Programming Languages (6)
Rust Memory Management

Kenjiro Taura

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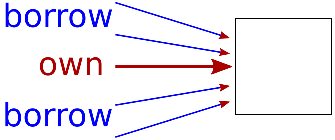
Rust's basic idea to memory management

- 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 ≈
   - 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 (≈ 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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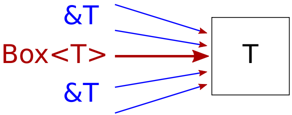
Pointer-like data types in Rust

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>`



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[1] we 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

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

```

- 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

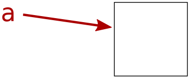
```
x = y;
// y can no longer be used
```

- e.g.,

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




}
```



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

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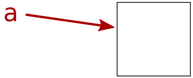
```
x = y;
// y can no longer be used
```

- e.g.,

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



}
```



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

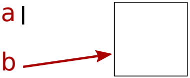
- to maintain only one "owner" pointer, an assignment in Rust *moves* the value out of righthand side, disallowing further use of it

```
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;


}
```



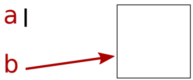
Assignments do *not copy*, but *move*, the value

- 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;
  a.x; // NG, the value has moved out
  b.x; // OK
}
```



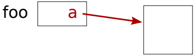
Argument-passing also moves the value

- 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



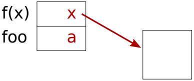
}
```



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

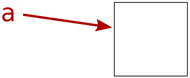
```
#[derive(Copy, Clone)]
struct S { ... }
```

- 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

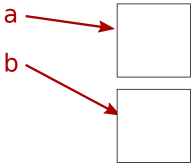
- define your struct with `#[derive(Copy, Clone)]` like

```
#[derive(Copy, Clone)]
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;


}
```



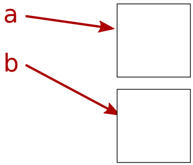
Copy trait

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

```
#[derive(Copy, Clone)]
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;
  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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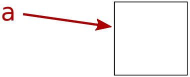
`Box<`T`>` makes an owning pointer

- 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




}
```



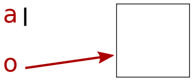
`Box<`T`>` makes an owning pointer

- 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)



}
```

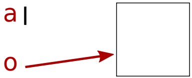


`Box<`T`>` makes an owning pointer

- 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


}
```

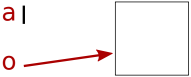


`Box<`T`>` makes an owning pointer

- 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

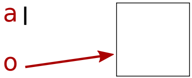
}
```



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

```
fn foo() {
  ...
  {
    let a = S{...};
    let p = Box::new(a);
  } // --- S{...} will die here, too
}
```

just like

```
fn foo() {
  ...
  {
    let a = S{...};
    let p = a;
  } // --- S{...} will die here
}
```

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

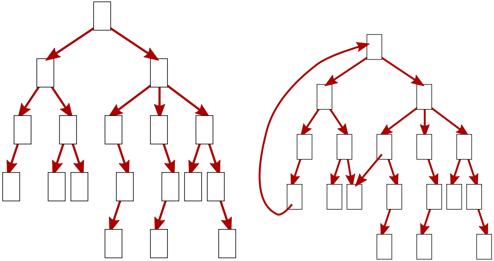
- for any value v of type T, you can only have one and only one (still usable) variable that refers to v, which is *either of type* T *or* `Box::<`T`>`
- in this sense, you can think of T as just another kind of pointer to T just like `Box::<`T`>`
- so is there any reason for Rust to have both T and `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 `Box<`T`>`),
  - 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
  - `Vec<`T`>` to represent nodes and `Vec<(i32,i32)>` 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

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

- 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

a : S

b : &S

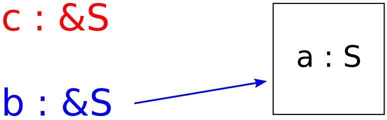
Borrowers rule in action

- 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
    // OK (both a and b live only until the end of the inner block)
    b = &a;

  }

}
```



Borrowers rule in action

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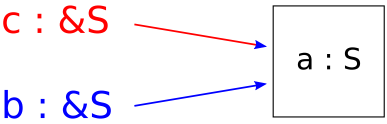
    let b:  &S; // another reference
    let a = S{x:  ...}; // allocate S
    // OK (both a and b live only until the end of the inner block)
    b = &a;
    c = b; // dangerous (c outlives a)
  }

}
```

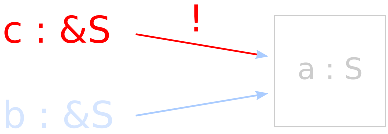


Borrowers rule in action

- 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* ≈ may be used in future (omitting details)

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

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

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

- 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 `&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 (α)
  c.x
}
```

A more precise statement of borrowers rule

1. for each borrowing reference (`&`T or `&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 (α)
  c.x
}
```

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1. for each borrowing reference (`&`T or `&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; // → α
    let a = S{x: ...}; // lives until α
    b = &a; // b's referent lifetime = a's lifetime
    c = b;
  } // a dies here (α)
  c.x
}
```

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  {
    let b: &S; // → α
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    b = &a; // b's referent lifetime = a's lifetime
    c = b; // c's referent lifetime = b's referent lifetime
  } // a dies here (α)
  c.x
}
```

A more precise statement of borrowers rule

1. for each borrowing reference (`&`T or `&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; // → α
  {
    let b: &S; // → α
    let a = S{x: ...}; // lives until α
    b = &a; // b's referent lifetime = a's lifetime
    c = b; // c's referent lifetime = b's referent lifetime
  } // a dies here (α)
  c.x
}
```

A more precise statement of borrowers rule

1. for each borrowing reference (`&`T or `&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; // → α
  {
    let b: &S; // → α
    let a = S{x: ...}; // lives until α
    b = &a; // b's referent lifetime = a's lifetime
    c = b; // c's referent lifetime = b's referent lifetime
  } // a dies here (α)
  c.x // NG (deref outside c's referent lifetime = α)
}
```

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

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

without knowing all its callers, and function calls passing references

```
let c = ...;
{
  let a = Q{...};
  let b = &a;
  f(c, b);
}
... 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

```
fn return_ref(...) -> &P {
  ...
  let p: &P = ...
  ...
  p // OK?
}
```

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

```
fn receive_ref() {
  ...
  let p: &P = return_ref(...);
  ...
  p.x // OK?
}
```

References in data structures

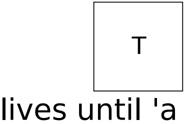
- problem: how to check the validity of dereferencing a pointer obtained from a data structure

```
fn ref_from_struct() {
  ...
  let p: &P = a.p;
  ...
  p.x // OK?
}
```

- 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 `&mut` T) carry *lifetime parameter* representing their referent lifetimes
- syntax:
  - `&'`a T : reference to "T whose lifetime is `'`a"
  - `&'`a `mut T` : ditto; except you can modify data through it



- *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

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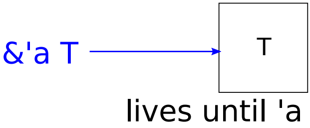


- *every* reference carries a lifetime parameter, though there are places you can omit them
- roughly, you must write them explicitly in function parameters, return types, and struct/enum fields; and can omit them for local variables

Attaching lifetime parameters to functions

- the following does not compile

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

- with errors like

```
|
| fn foo(ra: &i32, rb: &i32, rc: &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 ‘ra‘, ‘rb‘, or ‘rc‘
help: consider introducing a named lifetime parameter
|
| fn foo<’a>(ra: &’a i32, rb: &’a i32, rc: &’a i32) -> &’a i32 {
|       ++++      ++             ++             ++           ++
```

Why do we need an annotation, *fundamentally?*

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

```
{
  let r : &i32;
  let a = 123;
  {
    let b = 456;
    {
      let c = 789;
      r = foo(&a, &b, &c);
    }
  }
  *r
}
```

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

Attaching lifetime parameters to functions

- syntax:

```
fn $f$<'a,'b,'c,...>($p_0$ : $T_0$, $p_1$ : $T_1$, ...) -> $T_r$ { ... }
```

  $T_0, T_1, \cdots$ 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

-
  ```
  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`

```
{
  let r: &i32;
  let a = 123;
  {
    let b = 456;
    {
      let c = 789;
      r = foo(&a, &b, &c); // ’a ← shortest of {α, β, γ} = γ
      // and r’s type becomes &γ i32
    } // c’s lifetime (= γ) ends here
  } // b’s lifetime (= β) ends here
  *r // NG, as we are outside γ
} // a’s lifetime (= α) ends here
```

An alternative

-
```
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` $= \alpha$)
- as a result, the program we are discussing compiles

```
{
  let r: &i32;
  let a = 123;
  {
    let b = 456;
    {
      let c = 789;
      r = foo(&a, &b, &c); // 'a → shortest of {α} = α
      // and r's type becomes &α i32
    } // c's lifetime (= γ) ends here
  } // b's lifetime (= β) ends here
  *r // OK, as here is within α
} // a's lifetime (= α) ends here
```

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

- what if you try to fool the compiler by

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

- 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

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

  into

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

  with `bar` something like

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

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?

```
{
  let a = 123;
  let mut r = &0;
  {
    let b = 456;
    {
      let c = 789;
      bar(&mut r, &a, &b, &c); // r → ???
    } // c's lifetime (= γ) ends here
  } // b's lifetime (= β) ends here
  *r // OK???
} // 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

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

References in data structures

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

```
struct R {
  p: &i32
  ...
}
```

and functions returning `R`

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

or taking `R` (or reference to it)

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

References in data structures

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

```
struct R {
  p: &i32
  ...
}
```

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

```
struct R<'a> {
  p: &'a i32
  ...
}
```

- `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

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

and a function

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

so that the following compiles

```
  let s;
  let a = T{...};
  {
    let b = T{...};
    s = make_s(&a, &b);
  }
  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`

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

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

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

A more complex example Rust cannot verify

- say we now have data structures

```
struct T { x: i32 }
struct S {
  p: &T,
  q: &T
}
```

and a function

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

so that the following compiles

```
  let s;
  let a = T{...};
  {
    let b = T{...};
    s = make_s(&a, &b);
  }
  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`

```
struct S<’a, ’b> {
  p: &’a T,
  q: &’b T
}
```

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

```
fn make_s(a:  &’a T, b:  &’b T) -> S<’a, ’b> {
  S{p: a, q: b}
}
```

The compiler complains

```
[E0597] Error: ‘b‘ does not live long enough
    [command_36:1:1]
 16 │    s = make_s(&a, &b);
    .                  ---
    .                   +--- borrowed value does not live long enough
 17 │  }
    . _
    . +--- ‘b‘ dropped here while still borrowed
 18 │  s.p.x
    . -----
    .   +----- borrow later used here

```

- 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

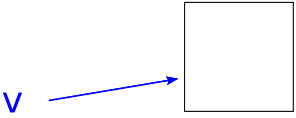
Contents

Why memory management is difficult

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

```
{
  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*

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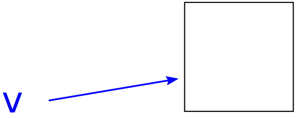
  let v = T{x:  ...};
  ...

}
```



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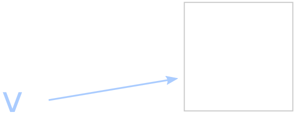
- the problem would have been trivial if *you could reclaim v's referent as soon as v goes out of scope*

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

} // OK to drop v's referent here?
```



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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*

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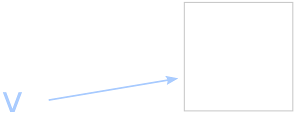

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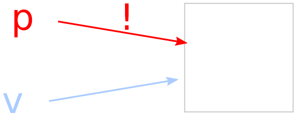
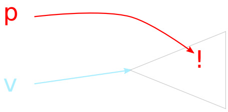
```
let p : &T;
{
  let v = T{x: ...};
  ...
  p = &v;
} // v never used below, but its referent is
... p.x ...
```



C vs. GC vs. Rust

- C/C++ : it's up to you

C/C++ GC Rust



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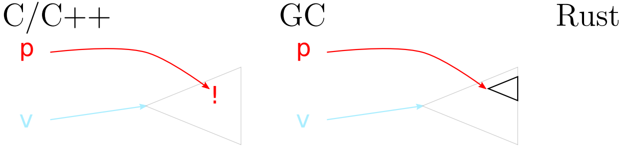
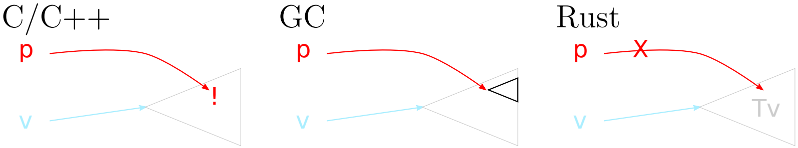


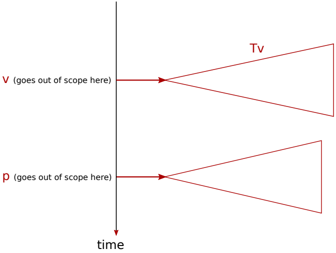
C vs. GC vs. Rust

- 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



How Rust achieved it?

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



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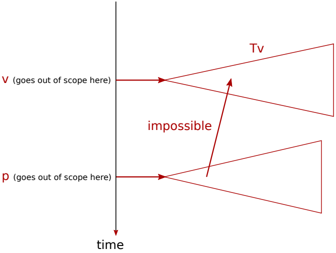
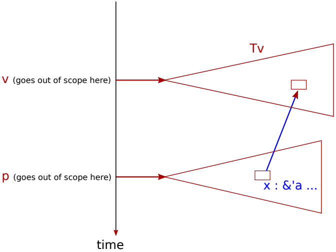
- $\Rightarrow$ there can be no *owning* pointers from outside T_v to inside T_v



How Rust achieved it?

- recall the "single-owner rule," which guarantees there is only one owning pointer to any node
- ⇒ there can be no *owning* pointers from outside T_v to inside T_v
- ⇒ any such pointer must be a borrowing pointer



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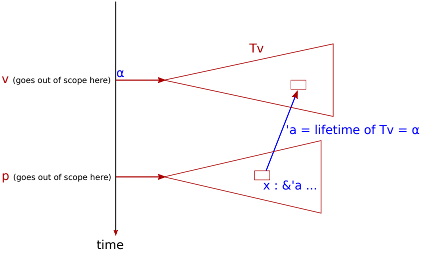

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- ⇒ there can be no *owning* pointers from outside T_v to inside T_v
- ⇒ any such pointer must be a borrowing pointer
- crucially, such a borrowing pointer must have a lifetime parameter of the referent
- as a result, a pointer that can reach T_v cannot be dereferenced after v goes out of scope