Place Capability Graphs

A General-Purpose Model of Rust's Ownership and Borrowing System

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Based on joint work with Zachary Grannan, Aurel Bílý, Jonáš Fiala, Jasper Geer, Markus de Medeiros, Peter Müller

What's so special about Rust's Type System?

- Ownership (plus borrowing) as a fundamental notion
  - Flexible ownership transfer ("move assignments")
- Clear mutability / immutability distinctions (immutable by default)
- Sophisticated *borrowed references* features
  - Temporarily allow access through aliased references
  - Borrows can cross function boundaries and be stored as first-class values
- "Aliasing XOR Mutability" Principle (mutable access is unique)
  - But this is subtle: uniqueness in terms of *currently-usable aliases*
  - Mutations via a borrowed reference will still become visible to the lender
  - This happens as and when borrows end (the lender becomes usable again)

Quick Rust intro on examples

Rust is attractive for analysis / verification

- Controlled aliasing (but aliasing is still significant)
- Many guarantees “for free” (memory safety, non-aliasing properties)
  - In fact, *the programmer still works hard* to demonstrate these
- But, type and borrow-checking are complex notions
  - *No accepted/complete formal definitions* (for any of the real language)
  - Sometimes unclear in practice why/how the compiler accepts a program
- Most complex aspect is the handling of “*borrow extents*”
  - By this, I mean the duration of certain (sets of) borrowed references
  - Intentionally distinct terminology from Rust (lifetimes, regions, origins, …)
  - Constraints generated on borrow extents; *borrow-checked* for satisfiability

Our new model: Place Capability Graphs

- Idea: we can explain (much of) Rust's design in terms of *capabilities*
  - In the sense of various memory-management type systems (e.g. Pony)
  - We call these *place* capabilities, as they connect to Rust *places* (locations)
- Place Capability Graphs are directed hypergraphs per program point
  - Various nodes represent capabilities as governed by the type-system
  - Several kinds of (hyper)edges: most are 1-many/many-1, especially in this talk
- Edges represent undoable reassignments of capabilities (e.g. borrows)
  - Nodes with children represent capabilities *not currently usable* (mostly)

Modelling Ownership

```
struct Pair { fst: String, snd: String }

fn replace_fst(mut p: Pair, s:String) -> Pair
{
1   let tmp = p.fst; // for illustration
2   p.fst  = s;
3   return p;
}
```

0;

Modelling Ownership

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0; unpack p;
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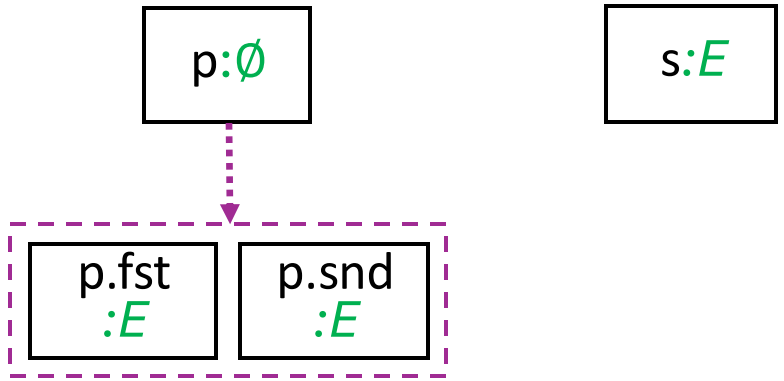

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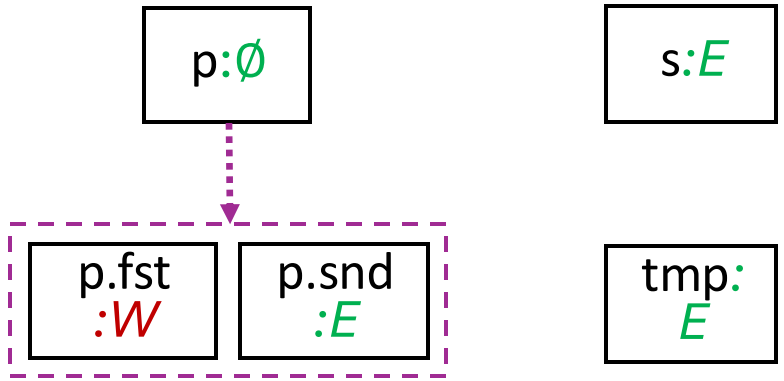

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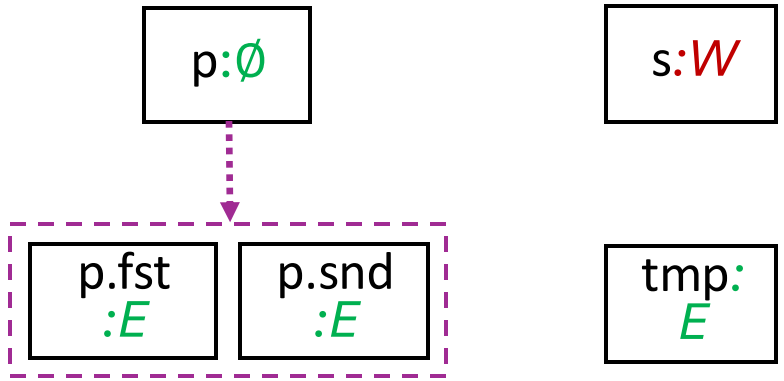

0; unpack p;
1;
2;

Modelling Ownership

```
struct Pair { fst: String, snd: String }

fn replace_fst(mut p: Pair, s:String) -> Pair
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1  let tmp = p.fst; // for illustration
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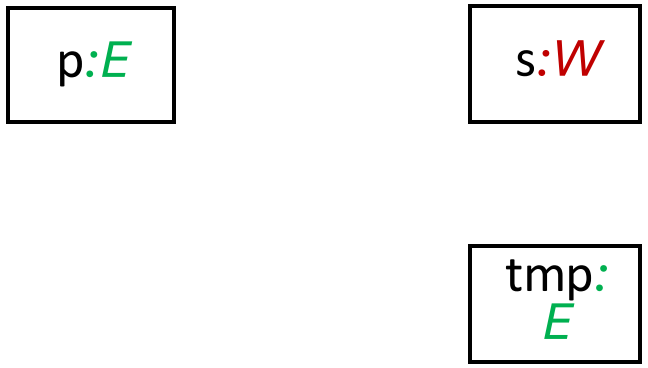


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Modelling Ownership

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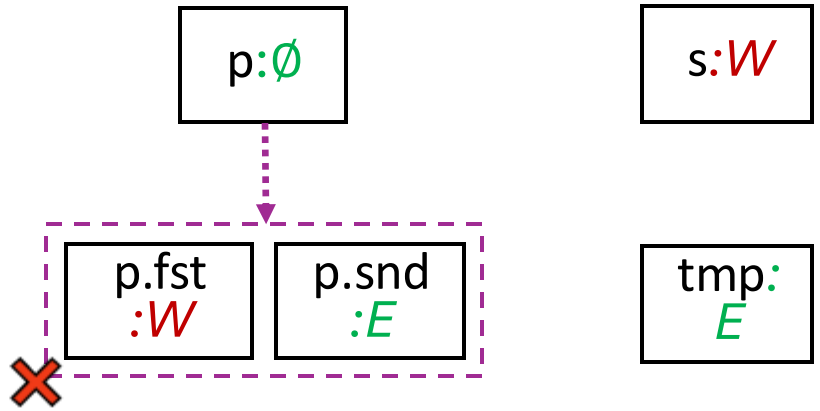


```
- use of partially moved value: 'pair'
```

Modelling Ownership

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```

p:*E*

s:*W*

tmp:
E

- Graph state reflects ownership
- Can identify type incorrect steps
- Annotations for type manipulations
- Generalises easily to control flow (at least, for only ownership…)
- Simple “join”, keeping weakest capabilities in either branch
- Rust’s type system defines usable places ~~without path sensitivity~~

```
0; unpack p;
1;
2; pack p;
3;
```

Modelling Borrowing

```
fn main() {
1   let mut x = 1;
2   let y = &mut x;
3   let z = &mut *y;
4   *z = 5;
5   *y = *y + 1;
6   println!("{}",x); // prints 6
}
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Modelling Borrowing

```
fn main() {
1   let mut x = 1;    // x : i32
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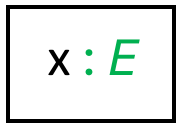


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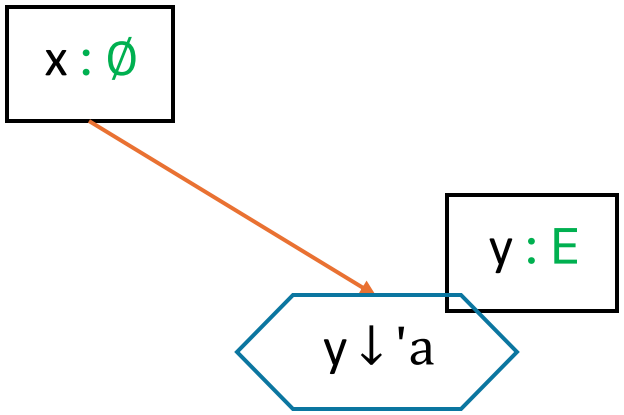
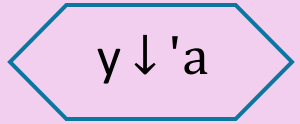


Lifetime Projection Nodes



- Represent a set of borrows:
  - Stored in the place (1st argument, here y)
  - In references with 2nd argument 'a as lifetime
    - i.e. in its declared type (& 'a mut i32)
  - At the current program point (implicit: this graph)
- Always occur simultaneously with their place's node
  - Think of them identifying parts of its capabilities
- Always occur when the *borrow checker* thinks the corresponding borrow extent is still live

Modelling Borrowing

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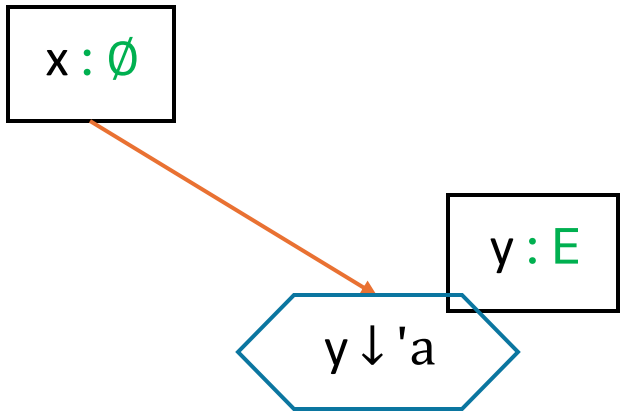


```
0;
1;
2;
```

Modelling Borrowing

```
fn main() {
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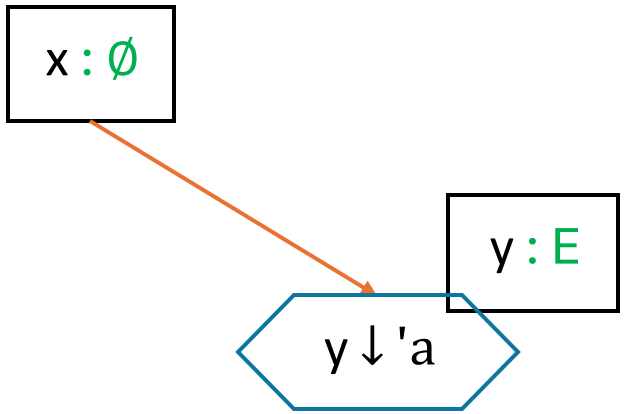


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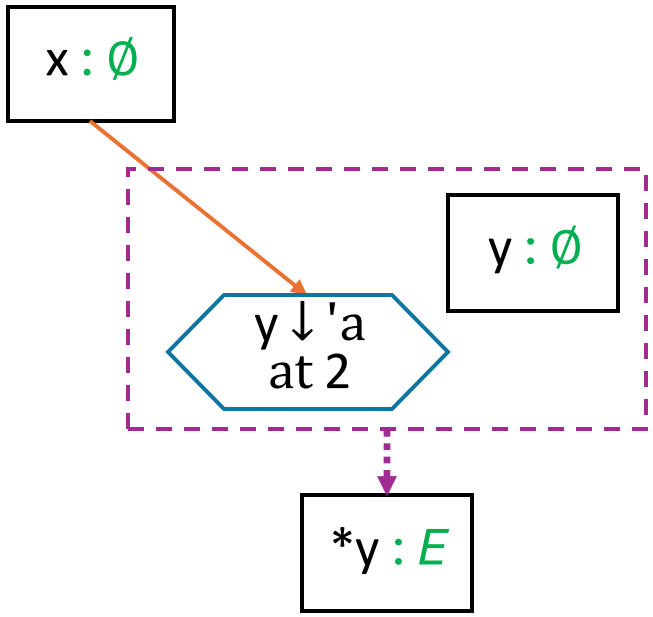

0;
1;
2; unpack y;

Labelled Nodes (at 2)

- Represent nodes as they *were* at an earlier program point (here: line 2)
- While y is unpacked, we don't have its lifetime projection (it's in pieces)
- Labelled node retains connections to where borrow came from, borrow extent

Modelling Borrowing

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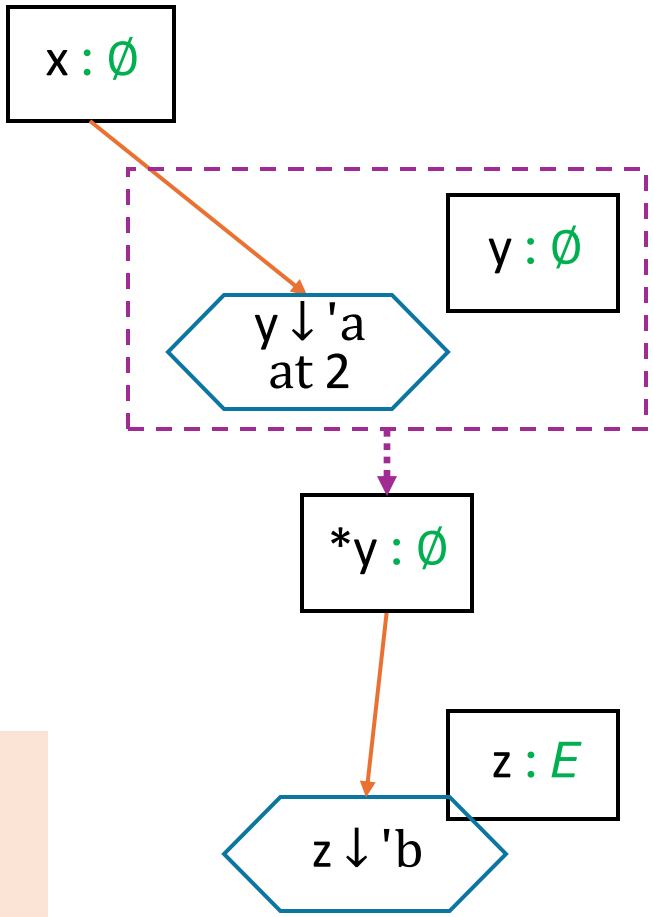


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0;
1;
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3;
```

Modelling Borrowing

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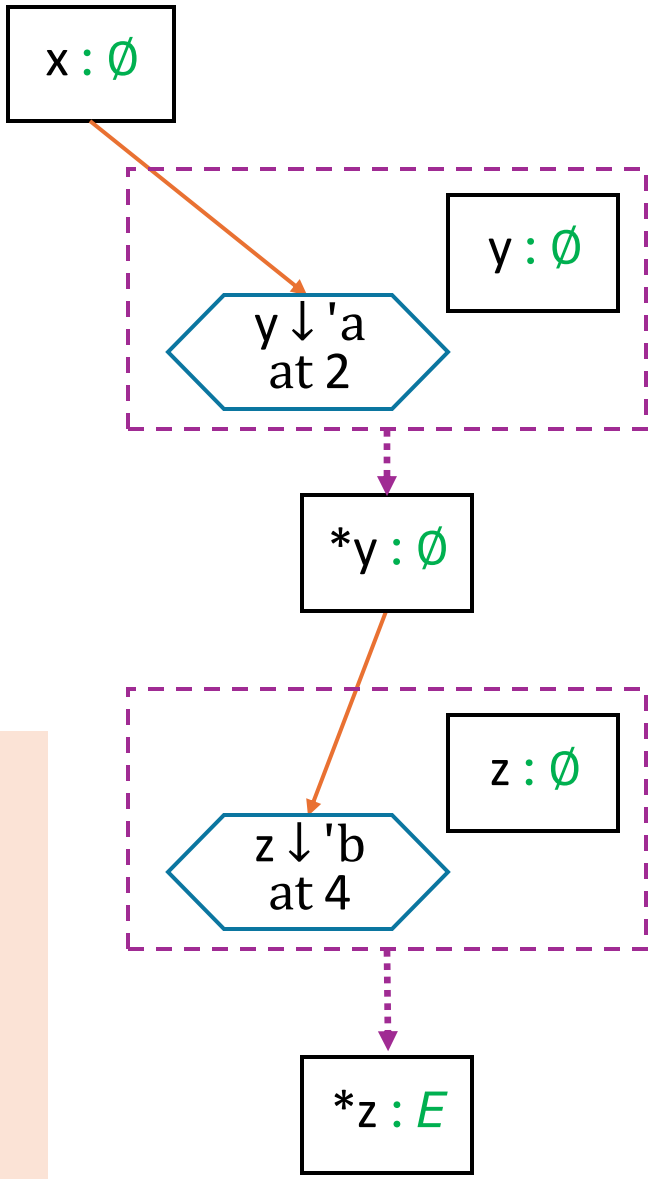
}
```

```
0;
1;
2; unpack y;
3; unpack z;
4;
```



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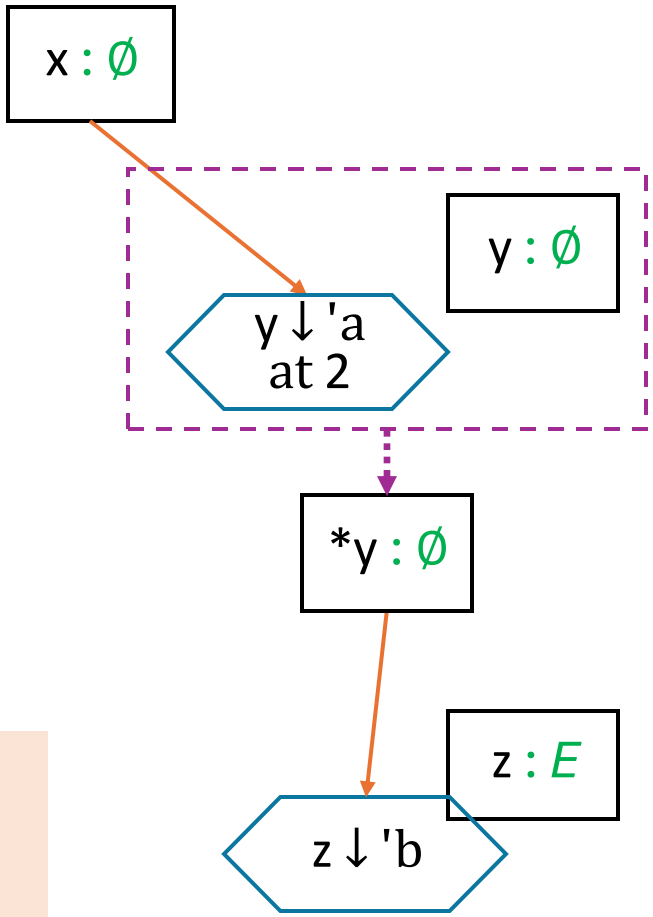


```
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1;
2; unpack y;
3; unpack z;
4; pack z;
```

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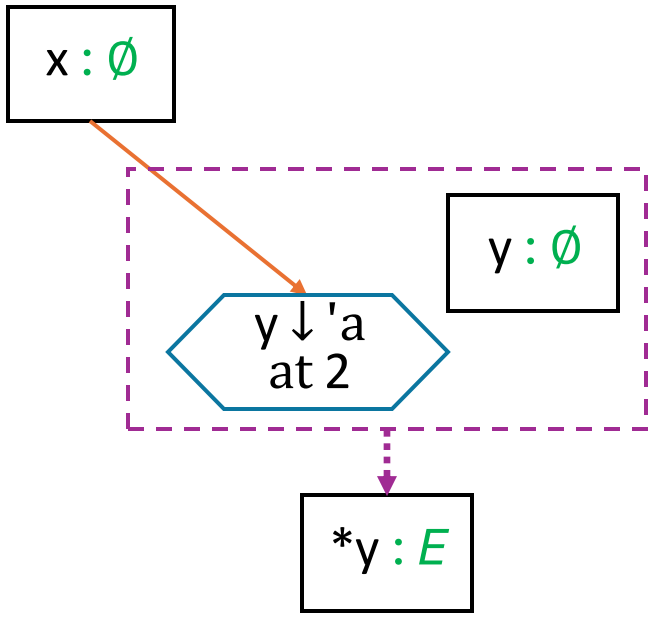


```
0;
1;
2; unpack y;
3; unpack z;
4; pack z; expire z ↓ 'b;
```

Modelling Borrowing

```
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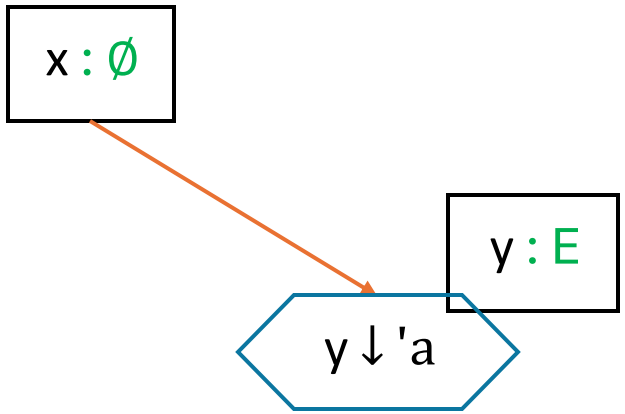

0;
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Modelling Borrowing

x : *E*

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Path Sensitivity

```
fn f(mut x: i32, mut y: i32, mut z: i32) {
  let r = if x > y {       // branch: c0/c1
    &mut x                 // bb1 (c0)
  } else {
    &mut y                 // bb2 (c1)
  };                       // bb3
  let s = if z > 5 {       // branch: c2/c3
    &mut *r                // bb4 (c2)
  } else {
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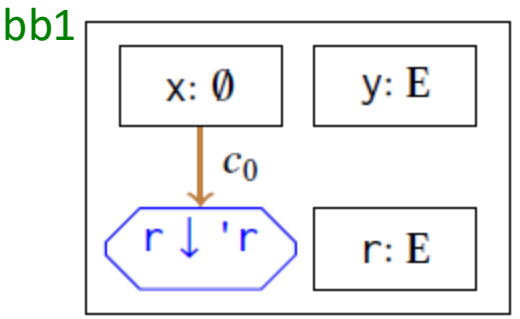
  };
  *s = 5; // bb6
}
```



- Borrows can start/end differently in each branch
- At each branch point, generate branch IDs
  - One for each branch choice (e.g. c_0/c_1)
- Edges created under branch are labelled with IDs

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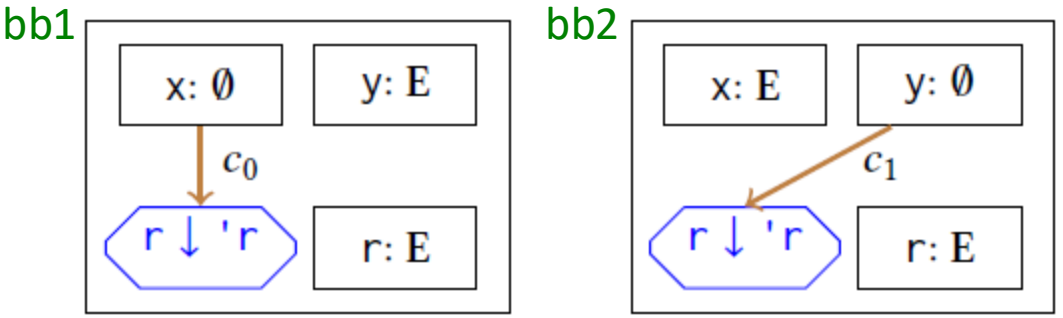

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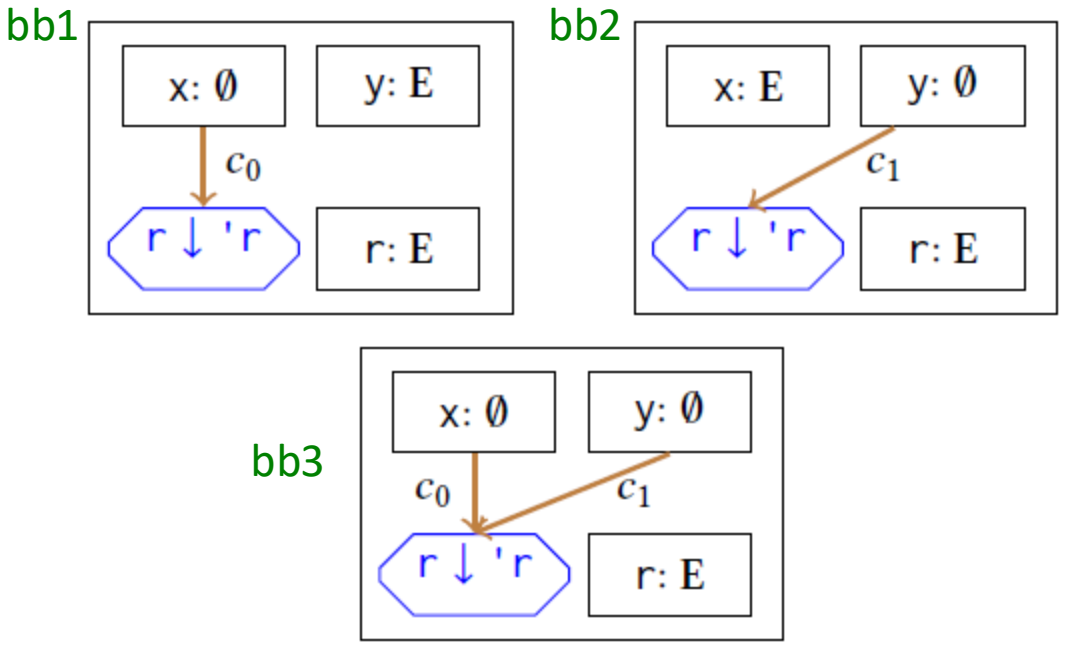

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- At each branch point, generate branch IDs
  - One for each branch choice (e.g. c_0/c_1)
- Edges created under branch are labelled with IDs
- This way, we can compactly represent graphs with partially-shared structure at the join point
  - We keep edges from both graphs
  - Places no longer live at join are removed

Path Sensitivity

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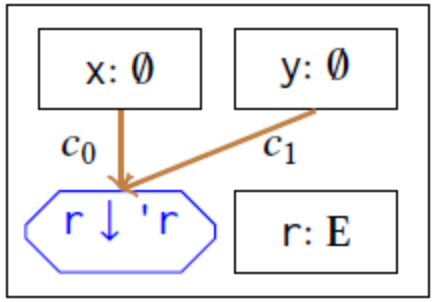

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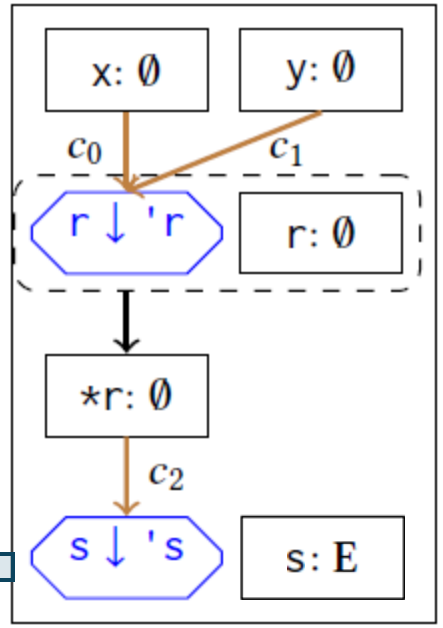

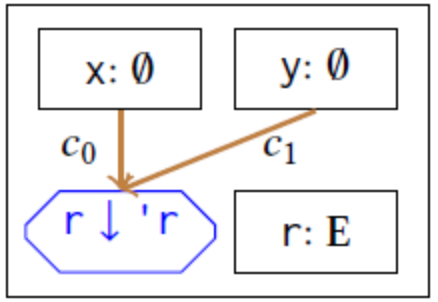

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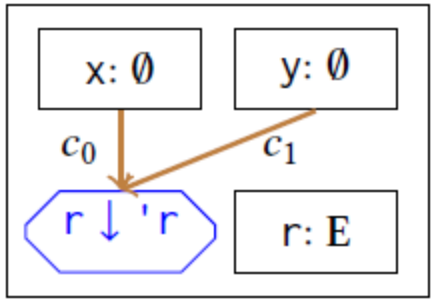
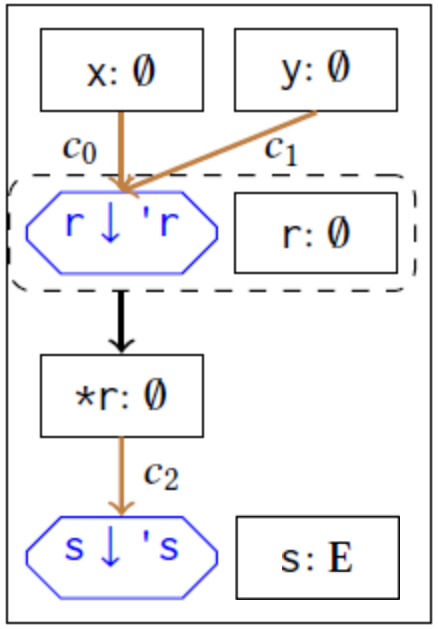
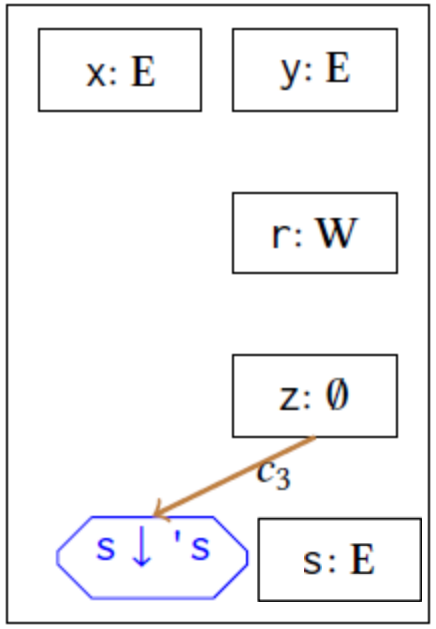
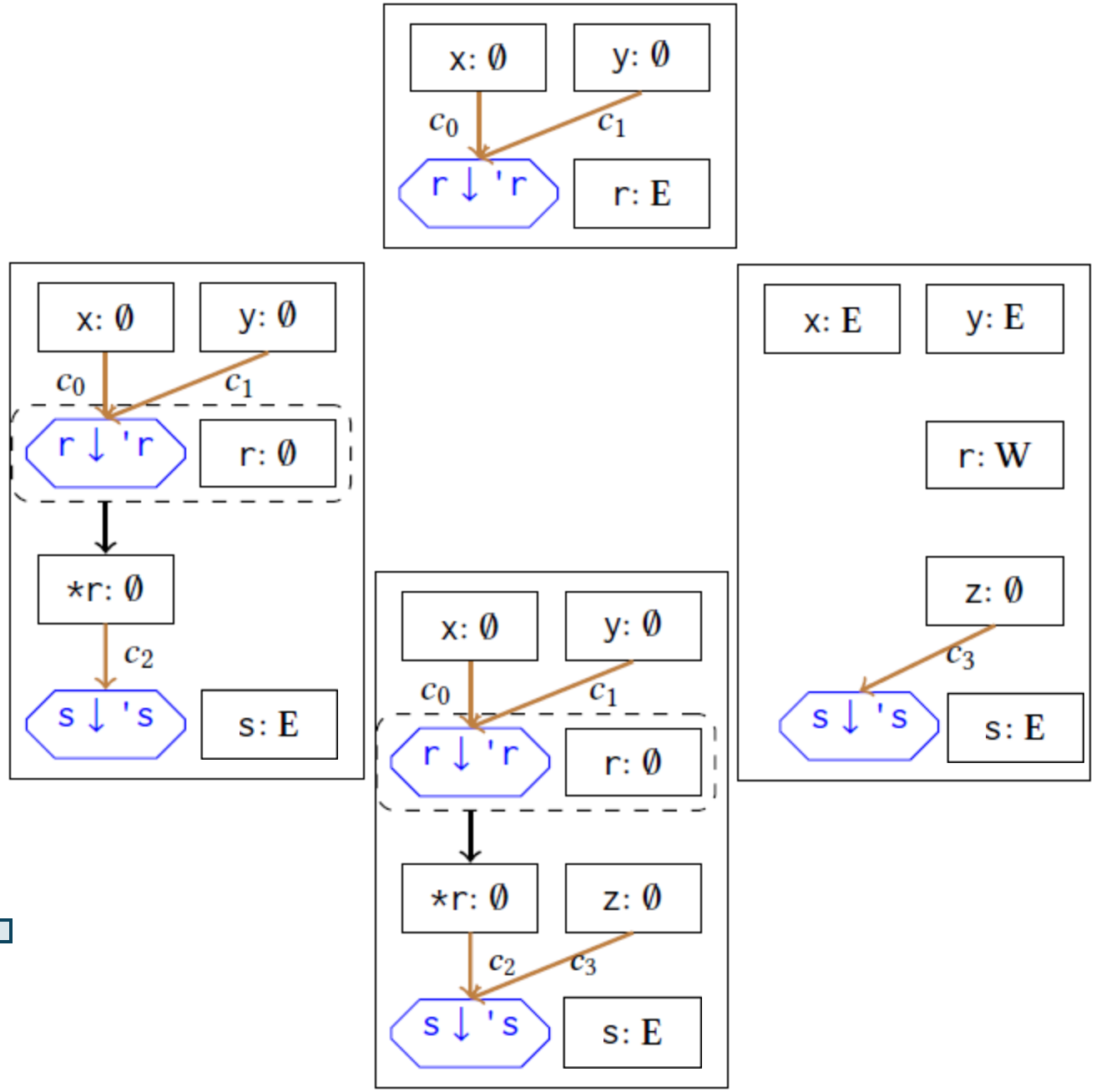






Path Sensitivity

```
fn f(mut x: i32, mut y: i32, mut z: i32) {
  let r = if x > y {      // branch: c0/c1
    &mut x                // bb1 (c0)
  } else {
    &mut y                // bb2 (c1)
  };                      // bb3
  let s = if z > 5 {      // branch: c2/c3
    &mut *r               // bb4 (c2)
  } else {
    &mut z                // bb5 (c3)
  };
  *s = 5; // bb6
}
```



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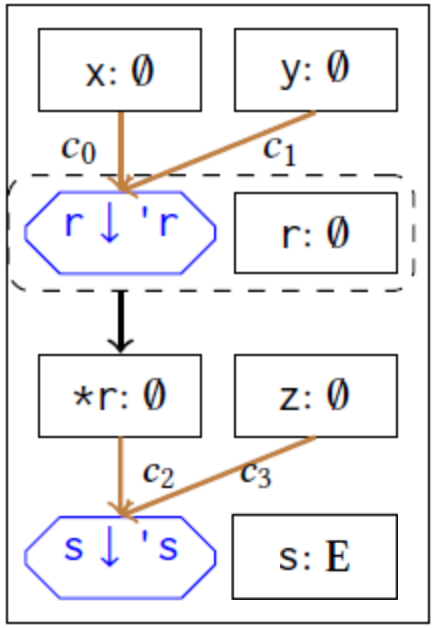
```
fn f(mut x: i32, mut y: i32, mut z: i32) {
  let r = if x > y {      // branch: c0/c1
    &mut x                          // bb1 (c0)
  } else {
    &mut y                          // bb2 (c1)
  };                                // bb3
  let s = if z > 5 {      // branch: c2/c3
    &mut *r                         // bb4 (c2)
  } else {
    &mut z                          // bb5 (c3)
  };
  *s = 5; // bb6
}
```

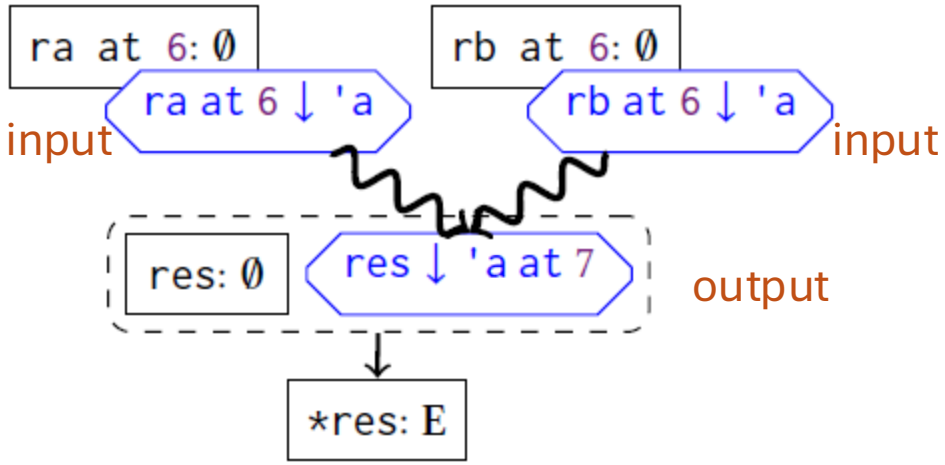
Maximal Sharing

- Resulting graph shares nodes and edges *unless* they differ in the two graphs
- Sharing the same graph from here *onwards* works because Rust is not path-sensitive
  - Graphs must agree on their leaves
  - So, we can extend them uniformly
- Sharing structure *above* a join is trickier
  - Edges may be removed during branch
  - But only the same edges! Feel free to ask..



Function Calls

```
1 fn choose<'a, T>(c: bool, rx: &'a mut T, ry: &'a mut T) -> &'a mut T {
2   if c { rx } else { ry }
3 }
4
5 fn foo<'a>(ra: &'a mut u32, rb: &'a mut u32) {
6   let res = choose(true, ra, rb);
7   *res = 10;
8 }
```



Abstract Edges

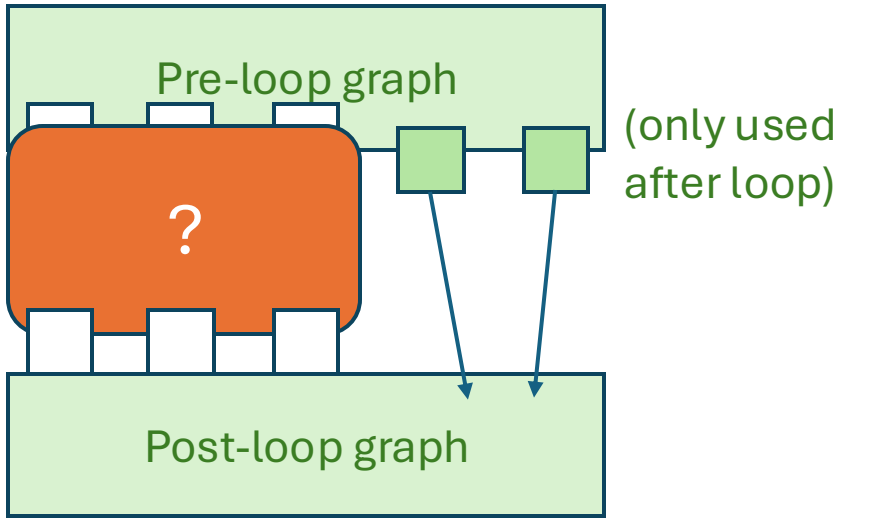
- Connect lifetime projection nodes (can be many-to-many)
- Represent (possible) flows of (re)borrows not tracked precisely
  - Some of the borrowed memory corresponding to source node(s) may currently be borrowed in the target node(s)
  - Corresponds to borrow-checking constraint on

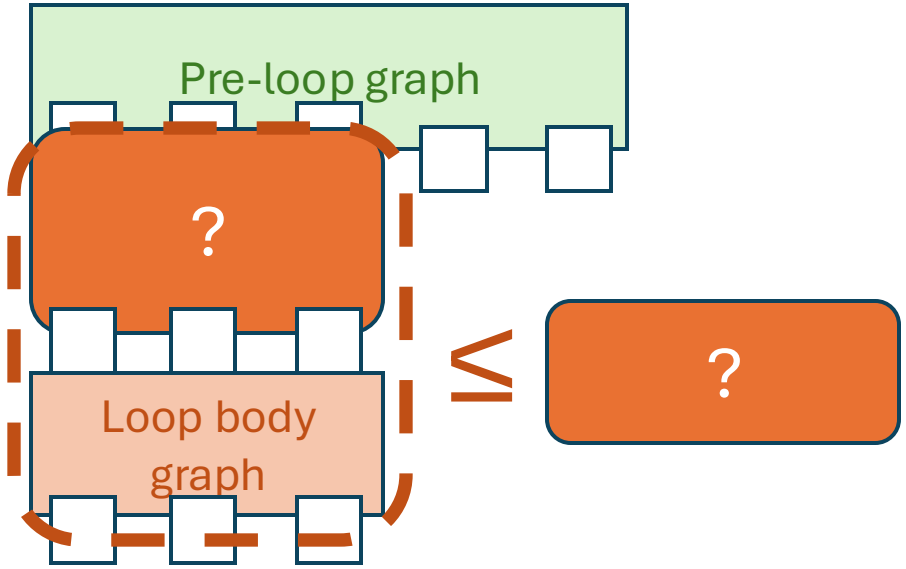
Handling Function Calls

- Calculate from function signature:
  - "input" lifetime projections
  - "output" lifetime projections
- For each input-output pair:
  - Connect with abstract edge iff borrow checker says source must outlive the target

Handling Loops – what is a loop invariant?

```
0 struct List { head: u32, tail: Option<Box<List>> }
1 fn penult<'a>(list: &'a mut List) -> Option<&'a mut u32>
2 {
3   let mut curr: &'a mut List = &mut *list;
4   let mut prev: Option<&'a mut u32> = None;
5   while let Some(ref mut tail) = curr.tail {
6     prev = Some(&mut curr.head); curr = &mut *tail;
7   }
8   prev
9 }
```





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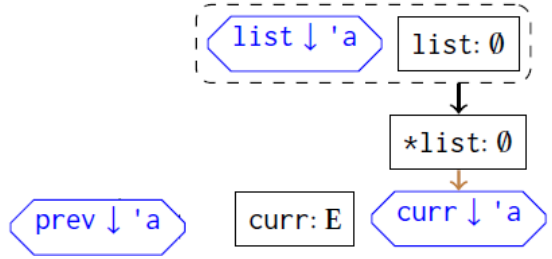
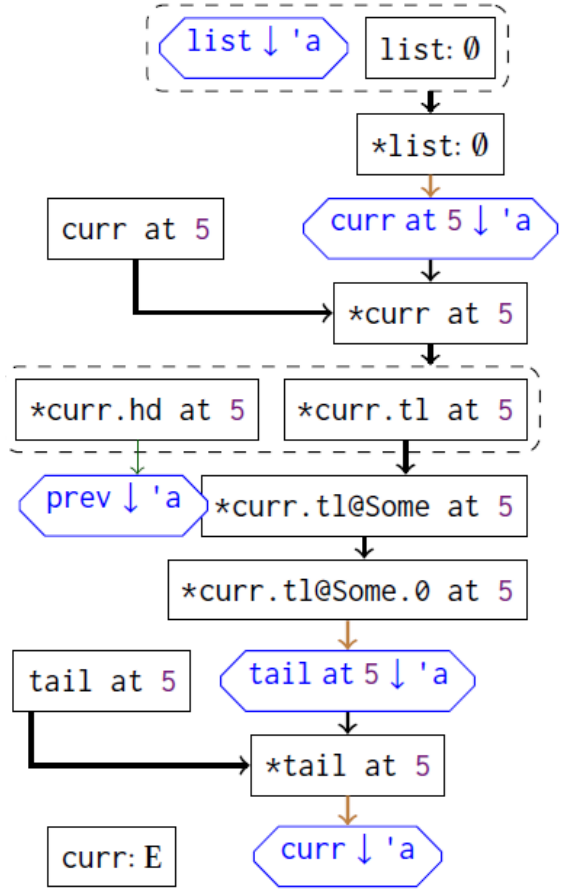
Key Ideas

- Initial graph (before loop) is already known
- Identify places accessed in loop body
  - Reborrowing inside loops is the challenge
- Analyse loop body with “havoced” copies:





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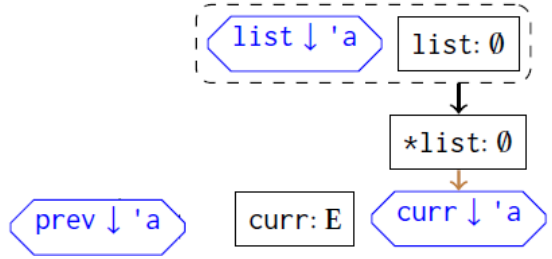

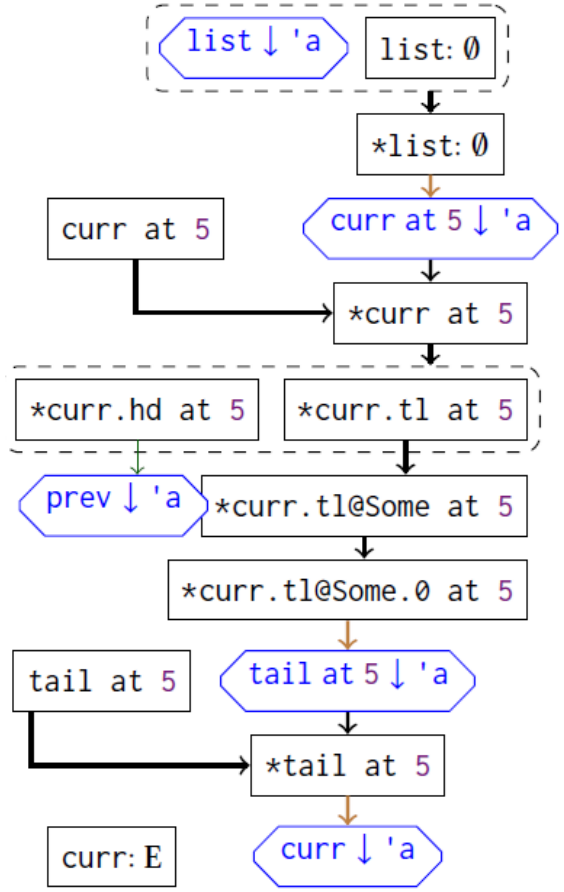

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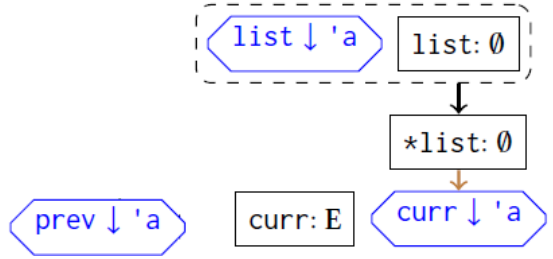

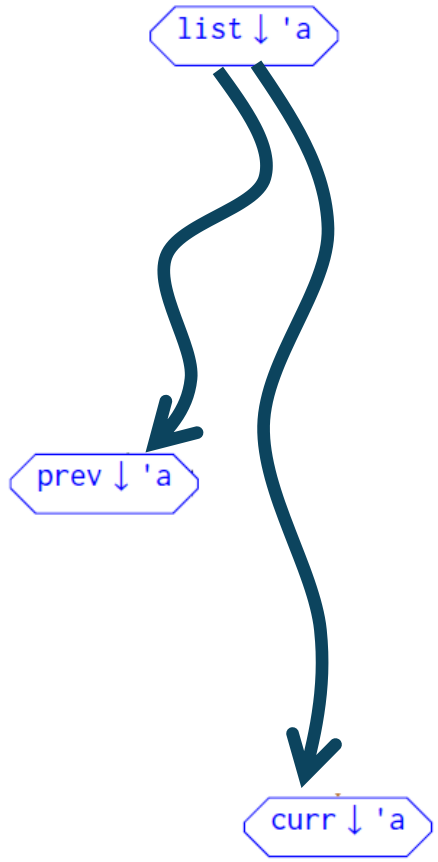

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- Abstract further - those live in current state:

Handling Loops

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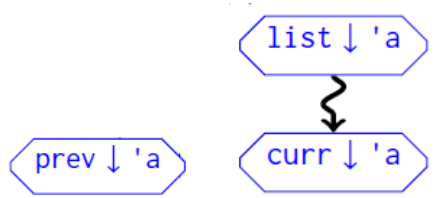
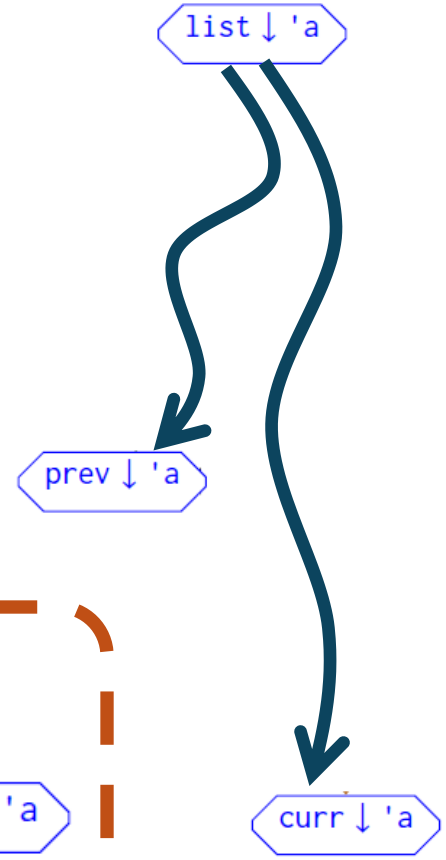
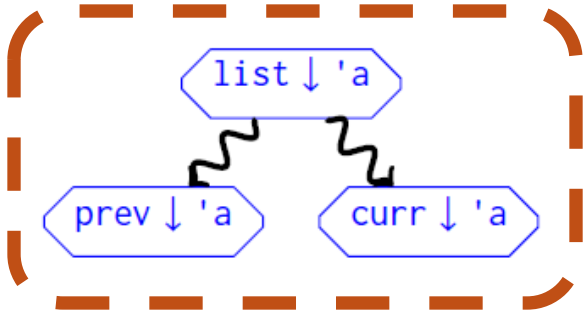
```





Key Ideas

- Initial graph (before loop) is already known
- Identify places accessed in loop body
  - Reborrowing inside loops is the challenge
- Analyse loop body with “havoced” copies:
- Abstract to only lifetime projection nodes:
- Abstract further - those live in current state:
- Apply same abstraction to initial graph
- Merge the graphs, keeping all edges:



Other features: no time, but ask if you like!

- PCG model supports general (safe Rust) types
  - Unpack notions generalise to e.g. enum -> cases projections
- Trickier: Rust composite types (structs, enums) can store borrows
  - The relevant source-level lifetimes are part of type declarations
  - Our lifetime projection nodes represent sets of borrows (for this reason)
  - e.g. ListRefs<‘a> places will get a lifetime projection node for ‘a
    - Represents entire set of borrows stored in the list, abstracted to one node
- Some generalisations are harder (and still being improved):
  - The notion of “inputs” and “outputs” to functions
  - Need for distinct versions of lifetime projection nodes in some cases
  - e.g. for a type &‘b mut ListRefs<‘a> passed into a function, the set of borrows represented by lifetime projection node ‘a for can itself be mutated!
- We have rules for this, but they are complex (currently on version

Evaluation: using the PCG model

Experimental evaluation(s)

- Automatically analysed functions in top 500 Rust crates (crates.io)
  - Successfully generated PCGs for (all of the code of) *98.4% of all functions*
  - Most unsupported functions involve *raw pointers* (unsafe code)

- How to gain confidence that these PCGs reflect Rust's *restrictions*?
  - e.g. that generated PCGs precisely reflect borrow-checker constraints
- We developed a form of automated mutation testing based on PCGs
  - Analyse the structure of our generated graphs for existing code
  - Use these to generate modified programs the graphs say *shouldn't* type-check
  - Re-run the compiler on these, and compare errors with these

PCG generation: functions in top 500 crates

Status	Details	Count
Success		119,338
Unsupported	DerefUnsafePtr	1,629
	~~ClosureCall~~	~~215~~
	InlineAssembly	80
	ExpansionOfAliasType	6
	IndexingNonIndexableType	5
	AssignBorrowToNonReferenceType	1
	Timeout	1
Total		121,274

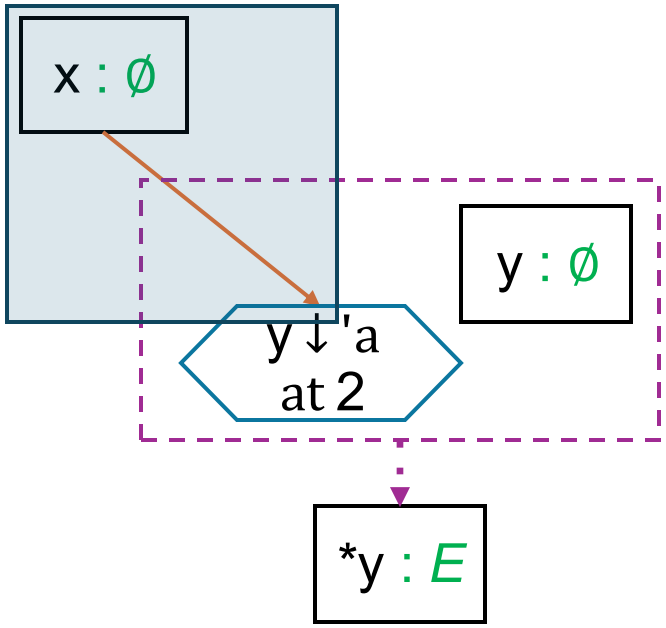
Hot off the press: now supported

Engineering Issue:
Normalizing type aliases erases regions

Macro-Generated Code
Fixable with performance optimizations

Mutation testing

```
fn main() {
1   let mut x = 1;
2   let y = &x;   // x is immutably borrowed
3   let z = &*y;  // x remains immutably borrowed
...
}
```



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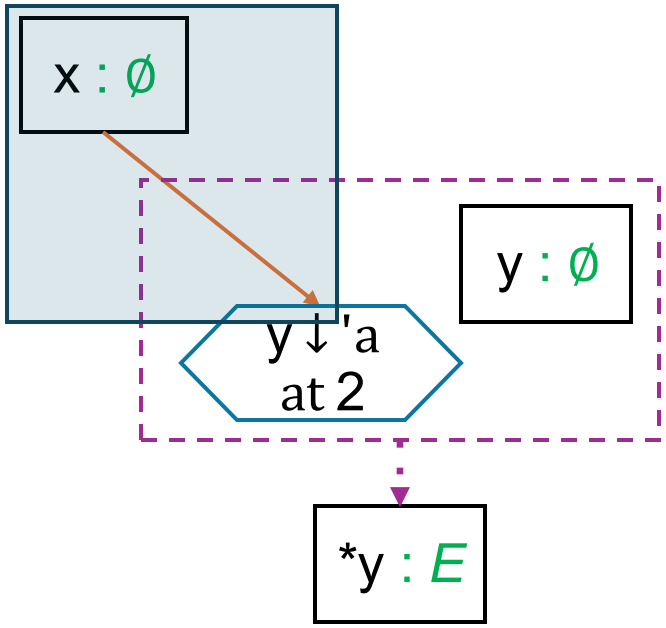


Mutation testing

```
fn main() {
1   let mut x = 1;
2   let y = &x;   // x is immutably borrowed
3   let m = &mut x; // mutation
4   let z = &*y;  // x remains immutably borrowed
…
}
```

```
cannot borrow `x` as mutable because it is also
borrowed as immutable
```

Mutation testing results

Mutation	*tot*	*fail*	*pass*	*%fail*
MutablyLendShared	1009867	1009497	370	99.96%
ReadFromWriteOnly	395299	395299	0	100.00%
WriteToShared	1009396	1008980	370	99.96%
MoveFromBorrowed	419555	419264	291	99.93%
BorrowExpiryOrder	196470	196374	96	99.96%
AbstractExpiryOrder	38220	38203	17	99.96%
Total	3068807	3067617	1144	99.96%

Note: failure is good!

Found bugs (fixed) in our implementation
But also very strange rustc behaviours - reporting

Integrating PCG into Rust Analysis Tools

- Used PCG to develop new prototype forks of Flowistry and Prusti tools
  - PCG is a standalone Rust crate supporting various queries; easy to hook up

- Flowistry – Information/Data Flow Analysis Tool
  - Replaced Flowistry's Alias Analysis with PCG queries
    - Thanks to Will Crichton for suggesting this possibility!
  - All existing test cases pass

- Prusti – Deductive Verifier for Rust
  - PCGs suitable for automating all core proof steps
  - Support for new features:
    - structs containing borrows, reborrowing across loops, etc.

Consuming the PCG in practice

- PCG implemented as a Rust crate – no external dependencies

- Clients can query PCG at a program point, to ask questions like:
  - *What is the capability of place x?*
  - *What places do *y alias (and under what conditions)?*

- Clients can query for PCG *annotations* between program points
  - *What capabilities were transferred at this program point?*
  - *What is the shape of the function call / loop invariant at this point?*
  - e.g. Prusti prototype translates PCG annotations into Viper commands

Future Work (ideas)

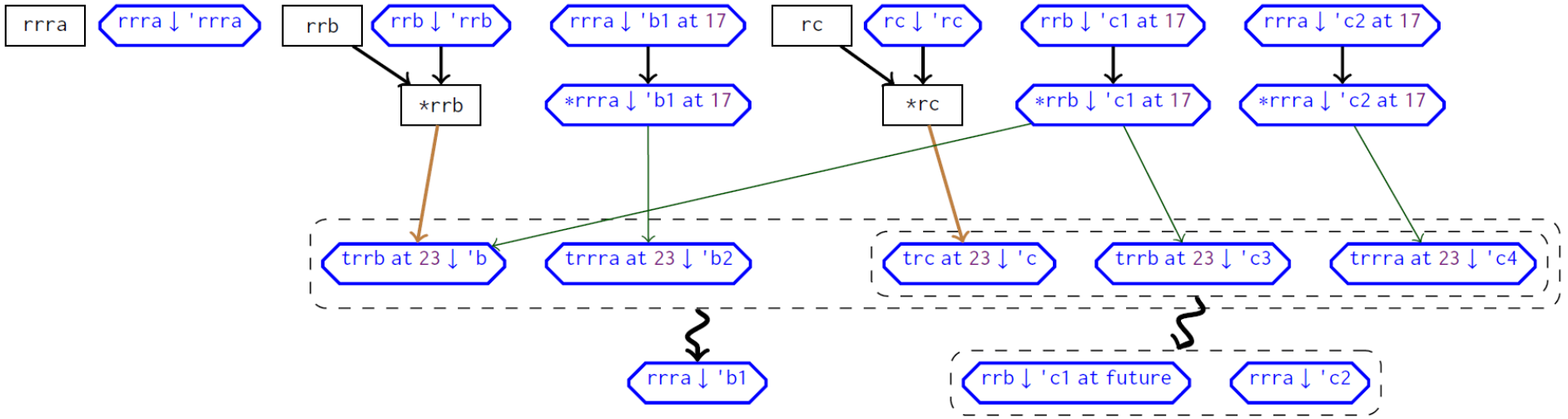
- Formalizing our PCG model
  - The graphs themselves (including nice properties around abstract edges)
  - The underlying capabilities (treated linearly, etc.)
  - Framing/immutability guarantees for actual program state
  - Extensions to symbolic execution (value information) over graphs
- Using PCG to visualize/debug/evaluate future borrow-checkers
- Possibly using the model to define borrow-checking
- Trying to simplify/justify rules for handling nested lifetimes
- Extension of the model to reason about some kinds of unsafe code
- Supporting other consumers of the model (analysis tools)
- .. your ideas? ☺

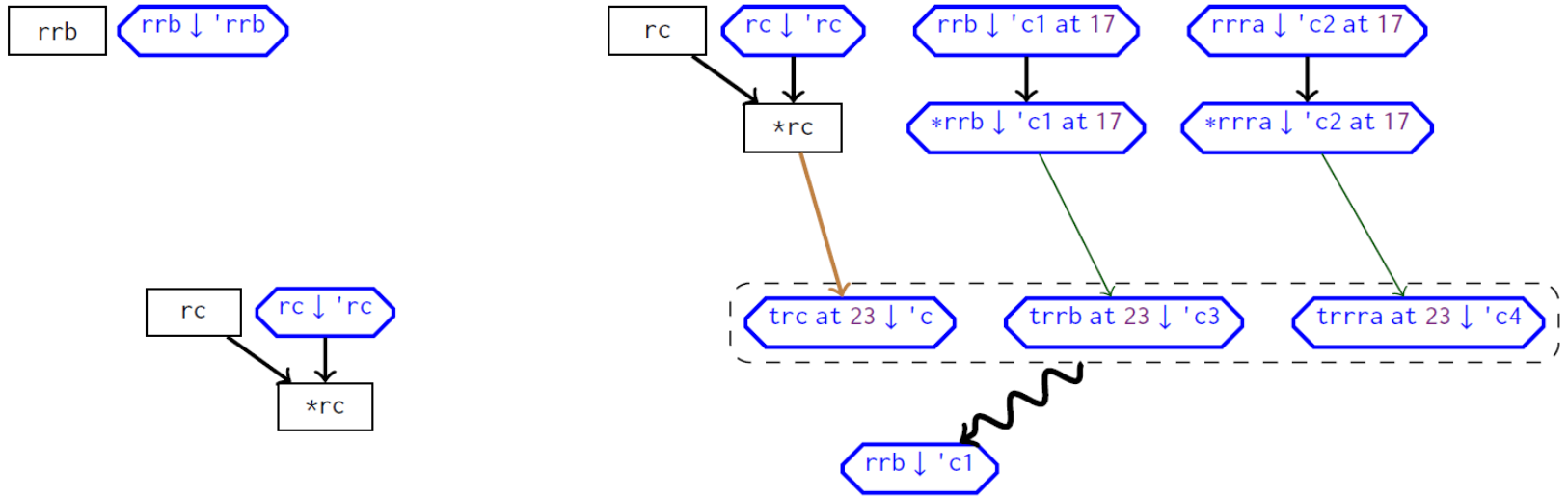
```rust
fn f<'a, 'b, 'c>(
    x: &'a mut &'b mut &'c mut i32,
    y: &'b mut &'c mut i32,
    z: &'c mut i32,
) { *y = z; *x = y; }

fn caller() {
    let mut a = 1;
    let mut b = 2;
    let mut c = 3;
    let mut ra = &mut a;
    let mut rb = &mut b;
    let mut rc = &mut c;
    let mut rra = &mut ra;
    let mut rrb = &mut rb;
    let mut rrra = &mut rra;

    f(rrra, rrb, rc);

    ***rrra = 1;
    **rrb = 1;
    *rc = 4;
}
```





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