Type-Intertwined Heap Analysis


Devin Coughlin


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Aarhus University
May 18, 2015

PLV

Lab: **Program analysis** in the **whole** bug mitigation **process**

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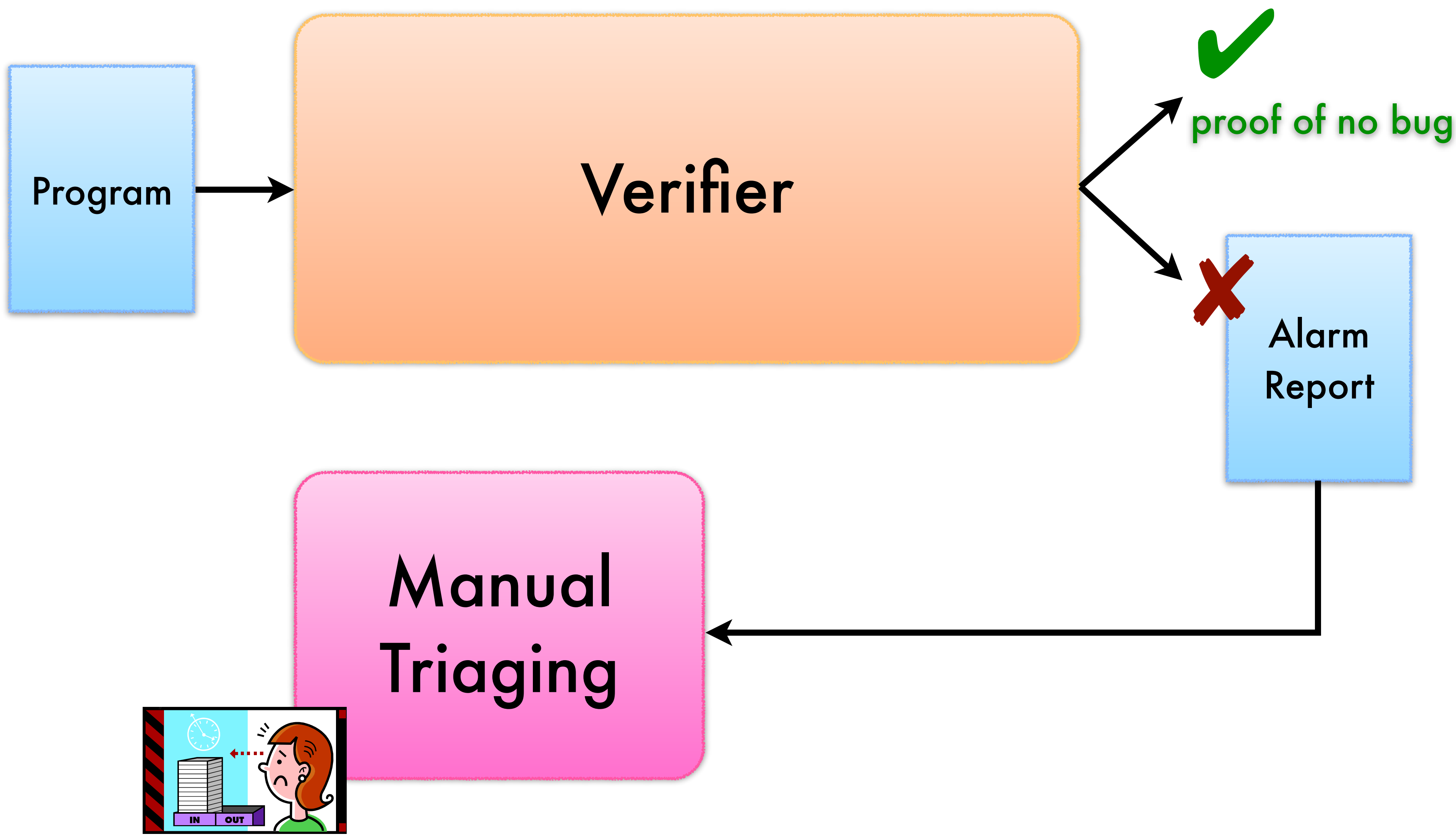

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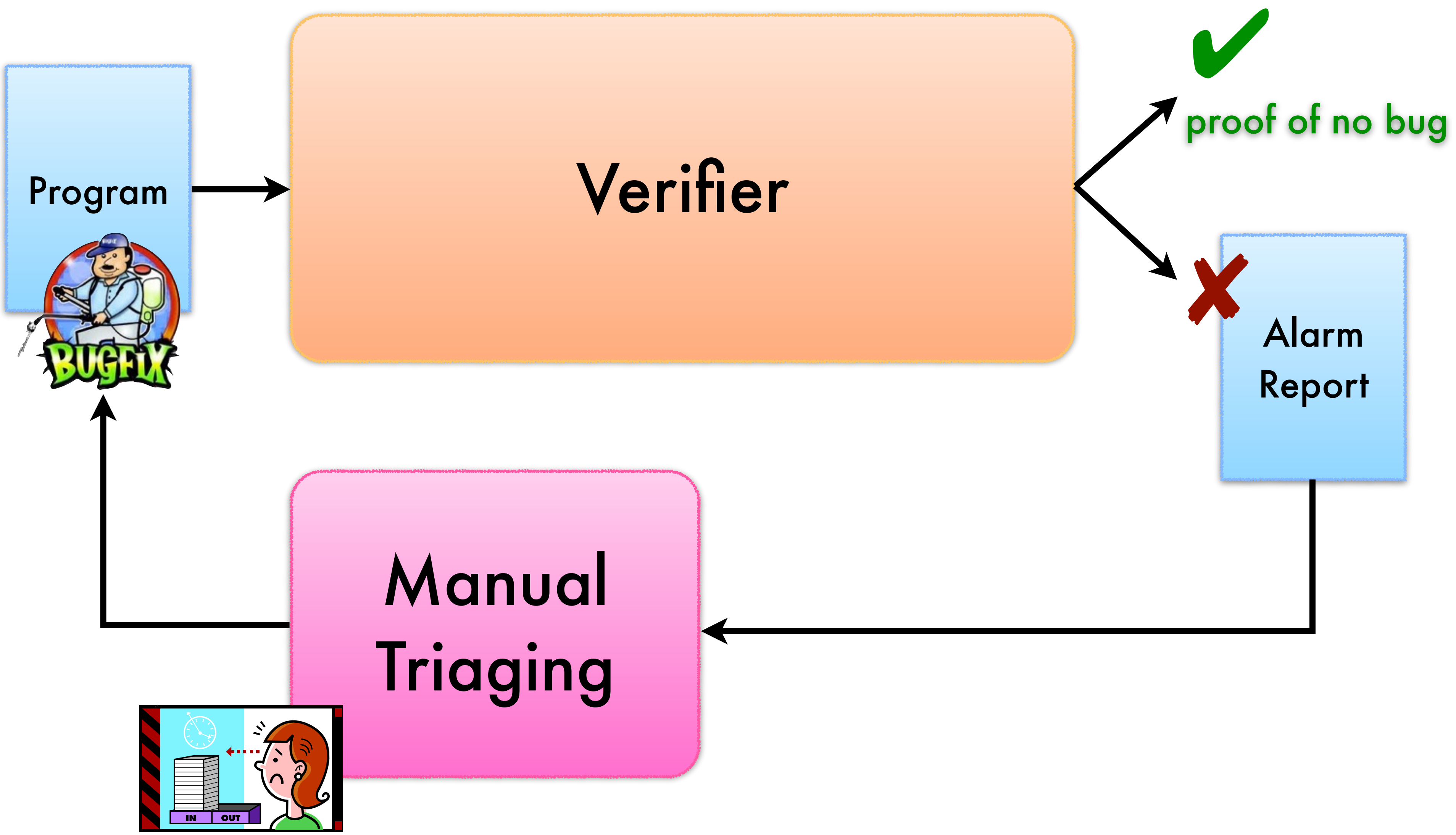

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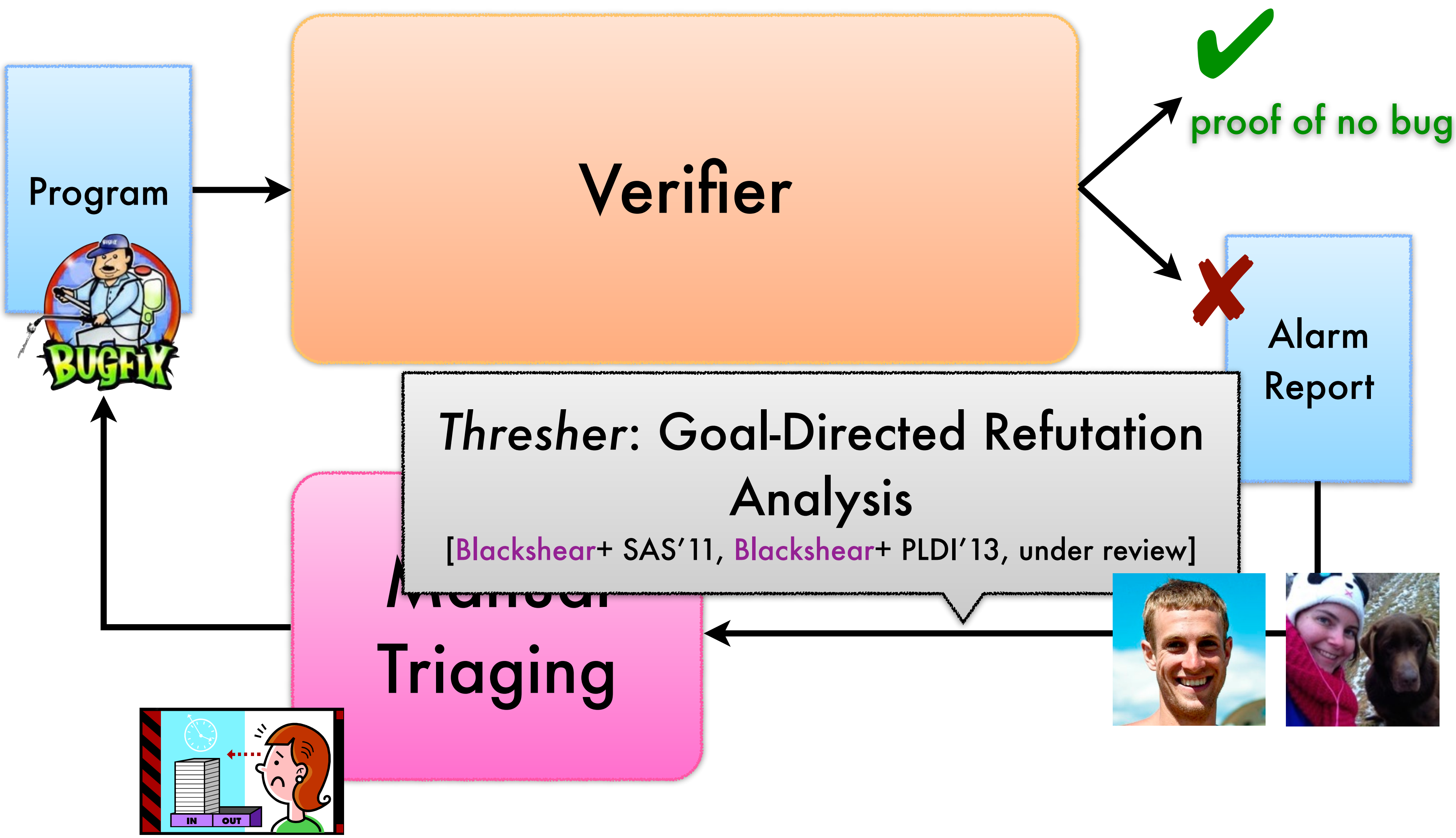

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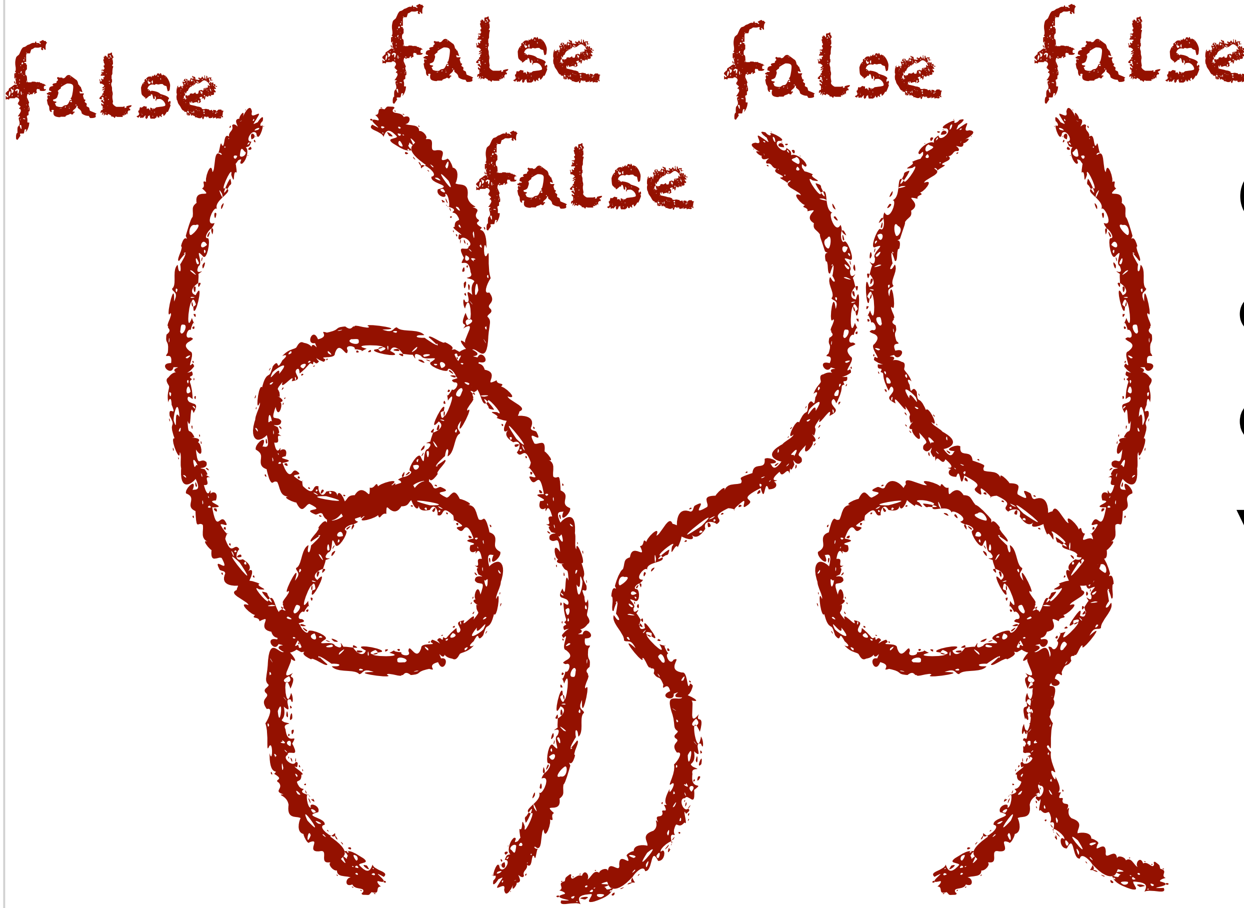


Given a program configuration **goal**, derive a **contradiction** w.r.t. its reachability

$$(x \mapsto \hat{x} * \hat{x} \cdot f \mapsto \hat{a} * \text{true}) \wedge \hat{a} \neq \text{null}$$

backwards abstract interpretation of separation logic

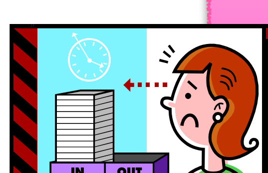
of no bug

Alarm Report

Thresher: Goal-Directed Refutation Analysis

[Blackshear+ SAS'11, Blackshear+ PLDI'13, under review]

Triaging



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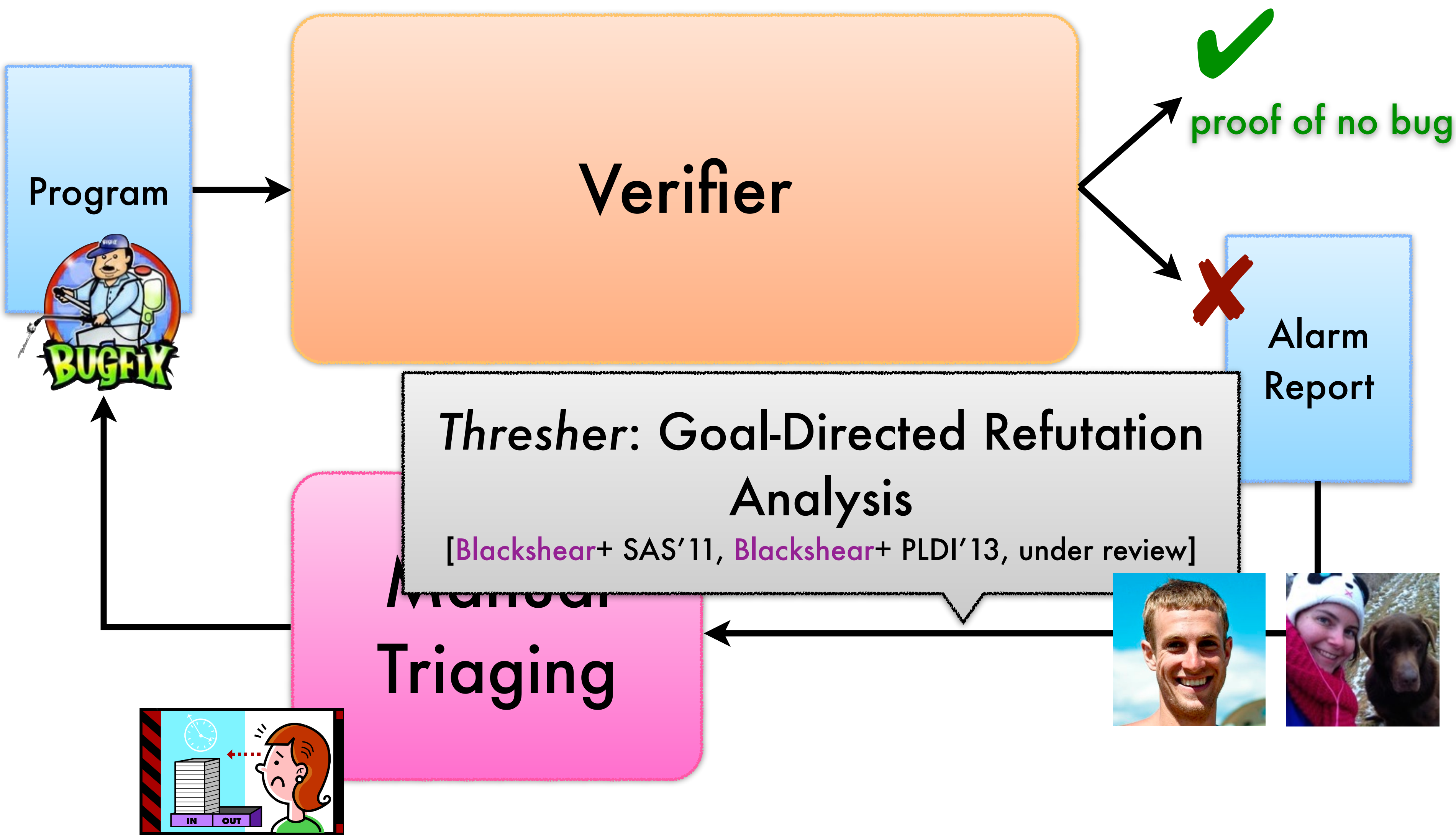

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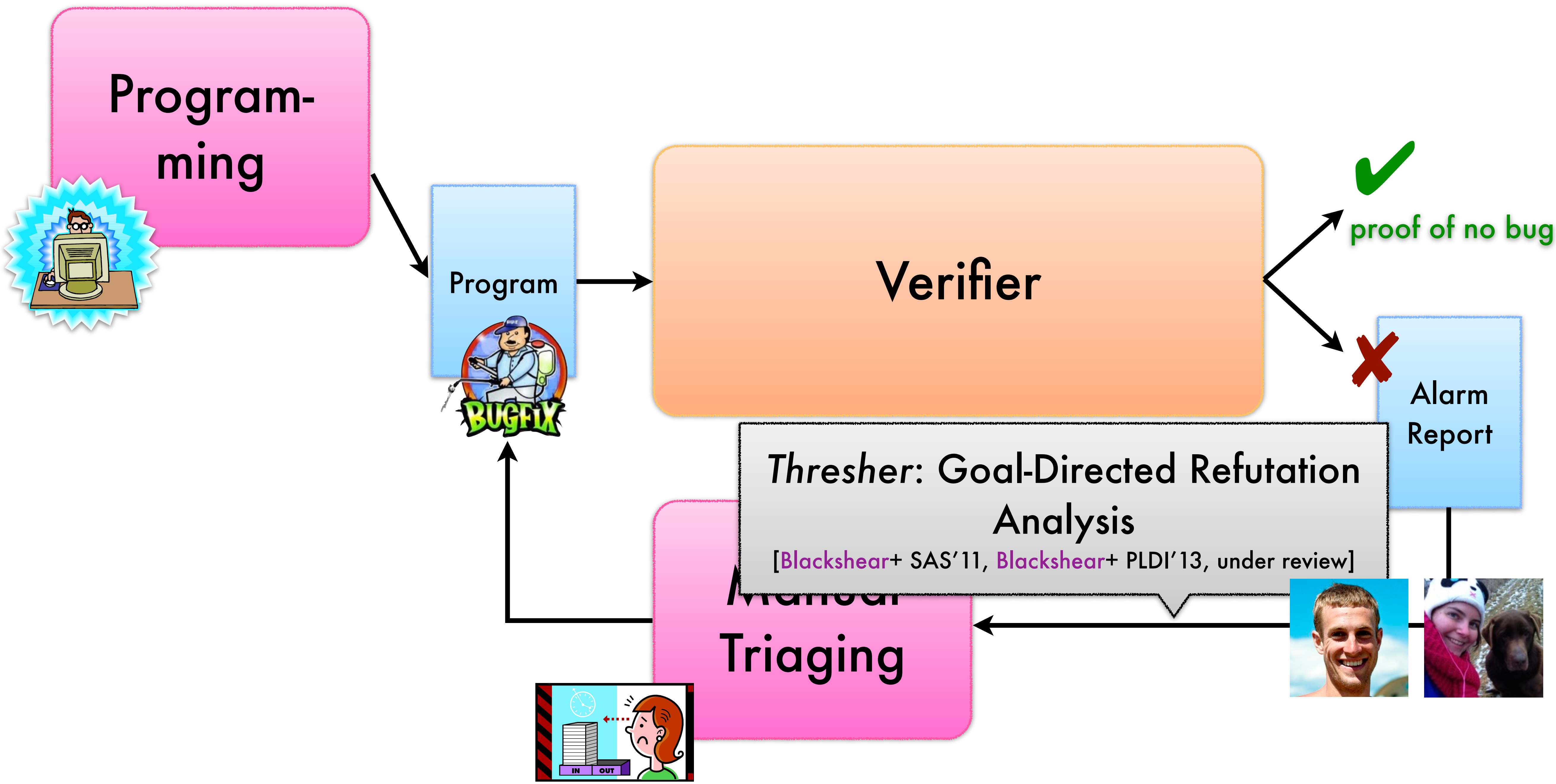

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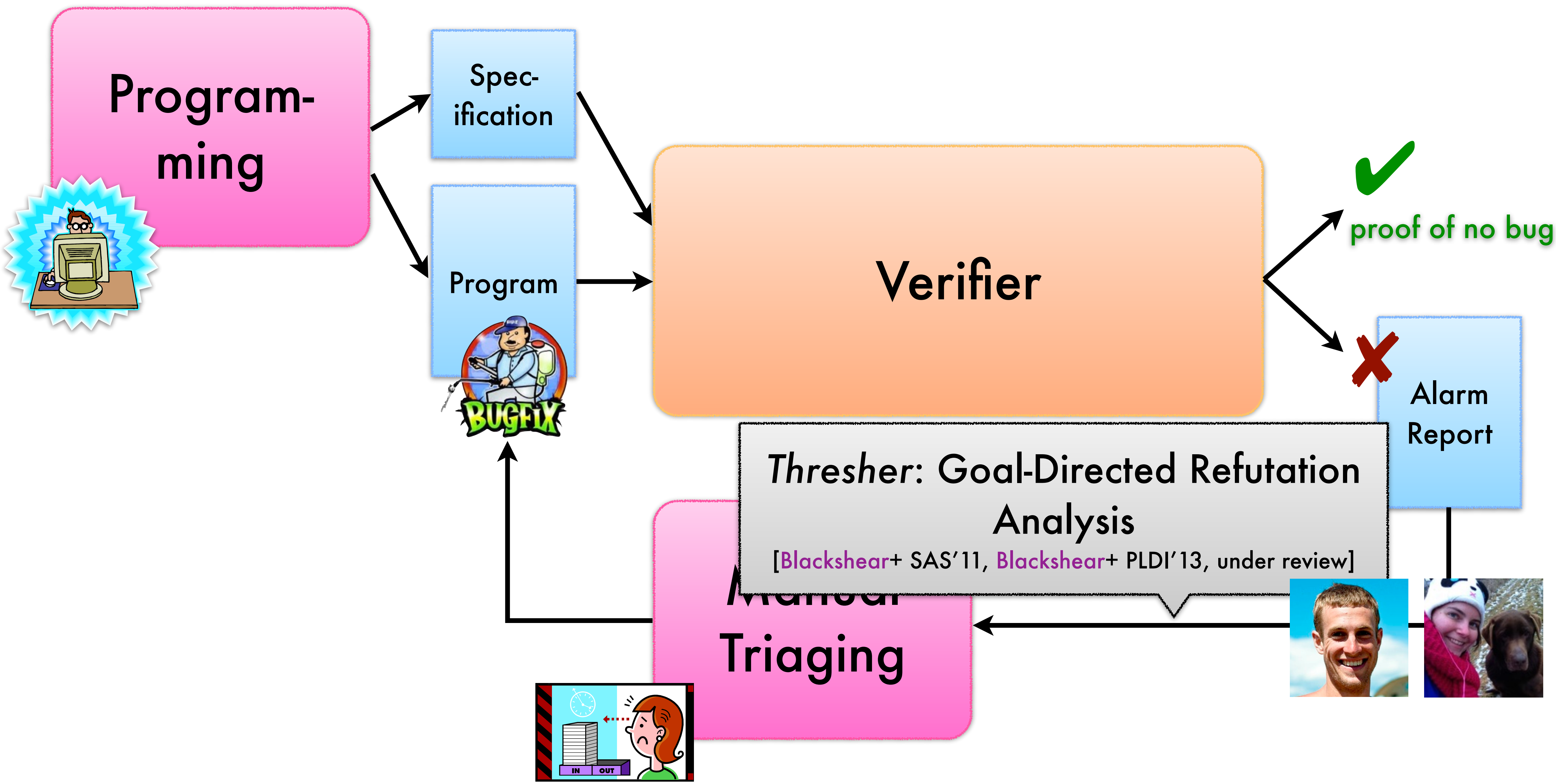

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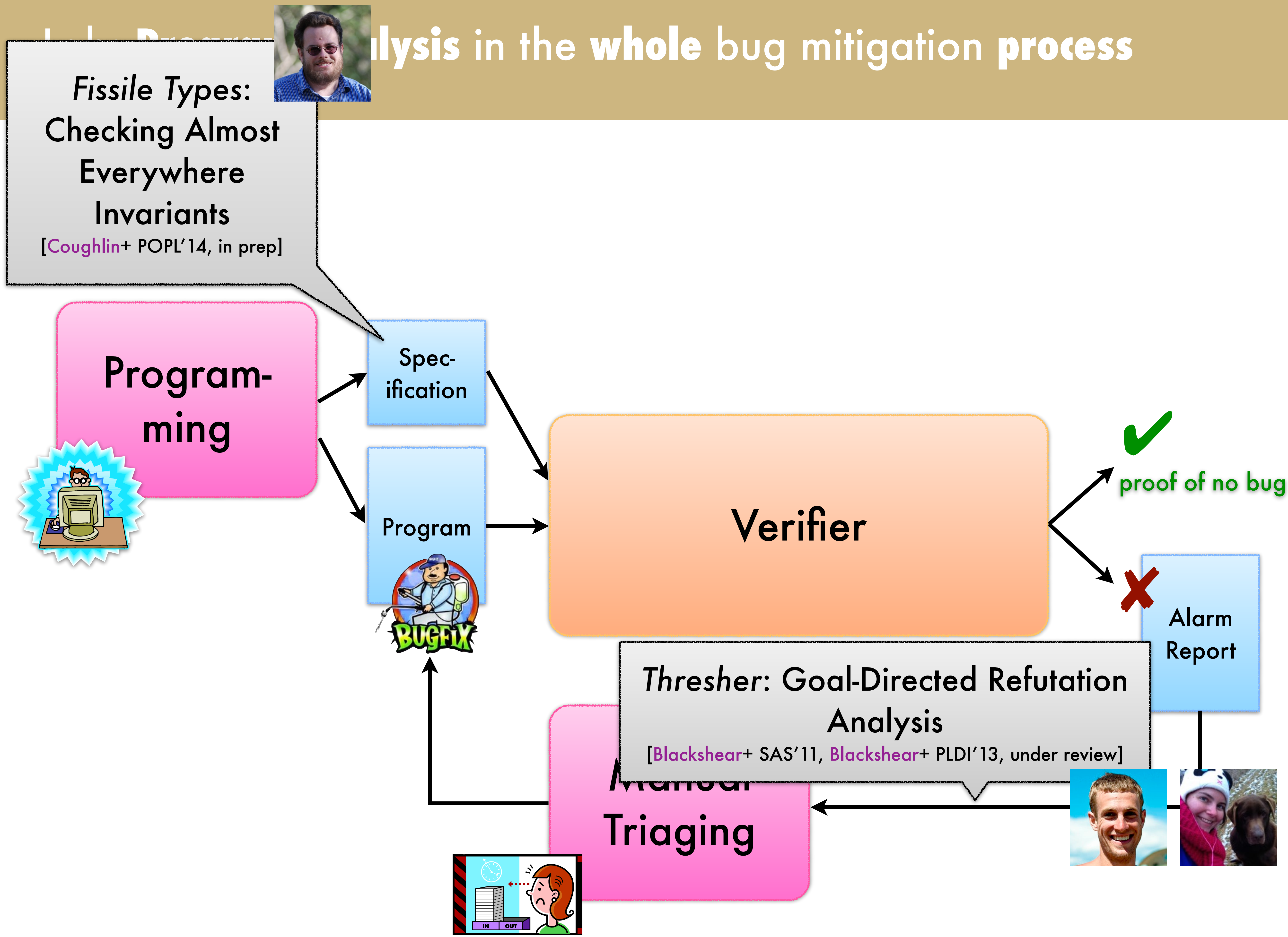

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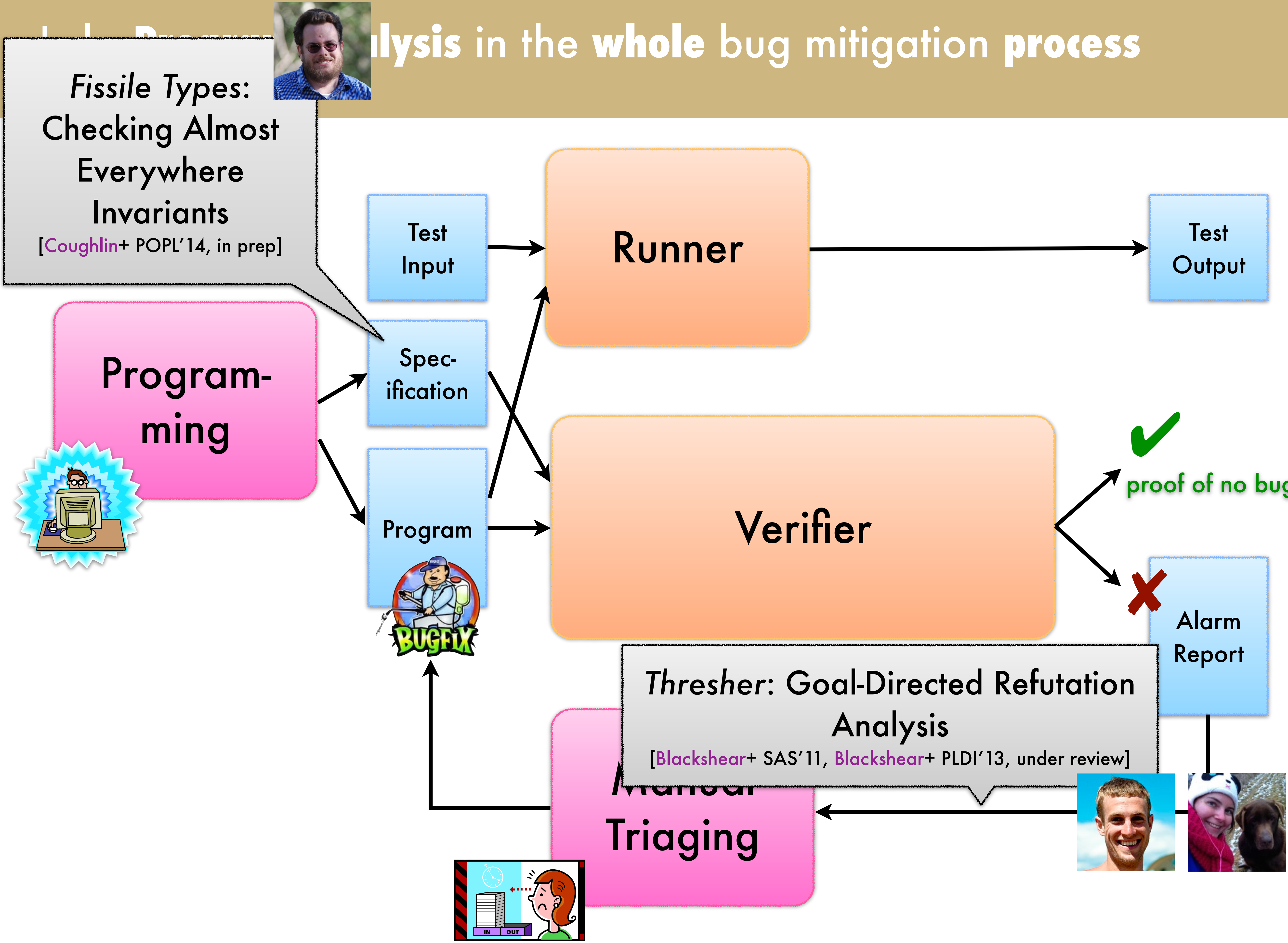

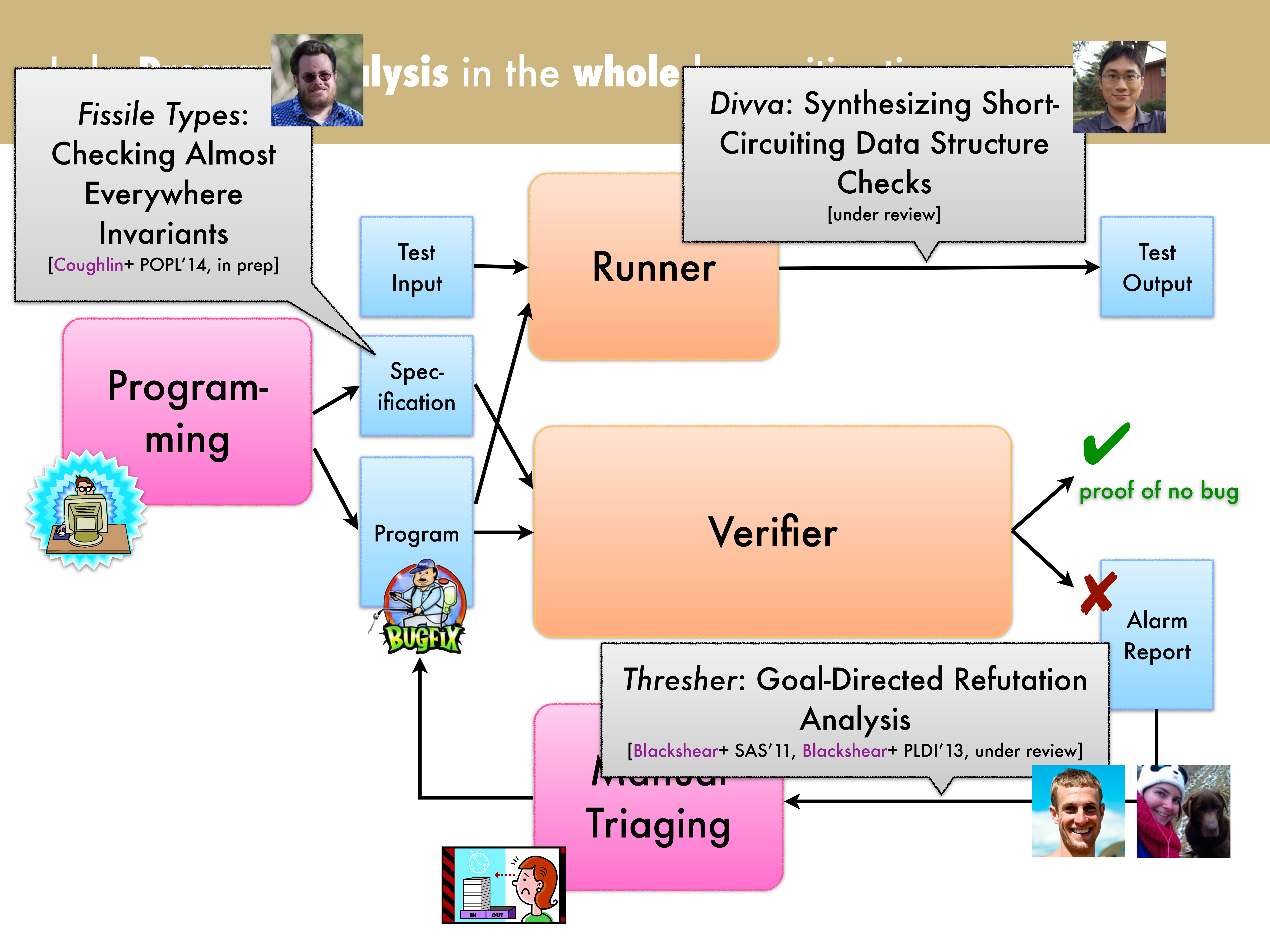
lysis in the whole
Fissile Types: Checking Almost Everywhere Invariants
[Coughlin+ POPL'14, in prep]
Divva: Synthesizing Short-Circuiting Data Structure Checks
[under review]
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Runner
Test Output
Program-ming
Spec-ification
Program
BUGFIX
Verifier
proof of no bug
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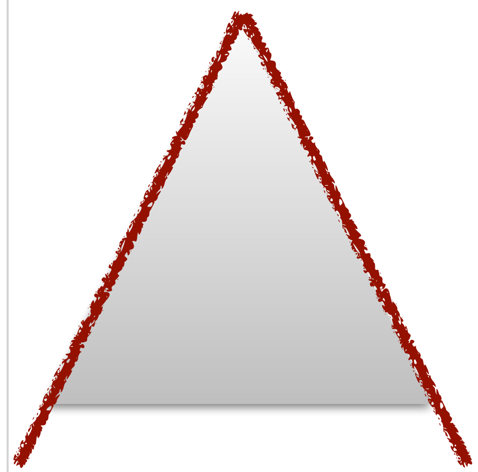

Use **static shape analysis** to **synthesize short-circuiting dynamic validation** of data structure invariants

uninterpreted inductive separation logic predicates

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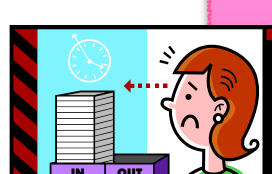

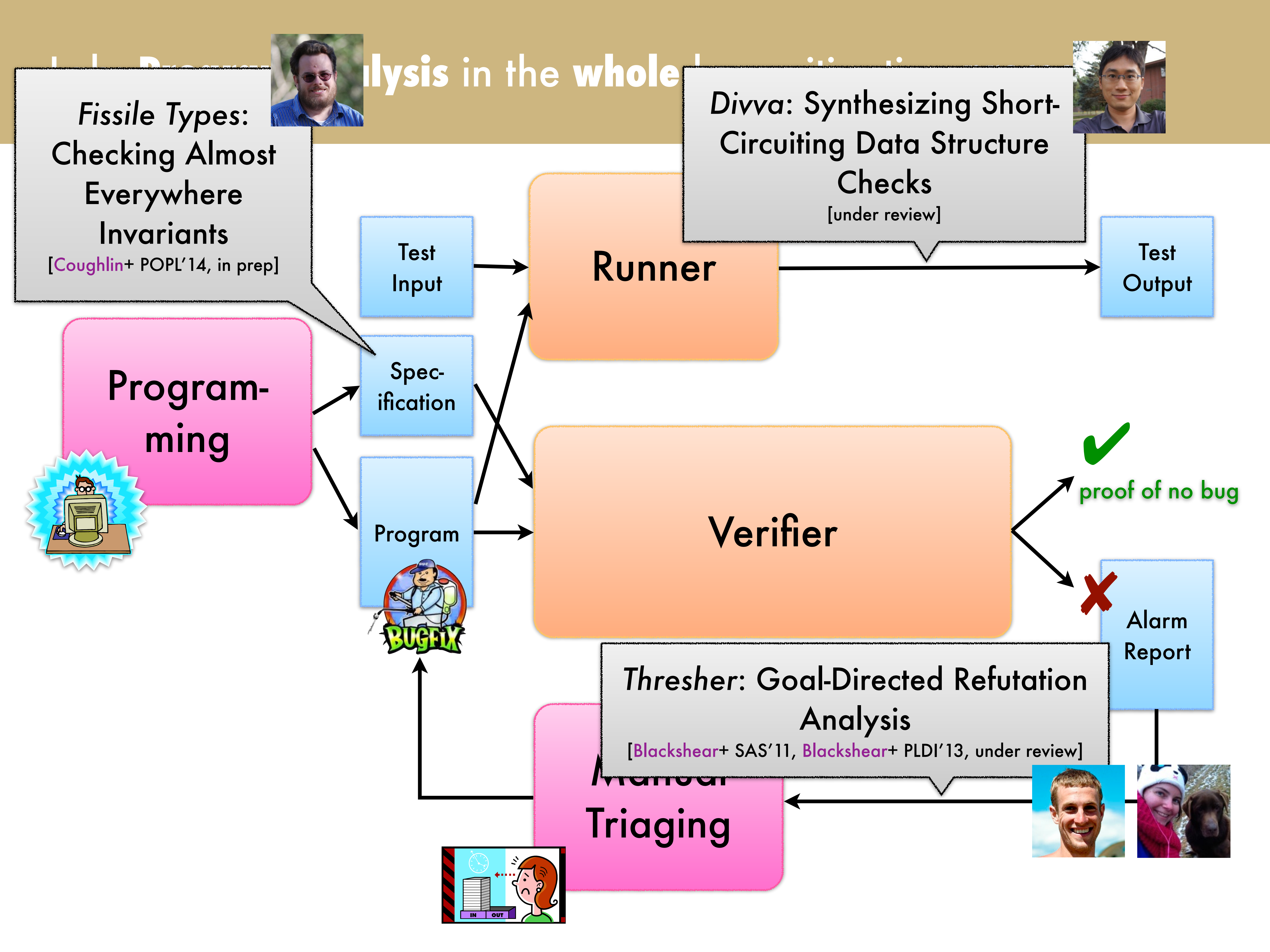

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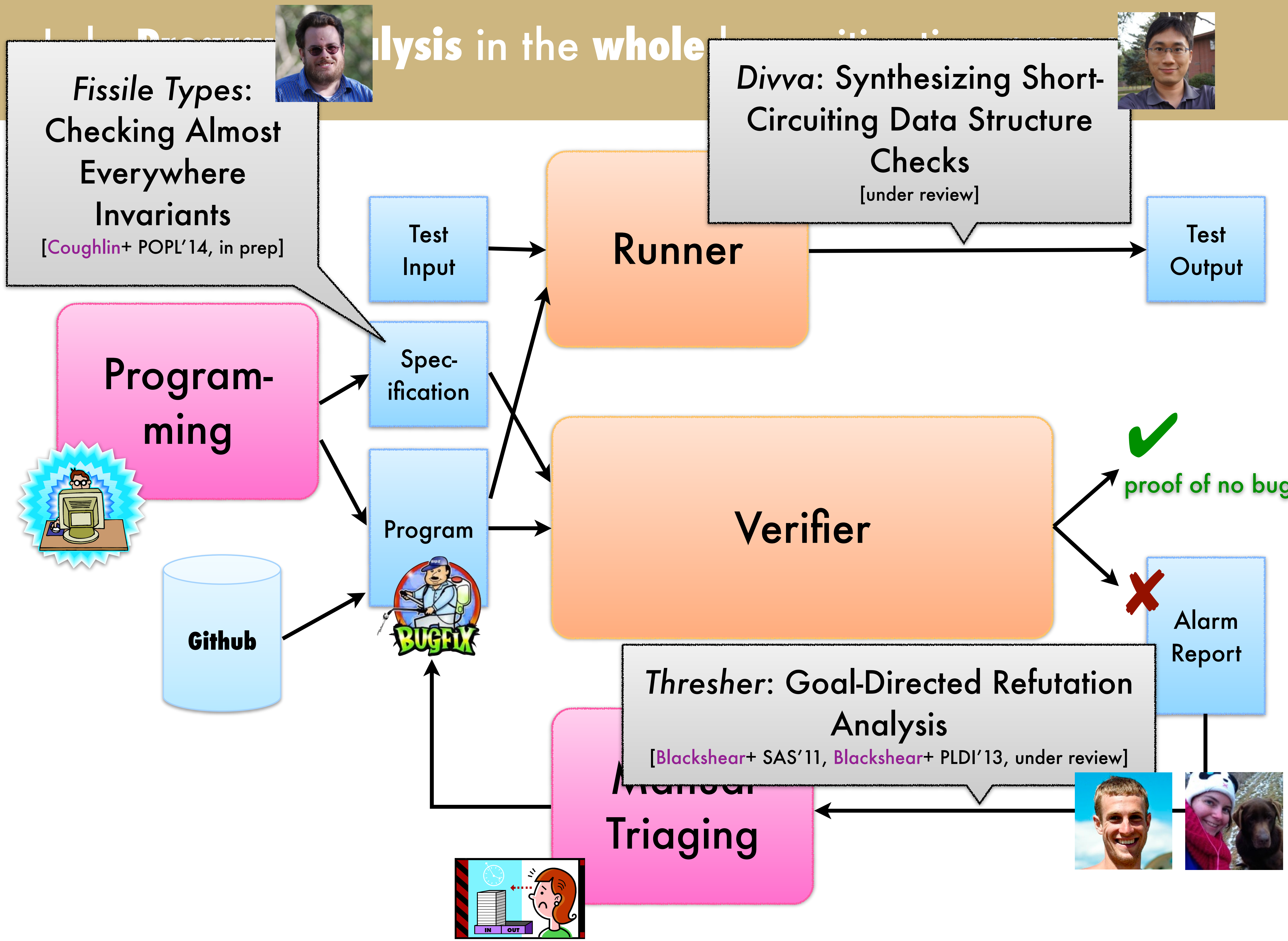

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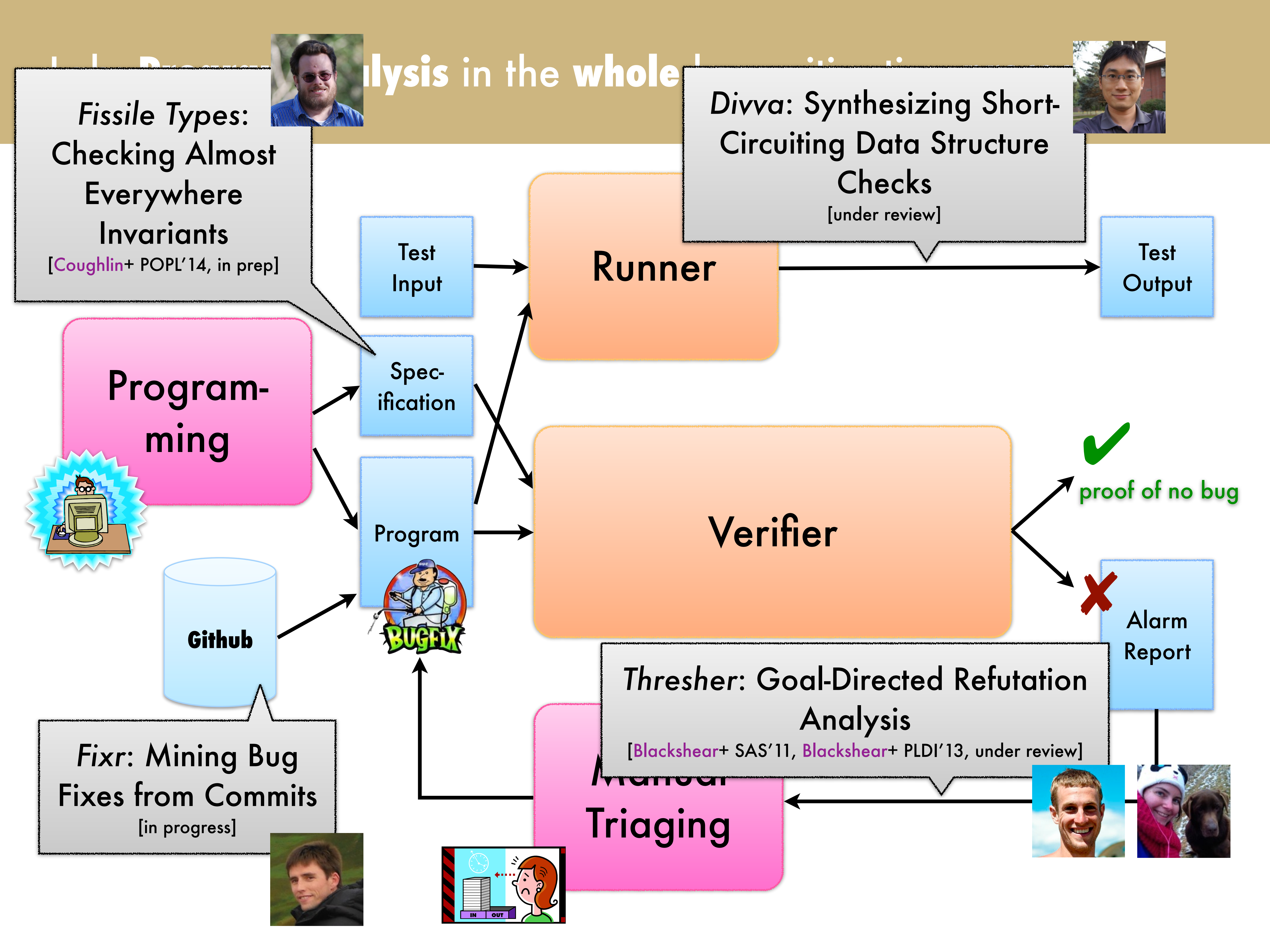

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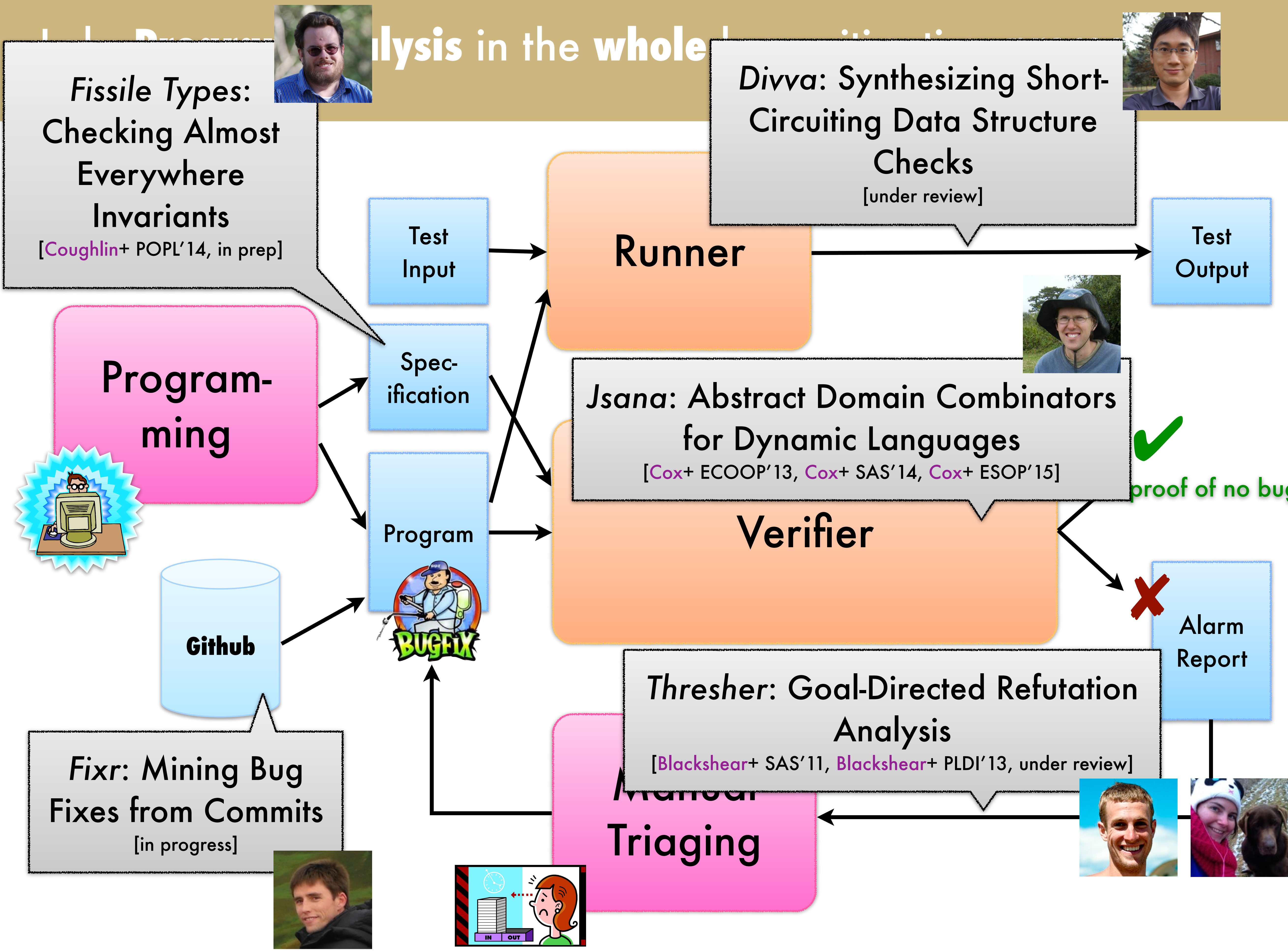

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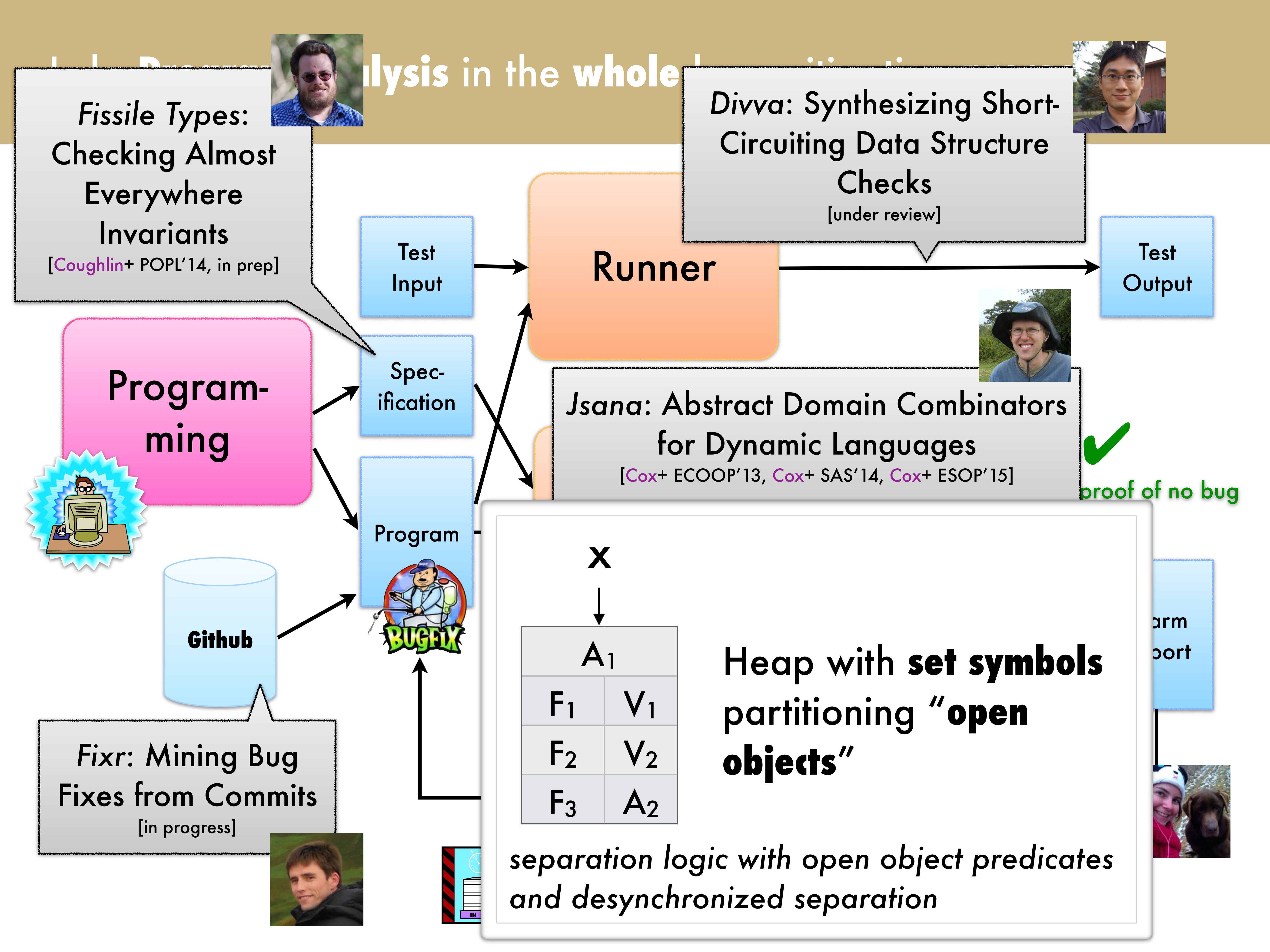

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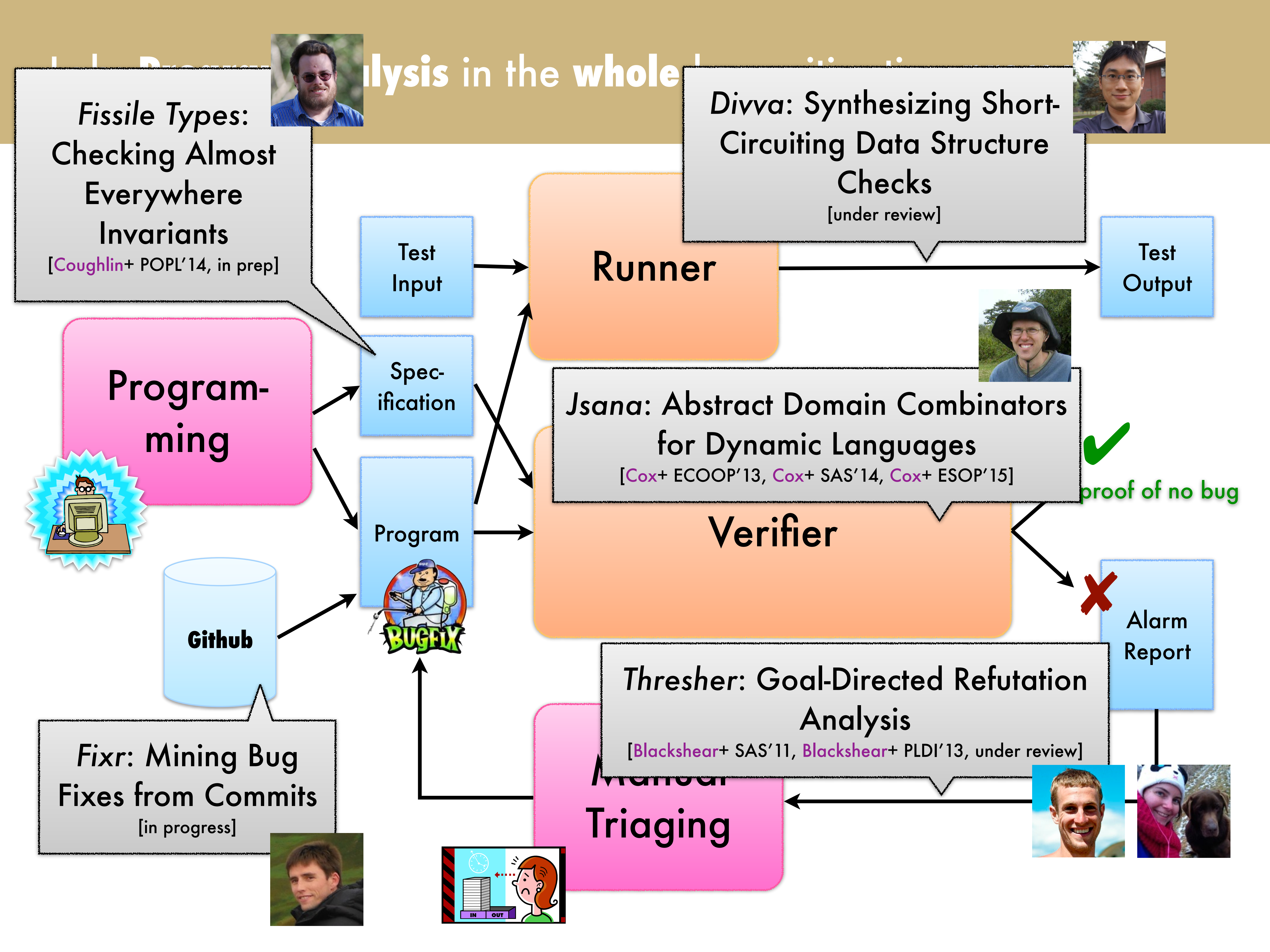
x
A1
F1 V1
F2 V2
F3 A2
Heap with set symbols partitioning "open objects"
separation logic with open object predicates and desynchronized separation



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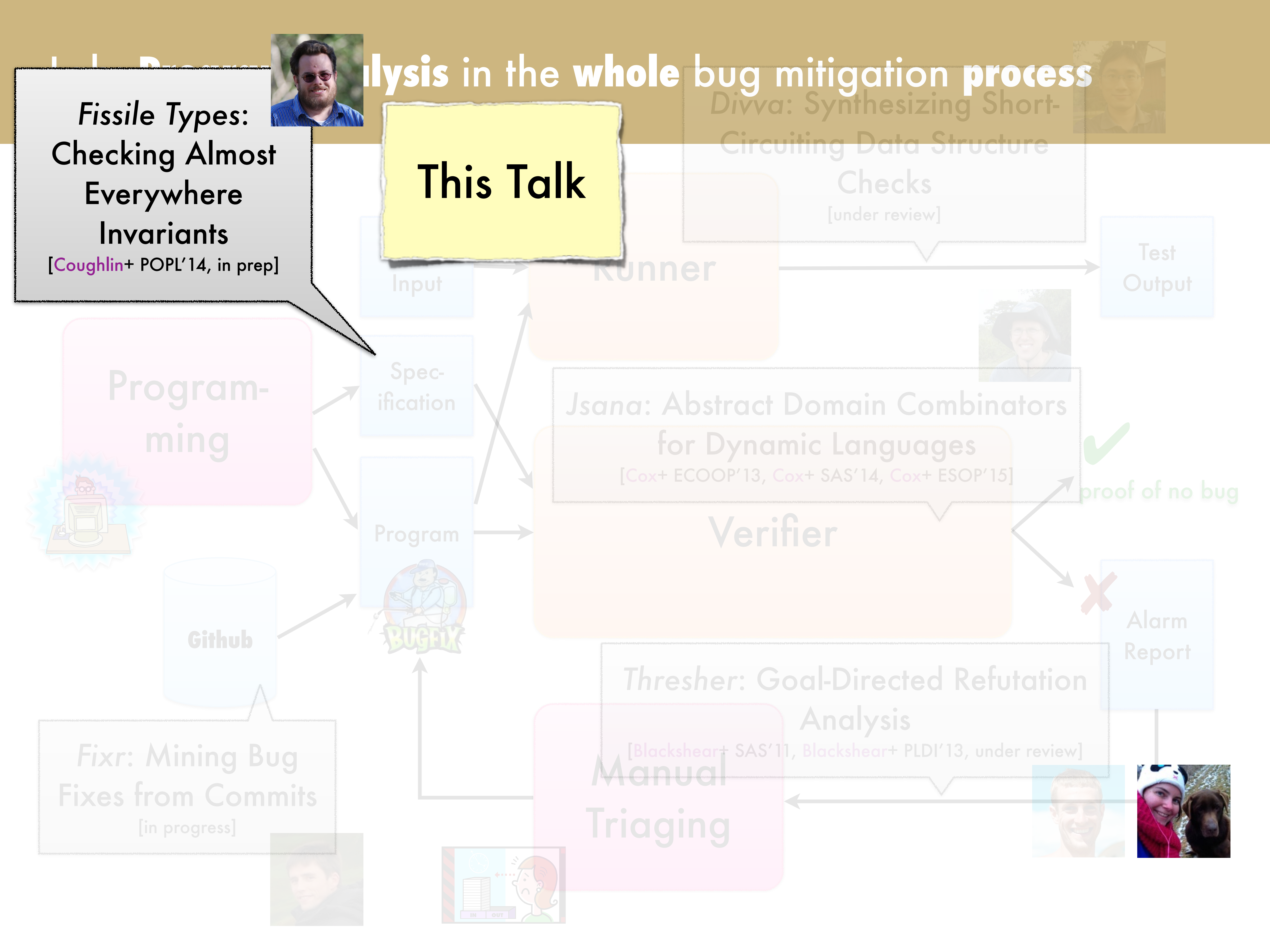
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How to **type check** a program that is **almost** well-typed?

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almost?

A motivating example

Property of interest:
reflective method call safety

Specification system:
dependent-refinement types

A motivating example

Property of interest:

reflective method call safety

type safety

Specification system:

dependent-refinement types

simple types

A motivating example

Property of interest:
reflective method call safety

Specification system:
dependent-refinement types

Reflective method call is **dispatch** based **on a run-time value**

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class Callback
 var sel: Str
 var obj: Obj

 def call()
  this.obj.[this.sel]()
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If `sel` held string "`notifyClick`" would call `notifyClick()` on `obj`.

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Calls method with name (selector) stored in on `sel` object stored in `obj`

Run-time error if `obj` does not **respond to** `sel` – i.e., method does not exist

A **dependent-refinement type** expresses the required **relationship**

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Shorthand for $\mathrm{obj} :: \{\nu : \mathsf{Obj} \mid \nu\ \mathsf{r2}\ \mathrm{sel}\}$

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Guarantees no `MethodNotFound` error in `call()`

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Array indexing safety is a similar **relationship**

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class Iterator
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 var buf: Obj[] | indexedBy idx

 def get(): Obj
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Guarantees no `ArrayOutOfBounds` error here

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Recurring theme: **Relationships** are important to **many safety properties**

Relationships can be broken

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Relationships can be broken

obj must **always** respond to sel

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`obj` must **always** respond to `sel`

False alarm: no run-time `MethodNotFound`

`o` guaranteed to respond to `s`

Type error: **old** `obj` may not respond to **new** `sel`

Why is this a false alarm?

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two reasoning styles

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two **reasoning styles**

Idea: Selectively **alternate** between and **intertwine** these two **reasoning styles** in verification

Idea: Selectively **alternate** between and **intertwine** these **two reasoning styles** in verification

$x : \tau, \ldots$

flow-insensitive typing

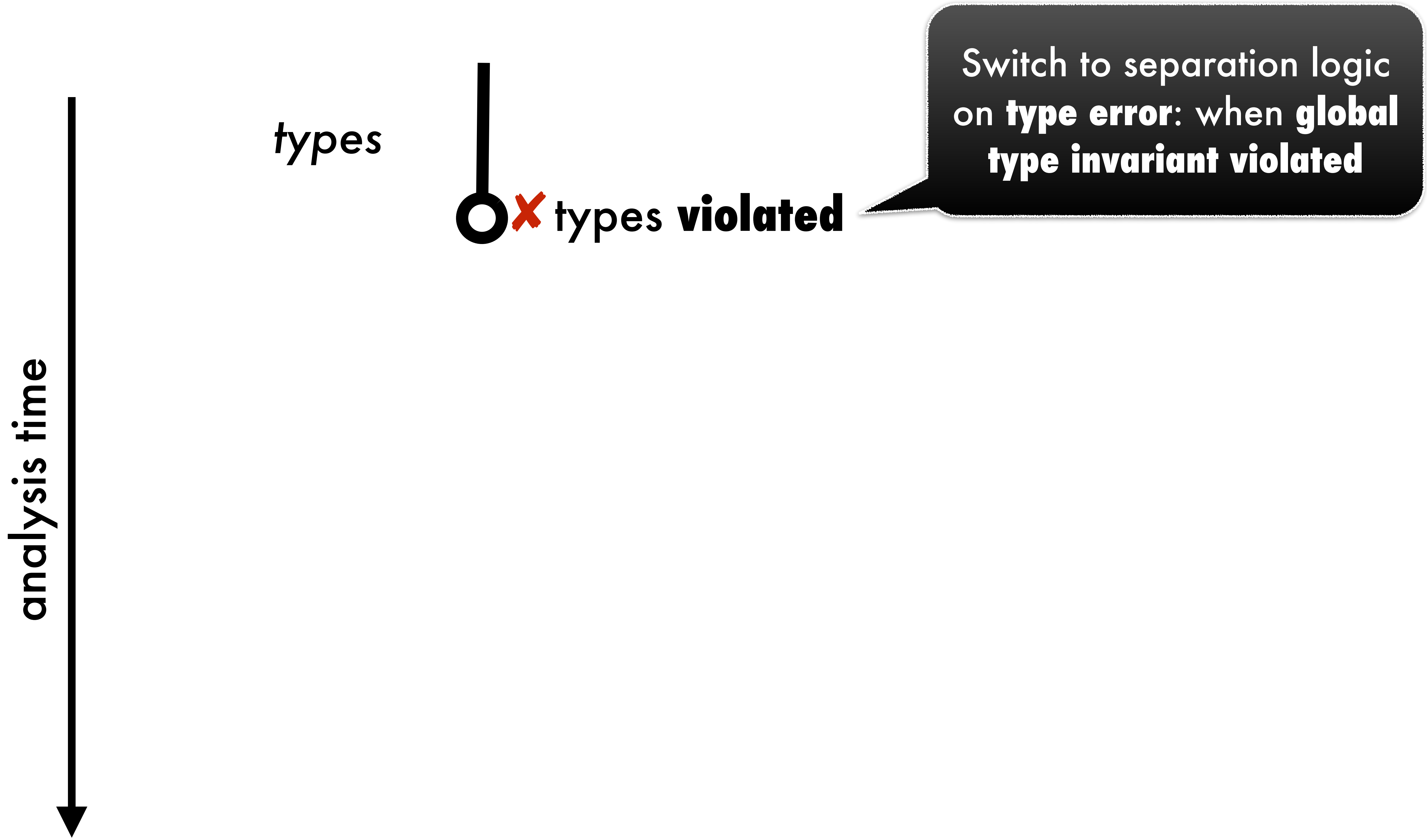
$x \mapsto \hat{a} * \hat{a} \cdot f \mapsto \hat{v} * \cdots$

flow-sensitive abstract interpretation

Verification of **almost-everywhere invariants** with **intertwined** type- and separation logic-based analysis

analysis time

Verification of **almost-everywhere invariants** with **intertwined** type- and separation logic-based analysis



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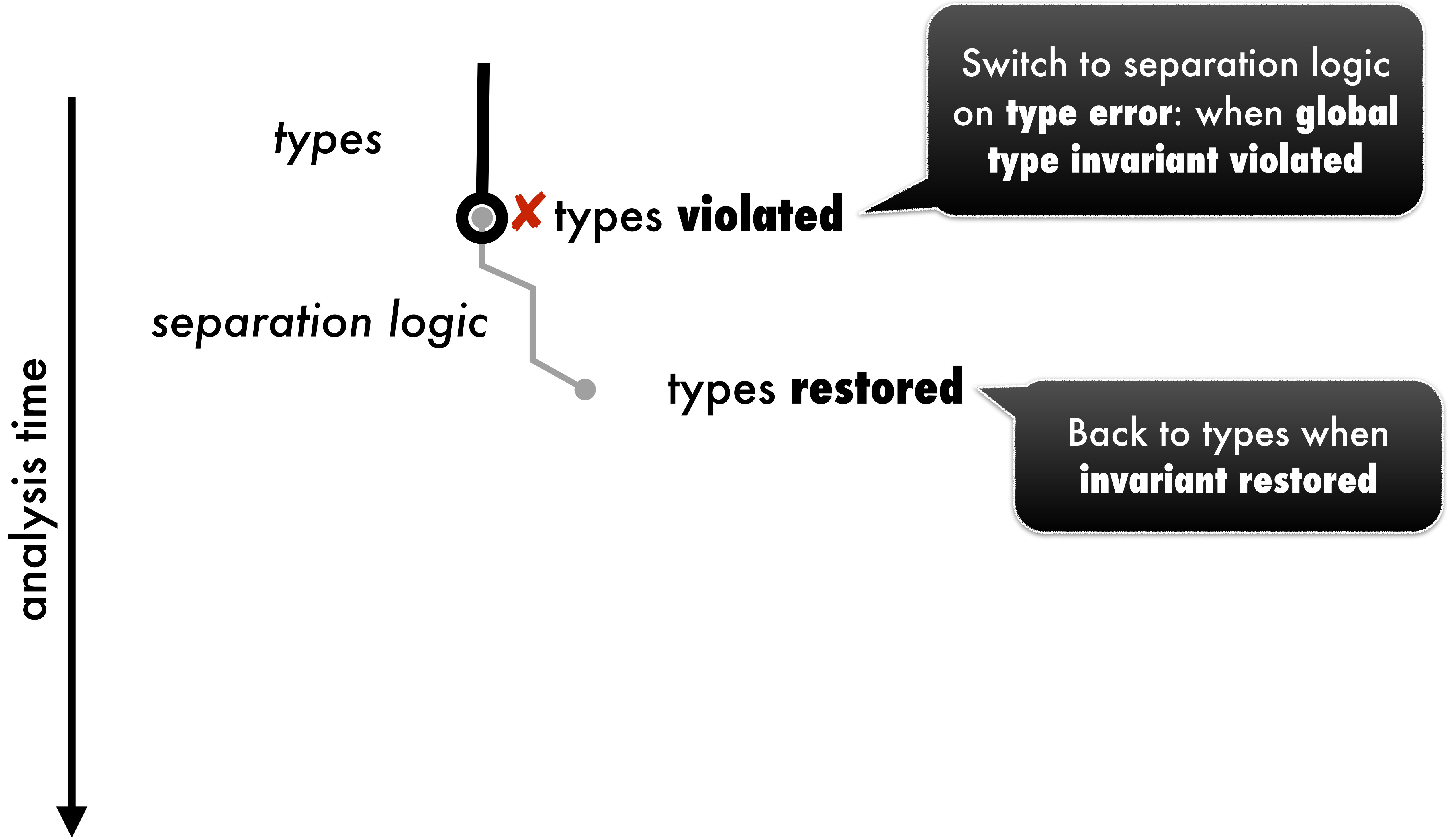

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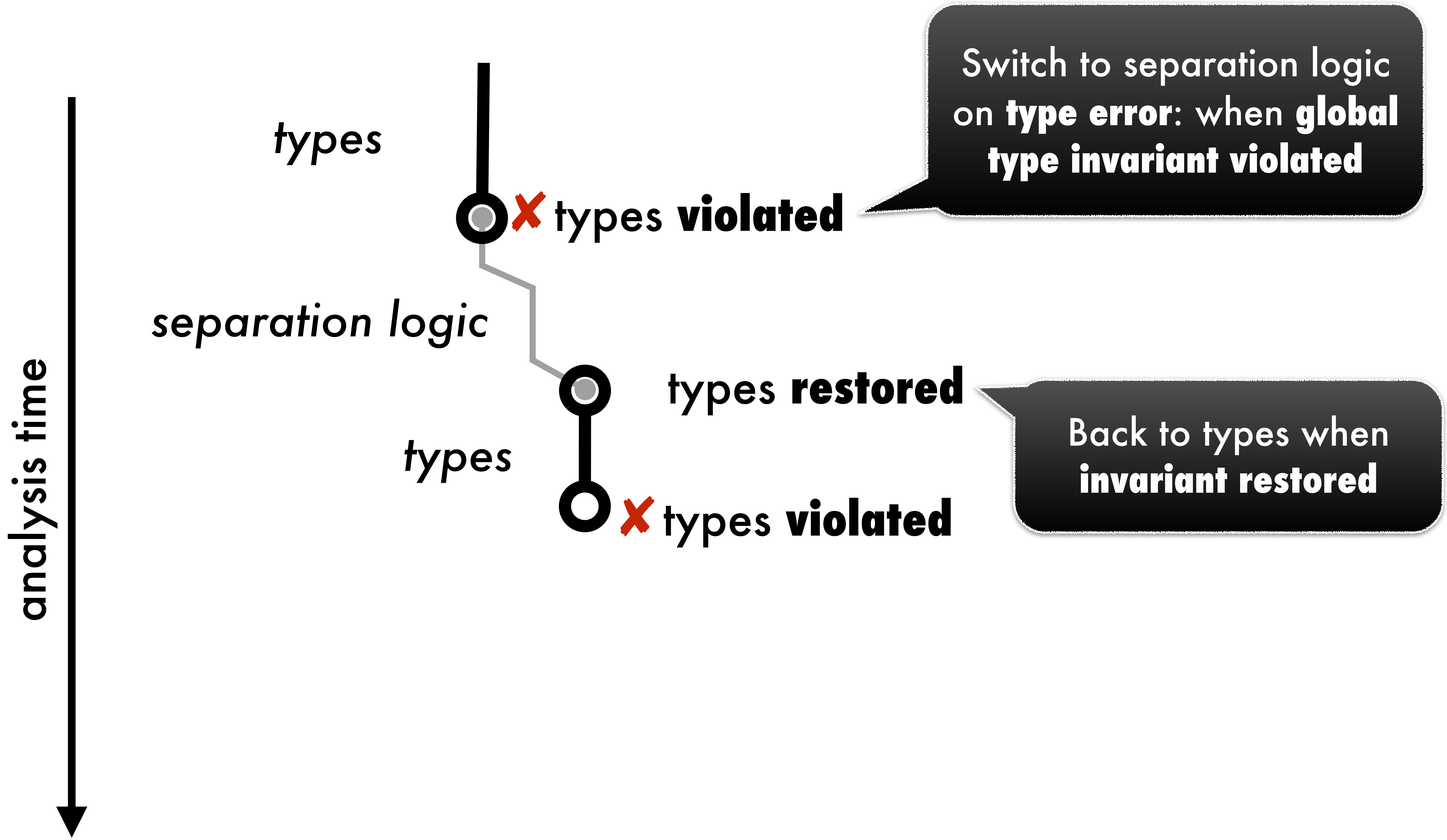

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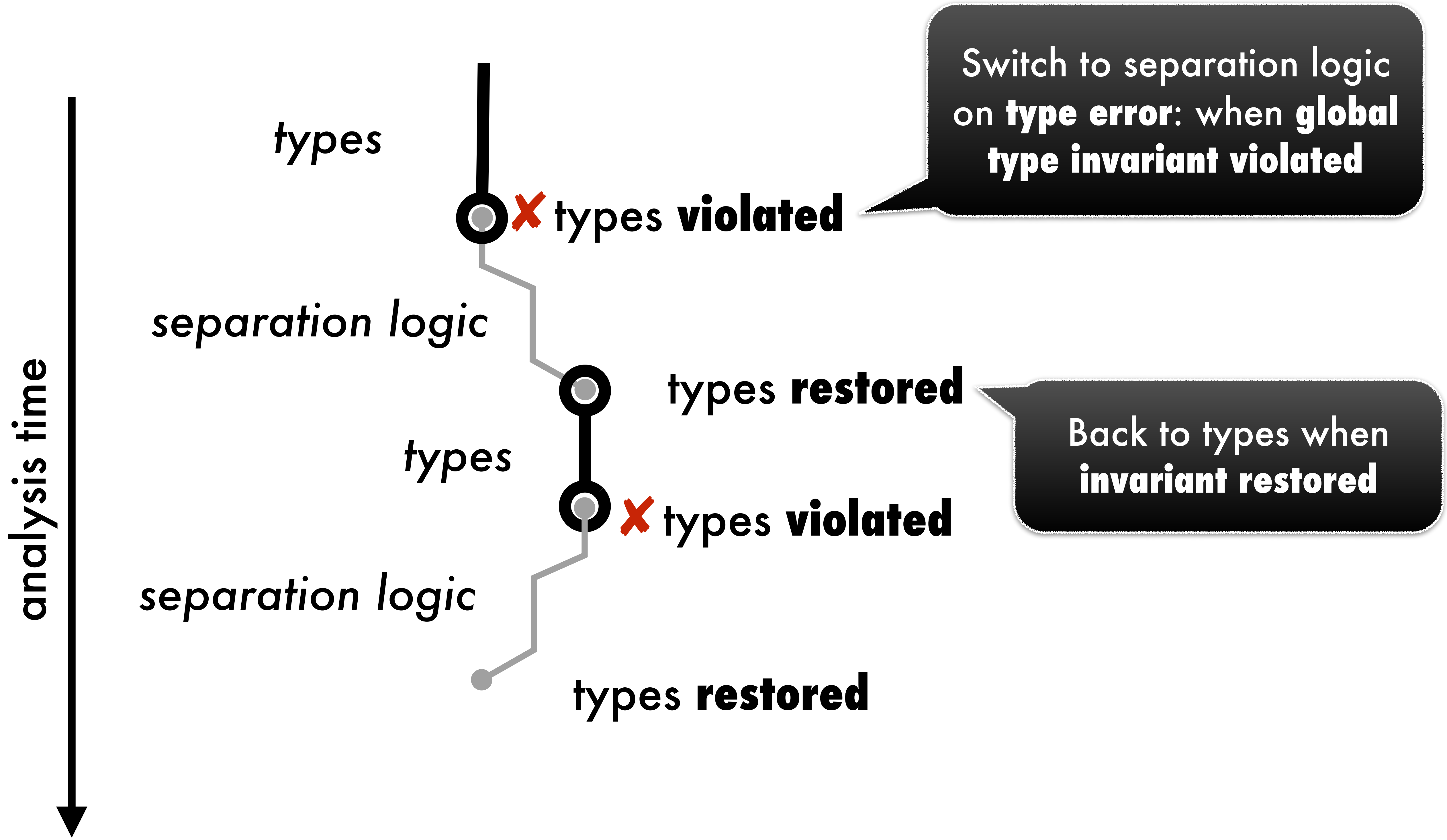

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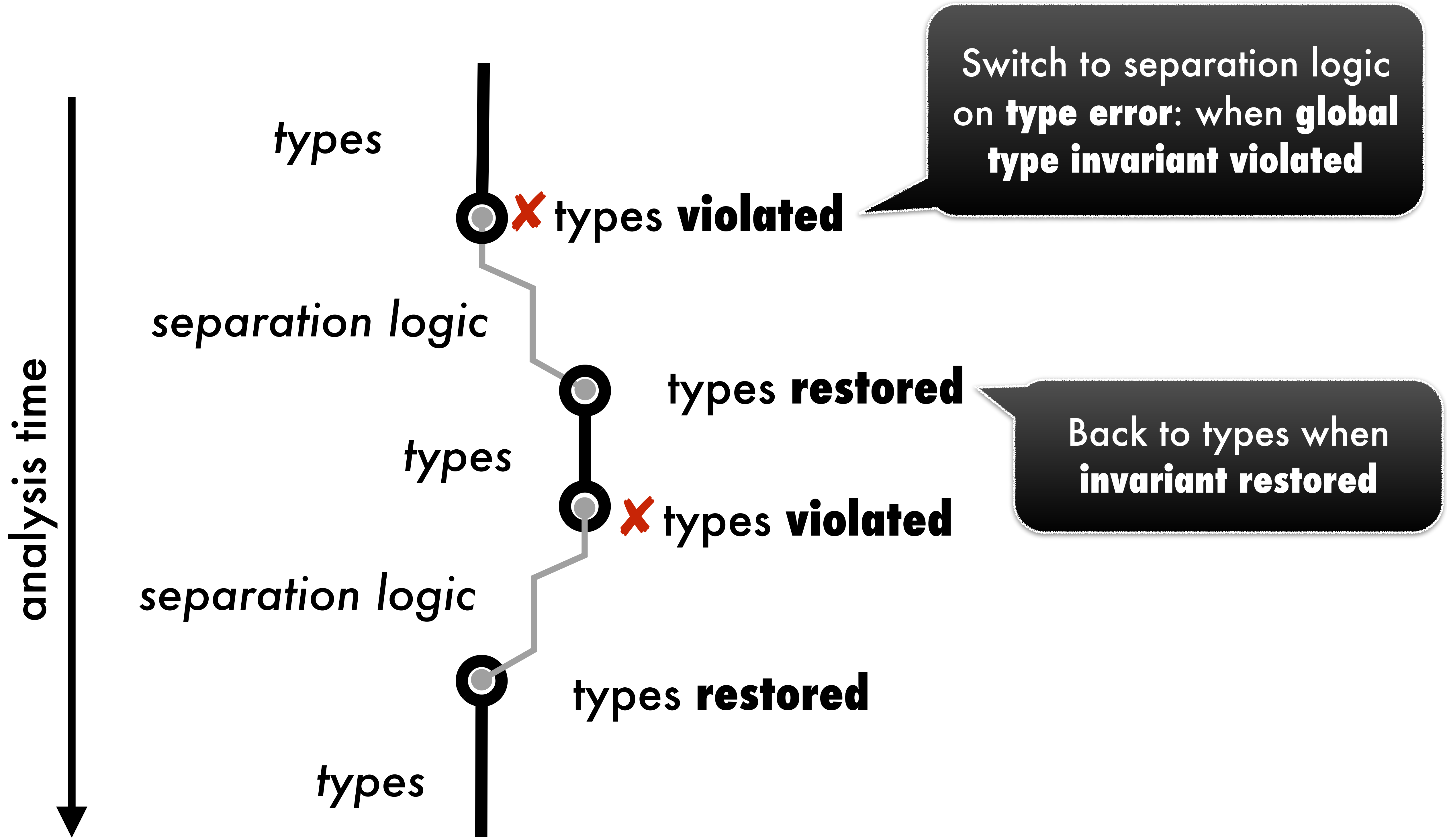

Key Ideas

ok Tolerating temporary violations with **almost type-consistent heaps**

Coughlin and Chang. *POPL* 2014.

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Type-intertwined framing with **gated separation**

Under preparation.

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Extend separation logic with a **summary** for an **almost type-consistent heap**

ok

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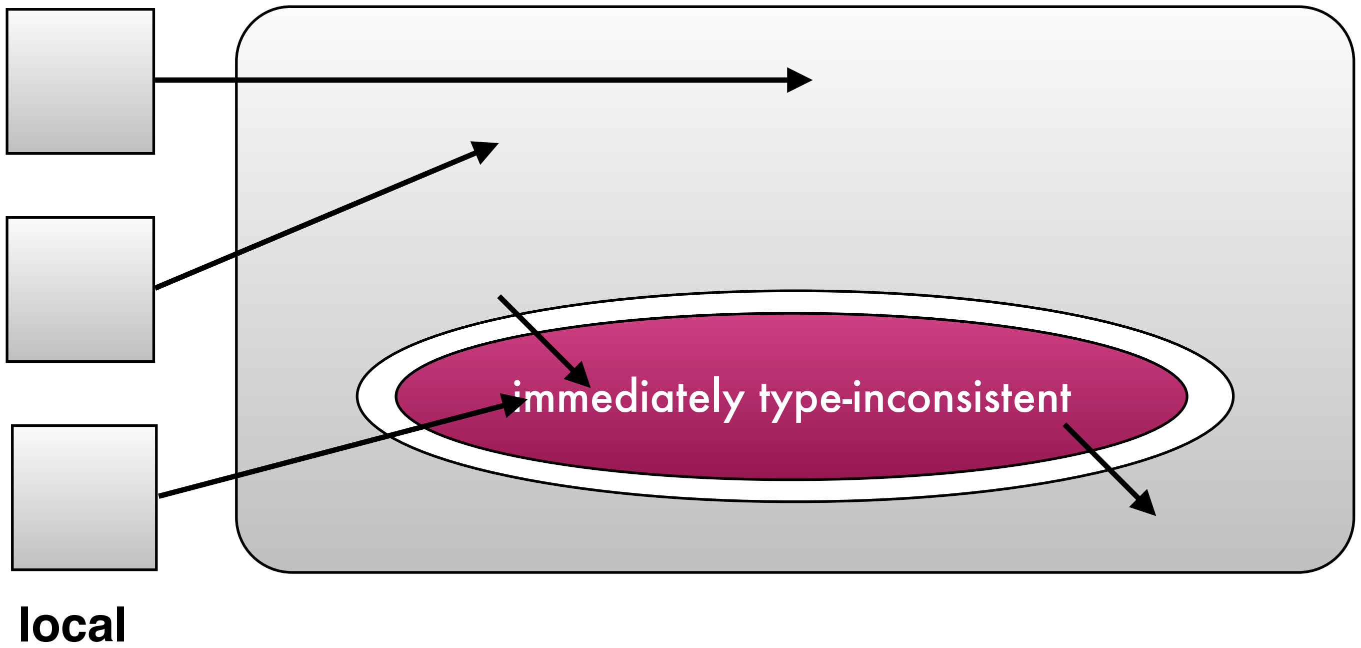
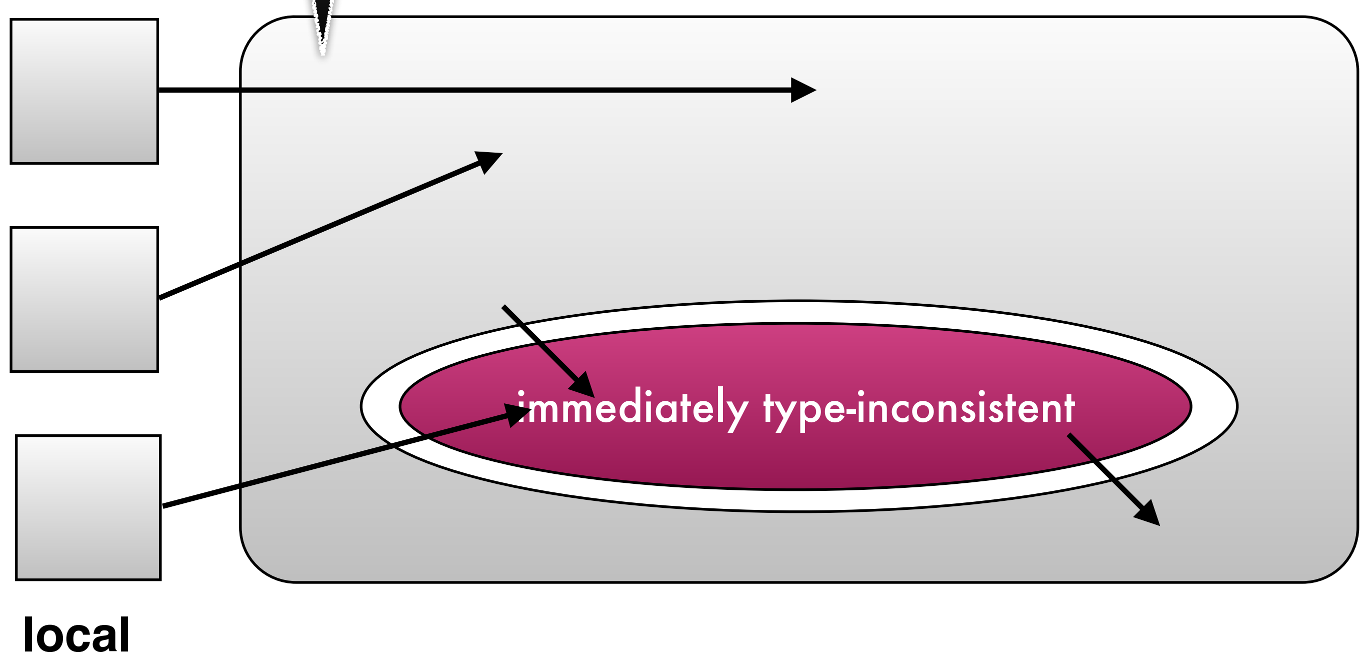


Extend separation logic with a **summary** for an **almost type-consistent heap**

ok

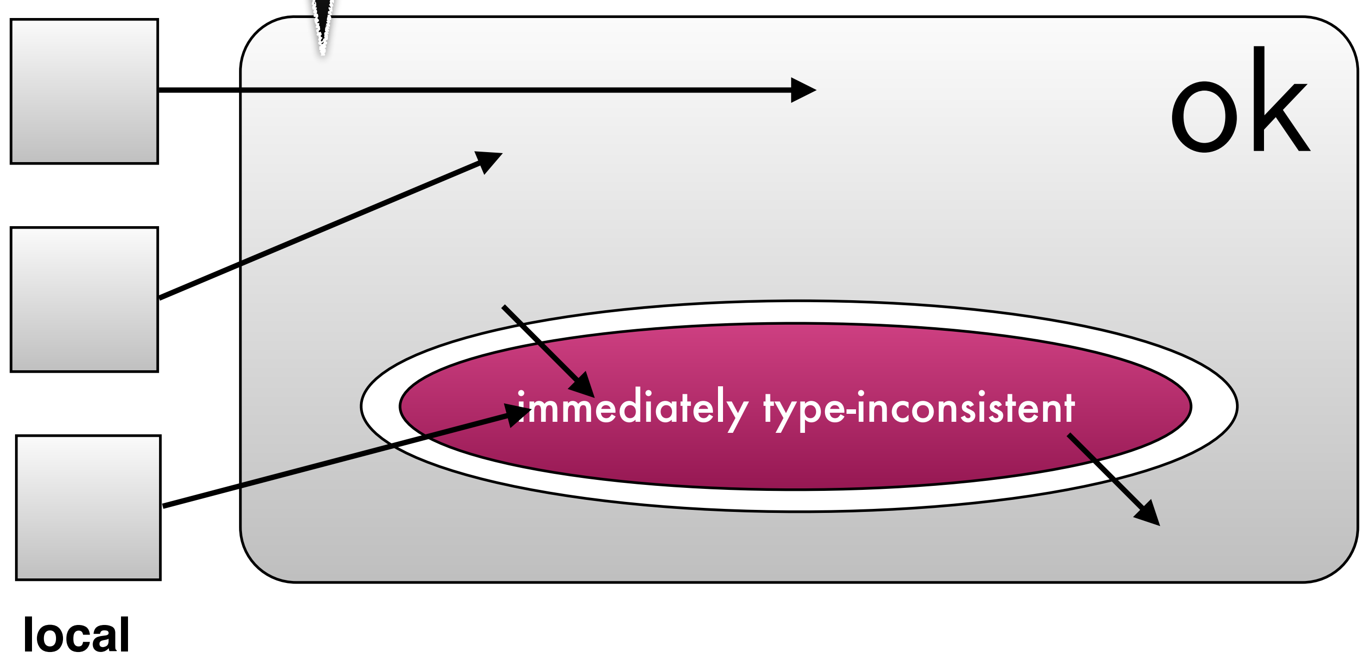
Summarize cells that are **not immediately type-inconsistent** into single formula literal



Extend separation logic with a **summary** for an **almost type-consistent heap**

ok

Summarize cells that are **not immediately type-inconsistent** into single formula literal



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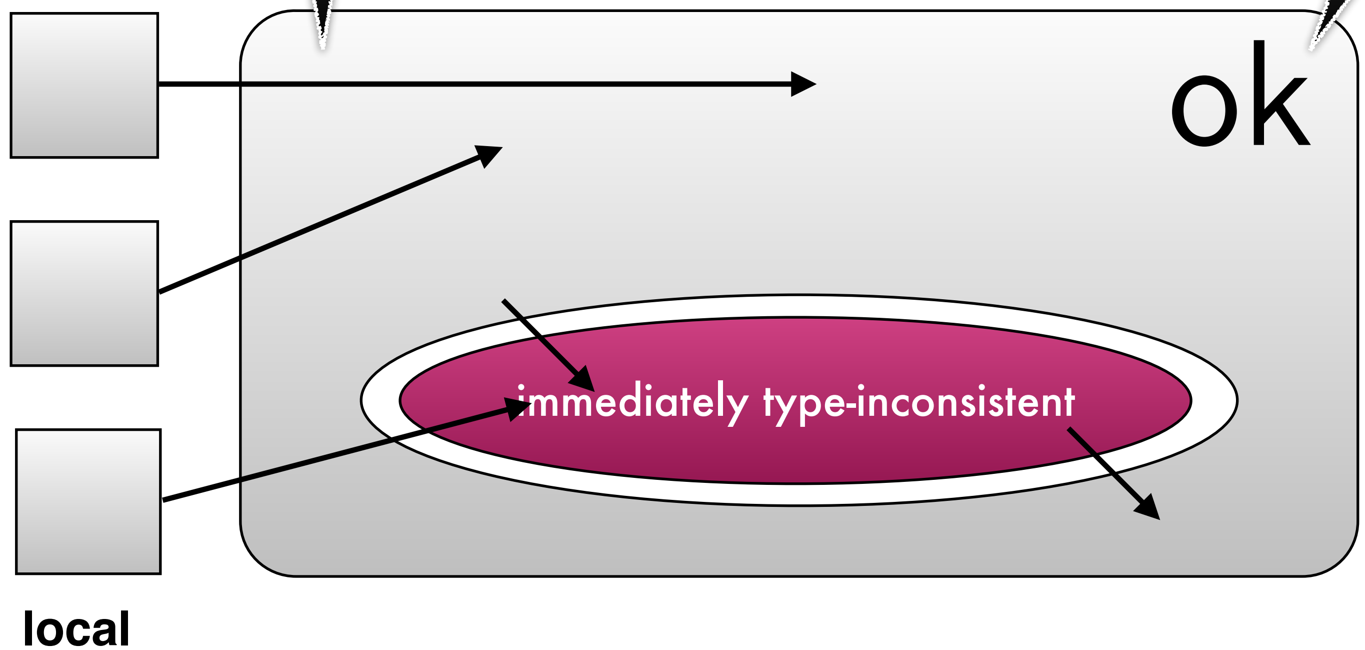
Describes storage **without** explicitly **enumerating** it



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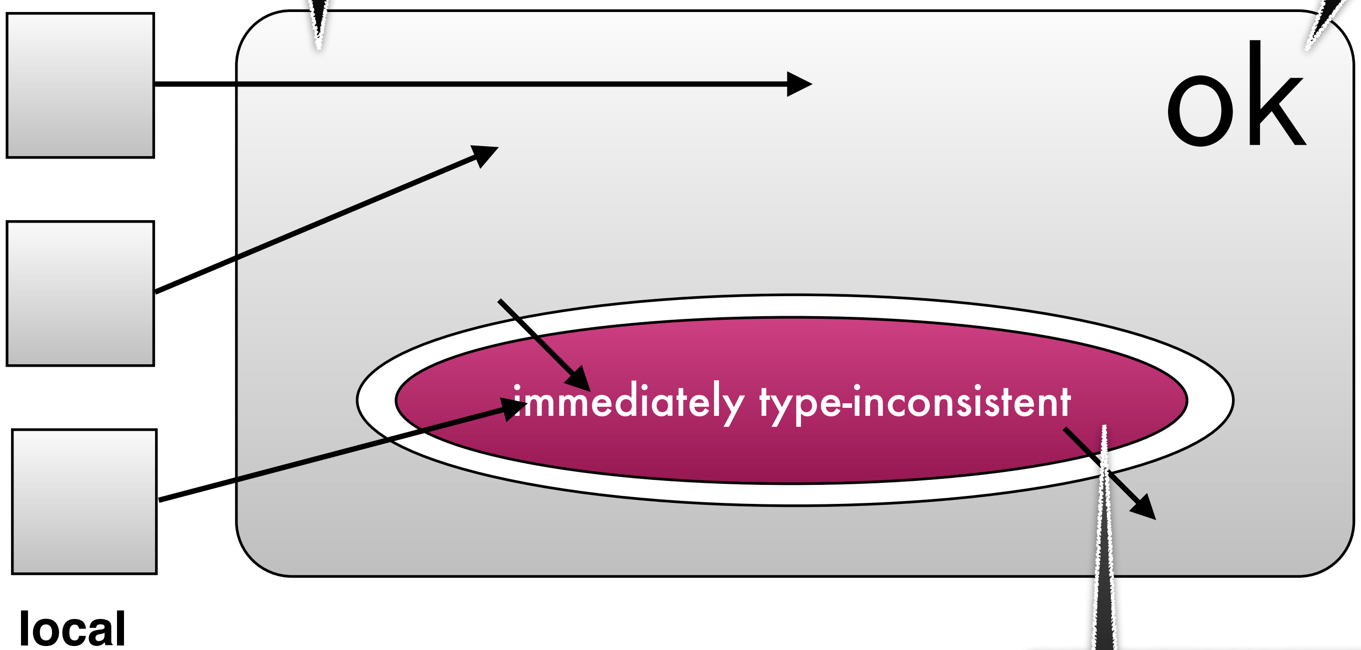

Value stored in location **differs from location's declared type**

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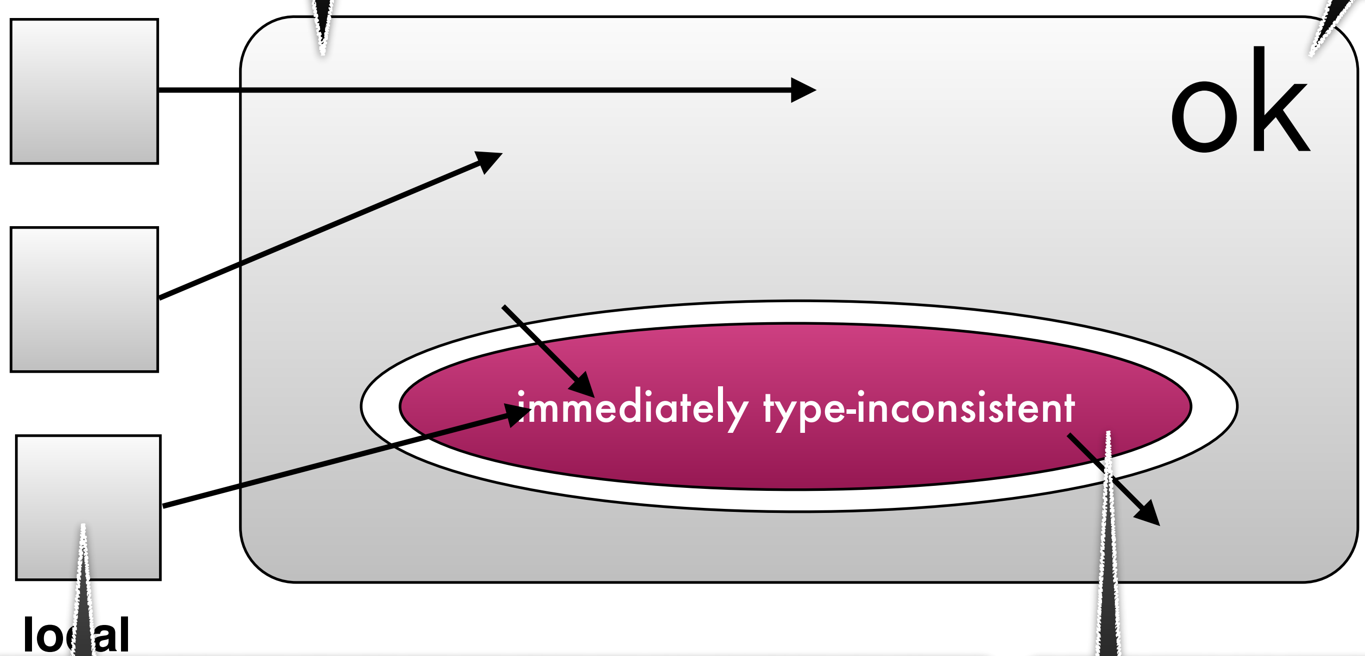

Not immediately type-inconsistent but still transitively type-inconsistent

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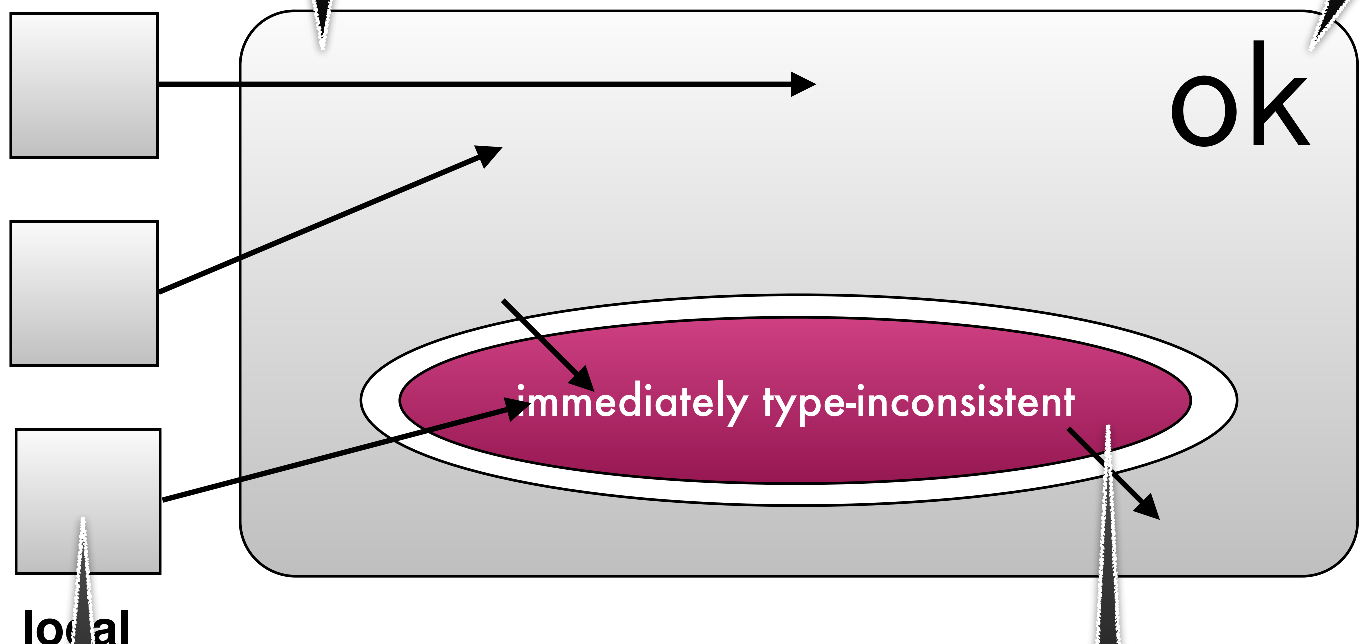

$$\mathsf{ok} \circledast \hat{a} \cdot f \mapsto \hat{v}$$

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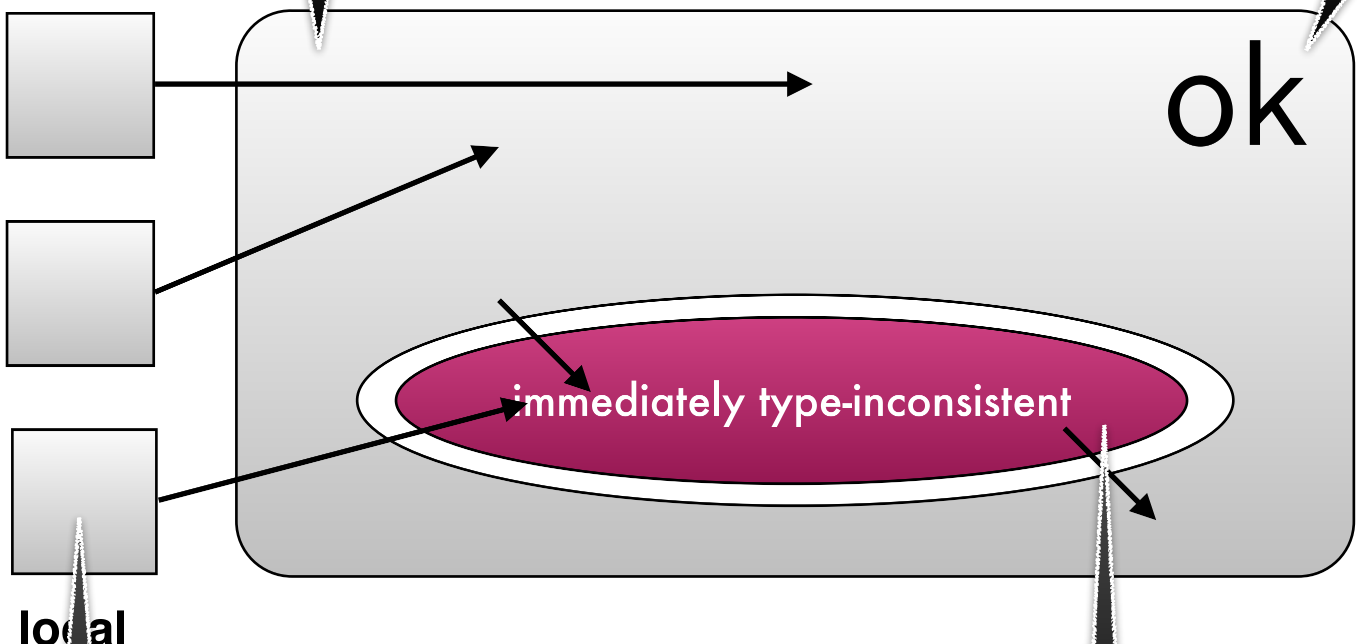

$$\mathsf{ok} * \hat{a}\cdot f \mapsto \hat{v}$$

Not immediately type-inconsistent but still transitively type-inconsistent

Value stored in location **differs from location's declared type**

Split heap into two regions: **almost type-consistent** and (potentially) **immediately type-inconsistent**

Separation logic can **materialize** from the almost type-consistent summary

```
def update(s: Str, o: Obj | r2 s)
  this.sel = s
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```

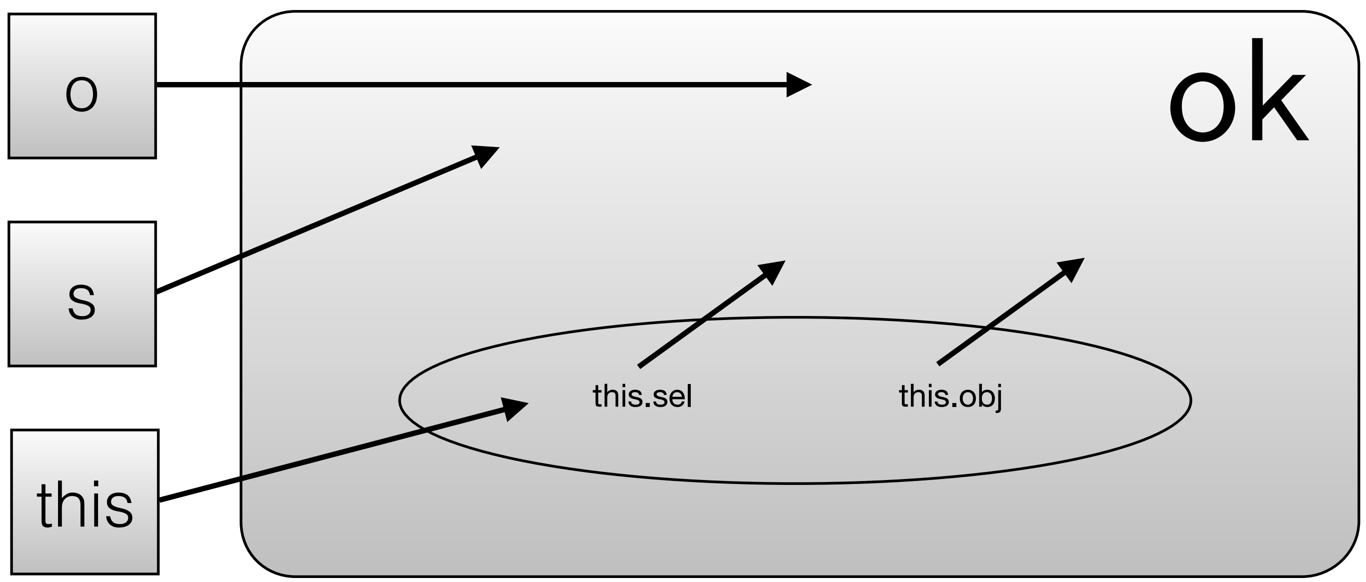

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Handoff to separation logic on type error, **heap** is **consistent** with declared types

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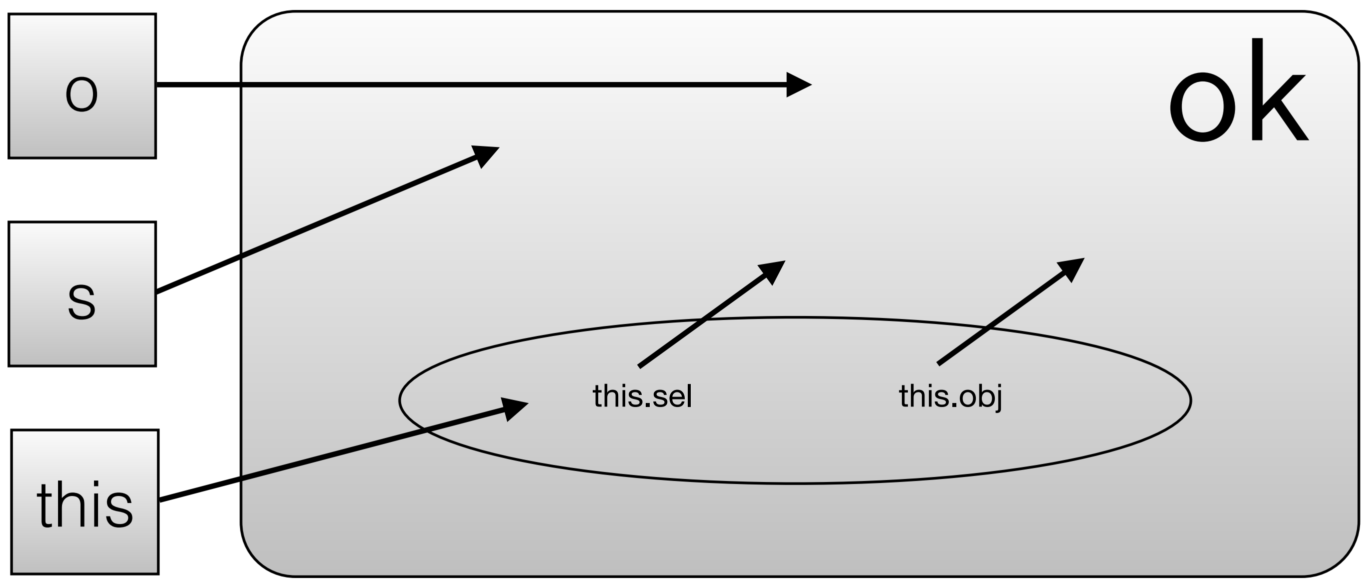

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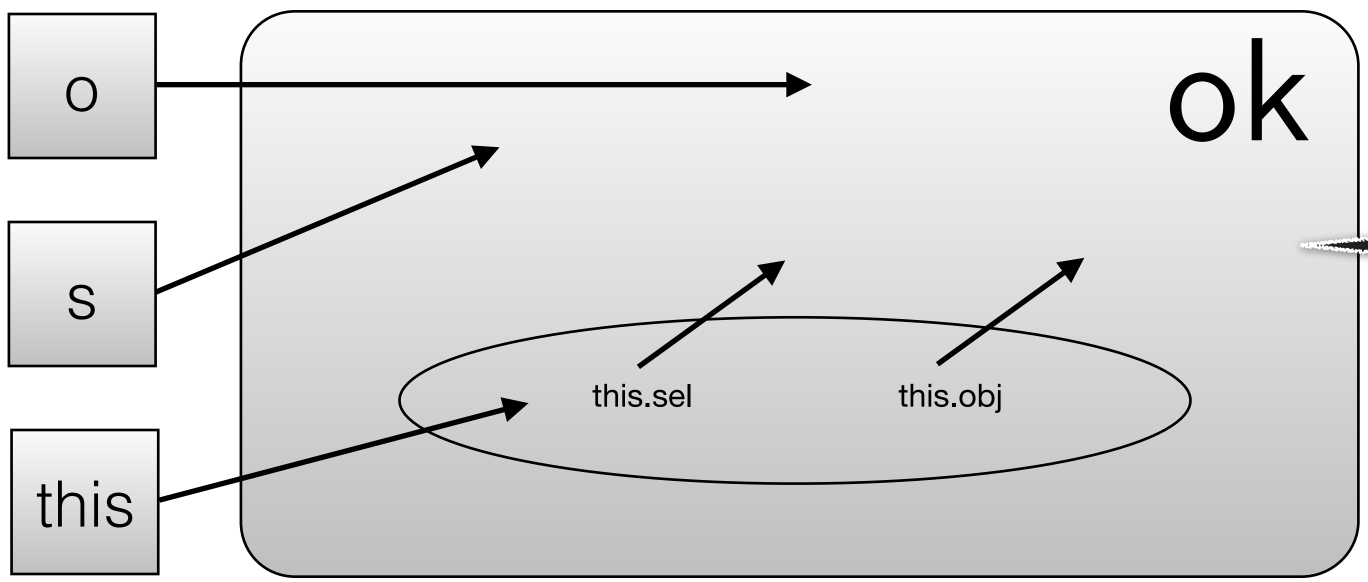

Entire heap consists of the almost type-consistent summary

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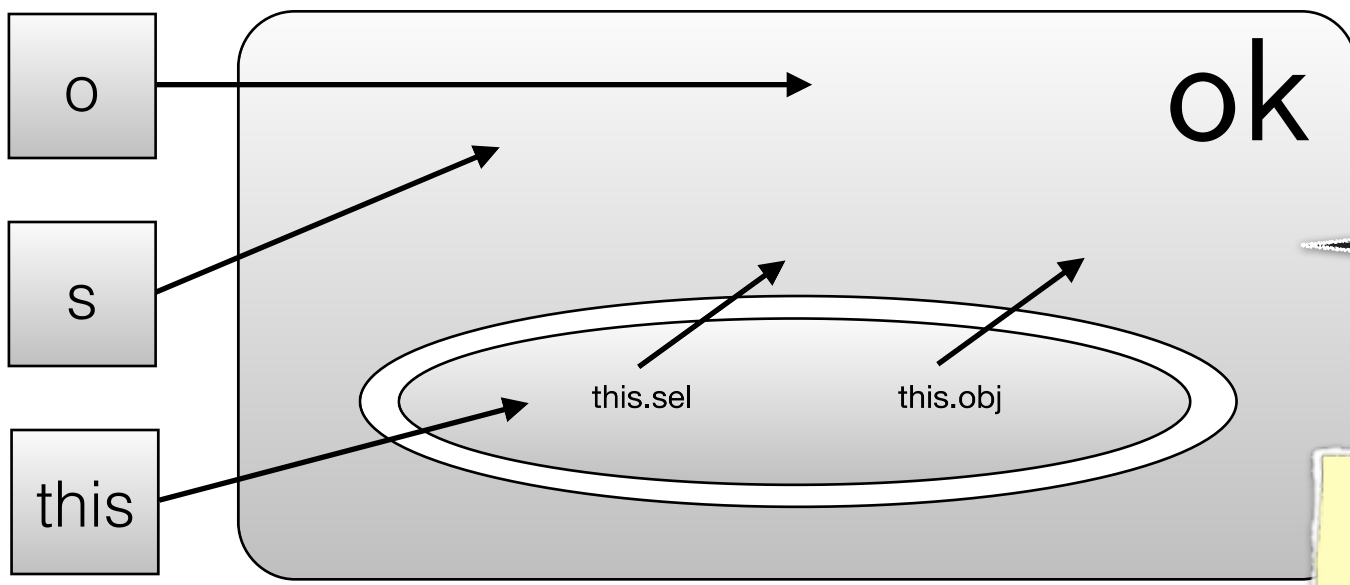

Entire heap consists of the almost type-consistent summary

materialize
`this.sel`
`this.obj`

Separation logic can **materialize** from the almost type-consistent summary

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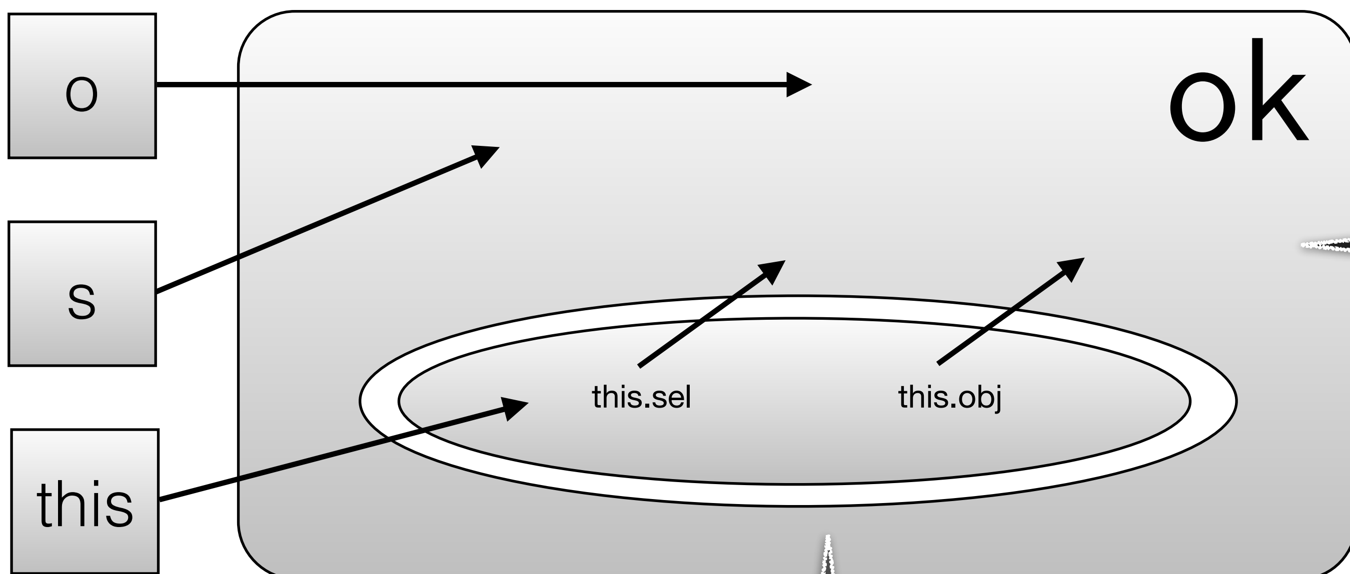

Entire heap consists of the almost type-consistent summary

Analysis reasons explicitly about contents of materialized cells

Values in **materialized** storage allowed to **differ from declared types**

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def update(s: Str, o: Obj | r2 s)
  this.sel = s
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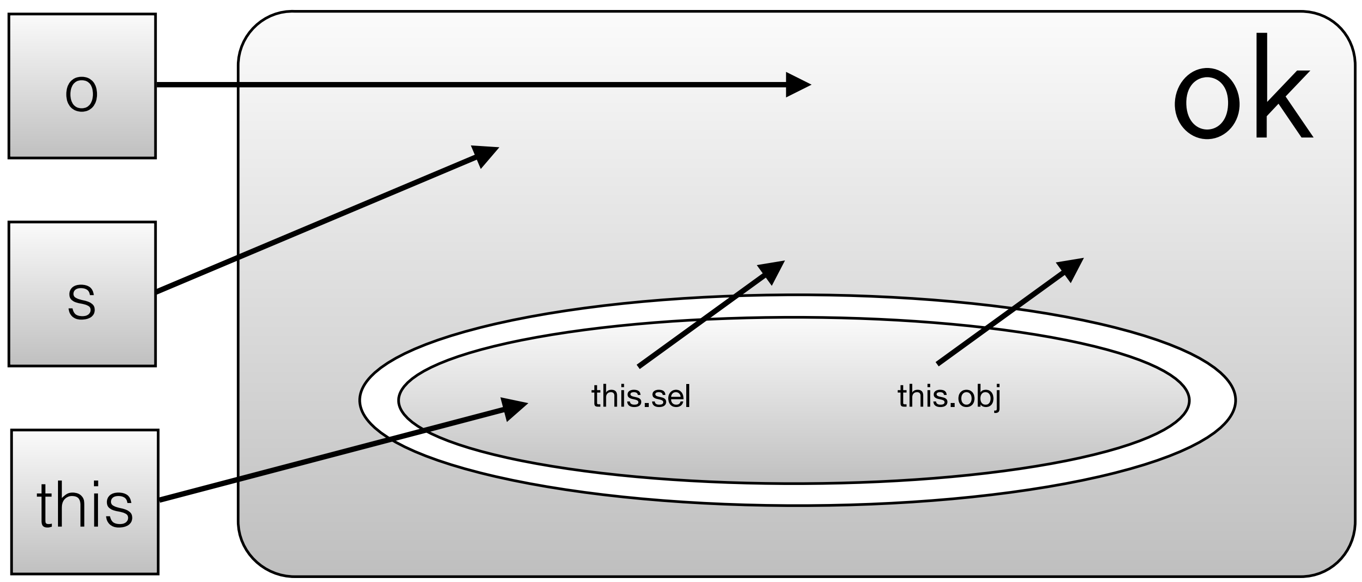

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Analysis performs **strong updates** on materialized cells

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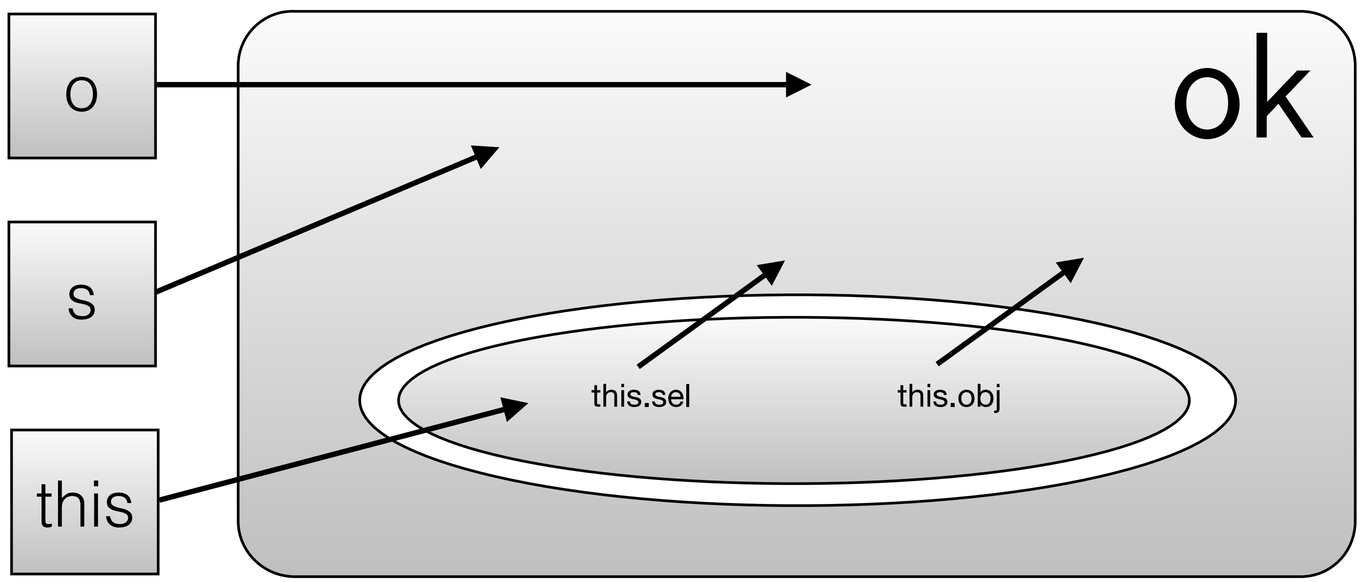

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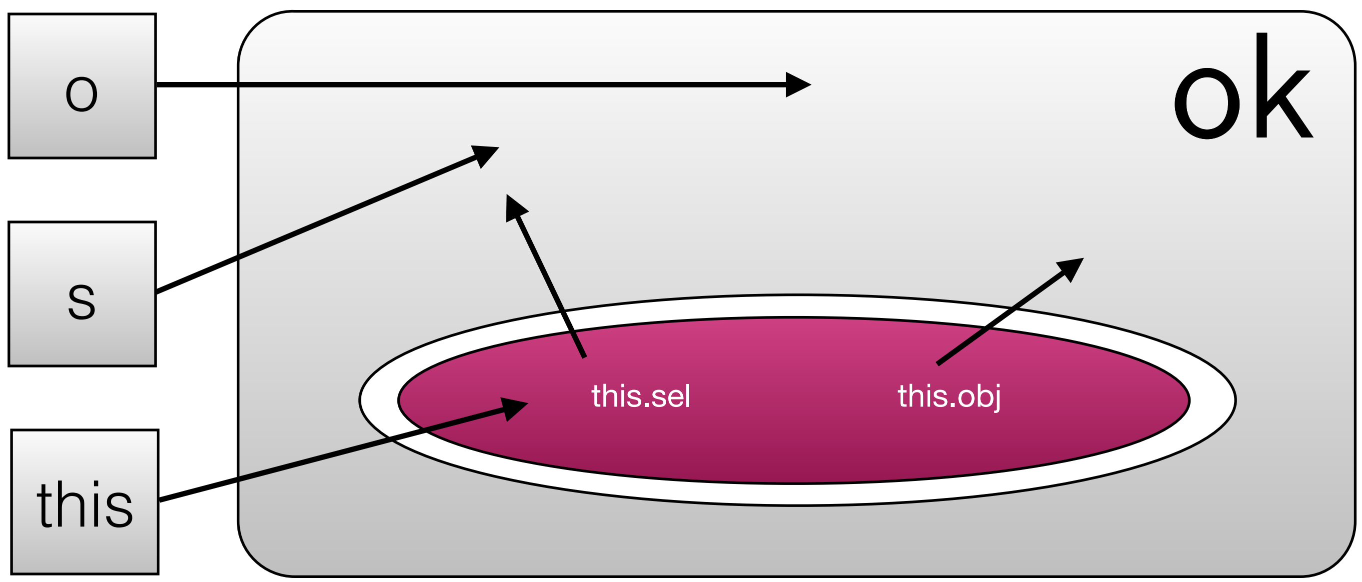

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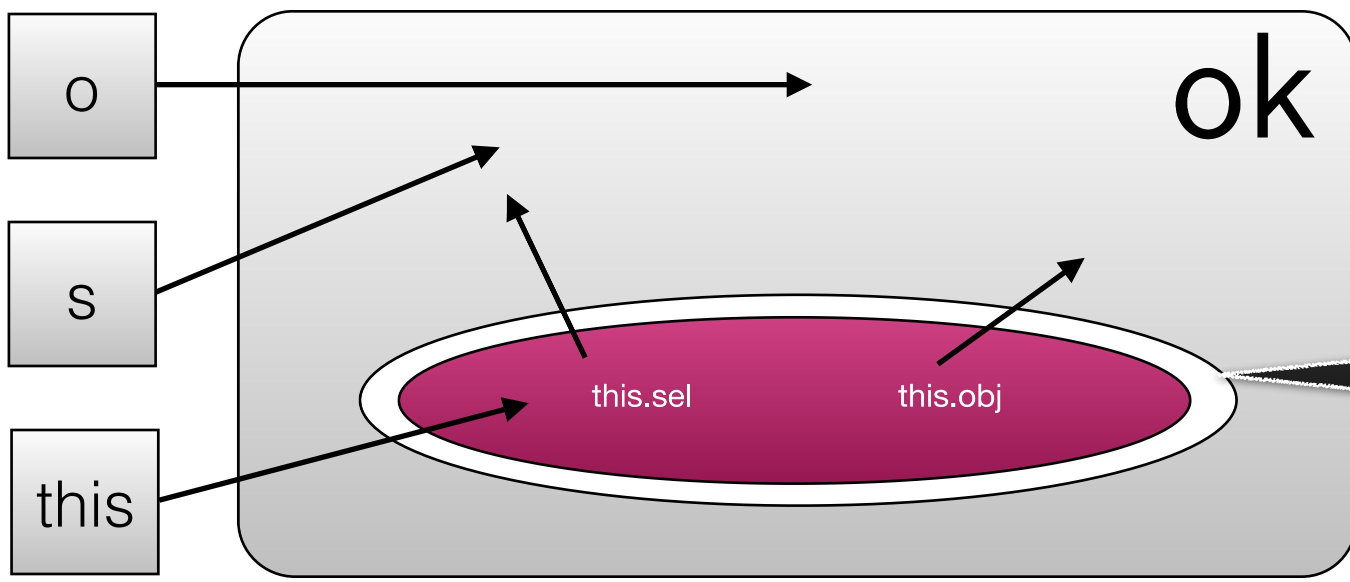

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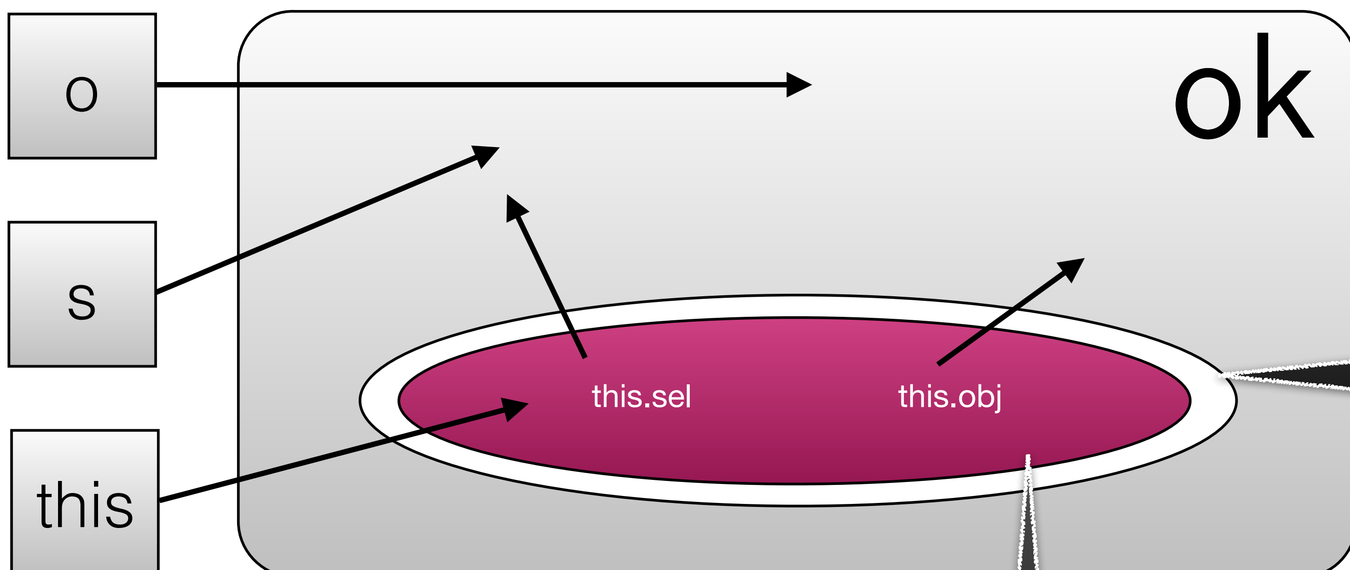

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`this.obj` does not respond to `this.sel`

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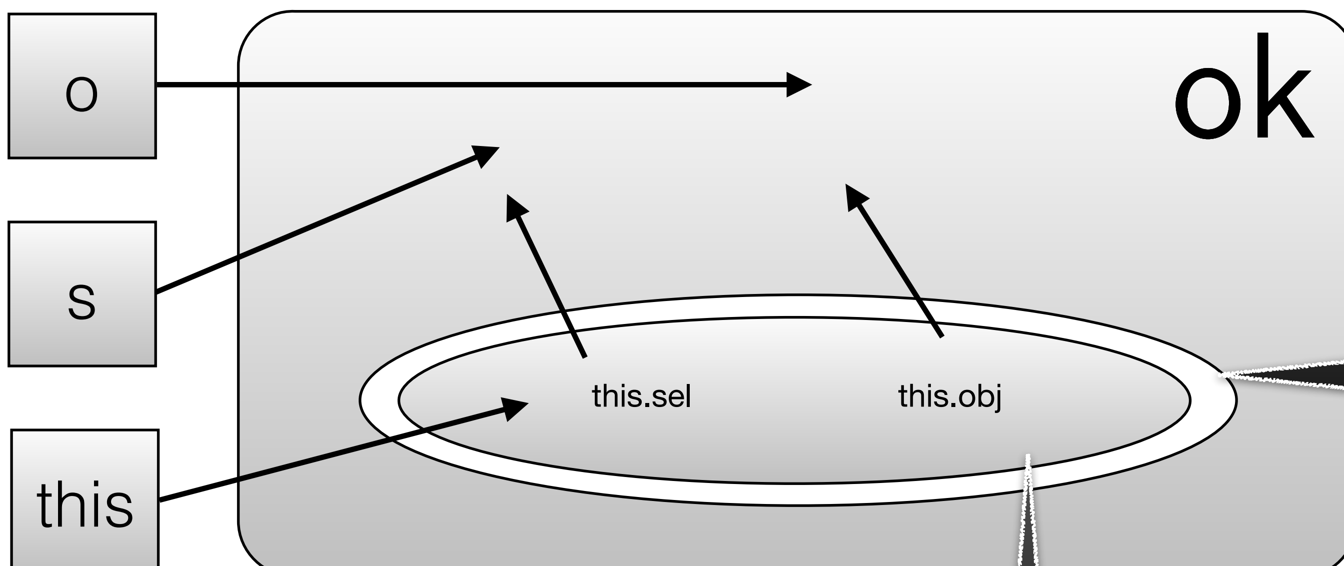

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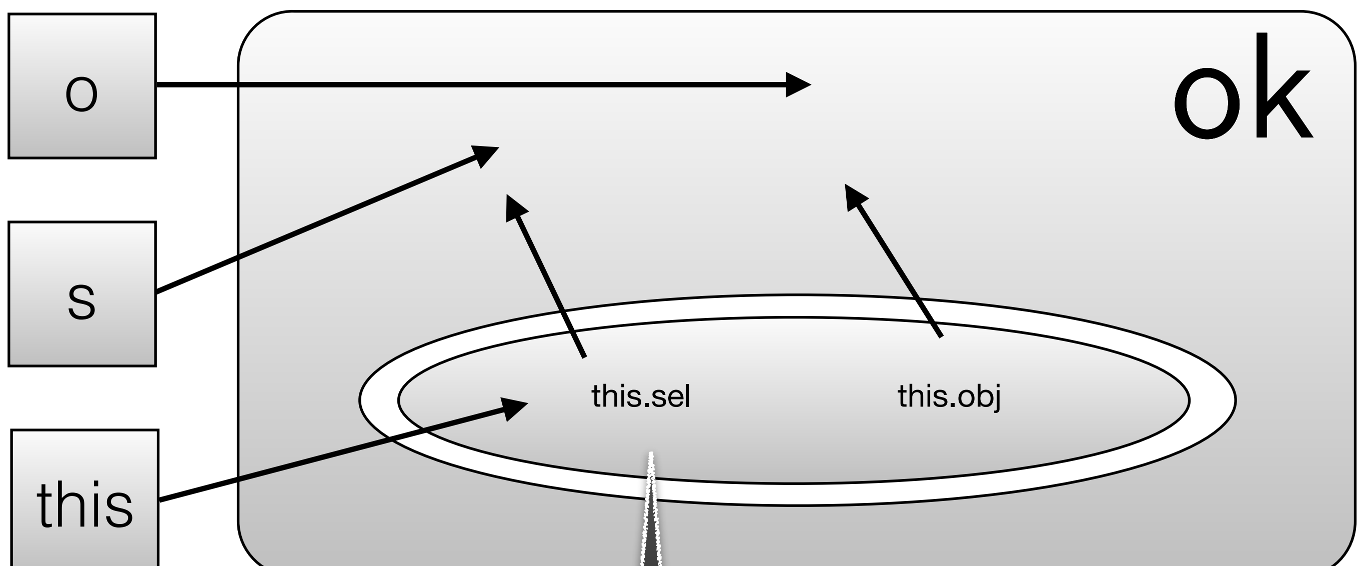

After second update, storage is **no longer immediately type-inconsistent** again

Can **summarize** not immediately type-inconsistent locations back into the almost type-consistent heap

```
def update(s: Str, o: Obj | r2 s)
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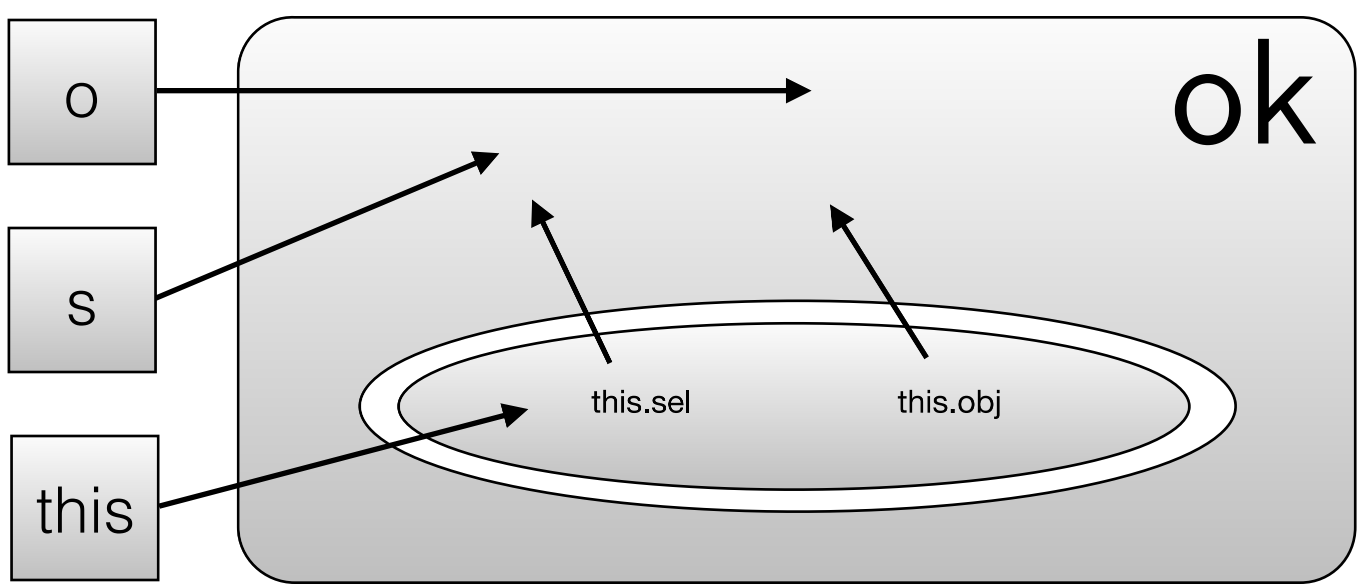

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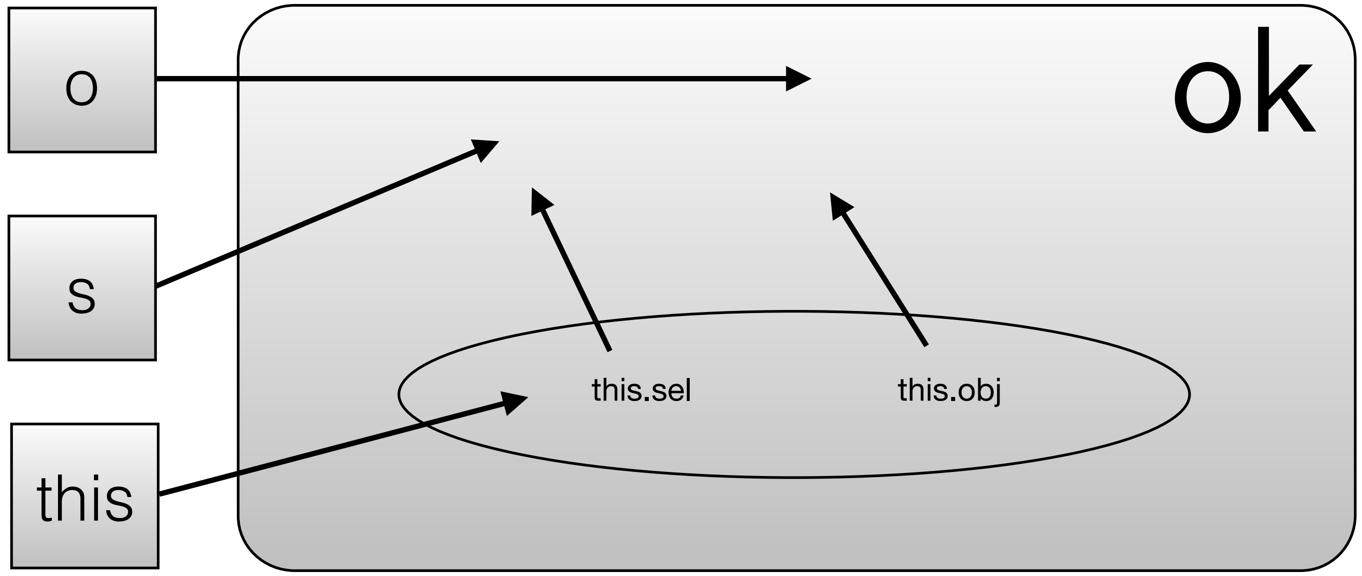

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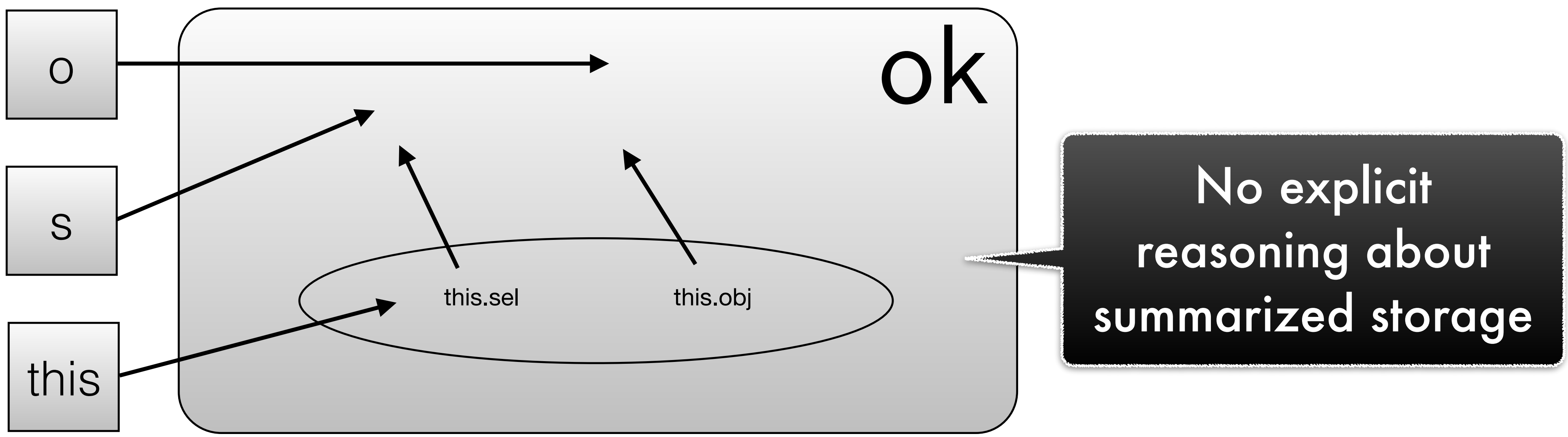

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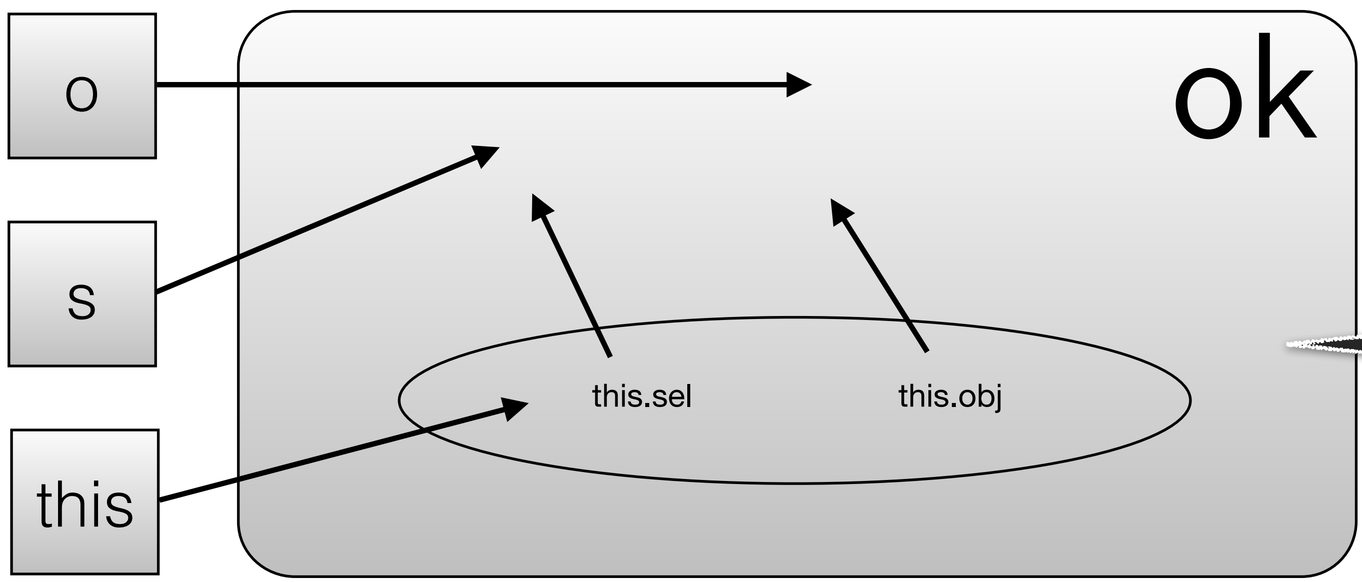

No explicit reasoning about summarized storage

If **entire heap** does **not** have immediately type-inconsistent locations then the heap is type-consistent

Can **summarize** not immediately type-inconsistent locations back into the almost type-consistent heap

Safe to **return to type checking**

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def update(s: Str, o: Obj | r2 s)
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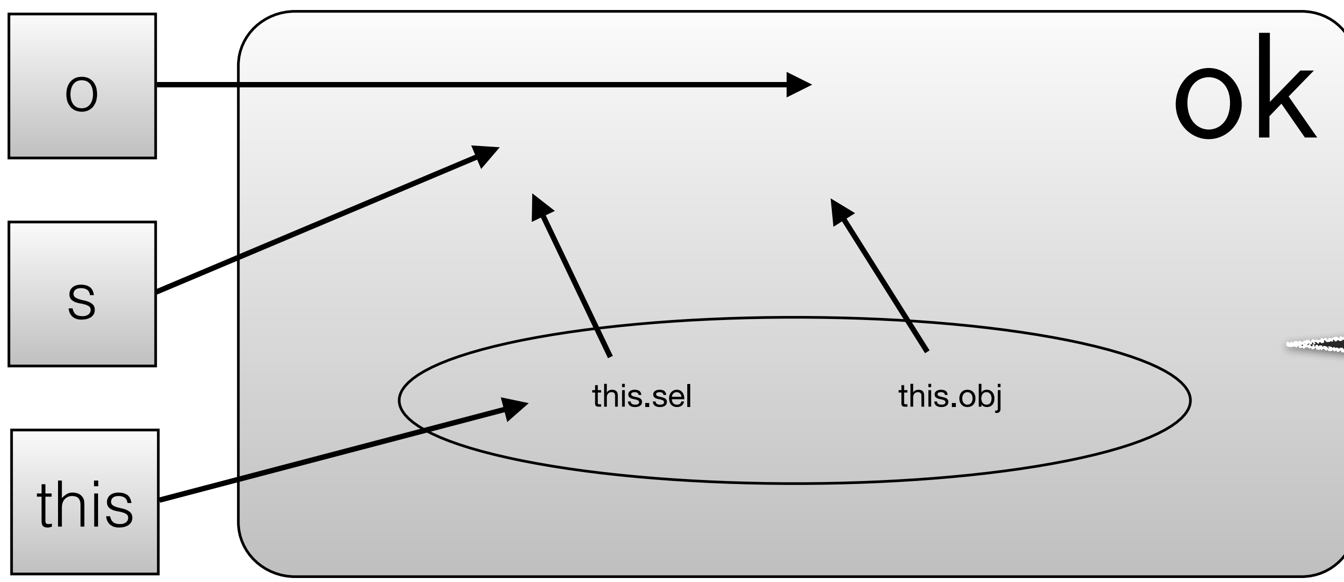

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[Fissile Types, *POPL* 2014]

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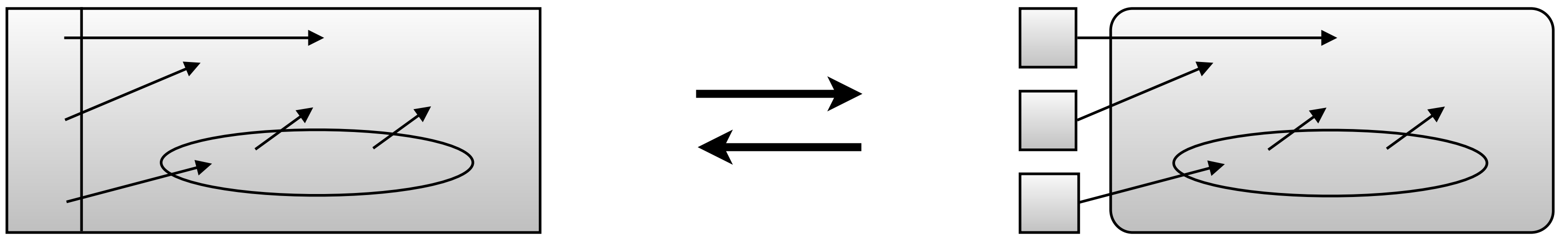
Theorem (*Soundness of Handoff*).

The entire state is **type-consistent** *iff* all locations are **not immediately type-inconsistent**.



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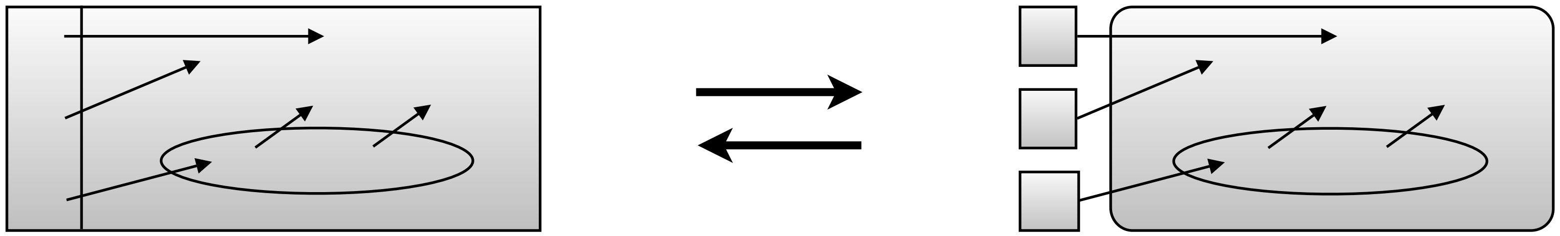
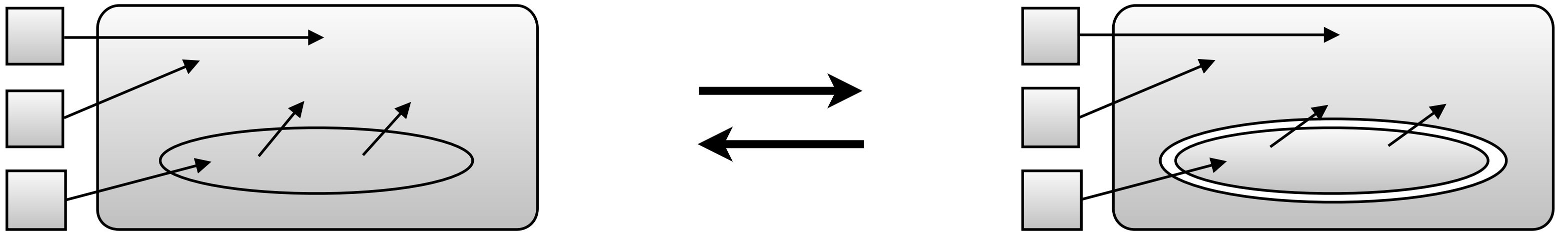


Theorem (*Soundness of Materialization/Summarization*).

Locations that are **not immediately type-inconsistent** can be safely *materialized* and *summarized* into the almost type-consistent heap **ok**.



Case Study: Reflection in Objective-C

Prototype analysis implementation

- Plugin for clang static analyzer in C++

9 Objective-C benchmarks

- 6 libraries and 3 applications
- 1,000 to 176,000 lines of code

Manual type annotations

- 76 r2 annotations on system libraries
- 136 annotations on benchmark code

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Why Objective-C?
Statically typed plus reflective method call

Prototype analysis implementation

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1,000 to 176,000 lines of code

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Empirical Evaluation Questions

Precision: What is improvement over **flow-insensitive checking** alone?

Cost: What is the cost of analysis in **running time**?

Precision

	size		false alarms	
benchmark	**(loc)**	**reflective call sites**	**flow-insensitive**	**almost-everywhere**
OAuth	1248	7	7	2 (-71%)
SCRecorder	2716	12	2	0 (-100%)
ZipKit	3301	28	0	0 (-)
Sparkle	5289	40	4	1 (-75%)
ASIHTTPRequest	14620	68	50	10 (-80%)
OmniFrameworks	160769	192	82	74 (-10%)
Vienna	37327	186	59	38 (-36%)
Skim	60211	207	43	43 (-0%)
Adium	176629	587	87	70 (-20%)
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Baseline: standard, **flow-insensitive** type analysis – no switching

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Almost everywhere techniques show 29% improvement in false alarms

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Also found a **real reflection bug** in Vienna, which we reported and which was fixed

Baseline: standard, **flow-insensitive** type analysis – no sw

Almost everywhere techniques show 29% improvement in false alarms

Cost: Analysis **Time**

	size	analysis time	
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Includes analysis time but **not parsing, base type checking**

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Does **not** include **system headers**

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Interactive speeds

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Higher rate for projects with **larger translation units**

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Fast: 5 to 38 kloc/s with most time spent **analyzing** sy

H **units**

Maintains key benefit of flow-insensitive analyses: **speed**

Key Ideas

ok Tolerating temporary violations with **almost type-consistent heaps**

Coughlin and Chang. *POPL* 2014.

Type-intertwined framing with **gated separation**

Under preparation.

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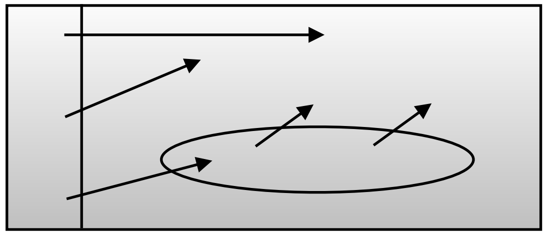

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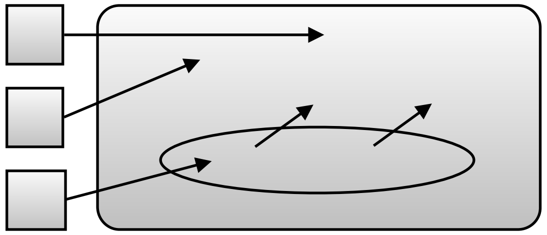
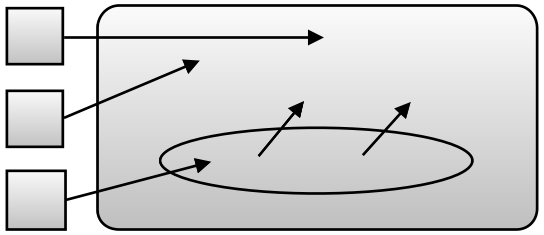


Theorem (*Soundness of Materialization/Summarization*).

Locations that are **not immediately type-inconsistent** can be safely *materialized* and *summarized* into the almost type-consistent heap **ok**.



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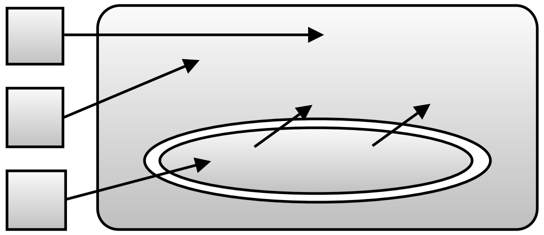

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[Fissile Types, *POPL* 2014]

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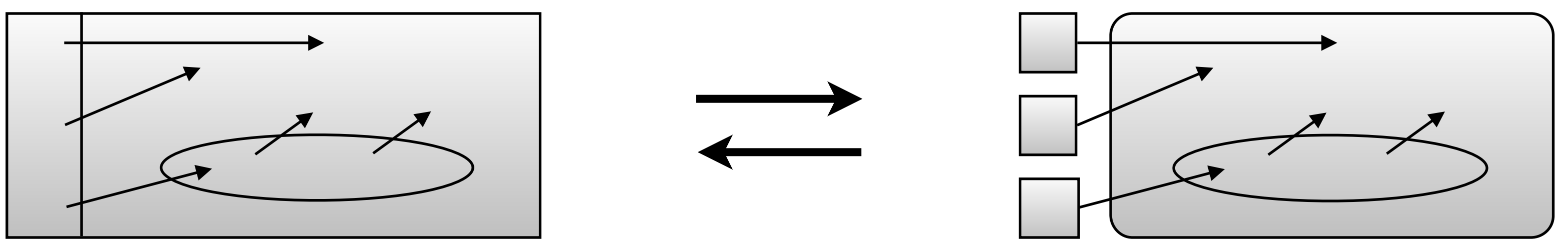

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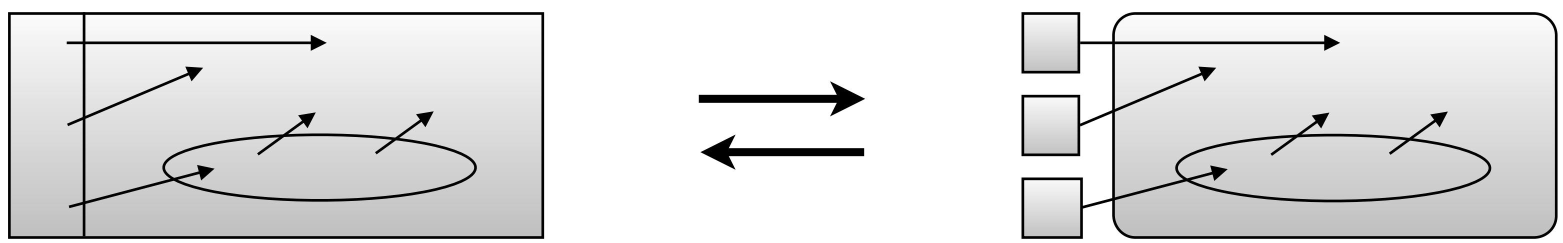

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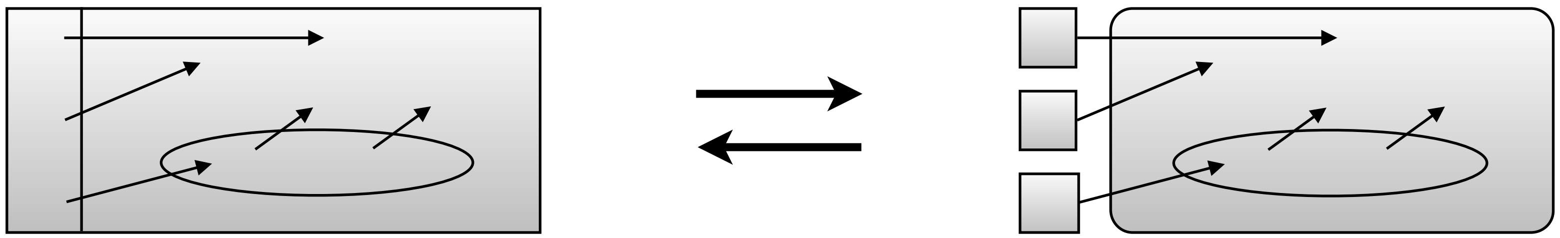

Theor

Locatio

materi

No way to **frame** and then handoff to types

Type-intertwined frame rule with standard separating conjunction is **unsound**

```
def badUpdate(s: Str, o: Obj | r2 s)
  this.sel = s
  this.call()
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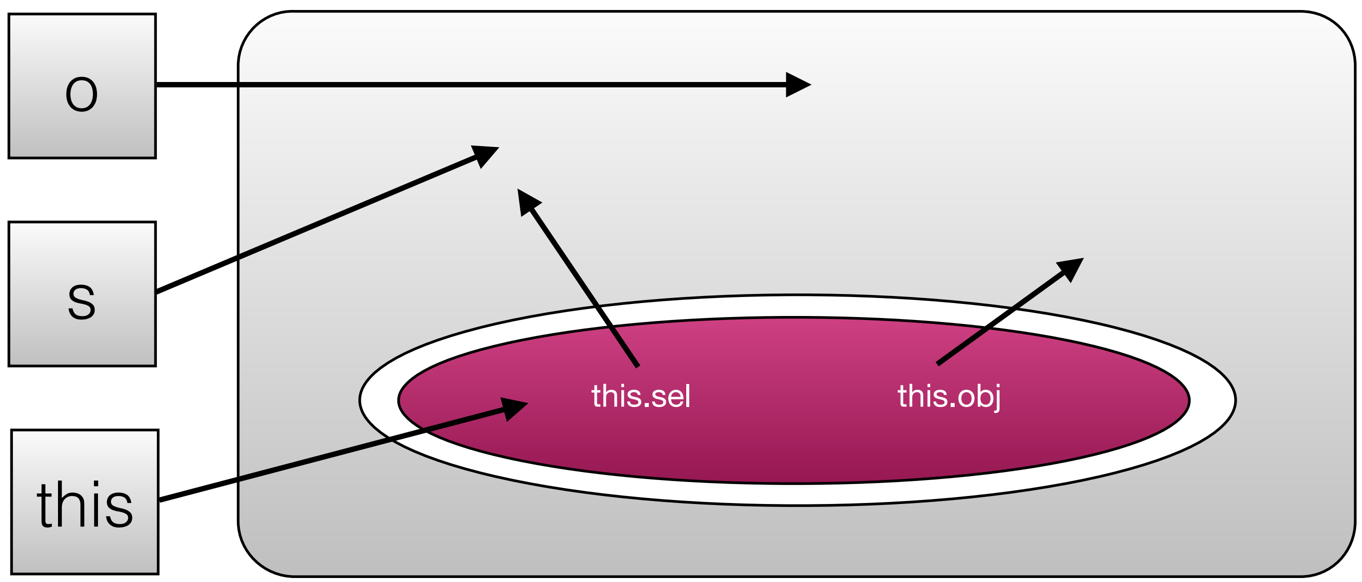
```



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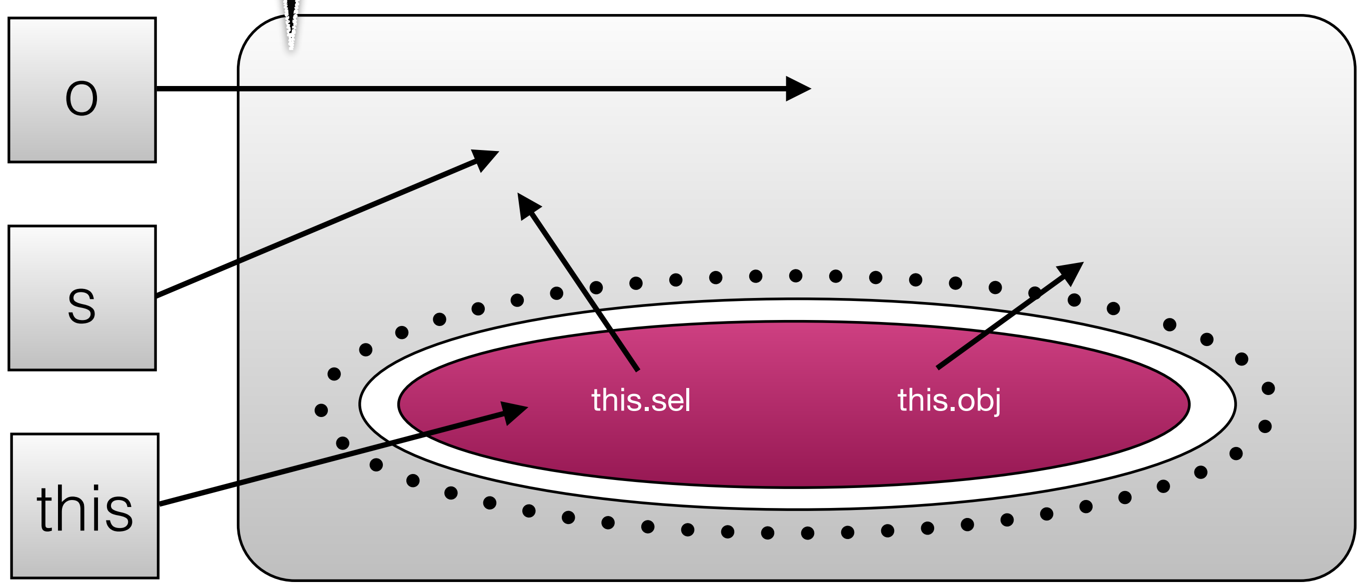

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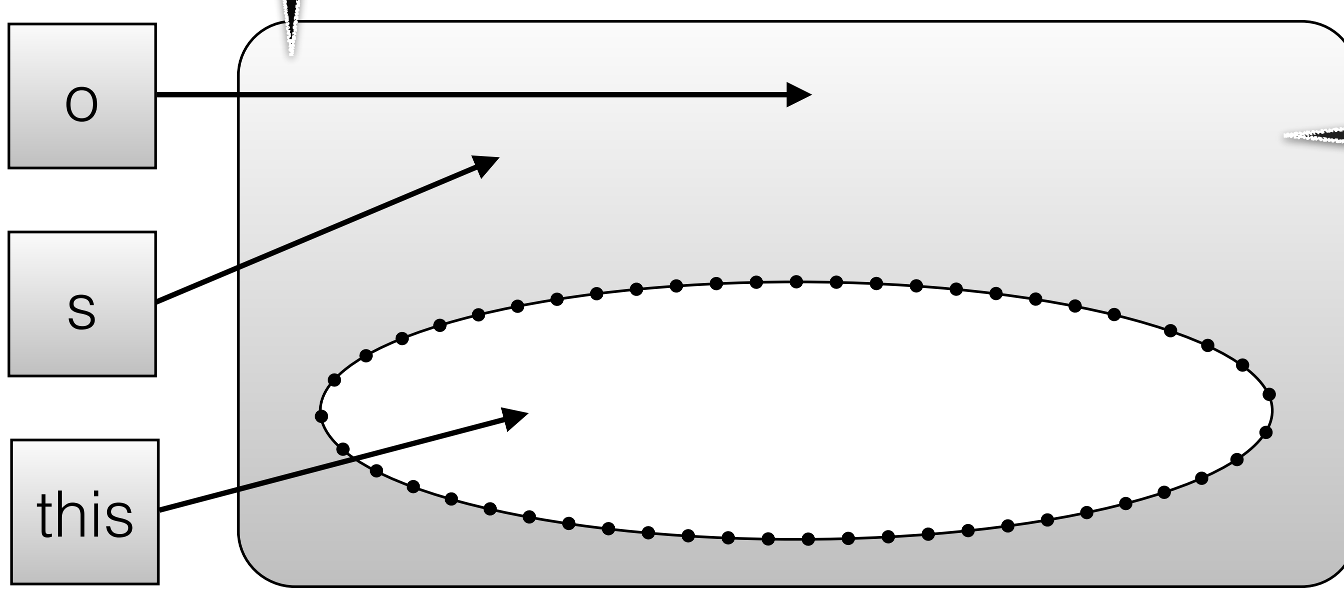

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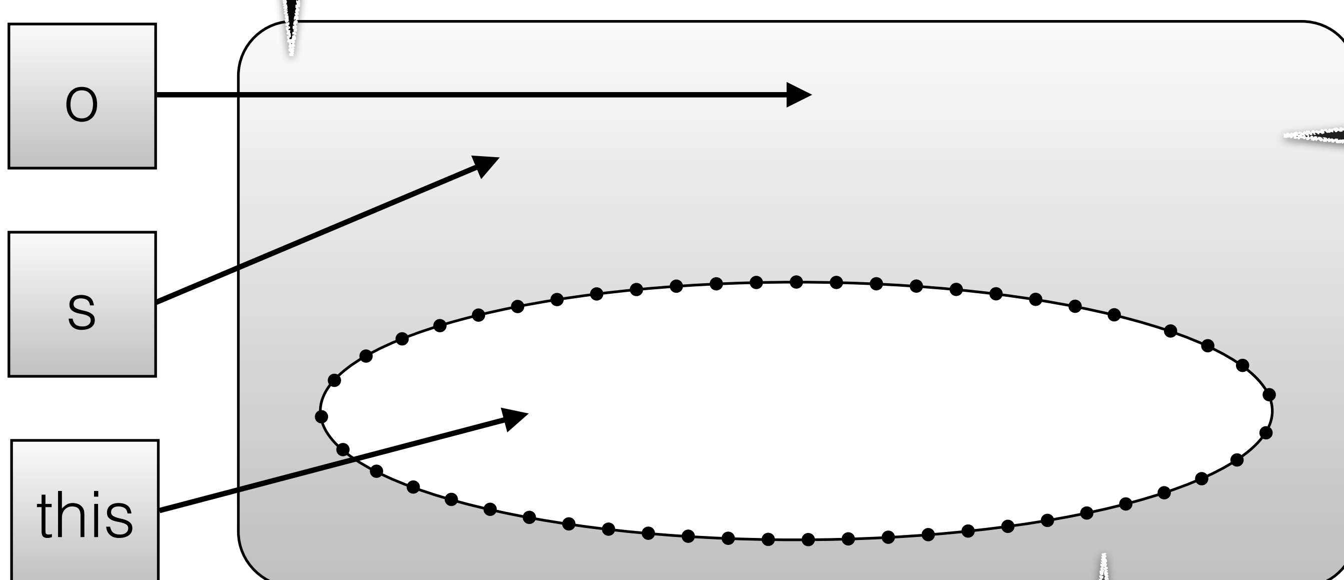

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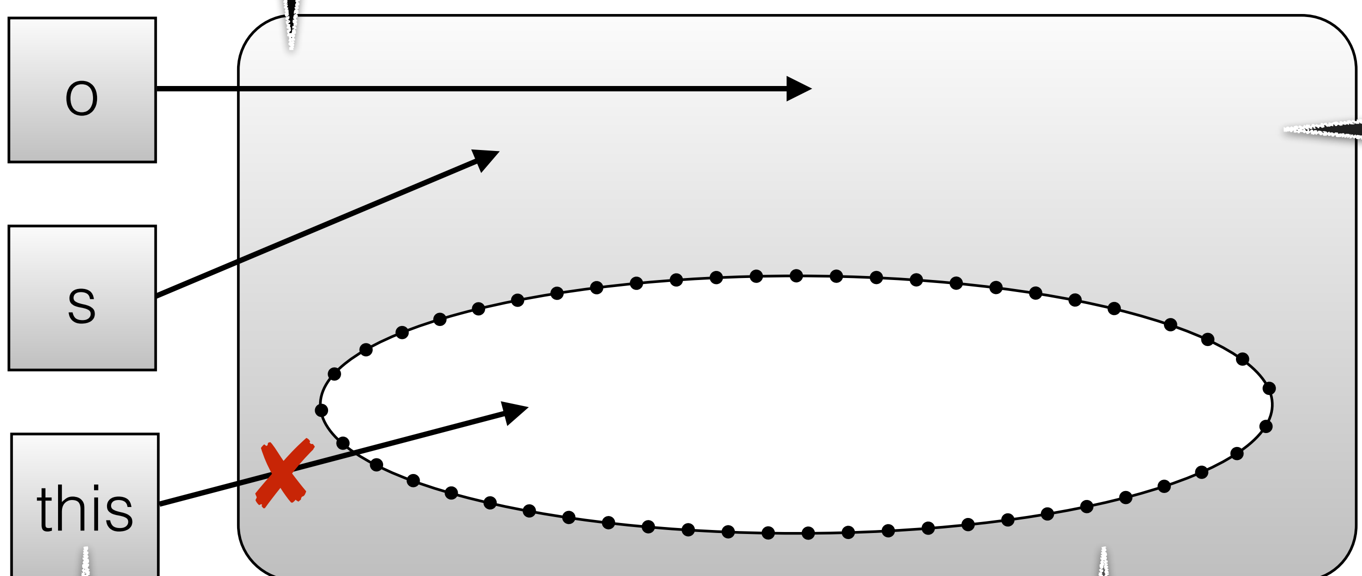

After framing out, entire heap is almost type-consistent

Points to type-inconsistent memory

Analysis might **unsoundly** switch to back to type checking

So what if there's no type-intertwined framing?

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```
class Callback
 var sel: Str
 var obj: Obj | r2 sel

 def call()
  this.obj.[this.sel]()
```

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var o = … object with a method m …
var cb = new Callback("m",o)
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```

Callback in JavaScript

JavaScript

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Callback in JavaScript

A class "meta-feature" **library**

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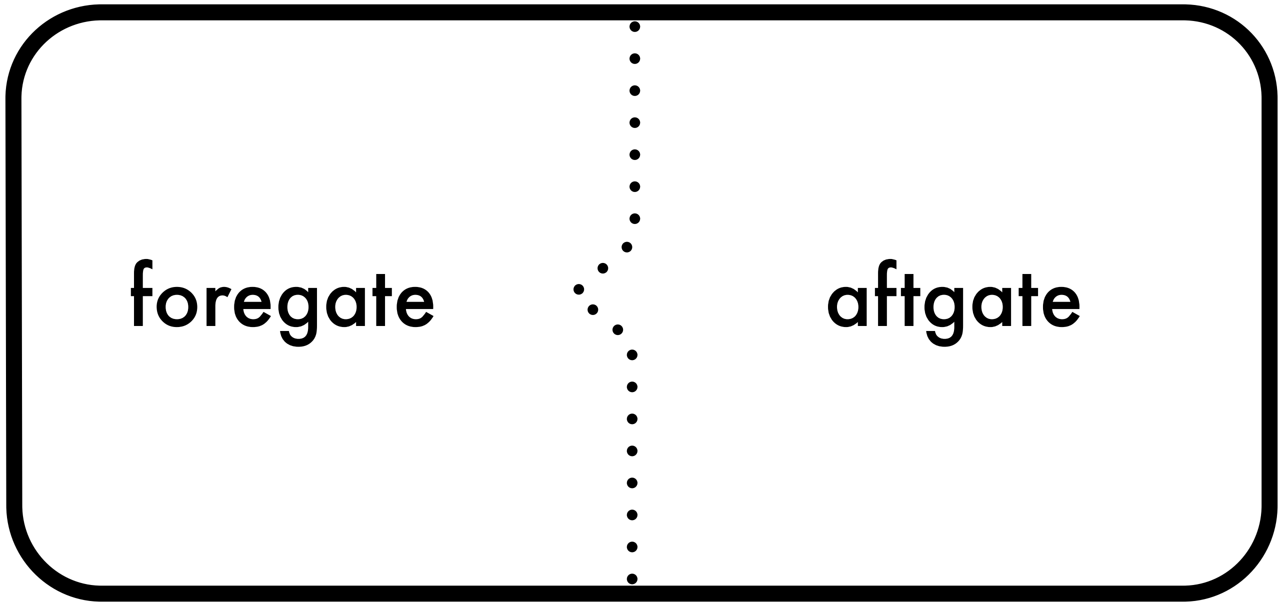
gated separation

Gated separation expresses a **dis-pointing** relation between **foregate** and **aftgate**



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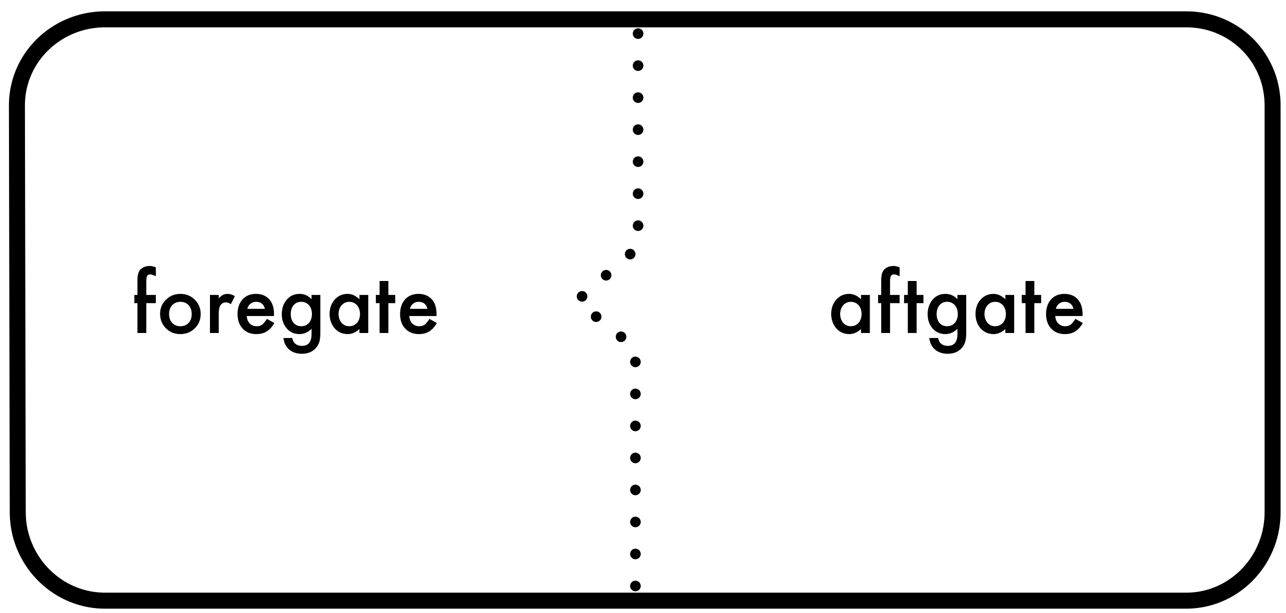
$M_{\mathrm{fore}} \triangleleft\!\!\!\!\ast \; M_{\mathrm{aft}}$



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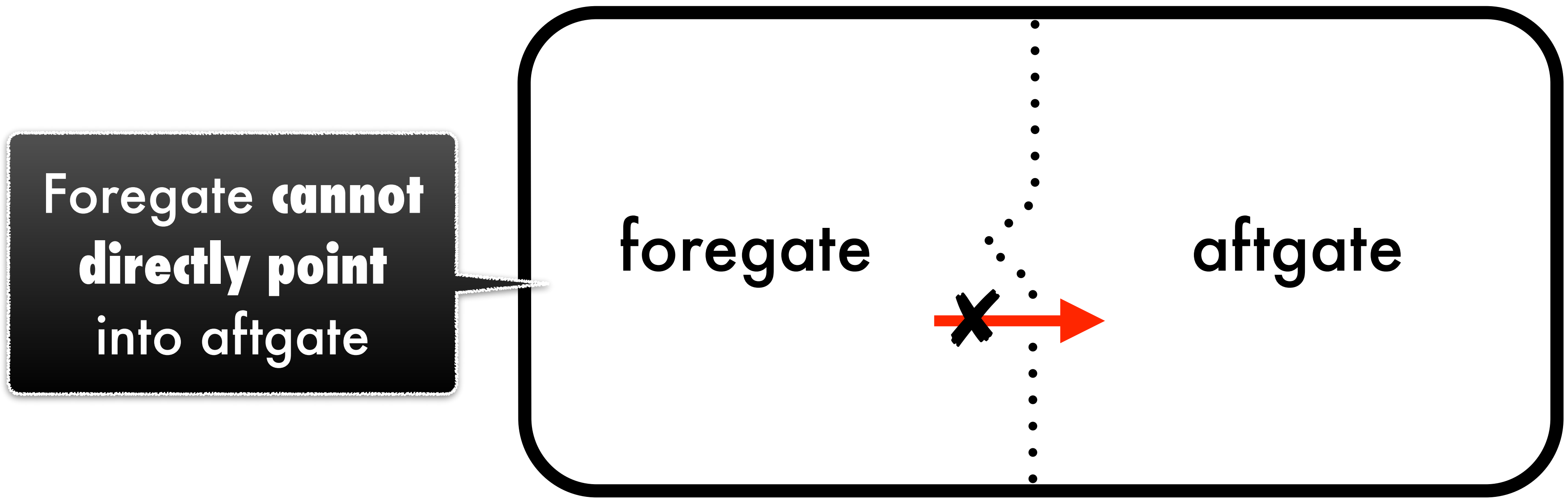

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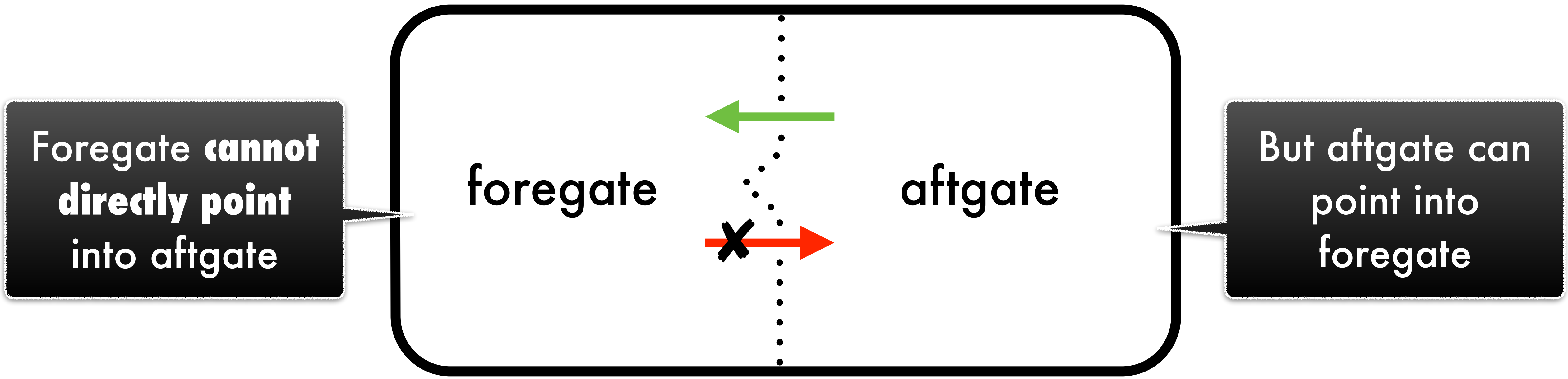

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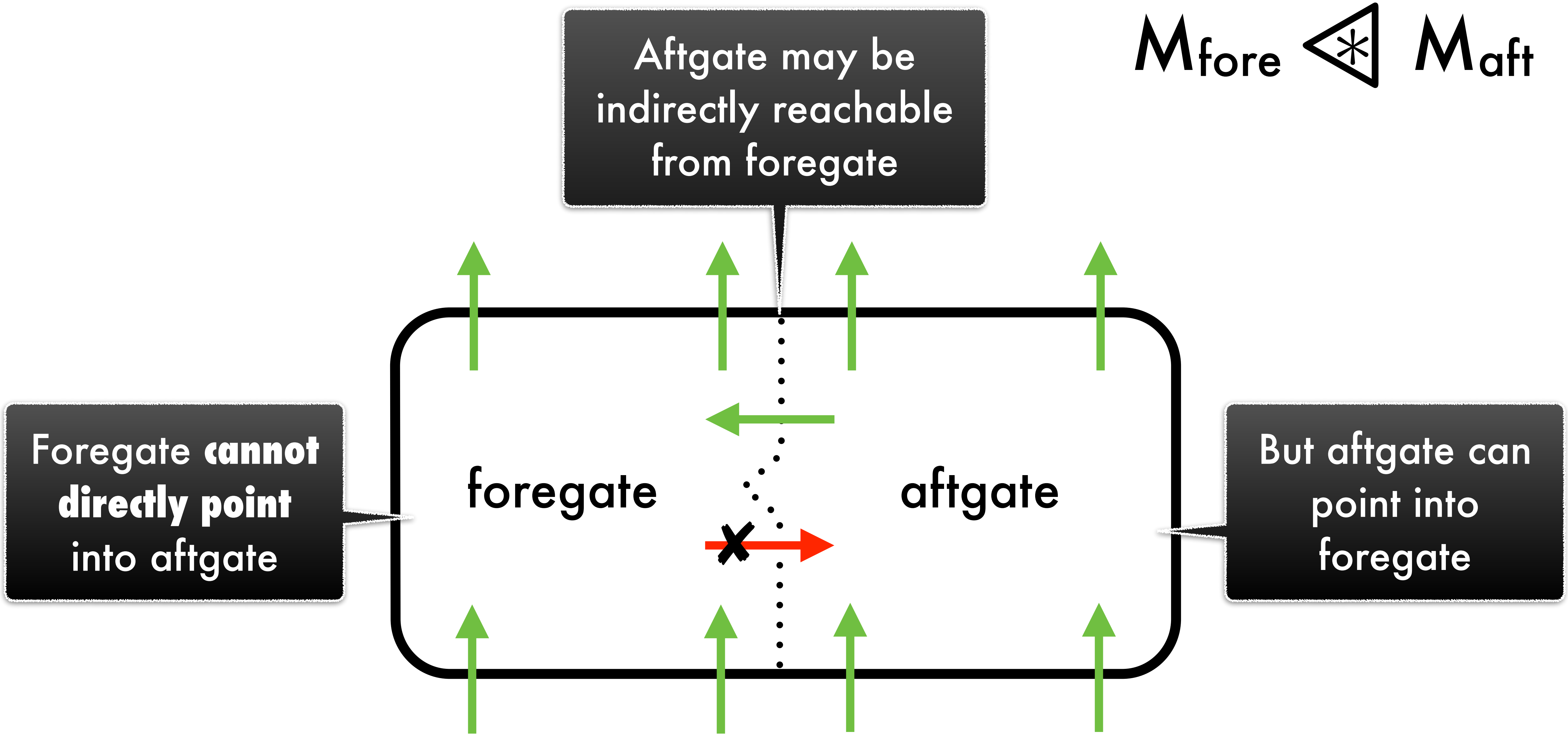

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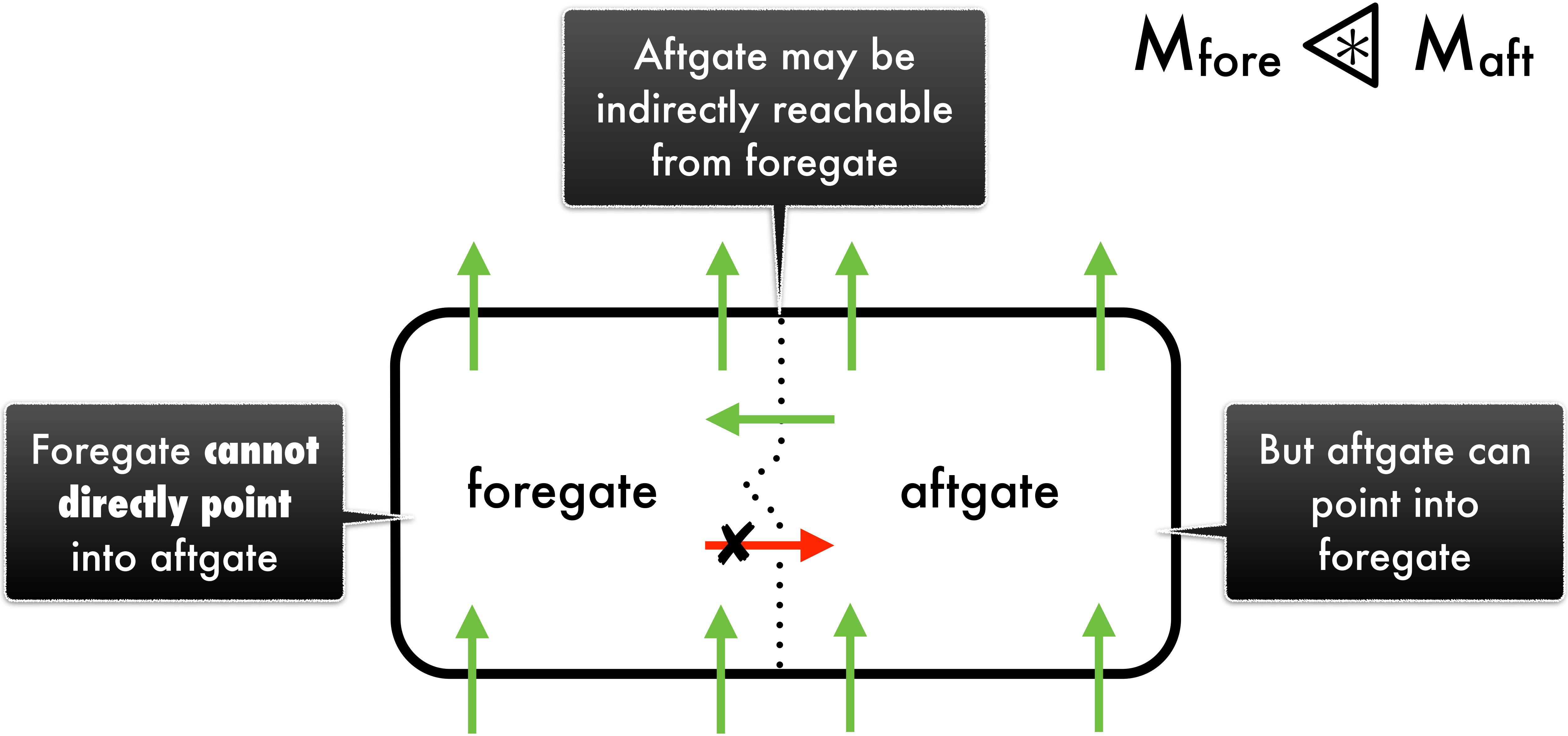

Gated separation is a **non-commutative strengthening** of standard separating conjunction restricting the **contents** of the **foregate**

Callback in JavaScript

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var Callback = Class({
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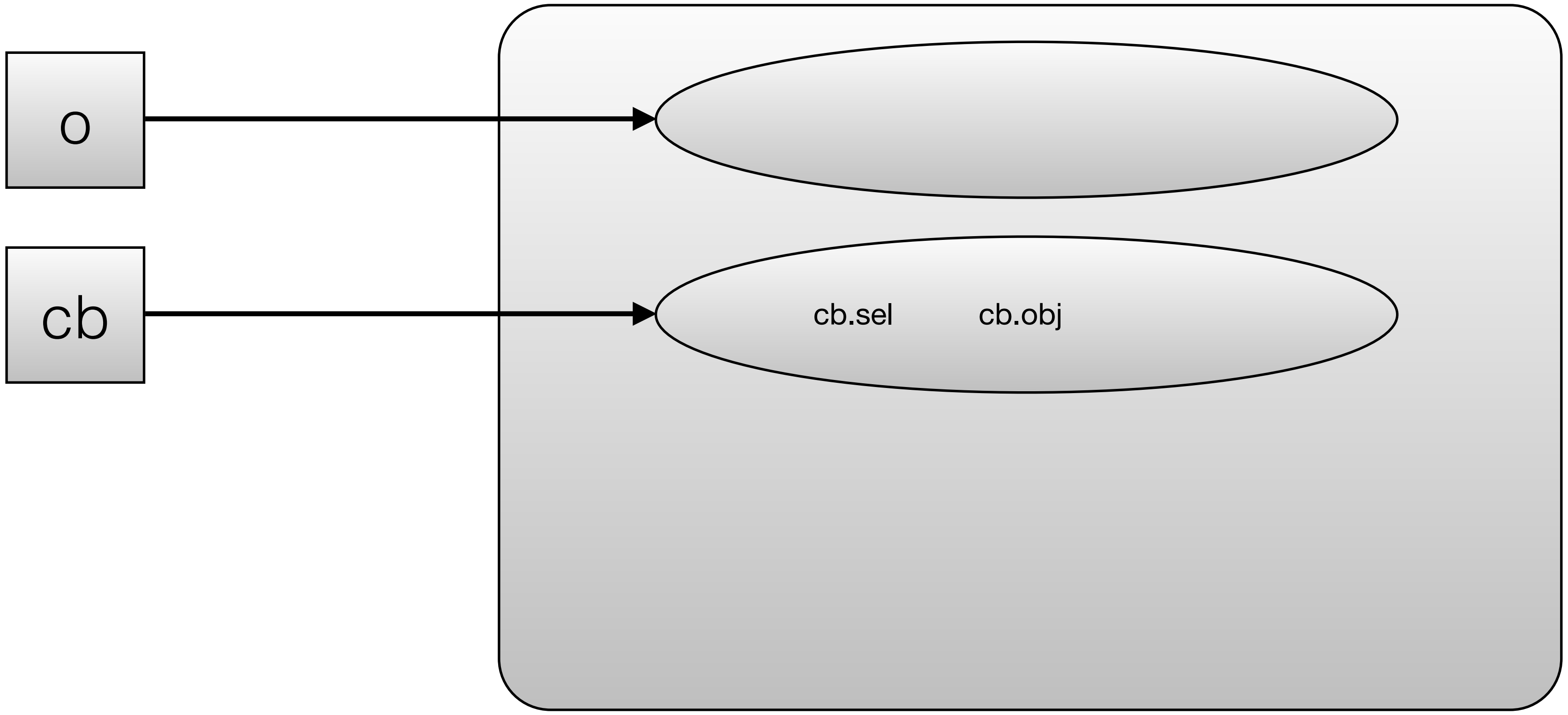


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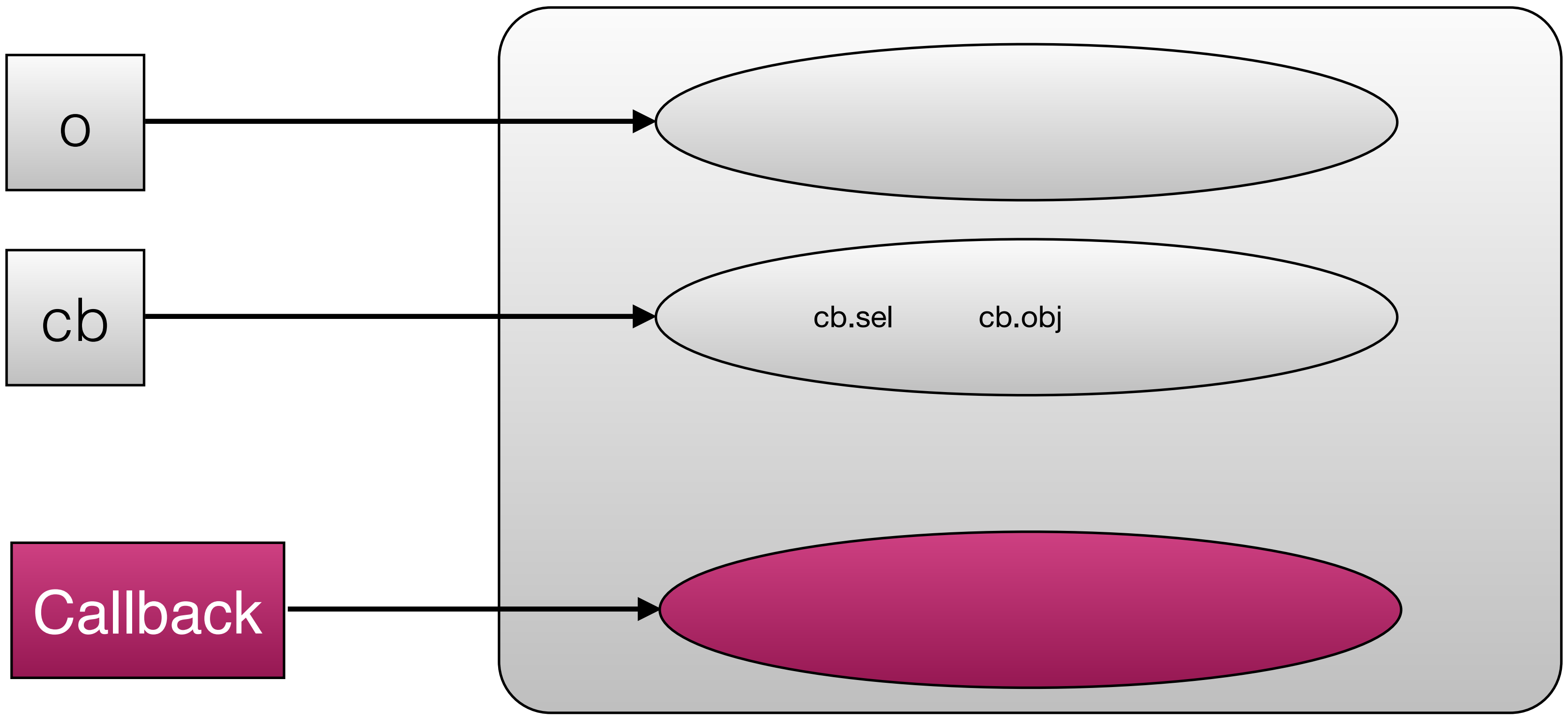


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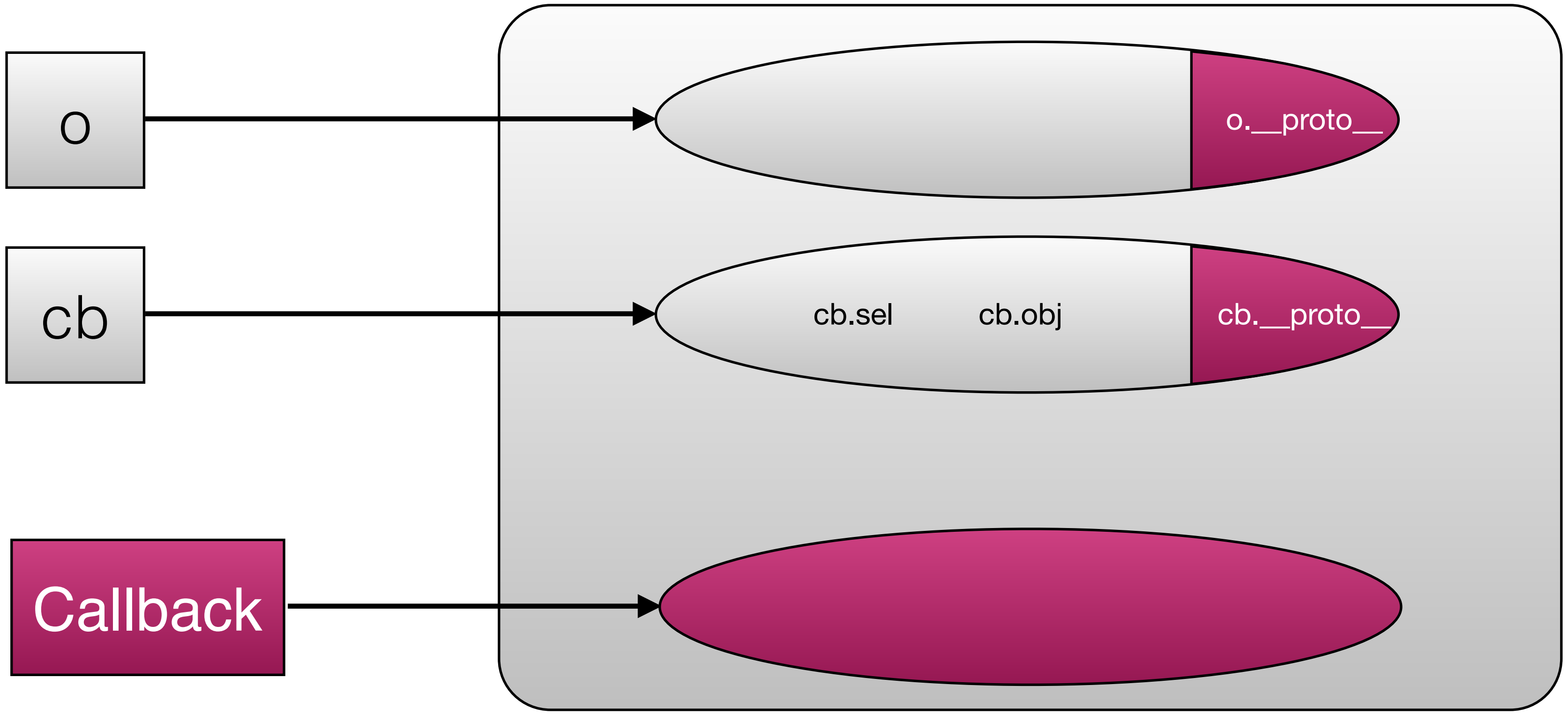


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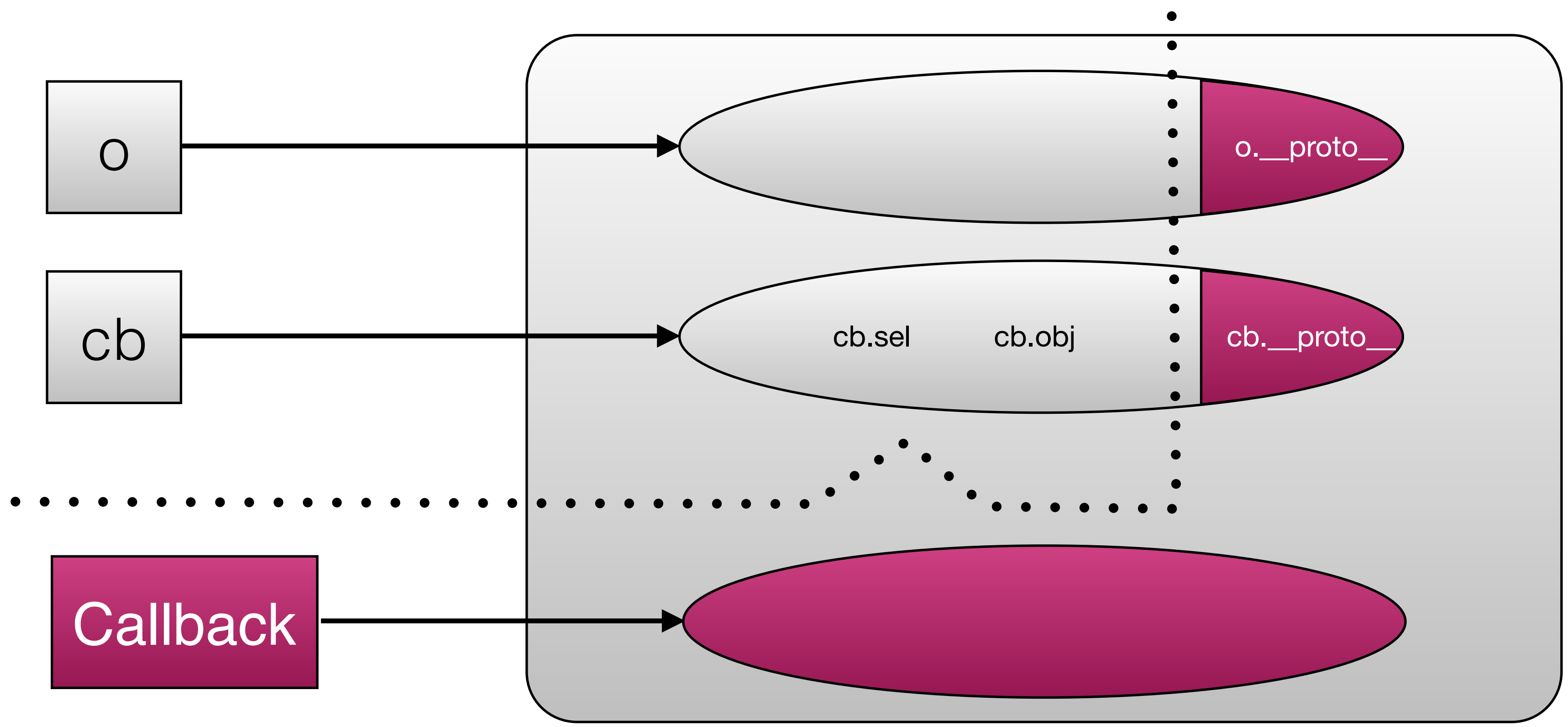

`var o =` *... object with a method m ...*

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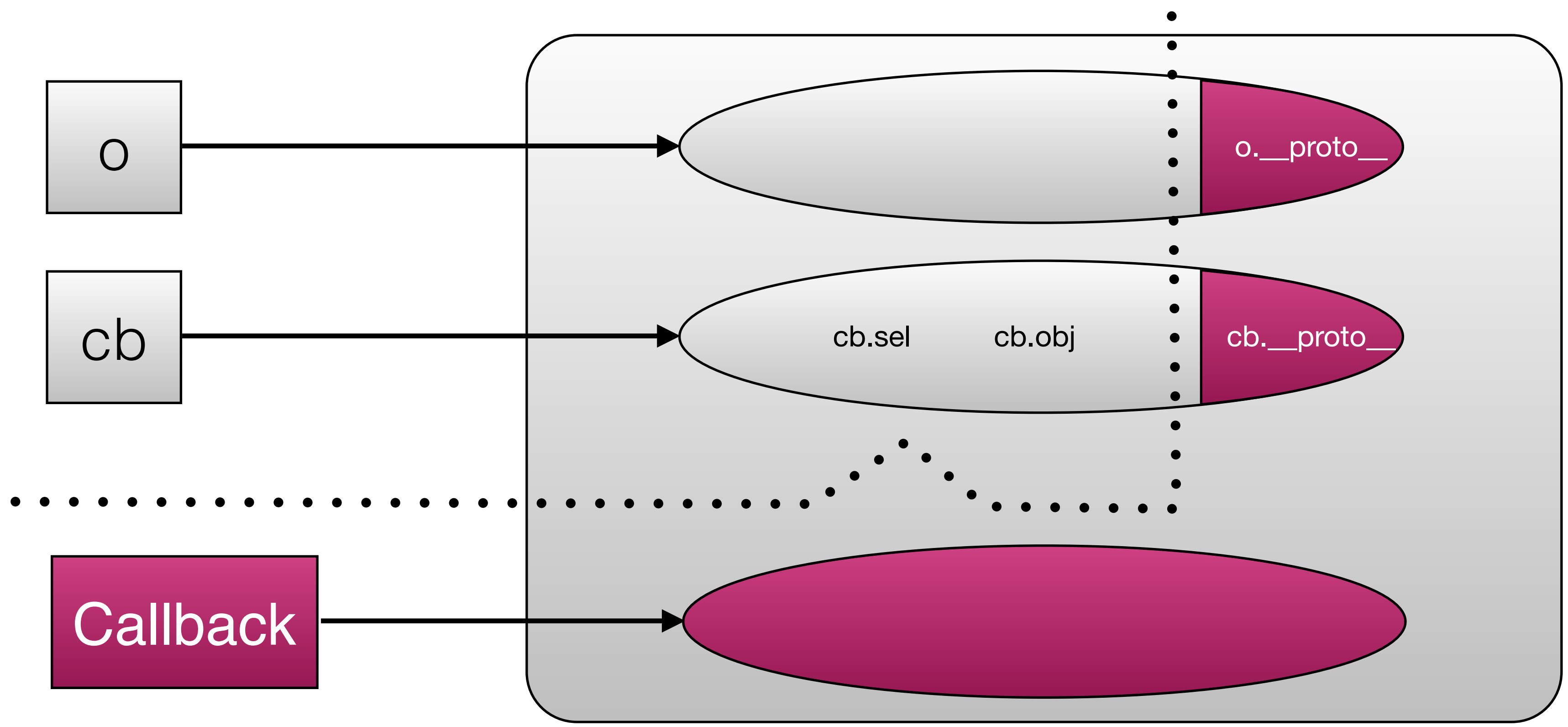


```
var o = ... ol
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cb.call()
```
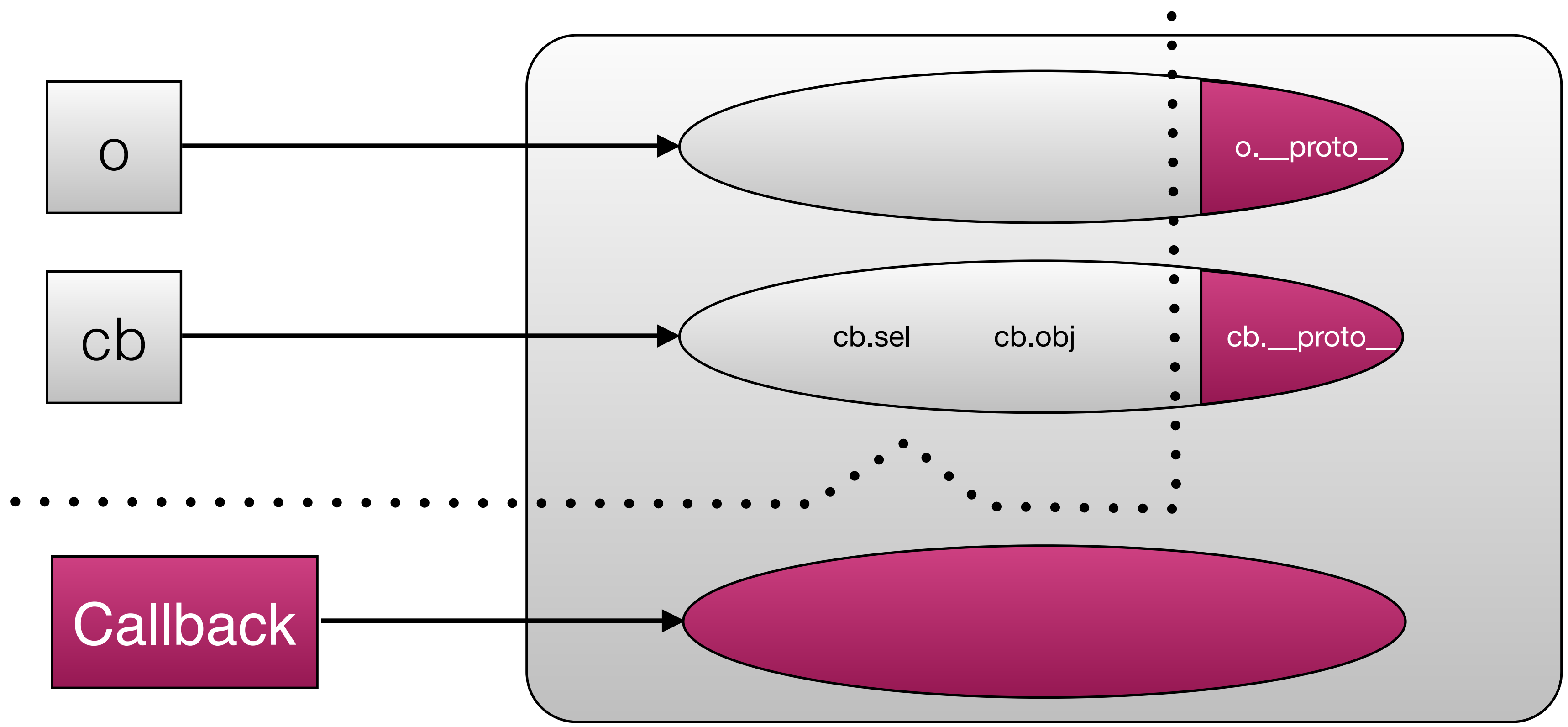

“Non-typeable heap” is gate-separated

Strong enough to ensure **type-intertwined frame rule** is sound

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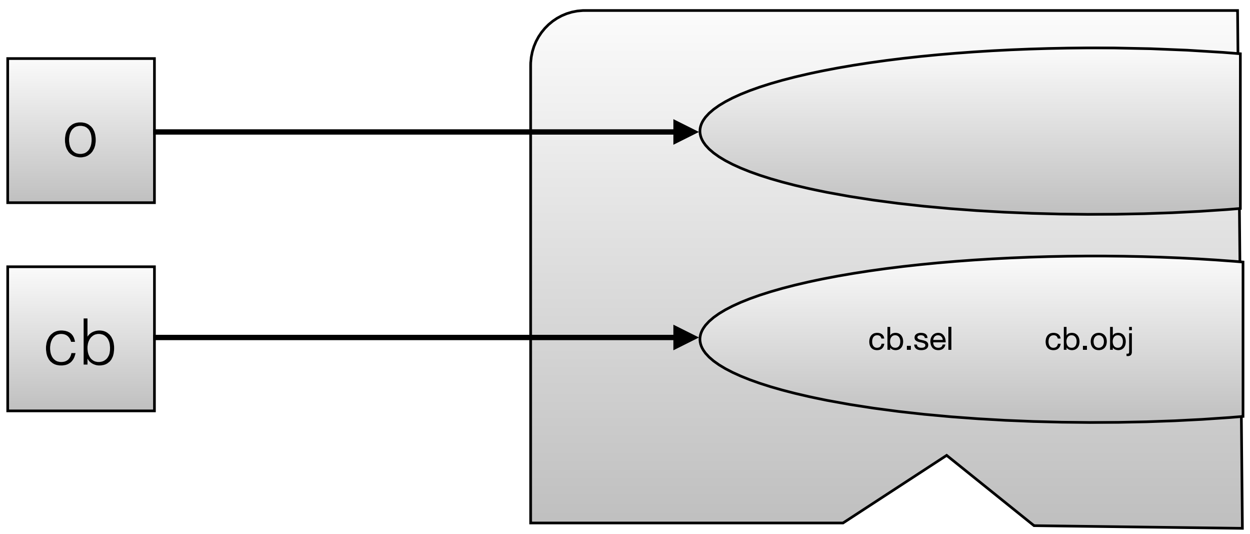


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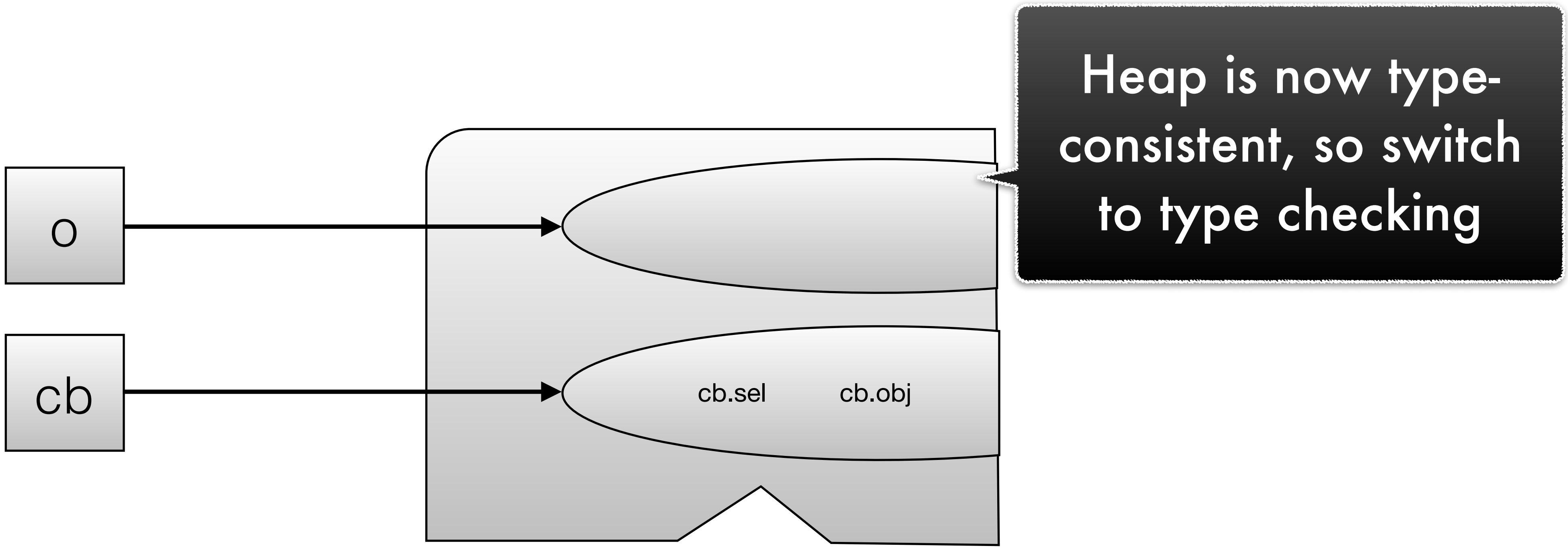


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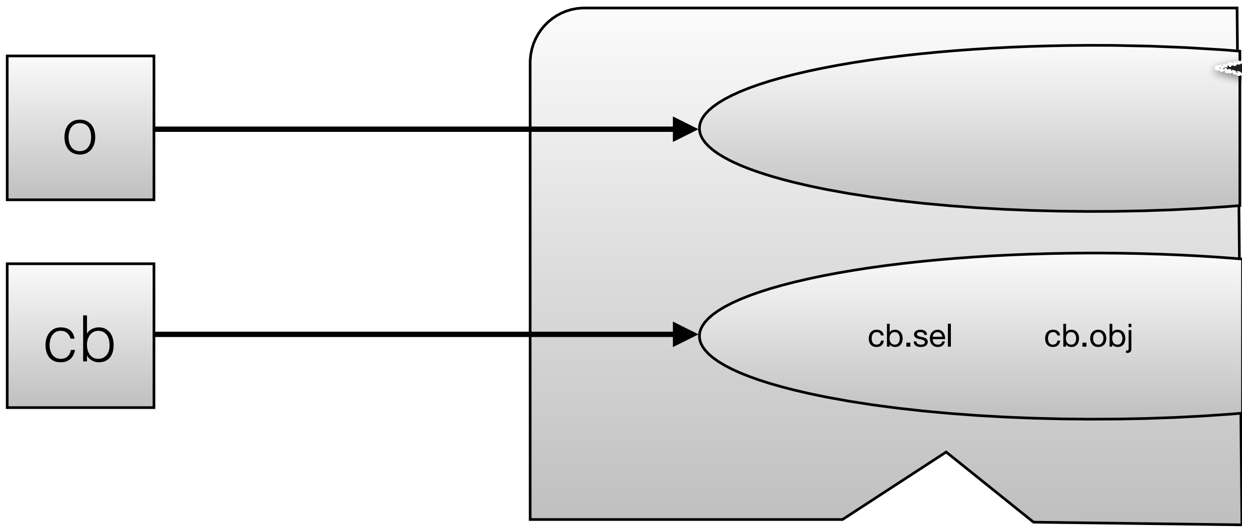

Heap is now type-consistent, so switch to type checking

```
var o = … ob
var cb = Ne
cb.call()
```

Framed-out memory **cannot be touched** during type checking because of gating

Challenge: **Static analysis** with gated separation

Challenge: **Static analysis** with gated separation

```
x.f = y
```

Challenge: **Static analysis** with gated separation

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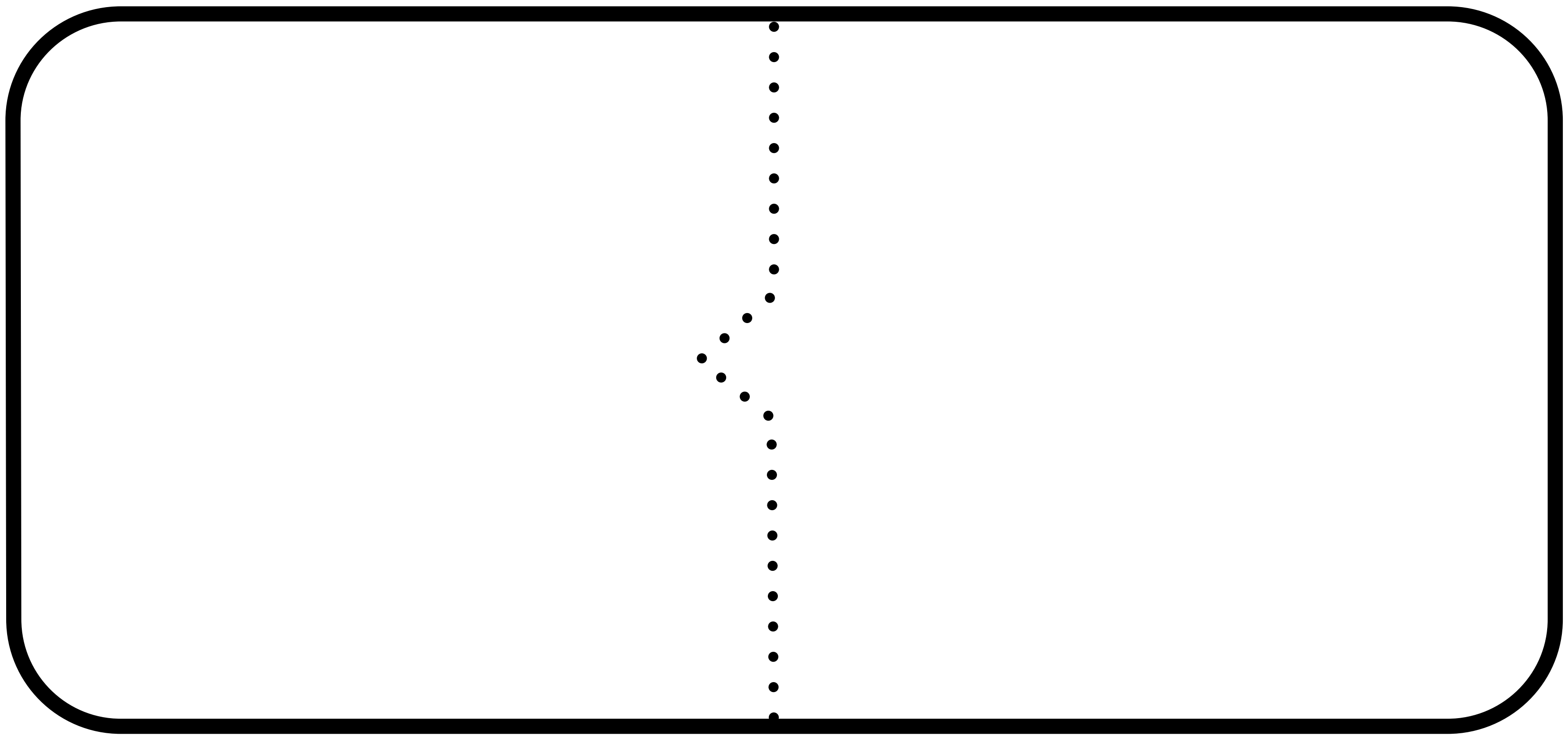

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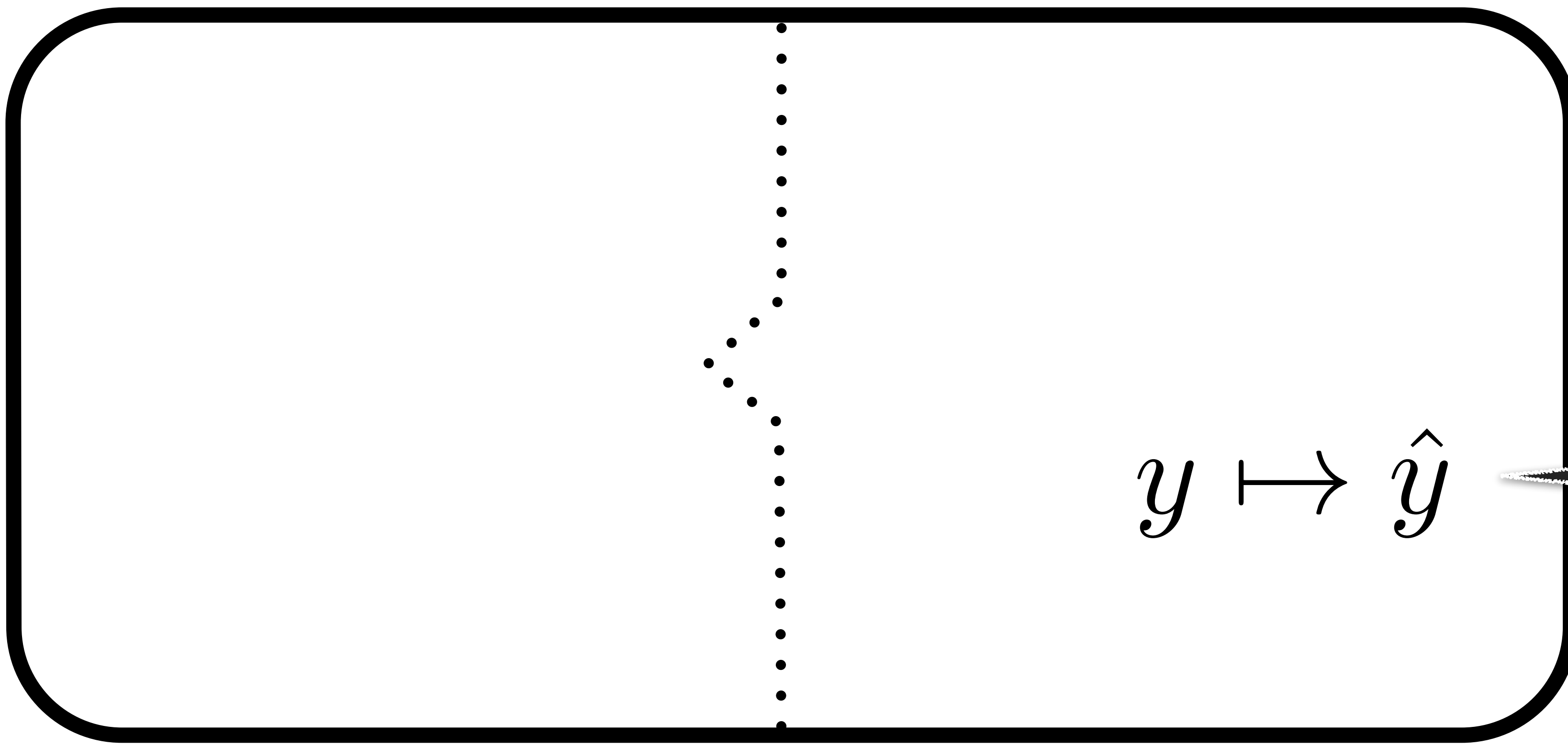

Value to be written

Challenge: **Static analysis** with gated separation

Cell to write in a foregate

`x.f = y`

$\hat{x} \cdot f \mapsto -$

$y \mapsto \hat{y}$

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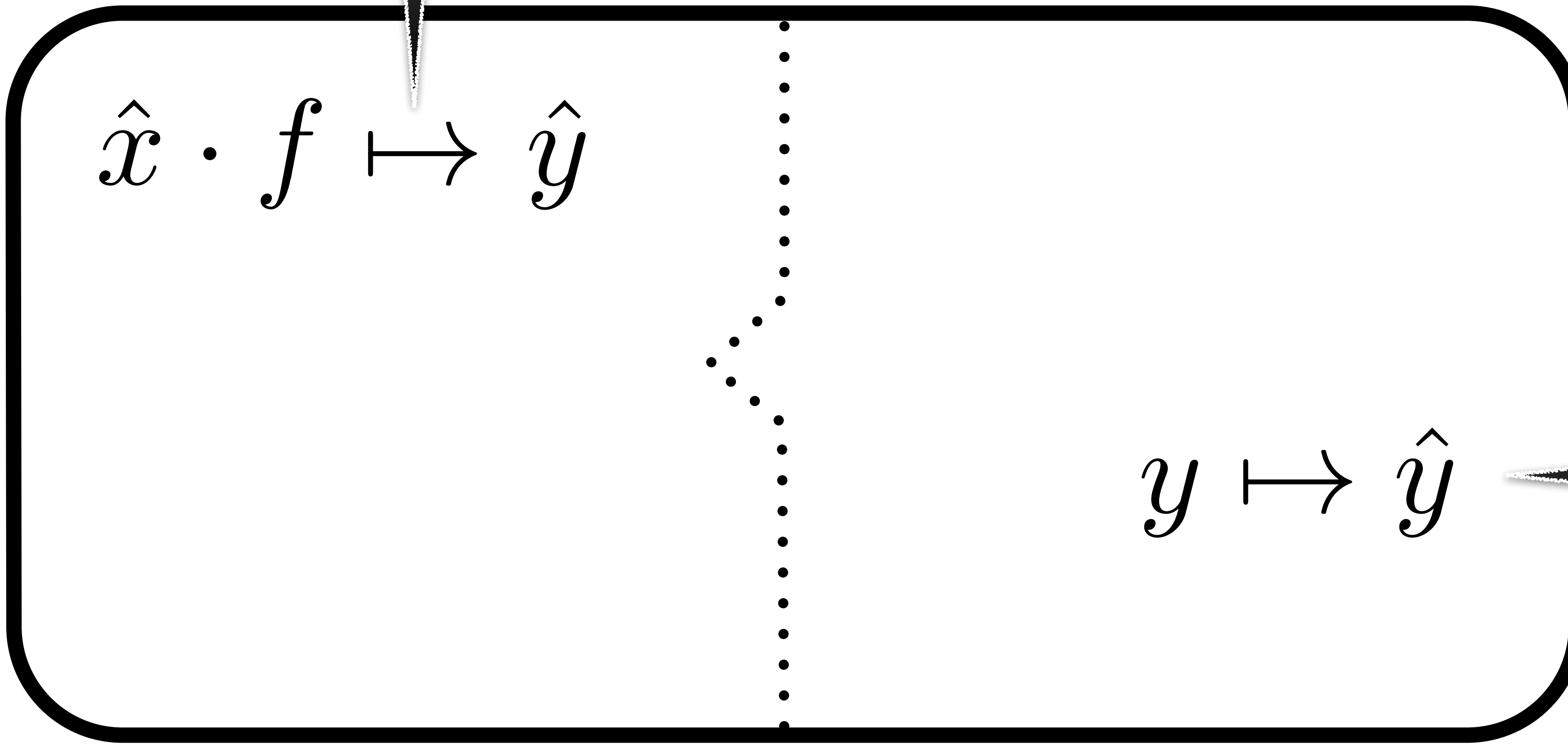

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Cell to write in a foregate

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$y \mapsto \hat{y}$

Value to be written

Sound? Not if $\hat{y}$ may be the address of a cell in the concretization of the aftgate

Challenge: **Static analysis** with gated separation

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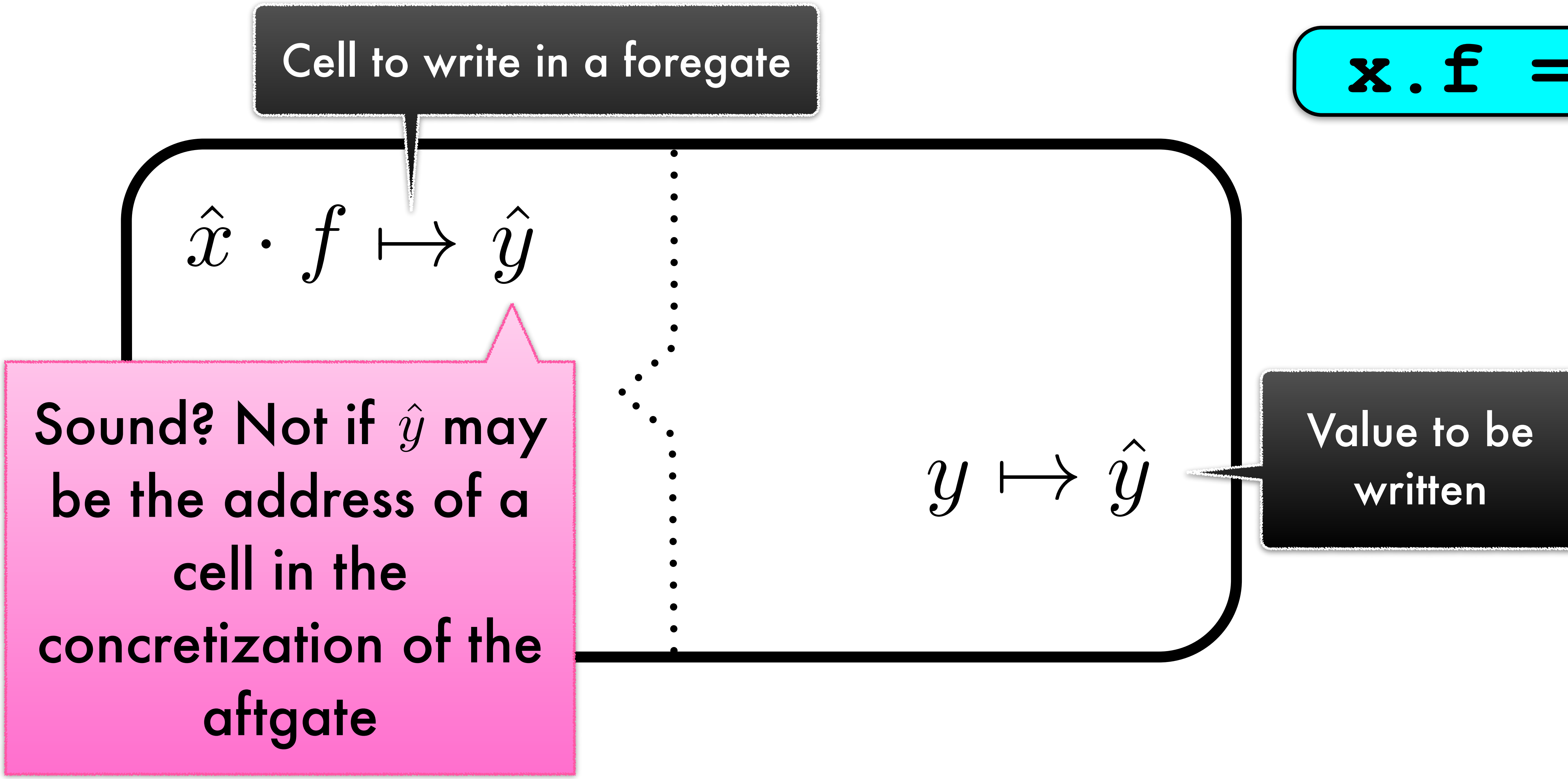

Transfer functions for **writes require rearrangement** and weakening **of gated separation**

How to **type check** a program that is **almost** well-typed?

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almost?

Type-Intertwined Separation Logic

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ok Tolerating temporary violations with **almost type-consistent heaps**

Coughlin and Chang. *POPL* 2014.

Type-Intertwined Separation Logic

ok

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When the type invariant is temporarily broken

Type-Intertwined Separation Logic

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When the type invariant is temporarily broken

$\triangleleft\!\!\!\ast$

Type-intertwined framing with **gated separation**

Under preparation.

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When the type invariant is temporarily broken

$\triangleleft\!\!\ast$ Type-intertwined framing with **gated separation**

Under preparation.

When the type invariant applies to only part of the heap

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CU PLV

Cerny

Chang

Hammer

Sankaranaryananan

Somenzi