Stacked Borrows: An Aliasing Model for Rust

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Rust – Mozilla's replacement for C/C++

Rust is the only language to provide…

- Low-level control à la C/C++
- Strong safety guarantees
- Modern, functional paradigms
- Industrial development and backing

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"mainstream"

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Core ingredient: sophisticated type system

Rust – Mozilla's replacement for C/C++

Goal: exploit the unique type information available in Rust for optimizations

Rust's reference type comes in two flavors:

1. Mutable reference: `&mut T`
   (no aliasing)
2. Shared reference: `&T`
   (no mutation by anyone)

Rust’s reference type comes in two flavors:

1. Mutable reference: `&mut T`

Rust’s reference types provide strong aliasing information.

The optimizer should exploit that!

Aliasing guarantees: `&mut T` Examples

```
fn test_noalias(x: &mut i32, y: &mut i32) -> i32 {
  // x, y cannot alias: they are unique pointers
  *x = 42;
  *y = 37;
  return *x; // must return 42
}
```

Aliasing guarantees: `&mut T` Examples

```rust
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  // unknown_function cannot have an alias to x
  unknown_function();
  return *x; // must return 42
}
```

Aliasing guarantees: `&mut T` Examples

escaped pointer

```
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  // unknown_function cannot have an alias to x
  unknown_function();
  return *x; // must return 42
}
```

unknown code

Aliasing guarantees: &T Examples

```
fn test_noalias_shared(x: &i32, y: &mut i32) -> i32 {
  let val = *x;
  // cannot mutate x: x points to immutable data
  *y = 37;
  return *x == val; // must return true
}
```

Aliasing guarantees: `&T` Examples

```
fn test_shared(x: &i32) -> bool {
  let val = *x;
  // unknown_function_shared cannot mutate x
  unknown_function_shared(x);
  return *x == val; // must return true
}
```

Aliasing guarantees: `&T` Examples

escaped pointer

```
fn test_shared(x: &i32) -> bool {
  let val = *x;
  // unknown_function_shared cannot mutate x
  unknown_function_shared(x);
  return *x == val; // must return true
}
```

unknown code with access to `x`

Aliasing guarantees: `&T` Examples

These optimizations are the wildest dreams of C compiler developers!

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But there is a problem:

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But there is a problem:

UNSAFE CODE!

Unsafe code can access hazardous operations that are banned in safe code.

```
unsafe fn hazardous(x: usize) -> i32 {
  // *mut T is the type of raw (unsafe) pointers
  let x_ptr = x as *mut i32;
  return *x_ptr; // dereferencing an arbitrary integer
}
```

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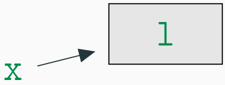
```

- Used for better performance, FFI, implementing many standard library types
- Generally encapsulated by safe APIs

```
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // must return 42
}
```

```rust
fn main() {
  let mut l = 13;

  let answer = test_unique(&mut l);
  println!("The answer is {}", answer);
}
```

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fn test_unique(x: &mut i32) -> i32 {
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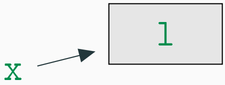
  unknown_function();
  return *x; // must return 42
}
```

```rust
static mut ALIAS: *mut i32 = ptr::null_mut();
fn main() {
  let mut l = 13;

  let answer = test_unique(&mut l);
  println!("The answer is {}", answer);
}
```

ALIAS is a raw pointer (`*mut T`)

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fn main() {
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}
fn unknown_function() {
  unsafe { *ALIAS = 7; }
}
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // should return 42, but returns 7
}
```

Overwrites *x with 7

```
static mut ALIAS: *mut i32 = ptr::null_mut();
fn main() {
  let mut l = 13;
  unsafe { ALIAS                 i32; }
  let answer = te                ;
  println!("The a             swer); // prints 7
}
fn unknown_functi
  unsafe { *ALIAS = 7; }
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fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // should return 42, but returns 7
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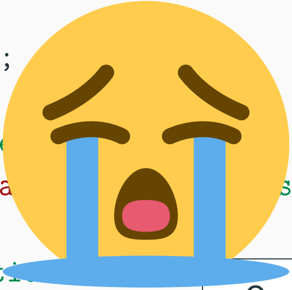
```



Overwrites *x with 7

```
static mut ALIAS: *mut i32 = ptr::null_mut();
fn main() {
  let mut l = 13;
  unsafe { ALIAS = &mut l as *mut i32; }
  let answer = test_unique(&mut l);
  println!("The answer is {}", answer); // prints 7
}

}
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // should return 42, but returns 7
}
```

Goal: rule out misbehaving programs

Review: Undefined Behavior

Use of unsafe code imposes
proof obligations on the programmer:

No use of dangling/NULL pointers, no data races, …

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Violation of proof obligation leads to
Undefined Behavior.

Image: dbeast32

Review: Undefined Behavior

Use of unsafe code imposes

Compilers can rely on these proof obligations when justifying optimizations

Violation of proof obligation leads to Undefined Behavior.

```rust
static mut ALIAS: *mut i32 = ptr::null_mut();
fn main() {
  let mut l = 13;
  unsafe { ALIAS = &mut l as *mut i32; }
  let answer = test_unique(&mut l);
  println!("The answer is {}", answer); // prints 7
}
fn unknown_function() {
  unsafe { *ALIAS = 7; }
}
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // should return 42, but returns 7
}
```

Plan: make this
Undefined Behavior

Stacked Borrows

Stacked Borrows

Aliasing model defining which pointers may be used to access memory, ensuring

- uniqueness of mutable references, and
- immutability of shared references.

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  - ✓ formal proof

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Stacked Borrows: Key Idea

Model proof obligations after existing static “borrow” check

Borrow Checker	Stacked Borrows
static	dynamic
only safe code	safe & unsafe code

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
```

```rust
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
```

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
*b = 3;
```

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
*b = 3;
*a = 4;
```

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
*b = 3;
*a = 4;
*b = 4; // ERROR: lifetime of ‘b‘ has ended
```

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
*b = 3;
*a = 4;
*b = 4; // ERROR: lifetime of ‘b‘ has ended
```

Conflicting use of a

1. The lender a does not get used until the lifetime of the loan has expired.

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
*b = 3;
*a = 4;
*b = 4; // ERROR: lifetime of ‘b‘ has ended
```

Conflicting use of `a`

1. The lender `a` does not get used until the lifetime of the loan has expired.
2. The recipient of the borrow `b` may only be used while its lifetime is ongoing.

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
*b = 3;
*a = 4;
*b = 4; // ERROR: lifetime of ‘b‘ has ended
```

Conflicting use of `a`

- Chain of borrows:
  `l` borrowed to `a` reborrowed to `b`
- Well-bracketed: no ABAB

```
let mut l = 13;
let a = &mut l; // a *borrows* from l
let b = &mut *a; // b *reborrows* from a
*b = 3;
*a = 4;
```

(Re)borrows are organized in a stack.

- Chain of borrows: `l` borrowed to `a` reborrowed to `b`
- Well-bracketed: no ABAB

Stacked Borrows ingredients

Pointer values carry a tag ($\mathit{PtrVal} \triangleq \mathit{Loc} \times \mathbb{N}$)

Example: (`0x40`, `1`)

references (`&mut T`) are identified by a tag

Stacked Borrows ingredients

Pointer values carry a tag ($\mathit{PtrVal} \triangleq \mathit{Loc} \times \mathbb{N}$)

Example: (`0x40`, `1`)

Every location in memory comes with an associated stack ($\mathit{Mem} \triangleq \mathit{Loc} \xrightarrow{\text{fin}} \mathit{Byte} \times \mathit{Stack}$)

```
⋮
0x40: 0xFE, [0: Unique, 1: Unique]
⋮
```

Stacked Borrows ingredients

Reference tagged 1 borrows from reference tagged 0

Every location in memory comes with an associated stack ($Mem \triangleq Loc \xrightharpoonup{\text{fin}} Byte \times Stack$)

$\vdots$

```
0x40: 0xFE, [0: Unique, 1: Unique]
```

$\vdots$

Stacked Borrows ingredients

Pointer values carry a tag ($PtrVal \triangleq Loc \times \mathbb{N}$)

For every use of a reference or raw pointer:

- Extra proof obligation:
  $\Rightarrow$ the tag must be in the stack
- Extra operational effect:
  $\Rightarrow$ pop elements further up off the stack

```
let mut l = 13;
let a = &mut l;
let b = &mut *a;
*b = 3;
*a = 4;
*b = 4; // ERROR: lifetime of ‘b‘ has ended
```

```
let mut l = 13; // Tag: 0
```

```
1: let mut l = 13; // Tag: 0
```

Stack:

```
[0: Unique]
```

```rust
let mut l = 13; // Tag: 0
let a = &mut l; // Tag: 1
```

Stack:

`[0: Unique, 1: Unique]`

Find old tag `0` on stack;
pop items above (none);
add new tag `1: Unique` above it

```
let mut l = 13; // Tag: 0
let a = &mut l; // Tag: 1
let b = &mut *a; // Tag: 2
```

Stack:

`[0: Unique, 1: Unique, 2: Unique]`

Find old tag `1` on stack;
pop items above (none);
add new tag `2: Unique` above it

```
let mut l = 13; // Tag: 0
let a = &mut l; // Tag: 1
let b = &mut *a; // Tag: 2
*b = 3;
```

Stack:

`[0: Unique, 1: Unique, 2: Unique]`

Find tag 2 on stack;
pop items above (none)

```
let mut l = 13; // Tag: 0
let a = &mut l; // Tag: 1
let b = &mut *a; // Tag: 2
*b = 3;
*a = 4;
```

Stack:

[0: Unique, 1: Unique, ~~2: Unique~~]

Find tag 1 on stack;
pop items above (2: Unique)

```rust
let mut l = 13; // Tag: 0
let a = &mut l; // Tag: 1
let b = &mut *a; // Tag: 2
*b = 3;
*a = 4;
*b = 4; // ERROR: lifetime of ‘b‘ has ended
```

Stack:

`[0: Unique, 1: Unique]`

Find tag 2 on stack – there is no such item! 💥

```
1: let mut l = 13; // Tag: 0
2: let a = &mut l; // Tag: 1
3: let b = &mut *a; // Tag: 2
4: *b = 3;
5: *a = 4;
6: *
```

Sta

[0:

Fin

In **safe** code, such Stacked Borrows violations 💥 are prevented by the **borrow checker**.

```
static mut ALIAS: *mut i32 = ptr::null_mut();
fn main() {
  let mut l = 13;
  unsafe { ALIAS = &mut l as *mut i32; }
  let answer = test_unique(&mut l);
  println!("The answer is {}", answer); // prints 7
}
fn unknown_function() {
  unsafe { *ALIAS = 7; }
}
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // should return 42, but returns 7
}
```

```
let mut l = 13;
let ALIAS = &mut l as *mut i32;
let x = &mut l; // was argument to test_unique
*x = 42;
unsafe { *ALIAS = 7; } // was unknown_function
println!("The answer is {}", *x);
```

```
let mut l = 13; // Tag: 0
```

```
1: let mut l = 13; // Tag: 0
```

Stack:

`[0: Unique]`

```
1: let mut l = 13; // Tag: 0
2: let ALIAS = &mut l as *mut i32; // Tag: ⊥
```

Stack:

`[0: Unique, ⊥: SharedRW]`

Find old tag `0` on stack;
pop items above (none);
add new tag `⊥: SharedRW` above it

```
1: let mut l = 13; // Tag: 0
2: let ALIAS = &mut l as *mut i32; // Tag: ⊥
3: let x = &mut l; // Tag: 1
```

Stack:

`[0: Unique,` ~~`⊥: SharedRW`~~`, 1: Unique]`

Find old tag `0` on stack;
pop items above (`⊥: SharedRW`);
push new tag `1: Unique`

```
1: let mut l = 13; // Tag: 0
2: let ALIAS = &mut l as *mut i32; // Tag: ⊥
3: let x = &mut l; // Tag: 1
4: *x = 42;
```

Stack:

`[0: Unique, 1: Unique]`

Find tag `1` on stack;
pop items above (none)

```
let mut l = 13; // Tag: 0
let ALIAS = &mut l as *mut i32; // Tag: ⊥
let x = &mut l; // Tag: 1
*x = 42;
unsafe { *ALIAS = 7; }
```

Stack:

`[0: Unique, 1: Unique]`

Find tag ⊥ on stack – there is no such item! 💥

```
1: let mut l = 13; // Tag: 0
2: let ALIAS = &mut l as *mut i32; // Tag: ⊥
3: let x = &mut l; // Tag: 1
4: *x = 42;
5: unsafe { *ALIAS = 7; }
```

It is undefined behavior to use a pointer whose tag is not on the stack.

Find tag ⊥ on stack – there is no such item! 💥

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Incomplete proof sketch

```
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // must return 42
}
```

Incomplete proof sketch

x's tag is at the top of the stack

```
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // must return 42
}
```

Incomplete proof sketch

x's tag is at the top of the stack

```
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // must return 42
}
```

if `unknown_function` accesses this memory, it will pop x's tag off the stack

Incomplete proof sketch

x's tag is at the top of the stack

```
fn test_unique(x: &mut i32) -> i32 {
  *x = 42;
  unknown_function();
  return *x; // must return 42
}
```

UB unless x's permission is still in the stack

if `unknown_function` accesses this memory, it will pop x's tag off the stack

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fn unknown_function() {
  unsafe { *ALIAS = 7; }
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fn test_unique(x: &mut i32) -> i32 {
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  return *x; // should return 42, but returns 7
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```

```rust
1: static mut ALIAS: *mut i32 = ptr::null_mut();
2: fn main() {
3:   let mut l = 13;
4:   unsafe { ALIAS = &mut l as *mut i32; }
5:   let answer = test_unique(&mut l);
6:   println!("The answer is {}", answer); // prints 7
7: }
8: fn unknown_function() {
9:   unsafe { *ALIAS = 7; }
10: }
```

```
error: Miri evaluation error: no item granting write access to tag <untagged> found in borrow stack.
  --> example.rs:9:12
   |
9  |   unsafe { *ALIAS = 7; }
   |            ^^^^^^^^^^^ no item granting write access to tag <untagged> found in borrow stack.
   |
note: inside call to `unknown_function` at example.rs:13:3
  --> example.rs:13:3
   |
13 |   unknown_function();
   |   ^^^^^^^^^^^^^^^^^^
   |
```

```
static mut ALIAS: *mut i32 = ptr::null_mut();
fn main() {
  let mut l = 13;
  unsafe { ALIAS = &mut l as *mut i32; }
  let answer = test_unique(&mut l);
```

The Rust standard library and an increasing number of user crates regularly have their test suites checked by Miri.

So far, this uncovered 11 aliasing violations. 💥

```
  *x = 42;
  unknown_function();
  return *x; // should return 42, but returns 7
}
```

What else?

What I didn't talk about:

- Shared references & interior mutability
- Protectors (enable writes to be moved across unknown code)

Future work:

- Concurrency
- Integrating Stacked Borrows into RustBelt

A dynamic model of Rust's reference checker ensures soundness of type-based optimizations, even in the presence of unsafe code.

Try Miri out yourself!

- Web version: `https://play.rust-lang.org/` (“Tools”)
- Installation: `rustup component add miri`
- Miri website: `https://github.com/rust-lang/miri/`

Also check out our project website:

`https://plv.mpi-sws.org/rustbelt`