Fissile Type Analysis: Modular Checking of Almost Everywhere Invariants

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July 30, 2014

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

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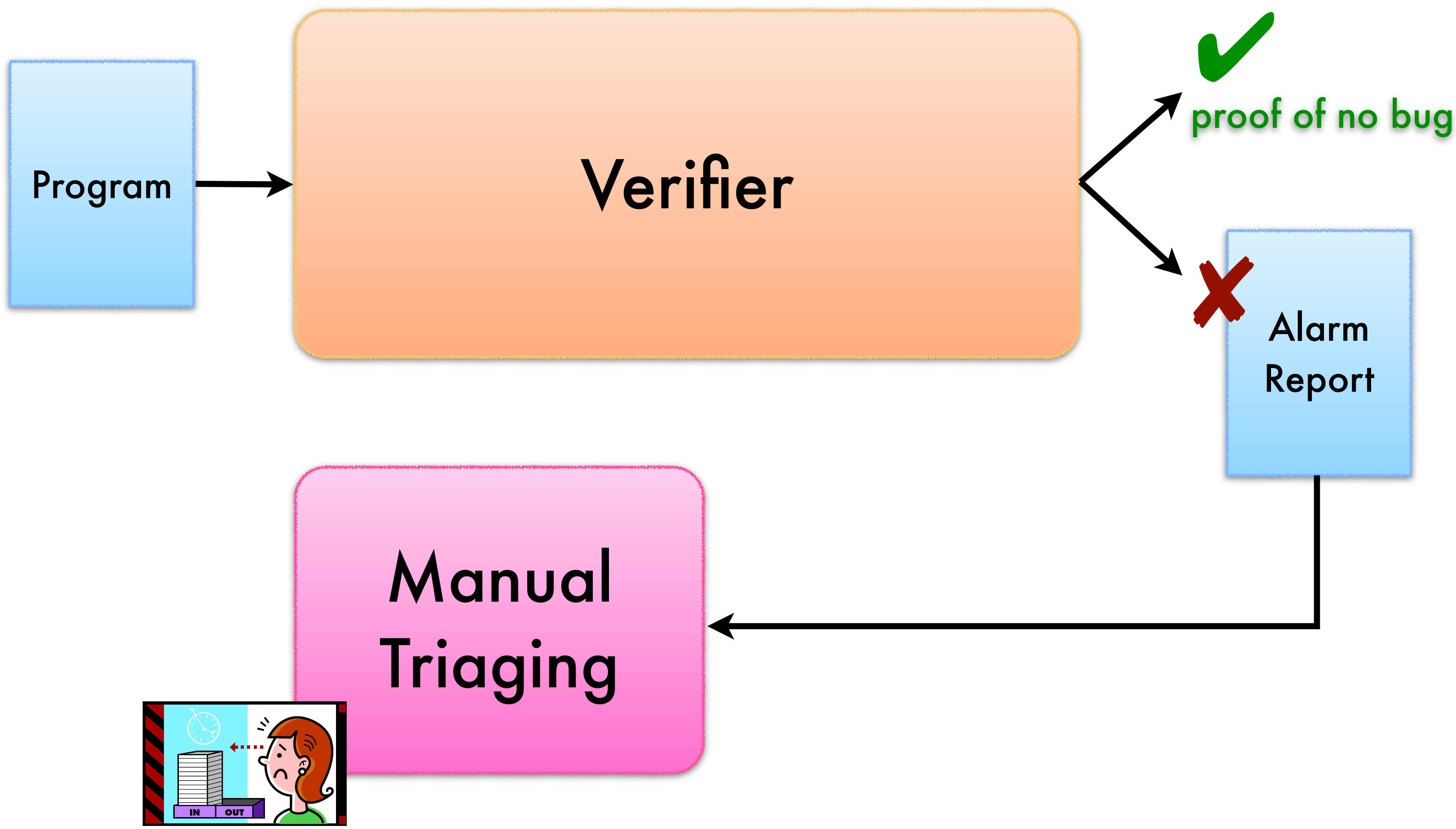

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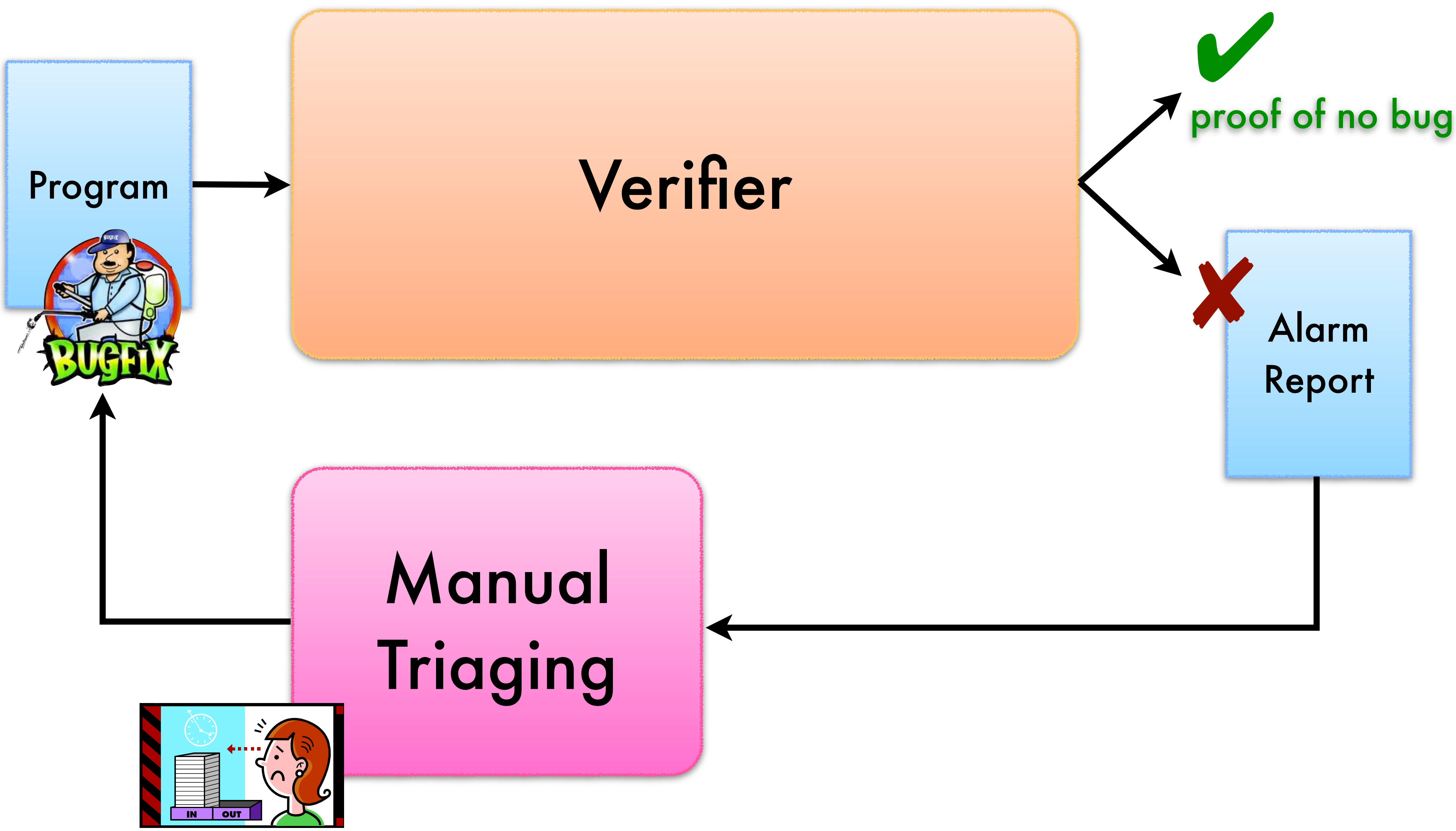

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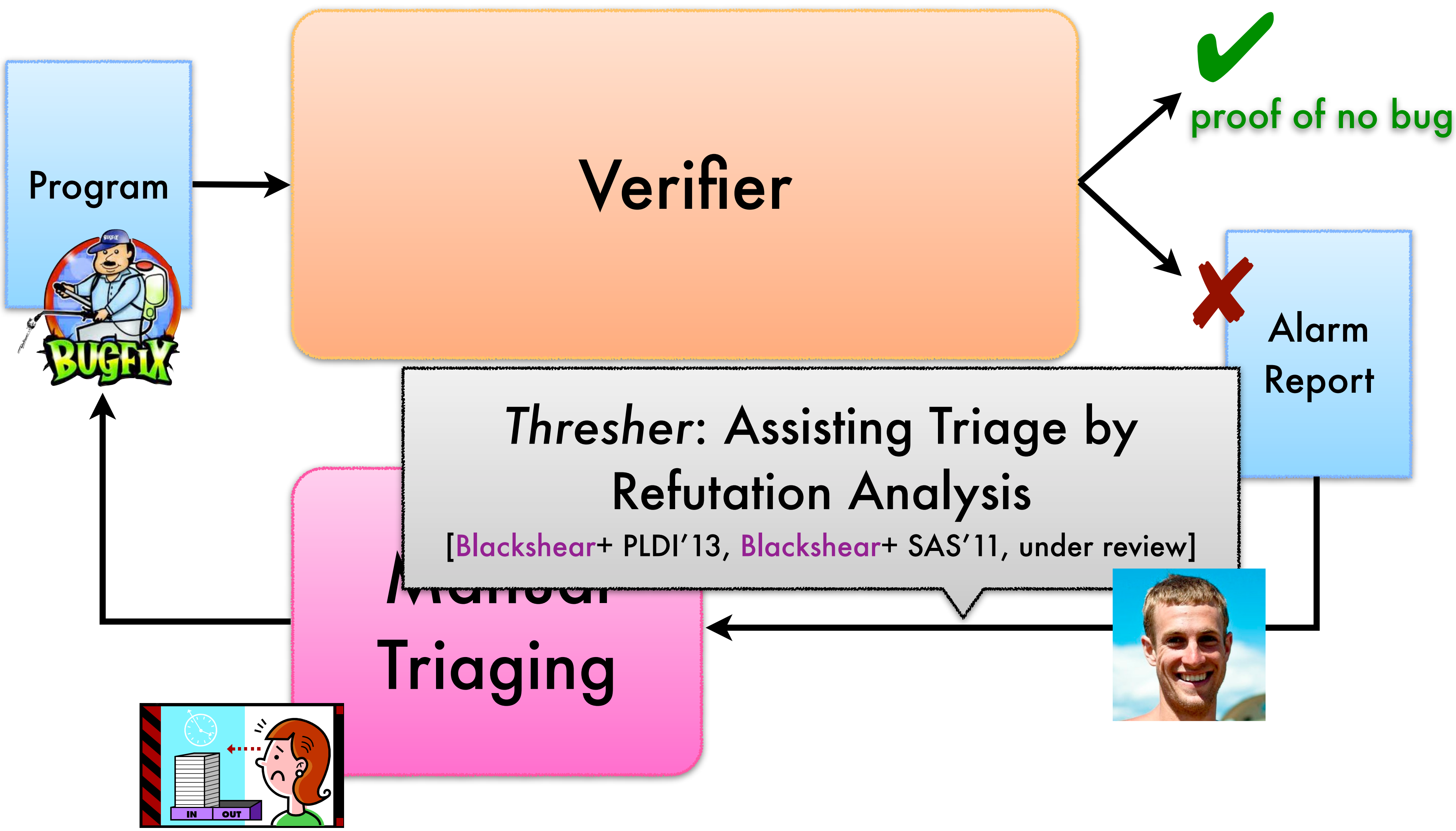

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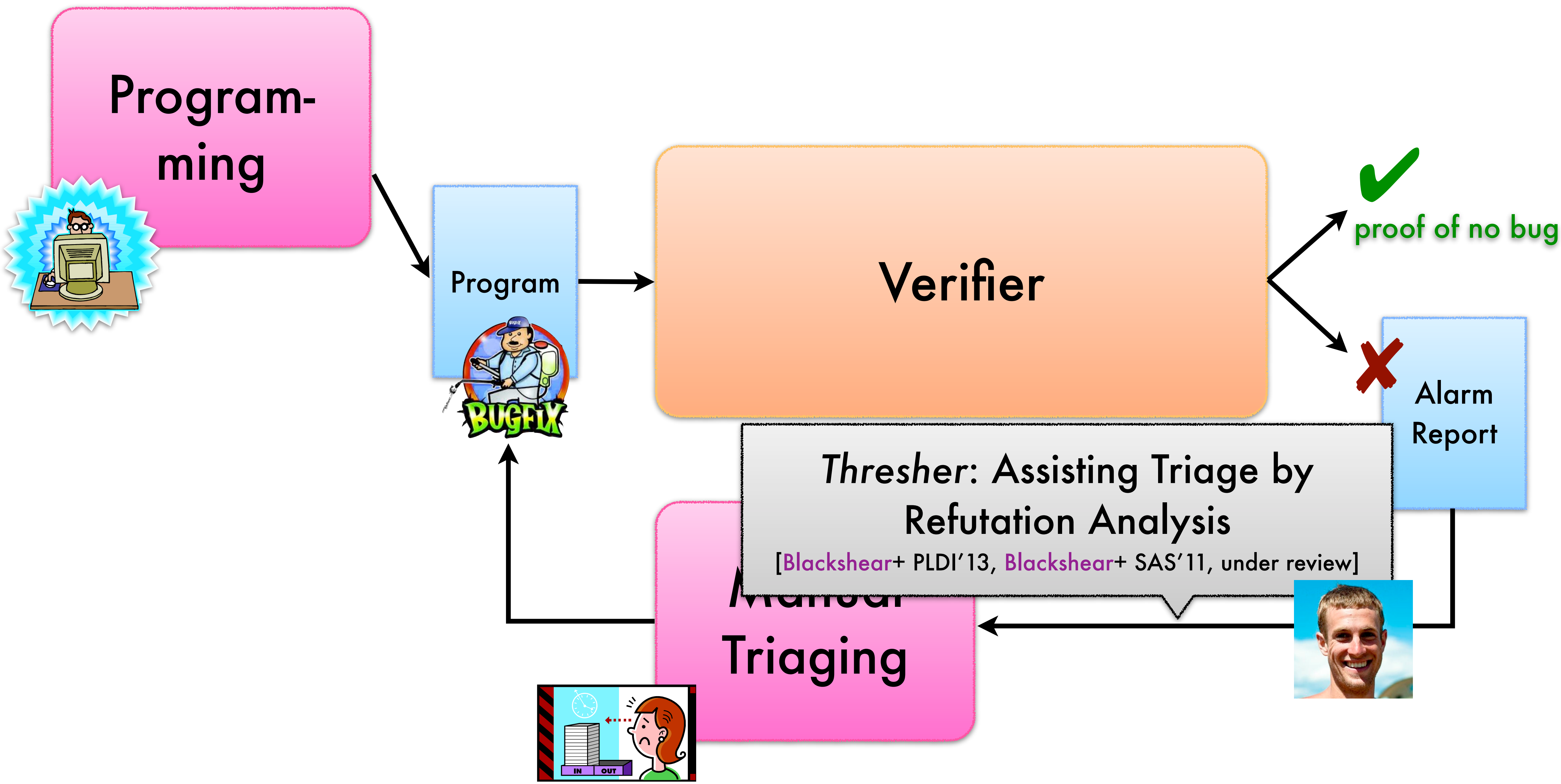

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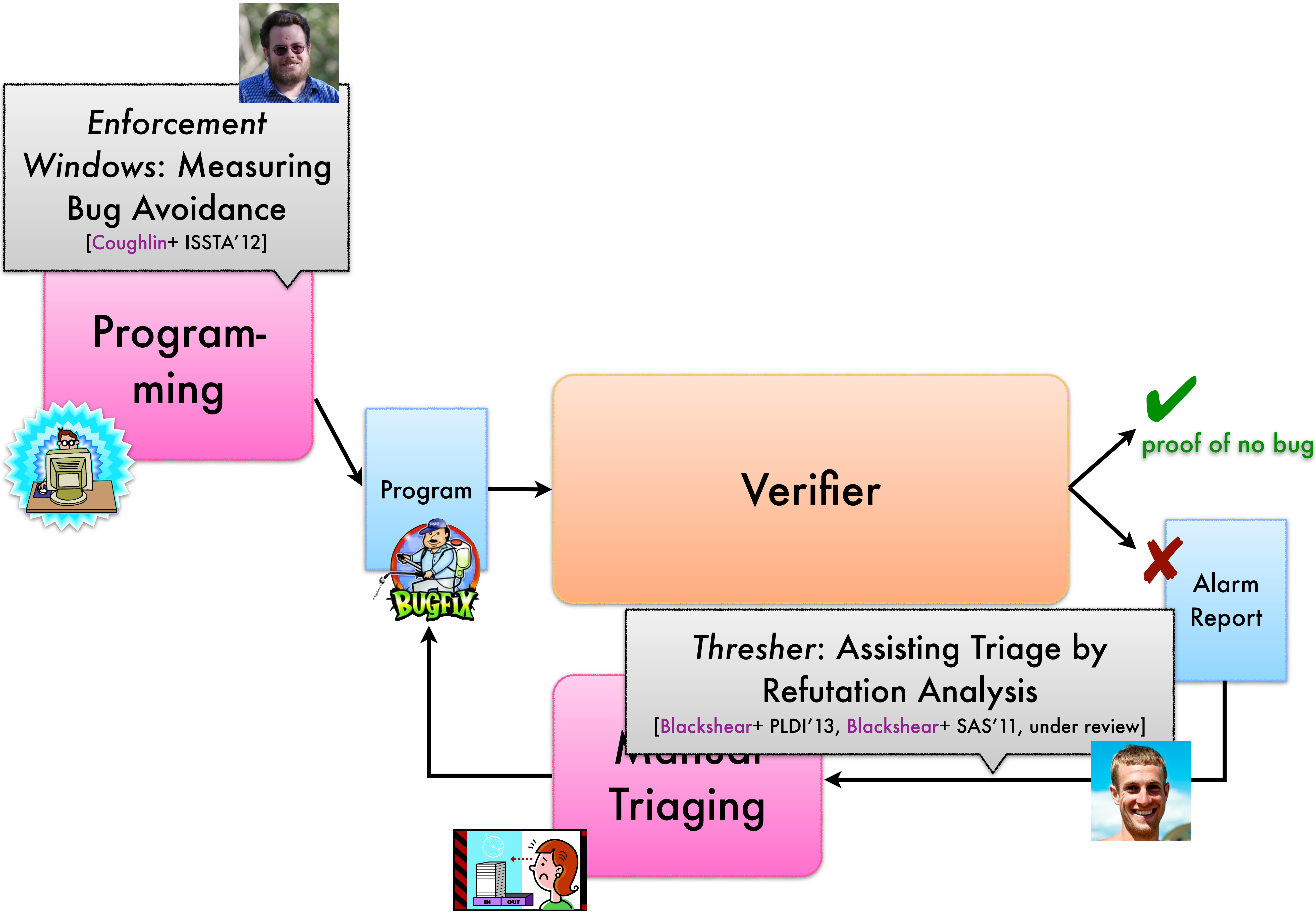

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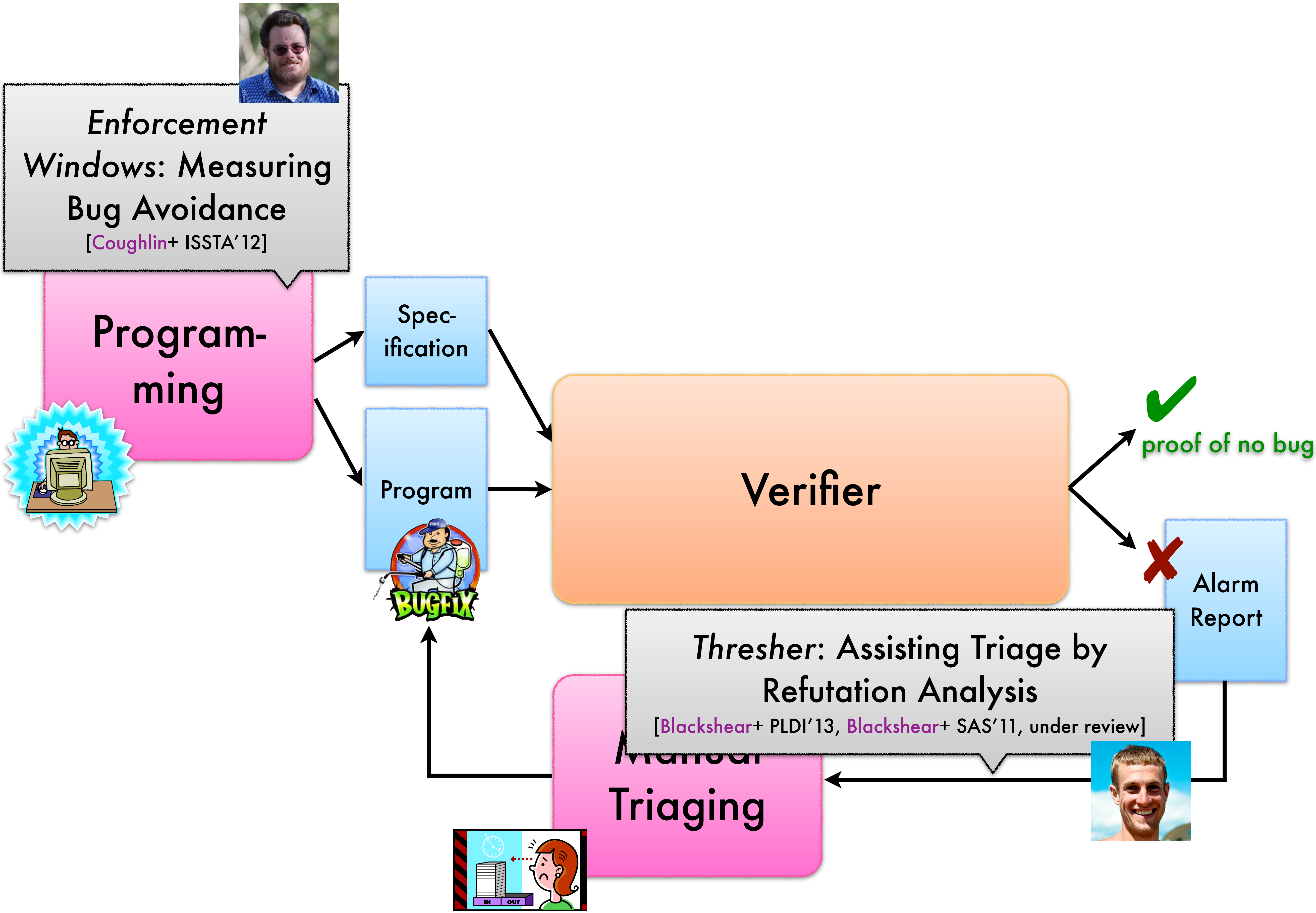

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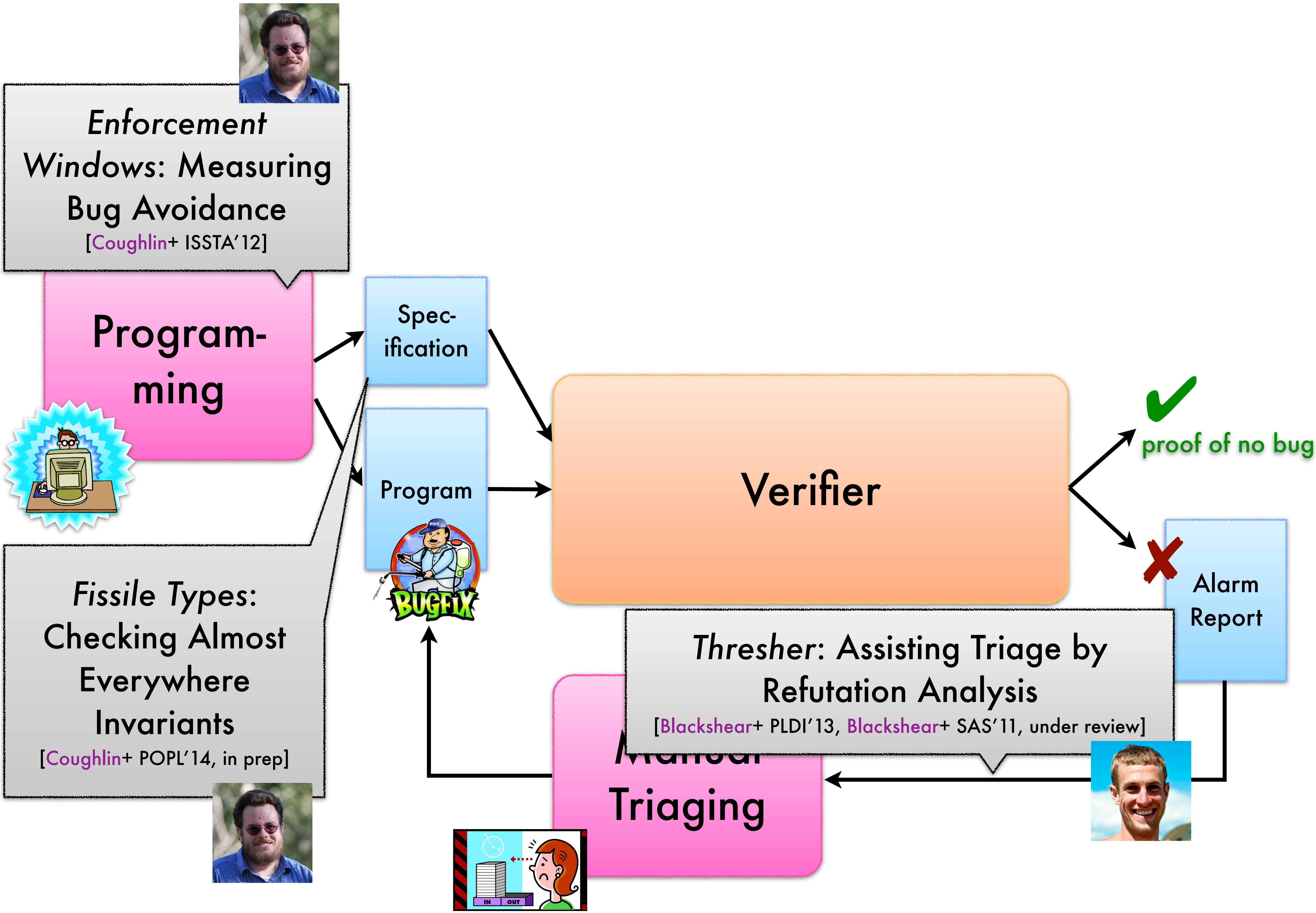

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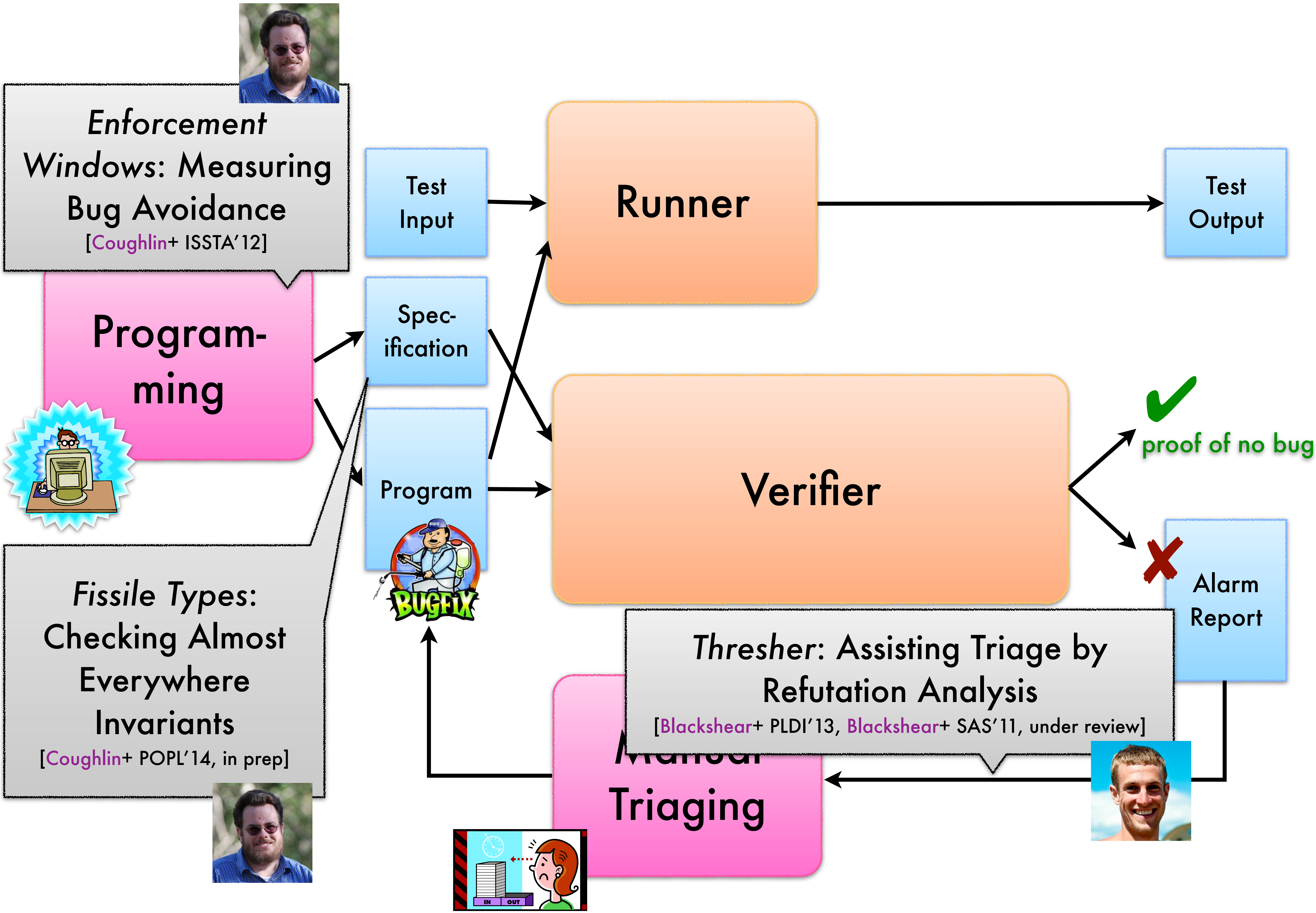

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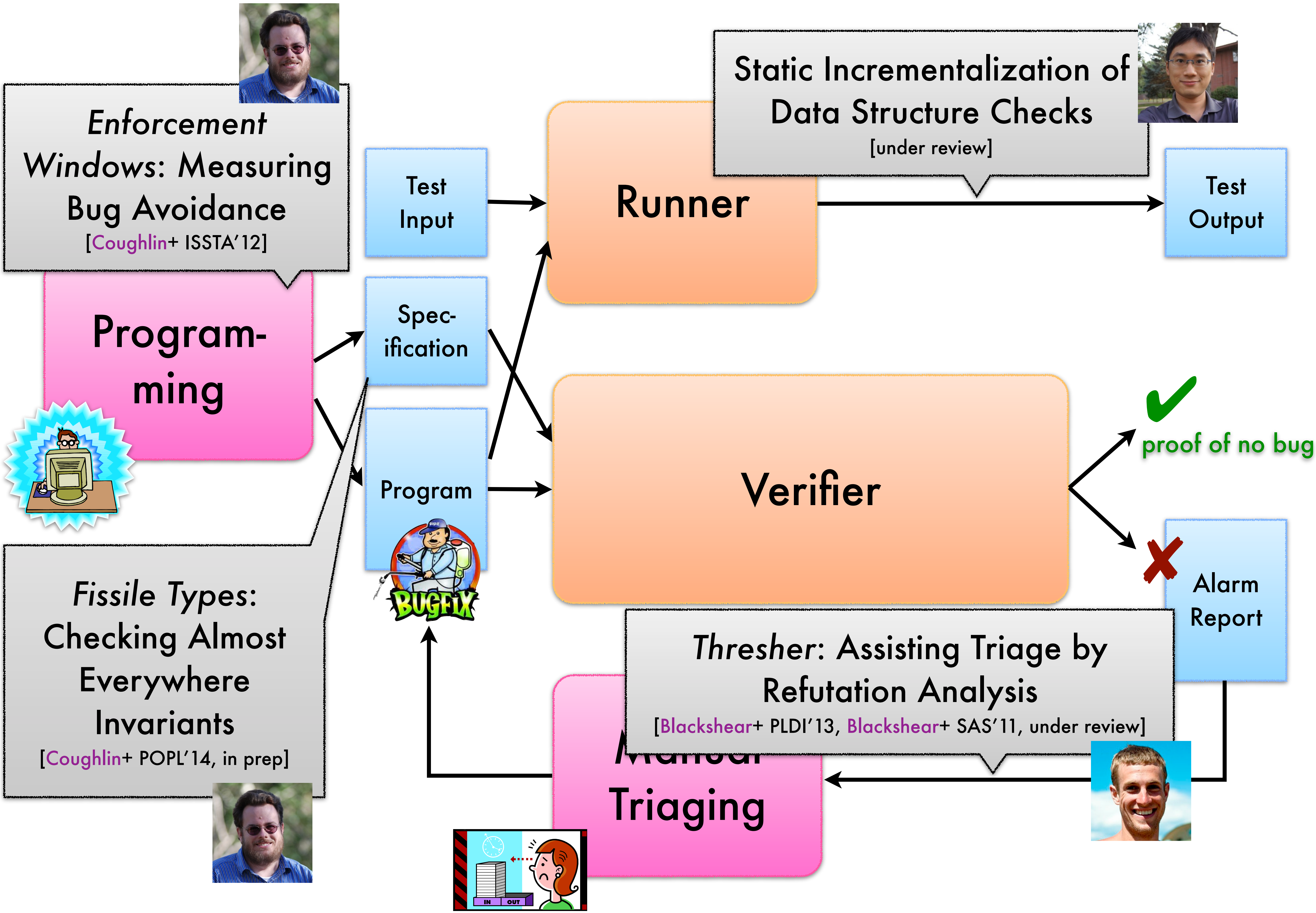

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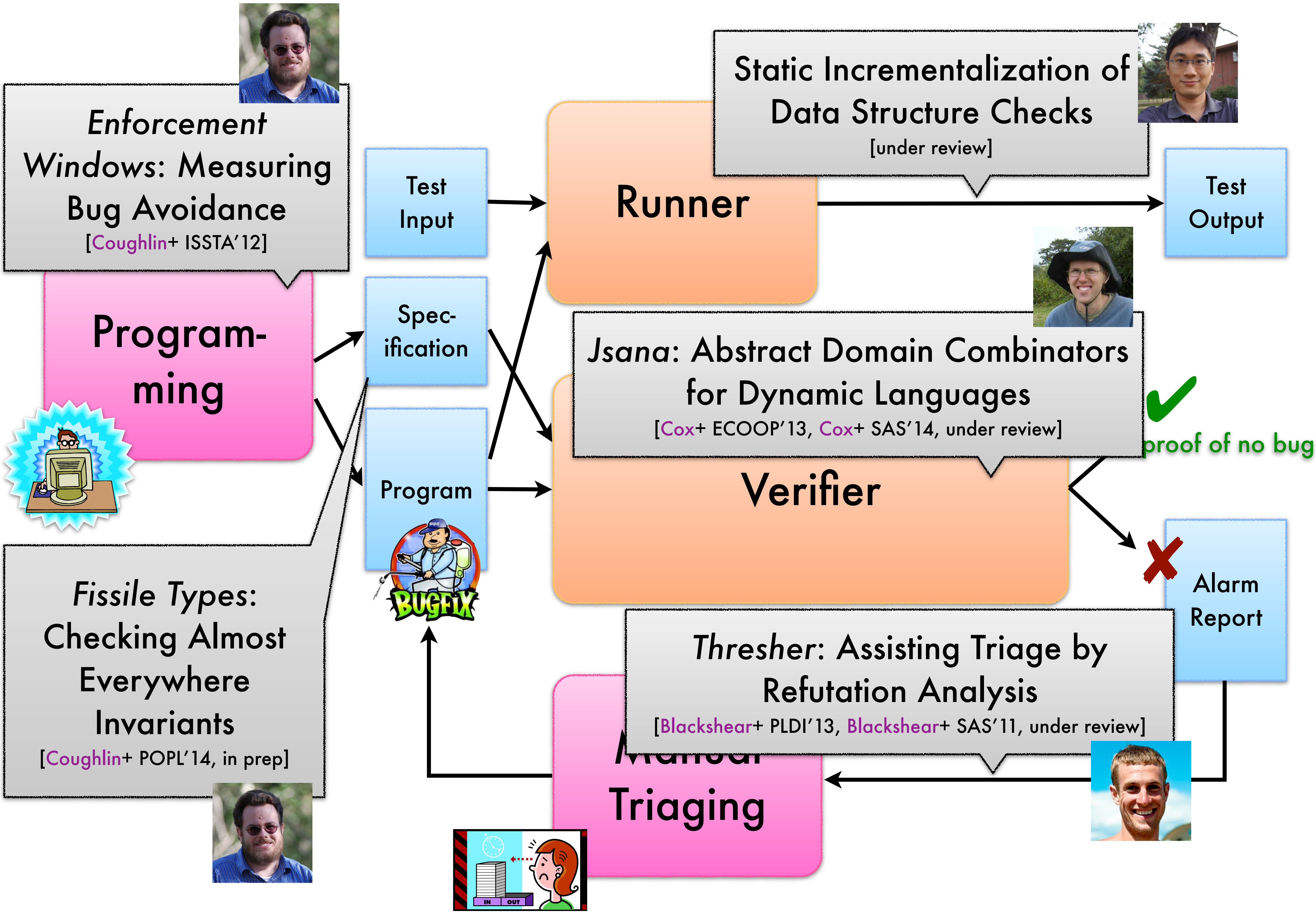

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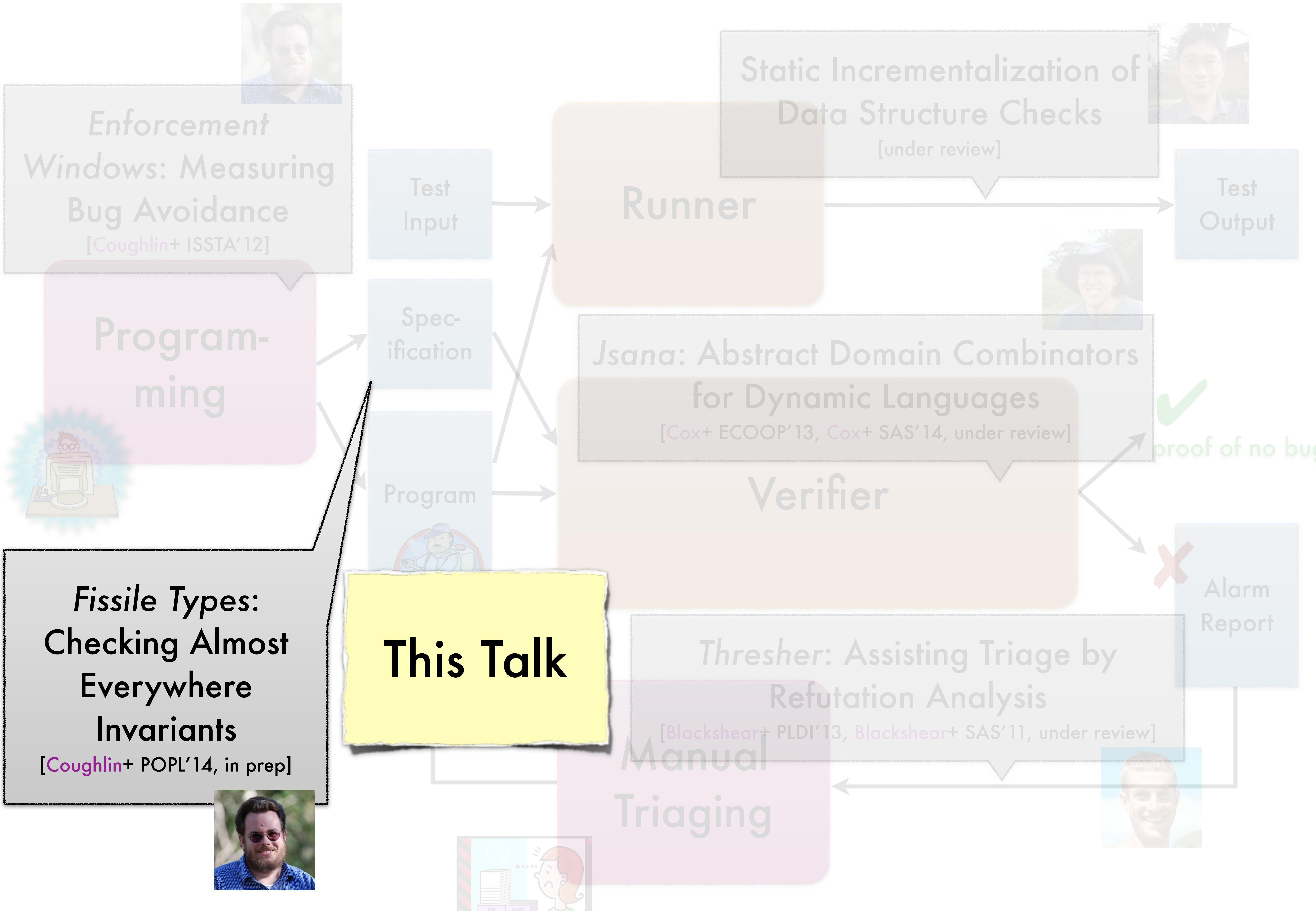

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Fissile Type Analysis:

Types and Separation Logic, Better Together


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

In this talk

Example property of interest:
safety of **reflective method calls**

Specification system:
dependent-refinement types

Reflective method call dispatches based on **runtime string value**

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

 def call()
  this.obj.[this.sel]()
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Calls method with **name** (selector) stored in `sel` on object stored in `obj`

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If `sel` held string "`notifyDidClick`" would call `notifyDidClick()` on `obj`.

Reflective method call dispatches based on **runtime string value**

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

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

Method Reflection and **the Great Divide**

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```
object.[string]()
```

Method Reflection and **the Great Divide**

reflective method call: dispatch based on **run-time value** (in string)

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Method Reflection and the Great Divide

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"static" folks

"web 2.0" developers

Method Reflection and the Great Divide

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“Static” folks, like type system designers, **worry**.

What gets called? What if **`object`** has **no method** named by **`string`**?

Method Reflection and the Great Divide

reflective method call: dispatch based on **run-time value** (in string)

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"static" folks | "web 2.0" developers

"Static" folks, like type system designers, **worry**.

What gets called? What if **`object`** has **no method** named by **`string`**?

"Web 2.0" developers think it's **cool**.

I can write flexible and compact code, so I will take it over **static safety**.

Method Reflection and the Great Divide

reflective method call: dispatch based on **run-time value** (in string)

```
object.[string]()
```

“static” folks

“web 2.0” developers

Bridge the divide to support both first-class **reflective** method call and **static checking** of reflection safety

Ensure reflection safety with **dependent-refinement type** expressing required **relationship**

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

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

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

Similar relationship for **array bounds** safety

```
class Iterator
 var idx : Int
 var buf : Obj[] | indexedBy idx

 def get(): Obj
  return this.buf[this.idx]
```

Similar relationship for **array bounds** safety

`idx` must be a valid index into `buf`

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idx must be a valid index into **buf**

Guarantees **no** "ArrayOutOfBounds" **error**

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These kinds of **relationships** are important to **many safety properties**

Updating relationship causes **type error**

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Field type says: `obj` must **always** respond to `sel`

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`o` guaranteed to respond to `s`

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False alarm: no runtime error

Two styles of **reasoning** to determine **false alarm**

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Reasoning by global **invariant**: call safe if **relationship holds**

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Reasoning about **effects** of **imperative updates**

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Reasoning about **effects of imperative updates**

Relationship violated

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Reasoning about **effects of imperative updates**

Relationship violated

Relationship restored

Reasoning by global **invariant**: call safe if **relationship holds**

Idea: **Selectively alternate** between **reasoning styles** in verification

Fissile Type Analysis **combines** two styles of **reasoning**

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Automated **reasoning**
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$\Gamma \vdash \cdots$

Flow-Insensitive Type Systems

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Automated **reasoning** about **execution**

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$$\gamma(\cdot) = \cdots$$

Abstract Interpretation/ Flow Analysis/ Model Checking

Verification of **almost-everywhere invariants** with **intertwined** type and flow analysis

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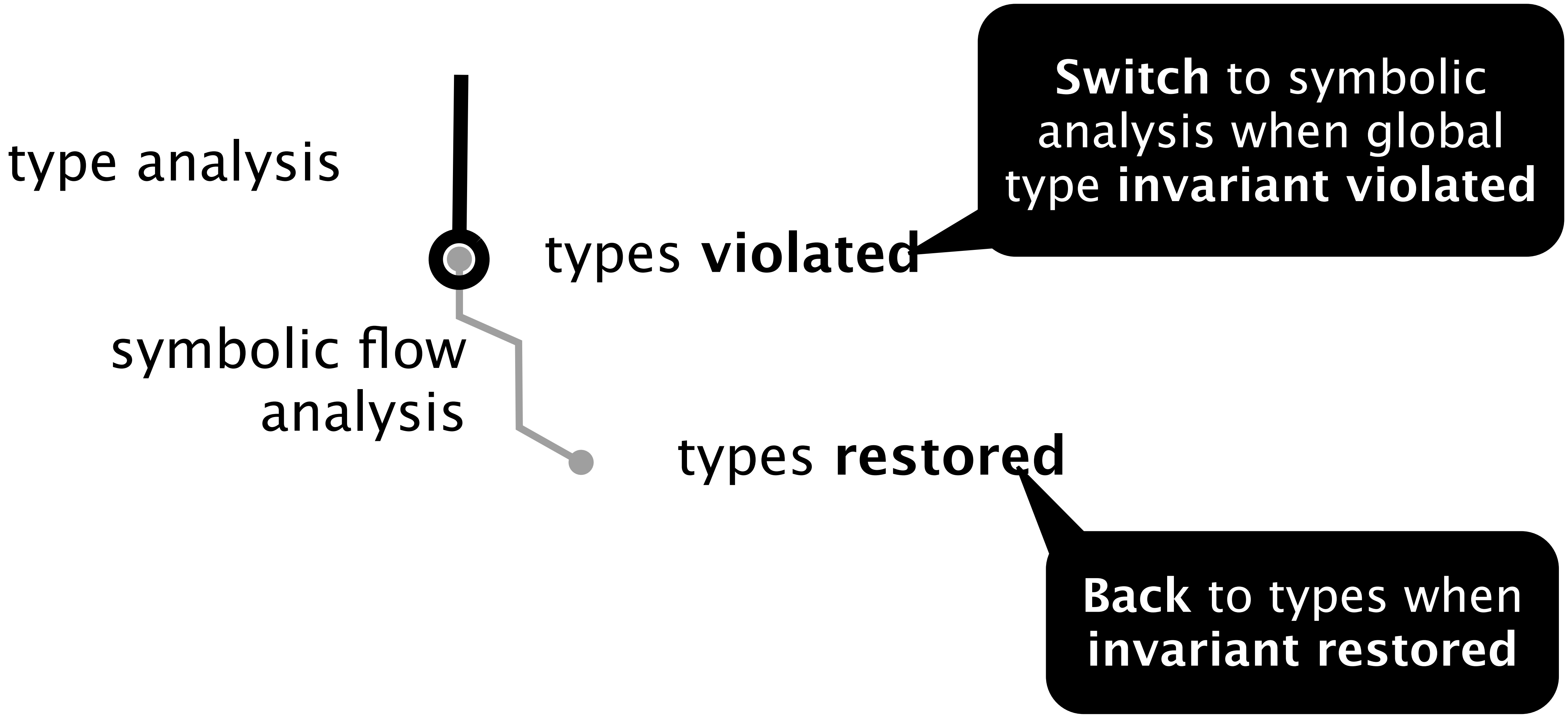
type analysis

types **violated**

Switch to symbolic analysis when global type **invariant violated**

Verification of **almost-everywhere invariants** with **intertwined** type and flow analysis



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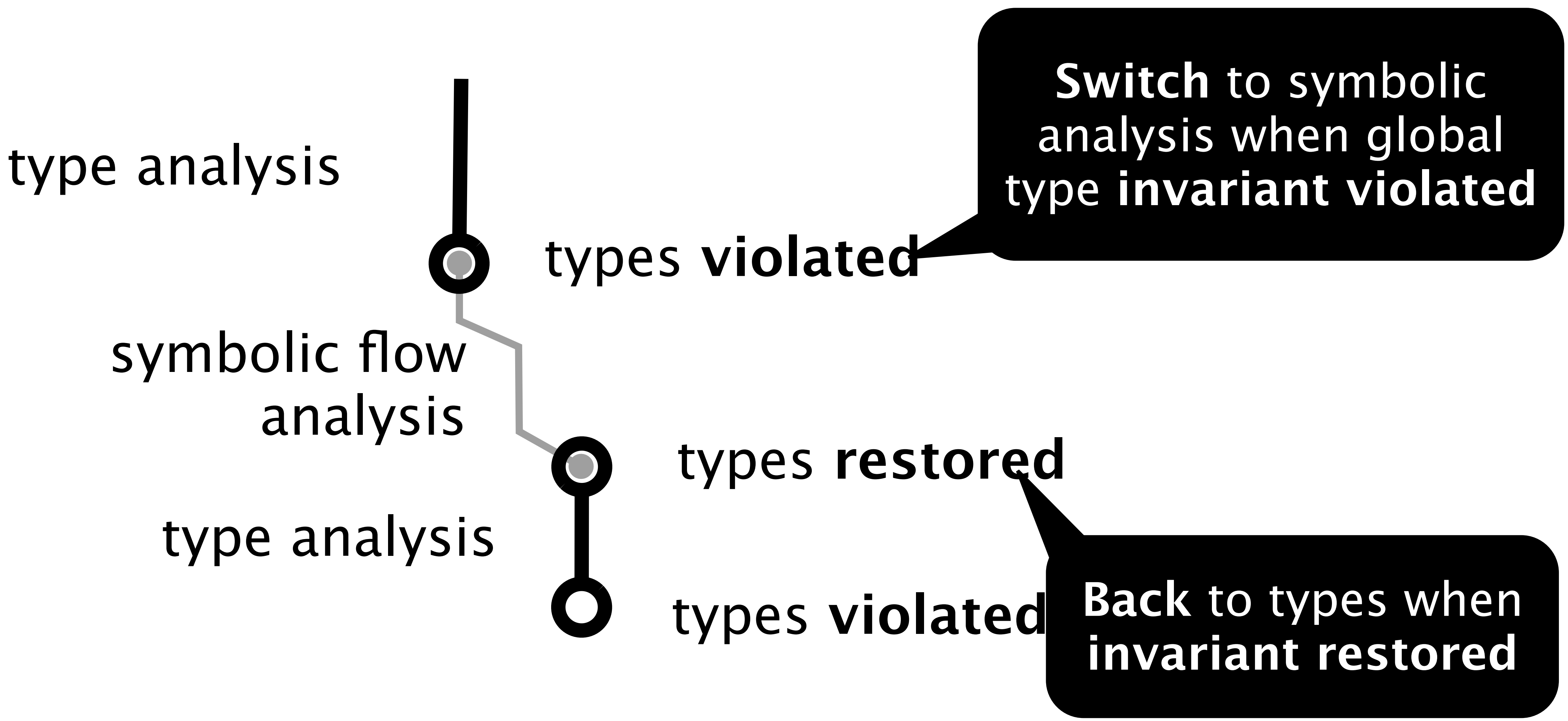

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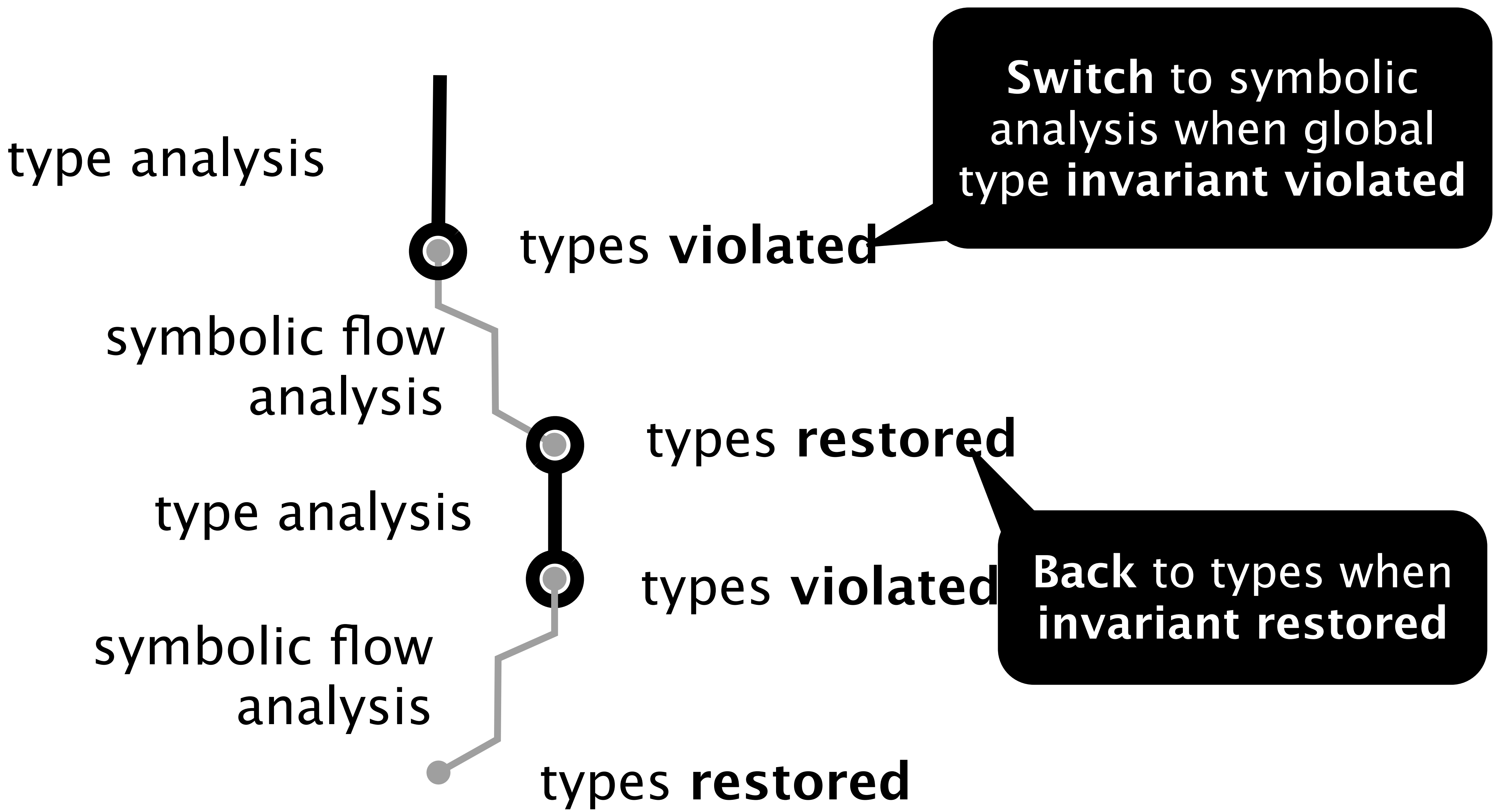

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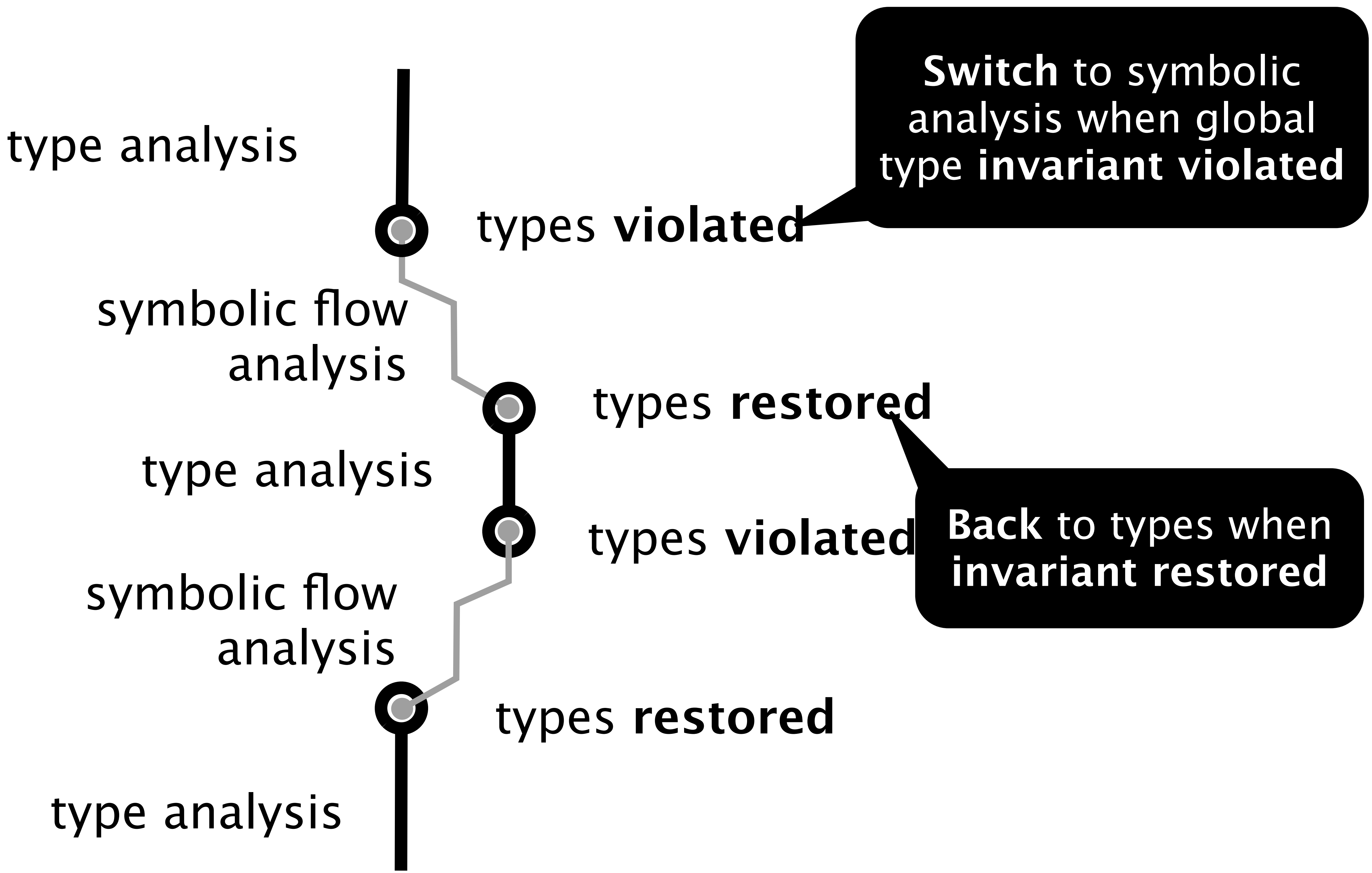

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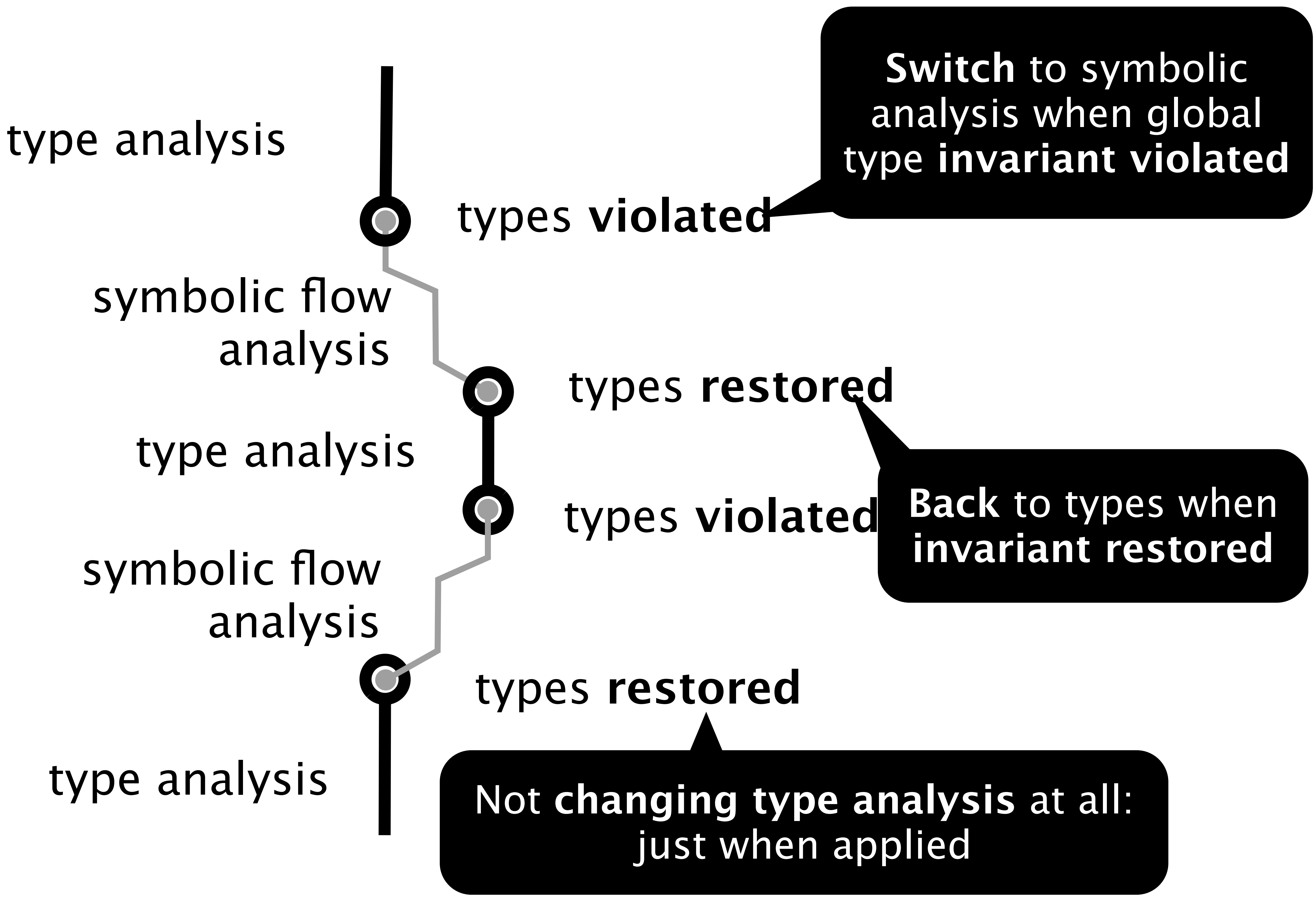

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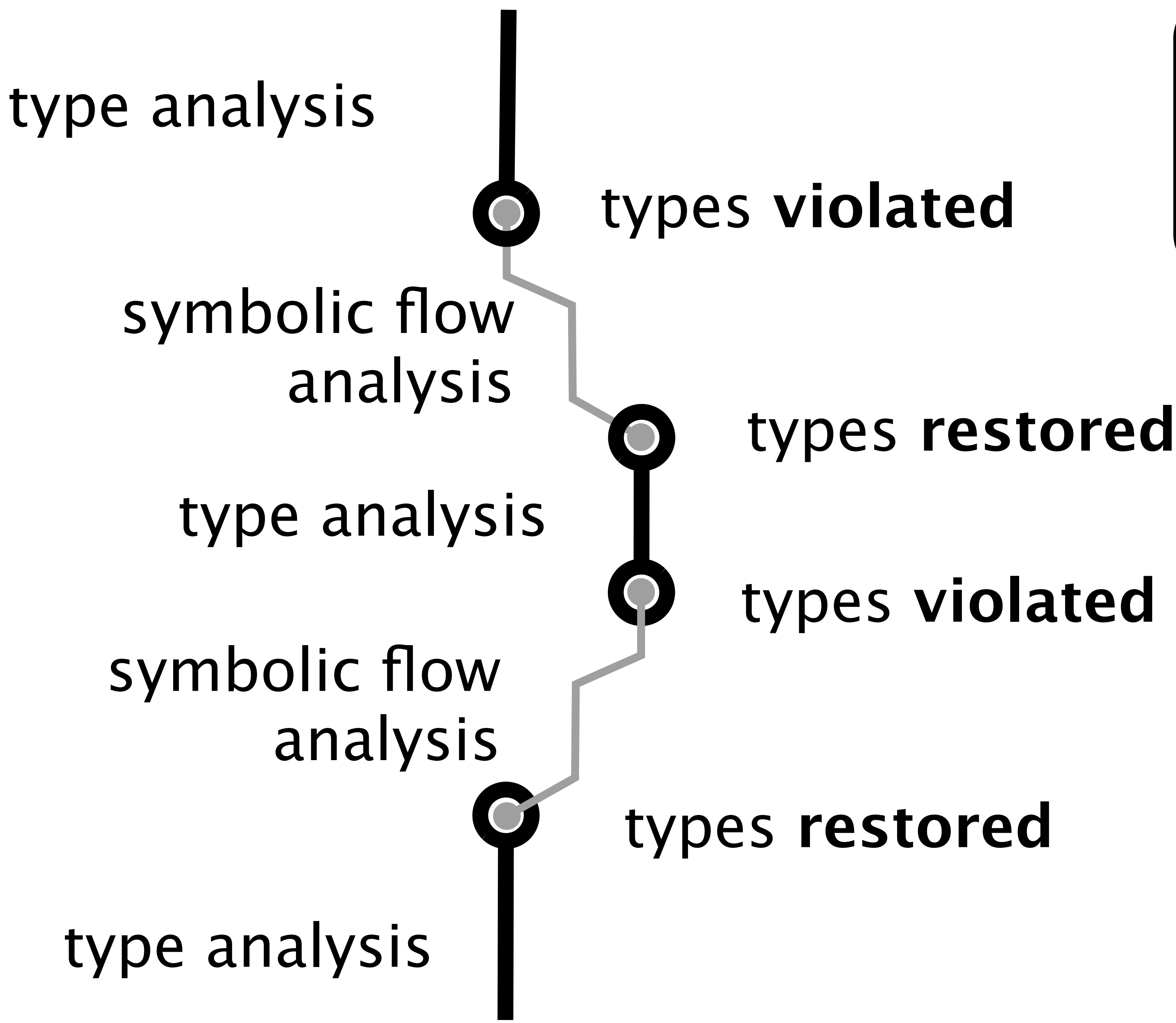
Effective when **global** type **invariant holds most of the time**



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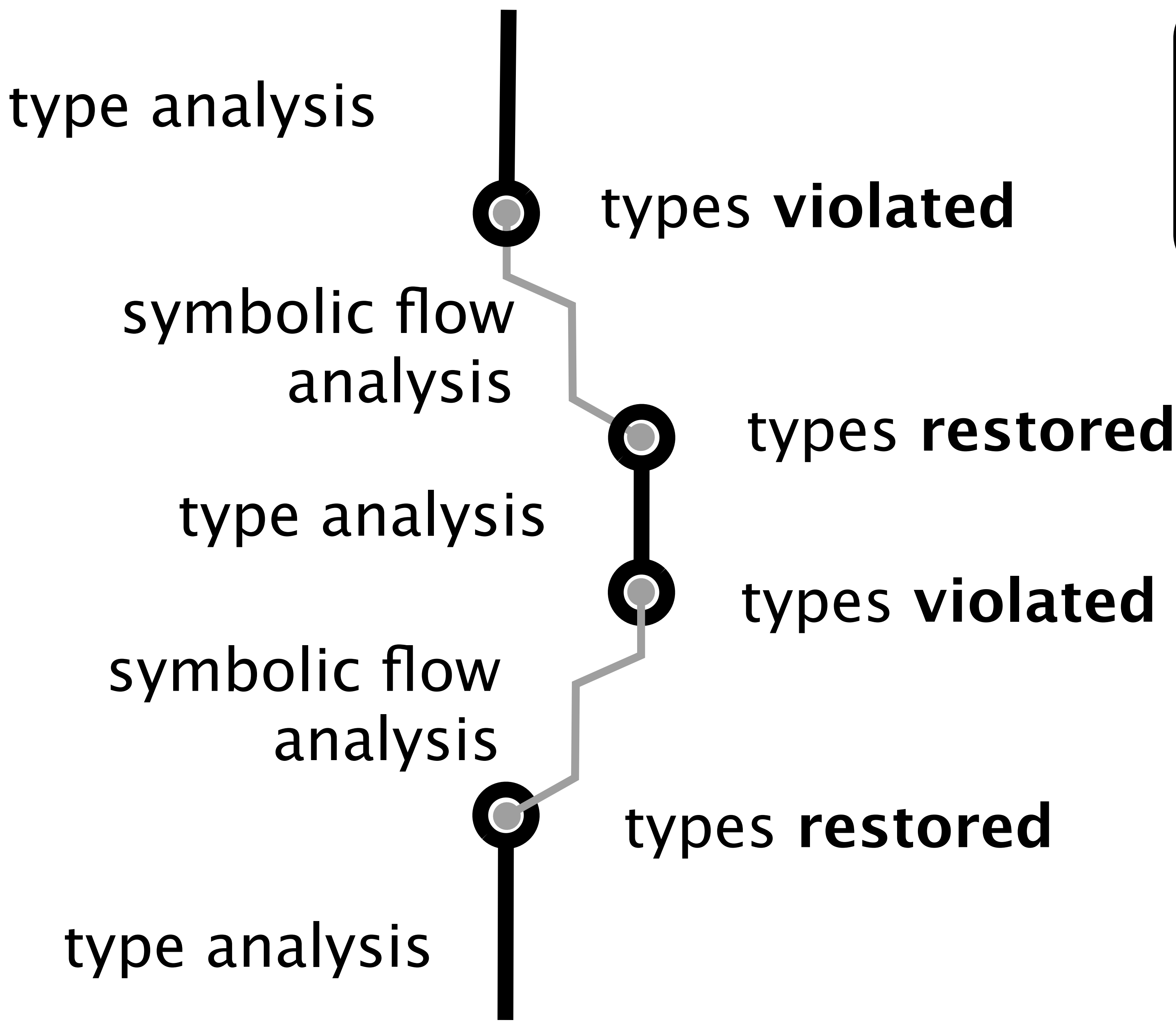

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- **Relationship updates**

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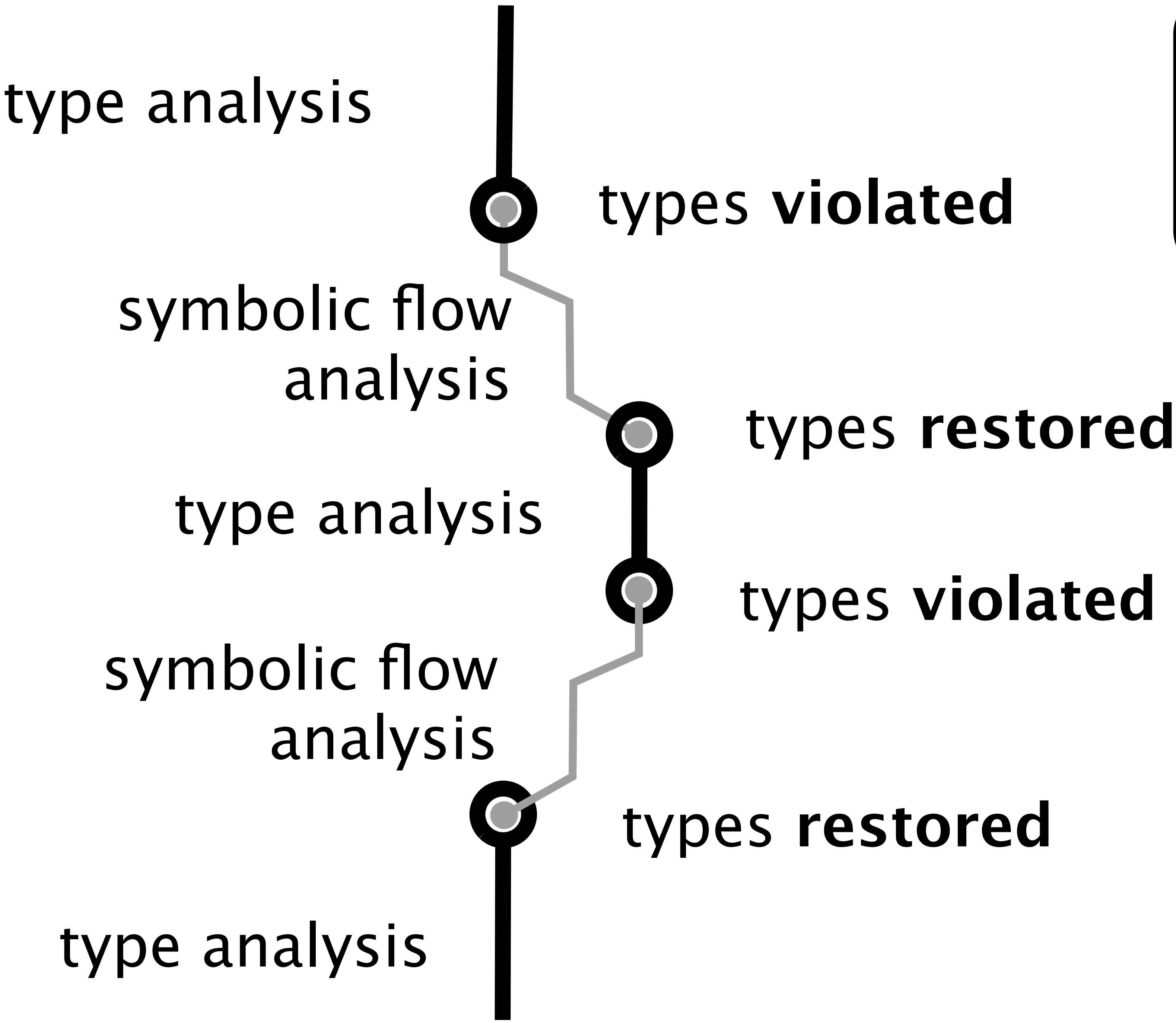

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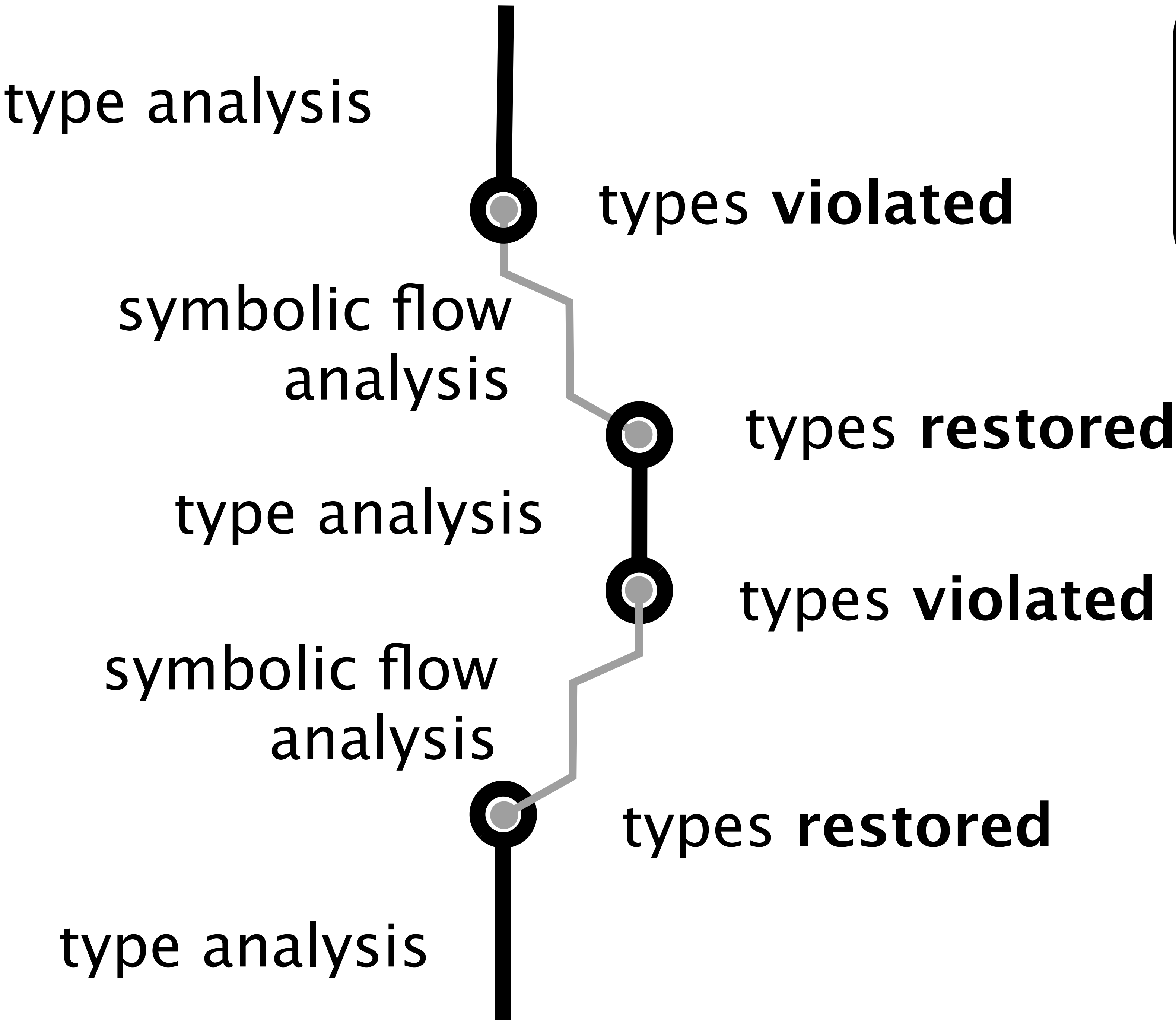

Effective when **global** type **invariant holds most of the time**

- **Relationship updates**
- **Occurrence typing**
- **Tagged unions**

Play to the **strengths** of each intertwined **analysis**

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Flow-Insensitive Types

- Easy to **specify global** invariants
- **Fast**
- Natural for **modular** reasoning
- Good **error reporting**

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Symbolic Flow Analysis

Natural for **local** reasoning about **heap mutation**
Precise
Can be disjunctive/path-sensitive

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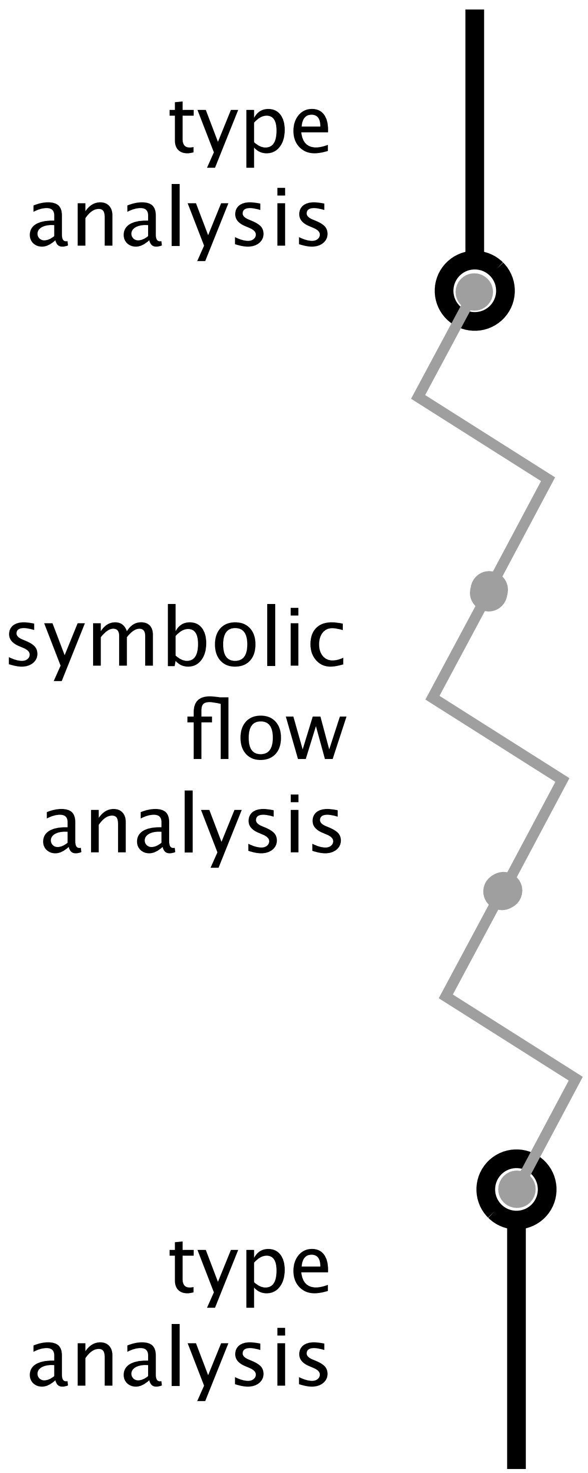
Complexity lies in **handoff** between analyses and in **symbolic analysis**

Key Contributions



1. **Translate** type invariant into symbolic state via **“symbolization”** of type environment

2. **Leverage** heap type invariant during symbolic analysis via **type-consistent materialization** and **summarization**

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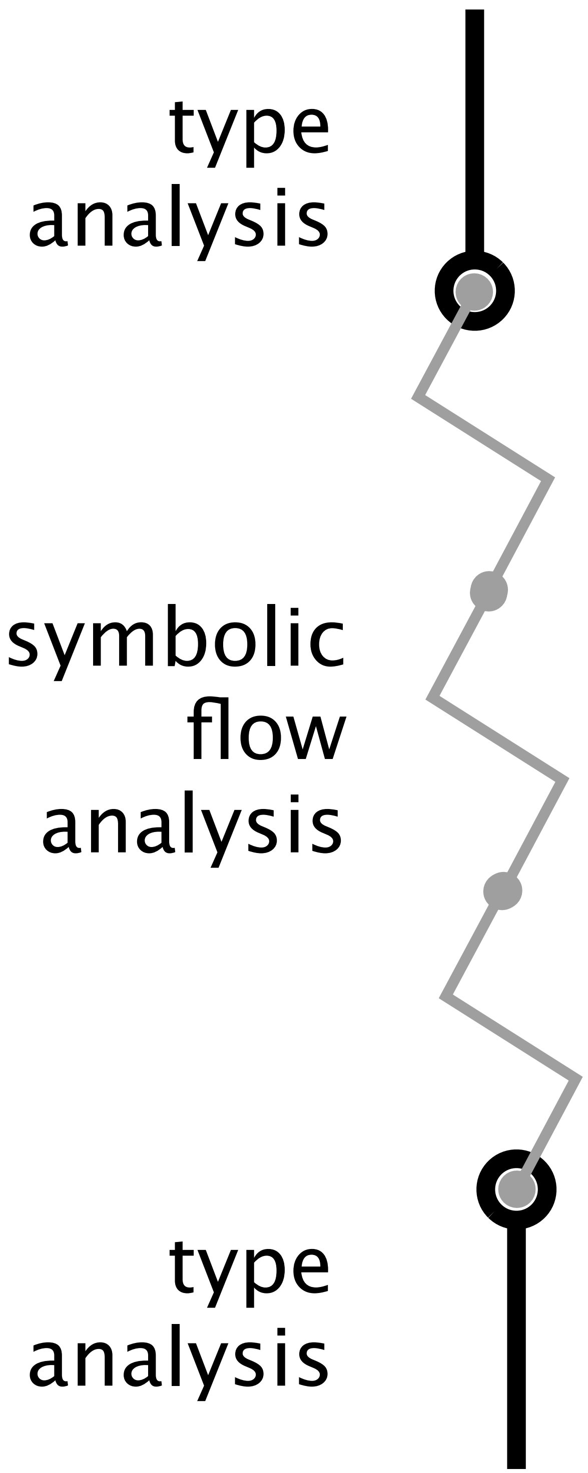

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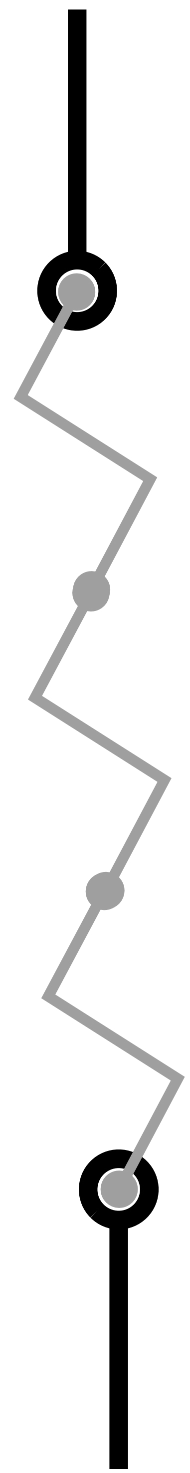

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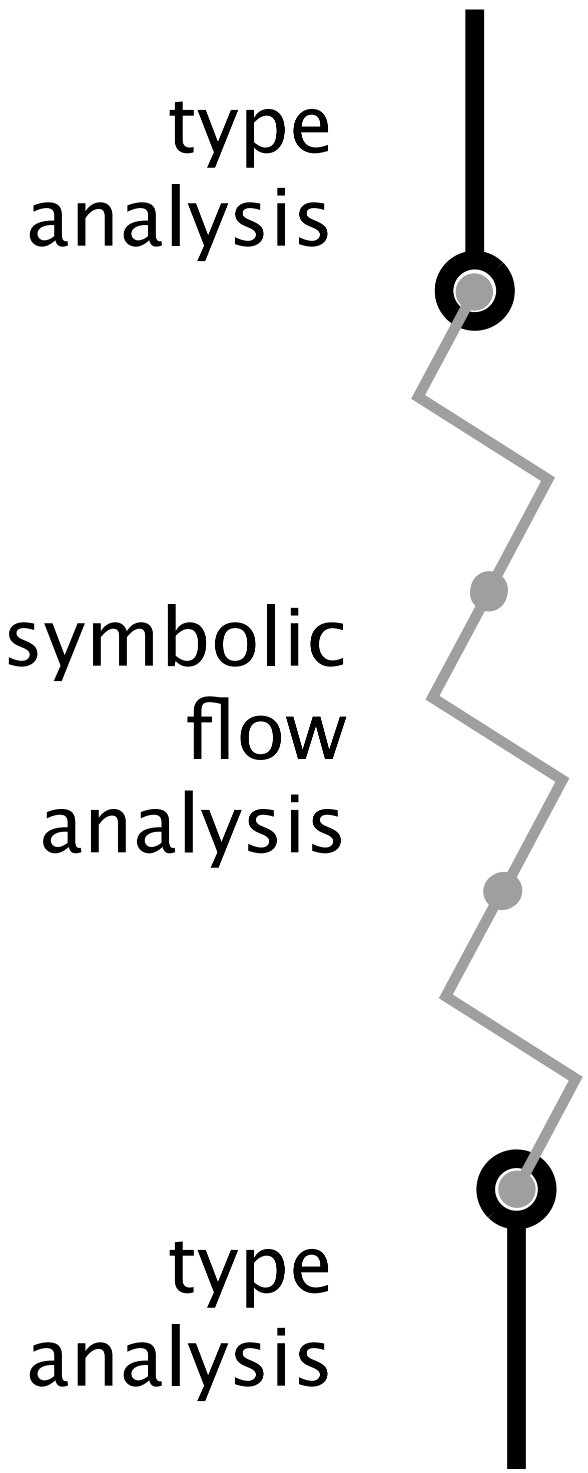

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Symbolization splits a **type environment** into **facts** about **values** and **storage** for those values

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Type environment

Maps local **variables** to dependent **types**

$$\Gamma \quad \begin{array}{l} s : \mathsf{Str} \\ o : \mathsf{Obj} \mid \mathsf{r2}\ s \\ \mathrm{this} : \mathsf{Callback} \end{array}$$

Refinements refer to **variables**

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symbolize $\longrightarrow$

Symbolic state

$$\widetilde{\mathrm{E}} \quad \begin{array}{l} \mathrm{s} : \widetilde{\mathrm{s}} \\ \mathrm{o} : \widetilde{\mathrm{o}} \\ \mathrm{this} : \widetilde{\mathrm{t}} \end{array}$$

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Maps local variables to symbolic **values**

Symbolic state

$$\widetilde{E} \quad \begin{array}{l} \mathrm{s} : \widetilde{\mathrm{s}} \\ \mathrm{o} : \widetilde{\mathrm{o}} \\ \mathrm{this} : \widetilde{\mathrm{t}} \end{array}$$

$$\widetilde{\Gamma} \quad \begin{array}{l} \widetilde{\mathrm{s}} : \mathsf{Str} \\ \widetilde{\mathrm{o}} : \mathsf{Obj} \mid \mathsf{r2}\ \widetilde{\mathrm{s}} \\ \widetilde{\mathrm{t}} : \mathsf{Callback} \end{array}$$

Symbolization splits a **type environment** into **facts** about **values** and **storage** for those values

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

Type environment

Maps local **variables** to dependent **types**

Γ $\begin{array}{l} s : \mathsf{Str} \\ o : \mathsf{Obj} \mid \mathsf{r2}\ s \\ \mathit{this} : \mathsf{Callback} \end{array}$

Refinements refer to **variables**

symbolize $\longrightarrow$

Maps local variables to symbolic **values**

Maps symbolic values to dependent types **lifted** to symbolic values (**symbolic facts**)

Symbolic state

$\widetilde{E}$ $\begin{array}{l} s : \widetilde{s} \\ o : \widetilde{o} \\ \mathit{this} : \widetilde{t} \end{array}$

$\widetilde{\Gamma}$ $\begin{array}{l} \widetilde{s} : \mathsf{Str} \\ \widetilde{o} : \mathsf{Obj} \mid \mathsf{r2}\ \widetilde{s} \\ \widetilde{t} : \mathsf{Callback} \end{array}$

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Type environment

Maps local **variables** to dependent **types**

Γ
s : Str
o : Obj | r2 s
this : Callback

Refinements refer to **variables**

symbolize

Maps local variables to symbolic **values**

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Symbolic state

$\widetilde{E}$
$s : \widetilde{s}$
$o : \widetilde{o}$
$\mathrm{this} : \widetilde{t}$

$\widetilde{\Gamma}$
$\widetilde{s}$: Str
$\widetilde{o}$: Obj | r2 $\widetilde{s}$
$\widetilde{t}$: Callback

Refinements refer to **values**

Symbolization allows **local variables** to hold values **inconsistent** with **declared types**

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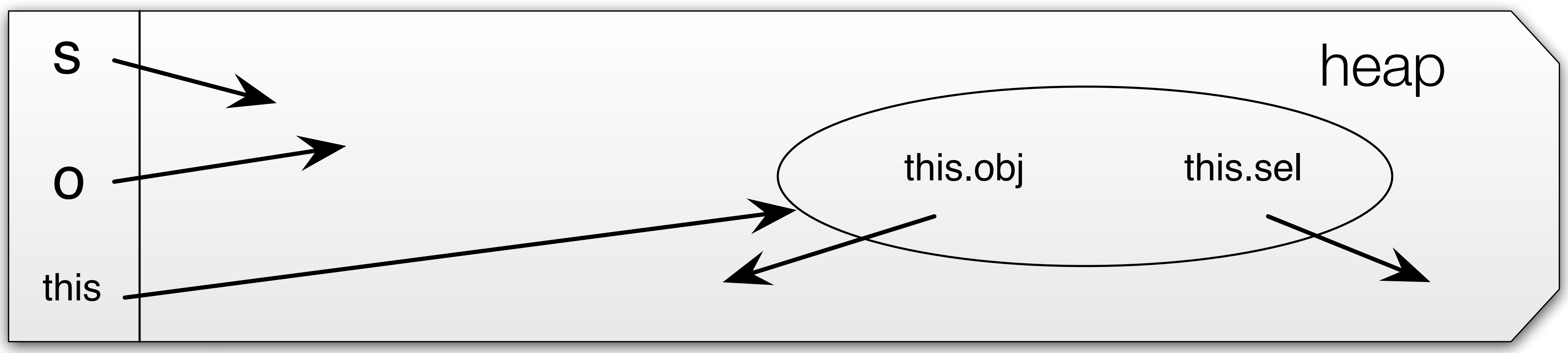

Symbolization allows **local variables** to hold values **inconsistent** with **declared types**

A type environment constrains local variables

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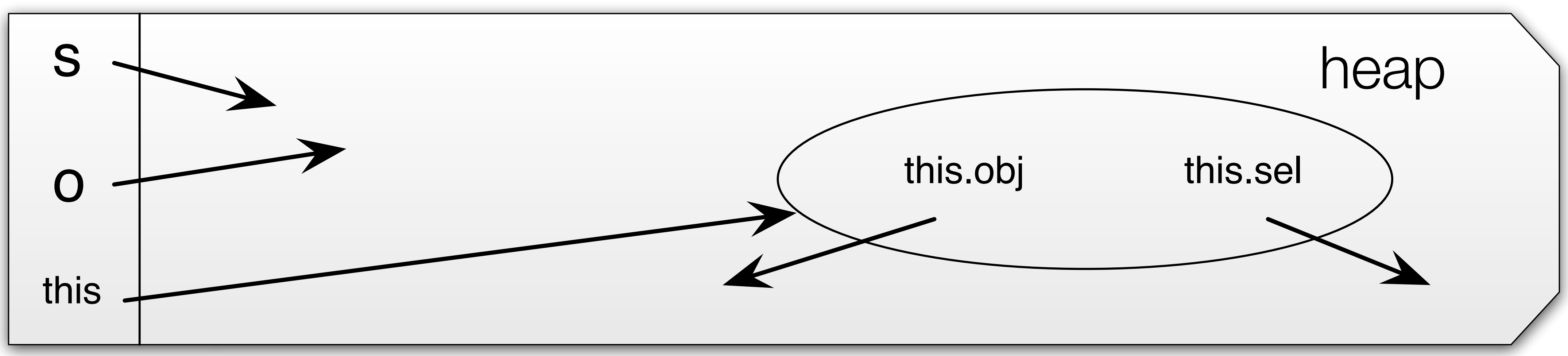

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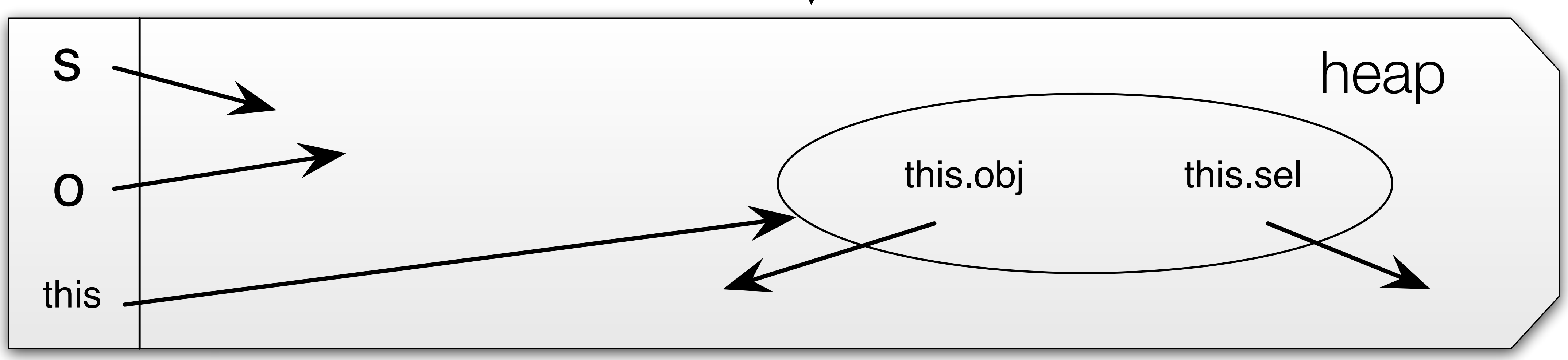
But also constrains the reachable heap to be **type-consistent**: fields must **conform** to **declared** types



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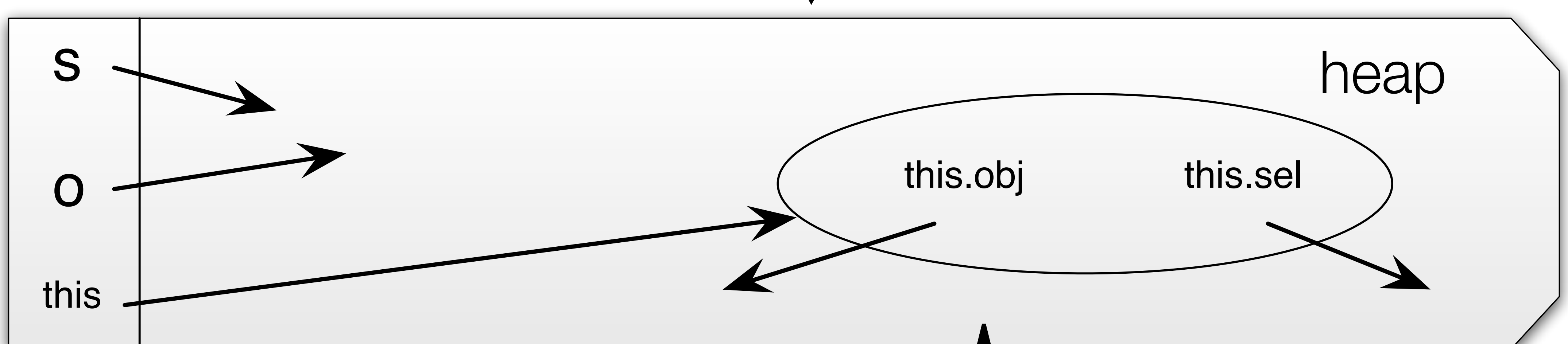

This picture captures the **fully type-consistent concrete** state

Symbolization allows **local variables** to hold values **inconsistent** with **declared types**

```
def update(s:Str, o:Obj | r2 s)
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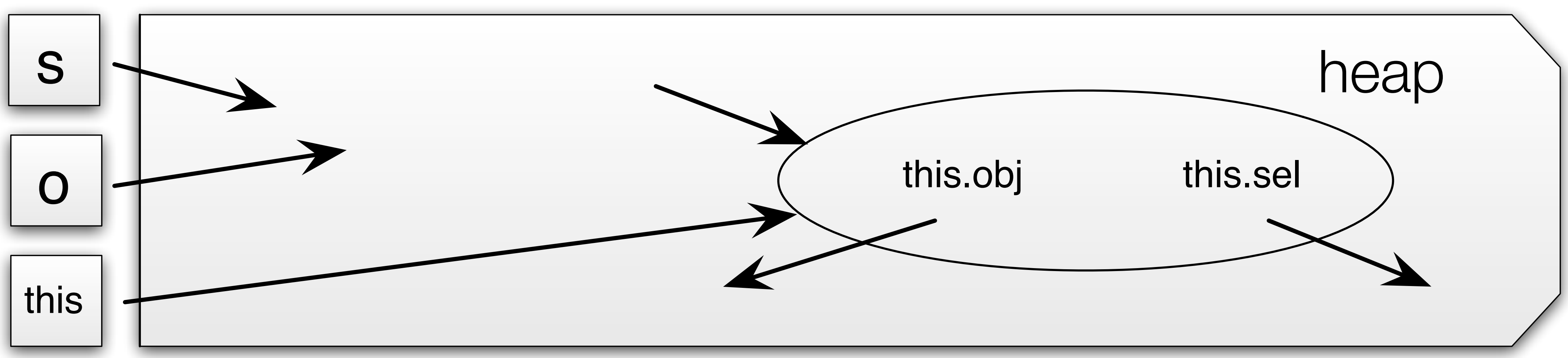
$$\Gamma \begin{array}{l} s : \mathsf{Str} \\ o : \mathsf{Obj} \mid \mathsf{r2}\ s \\ \mathrm{this} : \mathsf{Callback} \end{array} \xrightarrow{\textbf{symbolize}} \widetilde{\mathrm{E}} \quad \widetilde{\Gamma}$$



Symbolization allows **local variables** to hold values **inconsistent** with **declared types**

Symbolic environment
allows, e.g., int in s

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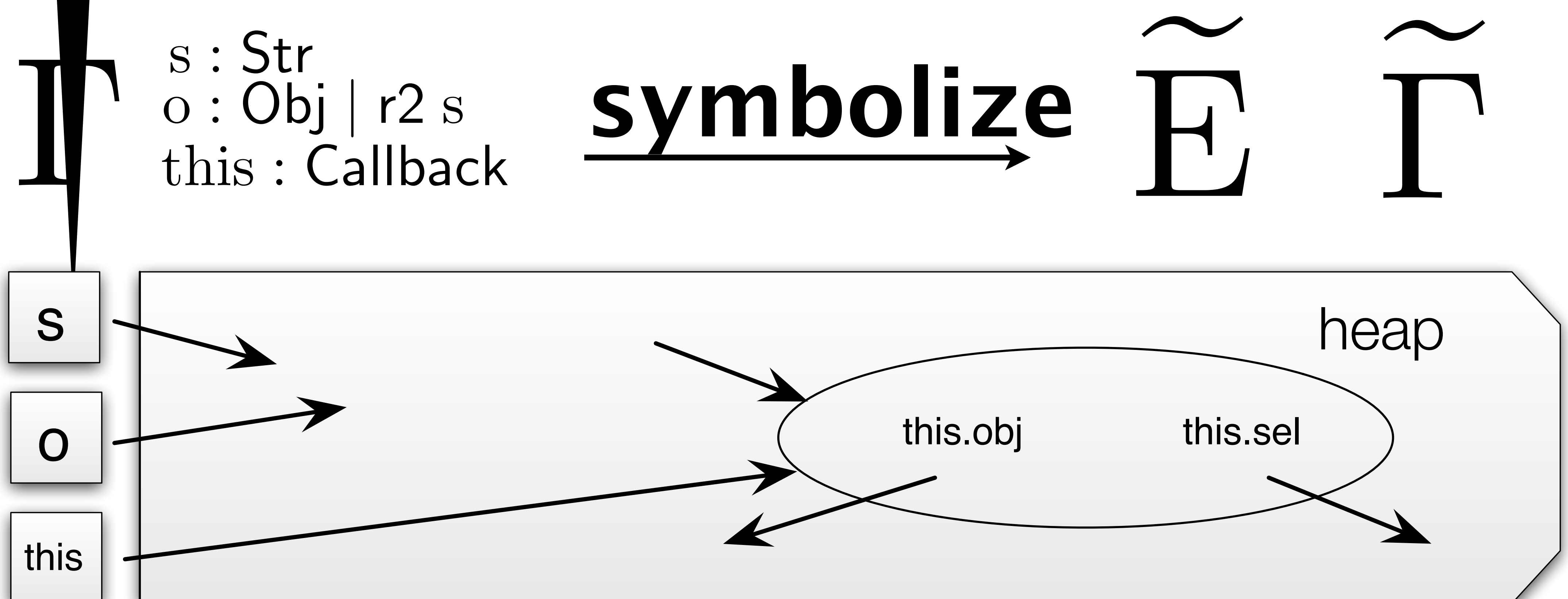

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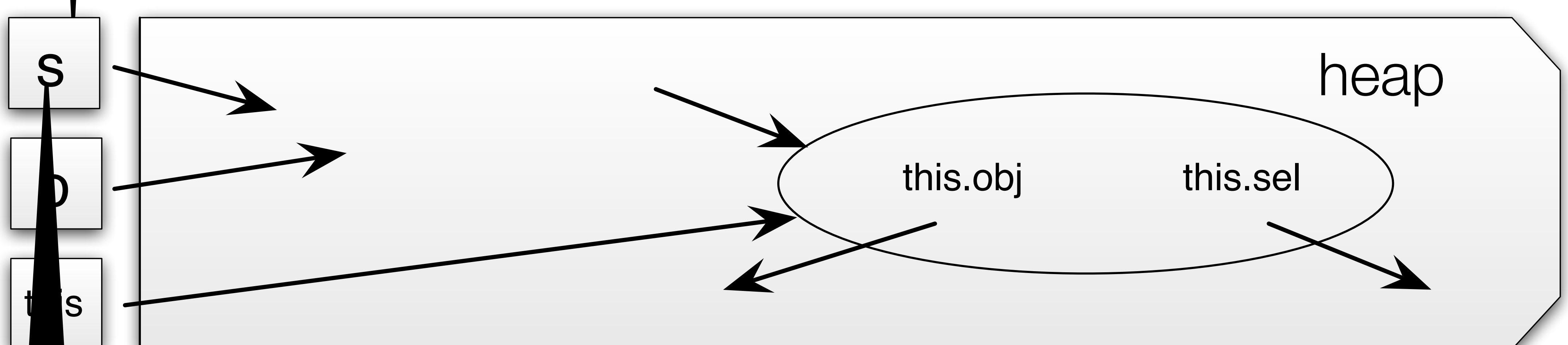

Immediately type-inconsistent: value stored **without dereferences violates** a type constraint

Symbolization allows **local variables** to hold values **inconsistent** with **declared types**

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allows, e.g., int in s

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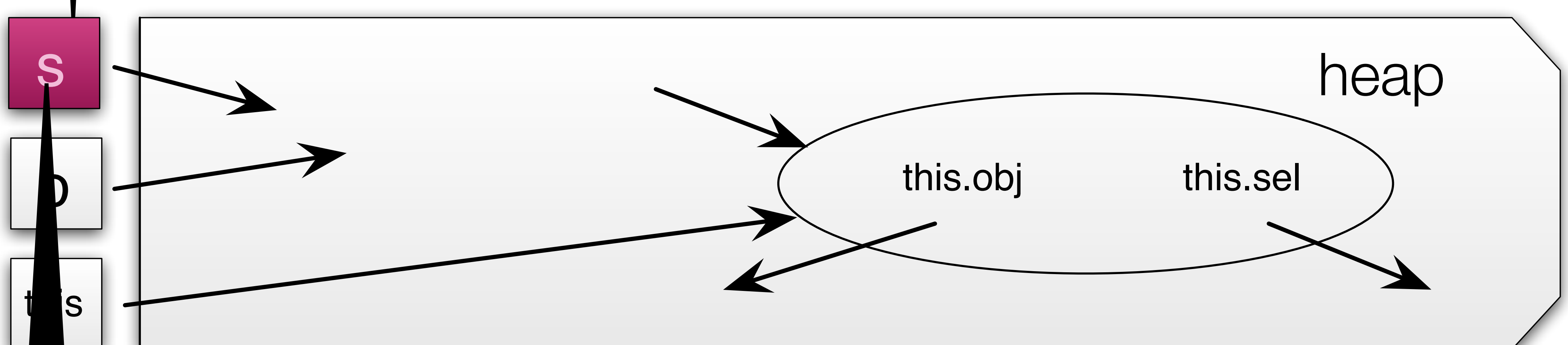
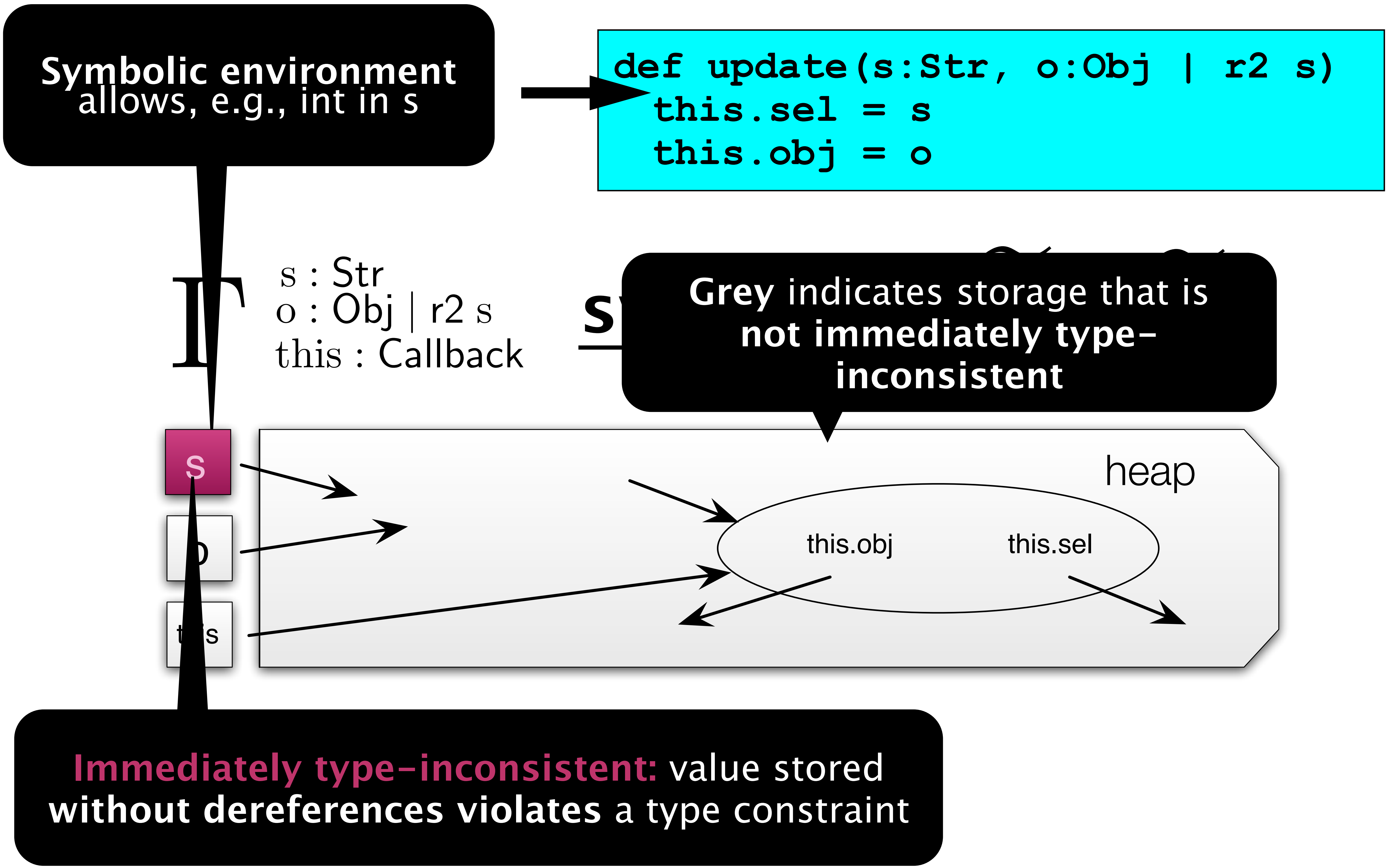


Immediately type-inconsistent: value stored **without dereferences violates** a type constraint

Symbolization allows **local variables** to hold values **inconsistent** with **declared types**



Symbolization **unpacks local cells**, but **symbolic facts** about **values** still **constrain the heap**

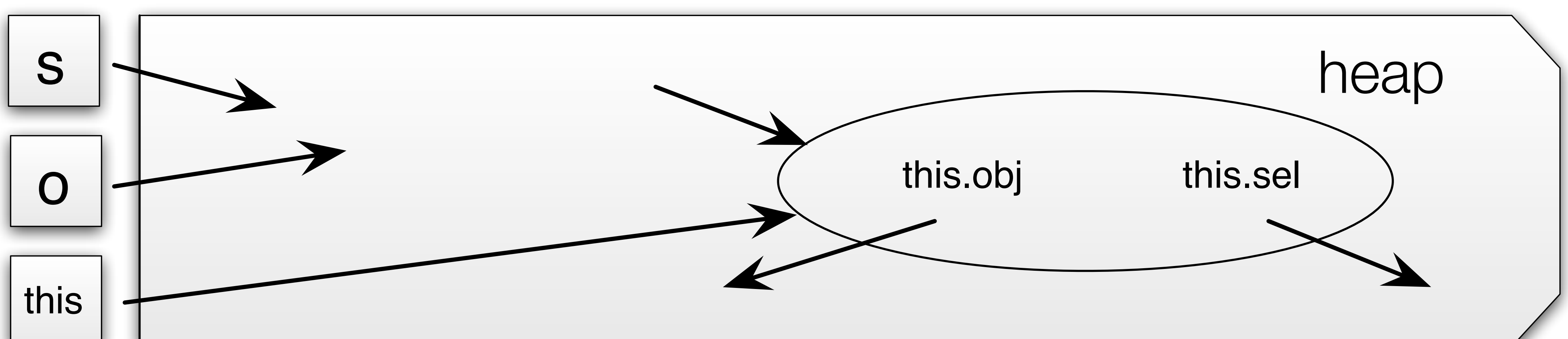
Type environment

$$\Gamma \quad \begin{array}{l} \mathrm{s} : \mathsf{Str} \\ \mathrm{o} : \mathsf{Obj} \mid \mathsf{r2}\ \mathrm{s} \\ \mathrm{this} : \mathsf{Callback} \end{array}$$

$\xrightarrow{\textbf{symbolize}}$

Symbolic fact map

$$\widetilde{\Gamma} \quad \begin{array}{l} \widetilde{\mathrm{s}} : \mathsf{Str} \\ \widetilde{\mathrm{o}} : \mathsf{Obj} \mid \mathsf{r2}\ \widetilde{\mathrm{s}} \\ \widetilde{\mathrm{t}} : \mathsf{Callback} \end{array}$$



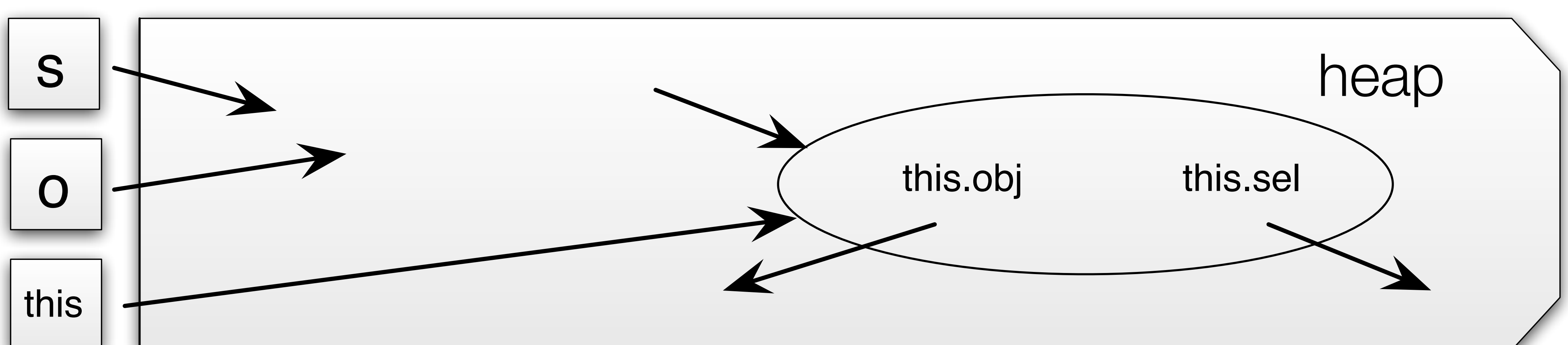
Symbolization **unpacks local cells**, but **symbolic facts** about **values** still **constrain the heap**

Type environment

Base types same on both sides

Symbolic fact map

$$\Gamma \quad \begin{array}{l} s : \mathsf{Str} \\ o : \mathsf{Obj} \mid \mathsf{r2}\ s \\ \mathrm{this} : \mathsf{Callback} \end{array} \quad \xrightarrow{\textbf{symbolize}} \quad \widetilde{\Gamma} \quad \begin{array}{l} \tilde{s} : \mathsf{Str} \\ \tilde{o} : \mathsf{Obj} \mid \mathsf{r2}\ \tilde{s} \\ \tilde{t} : \mathsf{Callback} \end{array}$$



Symbolization **unpacks local cells**, but **symbolic facts** about **values** still **constrain the heap**

Base types same on both sides

Type environment

$$\Gamma \quad \begin{array}{l} s : \mathsf{Str} \\ o : \mathsf{Obj} \mid \mathsf{r2}\ s \\ \mathrm{this} : \mathsf{Callback} \end{array}$$

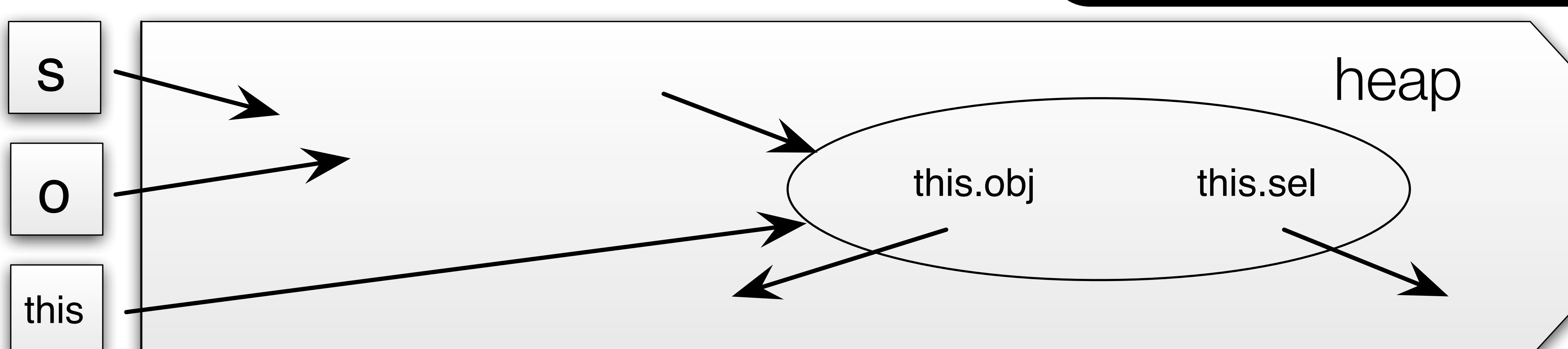
$$\xrightarrow{\textbf{symbolize}}$$

Symbolic fact map

$$\widetilde{\Gamma} \quad \begin{array}{l} \tilde{s} : \mathsf{Str} \\ \tilde{o} : \mathsf{Obj} \mid \mathsf{r2}\ \tilde{s} \\ \tilde{t} : \mathsf{Callback} \end{array}$$

$$\mathsf{Callback} \triangleq \{\mathrm{sel} : \mathsf{Str}, \mathrm{obj} : \mathsf{Obj} \mid \mathsf{r2}\ \mathrm{sel}\}$$

Base type field refinements still refer to **fields**



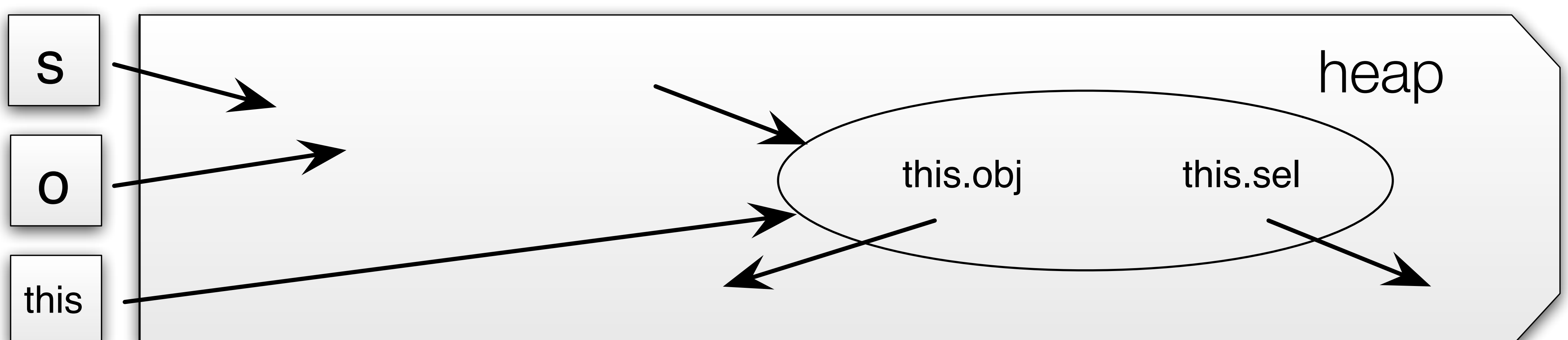
Summarize heap locations that are **not immediately type-inconsistent** with **okheap**

Symbolic Heap

$\widetilde{H}$ okheap

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

Concrete State



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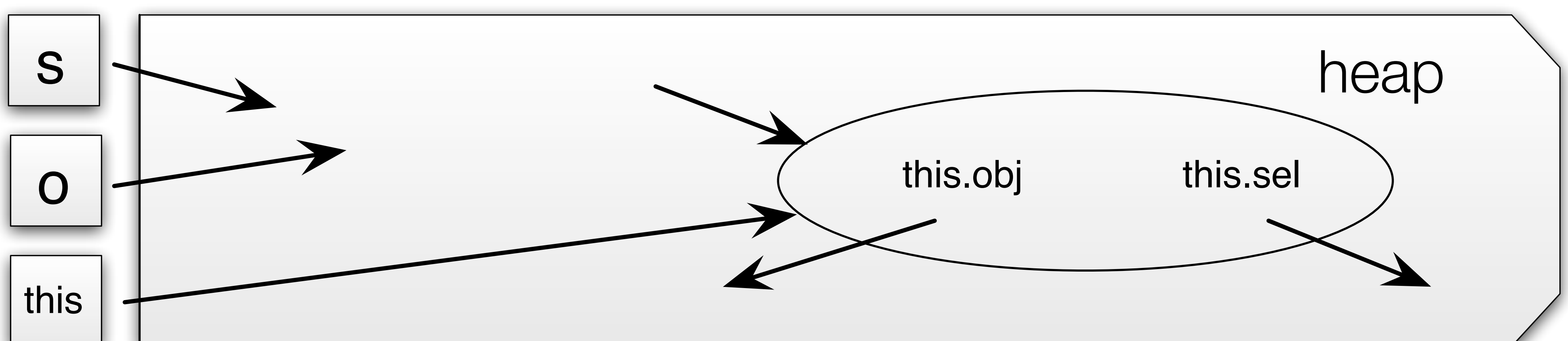

$\widetilde{H}$ okheap

Formula literal: **concretization** includes every subheap that is **not immediately type inconsistent**

Concrete State



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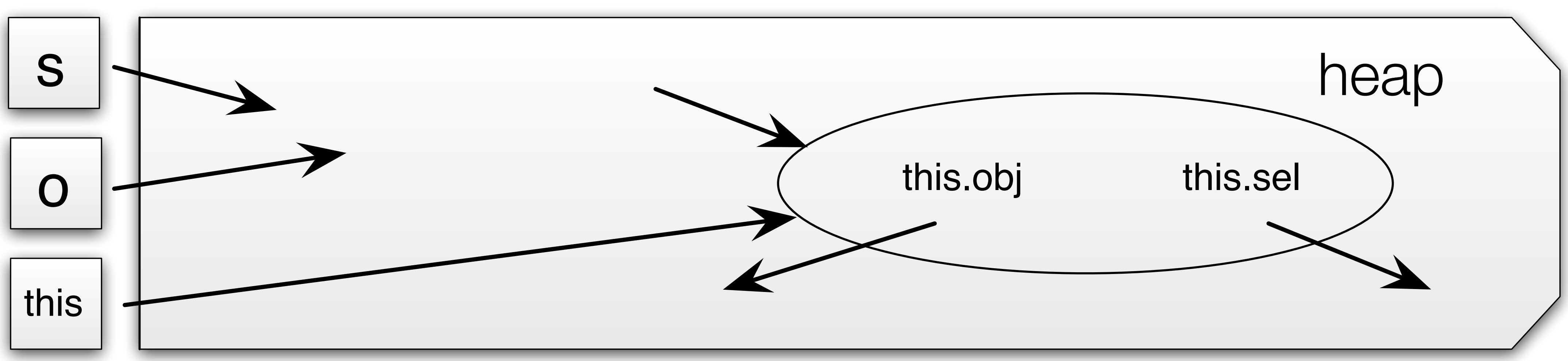
Describes storage **without explicitly enumerating it**

Concrete State



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Symbolic Heap

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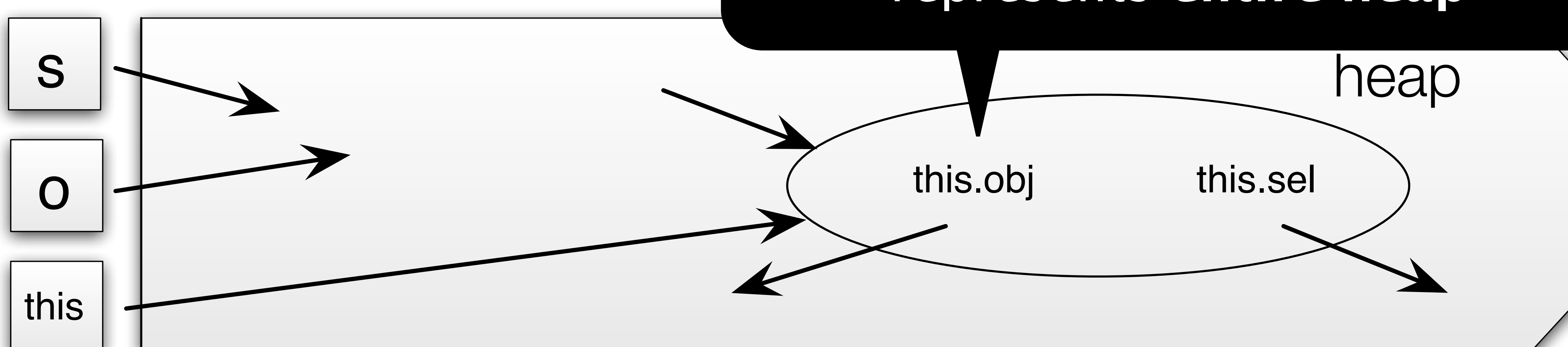
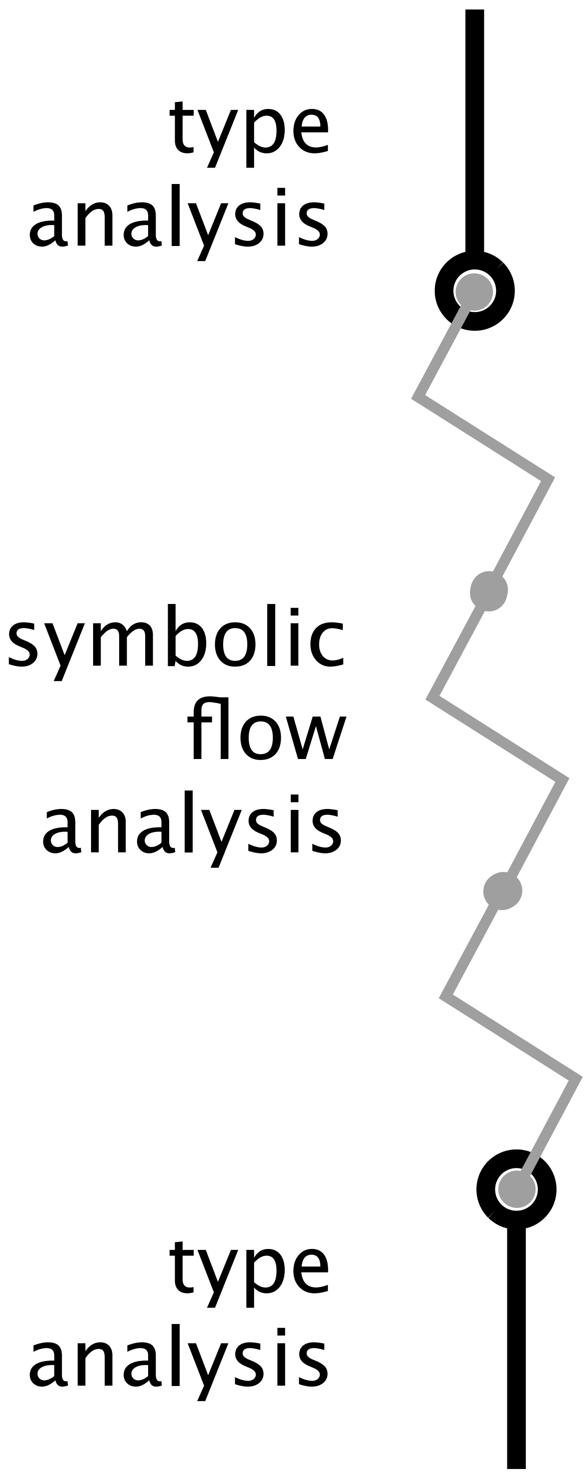
Describes storage **without explicitly enumerating it**

Concrete State

Immediately after switch, type **invariants still hold** so **okheap** represents **entire heap**



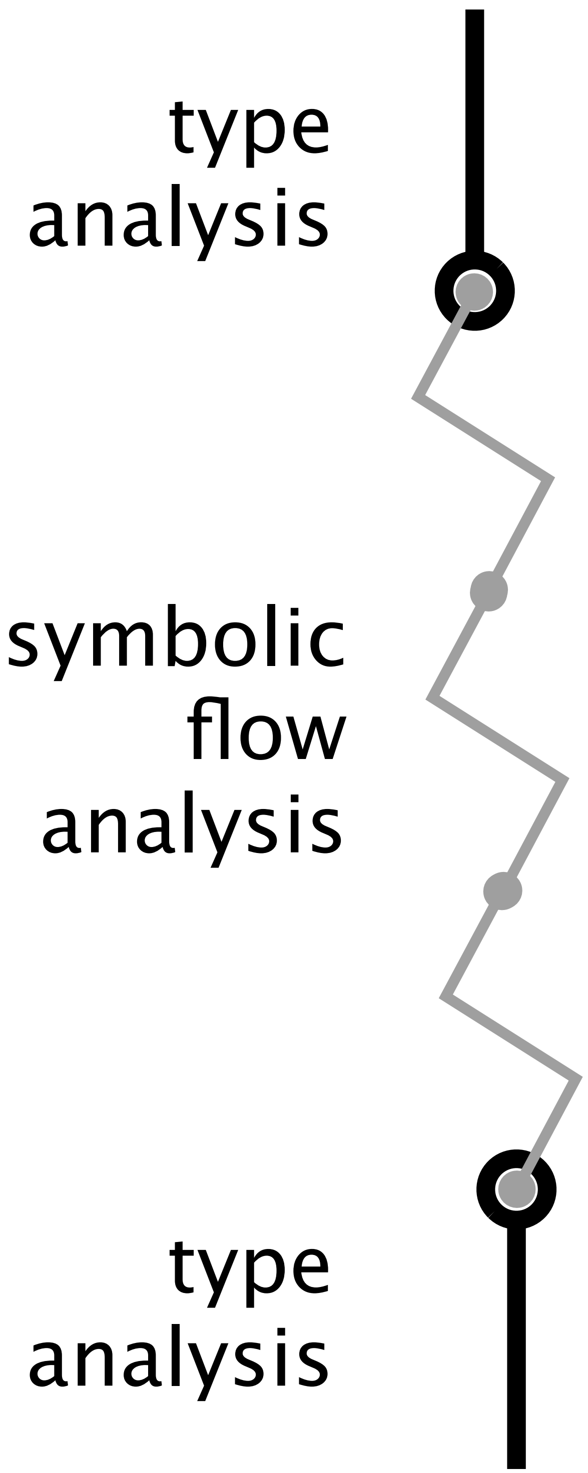
Key Contributions



1. **Translate** type invariant into symbolic state via **“symbolization”** of type environment

2. **Leverage** heap type invariant during symbolic analysis via **type-consistent materialization** and **summarization**

Key Contributions



1. **Translate** type invariant into symbolic state via **“symbolization”** of type environment

2. **Leverage** heap type invariant during symbolic analysis via **type-consistent materialization** and **summarization**

Leverage **heap type invariant** via **type-consistent materialization**

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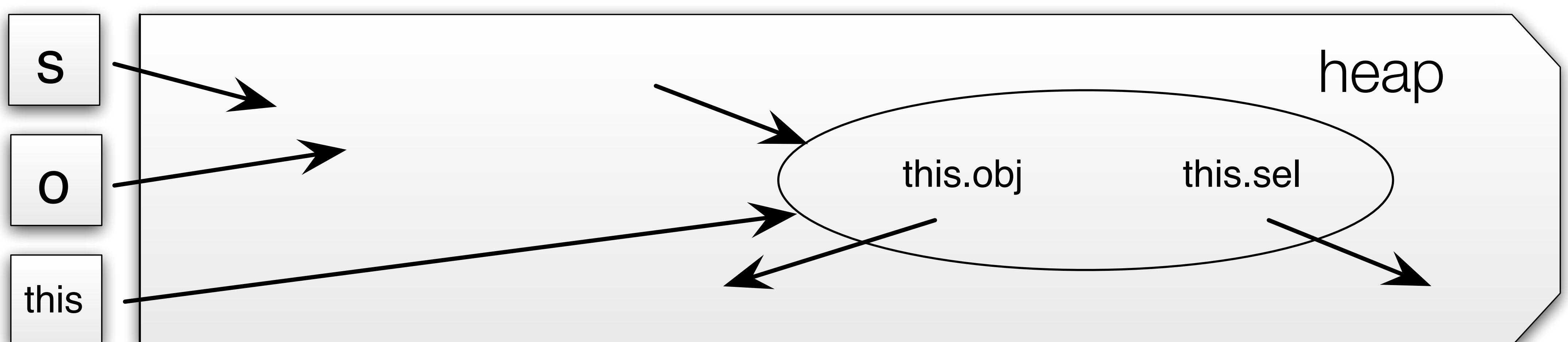

Symbolic State

$\widetilde{H}$ okheap

Concrete State



Leverage **heap type invariant** via **type-consistent materialization**

Materialize onto standard **separation-logic** explicit heap

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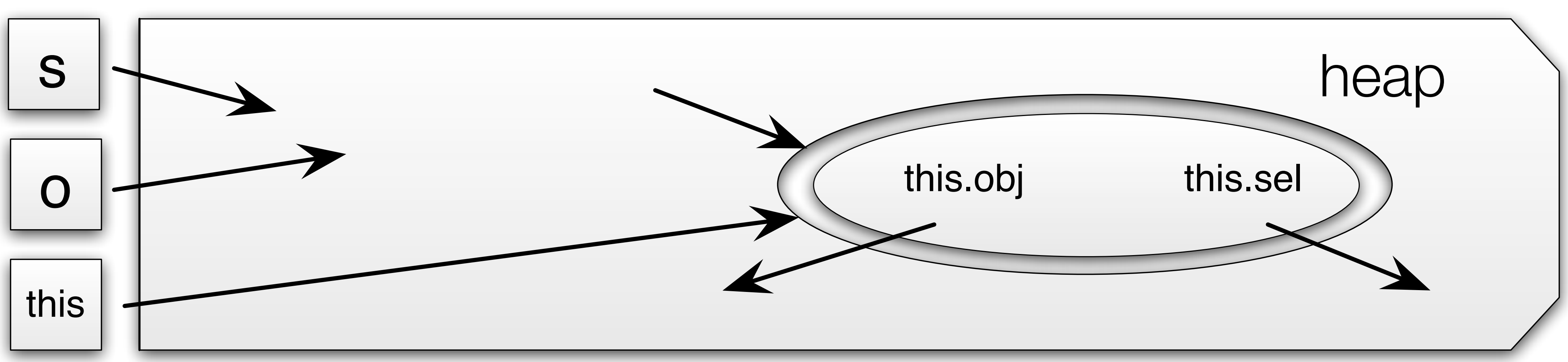

$$\widetilde{H} \qquad \text{okheap} \;*\; \widetilde{\text{this}} \mapsto \{\text{sel} \mapsto \widetilde{\text{sel}} * \text{obj} \mapsto \widetilde{\text{obj}}\}$$

Concrete State



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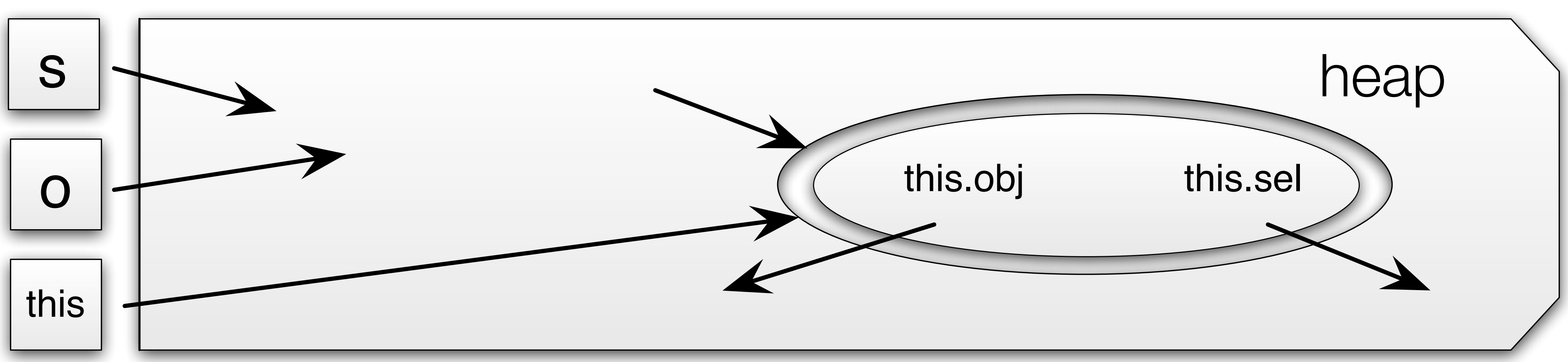
Must-alias and **disalias** guarantee requires **case split** on **materialization**

Concrete State



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def update(
  this.sel
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Materialized storage guaranteed to be **not immediately type-inconsistent**

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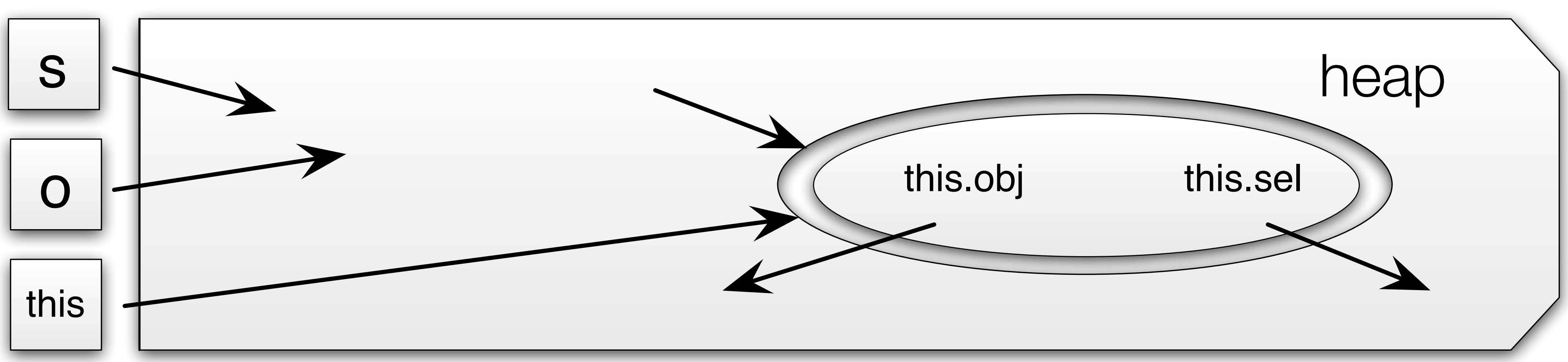

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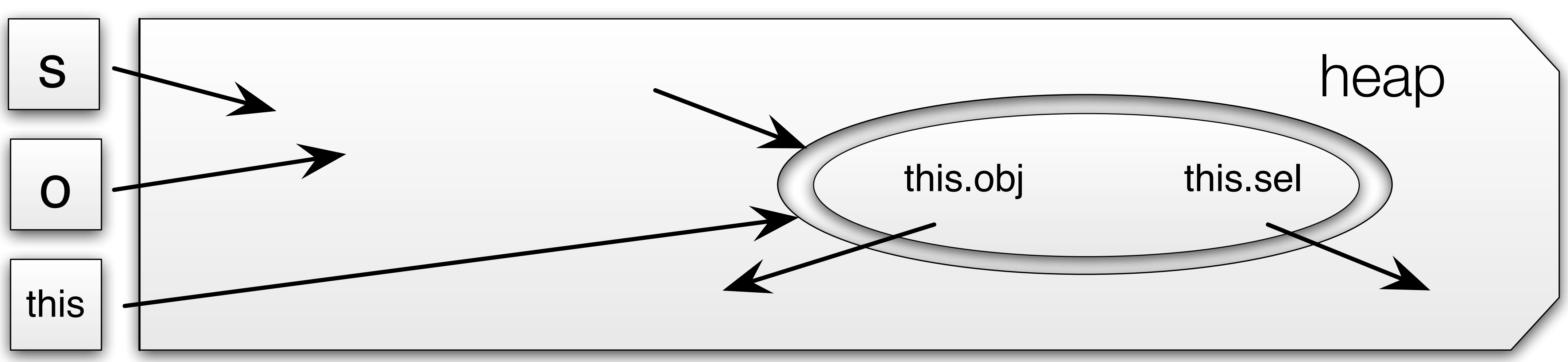
Value stored in `obj` **responds to** value stored in `sel`

Concrete State



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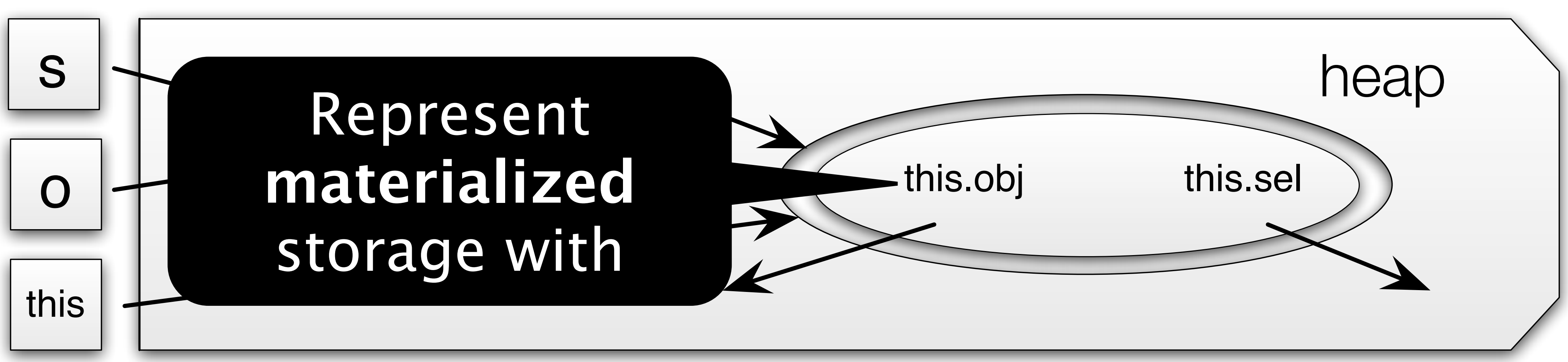

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Must-alias and **disalias** guarantee requires **case split** on **materialization**

Value stored in `obj` **responds to** value stored in `sel`

Concrete State

Analysis can assume that type invariant initially holds on all materialized storage

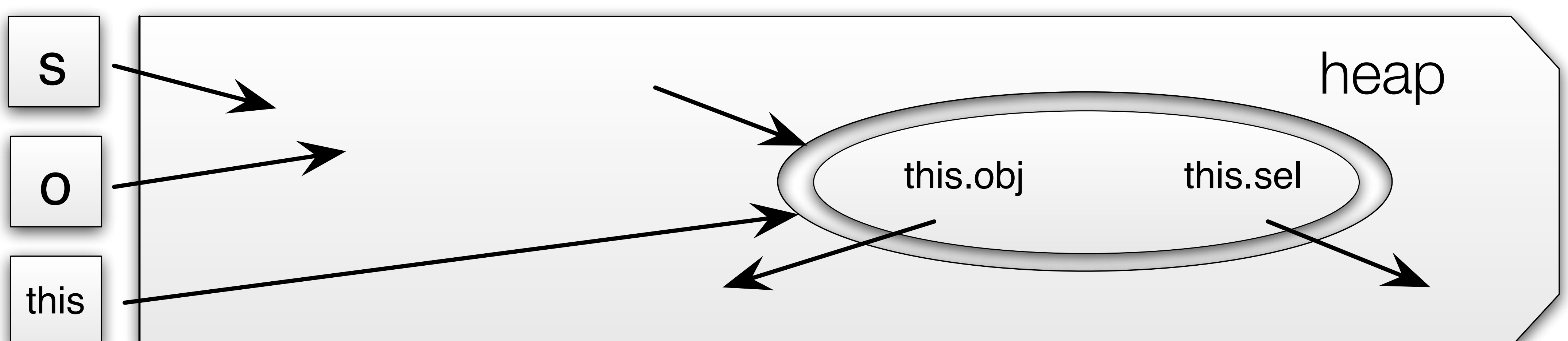
Strong updates on materialized storage to detect **invariant restoration**

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

Symbolic State

$$\widetilde{H} \qquad \text{okheap} \;*\; \widetilde{\text{this}} \mapsto \{\text{sel} \mapsto \widetilde{\text{sel}} * \text{obj} \mapsto \widetilde{\text{obj}}\}$$

Concrete State



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Symbolic State

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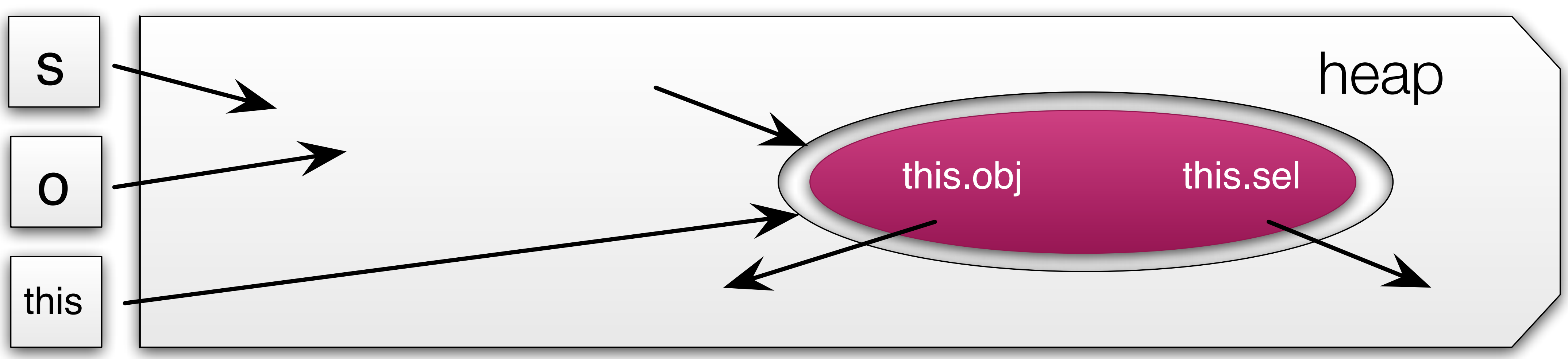
Concrete State



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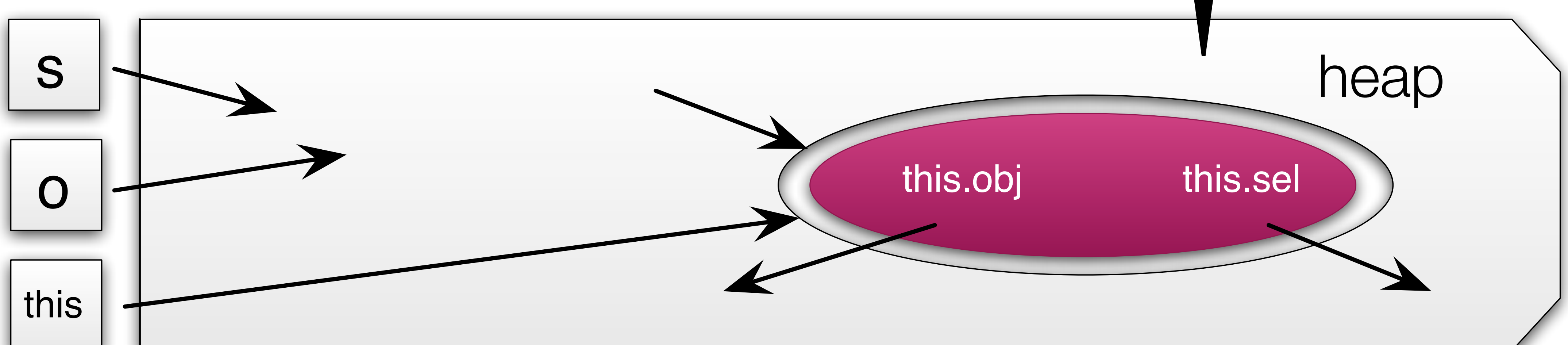
Symbolic State

$$\widetilde{H} \qquad \text{okheap} \; * \; \widetilde{\mathrm{this}} \mapsto \{\mathrm{sel} \mapsto \tilde{\mathrm{s}} * \mathrm{obj} \mapsto \widetilde{\mathrm{obj}}\}$$

Type invariant violated

Concrete State



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Symbolic State

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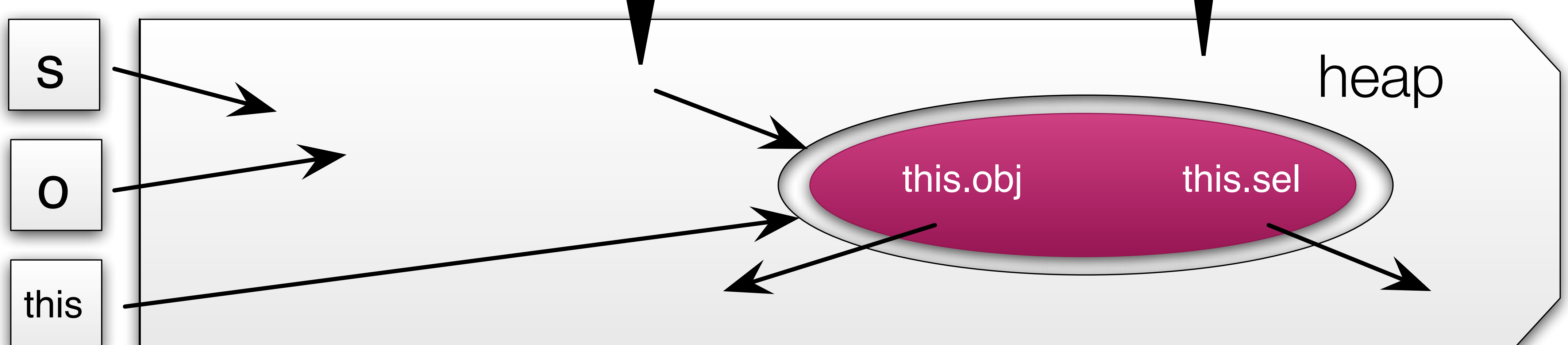
Surprising: can **soundly** permit **pointers in** and **out** of the region that is **not immediately type-inconsistent**

Type invariant **violated**



Strong updates on materialized storage to detect **invariant restoration**

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Symbolic State

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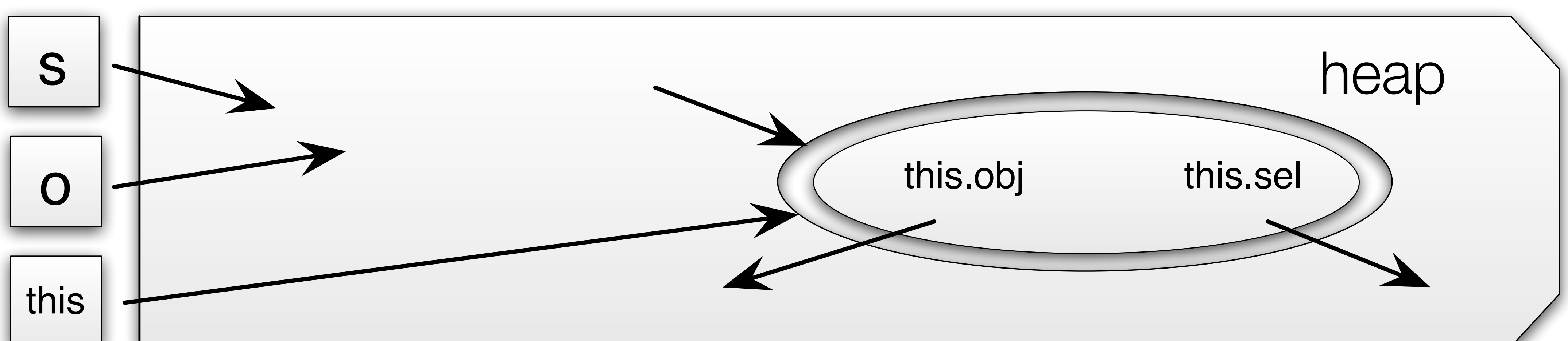
Concrete State



Strong updates on materialized storage to detect **invariant restoration**

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Symbolic State

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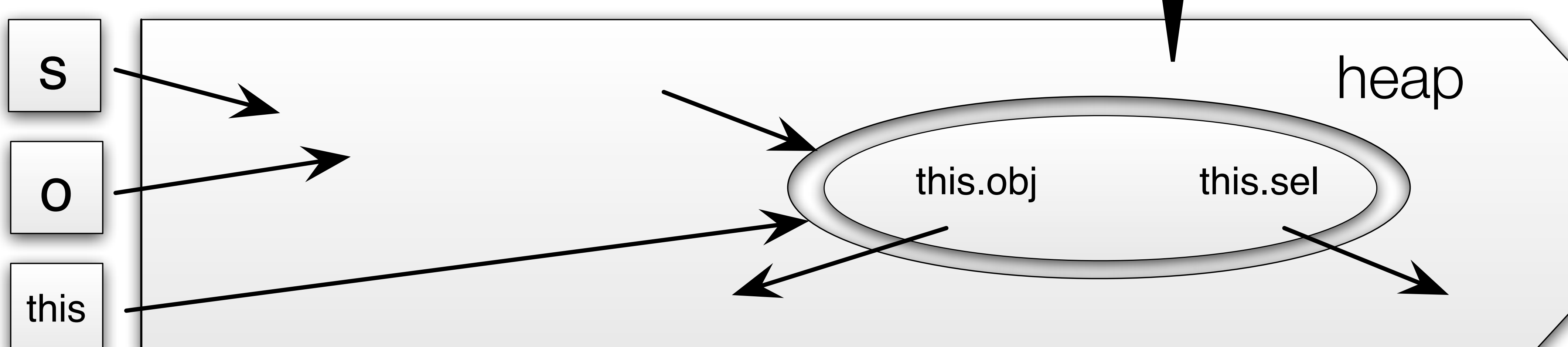
No longer immediately **type-inconsistent**

Concrete State



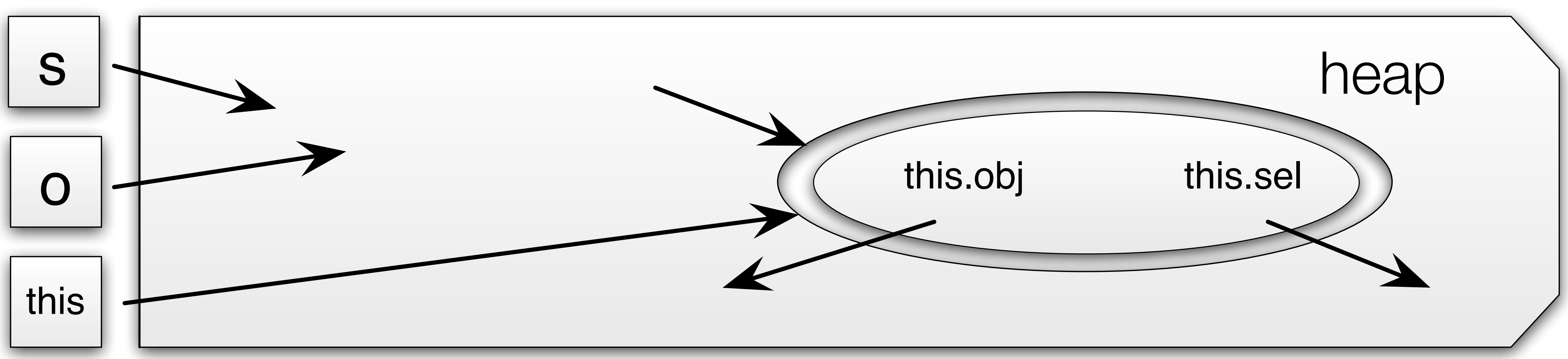
Safely **summarize** storage that is not immediately type inconsistent

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

Symbolic State

$$\widetilde{H} \qquad \text{okheap} \ * \ \widetilde{\text{this}} \mapsto \{\text{sel} \mapsto \tilde{\text{s}} * \text{obj} \mapsto \tilde{\text{o}} \}$$

Concrete State



Safely **summarize** storage that is not immediately type inconsistent

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Symbolic State

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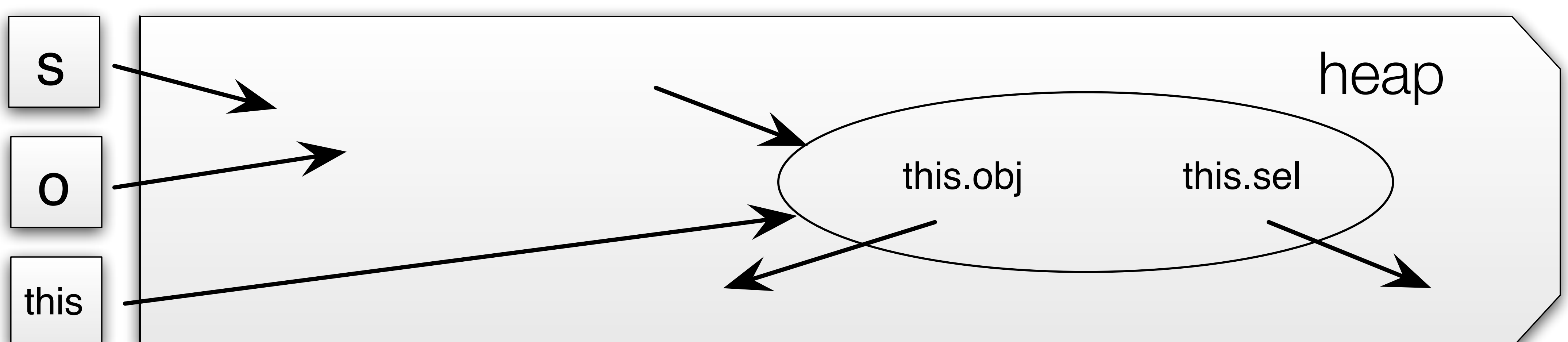

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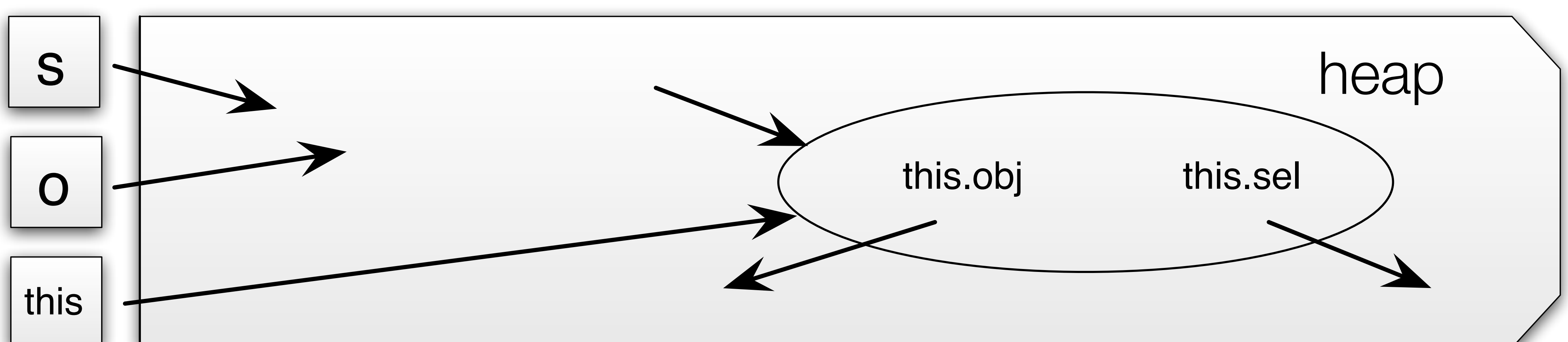

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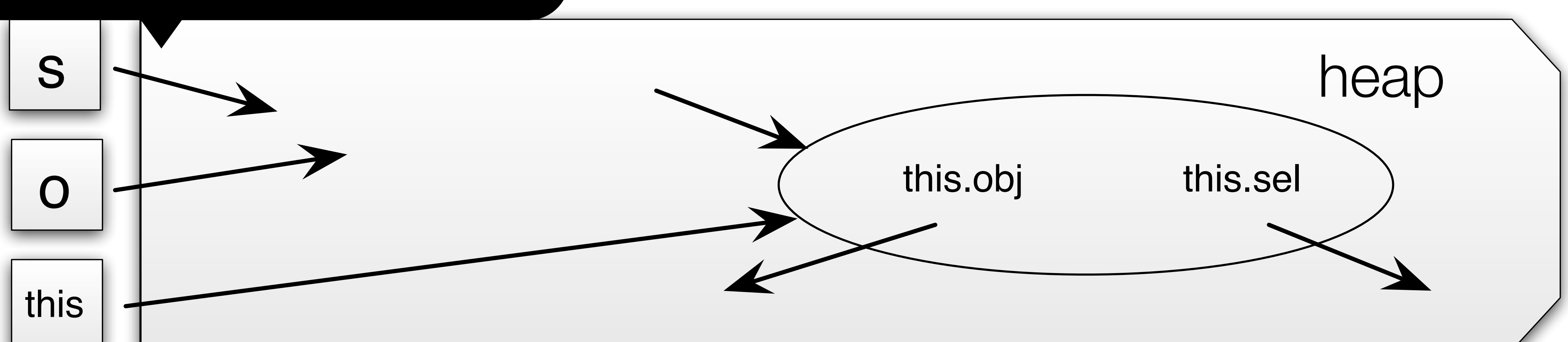

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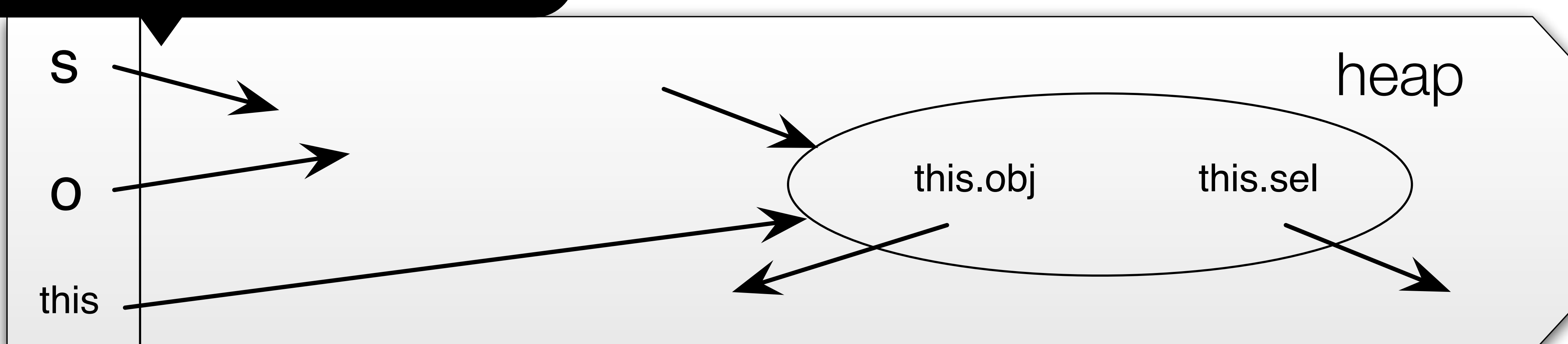
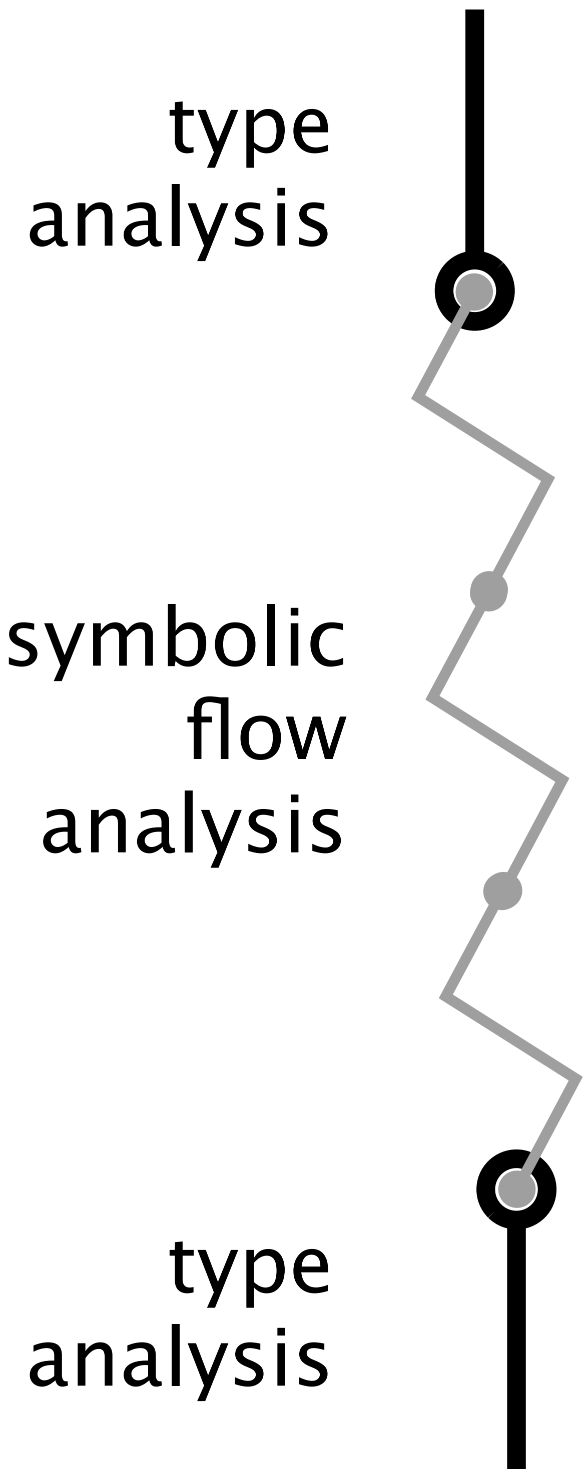


Key Contributions



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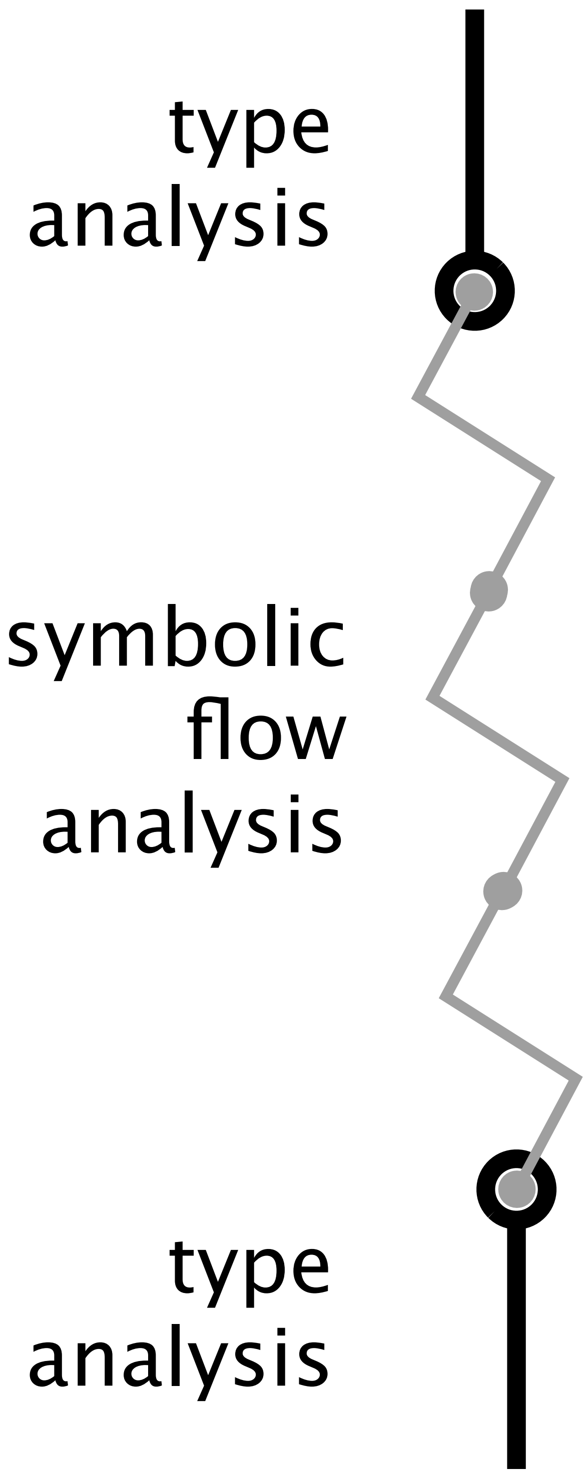

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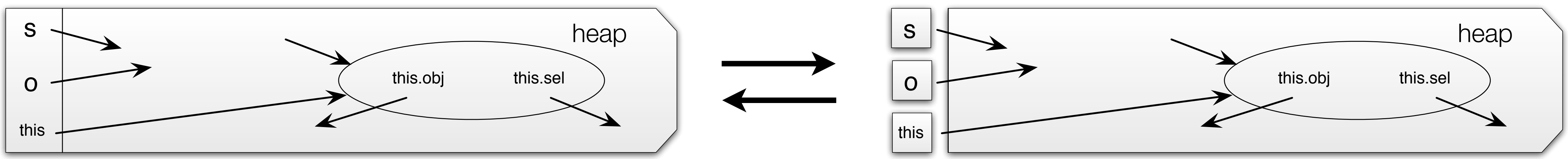

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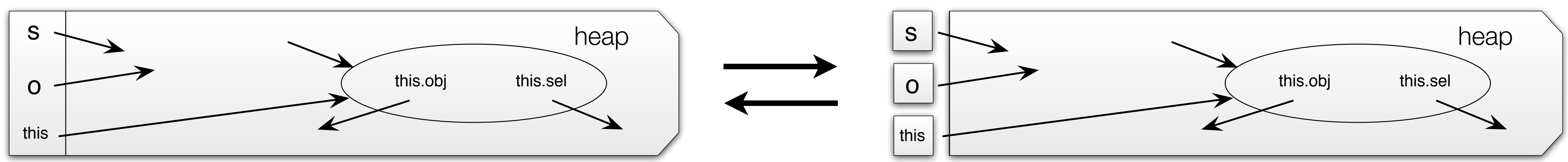

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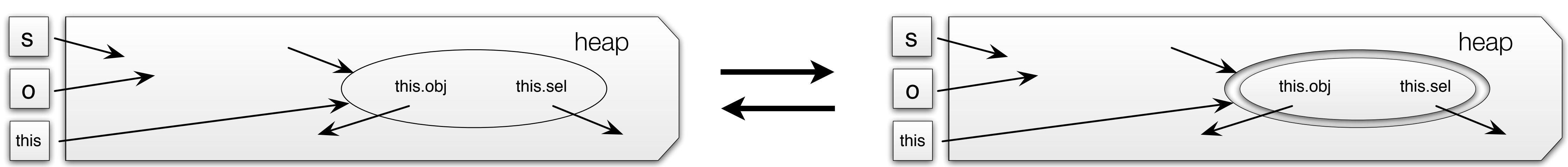

Evaluation

Analysis mechanics: How often is **symbolic reasoning** required?

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

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

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

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76 r2 annotations on **system libraries**

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Including **Skim, Adium,** and **OmniGraffle**

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Analysis **mechanics**

	size		
benchmark	**(loc)**	**symbolic sections**	**maximum materializations**
OAuth	1248	7	1
SCRecorder	2716	2	2
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Approaches limited to **one-at-a-time materialization not sufficient**

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	size		false alarms	
benchmark	(loc)	reflective call sites	flow-insensitive	almost-everywhere
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Also found a real reflection **bug** in Vienna, which we reported and which was **fixed**

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

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

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Theorem (Soundness of Handoff).

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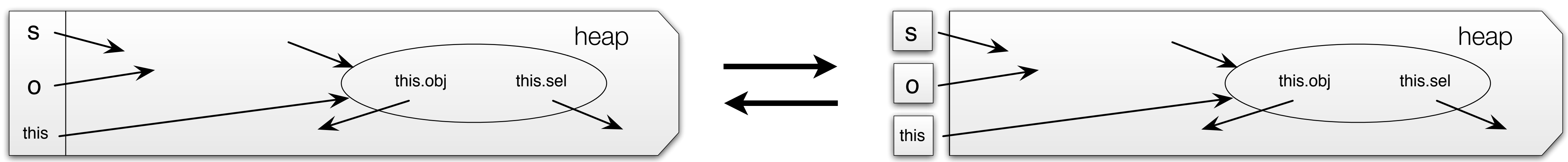

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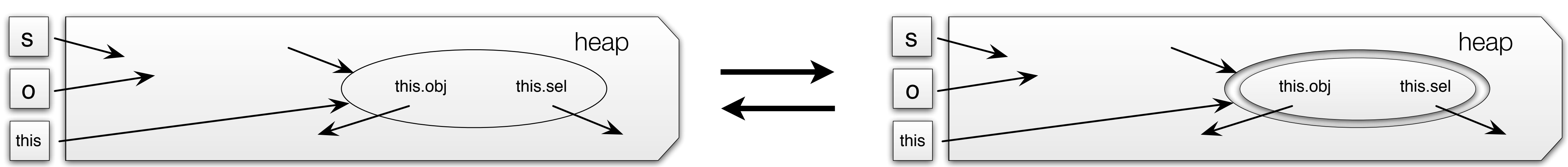

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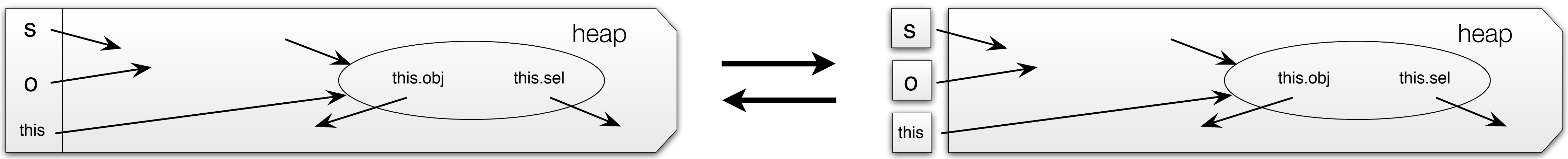

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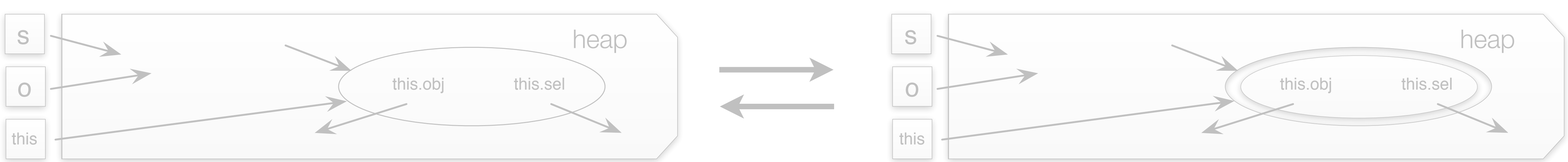

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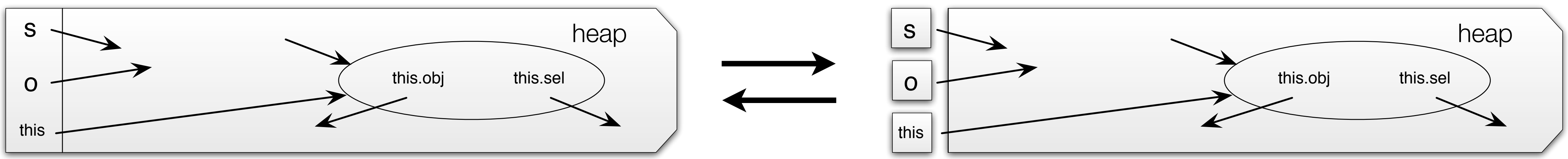

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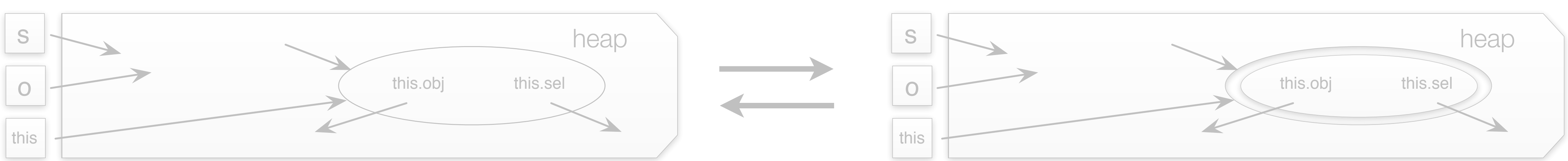

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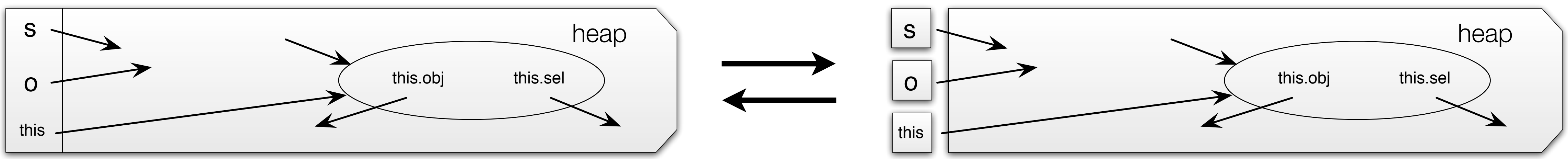

No locality or framing

Theo … arization).

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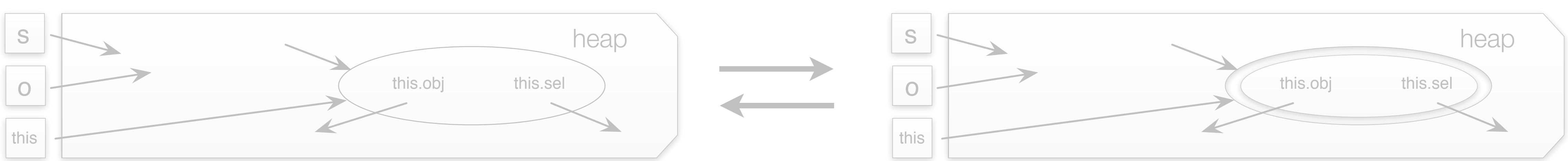

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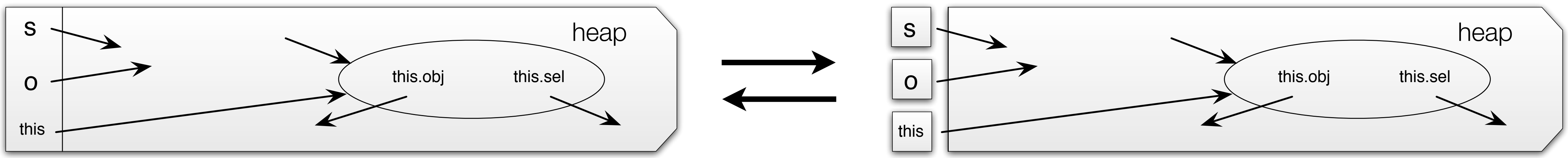

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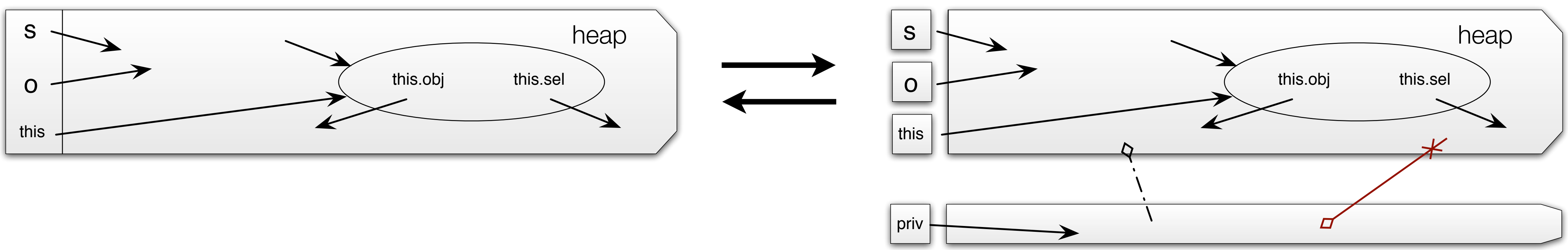

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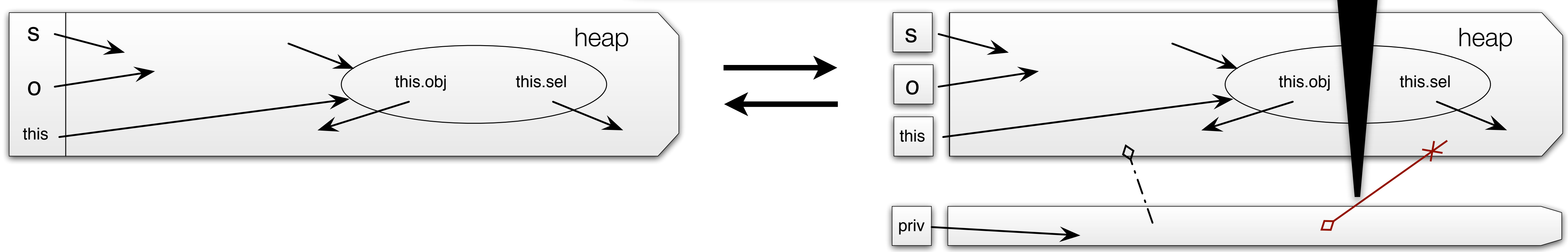

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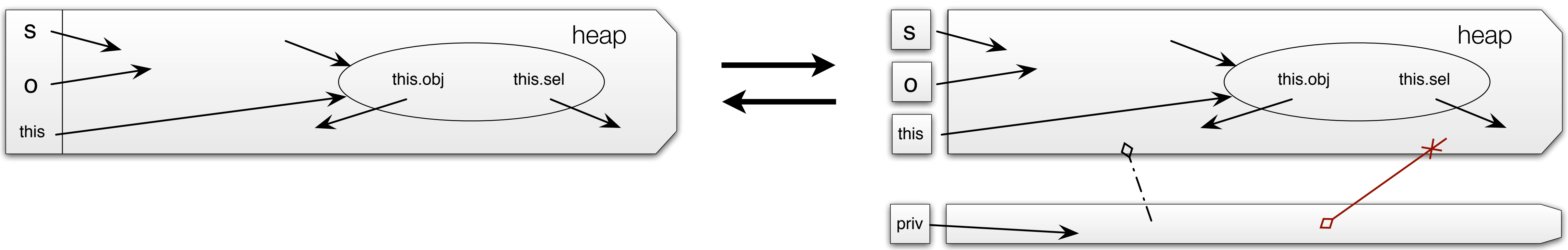

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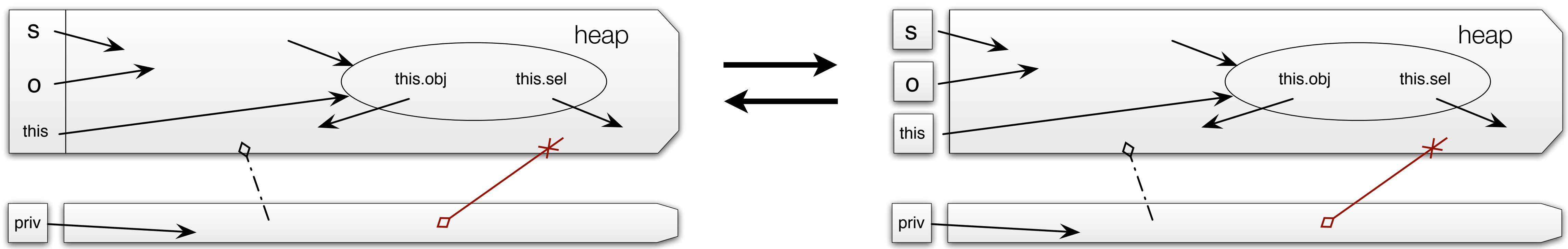

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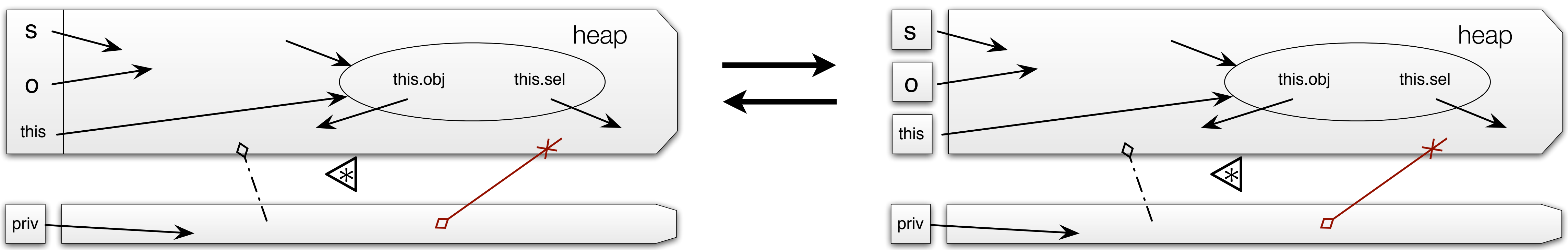

Next Steps: Gated Separation ⩤

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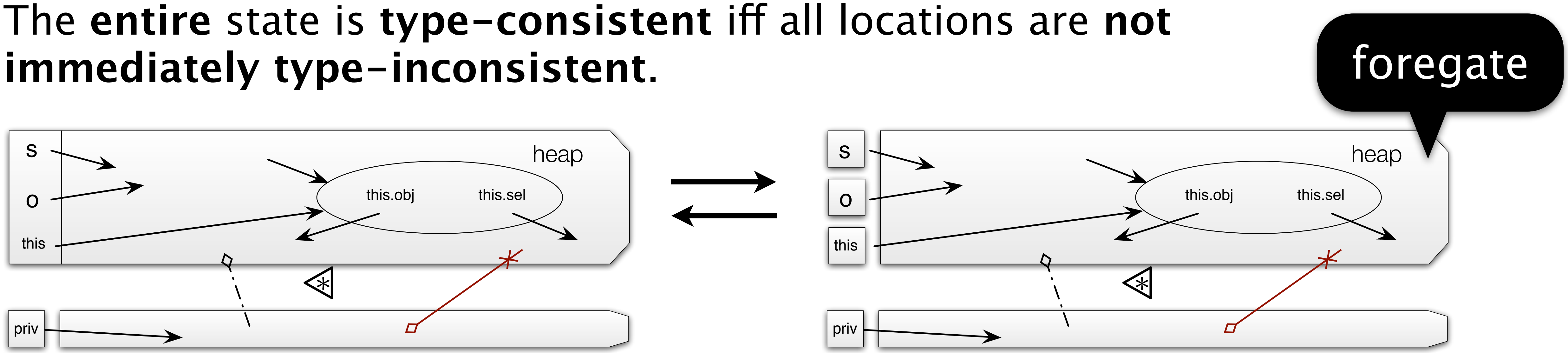

Next Steps: Gated Separation $\triangleleft\!\!\!\ast$

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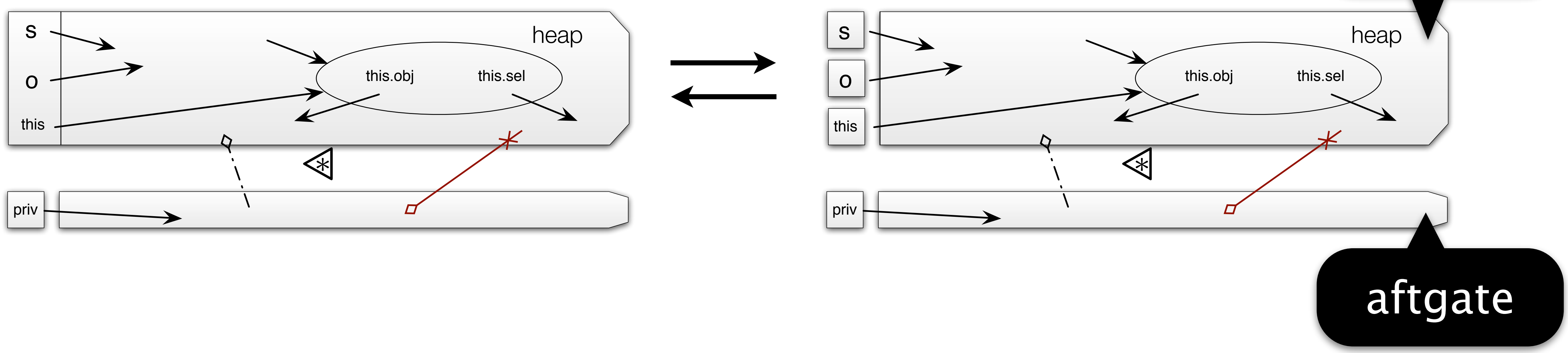
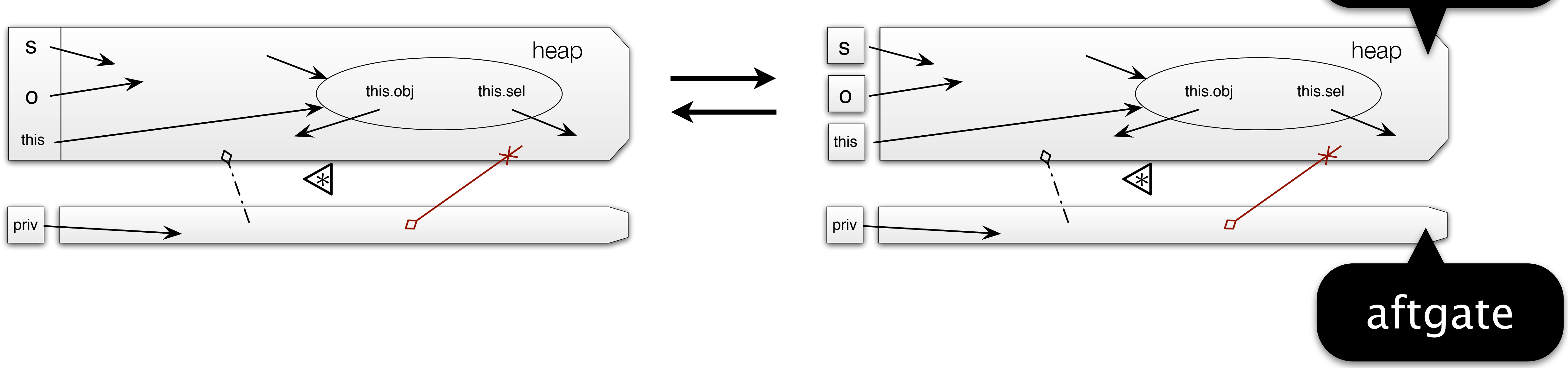


Next Steps: Gated Separation ⩤

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



Next Steps: Gated Separation $\triangleleft\!\!\ast$

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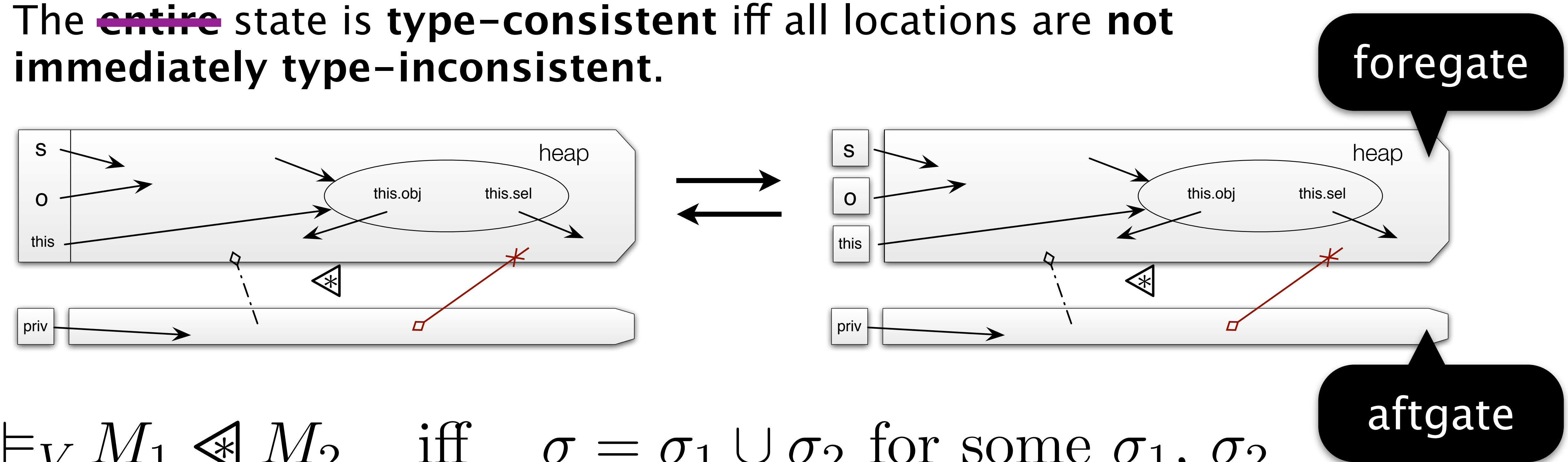

$$\sigma \models_V M_1 \triangleleft\!\!\ast\, M_2 \quad \text{iff} \quad \sigma = \sigma_1 \cup \sigma_2 \text{ for some } \sigma_1, \sigma_2$$
$$\text{where } \sigma_1 \models_V M_1 \text{ and } \sigma_2 \models_V M_2$$
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Next Steps: Gated Separation $\lhd\!\!\!\ast$

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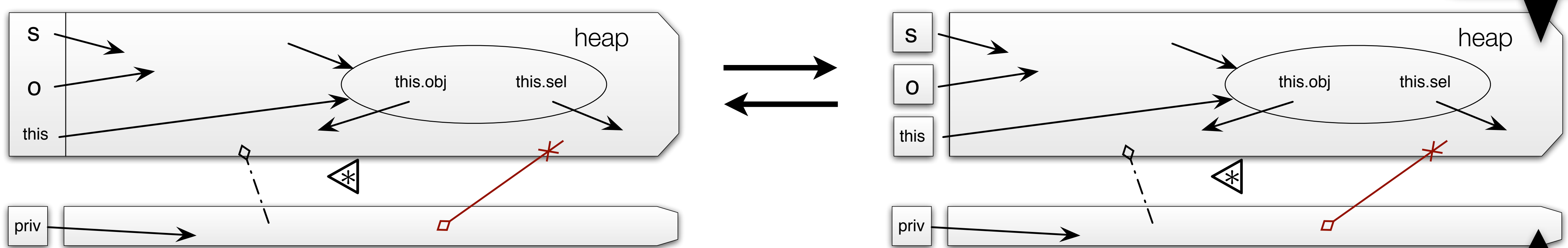
foregate



aftgate

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concrete

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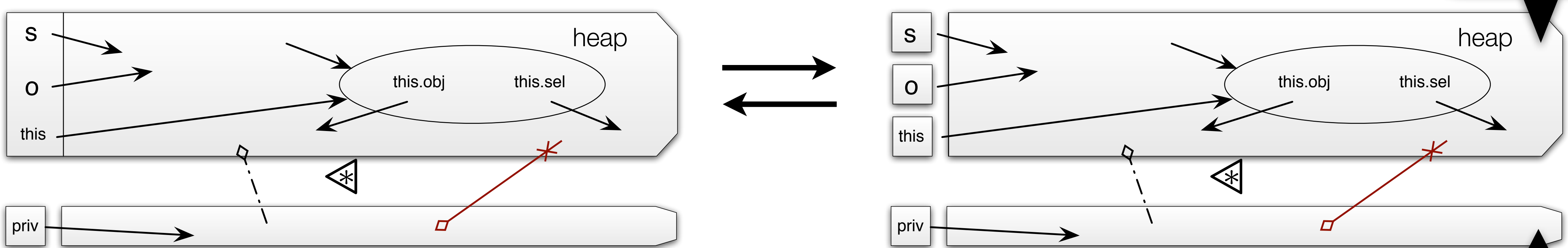

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concrete

abstract

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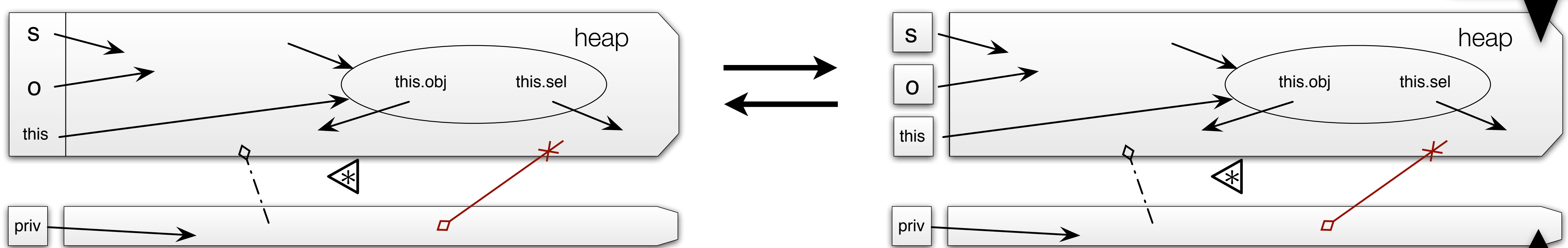

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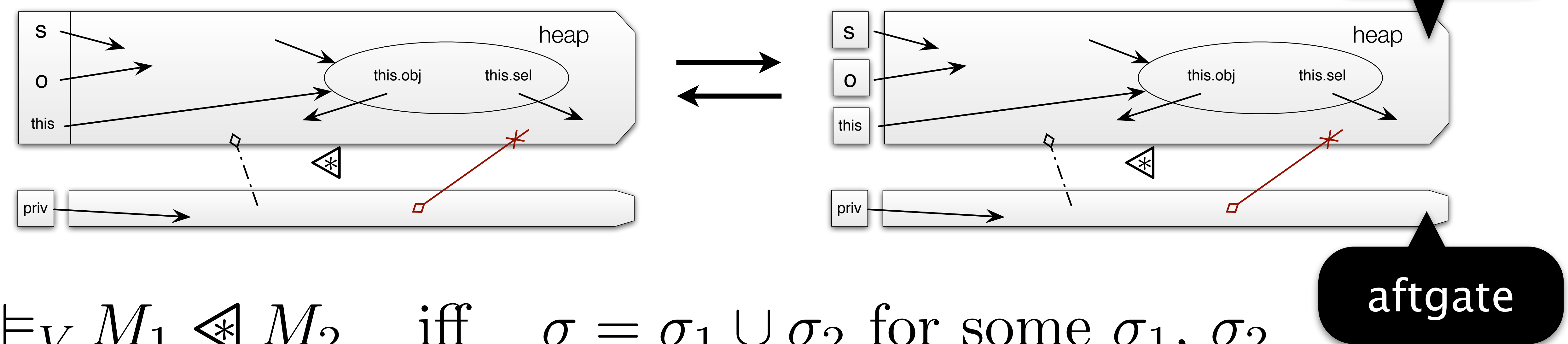

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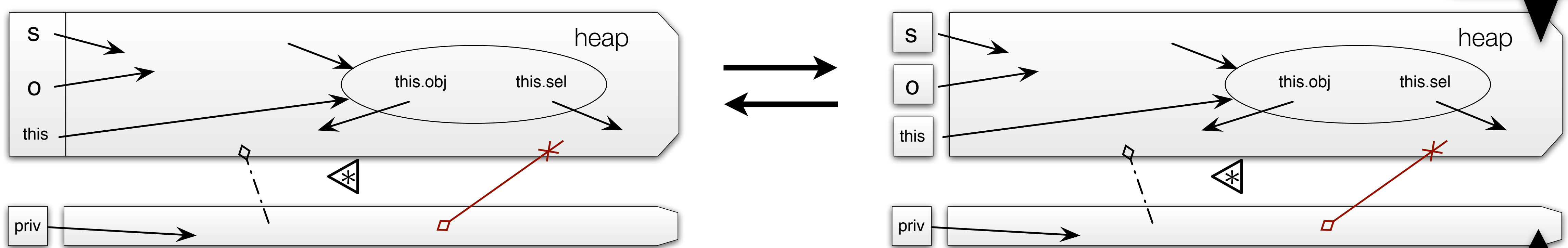

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Slightly stronger than $\ast$:
No **direct** pointers from “foregate” to “aftgate”

Next Steps: Type-Intertwined Framing

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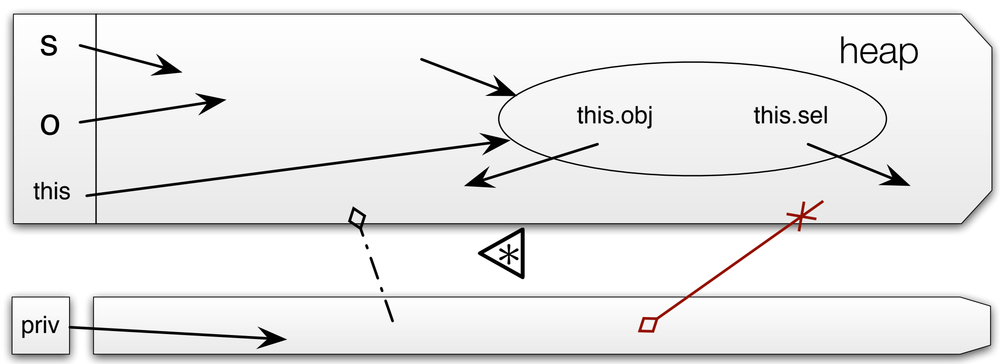

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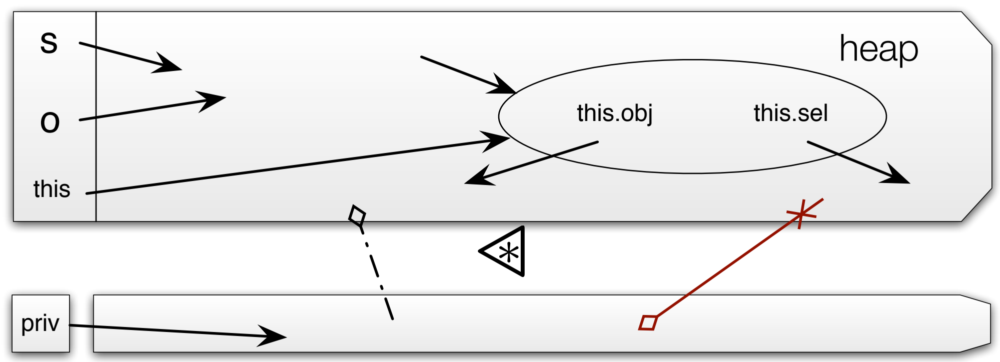
symbolic flow analysis



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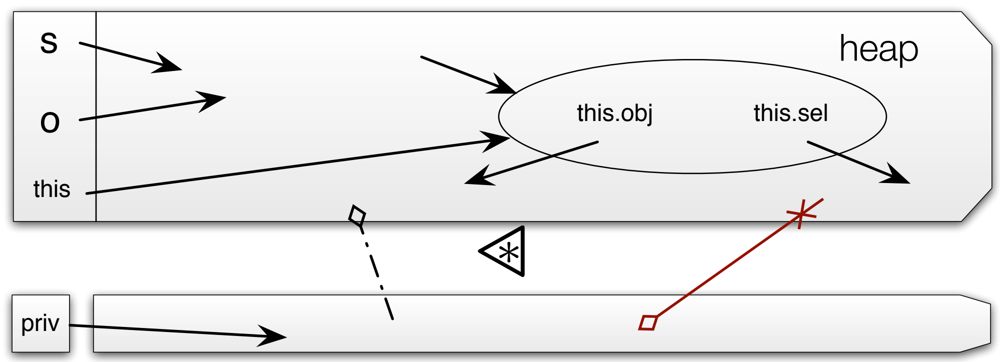
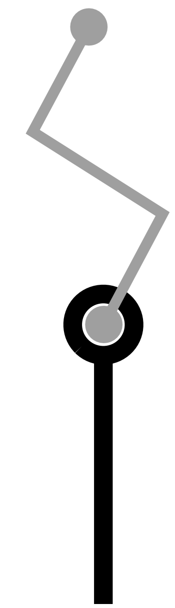


symbolic flow analysis

type analysis



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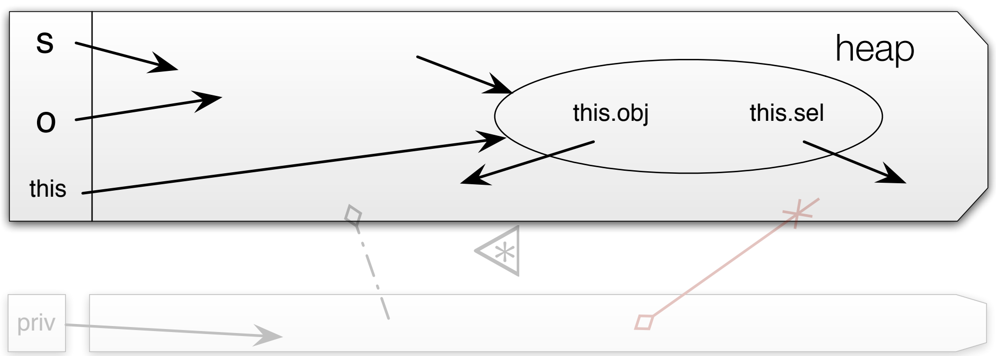

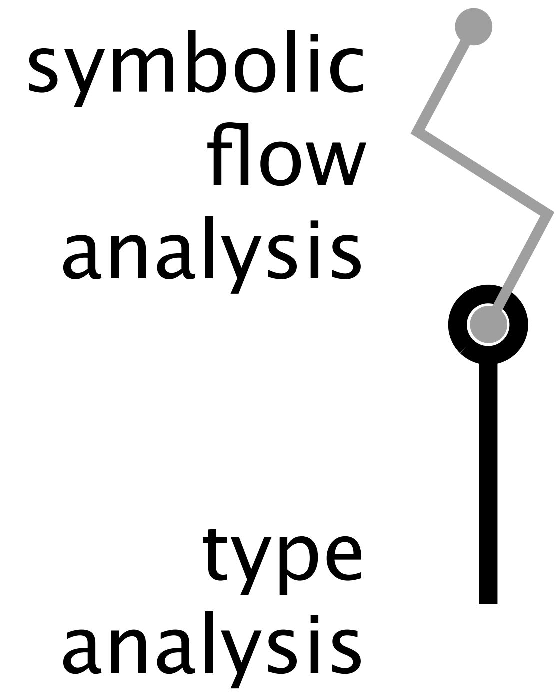

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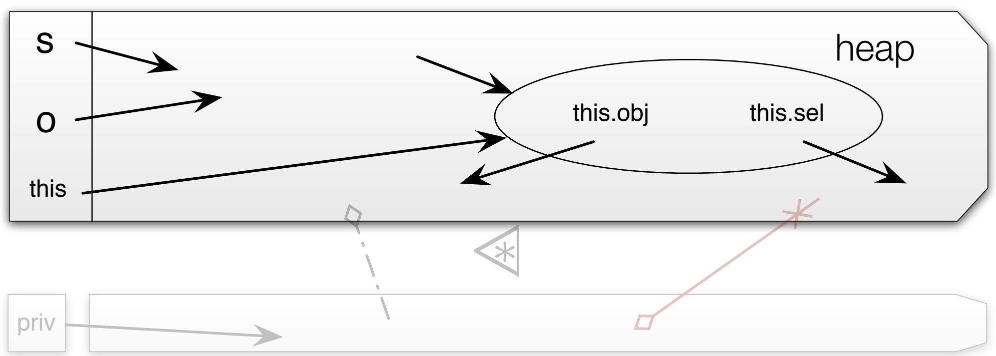

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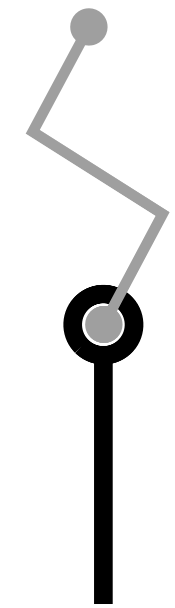

type analysis

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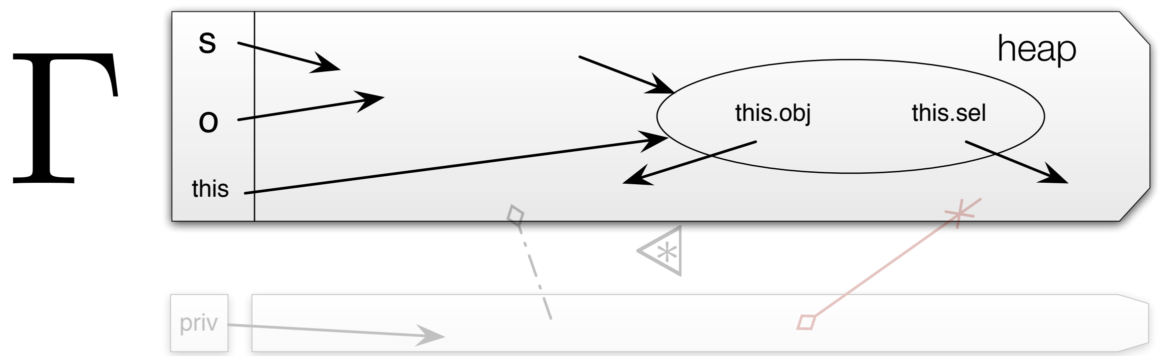

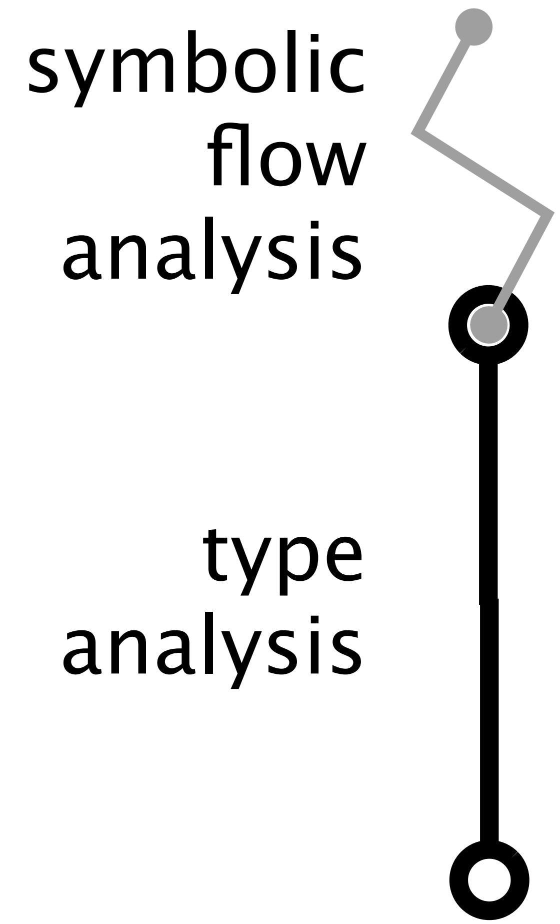

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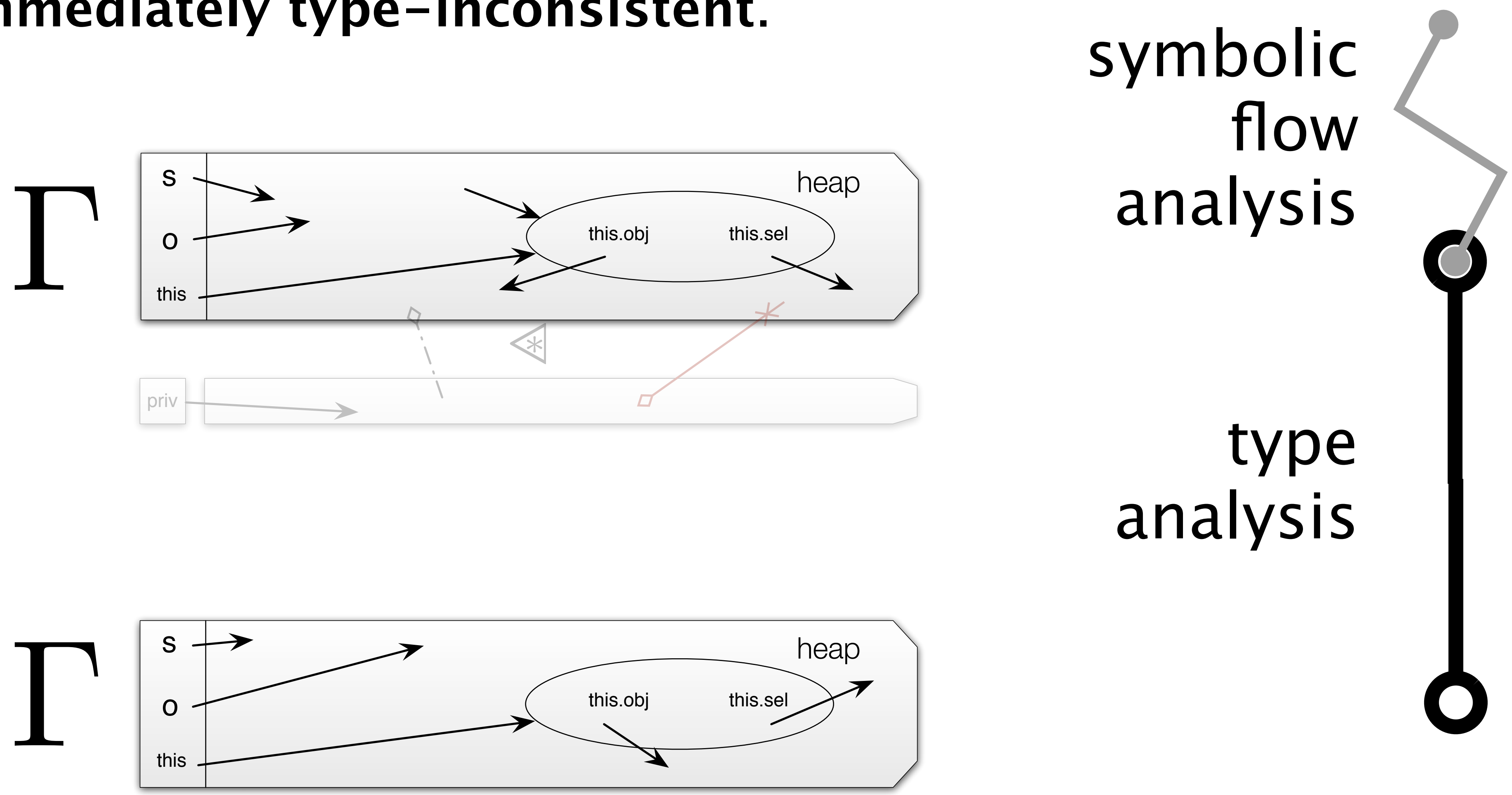

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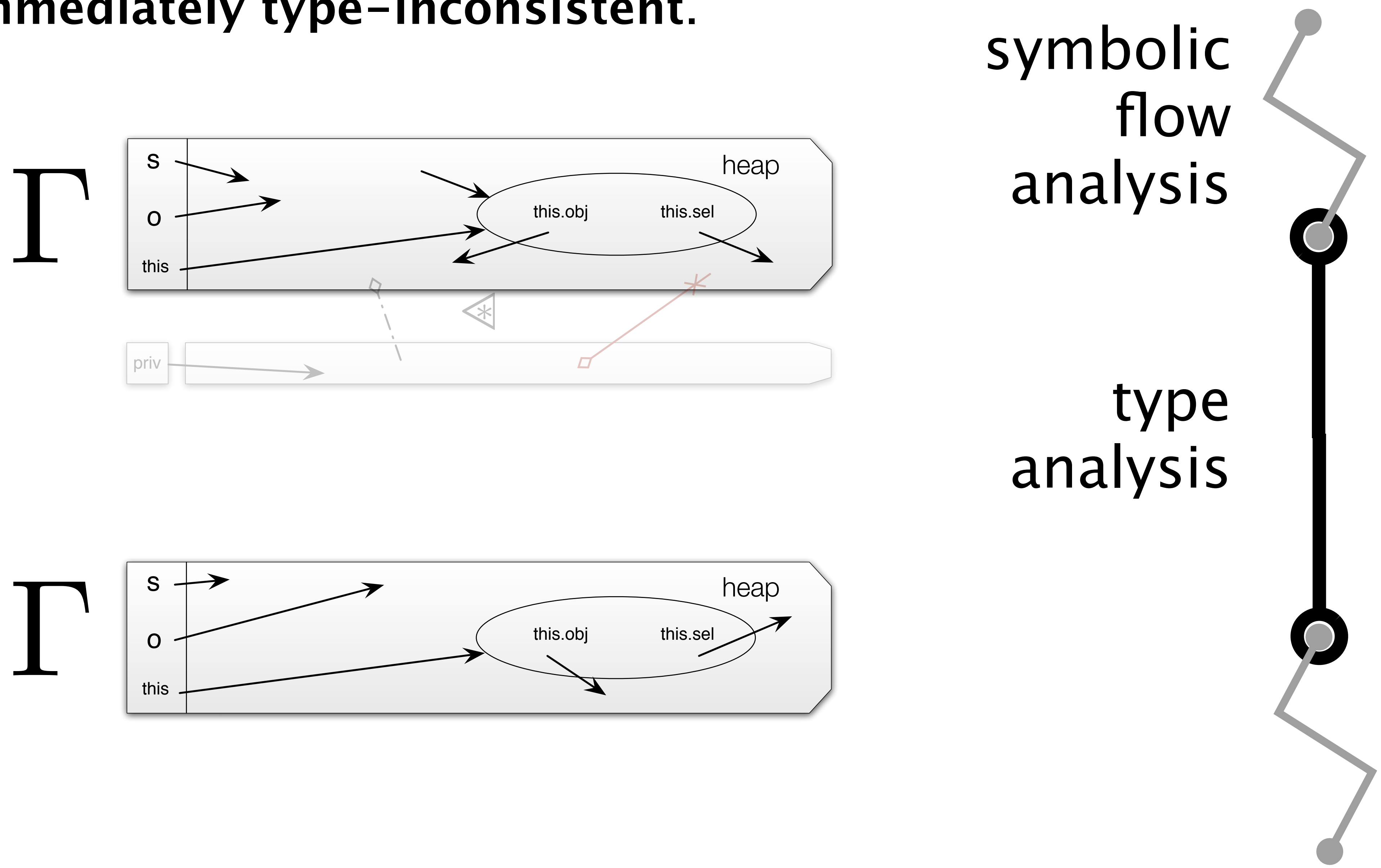

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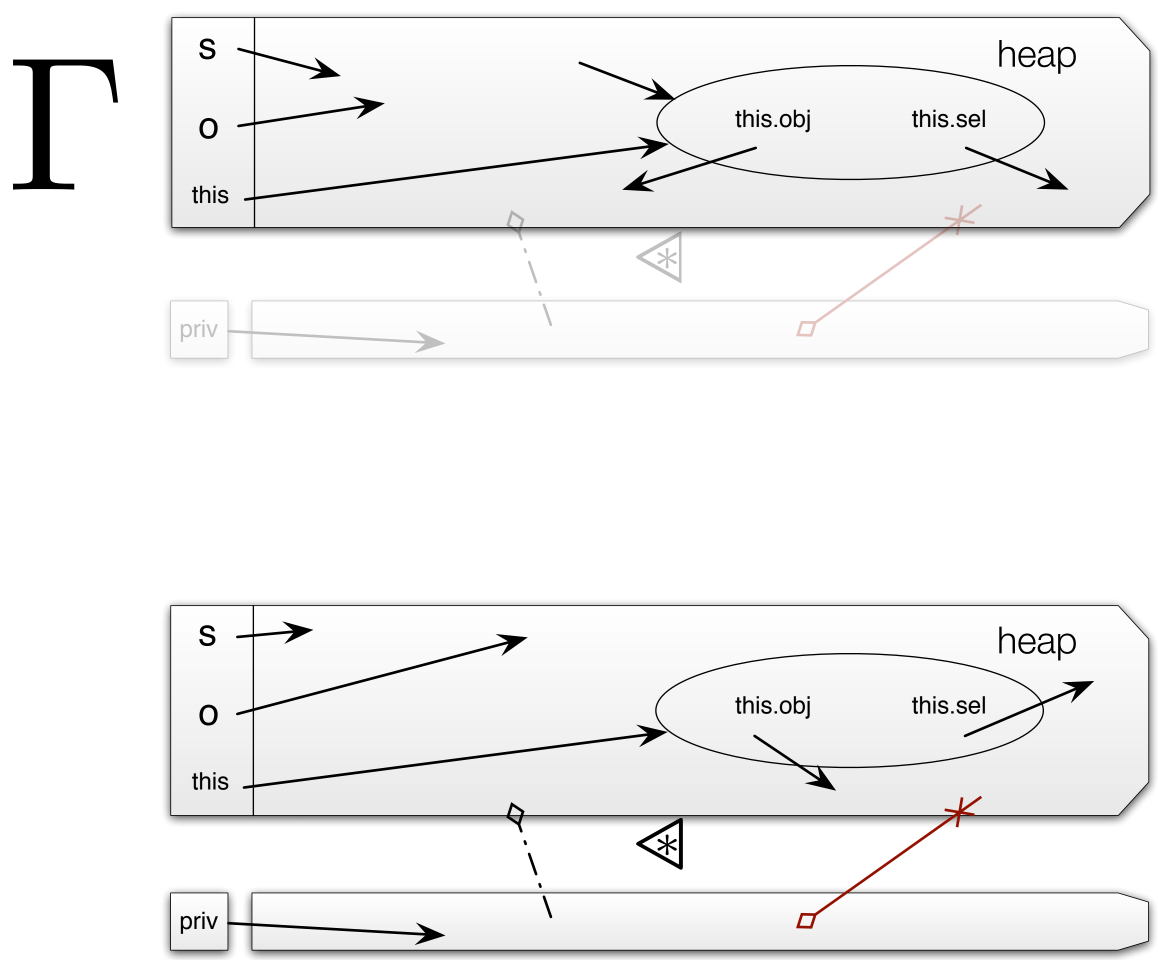

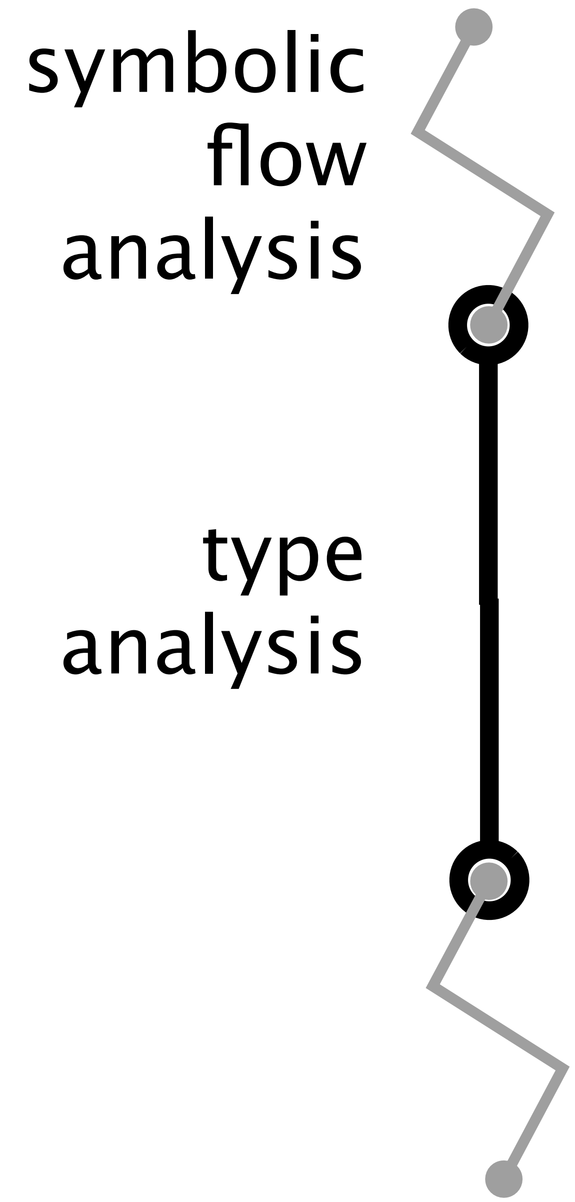

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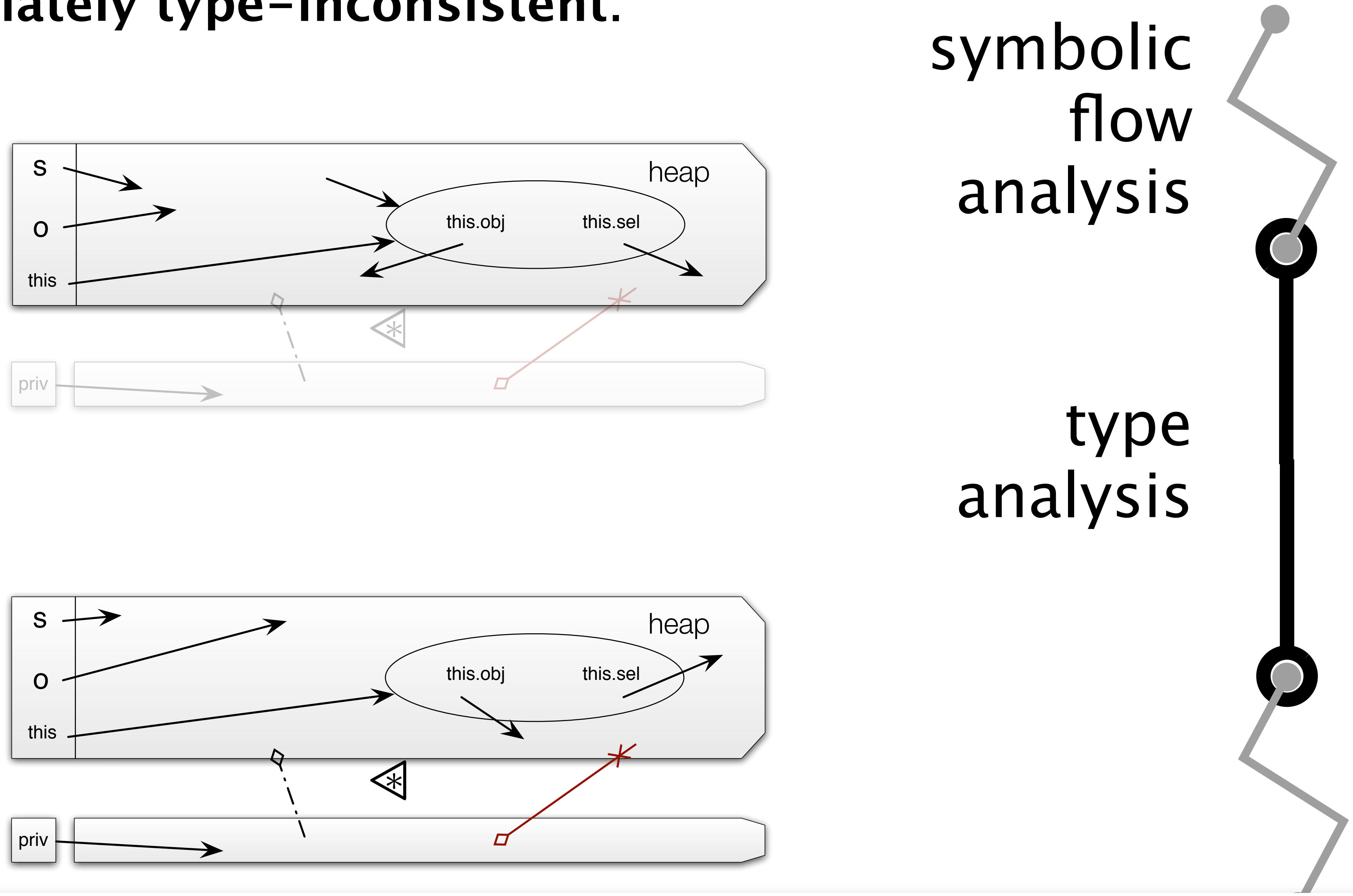

Type-intertwined framing is sound because "aftgate" is not reachable.

Summary

- Check **almost everywhere** heap invariants with **intertwined type** and **symbolic flow analysis**
  - **Translate** type environment into symbolic state with **symbolization**
  - **Leverage** heap type invariant during symbolic analysis via **type-consistent materialization** and **summarization**
- Approach is **very fast** and **scales to large programs**

Fissile Type Analysis yields significant **precision improvement** at **little cost** in performance

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Because **almost-everywhere** invariants hold **almost everywhere**

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www.cs.colorado.edu/~bec
pl.cs.colorado.edu

PLV

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Cerny


Chang

www.cs.colorado.edu/~bec
pl.cs.colorado.edu

PLV


Sankaranaryananan


Somenzi

Manual annotation **burden**

	size			false alarms				analysis time	
benchmark	**(loc)**	**reflective call sites**	**annotation count**	**flow-insens.**	**almost-everwhere**	**symbolic sections**	**max. mat-erializations**	**Time**	**Rate (kloc/s)**
OAUTH	1248	7	5	7	2 (–71%)	7	1	0.30s	4.1
SCRECORDER	2716	12	9	2	0 (–100%)	2	2	0.28s	9.8
ZIPKIT	3301	28	0	0	0 (–)	0	0	0.10s	33.8
SPARKLE	5289	40	0	4	1 (–75%)	3	1	0.78s	6.8
ASIHTTPREQUEST	14620	68	2	50	10 (–80%)	59	2	0.15s	90.2
OMNIFRAMEWORKS	160769	192	49	82	74 (–10%)	7	1	4.61s	34.9
VIENNA	37327	186	24	59	38 (–36%)	28	2	2.57s	14.5
SKIM	60211	207	7	43	43 (–0%)	0	0	2.55s	23.6
ADIUM	176629	587	40	87	70 (–20%)	16	1	7.50s	23.6
combined	461080	1327	136	334	238 (–29%)	125	2	18.83	24.5

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higher for frameworks exporting **reflective interfaces**

in-between for **applications** and large frameworks (which do both)

application code

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class MyButton {
  var cb : Callback = ...

  def setState(s : Str)
    var m = "draw" + s
    cb.update(self, m)
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  def draw()
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  def drawUp() ... end
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library code

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class Callback {
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Idiomatic reflection decouples **callbacks** and avoids **boilerplate**

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