collection of key/value pairs

- `HashMap<K,V>` in Java
- `std::unordered_map<K,V>` in C++
- `dict` in Python

What might be hard about these containers?

- Ownership?
- Mutable/immutable references?
- Trait implementations?

# What traits does `Vec` satisfy?

Can you check if two `Vec`s are equal?

Can you print a `Vec`

Can you clone a `Vec`?

Can you make a default value for `Vec`

# What traits does `Vec` satisfy?

"Passes through" many traits

- `PartialEq`/`Eq`
- `PartialOrd`/`Ord`
- `Clone`
- `Debug`

Implements some new traits

- `Default`

# Vec operations

Getting mutable/immutable references: easy!

```rust
let mut v = vec![1, 2, 3, 4, 5];
v.push(6);
v.push(7);
v.pop();
println!("{:?}", v);
```

Why a macro?

Remove last element

```rust
let x: &u32 = v.get(0).unwrap();
```

Returns an `Option`

```rust
let x: &mut u32 =
v.get_mut(0).unwrap();
*x = 10;
```

# Vec operations

Moving is a “zero-cost” operation

```
let s1: String = String::from("hello");
let s2: String = s1;
// access to `s1` is invalidated by compiler
```

How do we move out of an index?

```
let v: Vec<String> = ...;

let first: String = vec.????(0);
// access to vec[0] is invalidate by compiler??
```

# Vec operations

Moving is a "zero-cost" operation

```
let s1: String = String::from("hello");
let s2: String = s1;
// access to `s1` is invalidated by compiler
```

How do we move out of an index?

```
let v: Vec<String> = ...;

let first: String = vec.????(0);
// access to vec[0] is invalidate by compiler??
```

Options:

1. `v.get(0).unwrap().clone();`
2. `v.remove(0);`

Bottom line: can't move out of vector without modifying data structure

# HashMap

```rust
let mut map = HashMap::new();
map.insert(1905, String::from("Rust Programming"));
map.insert(3200, String::from("Introduction to Algorithms"));

let course_name = map.get(&1905).unwrap();
course_name.push('🦀');
```

**Insertion and removal**: by *move* (takes ownership)

**Lookup**: by *reference* (does not take ownership)

# HashMap

```rust
let mut map = HashMap::new();
map.insert(1905, String::from("Rust Programming"));
map.insert(3200, String::from("Introduction to Algorithms"));

let course_name = map.get(&1905).unwrap();
course_name.push('🦀');
```

**Insertion and removal**: by *move* (takes ownership)

**Lookup**: by *reference* (does not take ownership)

Don't be fooled!
`Vec` and `HashMap` don't have type annotations but can only hold values of a single type

# HashMap

```
let mut map = HashMap::new();
map.insert(1905, String::from("Rust Programming"));
map.insert(3200, String::from("Introduction to Algorithms"));

let course_name = map.get_mut(&1905).unwrap();
course_name.push('🦀');
```

**Insertion and removal**: by *move* (takes ownership)

**Lookup**: by *reference* (does not take ownership)

Why doesn't `course_name` need to be `mut`?

# Histograms

```
let grades = vec!['A', 'B', /* grades... */];
let mut histogram = HashMap::new();
```

# Histograms

```
let grades = vec!['A', 'B', /* grades... */];
let mut histogram = HashMap::new();
for grade in grades {
    if histogram.contains_key(&grade) {
        *histogram.get_mut(&grade).unwrap() +=
1;
    } else {
        histogram.insert(grade, 1);
    }
}
```

Boo! What do you not like?

# Entry API

```
let grades = vec!['A', 'B', /* grades...
*/];
let mut histogram = HashMap::new();
for grade in grades {
  *histogram.entry(grade).or_insert(0) += 1;
}
```

Entry API easily handles missing values

# Does this program compile?

```
fn main() {
 let mut h = HashMap::new();
 h.insert("k1", 0);
 let v1 = &h["k1"];
 h.insert("k2", 1);
 let v2 = &h["k2"];
 println!("{} {}", v1, v2);
}
```

Recall

- Ownership
- Mutable/Immutable reference rules

# Does this program compile?

```
fn main() {
 let mut h = HashMap::new();
 h.insert("k1", 0);
 let v1 = &h["k1"];
 h.insert("k2", 1);
 let v2 = &h["k2"];
 println!("{} {}", v1, v2);
}
```

Recall

- Ownership
- Mutable/Immutable reference rules

Mutate h while immutable reference exists

# Does this program compile?

```
fn main() {
 let mut h = HashMap::new();
 h.insert("k1", 0);
 h.insert("k2", 1);
 let v1 = &h["k1"];
 let v2 = &h["k2"];
 println!("{} {}", v1, v2);
}
```

Recall

- Ownership
- Mutable/Immutable reference rules

Mutate h while immutable reference exists

# Strings

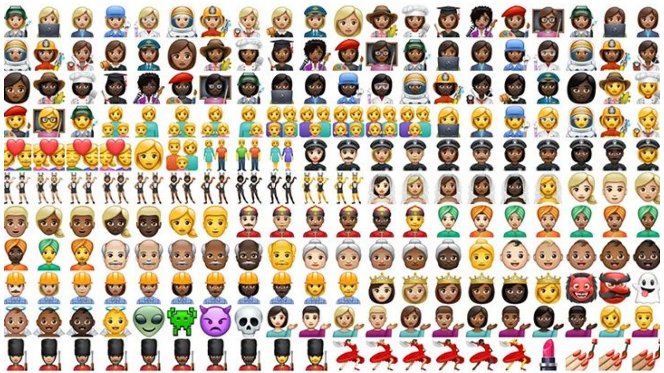
# What’s a character?

`char` is 1 byte (8 bits), right?

- $2^8$=256 possible values

So a `String` is just `Vec<char>`?

Where do all these characters come from?



# C character encoding: ASCII

This is where “a character is 1 byte” comes from

| Dec | Char | Dec | Char | Dec | Char | Dec | Char |
|---|---|---|---|---|---|---|---|
| 0 | NUL (null) | 32 | SPACE | 64 | @ | 96 | ` |
| 1 | SOH (start of heading) | 33 | ! | 65 | A | 97 | a |
| 2 | STX (start of text) | 34 | " | 66 | B | 98 | b |
| 3 | ETX (end of text) | 35 | # | 67 | C | 99 | c |
| 4 | EOT (end of transmission) | 36 | $ | 68 | D | 100 | d |
| 5 | ENQ (enquiry) | 37 | % | 69 | E | 101 | e |
| 6 | ACK (acknowledge) | 38 | & | 70 | F | 102 | f |
| 7 | BEL (bell) | 39 | ' | 71 | G | 103 | g |
| 8 | BS (backspace) | 40 | ( | 72 | H | 104 | h |
| 9 | TAB (horizontal tab) | 41 | ) | 73 | I | 105 | i |
| 10 | LF (NL line feed, new line) | 42 | * | 74 | J | 106 | j |
| 11 | VT (vertical tab) | 43 | + | 75 | K | 107 | k |
| 12 | FF (NP form feed, new page) | 44 | , | 76 | L | 108 | l |
| 13 | CR (carriage return) | 45 | - | 77 | M | 109 | m |
| 14 | SO (shift out) | 46 | . | 78 | N | 110 | n |
| 15 | SI (shift in) | 47 | / | 79 | O | 111 | o |
| 16 | DLE (data link escape) | 48 | 0 | 80 | P | 112 | p |
| 17 | DC1 (device control 1) | 49 | 1 | 81 | Q | 113 | q |
| 18 | DC2 (device control 2) | 50 | 2 | 82 | R | 114 | r |
| 19 | DC3 (device control 3) | 51 | 3 | 83 | S | 115 | s |
| 20 | DC4 (device control 4) | 52 | 4 | 84 | T | 116 | t |
| 21 | NAK (negative acknowledge) | 53 | 5 | 85 | U | 117 | u |
| 22 | SYN (synchronous idle) | 54 | 6 | 86 | V | 118 | v |
| 23 | ETB (end of trans. block) | 55 | 7 | 87 | W | 119 | w |
| 24 | CAN (cancel) | 56 | 8 | 88 | X | 120 | x |
| 25 | EM (end of medium) | 57 | 9 | 89 | Y | 121 | y |
| 26 | SUB (substitute) | 58 | : | 90 | Z | 122 | z |
| 27 | ESC (escape) | 59 | ; | 91 | [ | 123 | { |
| 28 | FS (file separator) | 60 | < | 92 | \ | 124 | \| |
| 29 | GS (group separator) | 61 | = | 93 | ] | 125 | } |
| 30 | RS (record separator) | 62 | > | 94 | ^ | 126 | ~ |
| 31 | US (unit separator) | 63 | ? | 95 | _ | 127 | DEL |

- Control characters (newline, tab)
- punctuation
- alphanumeric

# Moving on from ASCII

How to support all languages and characters?

- Just make `char` 32 bits?
    - All text is 4x bigger in memory
    - Not backwards compatible

ASCII only uses 7 bits

- Most significant bit is always `0` in ASCII chars

| | |
|---|---|
| `A` | 0100 0001 |
| `[` | 0101 1011 |
| `\n` | 0000 1010 |
| `6` | 0011 0110 |

# Variable length encoding

A `char` is 1 to 4 bytes

When starting to read a string, how long is the first character?

Look at the first byte

| | |
|---|---|
| `0xxxxxxx` | 0 bytes follow |
| `110xxxxx` | 1 byte follows |
| `1110xxxx` | 2 bytes follow |
| `11110xxx` | 3 bytes follow |

Example four-byte character

😊

`11110000 10011111 10011000 10001010`

four-byte character

continuation sequence

“UTF-8 encoding”

# Some byte sequences are not valid UTF-8

Invalid! Multi-byte character with trailing bytes that lack the continuation sequence

Example four-byte character

😊

`11110000 00011111 10011000 10001010`

four-byte character

continuation sequence

# `Vec<u8>` vs. `String`?

`Vec<u8>`

- 0 or more bytes of data contiguous in memory
- growable

`String`

- 0 or more bytes of data contiguous in memory
- growable
- Always valid UTF-8

How is this maintained?

# Assume-guarantee invariants

Creation methods:

Impossible to create `String` that doesn't satisfy invariant

- `String::new()`
- `String::from(&bytes)`

Modifying methods:

**assume** invariant holds at entry -> **guarantee** it still holds at return

- `String::push(&mut self, char)`
- `String::remove(&mut self, usize)`

# Two kinds of invariants

Type invariants

**Example:** a value of type `Option<u32>` will always be either `None` or a `u32`

**Enforced by:** compiler

Assume-guarantee invariants

**Example:** a value of type `String` always represents valid UTF-8

**Enforced by:** library developer

# Finally: `String`

Supports most operations you would expect

Creation

- `String::new()`
- `String::from(&str)`

Modification

- `String::push(&mut self, char)`
- `String::push_str(&mut self, &str)`
- `String::remove(&mut self, usize)`

Reading

- `String::len(&self)`

Does not support indexing—why?

Instead, use

- `.chars().nth(i)`
- `.bytes().nth(i)`

# Iterators

# Looping over a Vec

As we've seen:

```
let v = vec![1, 2, 3];

for element in v {
   println!("{}", element);
}
```

But wait! Looping is complicated

# Looping over a Vec

```
for element in v.iter() {
    // element: &T
}
```

Iterate by reference

- Read only element access

```
for element in v.iter_mut() {
    // element: &mut T
}
```

Iterate by mutable reference

- Read/write element access

```
for element in v.into_iter() {
    // element: T
}
```

Iterate by consumption

- Can’t use v afterwards

# Iterator adaptors

```
for (i, element) in v.iter().enumerate()
{
    println!("{}: {}", i, element);
}
```

Iterate over values *and indices*

```
for (x, y) in v1.iter().zip(v2.iter()) {
    println!("({}, {})", x, y);
}
```

Iterate over *two vectors simultaneously*

```
for x in v1.iter().chain(v2.iter()) {
    println!("{}", x);
}
```

Iterate over *two vectors sequentially*

# Iterators are a trait

```
let s = String::new();
for char in s.chars() {
    // ...
}

let map = HashMap::new();
for (k, v) in map {
    // ...
}

for v in map.values() {
    // ...
}
```

Can loop over anything that implements `Iterator`

```
trait Iterator {
    type Item;
    fn next(&mut self) -> Option<Self::Item>;
}
```