Rust Memory Management

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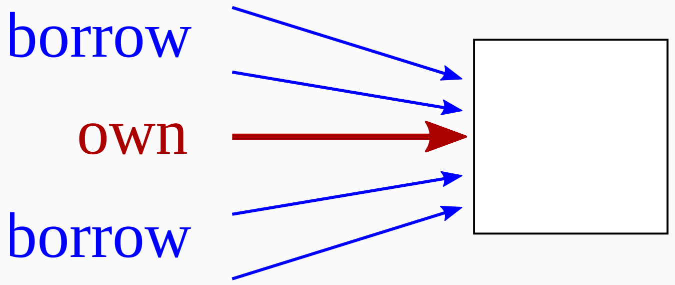
Introduction

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 owning pointer)*
  2. there are any number of non-owning pointers to it *(borrowing pointers)*
  3. *borrowing pointers cannot be dereferenced after the owning pointer goes away*
- ⇒ *it can safely reclaim the data when the owning pointer goes away*

"*single-ownership rule*"



```
{
  let a = S{x: …, y: …};
  …
} // what a points to will be gone here
```

The rules are enforced statically

- Rust enforces the rules (or, detect violations thereof)
  - *statically*, not *dynamically*
  - *compile-time*, not at *runtime*
  - *before* execution, not *during* execution

“borrow checker”

Escaping from the single ownership model

- there are actually some ways to get around the rules

1. reference counting pointers (≈ multiple owning pointers)
   - counts the number of owners *at runtime*, and reclaim the data when all these pointers are gone
2. unsafe/raw pointers (≈ totally up to you)

they are not specific to Rust, and we’ll not cover them below

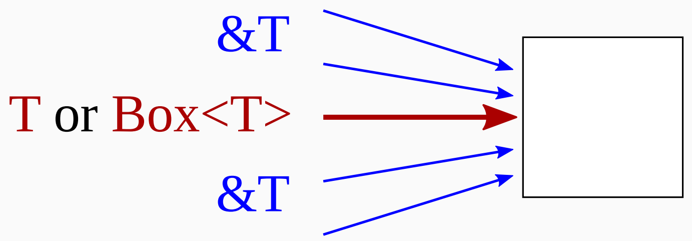
Rust Basics

Pointer-like data types in Rust

given a type T (`i32`, struct, enum, …), below are types representing "references (pointers) to T"

1. T : owning pointer to T
2. `Box<`T`>` (pronounced "*box* T") : owning pointer to T
3. &T (pronounced "*ref* T") : borrowing 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, `Box<`T`>` *and* &T



Pointer-making expressions

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

- `Box::new(`e`)` (of type `Box<`T`>`) : an owning pointer
- &e (of type &T) : a borrowing pointer

An example

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

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

Owning Pointers

Assignments of owning pointers

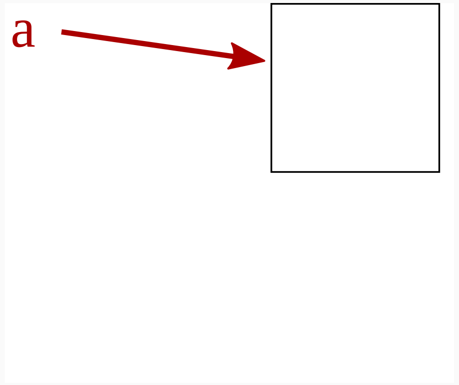
- to maintain the "single-owner" rule, an assignment of owning pointers in Rust *does not copy, but moves it* out of the righthand side, disallowing further use of it

`b = a;` *// a cannot be used below*

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



}
```

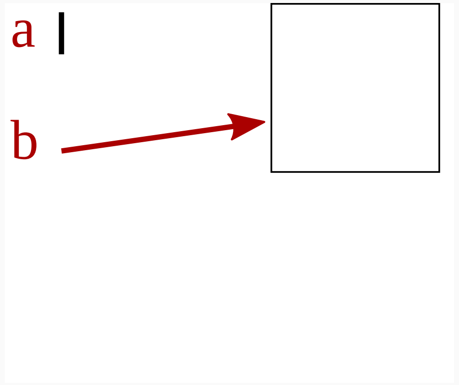


Assignments of owning pointers

- to maintain the “single-owner” rule, an assignment of owning pointers in Rust *does not copy, but moves it* out of the righthand side, disallowing further use of it

`b = a;` *// a cannot be used below*

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



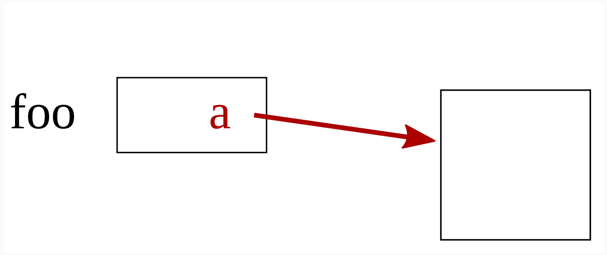
Argument-passing also moves the reference

- passing a value to a function also moves the reference out of the source

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



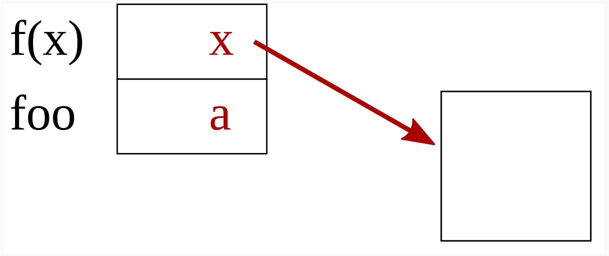
}
```



Argument-passing also moves the reference

- passing a value to a function also moves the reference out of the source

```
fn foo() {
  let a = S{x: …, y: …};
  … a.x …; // OK, as expected
  … a.y …; // OK, as expected
  // moves the reference out of a
  f(a);
  a.x; // NG, the reference has moved
}
```



Exceptions to “assignment moves the reference”

- you may notice the moving assignment contradicts what you have seen

  `b = a;` *// a cannot be used after this*

- if it applies everywhere, does the following program violate it?

```
fn foo() -> f64 {
  let a = 123.456;
  let b = a; // does the reference to 123.456 move out from a!?
  a + 0.789    // if so, is this invalid!?
}
```

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

Copy trait

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

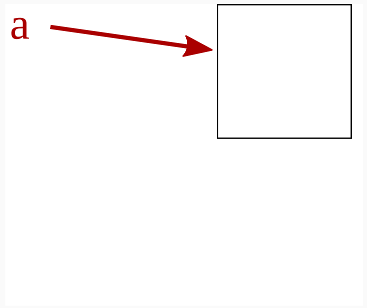
```
#[derive(Copy, Clone)]
struct S { … }
```

- ⇒ assignment or argument-passing of `S` *copies* the righthand side

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



}
```



- note: copy types trivially maintain the single-owner rule

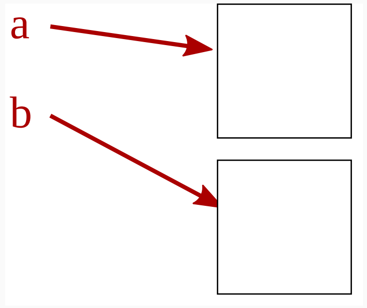
Copy trait

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

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

- ⇒ assignment or argument-passing of `S` *copies* the 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
}
```



- note: copy types trivially maintain the single-owner rule

Box<T> type

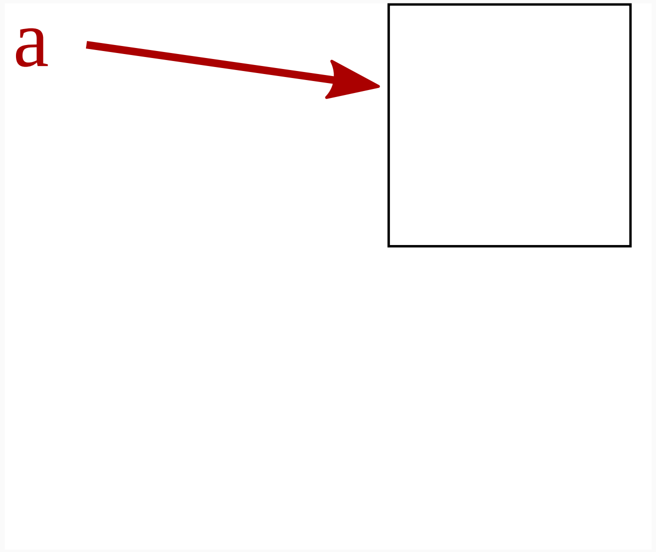
Box<T> makes an owning pointer

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

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



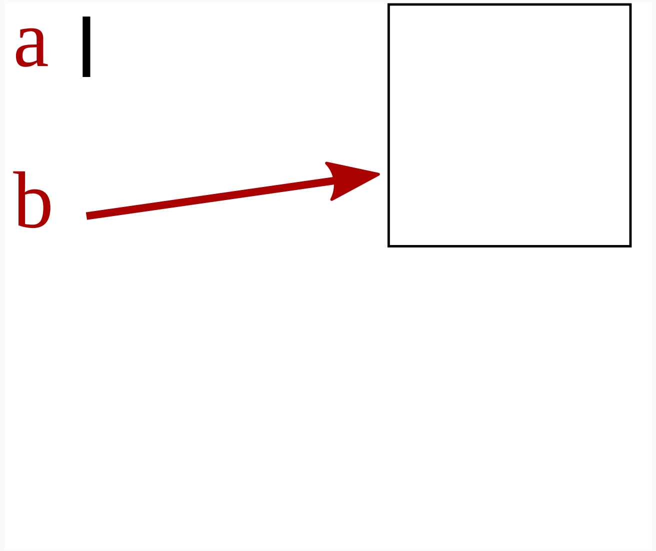

}
```



Box<T> makes an owning pointer

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

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



Difference between T and `Box`<T>?

- as you have seen, the effects of

```
let b = a
```

and

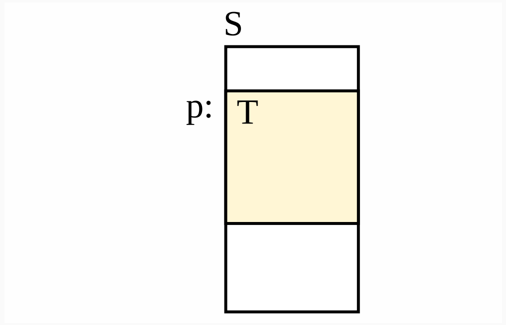
```
let b = Box::new(a)
```

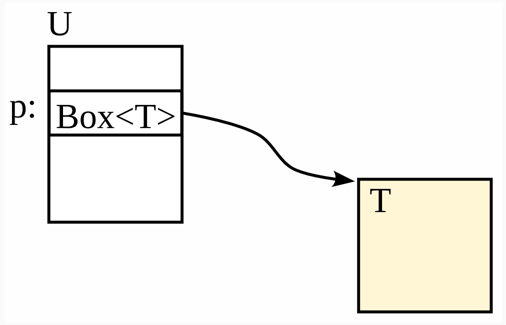
look very similar (identical)

- as far as data lifetime is concerned, it is in fact safe to say they are
- Rust has distinction between them for
  1. specifying data layout
  2. allowing dynamic dispatch only for `Box`<T>
  3. specifying where data are allocated (stack vs. heap)

Data layout differences between T and `Box<`T`>`

- `S` and `U` below have different data layouts
  - `struct S { …, p:` T`, }` "embeds" a T into `S`
  - `struct U { …, p: Box<`T`>, }` has `p` point to a separately allocated T



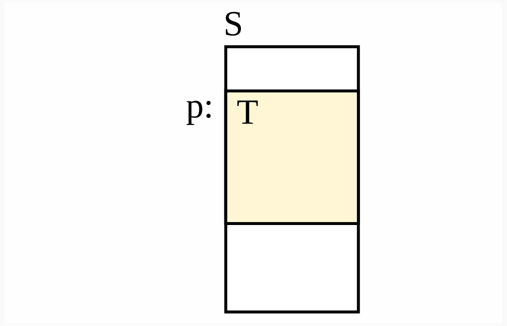


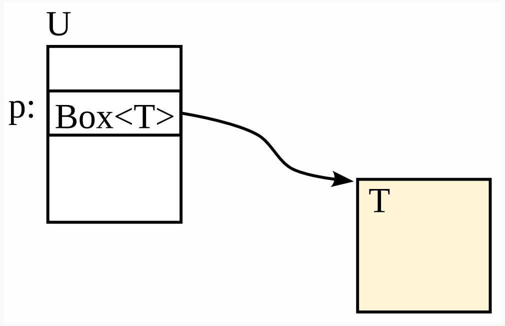
Data layout differences between T and `Box<`T`>`

- in particular, `Box<`T`>` is essential to define recursive data structures
  - `struct S { …, p: S, }` is not allowed, whereas
  - `struct U { …, p: Box<U>, }` is
- note: `U` above can never be constructed; a recursive data structure typically looks like
  - `struct U { …, p: Option<Box<U>>, }`

Data layout differences between T and `Box`<T>

- the distinction is insignificant when discussing lifetimes





- in both cases, data of T (yellow box) is gone exactly when the enclosing structure is gone
- another difference is that Rust allocates T on stack and move it to heap when `Box`<T> is made
- again, it has nothing to do with lifetime (unlike C/C++)

Owning pointers and control flows

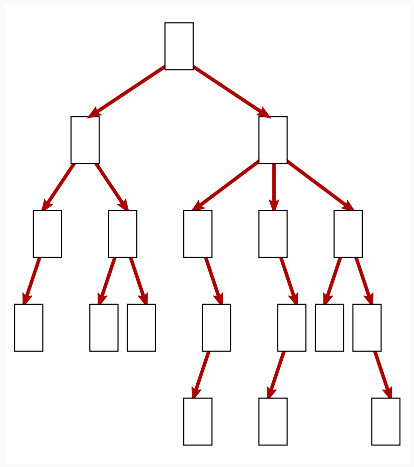
- Rust compiler determines, for each variable of owning pointer type (T or `Box<`T`>`), at which point the variable is can be used or *valid* (i.e., the value has not been moved out)
- it may be a *conservative* estimate

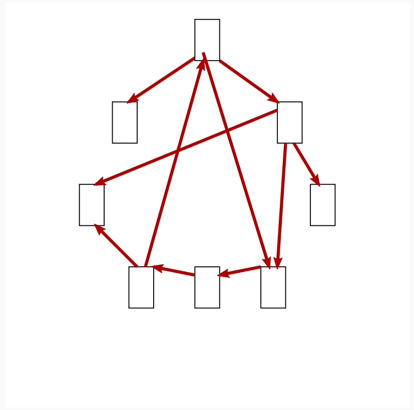
```
fn foo() {
  let a = S{x: …, y: …};
  if … {
    let b = a;
  }
  … a.x … // NG
}
```

```
fn foo() {
  let a = S{x: …, y: …};
  for … {
    let b = a; // NG
  }
}
```

A (huge) implication of the single-owner rule

- with only owning pointers (T and `Box<`T`>`),
  - you can make *a tree* of data,
  - but you *cannot make a general graph* with joins or cycles, where *a node may be pointed to by multiple nodes*
- to make a graph whose nodes are T, use either
  - &T to represent edges, or
  - `Vec<`T`>` to represent nodes and `Vec<(i32, i32)>` to represent edges

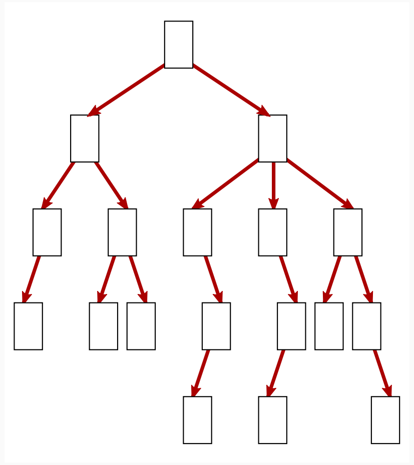




The (huge) implication to memory management

- with only owning pointers (i.e., no borrowing pointers)
- *whenever an owning pointer is gone* (e.g.,
  - a variable goes out of scope or
  - a variable or field is overwritten),

  the entire tree rooted from the pointer can be safely reclaimed



- Rust exactly does that, with the additional guarantee that *borrowing pointers are never dereferenced after its owning pointer is gone*

Borrowing pointers (&T)

Basics

- you can derive any number of borrowing pointers (&T) from T or `Box<`T`>`
- the owning pointer remains valid after a borrowing pointer has been made

```
let a = S{x: .., y: ..};
let b = &a;
… a.x + b.x … // OK
```

- the issue is how to prevent a program from *dereferencing borrowing pointers after its owning pointer is gone*

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








}
```

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

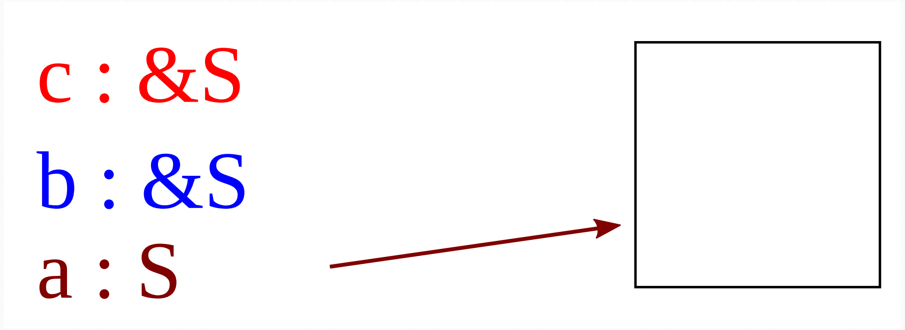
- a borrowing pointer cannot be dereferenced after its owning pointer is gone

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



  }

}
```



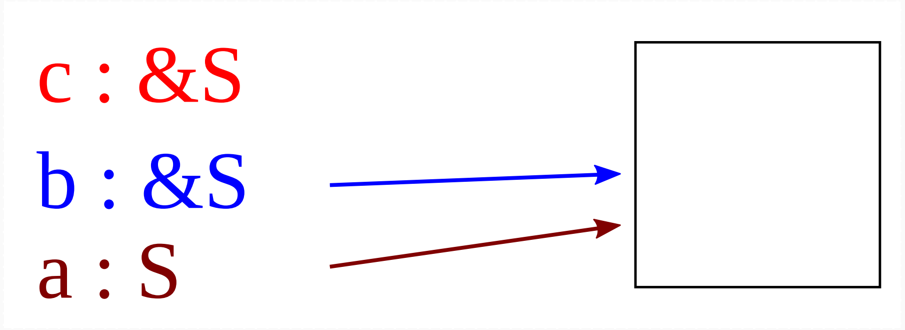
Borrowers rule in action

- 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;

  }

}
```

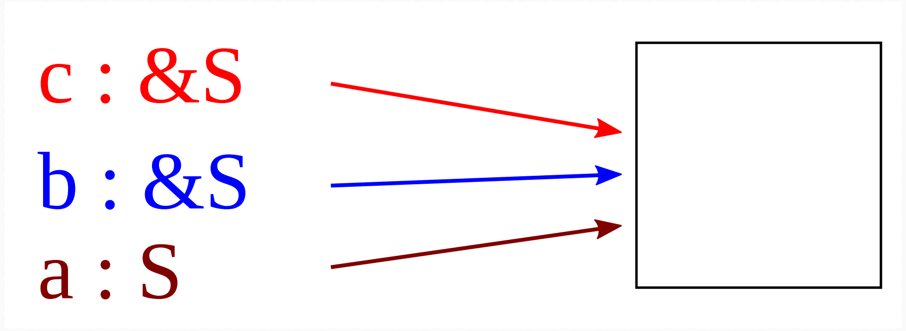


Borrowers rule in action

- 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)
  }

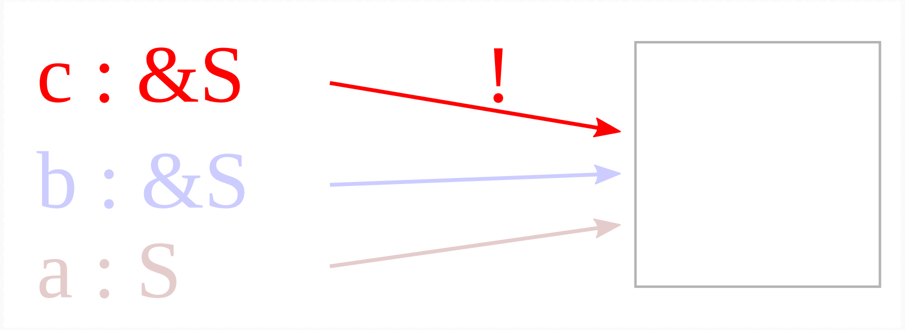
}
```



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)

- data cannot be modified through ordinary borrowing references &T

```
let a : S = S{x: 10, y: 20};
let b : &S = &a;
b.x = 100; // NG
```

- i.e., &T is the type of *immutable* references
- you can modify data only through *a mutable reference* (`&mut` T)

```
let mut a : S = S{x: 10, y: 20};
let b : &mut S = &mut a;
b.x = 100; // OK
```

- the difference is largely orthogonal to memory management

Borrow checking details

A technical remark about the borrow checking

- 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 }
```

How borrow checking works : lifetime

- *lifetime* of data
  - $=$ program points where the data has not been deallocated
  - $=$ program points where the data's owning pointer is valid
- for each borrowing pointer, Rust compiler determines the *lifetime* of data it points to *(referent lifetime)* as its static type
- upon assignment $p = q$ between borrowing pointers, it demands

$$\text{referent lifetime of } p \subset \text{referent lifetime of } q$$

How borrow checking basically works

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

1. the owning pointer `a`'s lifetime is the inner block (call it α)
2. due to the assignments,
   - `b`'s referent lifetime $\subset \alpha$
   - `c`'s referent lifetime $\subset \alpha$
3. $\therefore$ `c.x` outside the inner block ($\not\subset \alpha$) is invalid

Programming with borrowing references

- in more general cases, 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:

1. functions taking references, *without knowing all its callers*,

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

2. and function calls passing references, *without knowing the definition of `f`?*

```
let c = …;
{
  let a = Q{…};
  let b = &a;
  f(c, b);
} … c.x.y … // OK?
```

References in data structures

- problem: how to check the validity of:

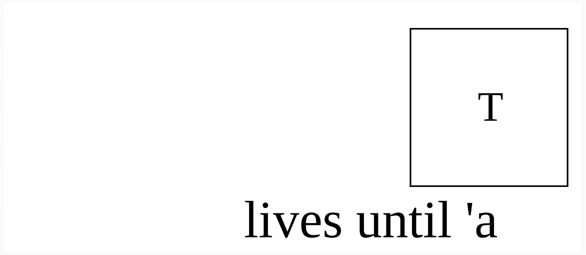
1. dereferencing a pointer obtained from a data structure

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

2. 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*



Reference type with a lifetime parameter

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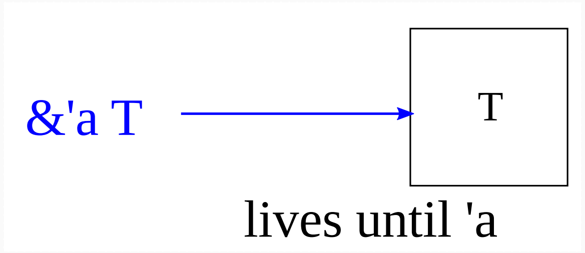
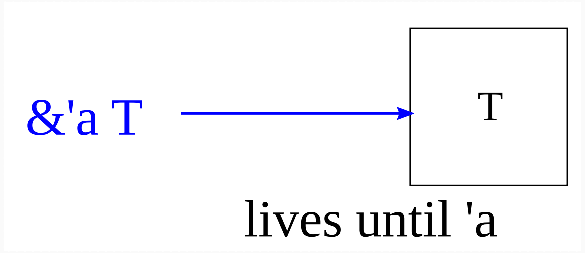
- syntax:
  - `&'`a T : reference to "T whose lifetime is `'`a"
  - `&'`a `mut` T : ditto; except you can modify data through it



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



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, …, 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 to the example

```
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 `'a` $\subset$ referent lifetimes of `x, y`, and `z`
- in this case,

`'a` $\subset$ (life time of `a`) $\cap$ (life time of `b`) $\cap$ (life time of `c`)

- 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 ← 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 annotation that works

```
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 that `'a` $\subset$ referent lifetimes of `x`
- 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 ← 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 that `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):

References in data structures

```
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 let `R` take the lifetime parameter:

```
struct R<‘a> {
  p: &’a i32
  …
}
```

- `R<'a>` represents *`R` whose `p` field points to an `i32` whose lifetime is `'a`*

References in data structures

- this way, a structure containing borrowing references exposes their referent lifetimes to its user

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);
```

Attaching lifetime parameters to data structure

```
}
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

A more complex example Rust cannot verify

```
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 doesn’t

- define `S` so that:
  - 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
```

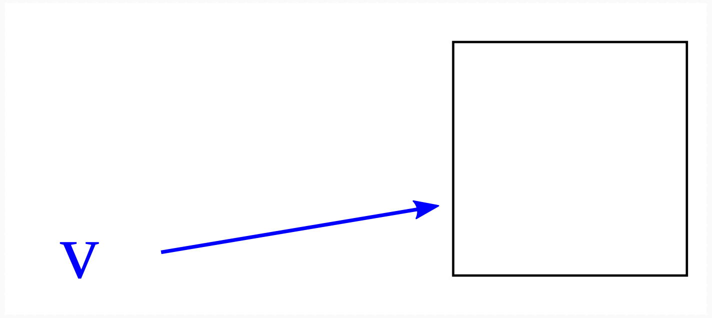
- I don’t know what is the exact spec of Rust that rejects this program, but it is apparently that Rust disallows *dereference of any struct any lifetime parameter of which is invalid at the point of dereference*
- in this example, `s : S<'a, 'b>` and one of its lifetime parameters (`'b`) is invalid at line 18

Summary

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*

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



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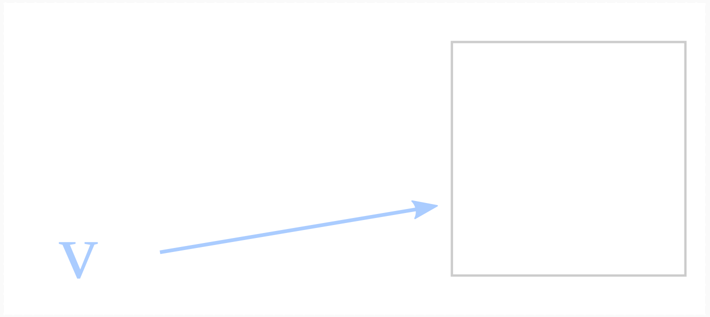
  …
  p = &v;
}
```
// v never used below, but its referent is … `p.x` …



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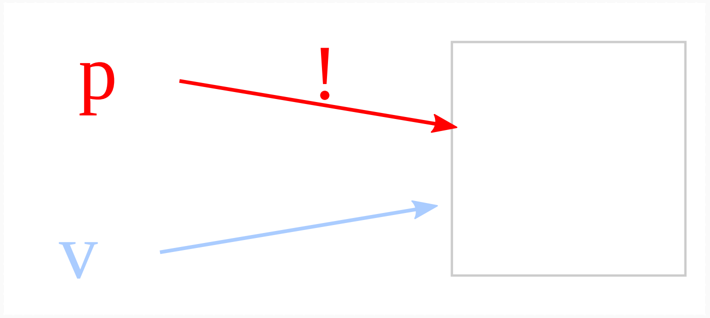
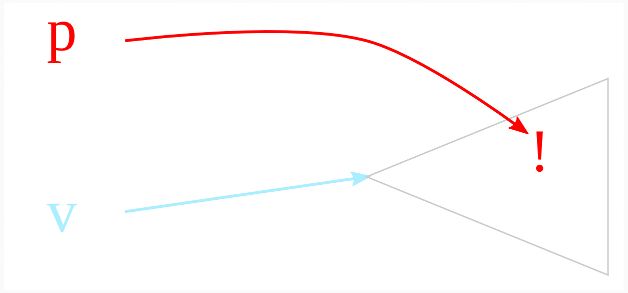


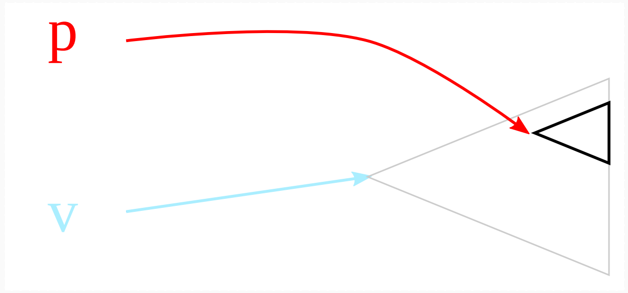
C vs. GC vs. Rust

- 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 guarantee such references are never dereferenced

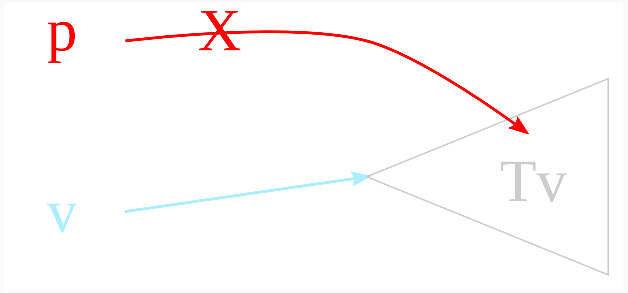
C/C++



GC

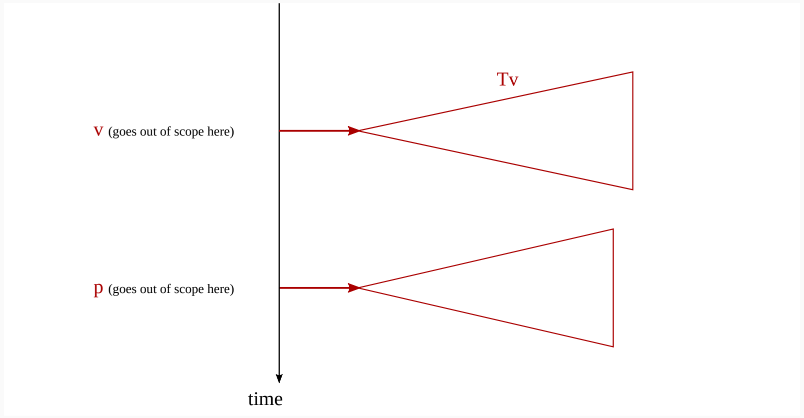


Rust



How Rust achieved it?

- say two data structures T_v rooted at variable `v` and T_p rooted at variable `p`
- assume `v` goes out of scope earlier than `p`
- we wish to guarantee when `v` goes out of scope, it is safe to reclaim the entire T_v
- generally it is of course not the case, as there may be pointers somewhere in $T_p \rightarrow$ somewhere in T_v



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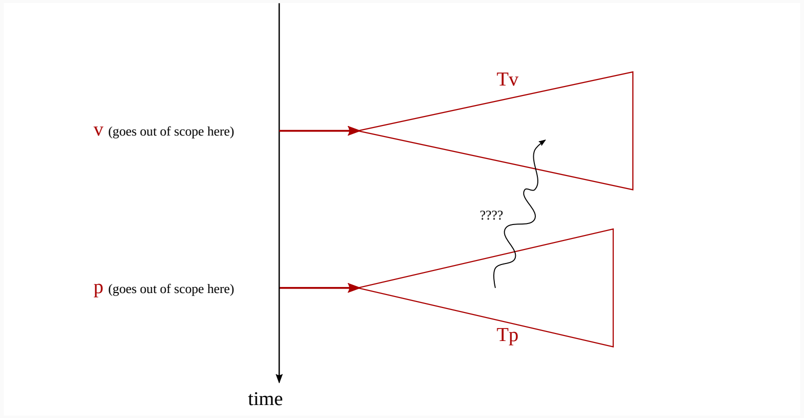

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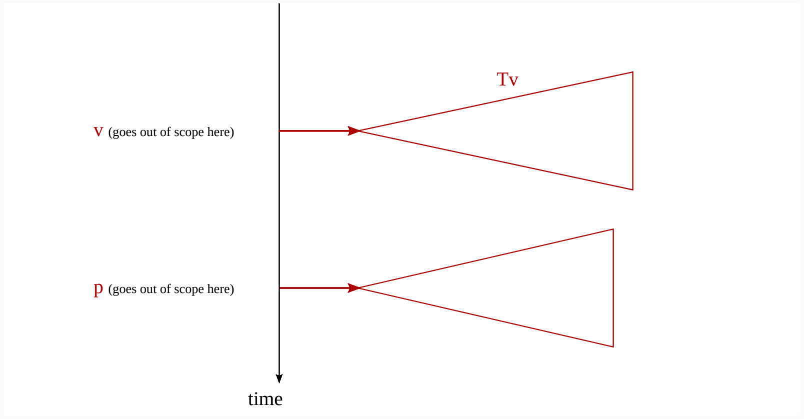
- recall the “single-owner rule,” which guarantees there is only one owning pointer to any node
- $\Rightarrow$ there can be no *owning* pointers from outside T_v to inside T_v
- $\Rightarrow$ any such pointer must be a borrowing pointer
- crucially, a borrowing pointer must have a lifetime parameter (lifetime of the referent); say `'a`



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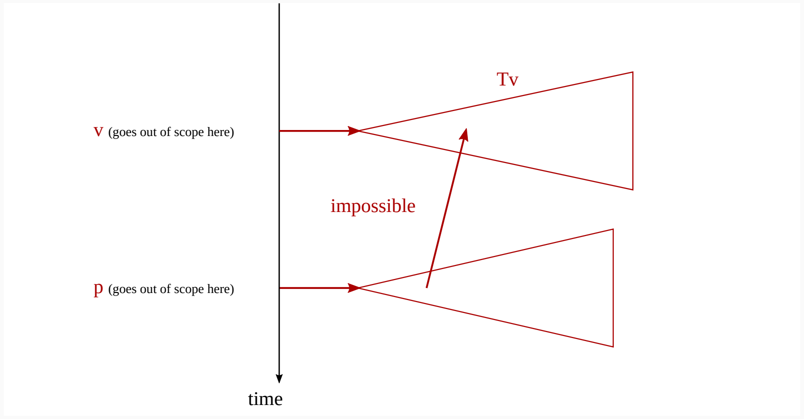

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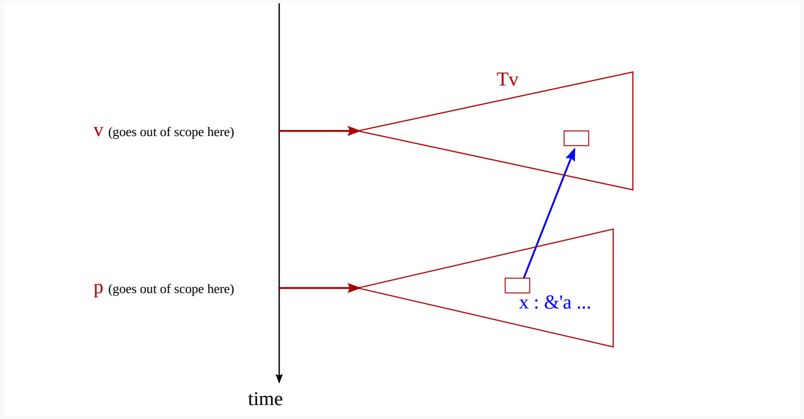

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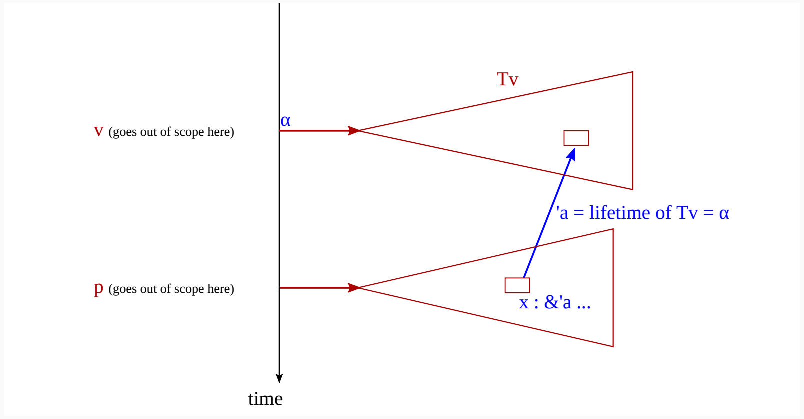
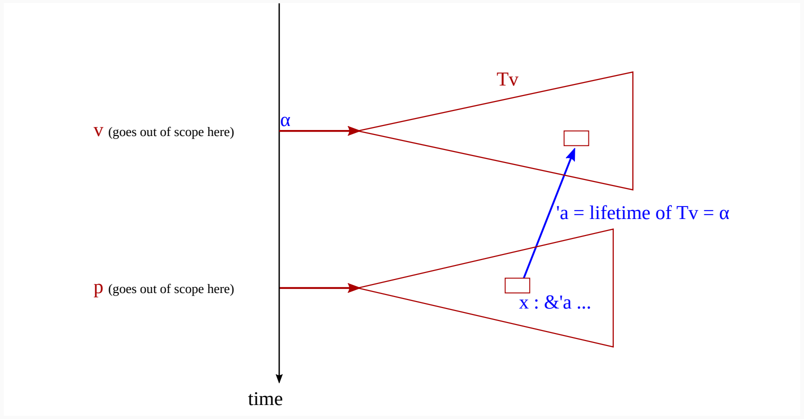


How Rust achieved it?

- any structure containing borrowing pointers must carry these parameters too, as part of its type (e.g., `S<'a>`)
- assignment to such borrowing pointers determines `'a` to end when the righthand side goes out of scope (α in the figure)
- by `'a` = α, the containing data structure (`T_p`, of type `S<'a>`) cannot be dereferenced



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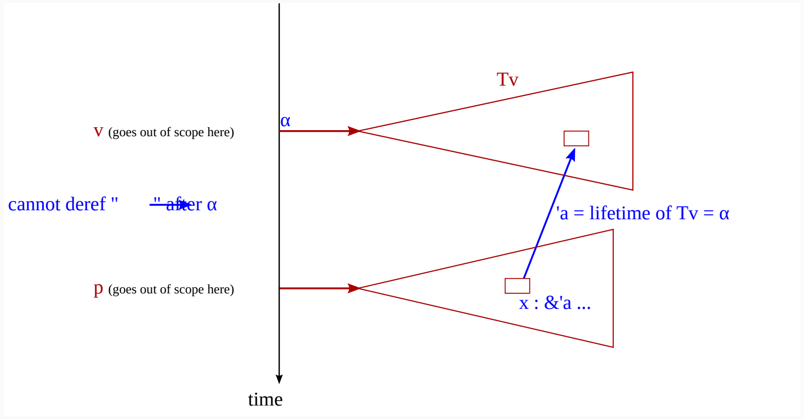
Tv
α
v (goes out of scope here)
cannot deref " " after α
'a = lifetime of Tv = α
p (goes out of scope here)
x : &'a ...
time