Tree Borrows

An aliasing model for Rust

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Rust

v1.0 2018
General-purpose
Safety- and performance-oriented

Not standardized, ongoing efforts

Features

Rich type system
→ Safety & Speed

ML-like

`unsafe`

C-like

Low-level primitives
→ Control

Purposes

Applications

Libraries

Systems

Tools

Libraries

Async, Algebra, UI,
Cryptography, Datetime
Data Structures, Parsing,
Filesystem, Web, ...

Repo: `crates.io`

Must avoid UB

`cargo` Package manager

Compilers

Rustc

Official

Fast, optimizing compiler.

Ignores UB

Miri

Sanitizer

Data races

Out of bounds

Uninitialized memory

Invalid layout

Aliasing conflicts: SB or TB *new!*

Specifies and detects UB

What is Undefined Behavior ?

Common pattern:

- for expressivity and performance the language introduces low level primitives
  (`std::mem::transmute`, pointer arithmetic, `Obj.magic`, ...),
- misuse of these primitives can interfere with compiler invariants (garbage collection, well-formedness of typed values, uniqueness, ...),
- guaranteeing deterministic behavior is
  - too expensive (runtime bounds checks, type markers, ...)
  - not feasible (undecidable at compile time)
  - or otherwise undesirable (wasted optimization potential)

What is Undefined Behavior ?

Solution

Make it UB to misuse these constructs.
If a compiler invariant is violated by a language primitive, the compiler can do literally anything.

UB as a contract

Deal between the programmer and the compiler: these primitives are dangerous, only use them if you really know what you are doing.

`unsafe`

Already a selling point of Rust: `unsafe` is explicit.
UB can only occur as a result of well-delimited blocks.

Common examples

Unchecked out-of-bounds accesses

Rust

```
let v = { let x = [0]; unsafe { x.get_unchecked(1) } };
```

C

```
int* x = malloc(sizeof(int)); int v = x[1];
```

OCaml

```
let v = (let x = [| 0 |] in Array.unsafe_get x 1)
```

Common examples

Dereferencing null

Rust

```
let v = unsafe { *(0 as *const usize as *mut usize) }
```

C

```
int v = *(int*)0
```

OCaml

```
let v = (let x: int ref = Obj.magic 0 in !x)
```

Common examples

Constructing an invalid value

Rust

```
let x: bool = unsafe { std::mem::transmute(2) };
```

C

```
bool x = ((union { int i; bool b }){ .i = 2 }).b;
```

OCaml

```
let x: bool = Obj.magic 2
```

Pointer types in Rust

```
// Raw pointers (unsafe)
*const T
*mut T
// (*const T ⊏ *mut T)

// References (safe)
&'a T // shared and immutable
&'a mut T // unique and mutable
// (&'a T ⊏ &'a mut T)
// ('a ⊂ 'b ⇒ &'a T ⊏ &'b T)
// ('a ⊂ 'b ⇒ &'a mut T ⊏ &'b mut T)

// Wrappers
UnsafeCell, Box, Unique, ...
```

Pointer types in Rust

Just like

```
// x: &mut bool
*x = 4;
```

is a type error (mismatched types `bool` and `u8`),

```
// x: &u8
*x = 4;
```

is also a type error (`&_` does not support assignment), and so is

```
// n: u8
let p = (&mut n, &mut n);
```

(impossible to satisfy lifetime constraints).
Mutability and uniqueness are part of the type!
Can we exploit that?

Is &mut really unique ?

```
let data: u64 = 0;
let r0: &mut u64 = &mut x;

let x: &mut u64 = unsafe { &mut *(r0 as *mut u64) };
let y: &mut u64 = unsafe { &mut *(r0 as *mut u64) };
*x += 1;
*y += 1;
```

Clearly x and y alias, even though they are both unrelated &mut.

Is &mut really unique ?

```
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```

Clearly x and y alias, even though they are both unrelated &mut.

unsafe can violate compiler invariants

unsafe code can violate uniqueness (and well-formedness) guarantees, so the compiler cannot rely on them for optimizations.

A motivating example for Aliasing UB

```
fn foo(x: &mut u64) {
    let val = *x;
    *x = 42;
    opaque();
    *x = val;
}
```

optimized into

```
fn foo(x: &mut u64) {
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Well-typedness of any program that calls `foo` implies uniqueness of `x` during the execution of `foo`: opaque cannot mutate `x`!

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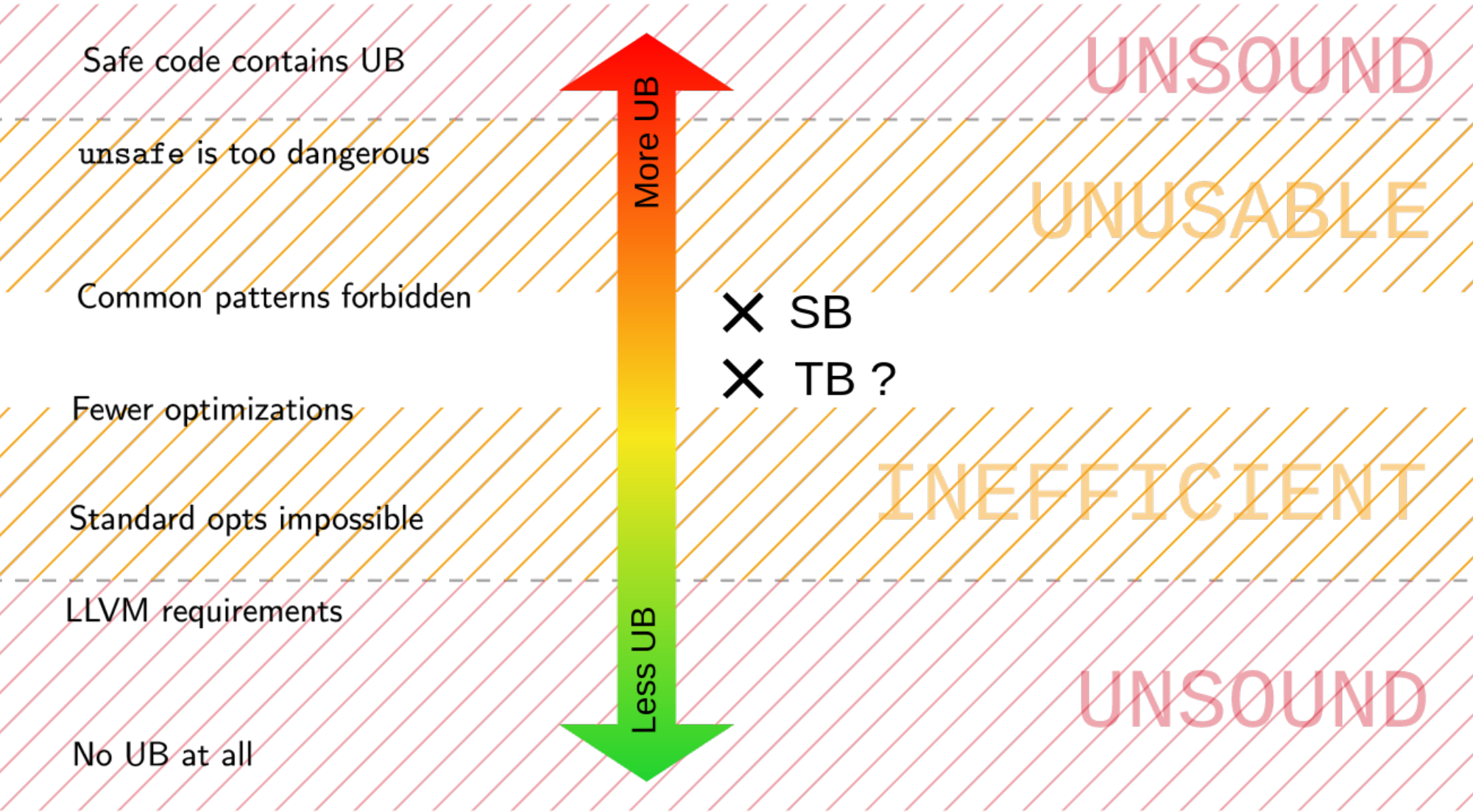
...except if the user uses `unsafe` to violate uniqueness
...which we are going to assume does not happen: violating uniqueness is UB!

How much UB is enough ? Too much ?



Tree Borrows: specification and detection of pointer aliasing UB

Starting observation

Proper usage of pointers (lifetime inclusion and inheritance of mutability) follows a tree discipline.

- when pointer dies, so do its children
- when pointer requires uniqueness, remove other branches

Key ideas

- per-location tracking of pointers
- each pointer has permissions
- on each reborrow a new identifier is added as a leaf of the tree
- a pointer can be used if its permission allows it (to be defined)
- using a pointer kills incompatible (to be defined) pointers

When are pointers different ?

LLVM and Rust specifications: “other references/pointers”
Suggests that two pointers to the same data are “different”.

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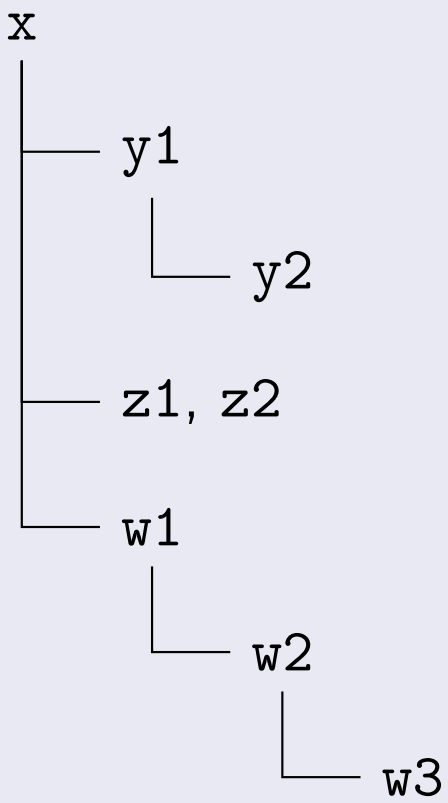
A pointer in our semantics is:

```
struct Pointer {
    address: usize,
    size: usize,
    tag: usize, // <- added specifically for TB/SB
}
```

Two pointers to the same data are not equal for TB/SB if they have different tags.

A Tree of pointers




```
let x = &mut 0u64;

let y1 = &mut *x;
let y2 = &*y1;

let z1 = &*x;
let z2 = z1 as *const u64;

foo(x);
fn foo(w2: &mut u64) {
    let w3 = &*w2;
}
```

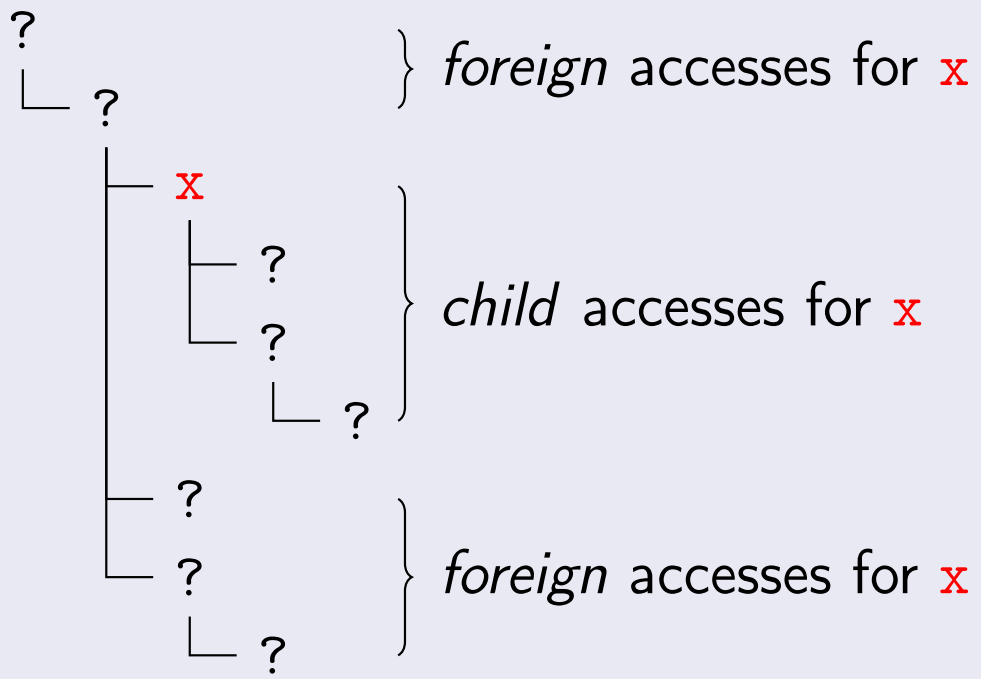
What's in the tree ?

Each pointer is given a tag

(Tree|Stacked) Borrows track:

- **permission**: per tag, per location;
- **hierarchy** between tags;
- accesses are done through a tag:
  - **require permissions** of the tag
    (UB if the permissions are insufficient)
  - **update permissions** of other tags
    (UB if the modification is forbidden)

One pointer, 2×2 kinds of accesses

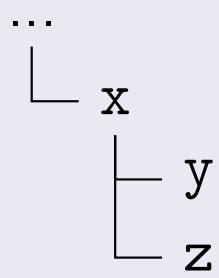


each *read* or *write*.

Kinds of accesses: examples

```
let x = &mut ...;
let y = &*x;
let z = &*x;

let _ = *y; // Read access; foreign for z; child for y, x.
*x = 1; // Write access; foreign for y, z; child for x.
```



Summary

- pointers identified by a tag;
- tags are stored in a tree structure;
  - reborrows create fresh tags,
  - new tag is a child of the reborrowed tag
- each tag has per-location permissions;
  - permissions allow or reject *child accesses* (done through child tags)
  - permissions evolve in response to *foreign accesses* (done through non-child tags).

How many permissions ?

In short: one permission per "kind of pointer"

- (interior) mutability,
- lifetime information,
- creation context,
- ...

Guarantees required of pointers determine behavior of permissions:

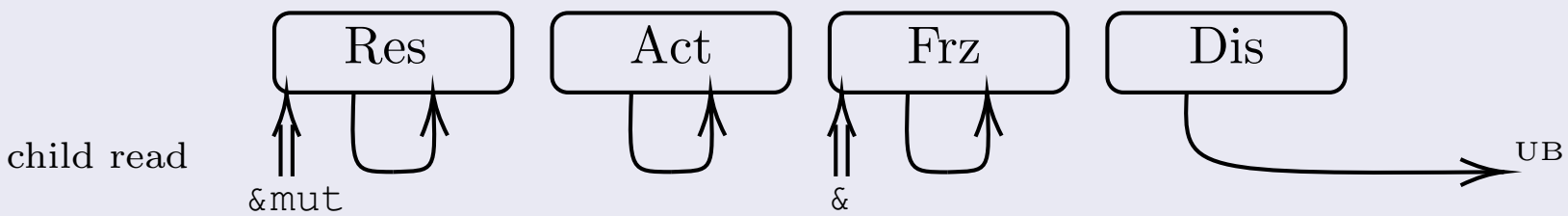
- pointer allows mutation
  $\Rightarrow$ permission allows child writes
- pointer guarantees uniqueness
  $\Rightarrow$ permission is invalidated by foreign accesses
- ...

Reserved, Active, Frozen, Disabled

Basic permissions to represent

- two phase borrowed (mutable in the future): `Reserved`,
- unique mutable references: `Active`,
- shared immutable references: `Frozen`,
- lifetime ended: `Disabled`.

Child read : must allow reading



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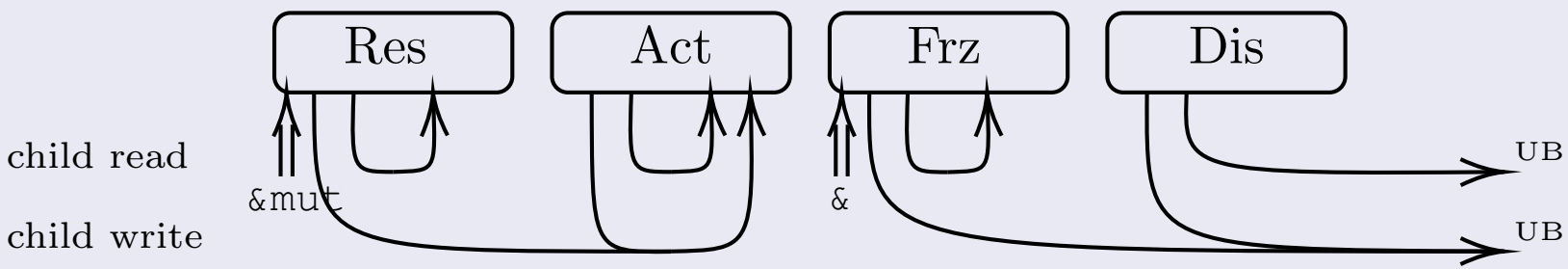

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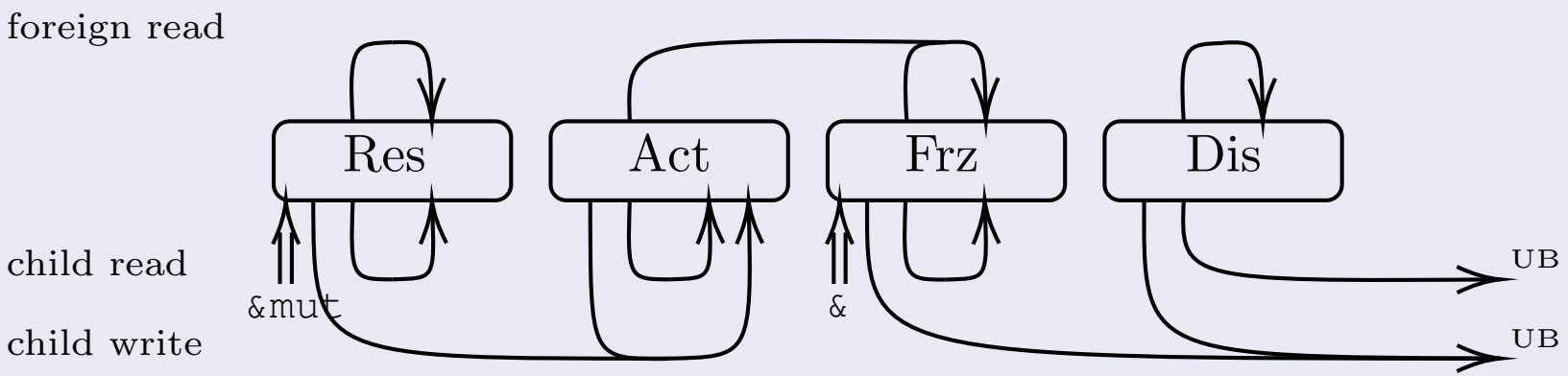

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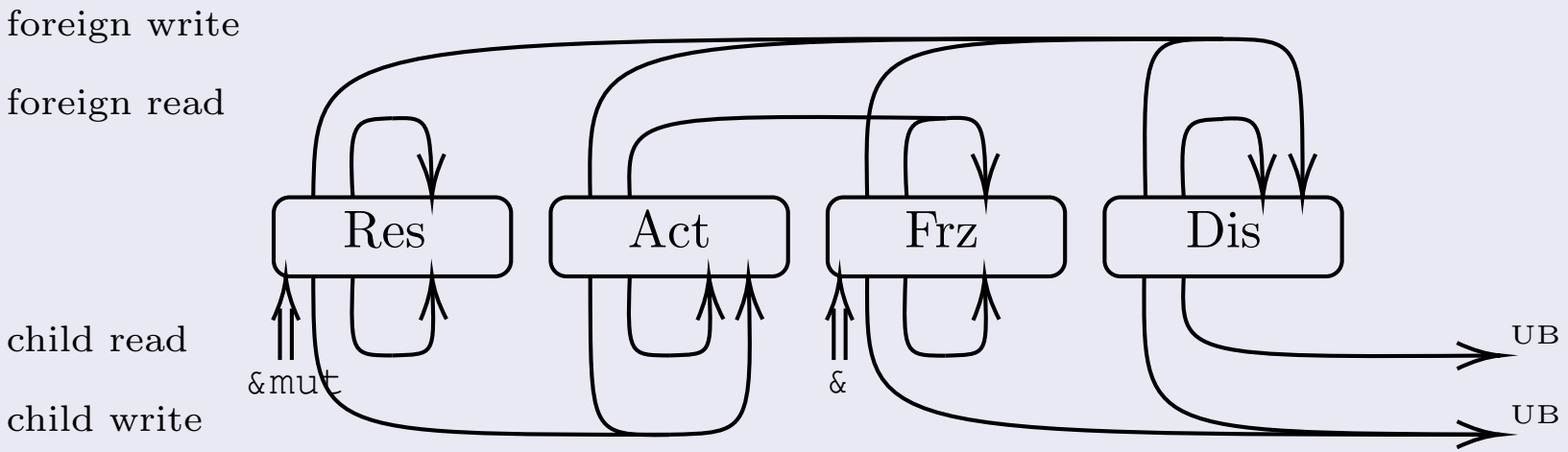
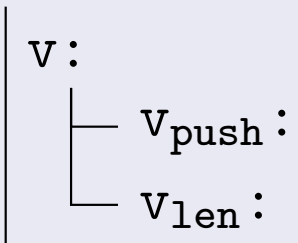


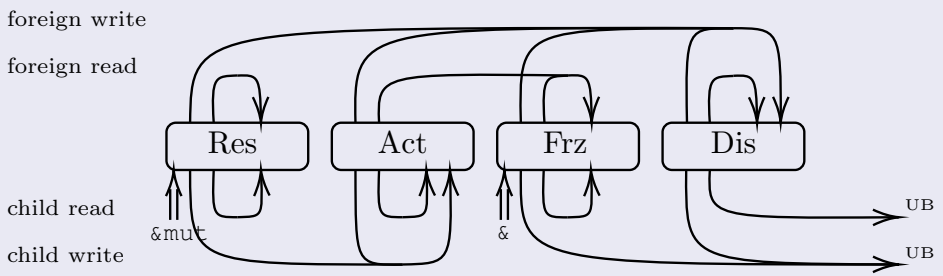
Example: `Reserved` in action

Two-phase borrows

Mutable reborrows in function arguments tolerate shared reborrows until function entry.

```
fn main() {
    let mut v =
        vec![1usize];
    v.push(
        v.len()
    );
}
```





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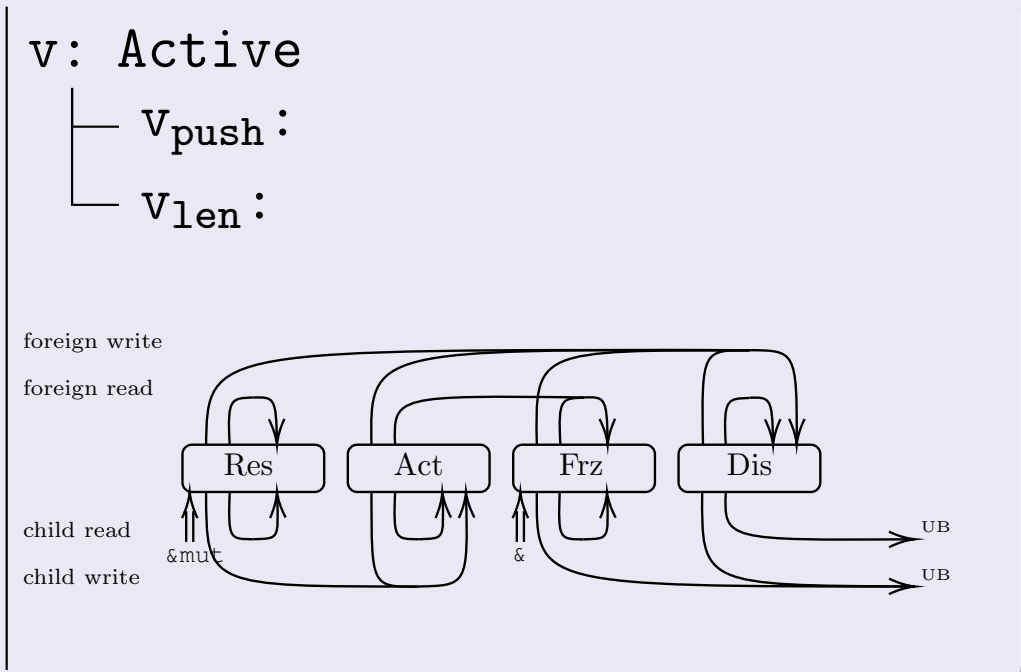

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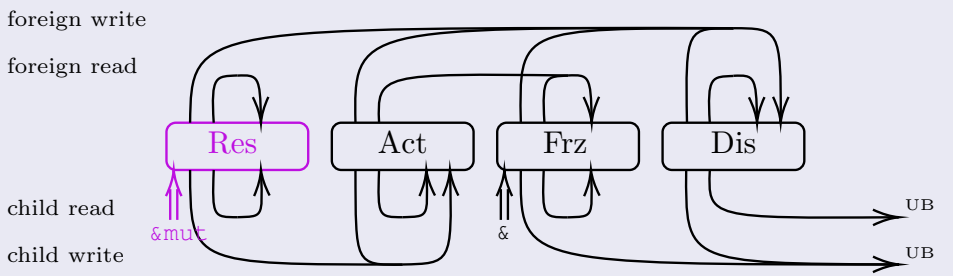
```
v: Active                    ← reborrow
├─ v_push: Reserved
└─ v_len:
```



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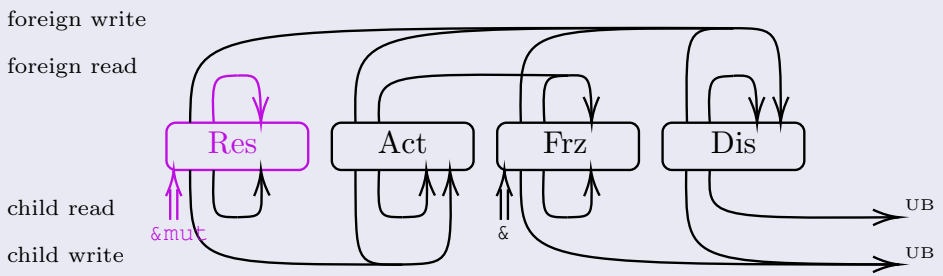
```
v: Active                    ← reborrow
 ├─ v_push: Reserved
 └─ v_len: Frozen            ← read
```



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 fn main() {
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>    v.push(
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>    );
 }
```
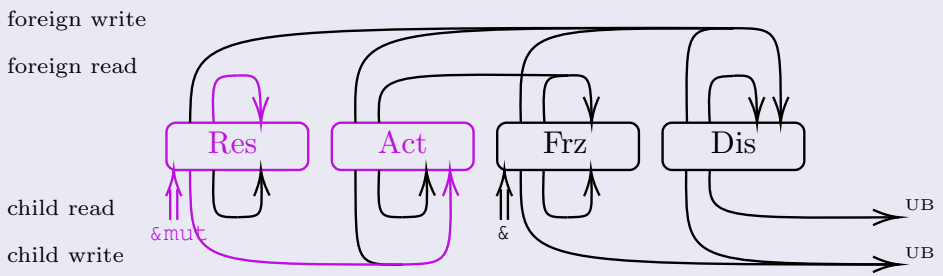

```
v: Active
├─ v_push: Active        ← write
└─ v_len: Disabled
```



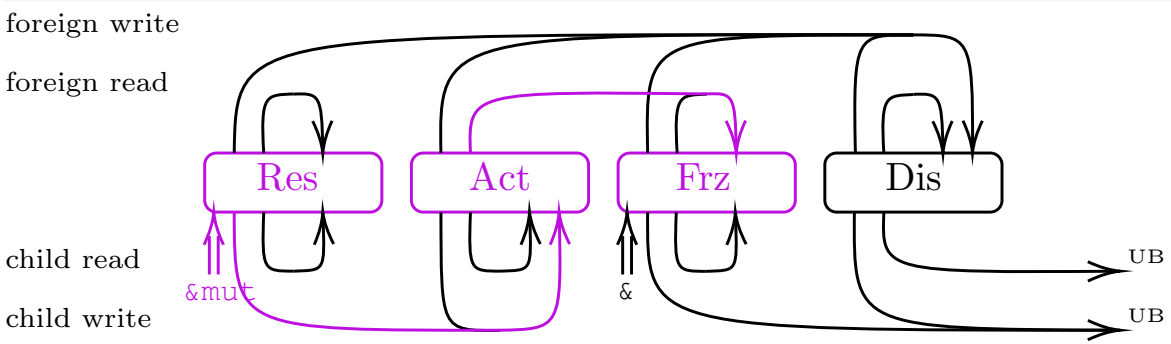
Loss of permissions too early

LLVM `noalias` (in TB terms)

No foreign access during the same function call as a child write.

Previous model: unsound

```
fn write(x: &mut u64) {
    *x = 42; // activation
    opaque(/* foreign read for x: noalias violation */);
}
```



Protectors lock permissions

Intuition

`noalias` requires exclusive access during the entire function call, so we remember the set of all functions that have not yet returned and enforce exclusivity for their arguments.

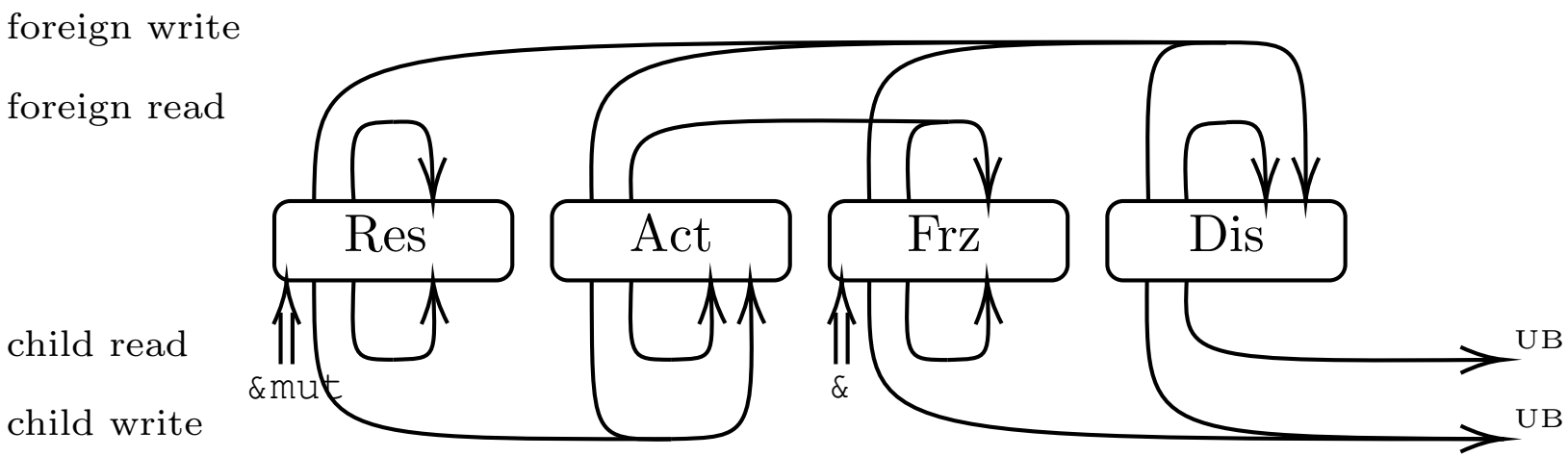
Concept adapted from Stacked Borrows: protectors.

- references get a protector on function entry
- protector lasts until the end of the call
- protectors strengthen the guarantees

$\downarrow 1 \setminus 2 \rightarrow$	$\uparrow$R	$\uparrow$W	$\downarrow$R	$\downarrow$W
$\uparrow$R	/	/	/	$\times$
$\uparrow$W	/	/	$\approx$	$\approx$
$\downarrow$R	/	$\times$	/	/
$\downarrow$W	$\times$	$\times$	/	/

/: not UB
$\times$: should be UB
$\approx$: should be UB earlier

Protectors lock permissions



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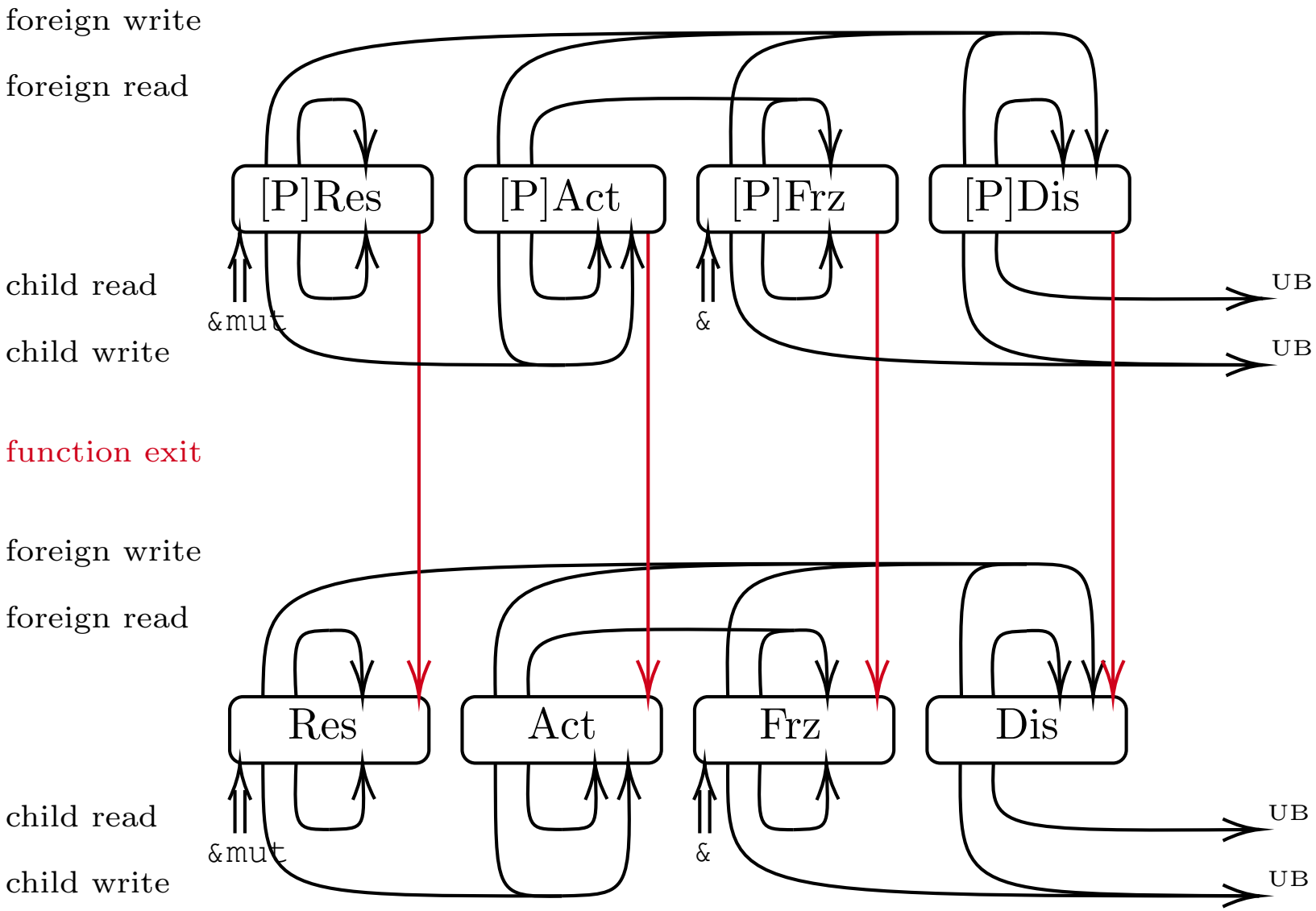

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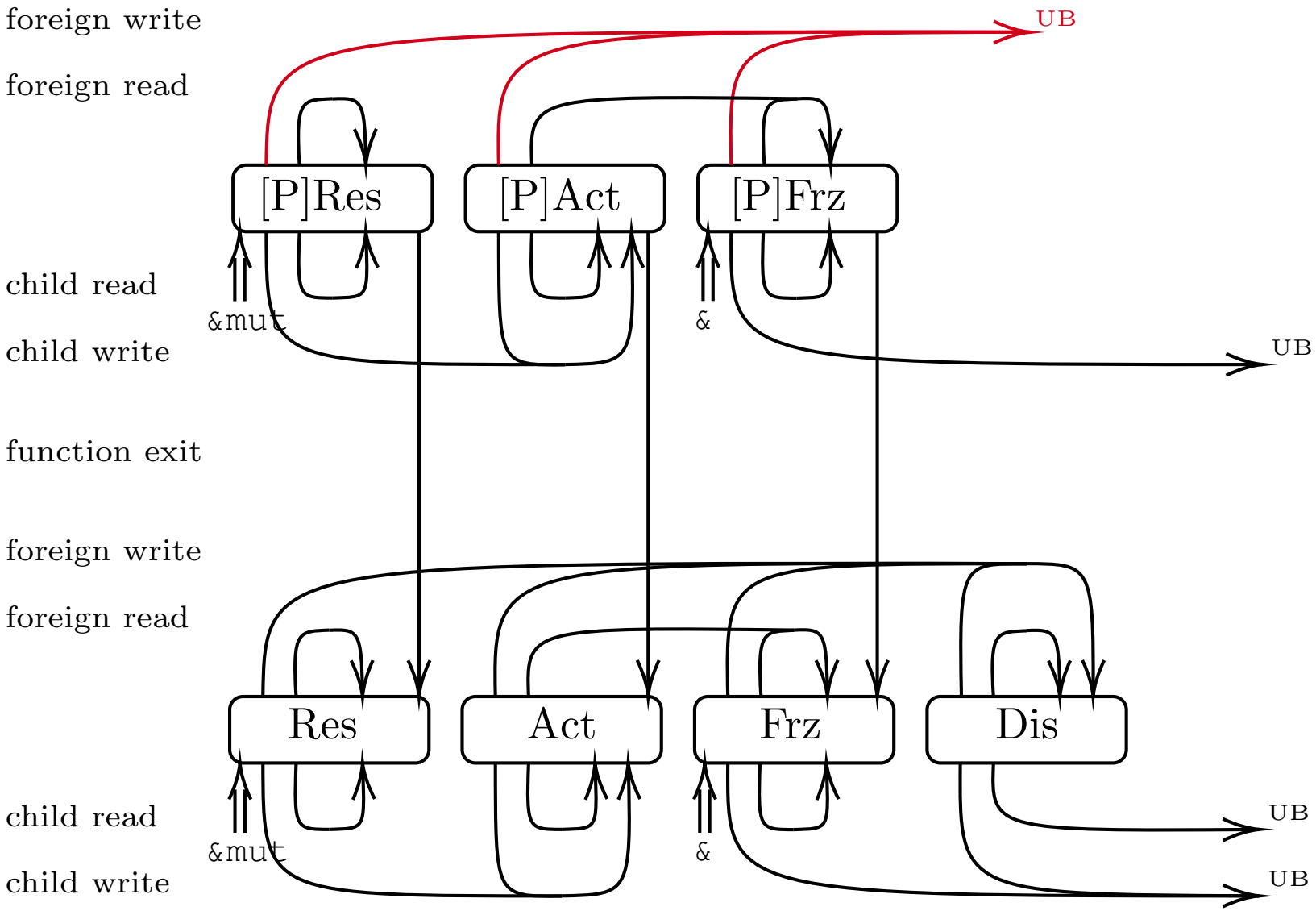

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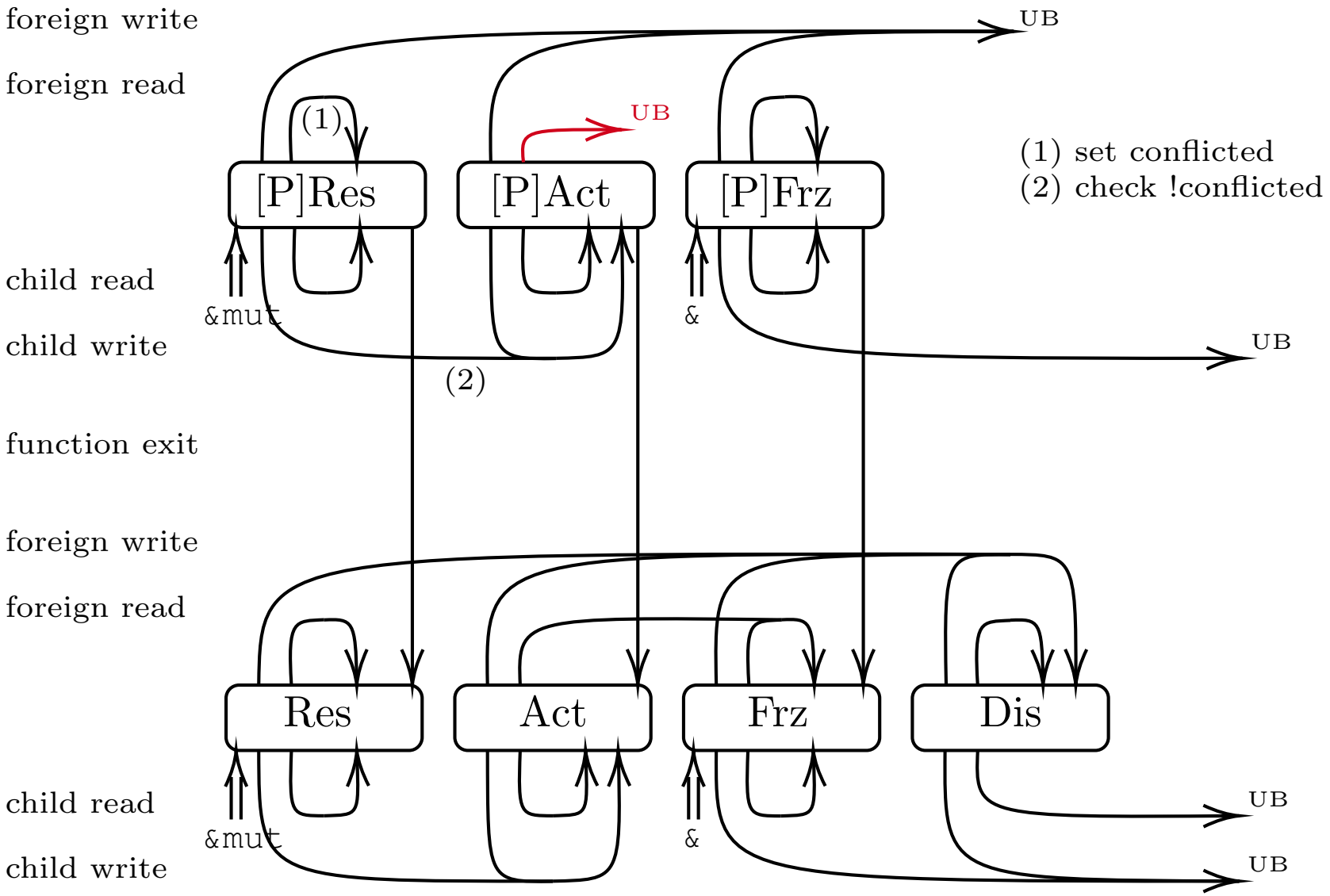

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With protectors: fixed

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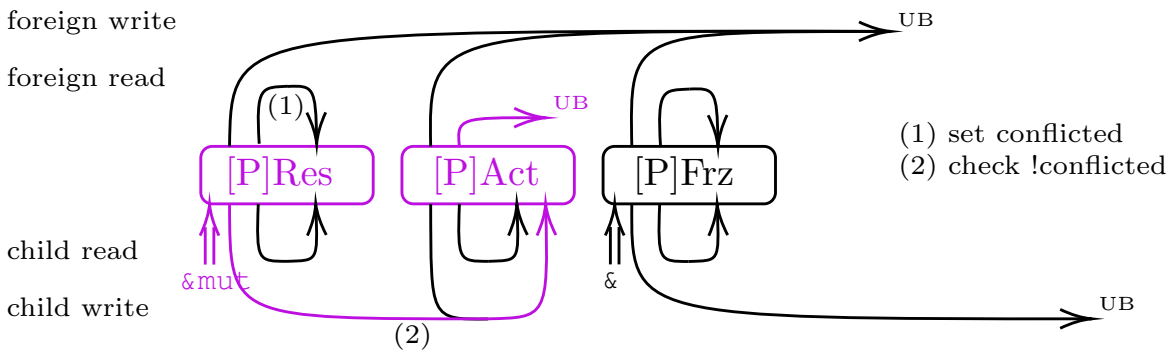

Why not just...

...insert an implicit read/write on function exit ?

```
fn write(x: &mut u64) { // with protector
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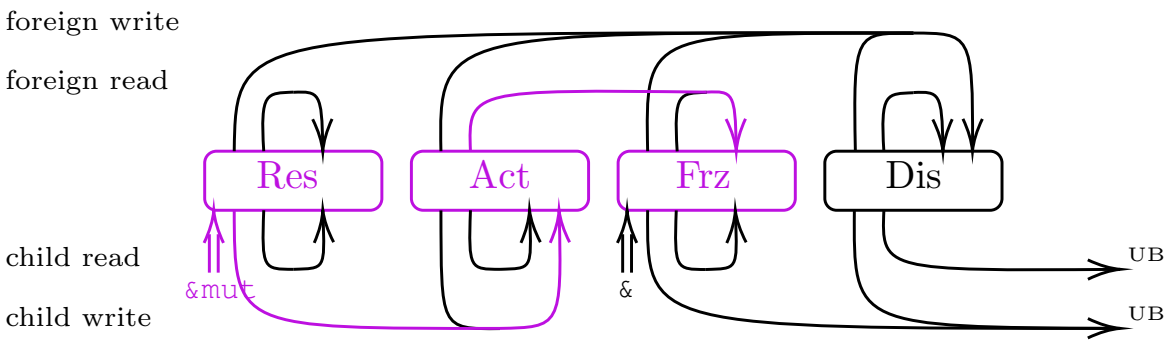

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```

- what if opaque doesn't terminate ?
- should we insert a read or a write ?

Summary

- `Reserved`, `Active`, `Frozen`, `Disabled` represent different possible states of pointers.
- Interactions with child and foreign accesses enforce uniqueness/immutability guarantees.
- Protectors are added on function entry to strengthen these guarantees up to the requirements of `noalias`.

Some standard optimizations

Possible in...	SB	TB
Swap call-read → read-call (speculative)	✓	✓
Swap read-call → call-read	✓*	✓*
▷ Swap read-read' → read'-read	✓*	✓
Swap call-write → write-call (speculative)	✓*	✗
▷ Swap write-call-write → write-write-call	✓*	✓*
Swap write-call → call-write	✓*	✓*
▷ Swap write-write'-read → write'-write-read	✓	✓*

*: only for protected references

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▷ Swap write-call-write → write-write-call	✓*	✓*	
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▷ Swap write-call-write → write-write-call	✓*	✓*
Swap write-call → call-write	✓*	✓*
▷ Swap write-write'-read → write'-write-read	✓	✓*

← TB only

*: only for protected references

Swap write-write

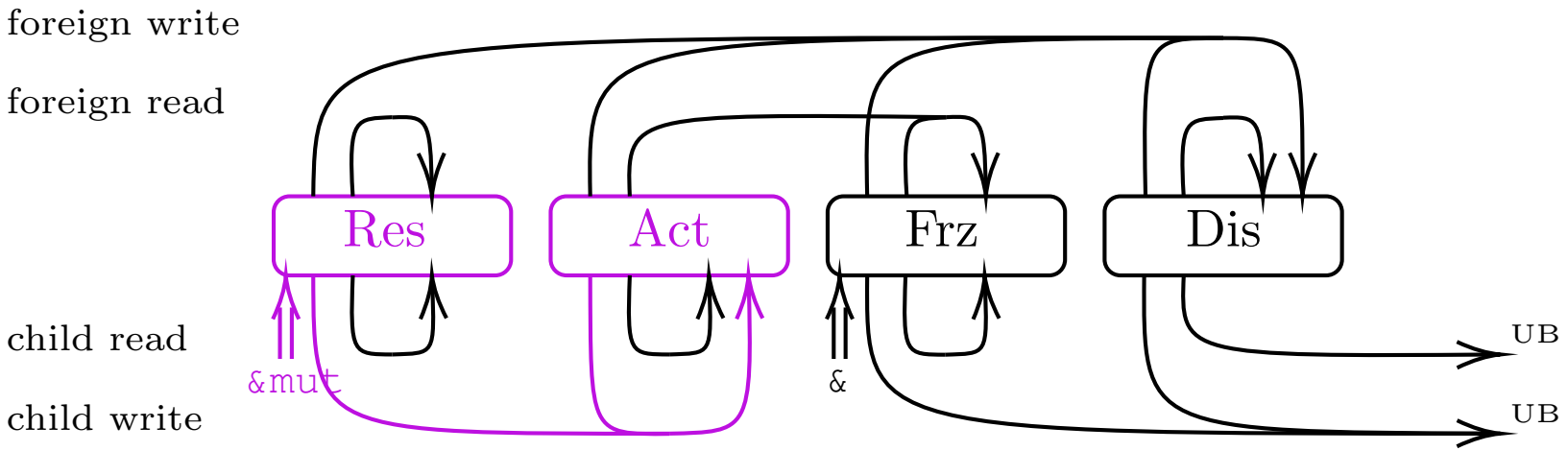
✓ Base model

```
let x = &mut ...;
let y = &mut ...;
*x = 42; // (optimization: move down ?)
*y = 19; // is this a foreign write ?

*x = 57;
```

Swap write-write

✓ Base model

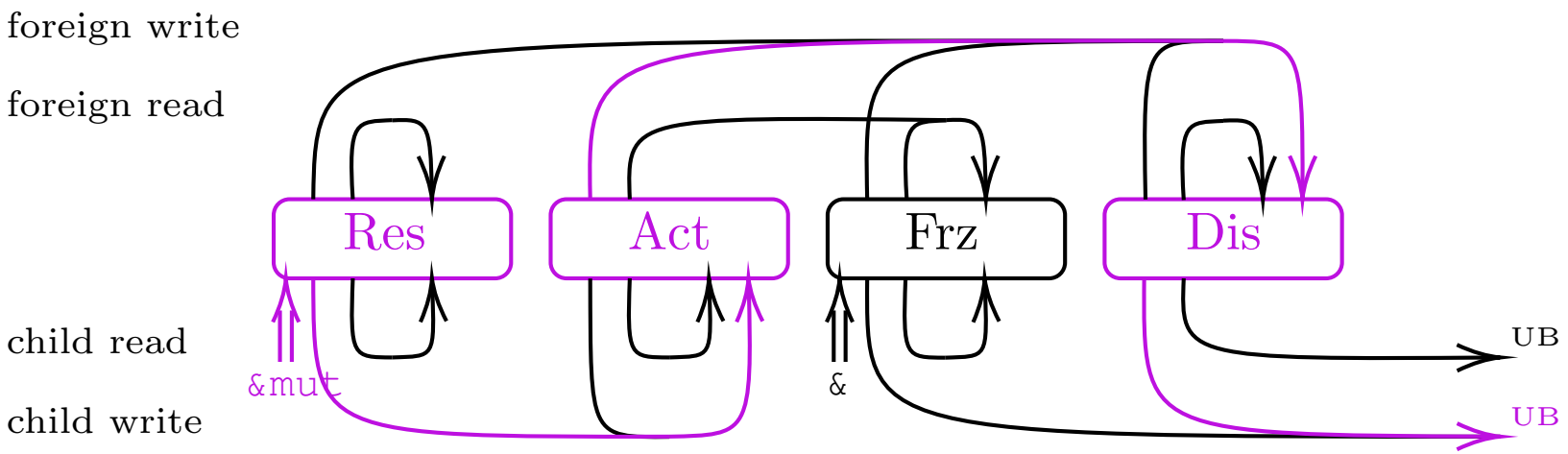
```
let x = &mut ...;
let y = &mut ...;
*x = 42; // (optimization: move down ?)
*y = 19; // is this a foreign write ? if yes

*x = 57;
```



Swap write-write

✓ Base model

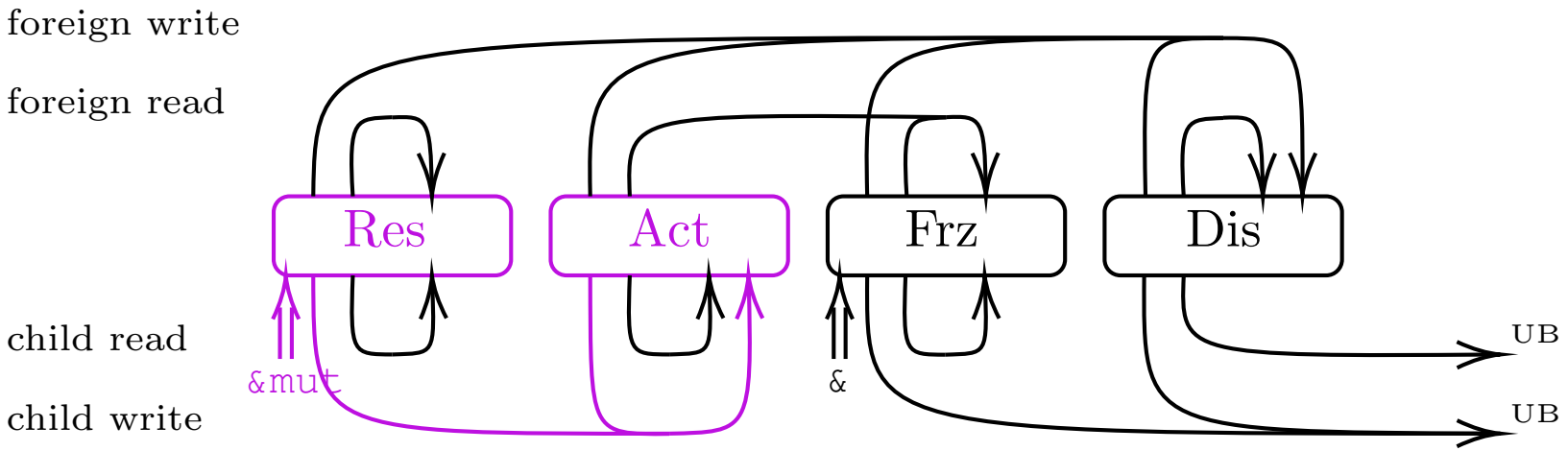
```
let x = &mut ...;
let y = &mut ...;
*x = 42; // (optimization: move down ?)
*y = 19; // is this a foreign write ? if not

*x = 57;
```



Swap write-write

✓ Base model

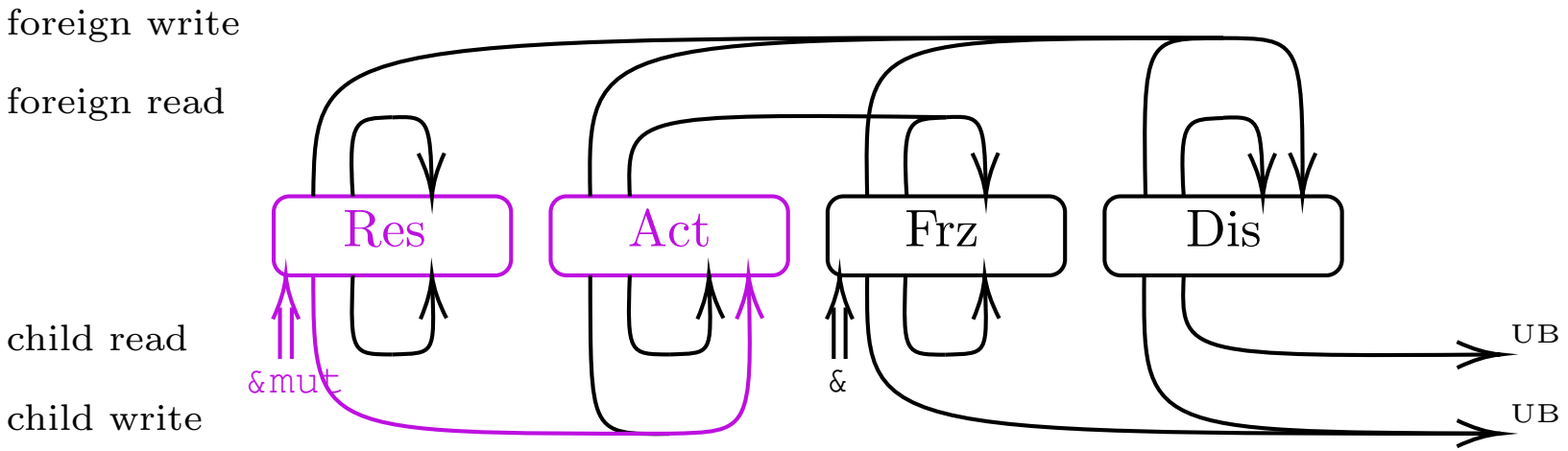
```
let x = &mut ...;
let y = &mut ...;

*y = 19; // assumed not to be a foreign write
*x = 42;
*x = 57;
```



Swap write-write

✓ Base model

```
let x = &mut ...;
let y = &mut ...;

*y = 19; // assumed not to be a foreign write

*x = 57;
```



Insert speculative read

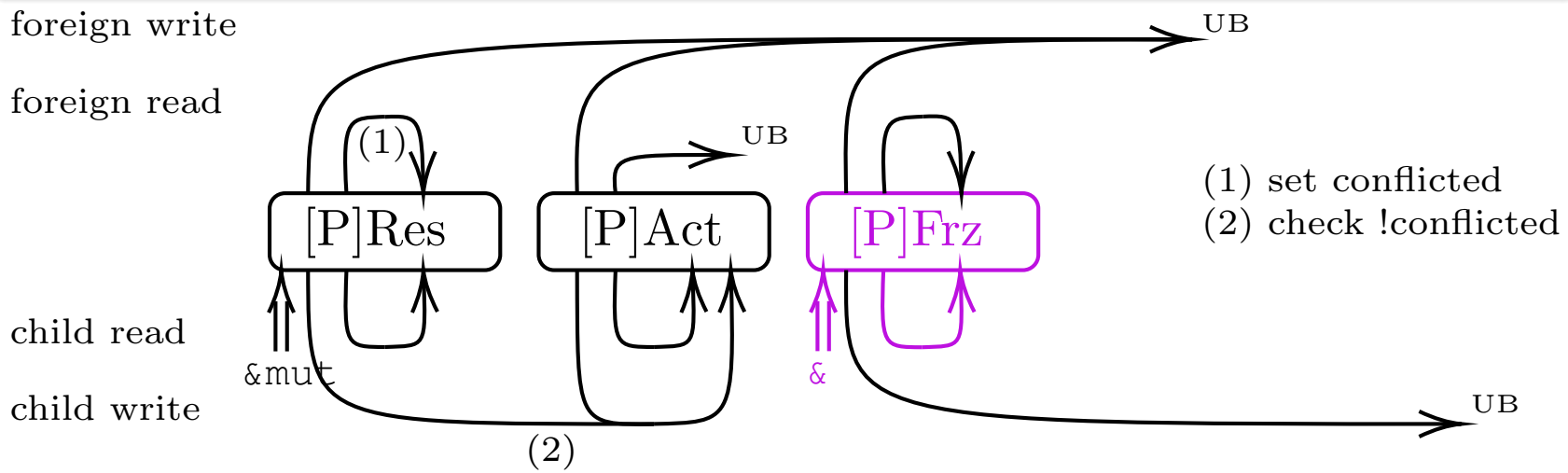
✓ Base model

```
fn read(x: &u64) -> u64 {

    opaque(/* contains foreign access ?          */);
    *x // (optimization: move up ?)
}
```

Insert speculative read

✓ Base model

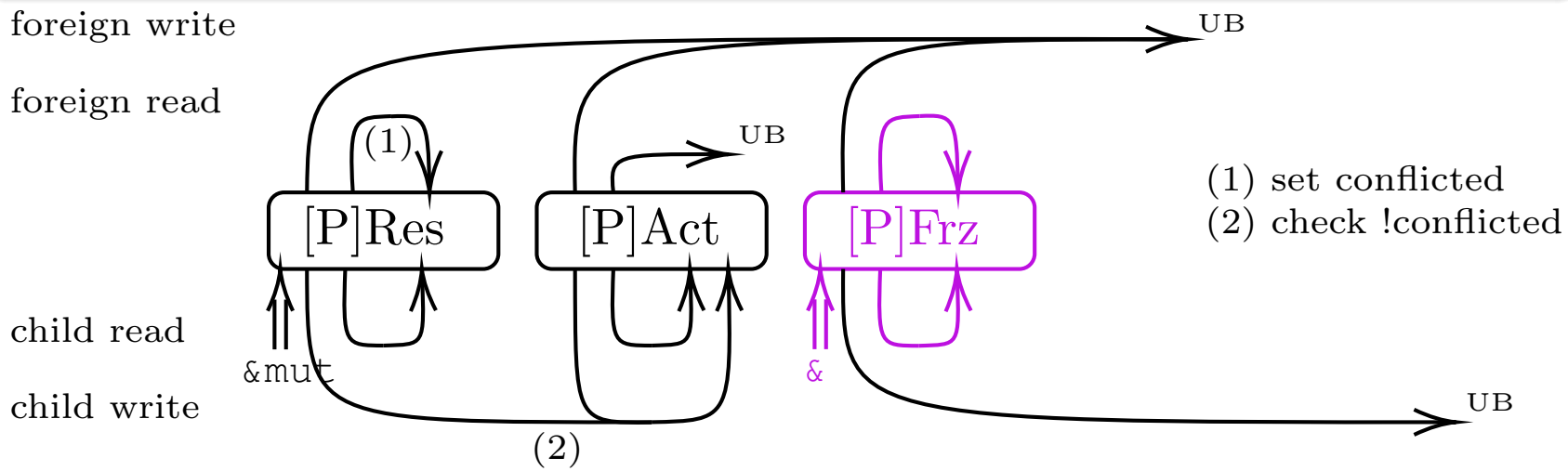
```
fn read(x: &u64) -> u64 {

    opaque(/* contains foreign access ? if none  */);
    *x // (optimization: move up ?)
}
```



Insert speculative read

✓ Base model

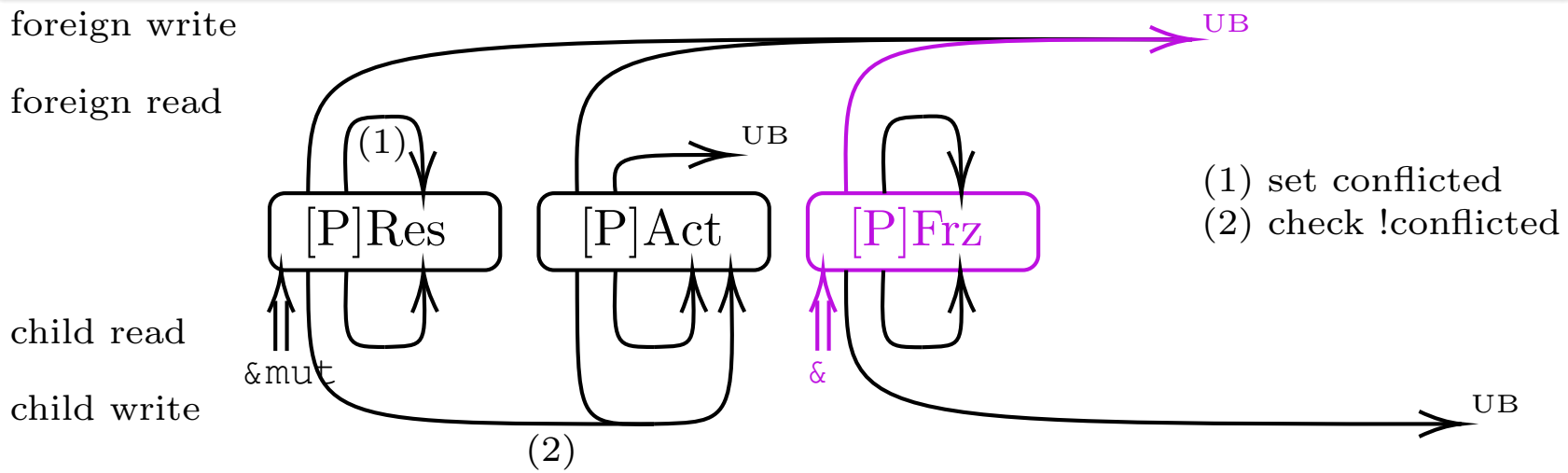
```
fn read(x: &u64) -> u64 {

    opaque(/* contains foreign access ? if read  */);
    *x // (optimization: move up ?)
}
```



Insert speculative read

✓ Base model

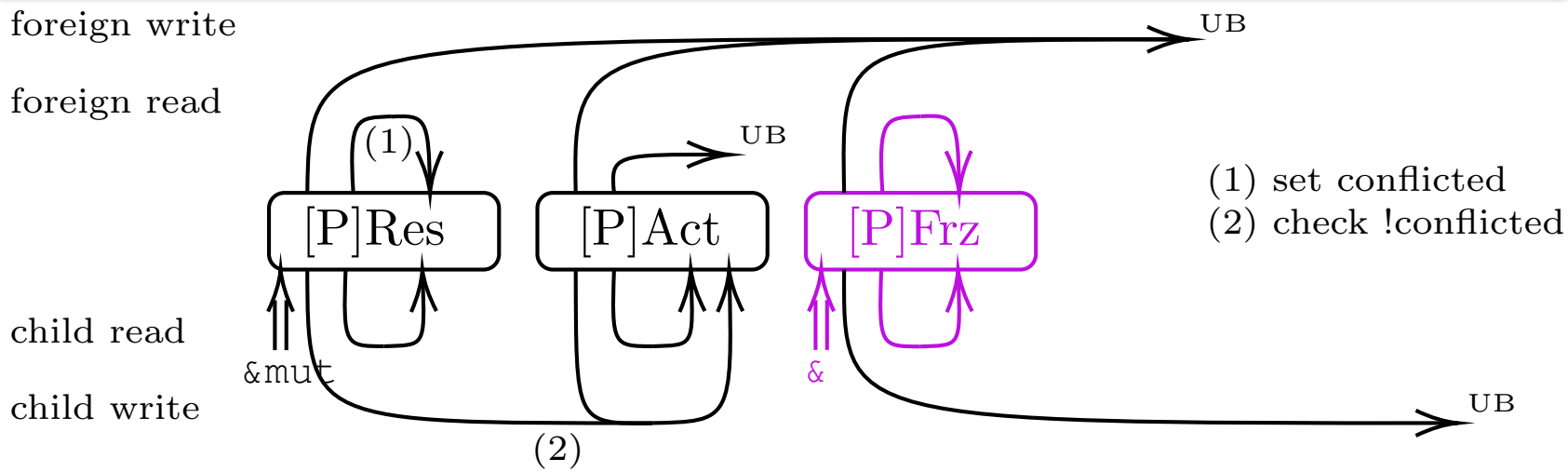
```
fn read(x: &u64) -> u64 {

    opaque(/* contains foreign access ? if write */);
    *x // (optimization: move up ?)
}
```



Insert speculative read

✓ Base model

```
fn read(x: &u64) -> u64 {
    let val = *x;
    opaque(/* assume no foreign write */);
    val
}
```



Insert speculative write

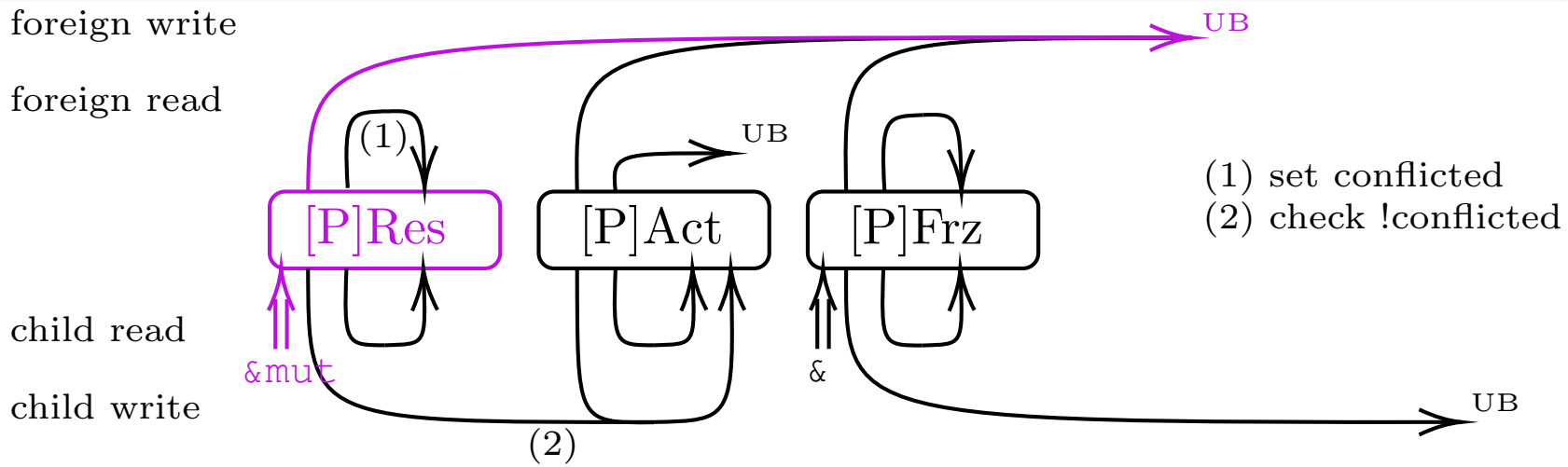
✗ Base model

```
fn foo(x: &mut u64) {

    opaque(/* contains foreign access ?                    */);
    *x = 42; // (optimization: move up ?)
}
```

Insert speculative write

✗ Base model

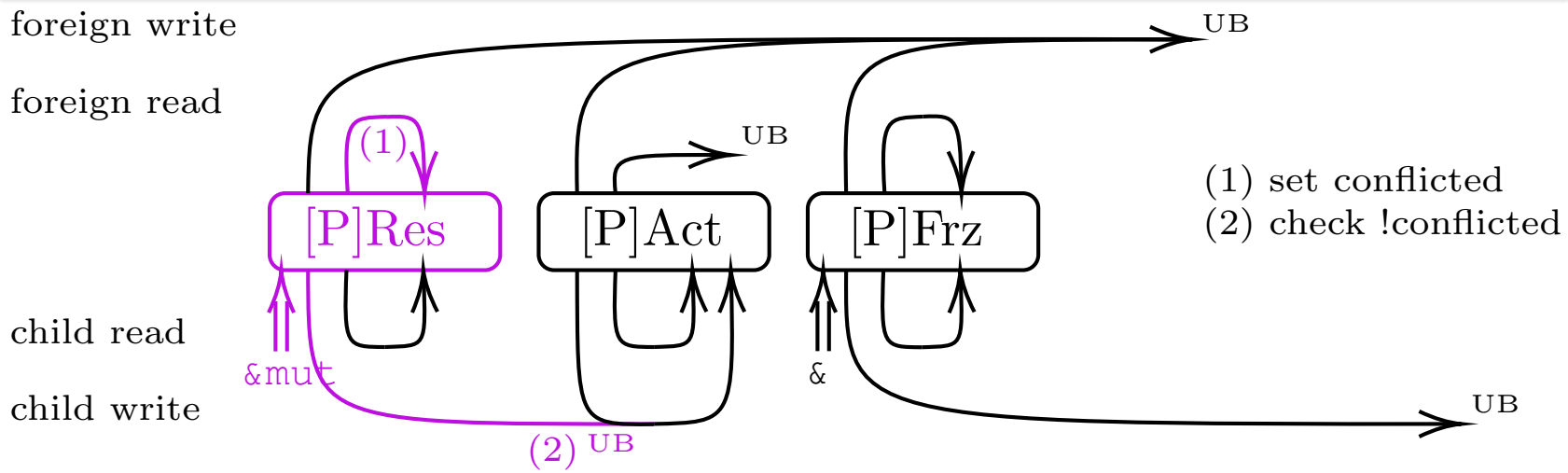
```
fn foo(x: &mut u64) {

    opaque(/* contains foreign access ? if write      */);
    *x = 42; // (optimization: move up ?)
}
```



Insert speculative write

✗ Base model

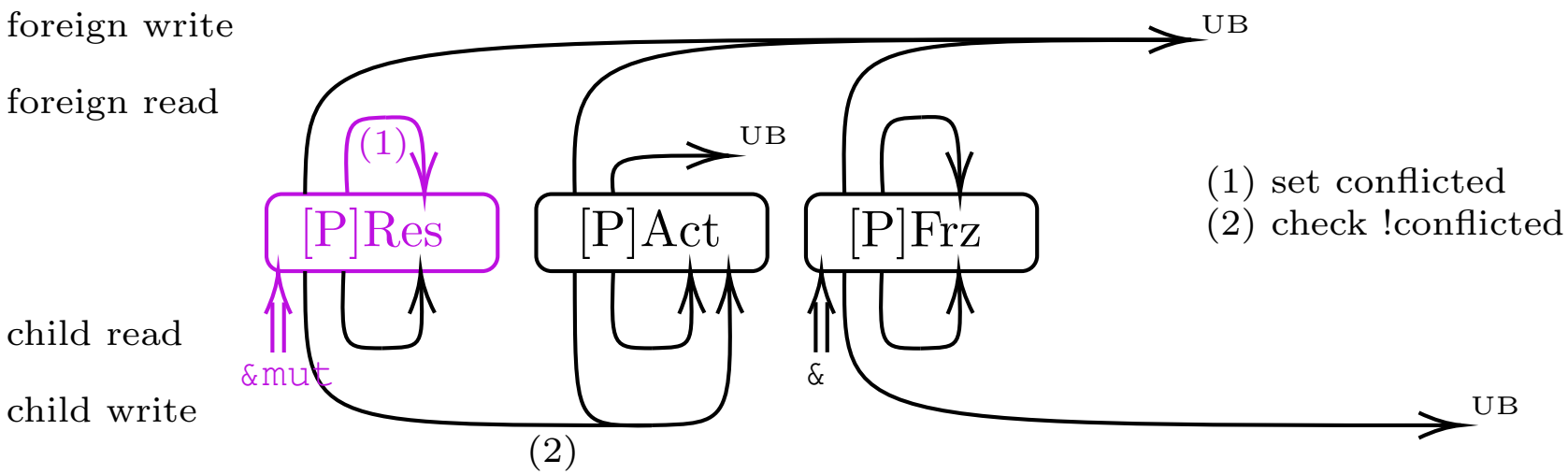
```
fn foo(x: &mut u64) {

    opaque(/* contains foreign access ? if read       */);
    *x = 42; // (optimization: move up ?)
}
```



Insert speculative write

✗ Base model

```
fn foo(x: &mut u64) {

    opaque(/* contains foreign access ? if read+loop */);
    *x = 42; // (optimization: move up ?)
}
```



Insert speculative write: blocker

`as_mut_ptr`: base model

- `&mut [T] -> *mut T`
- returns a `Reserved` child of the input

✓ Common pattern

```
let raw = buf.as_mut_ptr();
let shr = buf.as_ptr().add(1);
copy_nonoverlapping(shr, raw, 1);
```

```
buf: Active
  └─ ...
       └─ raw:  Reserved
```

Insert speculative write: blocker

`as_mut_ptr`: base model

- `&mut [T] -> *mut T`
- returns a `Reserved` child of the input

✓ Common pattern

```
let raw = buf.as_mut_ptr();
let shr = buf.as_ptr().add(1);
copy_nonoverlapping(shr, raw, 1);
```

```
buf: Active
  ├─ ...
  │   └─ raw:  Reserved
  └─ ...
      └─ shr:  Frozen
```

Insert speculative write: blocker

`as_mut_ptr`: base model

- `&mut [T] -> *mut T`
- returns a `Reserved` child of the input

✓ Common pattern

```
let raw = buf.as_mut_ptr();
let shr = buf.as_ptr().add(1);
copy_nonoverlapping(shr, raw, 1);
```

```
buf: Active
  ├─ ...
  │   └─ raw:  Active
  └─ ...
      └─ shr:  Disabled
```

Insert speculative write: blocker

`as_mut_ptr`: strengthened with speculative writes

- `&mut [T] -> *mut T`
- returns an `Active` child of the input

✗ Common pattern

```
let raw = buf.as_mut_ptr();
let shr = buf.as_ptr().add(1);
copy_nonoverlapping(shr, raw, 1);
```

```
buf: Active
  └─ ...
       └─ raw:  Active
```

Insert speculative write: blocker

`as_mut_ptr`: strengthened with speculative writes

- `&mut [T] -> *mut T`
- returns an `Active` child of the input

✗ Common pattern

```
let raw = buf.as_mut_ptr();
let shr = buf.as_ptr().add(1);
copy_nonoverlapping(shr, raw, 1);
```

```
buf: Active
├─ ...
│  └─ raw:  Frozen
└─ ...
   └─ shr:  Frozen
```

A more formal approach

One big invariant:

- must be preserved by any step of the program that does not cause UB
- must provide sufficient hypotheses for the optimizations we want

A more formal approach

An excerpt from the invariant for protected activated mutable references:

$$\forall t \in T, l \in L. \exists p, c. (p, t, c) \in \sigma_t.TREES(l).$$
$$p \neq \text{Disabled} \Rightarrow$$
$$\sigma_s.\text{MEM}(l) \sim \sigma_t.\text{MEM}(l)$$
$$\wedge\, p = \text{Active}$$
$$\wedge\, \forall t' \in \text{Children}_{\sigma_t}(t)\ .\ t'.\text{PERM}[l] = \text{Disabled}$$
$$\wedge\, \forall t' \in \text{Parents}_{\sigma_t}(t)\ .\ t'.\text{PERM}[l] = \text{Active}$$
$$\wedge\, \forall t' \in \text{Uncles}_{\sigma_t}(t)\ .\ t'.\text{PERM}[l] \in \{\text{Disabled, Res InMut}\}$$

What happens to this property when we do ...

...a foreign read ? a foreign write ? a reborrow ?

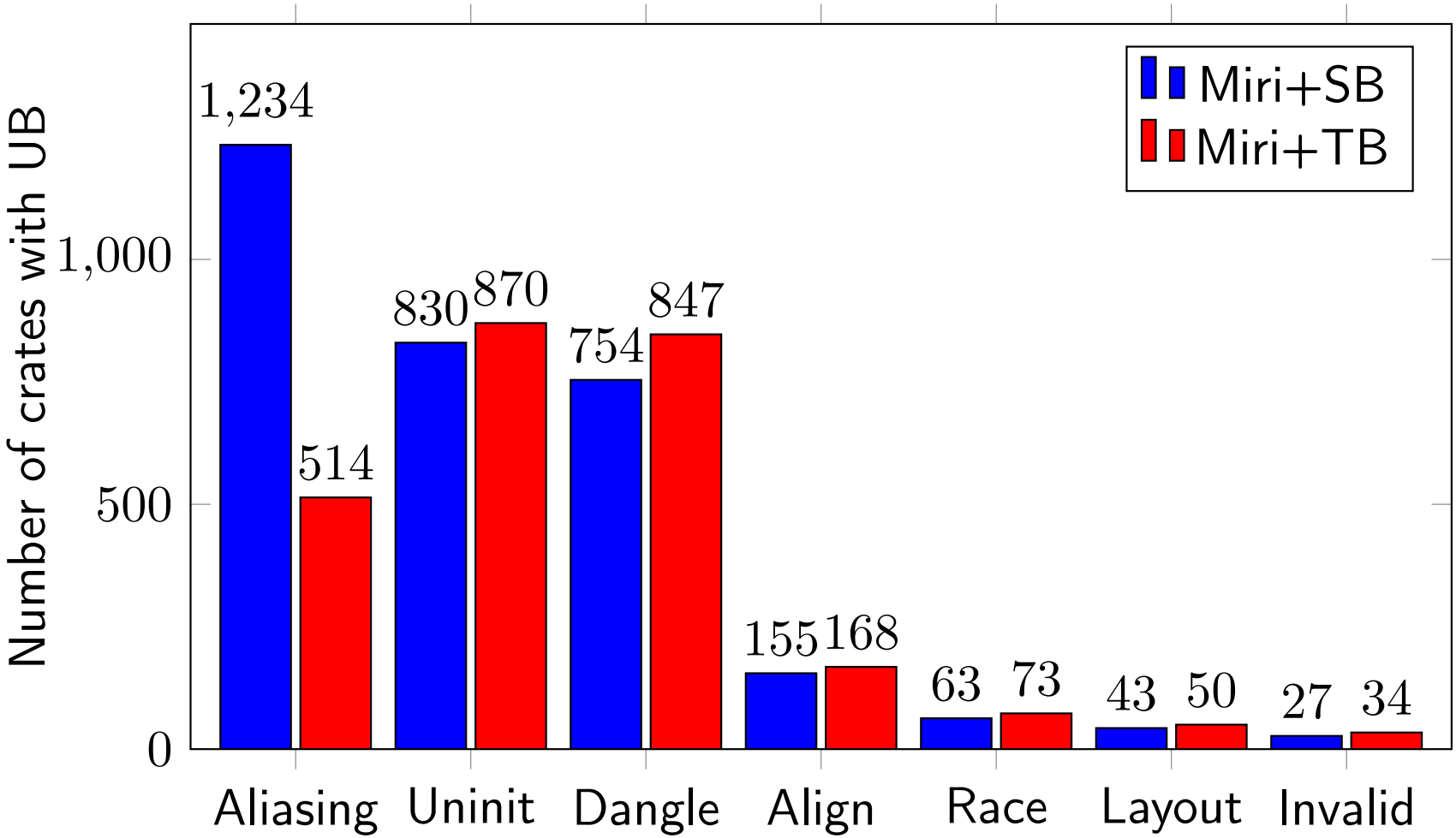
What does this allow ? $\rightarrow$ arbitrary child accesses

Summary

- TB allows read reorderings (SB does not)
- TB allows speculative reads (SB as well)
- TB forbids speculative writes (SB allows them)
  - the model can be strengthened to justify these optimizations...
  - ...at the cost of common patterns.

Counting crates with UB

Data obtained with the help of Ben Kimock using github:saethlin/miri-tools



Summary

- Tree Borrows UB is much less common on `crates.io` than Stacked Borrows UB
  $\Rightarrow$ fulfills goal of being more permissive

Notable examples

`tokio`, `pyo3`, `rkyv`, `eyre`, `ndarray`, `arrayvec`, `slotmap`, `nalgebra`, `json`.

- patterns allowed by Stacked Borrows but forbidden by Tree Borrows are theoretically possible but have not been found in actual code

Reception

TB has existed for one year

- ⊕ consensus that TB is simpler and more predictable than SB,
- ⊕ cases where TB is more permissive than SB are welcome (e.g. `&Header` pattern),
- ⊕ cases where TB is less permissive are rare (no complaints yet),
- ⊖ fewer optimizations (expected),
- ⊖ controversial granularity of interior mutability,
- ⊖ slight performance regression in Miri.

Questions ?

TB also has...

- tweaked rules for interactions between interior mutability and protectors/`Reserved`
- performance improvements compared to the naive implementation
  - many tricks to trim tree traversals
  - lazy initialization for out-of-range accesses
- ongoing attempt at formalization in Coq

Don't hesitate to test your code with Miri and send us your interesting/unexpected cases of UB!

`github:Vanille-N/tree-beamer/tree/lmf`
Complementary material: `perso.crans.org/vanille/treebor`