

Programming Languages (5)

Rust Memory Management

Kenjiro Taura

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`Box<T>` (owning pointer) type

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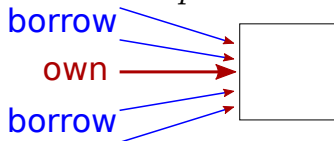
Borrow checking details

Summary

Rust's basic idea to memory management

- ▶ Rust maintains that, for any live object,
 1. there is one and only one pointer that “owns” it (*the owner pointer*)
 2. “*multiple borrowers*” : there are arbitrary number of non-owning pointers (*borrowing pointers*) pointing to it, but *they cannot be dereferenced after the owning pointer goes away*
- ▶ ⇒ *it can safely reclaim the data when the owning pointer goes away*

“single-owner-multiple-borrowers rule”



The rule is enforced statically

- ▶ Rust maintains the rule *statically* (as opposed to *dynamically*)
- ▶ equivalently,
 - ▶ *compile-time* rather than at *runtime*
 - ▶ *before* execution not *during* execution

Ways outside the basics

to be sure, there are some ways to get around the rules

1. **reference counting** \approx

- ▶ allows multiple owning pointers
- ▶ counts the number of owners at runtime, and reclaim the data when all owning pointers are gone

2. **unsafe/raw pointers** (\approx totally up to you)

but they are not specific to Rust, and we'll not cover them in the rest of this slide deck

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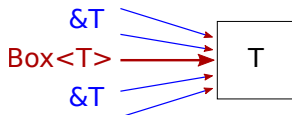
Summary

Pointer-like data types in Rust

given a type T (`i32`, struct, enum, ...), below are types representing “references (pointers) to T ”¹

1. `&T` (pronounced “*ref T*”) : **immutable borrowing pointer** to data of T (through which you cannot modify it)
2. `&mut T` (“*ref mute T*”) : **mutable borrowing pointer** to data of T (through which you can modify it)
3. `Box<T>` (*box T*) : **owning pointer** to T
4. `Rc<T>` and `Arc<T>` : shared (reference-counting) owning pointer to T
5. `*T` : unsafe pointer to T

following discussions are focused on `&T` and `Box<T>`



¹we use pointers and references interchangeably

Pointer-making expressions

given an expression e of type T , below are expressions that make pointers to the value of e

1. `& e` (of type `& T`) : an immutable borrowing pointer (through which you cannot modify the referent)
2. `&mut e` (of type `&mut T`) : a mutable borrowing pointer (through which you can modify the referent)
3. `Box::new(e)` (of type `Box< T >`) : an owning pointer

An example

```
1 {  
2   let mut a = S{x: ...}; // allocate memory for S  
3   let b: &S = &a; // make a borrowing pointer to a  
4   let c: &mut S = &mut a; // make a borrowing pointer to a  
5   let o: Box<S> = Box::new(a); // make an owning pointer to a  
6 }  
7
```

- ▶ note: type of variables can be omitted (spelled out for clarity)
- ▶ note: the above program violates several rules so it does not compile

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Assignments do *not copy*, but *move*, the value

- ▶ to maintain only one “owner” pointer, an assignment in Rust *moves* the value out of righthand side, disallowing further use of it

```
x = y;  
// y can no longer be used
```

- ▶ e.g.,

```
fn foo() {  
  let a = S{x: ..., y: ...};
```



```
}
```

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```
x = y;  
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- ▶ e.g.,

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  ... a.x ...; // OK, as expected  
  ... a.y ...; // OK, as expected  
}
```



Assignments do *not copy*, but *move*, the value

- ▶ to maintain only one “owner” pointer, an assignment in Rust *moves* the value out of righthand side, disallowing further use of it

```
x = y;  
// y can no longer be used
```

- ▶ e.g.,

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  ... a.x ...; // OK, as expected  
  ... a.y ...; // OK, as expected  
  // the value moves away from a to b  
  let b = a;  
  
}
```



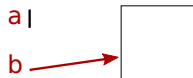
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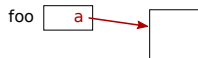
```
fn foo() {  
  let a = S{x: ..., y: ...};  
  ... a.x ...; // OK, as expected  
  ... a.y ...; // OK, as expected  
  // the value moves away from a to b  
  let b = a;  
  a.x; // NG, the value has moved out  
  b.x; // OK  
}
```



Argument-passing also moves the value

- ▶ passing a value to a function also moves the value out

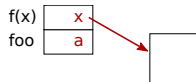
```
fn foo() {  
  let a = S{x: ..., y: ...};  
  ... a.x ...; // OK, as expected  
  ... a.y ...; // OK, as expected  
}
```



Argument-passing also moves the value

- ▶ passing a value to a function also moves the value out

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  ... a.x ...; // OK, as expected  
  ... a.y ...; // OK, as expected  
  // this also moves the value away from a  
  f(a);  
  a.x; // NG, the value has moved out  
}
```



Note: exceptions to “assignment moves the value”

- ▶ the value-moving assignment

```
x = y;  
// y can no longer be used
```

contradicts what you have seen

- ▶ does it apply to a primitive type, say `f64`?

```
fn foo() {  
  let a = 123.456;  
  // does the value move out from a!?  
  let b = a;  
  a + 0.789; // if so, is this invalid!?  
}
```

- ▶ answer: no, it does *not* apply to primitive types like `i32`, `f64`, etc.
- ▶ a more general answer: it does not apply to data types that implement `Copy` trait

Copy trait

- ▶ define your struct with `#[derive(Copy, Clone)]` like

```
1 #[derive(Copy, Clone)]  
2 struct S { ... }
```

- ▶ and assignment or argument-passing of `S` makes a copy of righthand side

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected
```



```
}
```

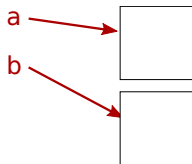
Copy trait

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```
1 #[derive(Copy, Clone)]  
2 struct S { ... }
```

- ▶ and assignment or argument-passing of `S` makes a copy of righthand side

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected  
  // the value is copied  
  let b = a;  
}
```



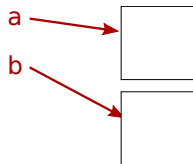
Copy trait

- ▶ define your struct with `#[derive(Copy, Clone)]` like

```
1 #[derive(Copy, Clone)]  
2 struct S { ... }
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- ▶ and assignment or argument-passing of `S` makes a copy of righthand side

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected  
  // the value is copied  
  let b = a;  
  a.x; // OK  
  b.x; // OK, too  
}
```



Copy types and the single-owner rule

- ▶ when a copy is made on every assignment or argument passing, the single-owner rule is trivially maintained
- ▶ below, we will only discuss types not implementing Copy trait (*non-Copy types*)

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Box<T> makes an owning pointer

- ▶ making a pointer by `Box::new(v)` moves the value out of `v`, too, and it becomes the owning pointer

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected
```



```
}
```


Box<T> makes an owning pointer

- ▶ making a pointer by `Box::new(v)` moves the value out of `v`, too, and it becomes the owning pointer

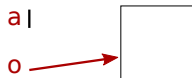
```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected  
  // OK, now o becomes the owning pointer  
  let o = Box::new(a)  
}
```



Box<T> makes an owning pointer

- ▶ making a pointer by `Box::new(v)` moves the value out of `v`, too, and it becomes the owning pointer

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected  
  // OK, now o becomes the owning pointer  
  let o = Box::new(a)  
  a.x; // NG, the value has moved out  
}
```



Box<T> makes an owning pointer

- ▶ making a pointer by `Box::new(v)` moves the value out of `v`, too, and it becomes the owning pointer

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected  
  // OK, now o becomes the owning pointer  
  let o = Box::new(a)  
  a.x; // NG, the value has moved out  
  (*o).x; // OK  
}
```



Box<T> makes an owning pointer

- ▶ making a pointer by `Box::new(v)` moves the value out of `v`, too, and it becomes the owning pointer

```
fn foo() {  
  let a = S{x: ..., y: ...};  
  a.x; // OK, as expected  
  a.y; // OK, as expected  
  // OK, now o becomes the owning pointer  
  let o = Box::new(a)  
  a.x; // NG, the value has moved out  
  (*o).x; // OK  
  o.x; // OK. abbreviation of (*o).x  
}
```



Make no mistake: making `Box::new(v)` does not affect lifetime

- ▶ `a = Box::new(v)` has no effect of making `v` live longer
- ▶ when `a` goes out of scope, `v` will be gone

```
1 fn foo() {  
2     ...  
3     {  
4         let a = S{...};  
5         let p = Box::new(a);  
6     } // --- S{...} will die here, too  
7 }
```

just like

```
1 fn foo() {  
2     ...  
3     {  
4         let a = S{...};  
5         let p = a;  
6     } // --- S{...} will die here  
7 }
```

Note: difference between T and `Box::<T>`?

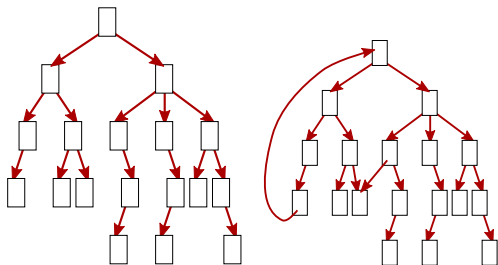
- ▶ for any value v of type T , you can only have one and only one (still usable) variable that refers to v , which is *either of type T or `Box::<T>`*
- ▶ in this sense, you can think of T as just another kind of pointer to T just like `Box::<T>`
- ▶ so is there any reason for Rust to have both T and `Box::<T>`?

T and `Box::<T>`

- ▶ the distinction becomes important when you reason about data layout
 - ▶ `struct S { p: T, ... }` “embeds” a T into S
 - ▶ `struct U { p: Box<T>, ... }` has p point to a separately allocated T
- ▶ in particular,
 - ▶ `struct S { p: S, ... }` is not allowed, whereas
 - ▶ `struct U { p: Box<U>, ... }` is
- ▶ the distinction is not important when discussing lifetimes (you can consider T a pointer without being confused)

A (huge) implication of the single-owner rule (1)

- ▶ with only owning pointers (T and $\text{Box}\langle T \rangle$),
 - ▶ you can make *trees of T* ,
 - ▶ but you *cannot make general graphs of T* (acyclic or cyclic), where *a node may be pointed to by multiple nodes*
- ▶ if you want to make graphs of T , you use either
 - ▶ $\&T$ to represent edges, or
 - ▶ $\text{Vec}\langle T \rangle$ to represent nodes and $\text{Vec}\langle (\text{i32}, \text{i32}) \rangle$ to represent edges



A (huge) implication of the single-owner rule (2)

- ▶ with only owning pointers, *no two names in scope ever refer to the same object (no aliasing)*
- ▶ **a** and **b** below *never* refer to the same object

```
1 fn take_two(a : Box<T>, b : Box<T>) {  
2   ...  
3 }
```

- ▶ a boon for the compiler
- ▶ a useful property to avoid mistakes, too

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Borrowers rule in action

- ▶ a borrowing pointer cannot be dereferenced after its owning pointer is gone

```
fn foo() -> i32 {  
    let c: &S; // a reference to S  
    { // an inner block  
  
    }  
}
```

c : &S

Borrowers rule in action

- ▶ a borrowing pointer cannot be dereferenced after its owning pointer is gone

```
fn foo() -> i32 {  
    let c: &S; // a reference to S  
    { // an inner block  
        let b: &S; // another reference  
  
    }  
}
```

c : &S

b : &S

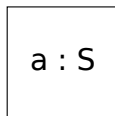
Borrowers rule in action

- ▶ a borrowing pointer cannot be dereferenced after its owning pointer is gone

```
fn foo() -> i32 {  
    let c: &S; // a reference to S  
    { // an inner block  
        let b: &S; // another reference  
        let a = S{x: ...}; // allocate S  
    }  
}
```

c : &S

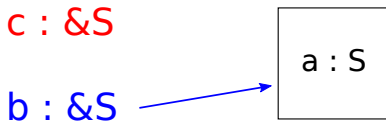
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Borrowers rule in action

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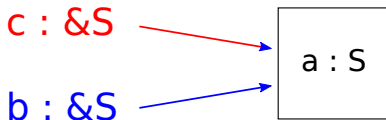
```
fn foo() -> i32 {  
  let c: &S; // a reference to S  
  { // an inner block  
    let b: &S; // another reference  
    let a = S{x: ...}; // allocate S  
    // OK (both a and b live only until the end of the inner block)  
    b = &a;  
  }  
}
```



Borrowers rule in action

- ▶ a borrowing pointer cannot be dereferenced after its owning pointer is gone

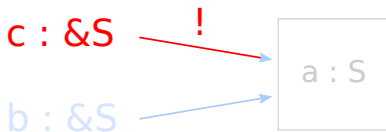
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fn foo() -> i32 {  
  let c: &S; // a reference to S  
  { // an inner block  
    let b: &S; // another reference  
    let a = S{x: ...}; // allocate S  
    // OK (both a and b live only until the end of the inner block)  
    b = &a;  
    c = b; // dangerous (c outlives a)  
  }  
}
```



Borrowers rule in action

- ▶ a borrowing pointer cannot be dereferenced after its owning pointer is gone

```
fn foo() -> i32 {  
  let c: &S; // a reference to S  
  { // an inner block  
    let b: &S; // another reference  
    let a = S{x: ...}; // allocate S  
    // OK (both a and b live only until the end of the inner block)  
    b = &a;  
    c = b; // dangerous (c outlives a)  
  } // a dies here, making c a dangling pointer  
}
```



Borrowers rule in action

- ▶ a borrowing pointer cannot be dereferenced after its owning pointer is gone

```
fn foo() -> i32 {  
    let c: &S; // a reference to S  
    { // an inner block  
        let b: &S; // another reference  
        let a = S{x: ...}; // allocate S  
        // OK (both a and b live only until the end of the inner block)  
        b = &a;  
        c = b; // dangerous (c outlives a)  
    } // a dies here, making c a dangling pointer  
    c.x // NG (deref a dangling pointer)  
}
```

A *mutable* borrowing reference (`&mut T`) has an additional restriction

- ▶ a stronger restriction is imposed on `&mut T`
 - ▶ you cannot use the originating (owning) pointer (`T` or `Box<T>`) or
 - ▶ derive other borrowing pointers (mutable or not) from a mutable borrowing reference (`&mut T`)

where a mutable borrowing reference is *active* in scope

- ▶ *active* \approx may be used in future (omitting details)

```
1 fn mut_ref() {
2     let mut a = S{x: ...};
3     let m = &mut a; // make a mutable ref to a
4     ... a.x ...;   // NG: cannot use a (the originating pointer)
5     let d = &a;    // NG: cannot borrow from a either
6     let c = m;    // NG: cannot derive another reference
7     m.x          // --- m is active up to this point
8     ... a.x ...; // OK: as m no longer active here
9 }
```

A mutable borrowing reference enjoys no aliasing, too (even stronger one)

- ▶ like an owning pointer, a mutable reference also enjoys the no aliasing property
- ▶ even more strongly, it cannot alias with other borrowing references (mutable or not)
- ▶ `p` below cannot be an alias of any of others
- ▶ `q` and `r` may be an alias of each other

```
1 fn take_many(p: &mut T, q: &T, r: &T, a: T, b: Box<T>) {  
2     ...  
3 }
```

- ▶ discussions below are focused on memory management, and apply both to immutable and mutable references

Working with `Box<T>` or `&T`

- ▶ `Box<T>` and `&T` are both pointers
- ▶ you might naturally wonder which one to use when
- ▶ generally, use `Box<T>` to *link data structures together*
- ▶ use `&T` to *work on existing data structures without any allocation or deallocation*
- ▶ for this reason, many functions that take data structures as input take `&T`

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A technical remark about borrowers rule

- ▶ it's *not a creation* of a dangling pointer, *per se*, that is not allowed, but *dereferencing* of it
- ▶ *a slightly modified code below compiles without an error*, despite that `c` becomes a dangling pointer to `a` (as it is not dereferenced past `a`'s lifetime)

```
fn foo() -> i32 {  
    let c: &S; // a reference to S  
    { // an inner block  
        let b: &S; // another reference  
        let a = S{x: ...}; // allocate S  
        // OK (both a and b live only until the end of the inner block)  
        b = &a;  
        c = b; // dangerous (c outlives a)  
    } // a dies here, making c a dangling pointer  
    // c.x don't deref c  
}
```

A more precise statement of borrowers rule

1. for each borrowing reference ($\&T$ or $\&\text{mut } T$ type), Rust compiler determines *the lifetime of data it points to (referent lifetime)* as part of its static type

```
fn foo() -> i32 {  
    let c: &S; // → ??  
    {  
        let b: &S; // → ??  
        let a = S{x: ...};  
        b = &a;  
        c = b;  
    } // a dies here ( $\alpha$ )  
    c.x  
}
```

A more precise statement of borrowers rule

1. for each borrowing reference ($\&T$ or $\&\text{mut } T$ type), Rust compiler determines *the lifetime of data it points to (referent lifetime)* as part of its static type
2. assignment between borrowing pointers ($p = q$) equate their referent lifetimes

```
fn foo() -> i32 {  
    let c: &S; // → ??  
    {  
        let b: &S; // → ??  
        let a = S{x: ...};  
        b = &a;  
        c = b;  
    } // a dies here ( $\alpha$ )  
    c.x  
}
```


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```
fn foo() -> i32 {  
    let c: &S; // → ??  
    {  
        let b: &S; // →  $\alpha$   
        let a = S{x: ...}; // lives until  $\alpha$   
        b = &a; // b's referent lifetime = a's lifetime  
        c = b;  
    } // a dies here ( $\alpha$ )  
    c.x  
}
```

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fn foo() -> i32 {  
    let c: &S; //  $\rightarrow \alpha$   
    {  
        let b: &S; //  $\rightarrow \alpha$   
        let a = S{x: ...}; // lives until  $\alpha$   
        b = &a; // b's referent lifetime = a's lifetime  
        c = b; // c's referent lifetime = b's referent lifetime  
    } // a dies here ( $\alpha$ )  
    c.x  
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1. for each borrowing reference ($\&T$ or $\&\text{mut } T$ type), Rust compiler determines *the lifetime of data it points to (referent lifetime)* as part of its static type
2. assignment between borrowing pointers ($p = q$) equate their referent lifetimes
3. dereferencing a borrowing pointer p (e.g., $p.x$) is allowed only within the p 's referent lifetime

```
fn foo() -> i32 {  
    let c: &S; //  $\rightarrow \alpha$   
    {  
        let b: &S; //  $\rightarrow \alpha$   
        let a = S{x: ...}; // lives until  $\alpha$   
        b = &a; // b's referent lifetime = a's lifetime  
        c = b; // c's referent lifetime = b's referent lifetime  
    } // a dies here ( $\alpha$ )  
    c.x  
}
```

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fn foo() -> i32 {  
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    {  
        let b: &S; //  $\rightarrow \alpha$   
        let a = S{x: ...}; // lives until  $\alpha$   
        b = &a; // b's referent lifetime = a's lifetime  
        c = b; // c's referent lifetime = b's referent lifetime  
    } // a dies here ( $\alpha$ )  
    c.x // NG (deref outside c's referent lifetime =  $\alpha$ )  
}
```

Programming with borrowing references

- ▶ programs using borrowing references must help compilers track their referent lifetimes
- ▶ this must be done for functions called from unknown places, function calls to unknown functions and data structures
- ▶ to this end, the programmer sometimes must annotate *reference types with their referent lifetimes*

References in function parameters

- ▶ problem: how to check the validity of functions taking references

```
1 fn p_points_q(p: &mut P, q: &Q) {  
2   p.x = q; // OK?  
3 }
```

without knowing all its callers, and function calls passing references

```
1 let c = ...;  
2 {  
3   let a = Q{...};  
4   let b = &a;  
5   f(c, b);  
6 }  
7 ... c.x.y ... // OK?
```

without knowing the definition of f?

References in function return values

- ▶ problem: how to check the validity of functions returning references

```
1 fn return_ref(...) -> &P {  
2     ...  
3     let p: &P = ...  
4     ...  
5     p // OK?  
6 }
```

without knowing its all callers, and function calls receiving references from function calls

```
1 fn receive_ref() {  
2     ...  
3     let p: &P = return_ref(...);  
4     ...  
5     p.x // OK?  
6 }
```

References in data structures

- ▶ problem: how to check the validity of dereferencing a pointer obtained from a data structure

```
1 fn ref_from_struct() {  
2     ...  
3     let p: &P = a.p;  
4     ...  
5     p.x // OK?  
6 }
```

- ▶ what about functions taking data structures containing references and returning another containing references, etc.?

Reference type with a lifetime parameter

- ▶ to address this problem, Rust's borrowing reference types ($\&T$ or $\&\text{mut } T$) carry *lifetime parameter* representing their referent lifetimes
- ▶ syntax:
 - ▶ $\&'a T$: reference to “ T whose lifetime is $'a$ ”
 - ▶ $\&'a \text{ mut } T$: ditto; except you can modify data through it

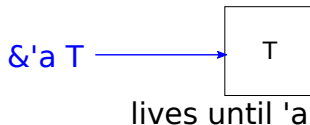


lives until 'a

- ▶ *every* reference carries a lifetime parameter, though there are places you can omit them
- ▶ roughly, you must write them explicitly in function parameters, return types, and struct/enum fields; and can omit them for local variables

Reference type with a lifetime parameter

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- ▶ roughly, you must write them explicitly in function parameters, return types, and struct/enum fields; and can omit them for local variables

Attaching lifetime parameters to functions

- ▶ the following does not compile

```
1 fn foo(ra: &i32, rb: &i32, rc: &i32) -> &i32 {  
2     ra  
3 }
```

- ▶ with errors like

```
1 |  
2 | fn foo(ra: &i32, rb: &i32, rc: &i32) -> &i32 {  
3 |           ----      ----      ----      ^ expected named lifetime parameter  
4 | |  
5 = help: this function's return type contains a borrowed value, but the signature does not  
   say whether it is borrowed from 'ra', 'rb', or 'rc'  
6 help: consider introducing a named lifetime parameter  
7 |  
8 | fn foo<'a>(ra: &'a i32, rb: &'a i32, rc: &'a i32) -> &'a i32 {  
9 |           ++++      ++           ++           ++           ++
```

Why do we need an annotation, *fundamentally*?

- ▶ without any annotation, how to know whether this is safe, *without knowing the definition of foo?*

```
1 {  
2   let r : &i32;  
3   let a = 123;  
4   {  
5     let b = 456;  
6     {  
7       let c = 789;  
8       r = foo(&a, &b, &c);  
9     }  
10  }  
11  *r  
12 }
```

- ▶ essentially, the compiler complains “tell me what kind of lifetime `foo(&a, &b, &c)` has”

Attaching lifetime parameters to functions

- ▶ syntax:

```
1 fn f<'a, 'b, 'c, ...>(p0 : T0, p1 : T1, ...) -> Tr { ... }
```

T_0, T_1, \dots and T_r may use `'a`, `'b`, `'c`, ... as lifetime parameters (e.g., `&'a i32`)

- ▶ `f<'a, 'b, 'c, ...>` is a function that takes parameters of respective lifetimes

One way to attach lifetime parameters

```
1 fn foo<'a>(ra: &'a i32, rb: &'a i32, rc: &'a i32) -> &'a i32
```

- ▶ effect: the return value is assumed to point to the shortest of the three
- ▶ why? generally, when Rust compiler finds `foo(x, y, z)`, it tries to determine `'a` so that it is contained in the lifetime of all (x , y and z)
- ▶ as a result, our program does not compile, even if `foo(&a, &b, &c)` in fact returns `&a`

```
1 {
2   let r: &i32;
3   let a = 123;
4   {
5     let b = 456;
6     {
7       let c = 789;
8       r = foo(&a, &b, &c); // 'a ← shortest of { $\alpha, \beta, \gamma$ } =  $\gamma$ 
9       // and r's type becomes  $\&\gamma$  i32
10      } // c's lifetime (=  $\gamma$ ) ends here
11    } // b's lifetime (=  $\beta$ ) ends here
12    *r // NG, as we are outside  $\gamma$ 
13  } // a's lifetime (=  $\alpha$ ) ends here
```

An alternative

```
1 fn foo<'a, 'b, 'c>(ra: &'a i32, rb: &'b i32, rc: &'c i32) -> &'a i32
```

- ▶ signifies that the return value points to data whose lifetime is `ra`'s referent lifetime (and has nothing to do with `rb`'s or `rc`'s)
- ▶ for `foo(x, y, z)`, Rust compiler tries to determine `'a` so it is contained in the lifetime of `x`'s referent (therefore `'a = α`)
- ▶ as a result, the program we are discussing compiles

```
1 {  
2   let r: &i32;  
3   let a = 123;  
4   {  
5     let b = 456;  
6     {  
7       let c = 789;  
8       r = foo(&a, &b, &c); // 'a → shortest of { $\alpha$ } =  $\alpha$   
9       // and r's type becomes & $\alpha$  i32  
10      } // c's lifetime (=  $\gamma$ ) ends here  
11     } // b's lifetime (=  $\beta$ ) ends here  
12     *r // OK, as here is within  $\alpha$   
13   } // a's lifetime (=  $\alpha$ ) ends here
```

Types with lifetime parameters capture/constrain the function's behavior

- ▶ what if you try to fool the compiler by

```
1 fn foo<'a, 'b, 'c>(ra: &'a i32, rb: &'b i32, rc: &'c i32) -> &'a i32
2     rb
3 }
```

- ▶ the compiler rejects returning `rb` (of type `&'b`) when the function's return type is `&'a`
- ▶ in general, *the compiler allows assignments only between references having the same lifetime parameter*

Another example (make a reference between inputs)

▶ what if we rewrite

```
1 r = foo(&a, &b, &c);
```

into

```
1 bar(&mut r, &a, &b, &c);
```

with bar something like

```
1 fn bar(r: &mut &i32, a: &i32, b: &i32, c: &i32) {  
2   *r = a;  
3 }
```

Make a reference between inputs

- ▶ how to specify lifetime parameters so that
 1. `*r = a;` in `bar`'s definition is allowed, and
 2. we can dereference `*r` at the end of the caller?

```
1 {
2   let a = 123;
3   let mut r = &0;
4   {
5     let b = 456;
6     {
7       let c = 789;
8       bar(&mut r, &a, &b, &c); // r → ???
9     } // c's lifetime (= γ) ends here
10  } // b's lifetime (= β) ends here
11  *r // OK???
12 } // a's lifetime (= α) ends here
```

Answer

- ▶ again, we need to signify `r` points to `a` (and not `b` or `c` after `bar(&r, &a, &b, &c)`)
- ▶ a working lifetime parameter is the following

```
1 fn bar<'a, 'b, 'c>(r: &mut &'a i32, a: &'a i32,  
2                   b: &'b i32, c: &'c i32) {  
3     *r = a;  
4 }
```

References in data structures

- ▶ problem: how to check the validity of programs using data structure containing a borrowing reference

```
1 struct R {  
2   p: &i32  
3   ...  
4 }
```

and functions returning R

```
1 fn ret_r(a: &i32, b: &i32, c: &i32) -> R {  
2   R{p: a}  
3 }
```

or taking R (or reference to it)

```
1 fn take_r(r: &mut R, a: &i32, b: &i32, c: &i32) {  
2   r.p = a;  
3 }
```

References in data structures

- ▶ you cannot simply have a field of type $\&T$ in struct/enum like this

```
1 struct R {  
2     p: &i32  
3     ...  
4 }
```

- ▶ you need to specify the lifetime parameter of `p`, and signifies that `R` takes a lifetime parameter

```
1 struct R<'a> {  
2     p: &'a i32  
3     ...  
4 }
```

- ▶ `R<'a>` represents `R` whose `p` field points `i32` whose lifetime is `'a`

Attaching lifetime parameters to data structure

- ▶ say we like to have data structures

```
1 struct T { x: i32 }  
2 struct S { p: &T }
```

and a function

```
1 fn make_s(a: &T, b: &T) -> S { S{p: a} }
```

so that the following compiles

```
1 let s;  
2 let a = T{...};  
3 {  
4     let b = T{...};  
5     s = make_s(&a, &b);  
6 }  
7 s.p.x
```

- ▶ the compiler needs to verify `s.p` points to `a`, not `b`
- ▶ we have to signify that by appropriate lifetime parameters

Answer

- ▶ define `S<'a>` so
 - ▶ its `p`'s referent lifetime is `'a`

```
1 struct S<'a> { p: &'a T }
```

- ▶ define `make_s` so it returns `S<'a>` where `'a` is the referent lifetime of its *first* parameter

```
1 fn make_s(a: &'a T, b: &'b T) -> S<'a> {  
2   S{p: a}  
3 }
```

A more complex example Rust cannot verify

- ▶ say we now have data structures

```
1 struct T { x: i32 }
2 struct S {
3     p: &T,
4     q: &T
5 }
```

and a function

```
1 fn make_s(a: &T, b: &T) -> S { S{p: a, q: b} }
```

so that the following compiles

```
1 let s;
2 let a = T{...};
3 {
4     let b = T{...};
5     s = make_s(&a, &b);
6 }
7 s.p.x
```

- ▶ again, the compiler needs to verify `s.p` points to `a`, not `b`

Answer that I thought should work but didn't

- ▶ define `S` so
 - ▶ its `p` points to `T` of lifetime `'a` and
 - ▶ its `q` points to `T` of lifetime `'b`

```
1 struct S<'a, 'b> {  
2   p: &'a T,  
3   q: &'b T  
4 }
```

- ▶ define `make_s` so it returns `S<'a, 'b>` where `'a` is the lifetime of its first parameter, like

```
1 fn make_s(a: &'a T, b: &'b T) -> S<'a, 'b> {  
2   S{p: a, q: b}  
3 }
```

The compiler complains

```
1 [E0597] Error: 'b' does not live long enough
2   [command_36:1:1]
3   16 |     s = make_s(&a, &b);
4       |           ---
5       |           +---- borrowed value does not live long enough
6   17 | }
7       | -
8       | +---- 'b' dropped here while still borrowed
9   18 | s.p.x
10      | -----
11      | +----- borrow later used here
12
```

- ▶ I don't know what is the exact spec of Rust that rejects this program, but I hypothesize that to dereference `s` for any field (`p`), all fields must be alive

Contents

Overview

Rust basics

Assignments move the value

`Box<T>` (owning pointer) type

`&T` (borrowing pointer) type

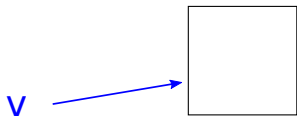
Borrow checking details

Summary

Why memory management is difficult

- ▶ every language wants to prevent *dereferencing a pointer to an already-reclaimed memory block (dangling pointer)*

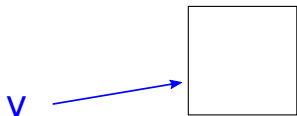
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{  
  let v = T{x: ...};  
  ...  
}
```



Why memory management is difficult

- ▶ *every language wants to prevent dereferencing a pointer to an already-reclaimed memory block (dangling pointer)*
- ▶ *the problem would have been trivial if you could reclaim v 's referent as soon as v goes out of scope*

```
{  
  let v = T{x: ...};  
  ...  
}
```



Why memory management is difficult

- ▶ every language wants to prevent *dereferencing a pointer to an already-reclaimed memory block (dangling pointer)*
- ▶ the problem would have been trivial if *you could reclaim v's referent as soon as v goes out of scope*

```
{  
  let v = T{x: ...};  
  ...  
} // OK to drop v's referent here?
```



Why memory management is difficult

- ▶ every language wants to prevent *dereferencing a pointer to an already-reclaimed memory block (dangling pointer)*
- ▶ the problem would have been trivial if *you could reclaim v 's referent as soon as v goes out of scope*
- ▶ this is not the case, as *v 's referent may still be reachable from other variables when v goes out of scope*

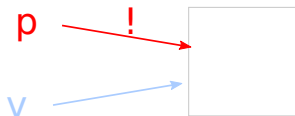
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  let v = T{x: ...};  
  ...  
}
```



Why memory management is difficult

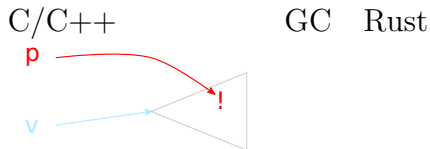
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- ▶ this is not the case, as *v's referent may still be reachable from other variables when v goes out of scope*

```
let p : &T;  
{  
  let v = T{x: ...};  
  ...  
  p = &v;  
} // v never used below, but its referent is  
... p.x ...
```



C vs. GC vs. Rust

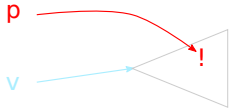
- ▶ C/C++ : it's up to you



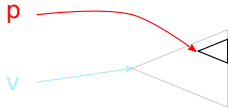
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C/C++



GC

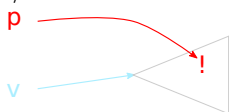


Rust

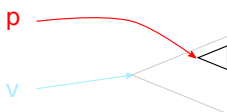
C vs. GC vs. Rust

- ▶ C/C++ : it's up to you
- ▶ GC : if it is reachable from other variables, I retain it for you
- ▶ Rust : when v goes out of scope,
 1. I reclaim T_v , all data *reachable from v through owning pointers*
 2. T_v may be reachable from other variables via borrowing references, but I nevertheless guarantees a reclaimed memory block is never accessed

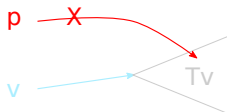
C/C++



GC

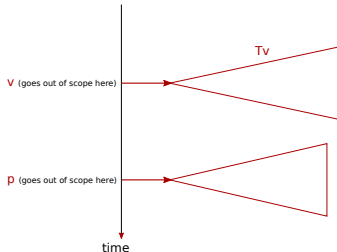


Rust



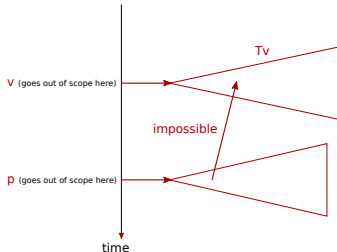
How Rust achieved it?

- ▶ recall the “single-owner rule,” which guarantees there is only one owning pointer to any node



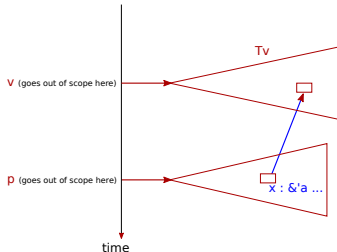
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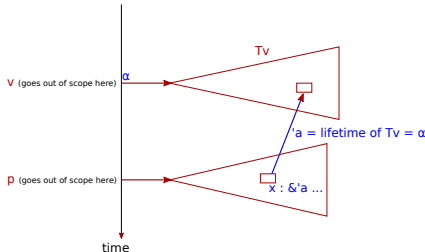
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- ▶ crucially, such a borrowing pointer must have a lifetime parameter of the referent



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- ▶ recall the “single-owner rule,” which guarantees there is only one owning pointer to any node
- ▶ \Rightarrow there can be no *owning* pointers from outside T_v to inside T_v
- ▶ \Rightarrow any such pointer must be a borrowing pointer
- ▶ crucially, such a borrowing pointer must have a lifetime parameter of the referent
- ▶ as a result, a pointer that can reach T_v cannot be dereferenced after v goes out of scope

