RUSTikales Rust for advanced coders

Plan for today

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1. Lifetimes

1. Lifetimes

- Recap: References are pointers to values

1. Lifetimes

The problem: Memory safety

```rust
fn example_1() {
    let a: Vec<i32> = vec![1, 2];
    let b: Vec<i32> = a;
    println!("{:?}", a);
}
```

1. Lifetimes

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}
```

Compiler moves the value of a into b

1. Lifetimes

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```

a	
content	
length	2
capacity	4

heap	
0xabc0	1
0xabc4	2
...	...

1. Lifetimes

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length	2
capacity	4

b	
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length	2
capacity	4

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1. Lifetimes

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content	
length	2
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b	
content	
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capacity	4

heap	
0xabc0	1
0xabc4	2
...	...

Ownership violation!
Memory would be freed twice at the end!

1. Lifetimes

The problem: Memory safety

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    let a: Vec<i32> = vec![1, 2];
    let b: Vec<i32> = a;
    println!("{:?}", a);
}
```

a	
content	???
length	???
capacity	???

heap	
0xabc0	1
0xabc4	2
...	...

b	
content	
length	2
capacity	4

Solution:
→ Move a into b
→ Invalidate a

1. Lifetimes

The problem: Memory safety

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    let a: Vec<i32> = vec![1, 2];
    let b: Vec<i32> = a;
    println!("{:?}", a);
}
```

a	
content	???
length	???
capacity	???

Error: a is not initialized, can‘t use it – It was moved

1. Lifetimes

The solution: References

```rust
fn example_1() {
    let a: Vec<i32> = vec![1, 2];
    let b: &Vec<i32> = &a;
    println!("{:?}", *b);
}
```

1. Lifetimes

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b	
pointer	

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1. Lifetimes

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}
```

b	
pointer	

a	
content	
length	2
capacity	4

heap	
0xabc0	1
0xabc4	2
...	...

No ownership violation:
→ a still owns the memory on the heap
→ b does not own a, it just points to it

1. Lifetimes

The solution: References

```rust
fn example_1() {
    let a: Vec<i32> = vec![1, 2];
    let b: &Vec<i32> = &a;
    println!("{:?}", *b);
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b	
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By dereferencing b, we get access to a
→ we print the vector

1. Lifetimes

The solution: References

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}
```

b	
pointer	

a	
content	
length	2
capacity	4

heap	
0xabc0	1
0xabc4	2
...	...

By dereferencing b, we get access to a
→ we print the vector
→ most of the time, derefs are implicit

1. Lifetimes

```rust
struct A { a: [i32; 5000] }
fn get(a: &A) {
    println!("a.a is {:?}", a.a);
}
fn example_2() {
    let a: A = A { a: [20; 5000] };
    get(&a);
}
```

1. Lifetimes

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struct A { a: [i32; 5000] }
fn get(a: &A) {
    println!("a.a is {:?}", a.a);
}
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    let a: A = A { a: [20; 5000] };
    get(&a);
}
```

big struct!

1. Lifetimes

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fn get(a: &A) {
    println!("a.a is {:?}", a.a);
}
fn example_2() {
    let a: A = A { a: [20; 5000] };
    get(&a);
}
```

By passing a reference, we don‘t need to copy the original value

1. Lifetimes

```rust
struct B { a: &A }
fn example_3() {
    let a: A = A { a: [20; 5000] };
    let b: B = B { a: &a };
    get(b.a);
}
```

1. Lifetimes

```rust
struct B { a: &A }
fn example_3() {
    let a: A = A { a: [20; 5000] };
    let b: B = B { a: &a };
    get(b.a);
}
```

Don‘t want to move/copy 20KB of data every time?
Just pass a reference!

2. Next time

- Slices
- Smart Pointers

1. Lifetimes

```rust
struct B { a: &A }
fn example_3() {
    let a: A = A { a: [20; 5000] };
    let b: B = B { a: &a };
    get(b.a);
}
```

Oh no

1. Lifetimes

```
error[E0106]: missing lifetime specifier
  --> src\ref_ex.rs:15:15
   |
15 | struct B { a: &A }
   |               ^ expected named lifetime parameter
   |
help: consider introducing a named lifetime parameter
   |
15 | struct B<'a> { a: &'a A }
   |         ++++       ++
```

Well, not quite.

1. Lifetimes

- References in its simplest form are memory addresses
  - can point to any memory, to the stack, to the heap

1. Lifetimes

- References in its simplest form are memory addresses
  - can point to any memory, to the stack, to the heap
- Pointers are easy to mishandle
  - dangling pointers
  - race conditions

1. Lifetimes

```c
int *f() {
    int x = 10;
    return &x;
}
int main(void) {
    int *hehe = f();
    printf("%d\n", *hehe);
    somethingElse();
    printf("%d\n", *hehe);
}
```

3/3

1. Lifetimes

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int *f() {
    int x = 10;
    return &x;
}
int main(void) {
    int *hehe = f();
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```

3/3

What does this C code print?

1. Lifetimes

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    printf("%d\n", *hehe);
}
```

3/3

What does this C code print?

→ We can‘t know.
→ The first printf() prints 10
→ somethingElse() may overwrite the memory the pointer is pointing to

1. Lifetimes

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int *f() {
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}
```

3/3

What does this C code print?

→ We can‘t know.
→ The first printf() prints 10
→ somethingElse() may overwrite the memory the pointer is pointing to

```c
void somethingElse() {
    int a = 420;
}
```

```
>main.exe
10
420
```

1. Lifetimes

- References in its simplest form are memory addresses
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- More is required to make them memory safe, and fit for Rust‘s goals

1. Lifetimes

- References in its simplest form are memory addresses
- Pointers are easy to mishandle
- More is required to make them memory safe, and fit for Rust‘s goals
- The compiler needs to analyze when and how references are valid
  - Part One: Borrow Checker
  - Part Two: Lifetimes

1. Lifetimes

- What *is* a lifetime?

1. Lifetimes

- What *is* a lifetime?
  - Rust docs

A *lifetime* is a construct the compiler (or more specifically, its *borrow checker*) uses to ensure all borrows are valid. Specifically, a variable's lifetime begins when it is created and ends when it is destroyed. While lifetimes and scopes are often referred to together, they are not the same.

https://doc.rust-lang.org/rust-by-example/scope/lifetime.html

1. Lifetimes

- What *is* a lifetime?
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    > A *lifetime* is a construct the compiler (or more specifically, its *borrow checker*) uses to ensure all borrows are valid. Specifically, a variable's lifetime begins when it is created and ends when it is destroyed. While lifetimes and scopes are often referred to together, they are not the same.

    - A lifetime is the time between creating and destroying a variable
    - Different from scopes
    - Used by the Borrow Checker

1. Lifetimes

- What *is* a lifetime?
  - Rust docs
  - Rustonomicon

Rust enforces these rules through *lifetimes*. Lifetimes are named regions of code that a reference must be valid for. Those regions may be fairly complex, as they correspond to paths of execution in the program. There may even be holes in these paths of execution, as it's possible to invalidate a reference as long as it's reinitialized before it's used again. Types which contain references (or pretend to) may also be tagged with lifetimes so that Rust can prevent them from being invalidated as well.

https://doc.rust-lang.org/nomicon/lifetimes.html

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- What *is* a lifetime?
  - Rust docs
  - Rustonomicon
    - Lifetimes enforce Borrow Checker rules
    - Named regions of code that a reference must be valid for
    - Tags for references

1. Lifetimes

- What *is* a lifetime?
  - Rust docs
  - Rustonomicon
  - „Effective Rust“

The lifetime of an item on the stack is the period where that item is guaranteed to stay in the same place; in other words, this is exactly the period where a *reference* (pointer) to the item is guaranteed not to become invalid.

This starts at the point where the item is created, and extends to where it is either *dropped* (Rust's equivalent to object destruction in C++) or *moved*.

https://www.lurklurk.org/effective-rust/lifetimes.html

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    - A lifetime is the time between creating and destroying an item on the stack
    - Lifetimes relate to memory locations
    - Periods in time where a reference is guaranteed to be valid

1. Lifetimes

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    - A lifetime is the time between creating and destroying an item on the stack
    - Lifetimes relate to memory locations
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1. Lifetimes

When we talked about references in Chapter 4, we left out an important detail: every reference in Rust has a *lifetime*, which is the scope for which that reference is valid. Most of the time lifetimes are implicit and inferred, just like most of the time types are inferred. Similarly to when we have to annotate types because multiple types are possible, there are cases where the lifetimes of references could be related in a few different ways, so Rust needs us to annotate the relationships using generic lifetime parameters so that it can make sure the actual references used at runtime will definitely be valid.

https://web.mit.edu/rust-lang_v1.25/arch/amd64_ubuntu1404/share/doc/rust/html/book/second-edition/ch10-03-lifetime-syntax.html

Rust enforces these rules through *lifetimes*. Lifetimes are named regions of code that a reference must be valid for. Those regions may be fairly complex, as they correspond to paths of execution in the program. There may even be holes in these paths of execution, as it's possible to invalidate a reference as long as it's reinitialized before it's used again. Types which contain references (or pretend to) may also be tagged with lifetimes so that Rust can prevent them from being invalidated as well.

The lifetime of an item on the stack is the period where that item is guaranteed to stay in the same place; in other words, this is exactly the period where a *reference* (pointer) to the item is guaranteed not to become invalid.

This starts at the point where the item is created, and extends to where it is either *dropped* (Rust's equivalent to object destruction in C++) or *moved*.

Introducing lifetimes

Lifetimes are what the Rust compiler uses to keep track of how long references are valid for. Checking references is one of the borrow checker's main responsibilities. Lifetimes help the borrow checker ensure that you never have invalid references.

https://blog.logrocket.com/understanding-lifetimes-in-rust/

Lifetimes are a way of tracking the scope of a reference to an object in memory. In Rust, every value has one owner, and when the owner goes out of scope, the value is dropped, and its memory is freed. Lifetimes allow Rust to ensure that a reference to an object remains valid for as long as it's needed.

https://earthly.dev/blog/rust-lifetimes-ownership-burrowing/

A *lifetime* is a construct the compiler (or more specifically, its *borrow checker*) uses to ensure all borrows are valid. Specifically, a variable's lifetime begins when it is created and ends when it is destroyed. While lifetimes and scopes are often referred to together, they are not the same.

1. Lifetimes

```rust
/// Perform the actual borrow checking.
///
/// Use `consumer_options: None` for the default behavior of returning
/// [`BorrowCheckResult`] only. Otherwise, return [`BodyWithBorrowckFacts`] according
/// to the given [`ConsumerOptions`].
#[instrument(skip(infcx, input_body, input_promoted), fields(id=?input_body.source.def_id()), level = "debug")]
fn do_mir_borrowck<'tcx>(
    infcx: &InferCtxt<'tcx>,
    input_body: &Body<'tcx>,
    input_promoted: &IndexSlice<Promoted, Body<'tcx>>,
    consumer_options: Option<ConsumerOptions>,
) -> (BorrowCheckResult<'tcx>, Option<Box<BodyWithBorrowckFacts<'tcx>>>) {
```

```rust
// Compute non-lexical lifetimes.
let nll::NllOutput {
    regioncx,
    opaque_type_values,
    polonius_input,
    polonius_output,
    opt_closure_req,
    nll_errors,
} = nll::compute_regions(
```

```rust
/// Computes the (non-lexical) regions from the input MIR.
///
/// This may result in errors being reported.
pub(crate) fn compute_regions<'cx, 'tcx>(
    infcx: &BorrowckInferCtxt<'_, 'tcx>,
    universal_regions: UniversalRegions<'tcx>,
    body: &Body<'tcx>,
    promoted: &IndexSlice<Promoted, Body<'tcx>>,
    location_table: &LocationTable,
    param_env: ty::ParamEnv<'tcx>,
    flow_inits: &mut ResultsCursor<'cx, 'tcx, MaybeInitializedPlaces<'cx, 'tcx>>,
    move_data: &MoveData<'tcx>,
    borrow_set: &BorrowSet<'tcx>,
    upvars: &[&ty::CapturedPlace<'tcx>],
    consumer_options: Option<ConsumerOptions>,
) -> NllOutput<'tcx> {
```

```rust
/// The output of `nll::compute_regions`. This includes the computed `Regio
/// closure requirements to propagate, and any generated errors.
pub(crate) struct NllOutput<'tcx> {
    pub regioncx: RegionInferenceContext<'tcx>,
    pub opaque_type_values: FxIndexMap<LocalDefId, OpaqueHiddenType<'tcx>>,
    pub polonius_input: Option<Box<AllFacts>>,
    pub polonius_output: Option<Rc<PoloniusOutput>>,
    pub opt_closure_req: Option<ClosureRegionRequirements<'tcx>>,
    pub nll_errors: RegionErrors<'tcx>,
}
```

https://github.com/rust-lang/rust/blob/master/compiler/rustc_borrowck/src/nll.rs
https://github.com/rust-lang/rust/blob/master/compiler/rustc_borrowck/src/lib.rs

1. Lifetimes

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    location_table: &LocationTable,
    param_env: ty::ParamEnv<'tcx>,
    flow_inits: &mut ResultsCursor<'cx, 'tcx, MaybeInitializedPlaces<'cx, 'tcx>>,
    move_data: &MoveData<'tcx>,
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    pub nll_errors: RegionErrors<'tcx>,
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1. Lifetimes

- Lifetimes are a construct of the compiler
  - Technically *everything* is a construct of the compiler

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- Lifetimes are a construct of the compiler
  - Technically *everything* is a construct of the compiler
- Lifetimes allow the compiler to analyze and optimize the final code
  - Lifetimes don't get into the final executable
  - Memory Safety guarantees

1. Lifetimes

- A lifetime describes two things

1. Lifetimes

- A lifetime describes two things
  - A region of code where the reference must be valid
  - A region of memory where the original value must live in

1. Lifetimes

```rust
pub fn main() {
    let a: i32 = 12;
    let mut b: &i32 = &a;
    if rng().gen_bool(0.5) {
        let c: i32 = 40;
        b = &c;
    }
    println!("{}", *b);
}
```

1. Lifetimes

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region of code where b must be valid

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region of code where b must be valid

ref	value
b	

var	value
a	12
c	40

1. Lifetimes

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    let a: i32 = 12;
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```

region of code where b must be valid

ref	value
b	

var	value
a	12
c	40

Depending on RNG, b may point to either a or c
→ When we *b, both memory locations must be alive

1. Lifetimes

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pub fn main() {
    let a: i32 = 12;
    let mut b: &i32 = &a;
    if rng().gen_bool(0.5) {
        let c: i32 = 40;
        b = &c;
    }
    println!("{}", *b);
}
```

c is alive here and then dropped

ref	value
b	

var	value
a	12
c	40

1. Lifetimes

```rust
pub fn main()
    let a: i3
    let mut b
    if rng().
        let c
        b = &c;
    }
    println!("{}", *b);
}
```

```
error[E0597]: `c` does not live long enough
  --> src\ex2.rs:10:13
   |
9  |         let c = 40;
   |             - binding `c` declared here
10 |         b = &c;
   |             ^^ borrowed value does not live long enough
11 |     }
   |     - `c` dropped here while still borrowed
12 |     println!("{}", *b);
   |                    -- borrow later used here
```

1. Lifetimes

- A lifetime describes two things
  - A region of code where the reference must be valid
  - A region of memory where the original value must live in
- The regions of code don't have to be contiguous

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- The regions of code don't have to be contiguous
  - References must only be valid between uses

1. Lifetimes

- A lifetime describes two things
  - A region of code where the reference must be valid
  - A region of memory where the original value must live in
- The regions of code don't have to be contiguous
  - References must only be valid between uses
  - Non-Lexical Lifetimes
    - The compiler is *very* good at figuring out the shortest required lifetimes for references

1. Lifetimes

```rust
pub fn main() {
    let mut r: &Vec<i32>;
    {
        let x: Vec<i32> = vec![2];
        r = &x;
        println!("{:?}", *r);
    }
    {
        let y: Vec<i32> = vec![2];
        r = &y;
        println!("{:?}", *r);
    }
}
```

1. Lifetimes

```rust
pub fn main() {
    let mut r: &Vec<i32>;
    {
        let x: Vec<i32> = vec![2];
        r = &x;
        println!("{:?}", *r);
    }
    {
        let y: Vec<i32> = vec![2];
        r = &y;
        println!("{:?}", *r);
    }
}
```

region of code where r must be valid

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1. Lifetimes

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pub fn main() {
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        let x: Vec<i32> = vec![2];
        r = &x;
        println!("{:?}", *r);
    }
    {
        let y: Vec<i32> = vec![2];
        r = &y;
        println!("{:?}", *r);
    }
}
```

region of code where r must be valid

We don‘t care about this section

region of code where r must be valid

1. Lifetimes

– Lifetimes get complicated when you cross the function border

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- Lifetimes get complicated when you cross the function border

```rust
fn f(v: &Vec<i32>) -> &i32 {
    &v[0]
}
pub fn main() {
    let v: Vec<i32> = vec![1, 2, 3];
    let first: &i32 = f(&v);
    println!("{}", *first);
}
```

1. Lifetimes

– Lifetimes get complicated when you cross the function border

```rust
fn f(v: &Vec<i32>) -> &i32 {
    &v[0]   How long is this reference alive? :^)
}
pub fn main() {
    let v: Vec<i32> = vec![1, 2, 3];
    let first: &i32 = f(&v);
    println!("{}", *first);
}
```

1. Lifetimes

– Lifetimes get complicated when you cross the function border

```rust
fn f(v: &Vec<i32>) -> &i32 {
    &v[0]
}
pub fn main() {
    let v: Vec<i32> = vec![1, 2, 3];
    let first: &i32 = f(&v);
    println!("{}", *first);
}
```

Lifetime elision, rule 2:
If there is exactly one input lifetime parameter, that lifetime is assigned to all output lifetime parameters

1. Lifetimes

– Lifetimes get complicated when you cross the function border

```rust
fn f(v: &Vec<i32>) -> &i32 {
    &v[0]
}
pub fn main() {
    let v: Vec<i32> = vec![1, 2, 3];
    let first: &i32 = f(&v);
    println!("{}", *first);
}
```

points to v[0], the compiler didn‘t complain!
first is valid as long as v is alive.

1. Lifetimes

– Lifetimes get complicated when you cross the function border

```
fn g(v1: &Vec<i32>, v2: &Vec<i32>) -> &i32 {
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
pub fn main() {
    let v1: Vec<i32> = vec![1, 2, 3];
    let v2: Vec<i32> = vec![4, 5];
    let first: &i32 = g(&v1, &v2);
    println!("{}", *first);
}
```

1. Lifetimes

– Lifetimes get complicated when you cross the function border

```rust
fn g(v1: &Vec<i32>, v2: &Vec<i32>) -> &i32 {
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
pub fn main() {
    let v1: Vec<i32> = vec![1, 2, 3];
    let v2: Vec<i32> = vec![4, 5];
    let first: &i32 = g(&v1, &v2);
    println!("{}", *first);
}
```

Swiggly lines of doom!

1. Lifetimes

- Lifetimes get complicated when you cross the function border

```
error[E0106]: missing lifetime specifier
  --> src\ex3.rs:10:39
   |
10 | fn g(v1: &Vec<i32>, v2: &Vec<i32>) -> &i32 {
   |          ---------      ---------     ^ 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 `v1` or `v2`
help: consider introducing a named lifetime parameter
   |
10 | fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
   |     ++++      ++                 ++                 ++
```

1. Lifetimes

- Lifetimes get complicated when you cross the function border
- What‘s the problem?

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- What‘s the problem?
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  - Randomly picking a lifetime doesn't work, because the lifetimes may be different

```rust
fn a(v: &Vec<i32>) -> &i32 {
    let v1: Vec<i32> = vec![4, 5];
    g(v1: v, v2: &v1)
}
```

1. Lifetimes

- Lifetimes get complicated when you cross the function border
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```
fn a(v: &Vec<i32>) -> &i32 {
    let v1: Vec<i32> = vec![4, 5];
    g(v1: v, v2: &v1)
}
```

g could return a reference to elements of v1, which is dropped here

1. Lifetimes

- Lifetimes get complicated when you cross the function border
- What's the problem?
  - According to the memory model, both vectors are somewhere in memory
  - The compiler knows* that the return value is from those vectors
  - It just doesn't know which vector it is from
  - Randomly picking a lifetime doesn't work, because the lifetimes may be different
- We have to provide more information about the lifetimes

1. Lifetimes

```rust
fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
pub fn main() {
    let v1: Vec<i32> = vec![1, 2, 3];
    let v2: Vec<i32> = vec![4, 5];
    let first: &i32 = g(&v1, &v2);
    println!("{}", *first);
}
```

1. Lifetimes

named lifetime parameter

```rust
fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
pub fn main() {
    let v1: Vec<i32> = vec![1, 2, 3];
    let v2: Vec<i32> = vec![4, 5];
    let first: &i32 = g(&v1, &v2);
    println!("{}", *first);
}
```

1. Lifetimes

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fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
```

This tells the compiler:

- There exists a smallest region of memory 'a such that:
  - The original v1 is in that region
  - The original v2 is in that region
  - The *return value is in that region

1. Lifetimes

```
fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
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This tells the compiler:

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  - The original v1 is in that region
  - The original v2 is in that region
  - The *return value is in that region
- There exists a region of code 'a such that:
  - The reference v1 is live in that region
  - The reference v2 is live in that region
  - The return value is live in that region

1. Lifetimes

```rust
fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
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- There exists a region of code ‘a such that:
  - The reference v1 is live in that region
  - The reference v2 is live in that region
  - The return value is live in that region

‘v1 [1 – 2 – 3]

‘v2 [4 – 5]

1. Lifetimes

```rust
fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
    if v1.len() > v2.len() { &v1[0] }
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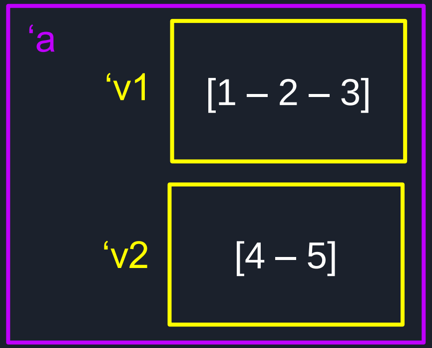

1. Lifetimes

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fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
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    else                   { &v2[0] }
}
```

This tells the compiler:

- There exists a smallest region of memory 'a such that:
  - The original v1 is in that region
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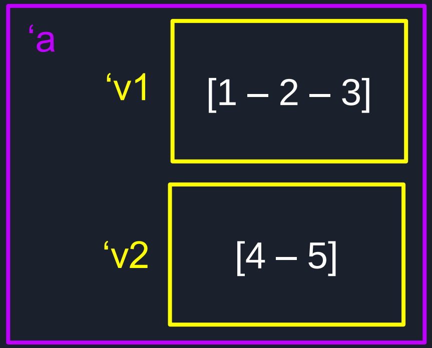
  - The *return value is in that region
- There exists a region of code 'a such that:
  - The reference v1 is live in that region
  - The reference v2 is live in that region
  - The return value is live in that region
- It does NOT mean:
  - v1 and v2 have the same lifetime



1. Lifetimes

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fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
fn a(v: &Vec<i32>) {
    let v1: Vec<i32> = vec![3, 4];
    let first: &i32 = g(v1: v, v2: &v1);
    println!("{}", *first);
}
pub fn main() {
    let v1: Vec<i32> = vec![1, 2, 3];
    a(&v1);
}
```

1. Lifetimes

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fn g<'a>(v1: &'a Vec<i32>, v2: &'a Vec<i32>) -> &'a i32 {
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    println!("{}", *first);
}
pub fn main() {
    let v1: Vec<i32> = vec![1, 2, 3];
    a(&v1);
}
```

It is easy to see that v lives longer than &v1, yet this still works

1. Lifetimes

- You can list as many lifetime parameters as you want, as long as you use them

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
-> &'r i32
where
    'v1: 'r,
    'v2: 'r
{
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
```

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
-> &'r i32
where
    'v1: 'r,
    'v2: 'r
{
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
```

v1 and v2 are totally unrelated, there‘s no connection

1. Lifetimes

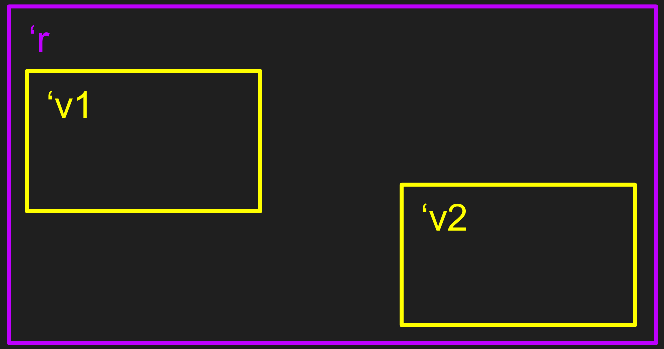
```
fn g<'v1, 'v2, 'r>(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
-> &'r i32
where
    'v1: 'r,
    'v2: 'r
{
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
```

However, ‘r must outlive both ‘v1 and ‘v2

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
-> &'r i32
where
    'v1: 'r,
    'v2: 'r
{
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
```

‘r refers to the smallest memory region such that ‘v1 and ‘v2 both have valid references into that region at the same point in time



1. Lifetimes

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fn g<'v1, 'v2, 'r>(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
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where
    'v1: 'r,
    'v2: 'r
{
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
```

This is also what the compiler does in the background when we only specify ‘a!
→ Subtyping and Variance

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>
(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
-> &'r i32 where 'v1: 'r, 'v2: 'r {
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    else                   { &v2[0] }
}
fn a(outer: &Vec<i32>) {
    let inner = vec![3, 4];
    let first = g(outer, &inner);
    println!("{}", *first);
}
fn e3() {
    let orig = vec![1, 2, 3];
    a(&orig);
}
```

Stackframe			
function	variable	value	refers to

1. Lifetimes

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function	variable	value	refers to
e3	orig	[1,2,3]	---

1. Lifetimes

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fn g<'v1, 'v2, 'r>
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Stackframe			
function	variable	value	refers to
e3	orig	[1,2,3]	---
a	outer	ref	orig
	inner		
	first		

1. Lifetimes

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}
fn a(outer: &Vec<i32>) {
    let inner = vec![3, 4];
    let first = g(outer, &inner);
    println!("{}", *first);
}
fn e3() {
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}
```

Stackframe			
function	variable	value	refers to
e3	orig	[1,2,3]	---
	outer	ref	orig
a	inner	[3,4]	---
	first		
	v1	ref	orig
g	v2	ref	inner
	result		

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>
(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
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    println!("{}", *first);
}
fn e3() {
    let orig = vec![1, 2, 3];
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```

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	first		
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	v2	ref	inner
	result		

‘r is the smallest lifetime such that ‘v1 and ‘v2 are both also alive inside it

1. Lifetimes

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    if v1.len() > v2.len() { &v1[0] }
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    let inner = vec![3, 4];
    let first = g(outer, &inner);
    println!("{}", *first);
}
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    let orig = vec![1, 2, 3];
    a(&orig);
}
```

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a	outer	ref	orig
	inner	[3,4]	---
	first		
g	v1	ref	orig
	v2	ref	inner
	result		

‘r is the smallest lifetime such that ‘v1 and ‘v2 are both also alive inside it
→ orig lives in e3

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>
(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
-> &'r i32 where 'v1: 'r, 'v2: 'r {
    if v1.len() > v2.len() { &v1[0] }
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fn a(outer: &Vec<i32>) {
    let inner = vec![3, 4];
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    println!("{}", *first);
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    a(&orig);
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Stackframe			
function	variable	value	refers to
e3	orig	[1,2,3]	---
	outer	ref	orig
a	inner	[3,4]	---
	first		
	v1	ref	orig
g	v2	ref	inner
	result		

'r is the smallest lifetime such that 'v1 and 'v2 are both also alive inside it

→ orig lives in e3

→ inner lives in a

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>
(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
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Stackframe			
function	variable	value	refers to
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	first		
	v1	ref	orig
g	v2	ref	inner
	result		

‘r is the smallest lifetime such that ‘v1 and ‘v2 are both also alive inside it

→ orig lives in e3

→ inner lives in a

→ inner does not live in e3

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>
(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
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    let inner = vec![3, 4];
    let first = g(outer, &inner);
    println!("{}", *first);
}
fn e3() {
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    a(&orig);
}
```

Stackframe			
function	variable	value	refers to
e3	orig	[1,2,3]	---
a	outer	ref	orig
	inner	[3,4]	---
	first		
g	v1	ref	orig
	v2	ref	inner
	result	ref	both

'r is the smallest lifetime such that 'v1 and 'v2 are both also alive inside it
→ orig lives in e3
→ inner lives in a
→ inner does not live in e3
→ return reference 'r alive in a
→ not allowed to escape to e3

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>
(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
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}
```

Stackframe			
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	inner	[3,4]	---
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1. Lifetimes

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}
```

Stackframe			
function	variable	value	refers to
e3	orig	[1,2,3]	---
a	outer	ref	orig
	inner	[3,4]	---
	first	ref	both

Use is valid, both original values are alive

1. Lifetimes

```rust
fn g<'v1, 'v2, 'r>
(v1: &'v1 Vec<i32>, v2: &'v2 Vec<i32>)
-> &'r i32 where 'v1: 'r, 'v2: 'r {
    if v1.len() > v2.len() { &v1[0] }
    else                   { &v2[0] }
}
fn a(outer: &Vec<i32>) {
    let inner = vec![3, 4];
    let first = g(outer, &inner);
    println!("{}", *first);
}
fn e3() {
    let orig = vec![1, 2, 3];
    a(&orig);
}
```

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1. Lifetimes

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1. Lifetimes

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  - For that, you *have to* specify lifetime parameters
    - Structs are way more flexible than functions, you can use them literally everywhere
      → Inferring lifetimes is way harder :^)

1. Lifetimes

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  - Less memory usage
  - Less computation (cloning is expensive)

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- At the same time, in many situations you do not want that
  - Explicit lifetimes makes your code harder to use and maintain
    - All lifetimes have to line up, in every case, or it falls apart quickly

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  - Explicit lifetimes makes your code harder to use and maintain
  - Lifetime infection will make your code unreadable

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struct A<'b> {
    b: B<'b>,
}
struct B<'b> {
    i: &'b i32,
}
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A itself doesn‘t need a lifetime parameter! But you have to propagate it, it‘s now also A‘s business

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- Many situations arise when you need that, and many where you want that
- At the same time, in many situations you do not want that
- If things go out of hand:
  - Read about Ownership again, do they need references? Isn‘t it better to own the data?
  - Use Smart Pointers

1. Lifetimes

```rust
struct Flags {
    do_stuff: bool,
    something: bool,
}
1 implementation
struct Parser<'f, 's> {
    flags: &'f Flags,
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→ The original source text has to outlive the Parser

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Two lifetime parameters

→ The original Flags struct has to outlive the Parser

→ The original source text has to outlive the Parser

→ The original Flags struct is unrelated to the original source text

1. Lifetimes

```rust
impl<'f, 's> Parser<'f, 's> {
    fn new(flags: &'f Flags, original: &'s str) -> Self {
        Self { flags, original }
    }
    fn next(&mut self) -> Option<&str> {
        let tkn: &str = self.original.split_whitespace().next()?;
        self.original = &self.original[(tkn.len()+1)..];
        Some(tkn)
    }
}
```

1. Lifetimes

```rust
impl<'f, 's> Parser<'f, 's> { // Declares lifetime parameters for the whole struct
    fn new(flags: &'f Flags, original: &'s str) -> Self {
        Self { flags, original }
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Declares lifetime parameters for the whole struct

Can be used in all methods and associated functions

→ No need to annotate new() with them again

1. Lifetimes

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Lifetime elision, rule 3:
if there are multiple input lifetime parameters, but one of them is &self or &mut self because this is a method, the lifetime of self is assigned to all output lifetime parameters

1. Lifetimes

```
pub fn main() {
    let args: Args = std::env::args();
    let flags: Flags = Flags::parse_arg(args);
    let content: String = match fs::read_to_string(path: "./foo.txt") {
        Ok(content: String) => content,
        Err(e: Error) => panic!("{}", e)
    };
    let mut parser: Parser = Parser::new(&flags, original: &content);
    while let Some(tkn: &str) = parser.next() {
        println!("{}", tkn);
    }
}
```

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flags are alive here

1. Lifetimes

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flags are alive here
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    };
    let mut parser: Parser = Parser::new(&flags, original: &content);
    while let Some(tkn: &str) = parser.next() {
        println!("{}", tkn); tkn is a reference into the content
    }
}
```

flags are alive here
content is alive here
parser is alive here
tkn is alive here

1. Lifetimes

Borrowed data does not outlive original → Lifetimes valid, Borrow Checker passed!

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    };
    let mut parser: Parser = Parser::new(&flags, original: &content);
    while let Some(tkn: &str) = parser.next() {
        println!("{}", tkn); 
    }
}
```

tkn is a reference into the content

flags are alive here
content is alive here
parser is alive here
tkn is alive here

2. Next time

- Slices
- Smart Pointers