Coupled Borrows

Expanding Core Proof Inference in Prusti

July 2023

Rust, Prusti, and Memory Safety

Rust compiler guarantees memory safety.

- Affine Types
- "Aliasing XOR Mutability"
- Ownership, Borrowing

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Prusti

Decidable memory safety analysis $\rightsquigarrow$ automated core proof

Rust, Prusti, and Memory Safety

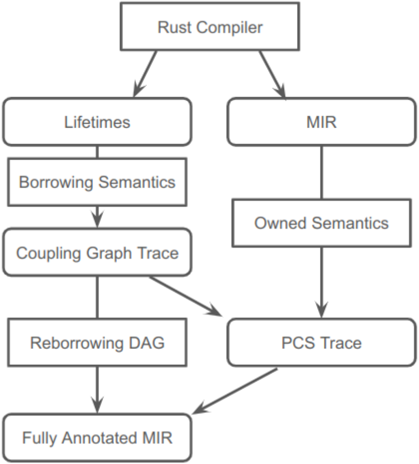
Released version of Prusti has limited support for

- Reborrowing inside loops
- Shared borrows
- Reborrowing at function boundaries
- Borrows inside structs

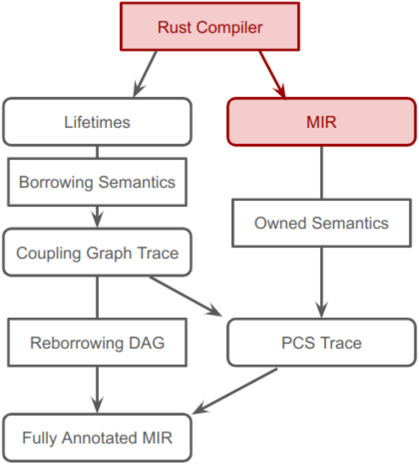
Main Problem

How can we extend Prusti's *model of Rust* to automatically support these features going forward?

Overview


Rust Compiler
Lifetimes
MIR
Borrowing Semantics
Owned Semantics
Coupling Graph Trace
Reborrowing DAG
PCS Trace
Fully Annotated MIR

Overview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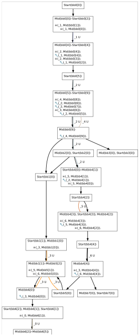
Background: MIR

MIR: Mid-level Intermediate Representation

Place: Represent accessible memory as $(\mathrm{local}, [\mathrm{projection}])$.

- locals: arguments, locally declared variables: `_1`, `_2`, ...
- projection:
  - dereference (`*_1`)
  - field access (`_2.0`)
  - enum variant downcast (`_3 as Some`)
  - more including indexing, slices, type casts ...

1st notion of memory safety



Result of definite accessibility analysis.
Traces accessibility through the MIR.

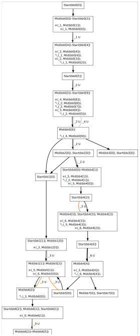
Memory Safety in Rust

Fixed point analyses over MIR.

Ensures definite accessibility before use.

$\Rightarrow$ No use after free errors.

1^{st} notion of memory safety



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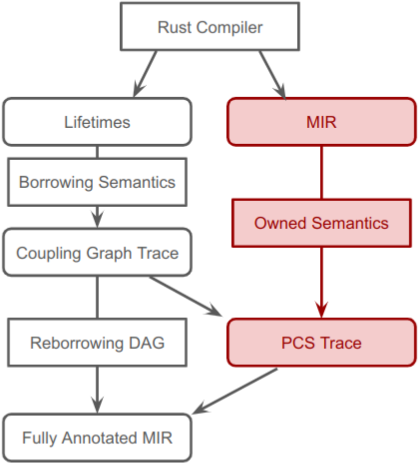
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Setting: Ownership

```rust
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
}
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Prusti's Approach to Explaining Owned Data

1. Model program state as *capabilities* to memory.
2. Describe *rules* in terms of that state.
3. Exploit *approximations* from the type system.

Capabilities

Things we can *do* with places: Capabilities.

Program state (all places): Place Capability Summary (PCS).

Capability		Read?	Write?	Nonaliasing?	Example
exclusive	`E p`	yes	yes	yes	`let mut p = ();`
immutable	`R p`	yes	no	yes	`let p = ();`
shared	`S p`	yes	no	no	`*p` where `p:&()`
write	`e p`	no	yes	yes	`let mut p:();`
allocated	`r p`	no	no	yes	`drop(p); p`

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Things we can *do* with places: Capabilities.

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write	`e p`	no	yes	yes	`let mut p:();`
allocated	`r p`	no	no	yes	`drop(p); p`

Missing rows:

- No permissions.
- Write to aliased memory.

Example: Owned Data

```
StorageLive(1);
StorageLive(2);

2 = T{};

1 = move 2;

0 = ();

StorageDead(2);


StorageDead(1);

return;
```

```rust
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
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Example: Owned Data

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//                { e 0 }
StorageLive(1);
StorageLive(2);

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StorageDead(1);

return;
```

```
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
}
```

Rule:

allocate return place as e

Example: Owned Data

```
//                { e 0 }
StorageLive(1);
StorageLive(2);
//                { e 0, e 1, e 2 }
2 = T{};

1 = move 2;

0 = ();

StorageDead(2);



StorageDead(1);

return;
```

```
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
}
```

Rule:

{ } StorageLive(1) { e 1 }

{ } StorageLive(2) { e 2 }

Example: Owned Data

```
//                  { e 0 }
StorageLive(1);
StorageLive(2);
//                  { e 0, e 1, e 2 }
2 = T{};
//                  { e 0, e 1, E 2 }
1 = move 2;

0 = ();

StorageDead(2);



StorageDead(1);

return;
```

```
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
}
```

Rule:

```
{e 2}
  2 = (const)
{E 2}
```

Example: Owned Data

```
//              { e 0 }
StorageLive(1);
StorageLive(2);
//              { e 0, e 1, e 2 }
2 = T{};
//              { e 0, e 1, E 2 }
1 = move 2;
//              { e 0, R 1, e 2 }
0 = ();

StorageDead(2);



StorageDead(1);

return;
```

```
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
}
```

Rule:

```
{E 2, e 1}
  1 = move 2
{e 2, R 1}
```

Example: Owned Data

```
//                { e 0 }
StorageLive(1);
StorageLive(2);
//                { e 0, e 1, e 2 }
2 = T{};
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//                { E 0, R 1, e 2 }
StorageDead(2);



StorageDead(1);

return;
```

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struct T {}
fn main() {
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    let mut t2 = T {};
    t1 = t2;
}
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Rule:

```
{e 0}
  0 = (const)
{E 0}
```

Example: Owned Data

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StorageLive(2);
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//                { e 0, e 1, E 2 }
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0 = ();
//                { E 0, R 1, e 2 }
StorageDead(2);
//                { E 0, R 1 }


StorageDead(1);

return;
```

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struct T {}
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```
{e 2}
  StorageDead(2)
{ }
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//                { e 0 }
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//                { e 0, e 1, E 2 }
1 = move 2;
//                { e 0, R 1, e 2 }
0 = ();
//                { E 0, R 1, e 2 }
StorageDead(2);
//                { E 0, R 1 }
//                drop(1)
//                { E 0, r 1 }
StorageDead(1);

return;
```

```
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
}
```

Rule:

```
{R 1}
  drop(1)
{r 1}
```

Example: Owned Data

```
//                { e 0 }
StorageLive(1);
StorageLive(2);
//                { e 0, e 1, e 2 }
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1 = move 2;
//                { e 0, R 1, e 2 }
0 = ();
//                { E 0, R 1, e 2 }
StorageDead(2);
//                { E 0, R 1 }
//                drop(1)
//                { E 0, r 1 }
StorageDead(1);
//                { E 0 }
return;
```

```
struct T {}
fn main() {
    let t1: T;
    let mut t2 = T {};
    t1 = t2;
}
```

Rule:

```
{r 1}
  StorageDead(1)
{ }
```

Example: Owned Data

```
//              { e 0 }
StorageLive(1);
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//              { e 0, e 1, e 2 }
2 = T{};
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StorageDead(2);
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//              drop(1)
//              { E 0, r 1 }
StorageDead(1);
//              { E 0 }
return;
//              { }
```

```
struct T {}
fn main() {
    let t1: T;
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    t1 = t2;
}
```

Rule:

```
{E 0}
  return
{ }
```

Example: Packing and Unpacking

```
struct T {}
struct S { f: T, g: T }

StorageLive(s);
StorageLive(x);
s = S {f: T{}, g: T{}};
//                    { E s, e x }


x = move s.g;
```

Example: Packing and Unpacking

```
struct T {}
struct S { f: T, g: T }

StorageLive(s);
StorageLive(x);
s = S {f: T{}, g: T{}};
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//                    unpack(E s)
//                    { E s.f, E s.g, e x }
x = move s.g;
```

Rule:

```
{E s}
  unpack(E s)
{E s.f, E s.g}
```

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//                    { E s.f, E s.g, e x }
x = move s.g;
//                    { E s.f, e s.g, R x }
```

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struct T {}
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StorageLive(s);
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StorageLive(y);
y = s;
```

Example: Packing and Unpacking

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struct T {}
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StorageLive(s);
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//                    unpack(E s)
//                    { E s.f, E s.g, e x }
x = move s.g;
//                    { E s.f, e s.g, R x }

StorageLive(y);
y = s;
// Error
// can't obtain (E s) from
// { E s.f, e s.g, R x, e y }
```

```
error[E0382]: use of partially moved value: `s`
 --> src/main.rs:7:13
  |
6 |     let x = s.g;
  |             --- value partially moved here
7 |     let y = s;
  |             ^ value used here after partial move
  |
  = note: partial move occurs because `s.g` has type `T`,
    which does not implement the `Copy` trait
```

Example: Packing and Unpacking

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struct T {}
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StorageLive(s);
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s = S {f: T{}, g: T{}};
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s.g = T{};




y = s;
```

Example: Packing and Unpacking

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struct T {}
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//                    { E s.f, E s.g, e x }
x = move s.g;
//                    { E s.f, e s.g, R x }


s.g = T{};
//                    { E s.f, E s.g, R x, e y }
//                    pack(E s)
//                    { E s, R x, e y }
y = s;
//                    { e s, R x, R y }
```

Rule:

```
{E s.f, E s.g}
  pack(E s)
{E s}
```

Example: Packing and Unpacking

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//                    pack(E s)
//                    { E s, R x, e y }
y = s;
//                    { e s, R x, R y }
```

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x = move s.g;
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StorageDead(s);
```

Example: Packing and Unpacking

```
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StorageLive(s);
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s = S {f: T{}, g: T{}};
//                    { E s, e x }
//                    unpack(E s)
//                    { E s.f, E s.g, e x }
x = move s.g;
//                    { E s.f, e s.g, R x }


//                    drop(e s.f)
//                    { e s.f, e s.g, R x }
//                    pack(e s)
//                    { e s, R x }
StorageDead(s);
//                    { R x }
```

Join Points

```
fn test(b: bool, t: T) {
    if b {
        StorageLive(u);
        u = move t;
//      drop(u)
        StorageDead(u);
//                           { R b, r t }
    } else {
//                           { R b, R t }


    }

}
```

Join Points

```
fn test(b: bool, t: T) {
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```

Which capabilities does the program have after the `if` statement?

Join Points

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fn test(b: bool, t: T) {
    if b {
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//      drop(u)
        StorageDead(u);
//                          { R b, r t }
    } else {
//                          { R b, R t }
//                          drop(t)
//                          { R b, r t }
    }
//                          { R b, r t }
}
```

Which capabilities does the program have after the `if` statement?

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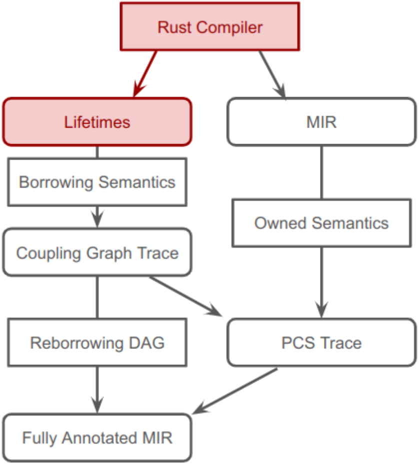
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Mutable Borrows

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let x = &mut z;
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```
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```

`x` will have some kind of control over `z`'s memory for some time.

- `E *x`, and no capability for `z`.
- Eventually, we relinquish `E *x` and regain `E z`.

2^{nd} notion of memory safety

```
let (x: &'a mut T) = (&mut z: &'bw0 mut T);
```

2^{nd} notion of memory safety

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let (x: &'a mut T) = (&mut z: &'bw0 mut T);
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- `x` needs to be usable for `'a`.

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```
let (x: &'a mut T) = (&mut z: &'bw0 mut T);
```

- `x` needs to be usable for `'a`.
- The borrow can last for `'bw0` before it must be given back.
  - Called an *invalidation* of `'bw0`.

2^{nd} notion of memory safety

```
let (x: &'a mut T) = (&mut z: &'bw0 mut T);
```

- `x` needs to be usable for `'a`.
- The borrow can last for `'bw0` before it must be given back.
  - Called an *invalidation* of `'bw0`.
- Require `'bw0 <:'a` (read `'bw0` *outlives* `'a`)

2^{nd} notion of memory safety

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let (x: &'a mut T) = (&mut z: &'bw0 mut T);
```

- `x` needs to be usable for `'a`.
- The borrow can last for `'bw0` before it must be given back.
  - Called an *invalidation* of `'bw0`.
- Require `'bw0 <:'a` (read `'bw0` *outlives* `'a`)

Memory Safety in Rust

Fixed point analysis over MIR.

Memory is definitely not borrowed from when invalidated.

$\Rightarrow$ No dangling pointers.

2^{nd} notion of memory safety

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let (x: &'a mut T) = (&mut z: &'bw0 mut T);
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- `x` needs to be usable for `'a`.
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Fixed point analysis over MIR.

Memory is definitely not borrowed from when invalidated.

⇒ No dangling pointers.

```
struct T {}
fn test(b: bool, mut t1: T, mut t2: T) {
    let mut x = &mut t1;
    let mut y = &mut t2;
    if b {
        let tmp = x;
        x = &mut (*y);
        y = &mut (*tmp);
    }
    let usage_x = x;
    let usage_y = y;
}
```

```
struct T {}
fn test(b: bool, mut t1: T, mut t2: T) {
    let mut x = &mut t1;
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        x = &mut (*y);
        y = &mut (*tmp);
    }
    let usage_x = x;   ←
    let usage_y = y;
}
```

x? Yes
y? Yes
t1? No: borrowed
t2? No: borrowed

```
struct T {}
fn test(b: bool, mut t1: T, mut t2: T) {
    let mut x = &mut t1;
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        x = &mut (*y);
        y = &mut (*tmp);
    }
    let usage_x = x;
    let usage_y = y;     ←
}
```

x? No: moved out

y? Yes

t1? No: maybe borrowed

t2? No: maybe borrowed

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struct T {}
fn test(b: bool, mut t1: T, mut t2: T) {
    let mut x = &mut t1;
    let mut y = &mut t2;
    if b {
        let tmp = x;
        x = &mut (*y);
        y = &mut (*tmp);
    }
    let usage_x = x;
    let usage_y = y;      ←
}
```

x? No: moved out
y? No: moved out
t1? Yes
t2? Yes

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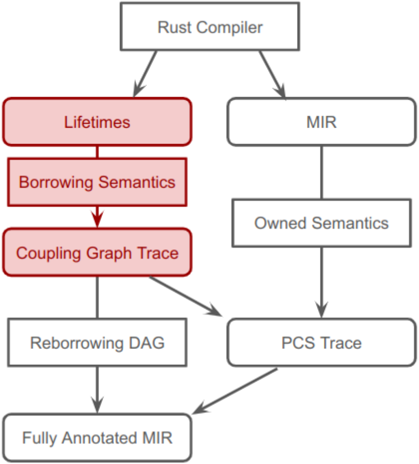
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Setting: Mutable Borrows

Prusti's Approach to Explaining Borrowed Data

1. Model borrow checker state as *DAG* of capabilities.
2. Describe *rules* in terms of that state.
3. Exploit *approximations* from the borrow checker.

Capabilities for Borrows

Two complementary views:

- Temporary transfer of ownership
- Pointers with affine referent

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The second leads to a repacking rule for borrows:

- `let mut x = &mut t1;`

  `{E x} unpack(x) {e x, E (*x)}`

Capabilities for Borrows

Two complementary views:

- Temporary transfer of ownership
- Pointers with affine referent

The second leads to a repacking rule for borrows:

- `let mut x = &mut t1;`

  `{E x} unpack(x) {e x, E (*x)}`
- `let tmp = x;`

  `{R tmp} unpack(tmp) {r tmp, E (*tmp)}`

The Coupling Graph

- Directed Acyclic Hypergraph of Capabilities.

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- Outlives relationships become abstract capability exchanges.
  - Explains how to give back capabilities when borrows expire.

The Coupling Graph

- Directed Acyclic Hypergraph of Capabilities.
- Outlives relationships become abstract capability exchanges.
  - Explains how to give back capabilities when borrows expire.
- Readily approximated, same way as the borrow checker.
  - Leaves correspond to definitely not borrowed places.
  - Rules for coupling edges (abstracting subgraphs at join points).

Coupling Graph Rewrite Rules

```
// { E t1, e x, e z, e w }

x = &mut t1; // { E x, e z, e w }
```

{ E *x } → { E t1 }

Coupling Graph Rewrite Rules

```
// { E t1, e x, e z, e w }

x = &mut t1; // { E x, e z, e w }
```

{ E *x } → { E t1 }

```
z = move x; // { e x, E z, e w }
```

{ E *z } → { E@l *x } → { E t1 }

Coupling Graph Rewrite Rules

```
// { E t1, e x, e z, e w }

x = &mut t1; // { E x, e z, e w }

                { E *x } → { E t1 }

z = move x; // { e x, E z, e w }

           { E *z } → { E@l *x } → { E t1 }

unpack(z); // { e x, e z, E (*z), e w }
```

Coupling Graph Rewrite Rules

```
// { E t1, e x, e z, e w }

x = &mut t1; // { E x, e z, e w }
```

{ E *x } → { E t1 }

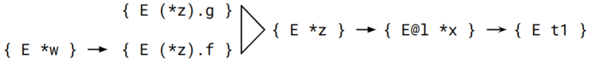
```
z = move x; // { e x, E z, e w }
```

{ E *z } → { E@l *x } → { E t1 }

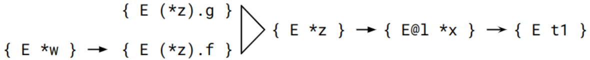
```
unpack(z); // { e x, e z, E (*z), e w }
unpack(*z); // { e x, e z, E (*z).f, E (*z).g, e w }
```

{ E (*z).g } { E (*z).f } ▷ { E *z } → { E@l *x } → { E t1 }

```
w = &mut (*z).f; // { e x, e z, E (*z).g, E w }
```

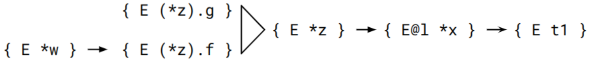


```
w = &mut (*z).f; // { e x, e z, E (*z).g, E w }
```



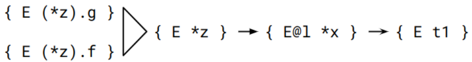

```
unpack(w); // { e x, e z, E (*z).g, e w, E (* w) }
```

```
w = &mut (*z).f; // { e x, e z, E (*z).g, E w }
```




```
unpack(w); // { e x, e z, E (*z).g, e w, E (* w) }

/* w expires */ // { e x, e z, E (*z).g, E (*z).f, e w }
```



```
w = &mut (*z).f; // { e x, e z, E (*z).g, E w }
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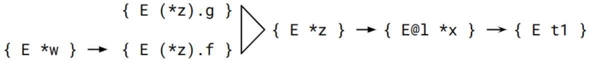
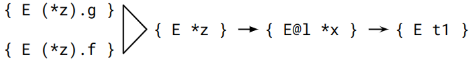



```
unpack(w); // { e x, e z, E (*z).g, e w, E (* w) }

/* w expires */ // { e x, e z, E (*z).g, E (*z).f, e w }
```




```
/* z expires */ // { E t1, e x, e z, e w }
```

```rust
struct T {}
fn test(b: bool, mut t1: T, mut t2: T) {
    let mut x = &mut t1;
    let mut y = &mut t2;
    if b {
        let tmp = x;
        x = &mut (*y);
        y = &mut (*tmp);
    }
    let usage_x = x;
    let usage_y = y;
}
```

Coupling Graph “if” branch:

```
{E (*x: T)} ⟶ {‘0} ⟶ ... ⟶ {bw1} ⟶ {E (t2: T)}
{E (*y: T)} ⟶ {‘1} ⟶ ... ⟶ {bw0} ⟶ {E (t1: T)}
```

Coupling Graph “else” branch:

```
{E (*x: T)} ⟶ {‘0} ⟶ {bw0} ⟶ {E (t1: T)}
{E (*y: T)} ⟶ {‘1} ⟶ {bw1} ⟶ {E (t2: T)}
```

Coupling Graph “if” branch:

{E (*x: T)} ⟶ {‘0} ⟶ ... ⟶ {bw1} ⟶ {E (t2: T)}

{E (*y: T)} ⟶ {‘1} ⟶ ... ⟶ {bw0} ⟶ {E (t1: T)}

Coupling Graph “else” branch:

{E (*x: T)} ⟶ {‘0} ⟶ {bw0} ⟶ {E (t1: T)}

{E (*y: T)} ⟶ {‘1} ⟶ {bw1} ⟶ {E (t2: T)}

Coupled:

{E (*x: T)} ⟶ {‘0} {bw1} ⟶ {E (t2: T)}

{E (*y: T)} ⟶ {‘1} {bw0} ⟶ {E (t1: T)}

Coupling Graph "if" branch:

```
{E (*x: T)} → {'0} → ... → {bw1} → {E (t2: T)}

{E (*y: T)} → {'1} → ... → {bw0} → {E (t1: T)}
```

Coupling Graph "else" branch:

```
{E (*x: T)} → {'0} → {bw0} → {E (t1: T)}

{E (*y: T)} → {'1} → {bw1} → {E (t2: T)}
```

Coupled:

```
{E (*x: T)} → {'0}          {bw1} → {E (t2: T)}

{E (*y: T)} → {'1}          {bw0} → {E (t1: T)}
```


{E (*x: T)}
{'0}
{E (*y: T)}
{'1}
{bw1}
{E (t2: T)}
{bw0}
{E (t1: T)}

Lifetime `'0` expires:

- Consumes `E (*x:T)`

Lifetime '0 expires:

- Consumes `E (*x:T)`

Lifetime '1 expires

- Remainder of graph can expire
- Consumes `E (*y:T)`; {`E (t1:T), E (t2:T)`} regained.

Coupled Borrows as Loop Invariants

```
struct T {}
fn test(f: fn() -> bool, mut t1: T, mut t2: T) {
    let mut x = &mut t1;
    let mut y = &mut t2;
    while f() {
        let tmp = x;
        x = &mut (*y);
        y = &mut (*tmp);
    }
    let usage_x = x;
    let usage_y = y;
}
```

Coupled Borrows as Loop Invariants

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fn test(f: fn() -> bool, mut t1: T, mut t2: T) {
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Coupled Borrows as Loop Invariants

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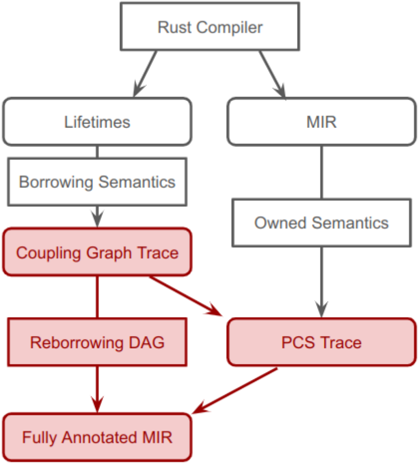
    }
    let usage_x = x;
    let usage_y = y;
}
```

stable under the loop body!

Overview


Rust Compiler
Lifetimes
MIR
Borrowing Semantics
Owned Semantics
Coupling Graph Trace
Reborrowing DAG
PCS Trace
Fully Annotated MIR

The rest of the story

- Coupling graph edges govern subsets of a *reborrowing DAG*.

The rest of the story

- Coupling graph edges govern subsets of a *reborrowing DAG*.
- Viper: Coupled edges can be packaged as magic wands
  - Apply wands at expiry or repackage of last coupled edge.
- Coupled edges at simple join points do not need magic wands.

Shared Borrows, S subtyping

```
fn test(n: u32) {
    let b0 = &n;
    let b1 = &n;
    /* clone n */
    let _ = n;
    let _ = b0;
    let _ = b1;
}
```

Shared Borrows, S subtyping

```
fn test(n: u32) {
    let b0 = &n;
    let b1 = &n;
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    let _ = n;
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}
```

{ R n, e b0, e b1 }

Shared Borrows, S subtyping

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}
```
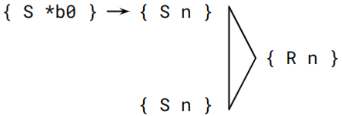

{ S n, R b0, e b1 }

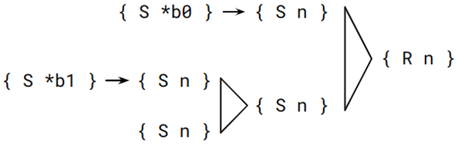


- { R b0 } unpack(b0) { r b0, S (*b0) }
- { R n, e b0 } b0 = &n; { R b0, S n }

Shared Borrows, S subtyping

```
fn test(n: u32) {
    let b0 = &n;
    let b1 = &n;
    /* clone n */
    let _ = n;
    let _ = b0;
    let _ = b1;
}
```

{ S n, R b0, R b1 }



- { R b0 } unpack(b0) { r b0, S (*b0) }
- { R n, e b0 } b0 = &n; { R b0, S n }
- { S n, e b1 } b1 = &n; { S b0, S n }

Shared Borrows, S subtyping

```
fn test(n: u32) {
    let b0 = &n;
    let b1 = &n;
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    let _ = n;
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```

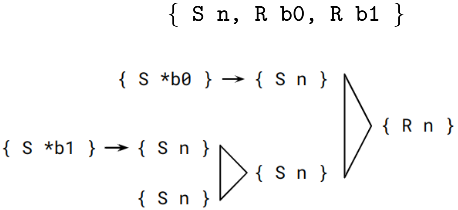

- { R b0 } unpack(b0) { r b0, S (*b0) }
- { R n, e b0 } b0 = &n; { R b0, S n }
- { S n, e b1 } b1 = &n; { S b0, S n }
- { R n, _ } _ = clone n; { R n, _ }
- { S n, _ } _ = clone n; { S n, _ }

Function Calls, Expiry Tools

```
fn test<'a, 'b, 'c, 'd>(x: &'a mut T, y: &'b mut T)
    -> (&'c mut T, &'d mut T)
where 'c <: 'a, 'c <: 'b, 'd <: 'b { /* ... */ }

let s = &mut t0;
let t = &mut t1;
let (m, n) = test(s, t);
```

[1] *Extended Support for Borrowing and Lifetimes in Prusti*

Function Calls, Expiry Tools

```
fn test<'a, 'b, 'c, 'd>(x: &'a mut T, y: &'b mut T)
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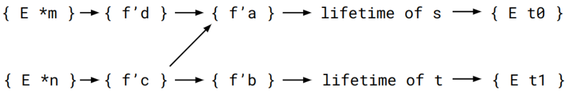

- Caller: Lorenz Gorse showed how to encode to Viper[1].

[1] *Extended Support for Borrowing and Lifetimes in Prusti*

Function Calls, Expiry Tools

```
fn test<'a, 'b, 'c, 'd>(x: &'a mut T, y: &'b mut T)
    -> (&'c mut T, &'d mut T)
where 'c <: 'a, 'c <: 'b, 'd <: 'b { /* ... */ }

let s = &mut t0;
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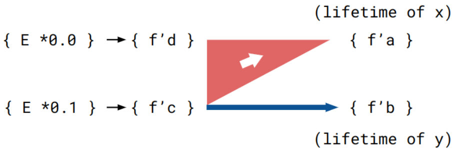
```



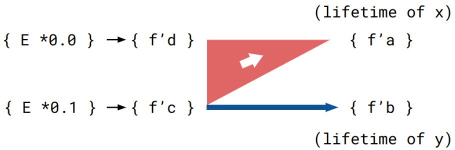
- Caller: Lorenz Gorse showed how to encode to Viper[1].
- Callee: Polonius ensures we couple the above edges.

[1] *Extended Support for Borrowing and Lifetimes in Prusti*

Function Calls, Expiry Tools

```
fn test<'a, 'b, 'c, 'd>(x: &'a mut T, y: &'b mut T)
    -> (&'c mut T, &'d mut T)
where 'c <: 'a, 'c <: 'b, 'd <: 'b { /* ... */ }

let s = &mut t0;
let t = &mut t1;
let (m, n) = test(s, t)
```



- Caller: Lorenz Gorse showed how to encode to Viper[1].
- Callee: Polonius ensures we couple the above edges.
- *Expiry tools reify coupling graph expiry rules.*

[1] *Extended Support for Borrowing and Lifetimes in Prusti*

Borrows in Structs

```
struct BorrowsLL<'a, S> {
    data: &'a mut T,
    next: Option<Box<BorrowsLL<'a, S>>>
}
let x: BorrowsLL<'a, T> = /* ... */;
```

Borrows in Structs

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struct BorrowsLL<'a, S> {
    data: &'a mut T,
    next: Option<Box<BorrowsLL<'a, S>>>
}
let x: BorrowsLL<'a, T> = /* ... */;
```

{ x'a } → (unbounded)

- Lazily add unpacking edges only on dereferences.

```
{ E (z: &'0 mut T) }
{'0} → { bw0 } → { E (t: T) }

unpack(z);

{ e (z: &'0 mut T), E (*z: T) }
{ E (*z: T) }→ {'0} → { bw0 } → { E (t: T) }
```

Borrows in Structs

```
struct BorrowsLL<'a, S> {
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Borrows in Structs

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```
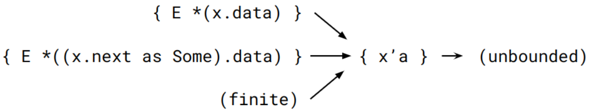

{ x'a } → (unbounded)

- Lazily add unpacking edges only on dereferences.
- `{ E x } unpack(x) { E x.data, E x.next }`

Borrows in Structs

```rust
struct BorrowsLL<'a, S> {
    data: &'a mut T,
    next: Option<Box<BorrowsLL<'a, S>>>
}
let x: BorrowsLL<'a, T> = /* ... */;
```



- Lazily add unpacking edges only on dereferences.
- { E x } unpack(x) { E x.data, E x.next }
- { E x.data } unpack(x.data) { e x.data, E *(x.data) }
- Coupling and PCS Joins ensure graph and PCS are always finite.

Thank you for your attention!

Status/next steps:

- Implementation in Prusti
- Completeness proof
- Explore connections to other tools

Documentation and examples: Will be ready soon!