

Tree Borrows

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Strong guarantees for references



`&mut` → mutation, no aliasing

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⁴for non-interior-mutable types

Absence of aliasing + mutability allows optimizations

```
fn foo(y: &mut u64) {  
    let val = *y;  
    *y = 42;  
  
    *y = val;  
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    opaque();  
    *y = val;  
}
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```
static mut X: u64 = 0;
```

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}
```

```
static mut X: u64 = 0;

fn main() {
    foo(unsafe { &mut X });
}

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    *y = 42;
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    *y = val;
}
```

```
static mut X: u64 = 0;

fn main() {
    foo(unsafe { &mut X });
}

fn foo(y: &mut u64) {
    let val = *y;
    *y = 42;
    println!("{}", unsafe { X }); // prints 42
    *y = val;
}
```

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static mut X: u64 = 0;

fn main() {
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}

fn foo(y: &mut u64) {
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    println!("{}", unsafe { X }); // prints 0
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```

Optimization changes observable behavior...
Is the optimization incorrect?

It's not the optimization that is wrong, it's the code

Tree Borrows enforces aliasing rules by adding proof obligations to **unsafe** blocks.

Code that violates these rules is declared **Undefined Behavior**.

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Code that violates these rules is declared **Undefined Behavior**.

Sounds familiar?

Stacked Borrows has the same purpose,
Tree Borrows is its successor.

Stacked Borrows

Adds **extra state** to the abstract machine to track provenance.
Distinguishes pointers to the same location with a **tag**.

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Adds **extra state** to the abstract machine to track provenance.
Distinguishes pointers to the same location with a **tag**.

Uses a **stack** to store permissions.
Enforces that borrows are well-bracketed.

However, Stacked Borrows...

- does not handle two-phase borrows (gives up on any optimization)

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    vec.push(vec[0]);  
//    ^^^ 1. implicit &mut in function arguments  
//           ^^^^^^ 2. read-only operation before function  
//                   entry does not invalidate the &mut
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    vec.push(vec[0]);  
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- forbids common **unsafe** patterns (declared UB)

```
let from = data.as_ptr();  
// SB inserts an implicit write, killing the raw pointer  
let to = data.as_mut_ptr();  
copy_nonoverlapping(from, to.add(1), 1); // UB
```

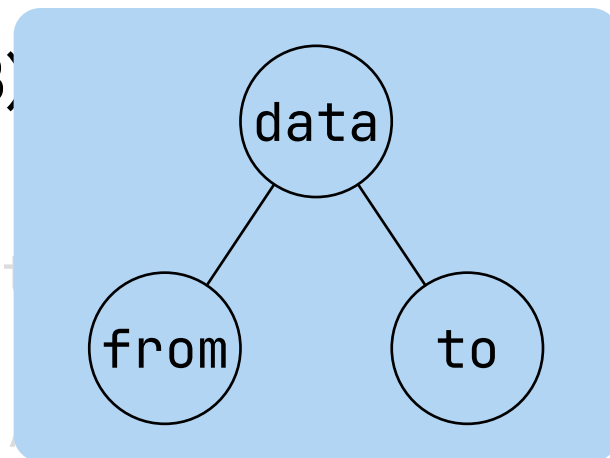
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vec.push(vec[0]);
```

```
// ^^^ 1. implicit &mut in function arguments
```

The stack is too rigid to represent the exact relationship

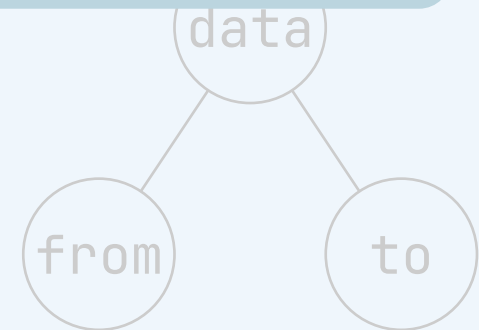
- for

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Stacked Borrows \rightsquigarrow Tree Borrows

Stack is not precise enough.

Use a **tree** instead \rightarrow accurate tracking of pointer ancestry

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Use a **tree** instead \rightarrow accurate tracking of pointer ancestry

Results in

- accurate handling of two-phase borrows
- more permitted patterns
- simpler rules, fewer exceptions

Design constraints

Enough UB

- strict enough that interesting **optimizations** are possible
 - guided by desirable optimizations, and expected UB
 - *formalized in Coq, ongoing work to prove correctness*

Design constraints

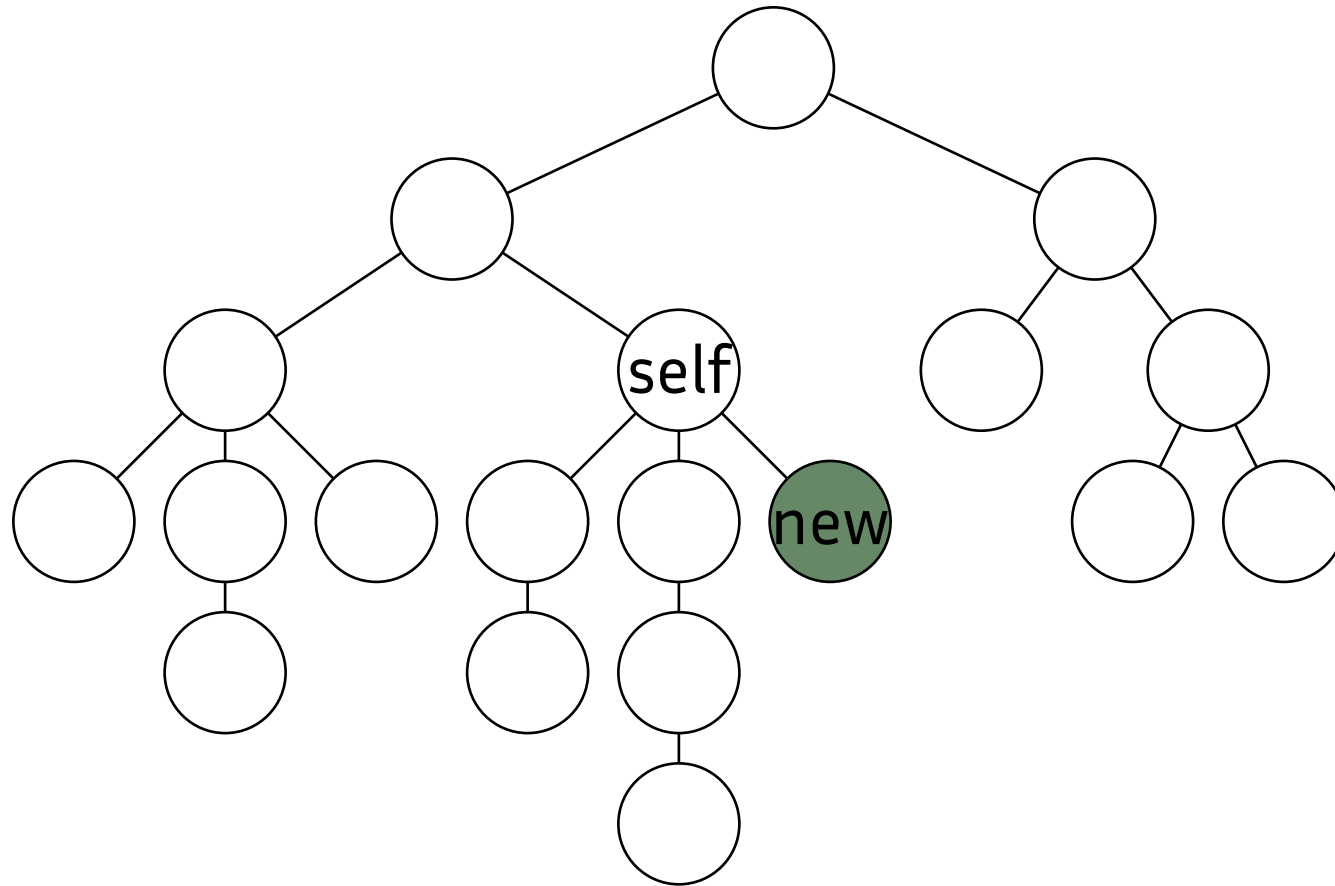
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- strict enough that interesting **optimizations** are possible
 - guided by desirable optimizations, and expected UB
 - *formalized in Coq, ongoing work to prove correctness*

Not too much

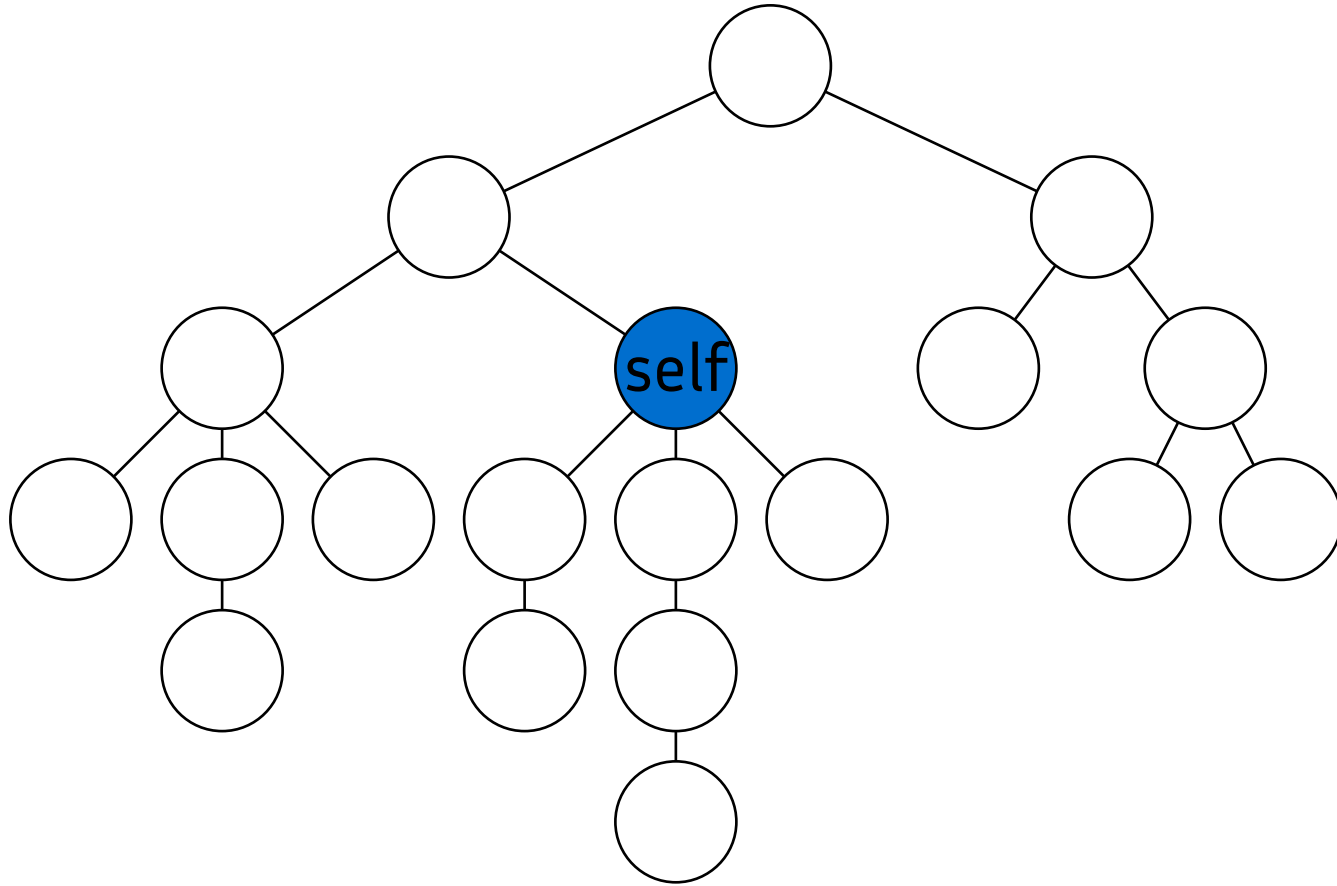
- permissive enough that **existing libraries** are correct
 - guided by common patterns, complaints about Stacked Borrows
 - *implemented in the Miri interpreter, checked against libraries*

Tracking relationships

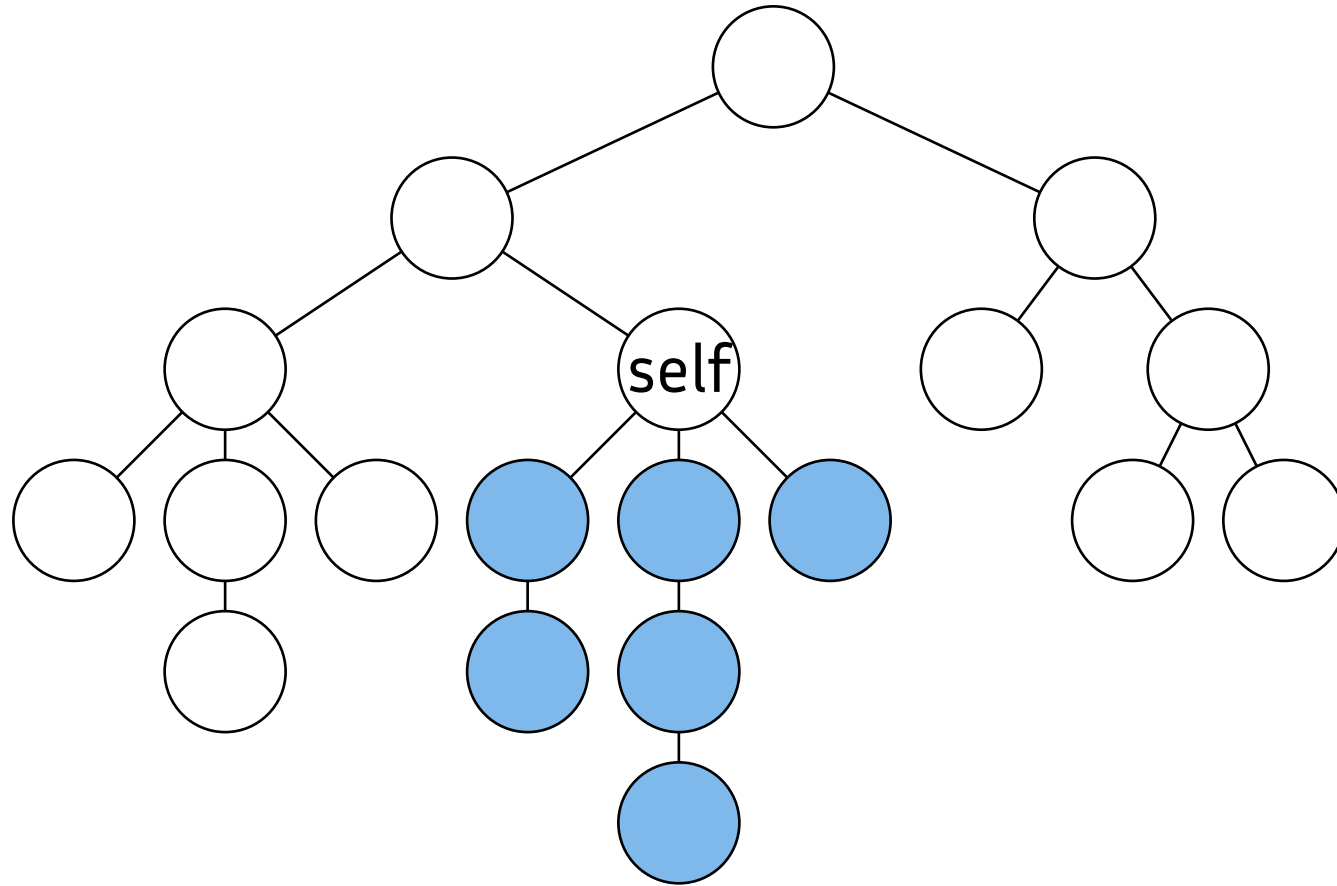


reborrows
create
immediate children

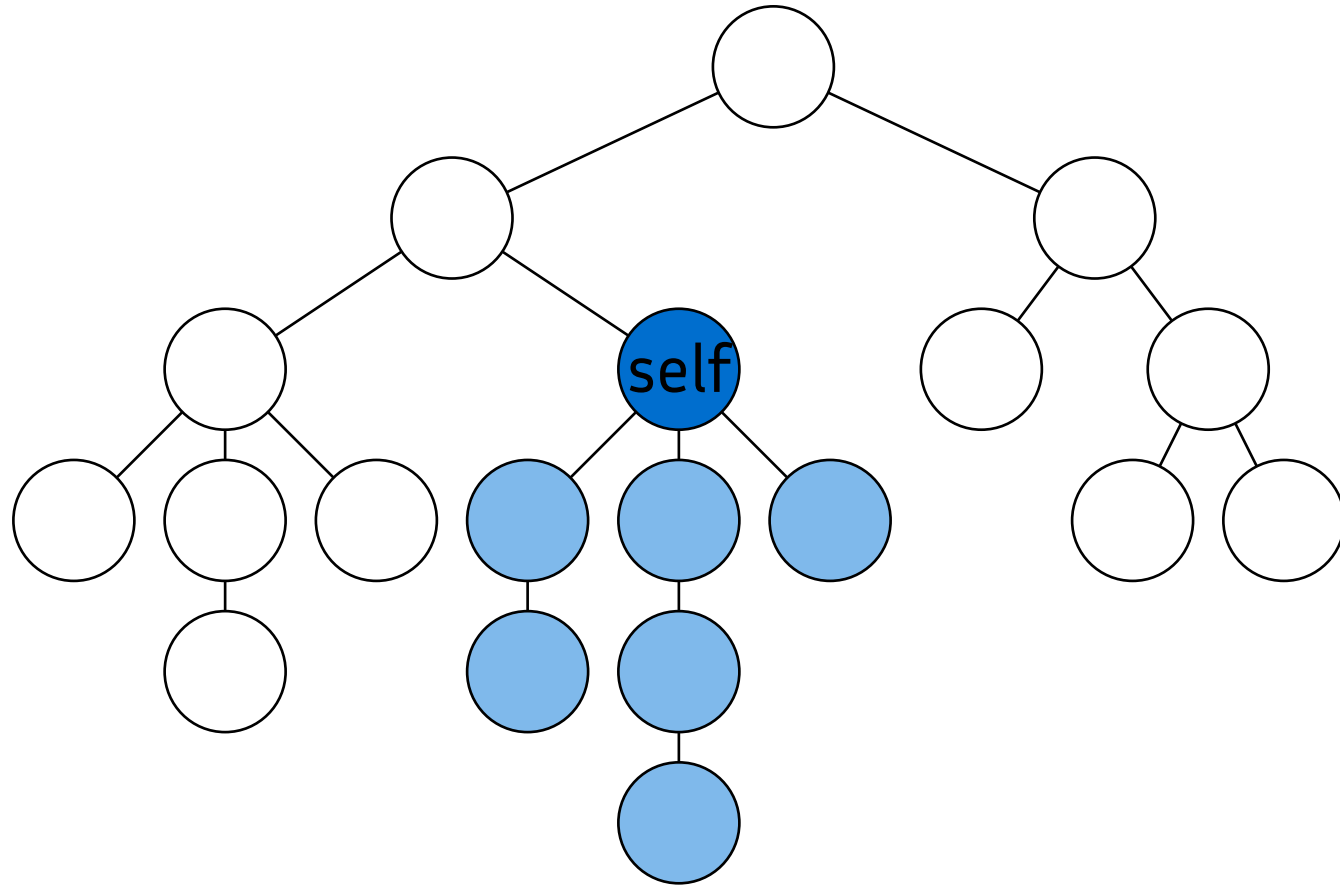
```
let new = &*self;
```



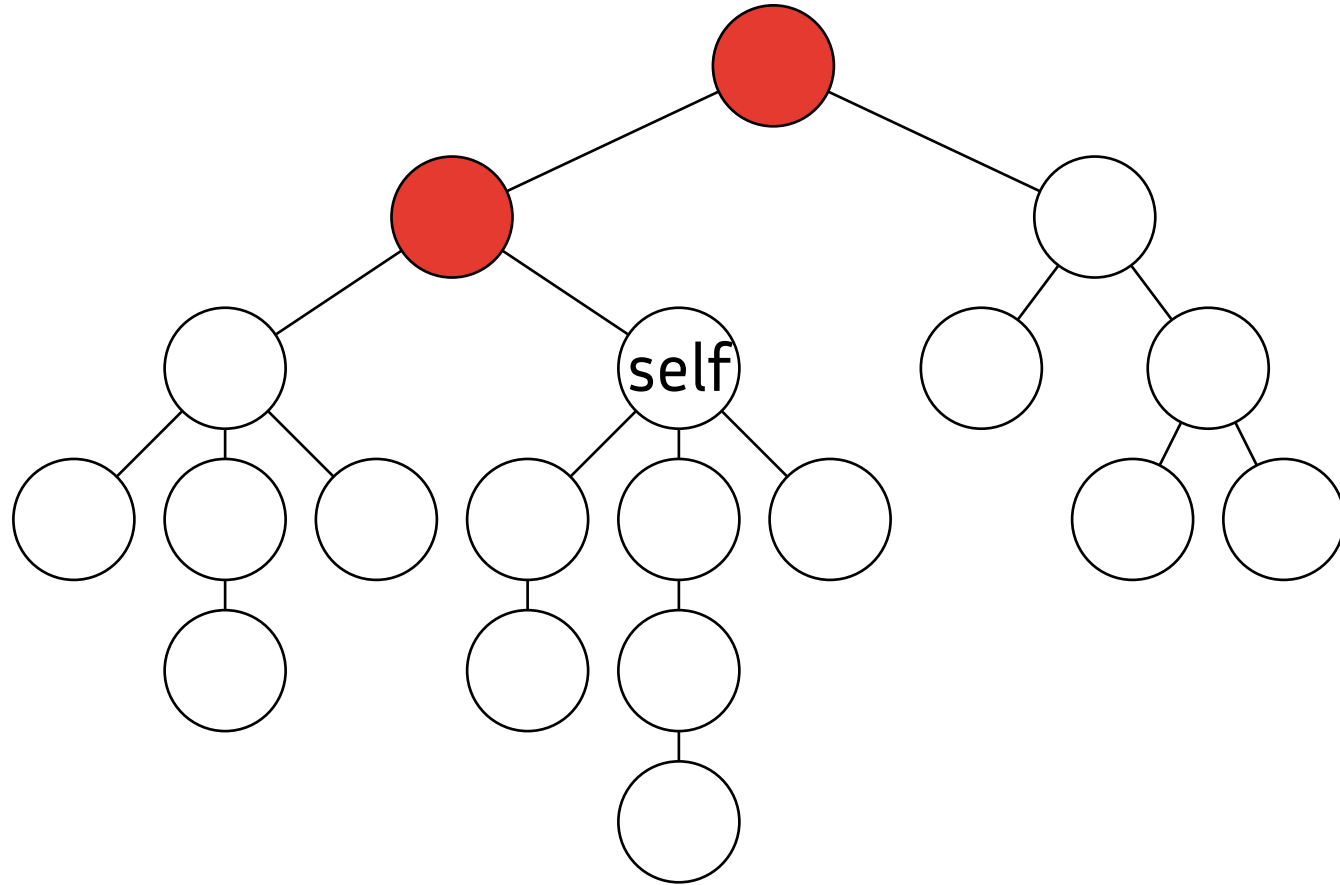
self & strict children
→ children



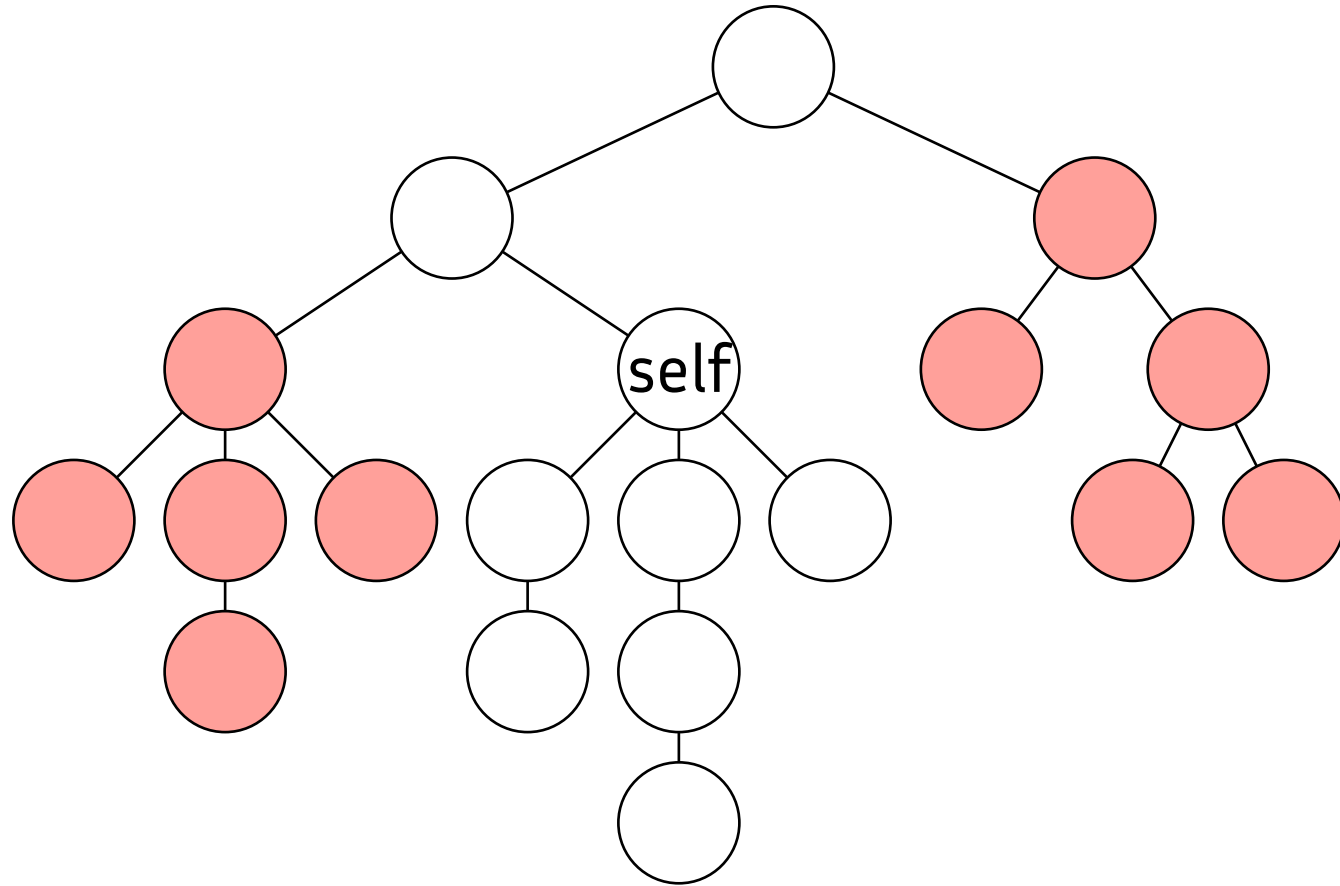
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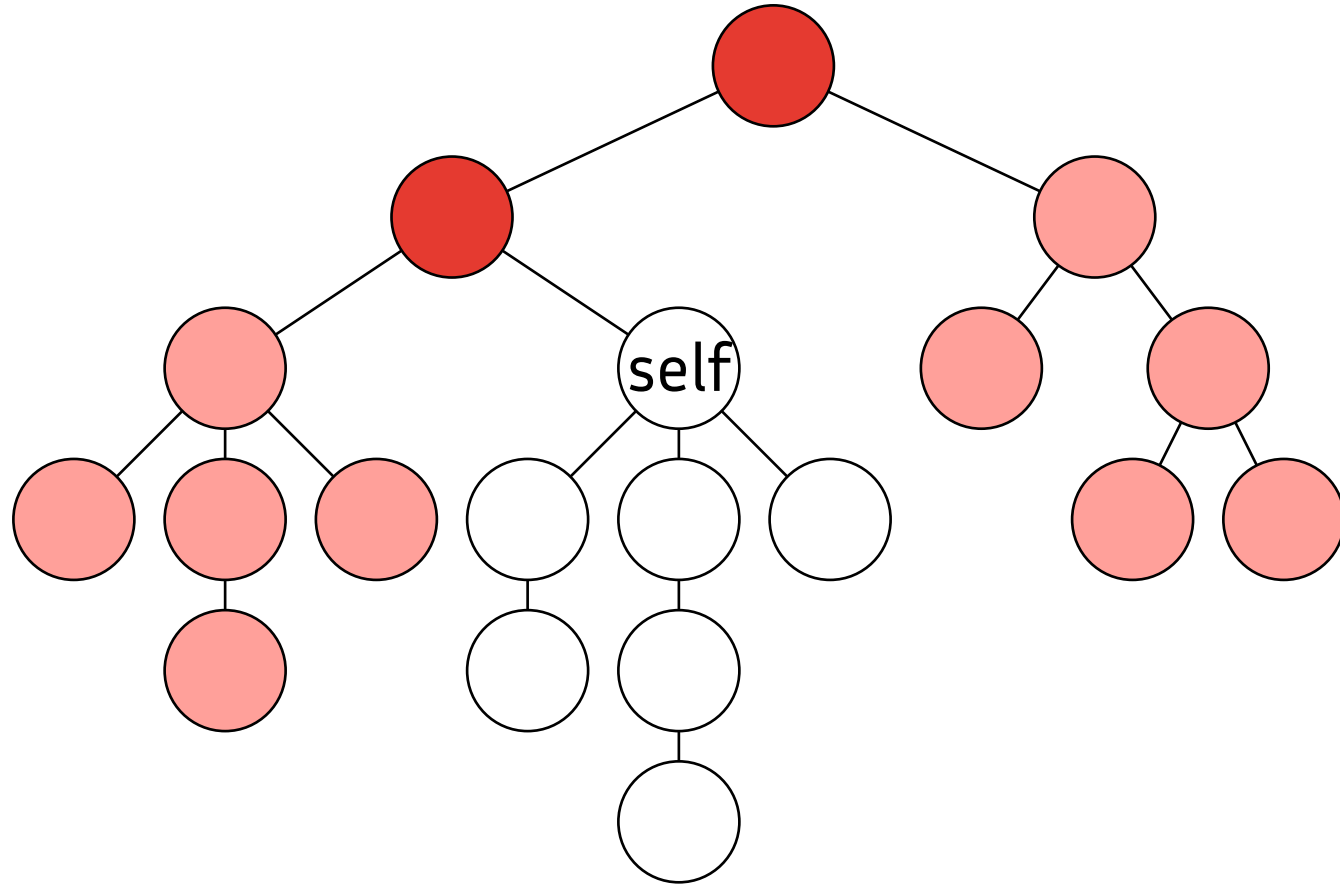
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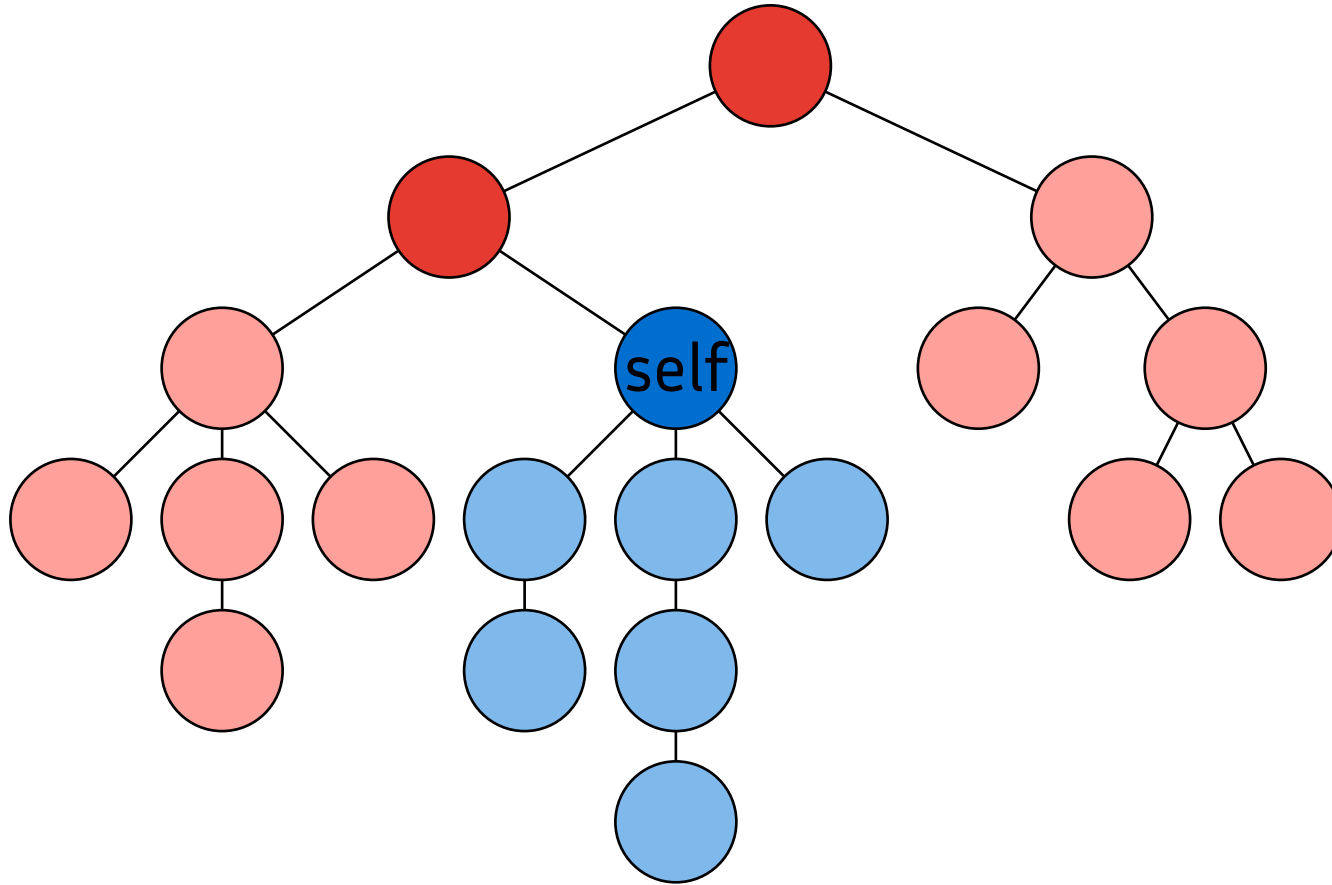
parents & cousins
→ foreign



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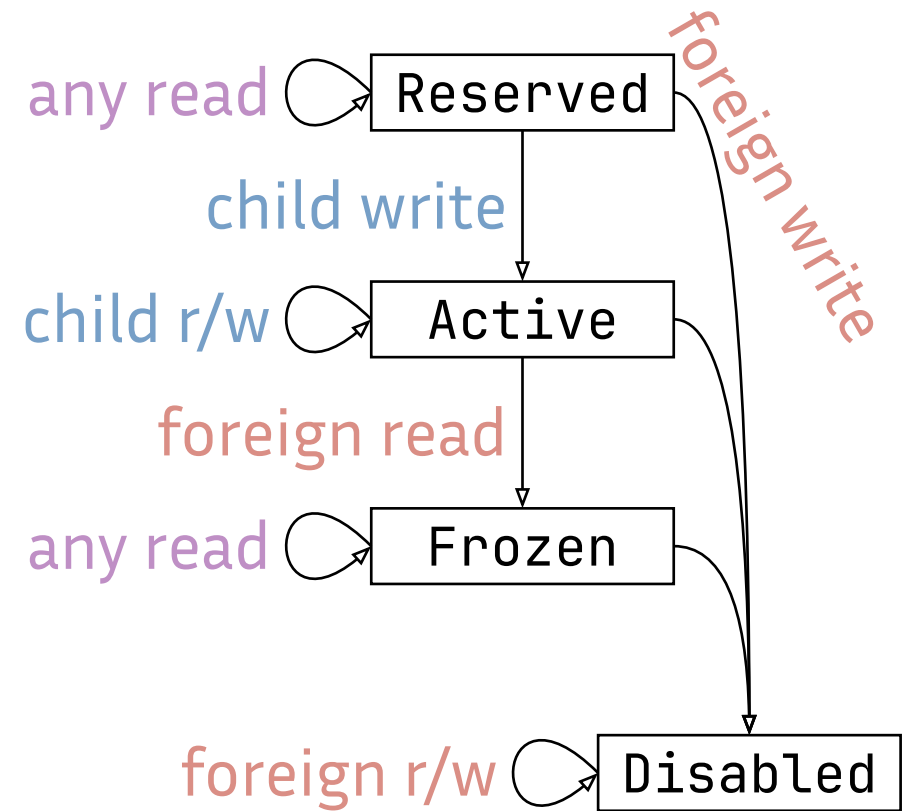
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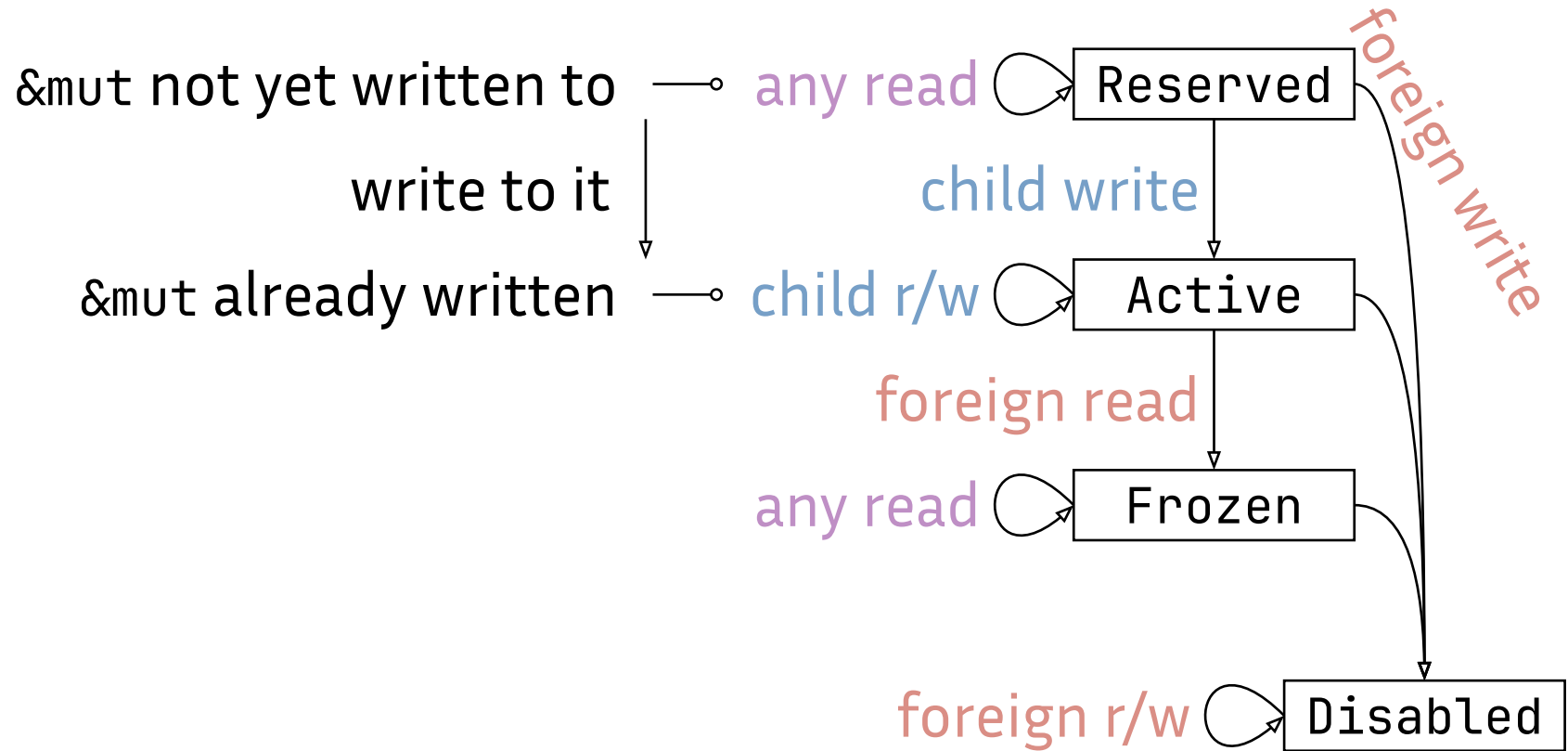
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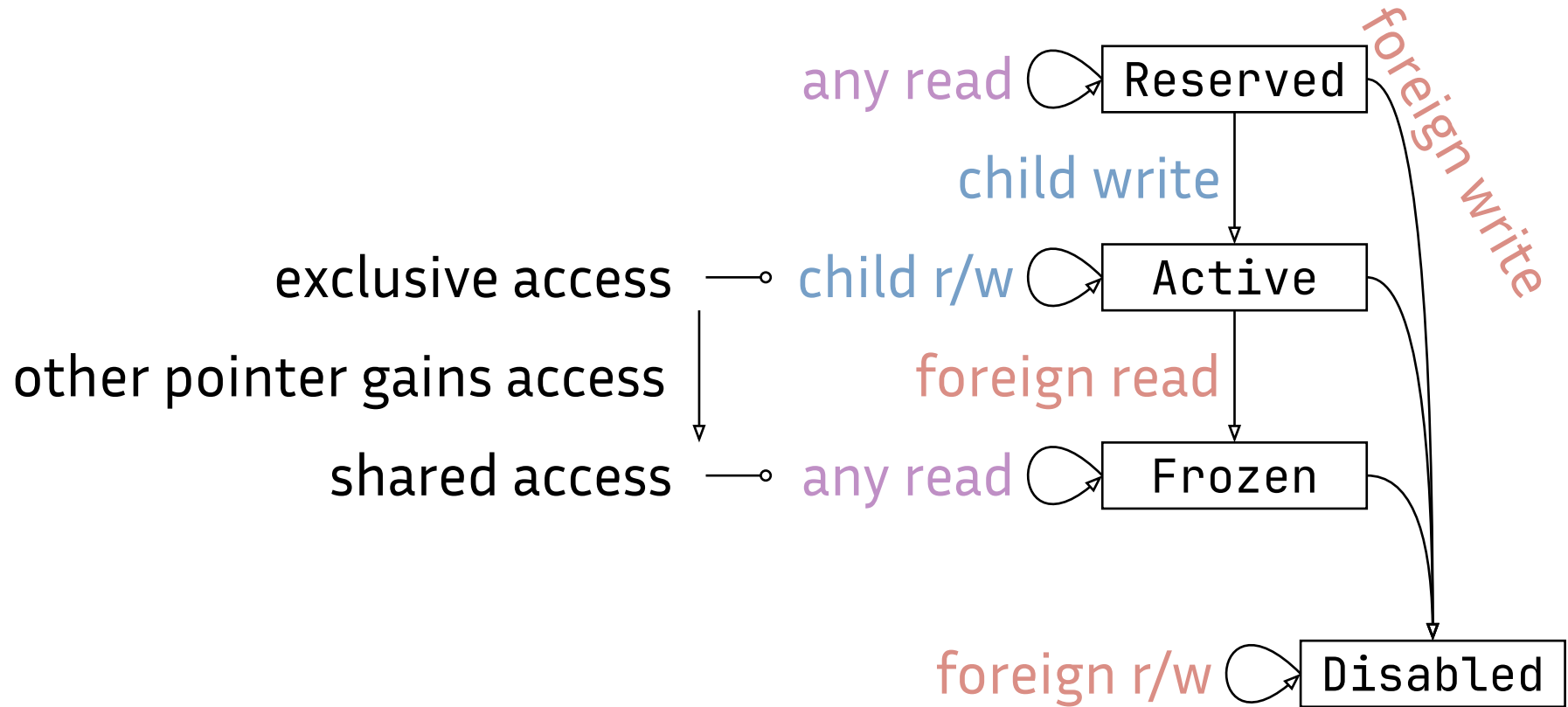
State machine

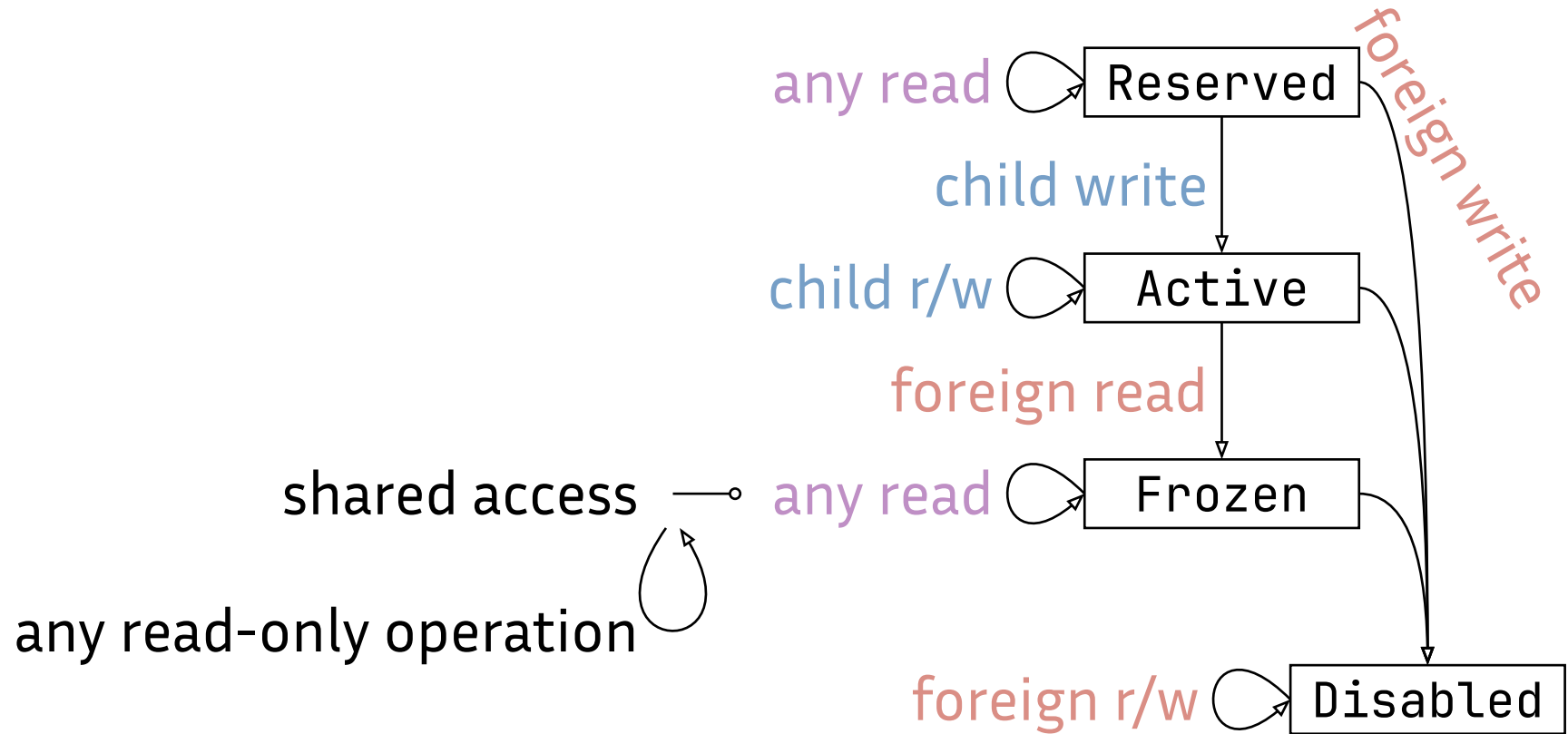
Per-location permission

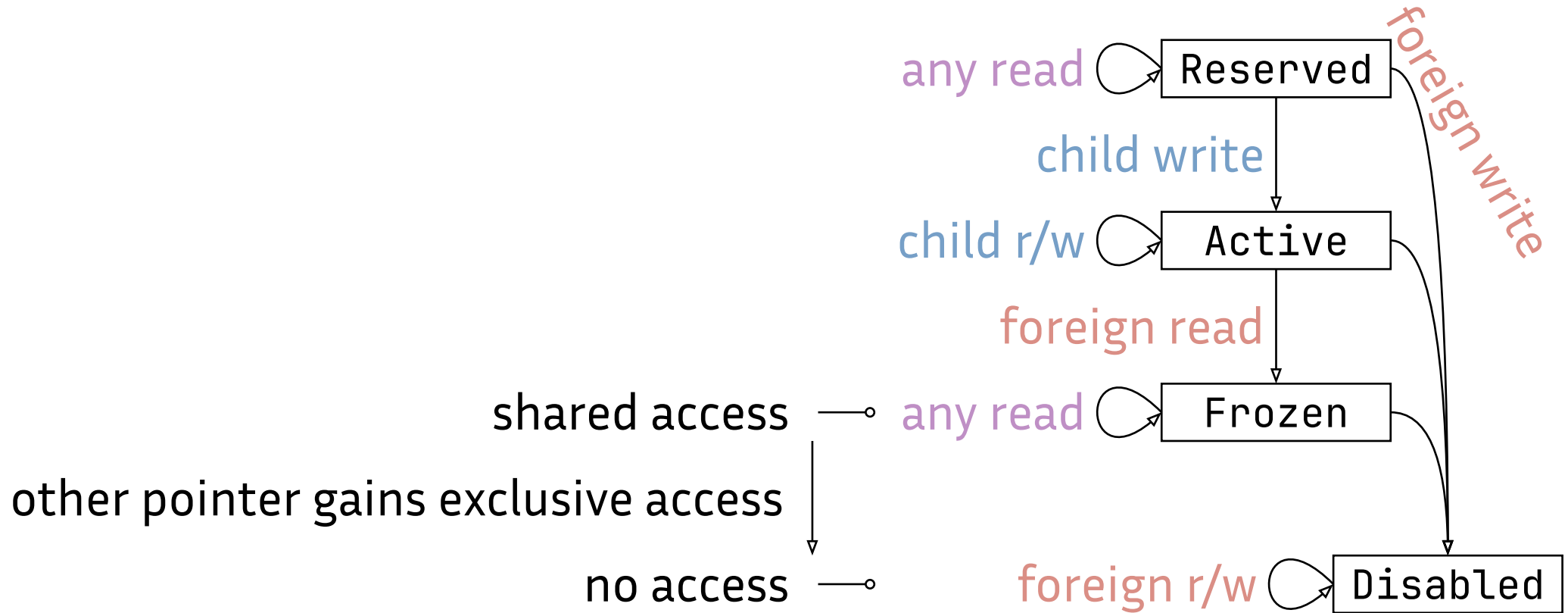
After creation each pointer experiences a sequence of child/foreign read/write accesses and gains/loses permissions in consequence











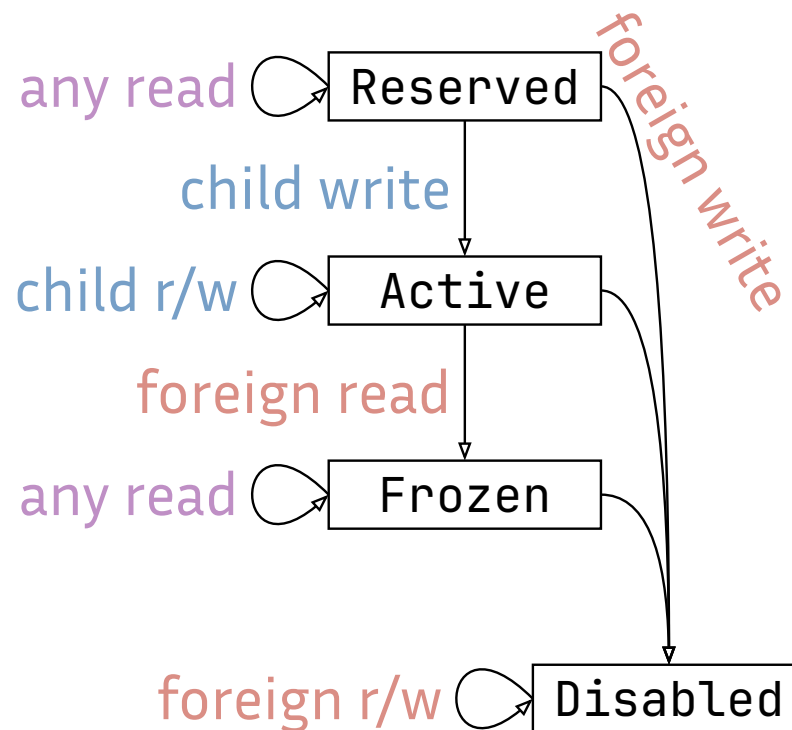
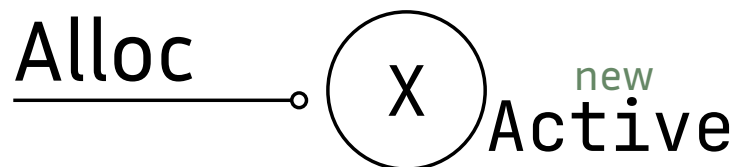
First example contains UB

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```
static mut X = 0;  
let y = &mut X;  
let val = *y;  
*y = 42;  
print!(X); // read access violates uniqueness of y  
*y = val;
```

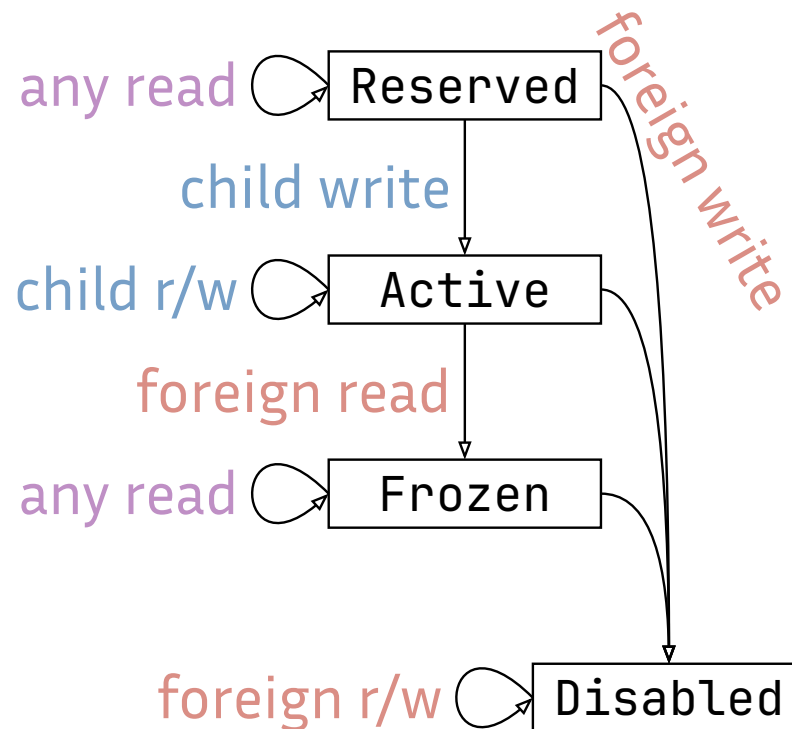
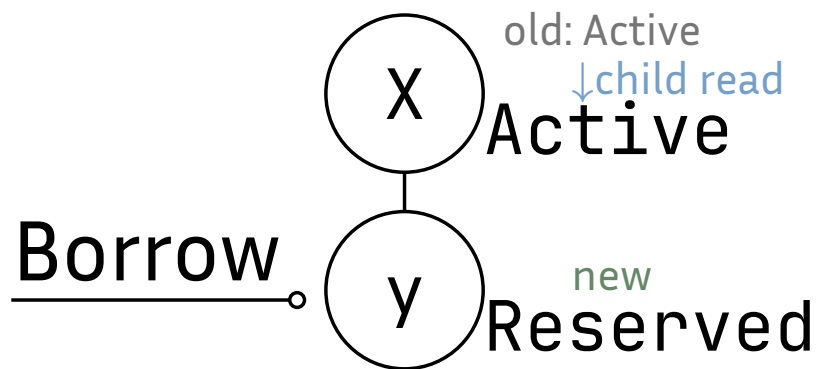
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Alloc X —○ static mut X = 0;  
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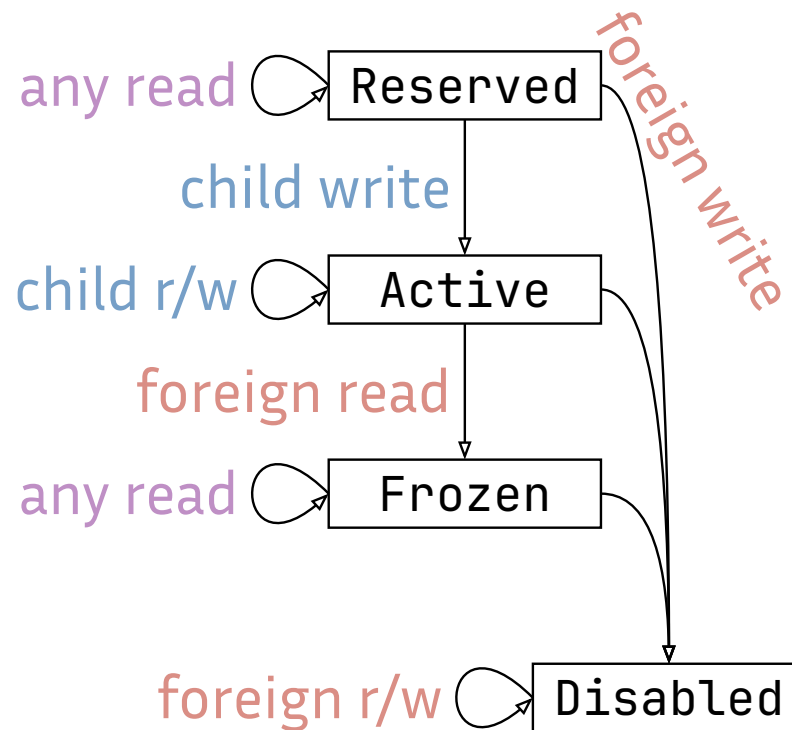
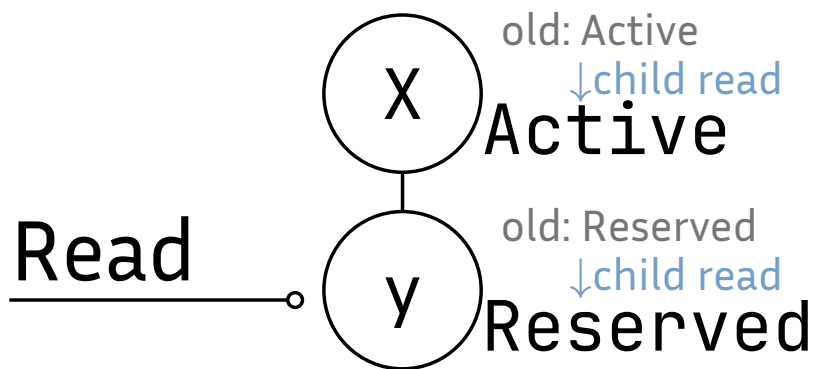
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Borrow y — `static mut X = 0;`
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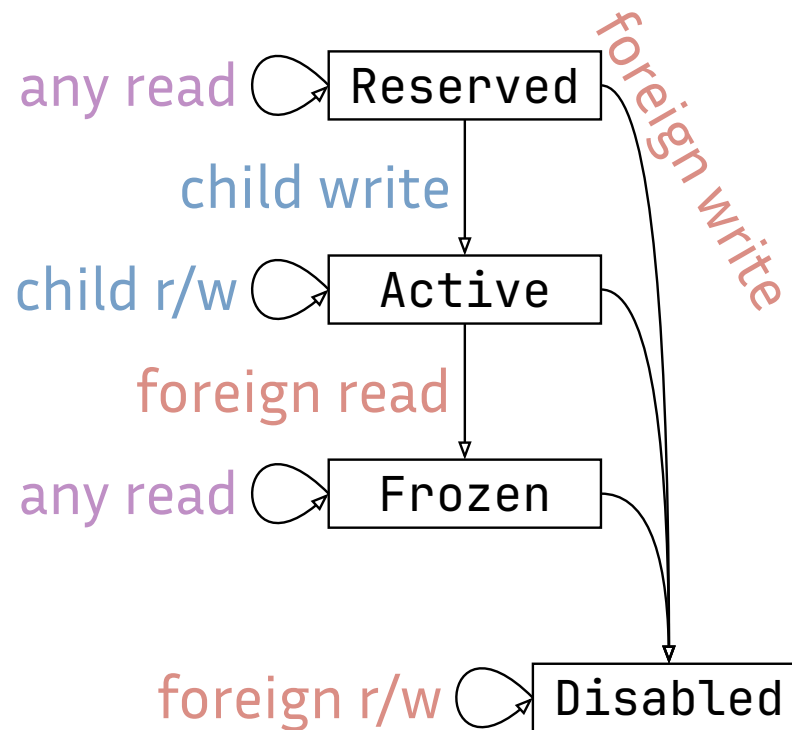
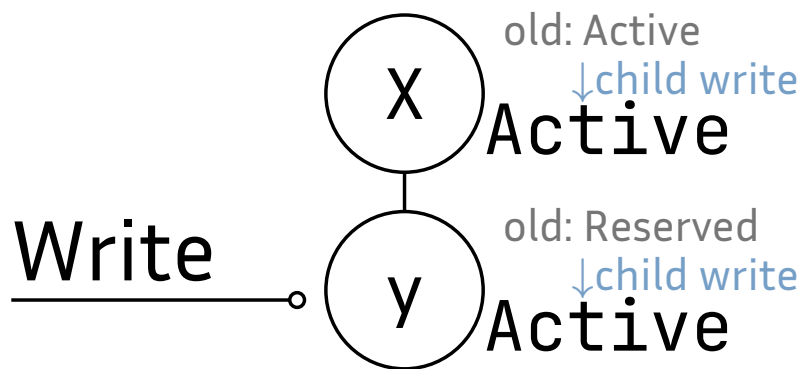

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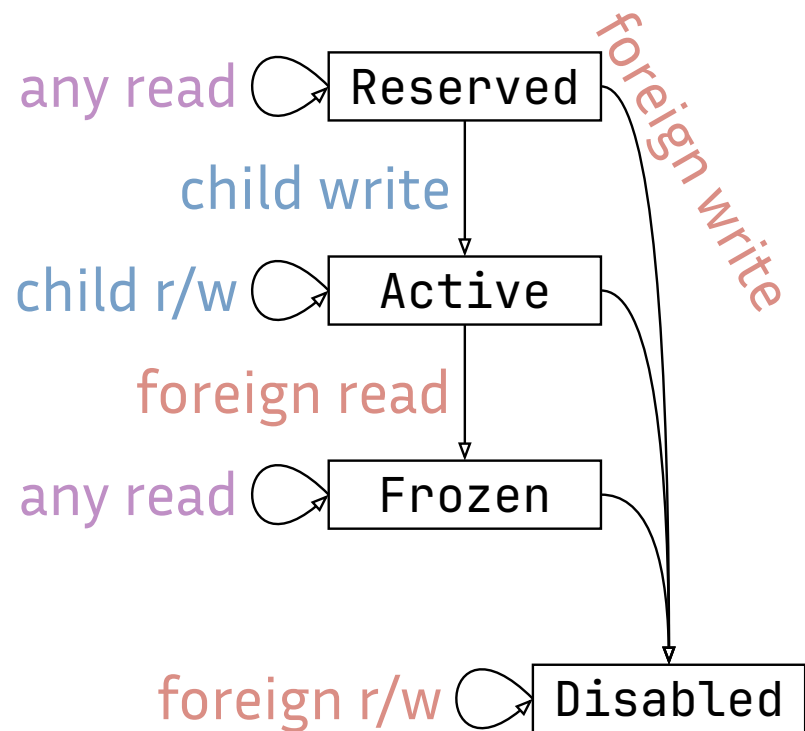
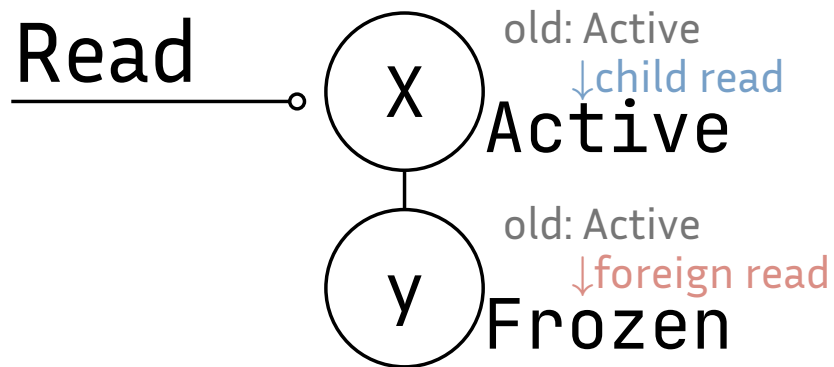
```

static mut X = 0;
let y = &mut X;
let val = *y;
Write y — *y = 42;
print!(X);
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```



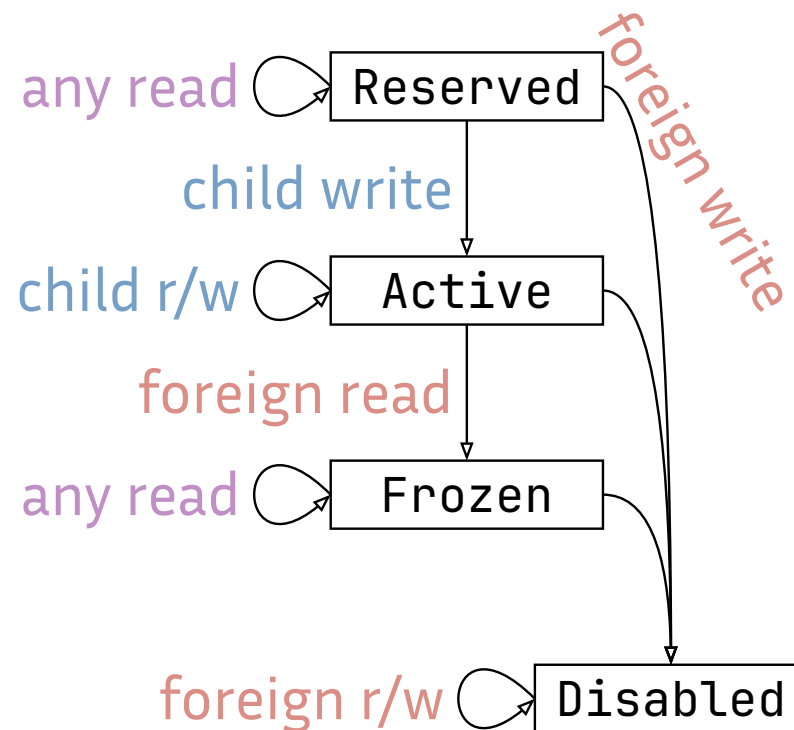
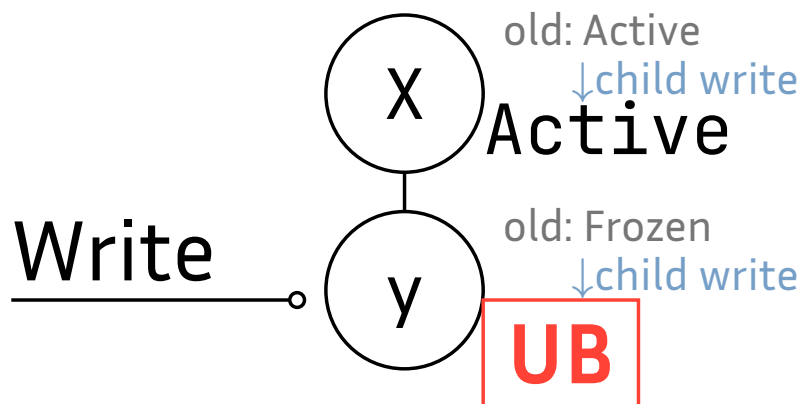
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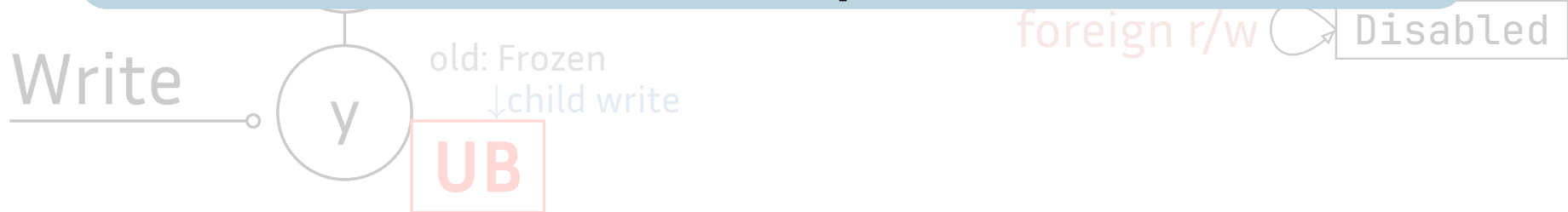
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println!(X);
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Write

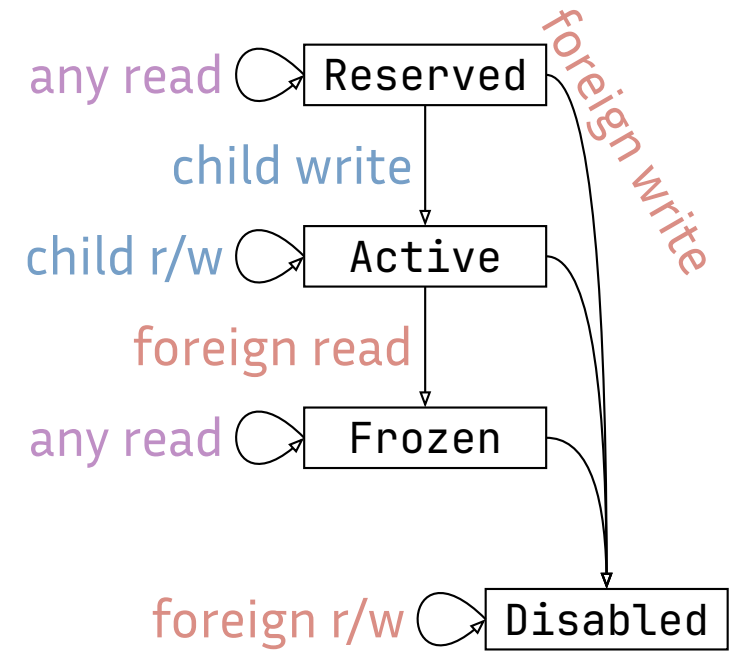
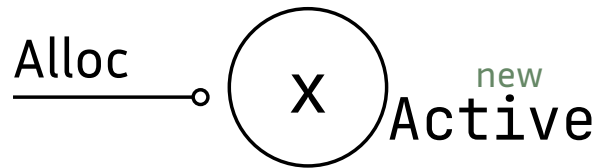
- Exclusively owned **&mut** is Active
- Transitions from Active detect violations of uniqueness



Raw pointers

```
let mut x = 0u64;  
let r = addr_of_mut!(x);  
x = 42; // x and r should be interchangeable  
r.write(50);
```

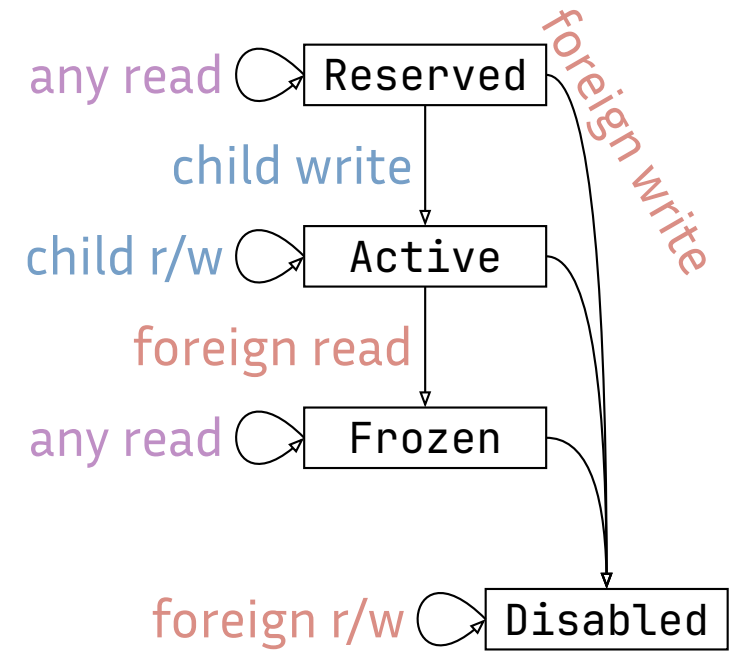
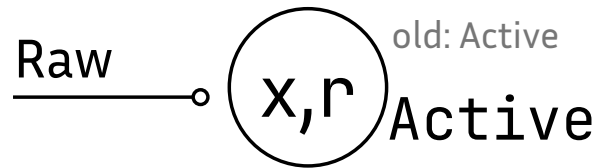
Alloc x — `let mut x = 0u64;`
`let r = addr_of_mut!(x);`
`x = 42;`
`r.write(50);`



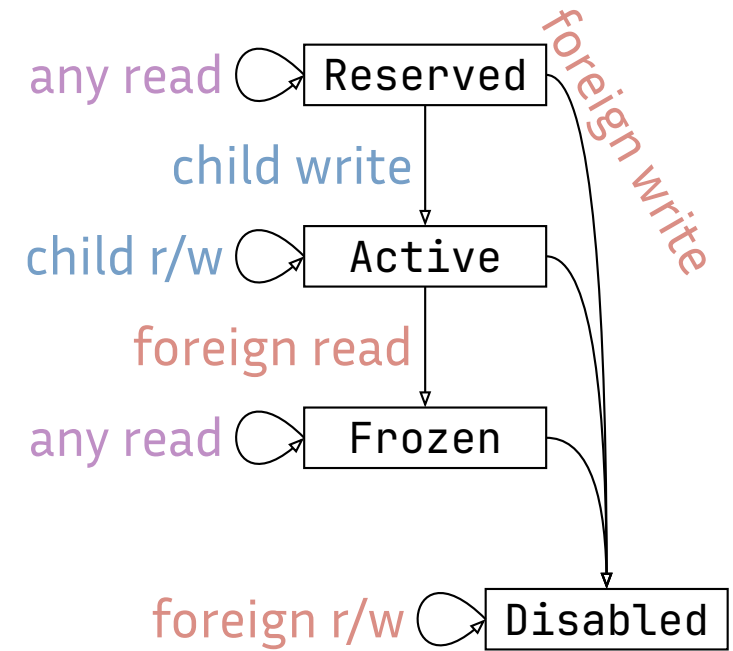

```

let mut x = 0u64;
Raw r —○ let r = addr_of_mut!(x);
x = 42;
r.write(50);

```



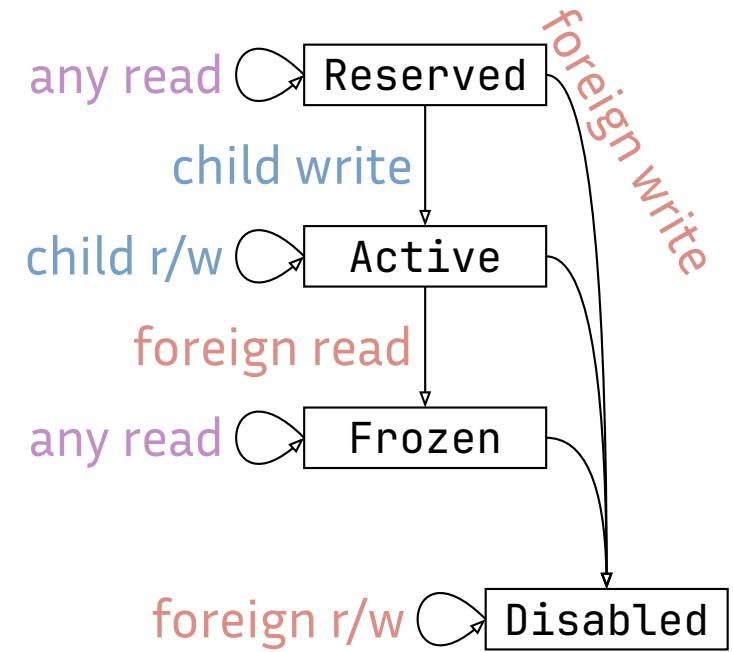
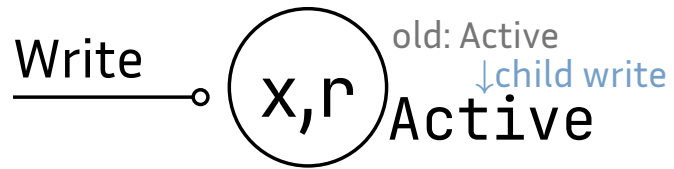
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let mut x = 0u64;  
let r = addr_of_mut!(x);  
Write x —> x = 42;  
r.write(50);
```



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let mut x = 0u64;
let r = addr_of_mut!(x);
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Write r —○ r.write(50);

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Write r —◦ r.write(50);
```



- Raw pointers inherit tag (and permissions with it)
- Same approach for interior mutability

**All mutable references are
two-phase borrows**

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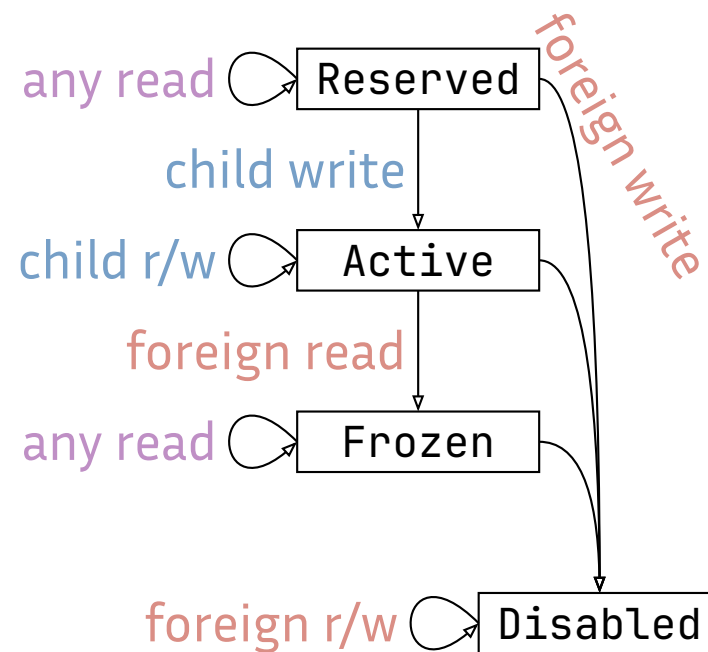
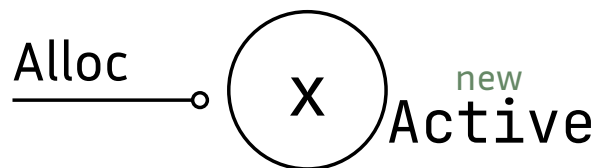
```
let mut x = 0u64;  
let y = &*addr_of!(x);  
let z = &mut x;    // Create mutable reference  
let v = read(y);  
write(z, 42);      // Use it mutably
```

All mutable references are two-phase borrows

```
let mut x = 0u64;  
let y = &*addr_of!(x);  
let z = &mut x;  
let v = read(y); // Read accesses still allowed  
write(z, 42);
```

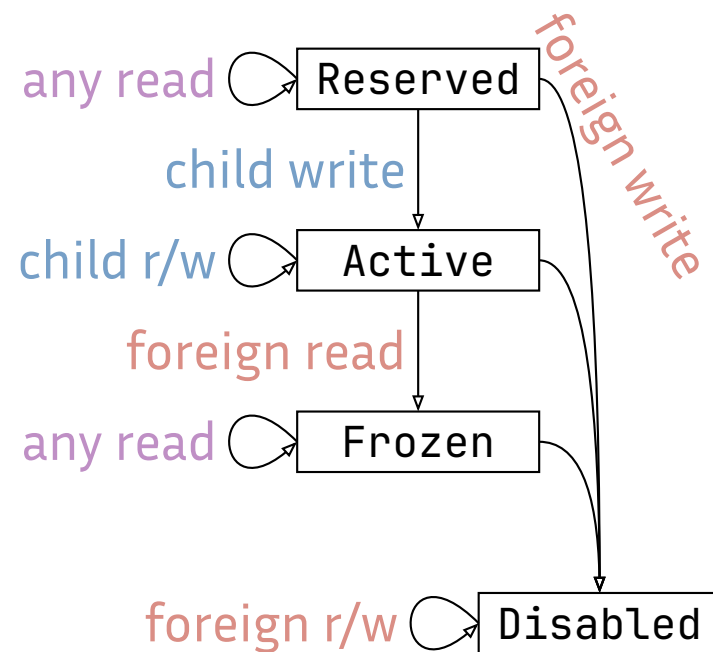
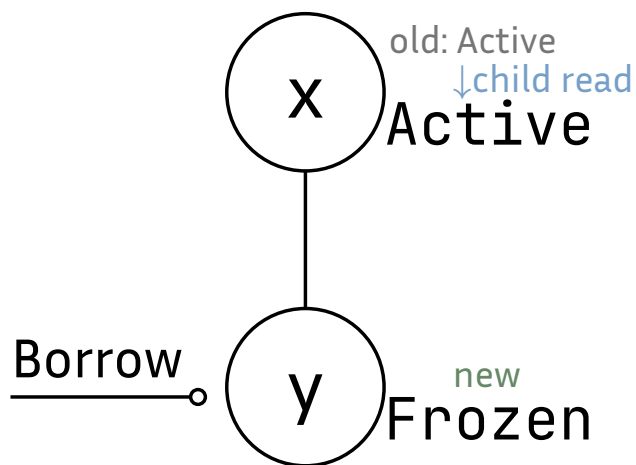
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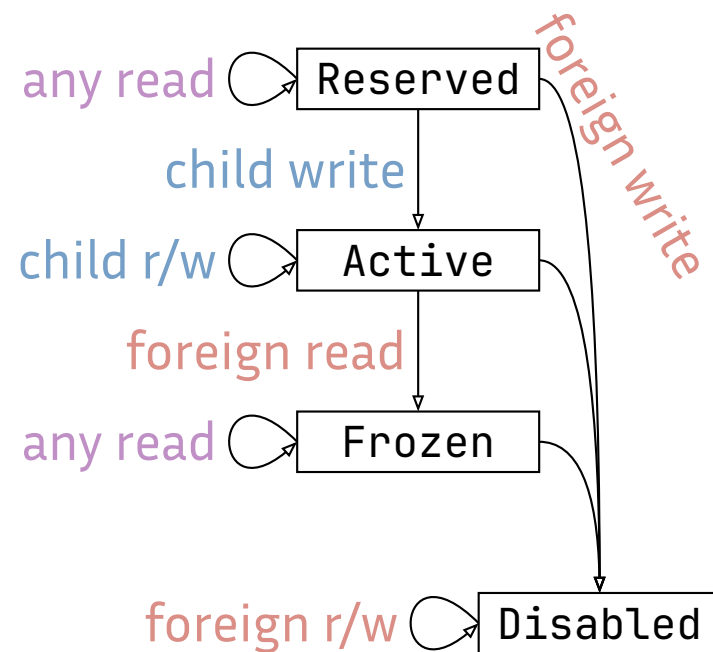
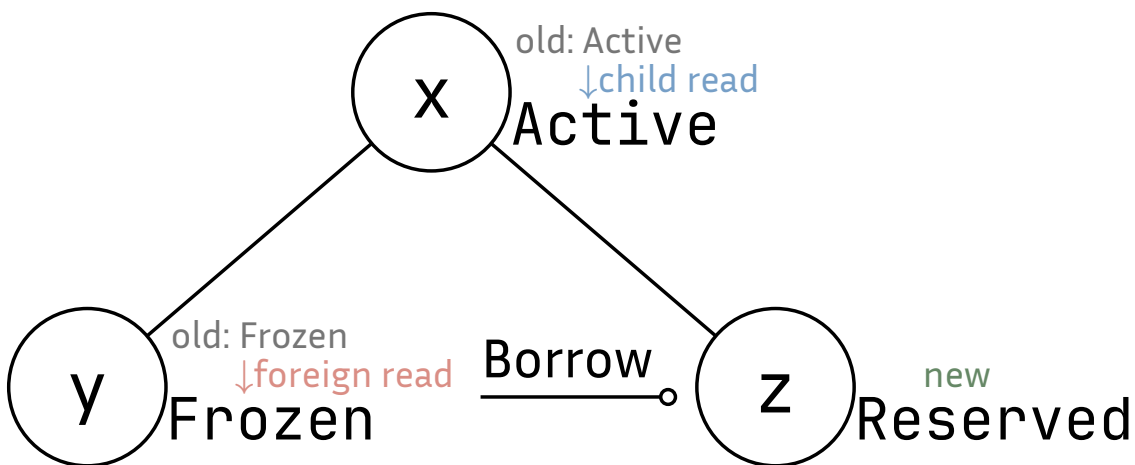
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let mut x = 0u64;  
Borrow y — let y = &*addr_of!(x);  
let z = &mut x;  
let v = read(y);  
write(z, 42);
```



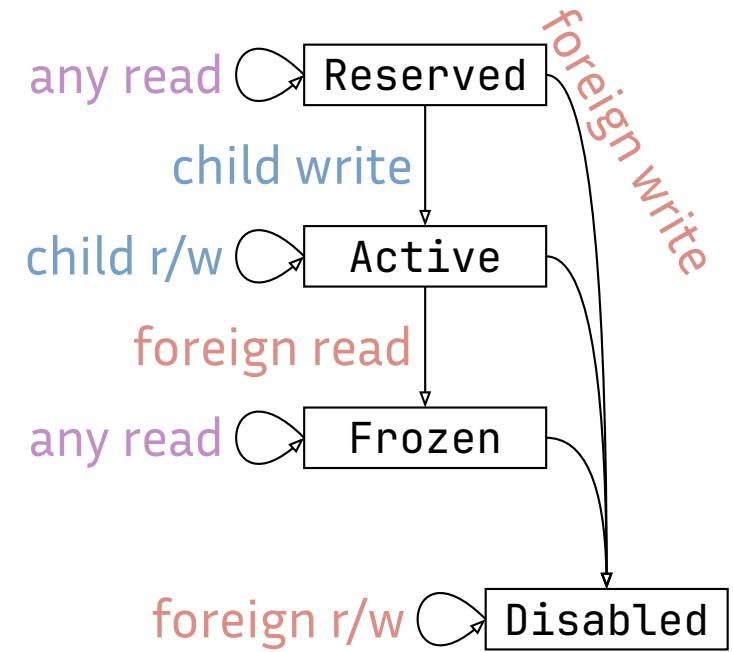
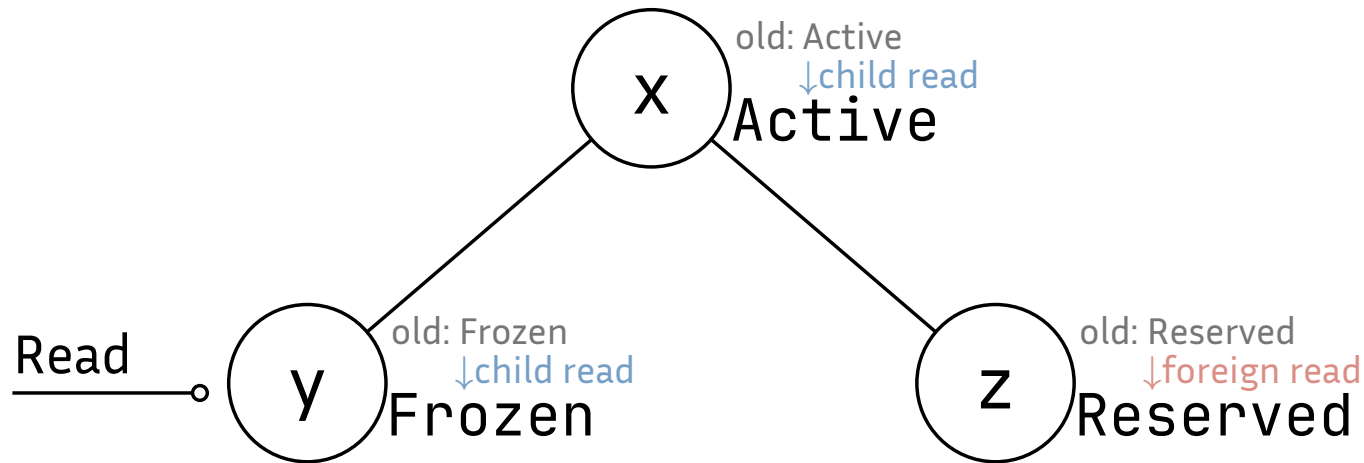
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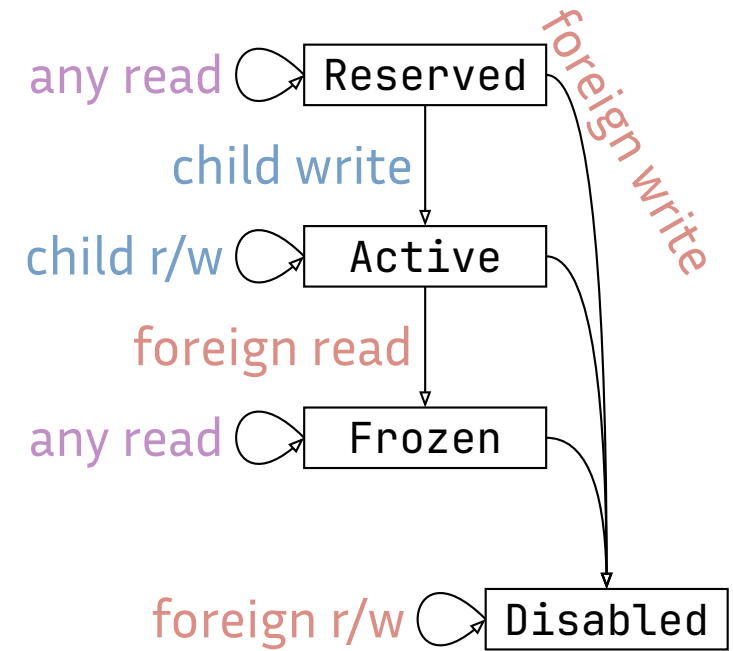
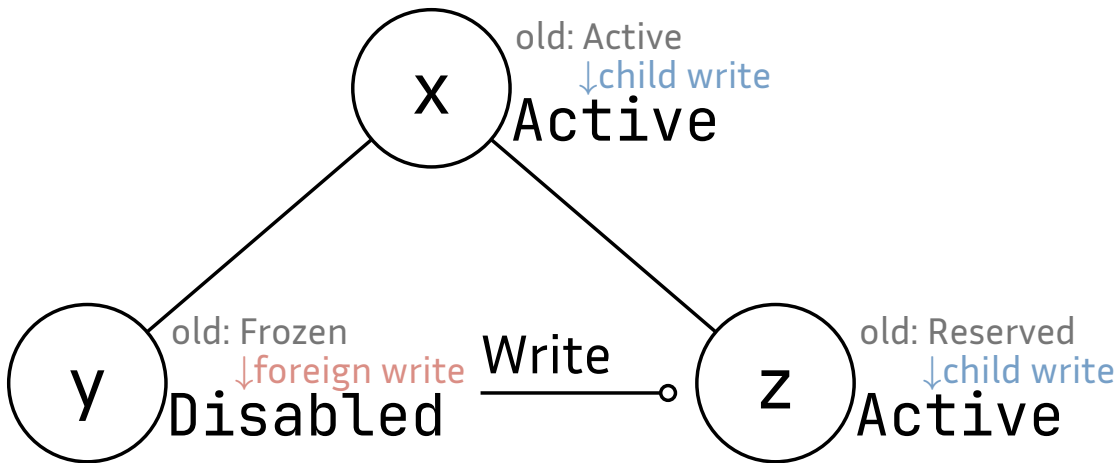
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let z = &mut x;  
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Write v — write(z, 42);
```

- **&mut** starts Reserved
- Reserved tolerates all read accesses
- Tree structure makes this possible



Conclusion

Learn more:

<https://perso.crans.org/vanille/treebor/>

- protectors on function arguments
- no range restriction on reborrow



Try it out:

<https://github.com/rust-lang/miri>

- use the flag `-Zmiri-tree-borrows`
- **test** your unsafe code, **report** any surprises!

