Fissile Type Analysis: Modular Checking of Almost Everywhere Invariants

Devin Coughlin
University of Colorado Boulder

Bor-Yuh Evan Chang 張博聿
University of Colorado Boulder

National Taiwan University 國立臺灣大學
August 1, 2014

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

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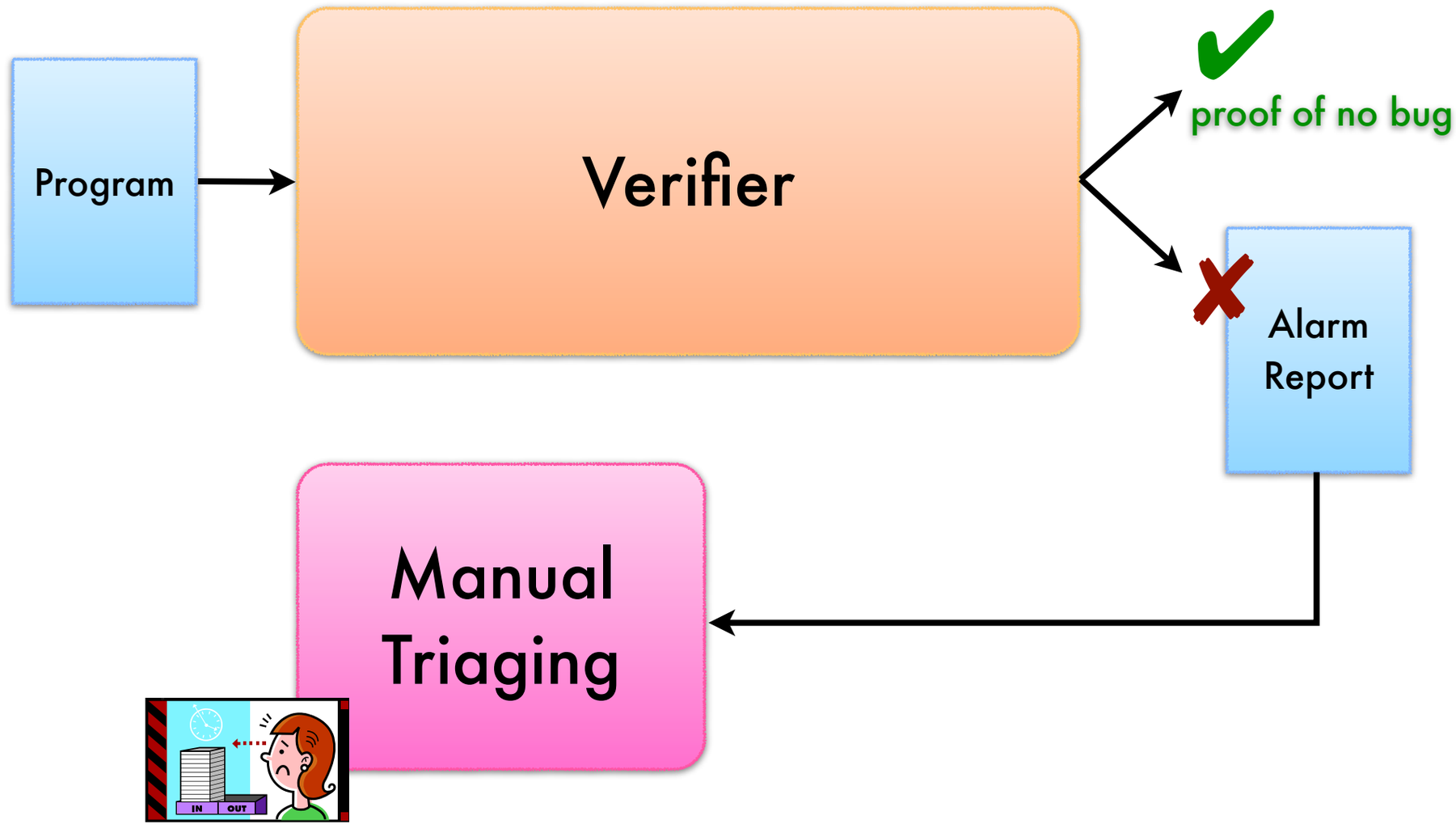

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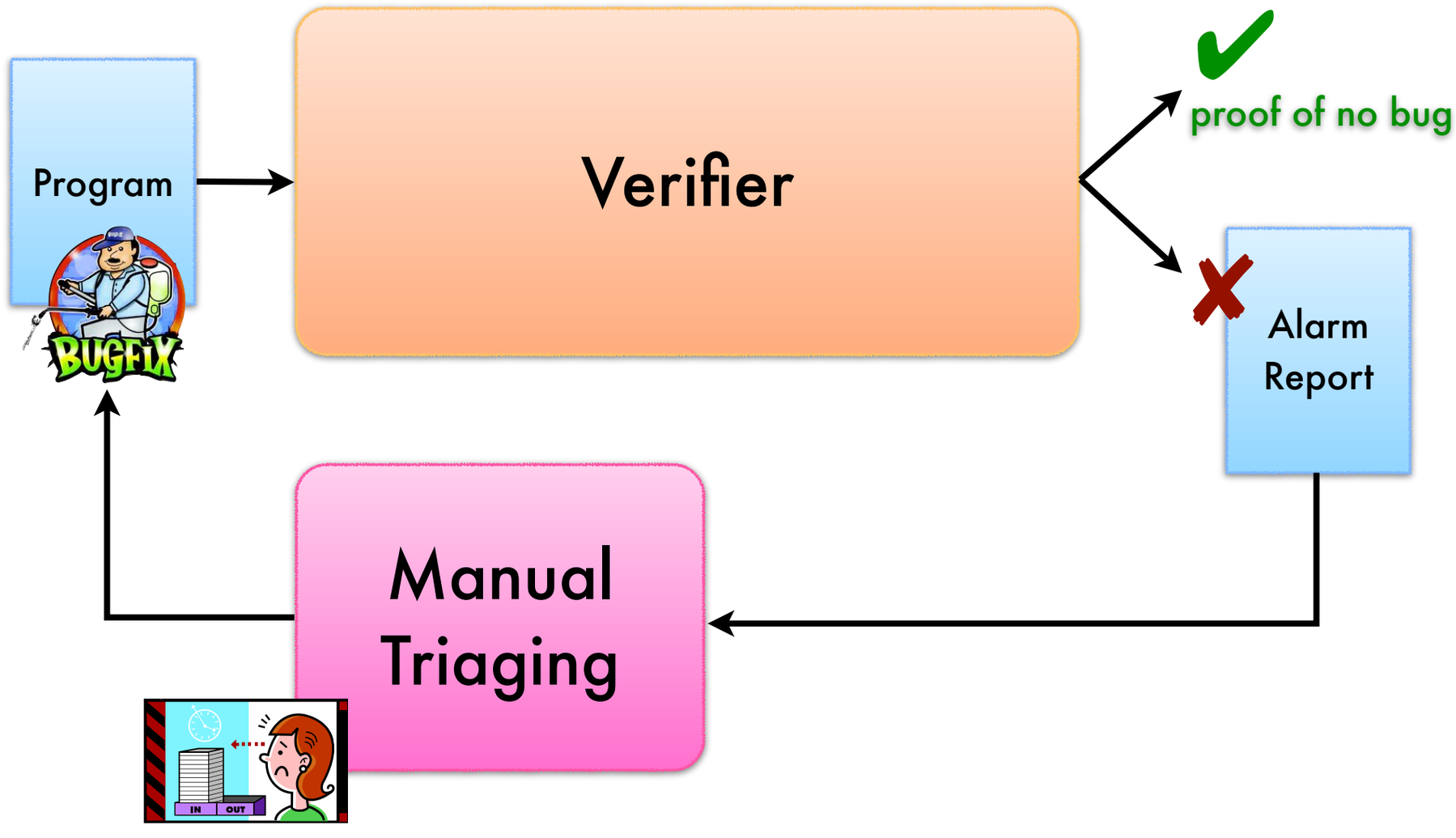

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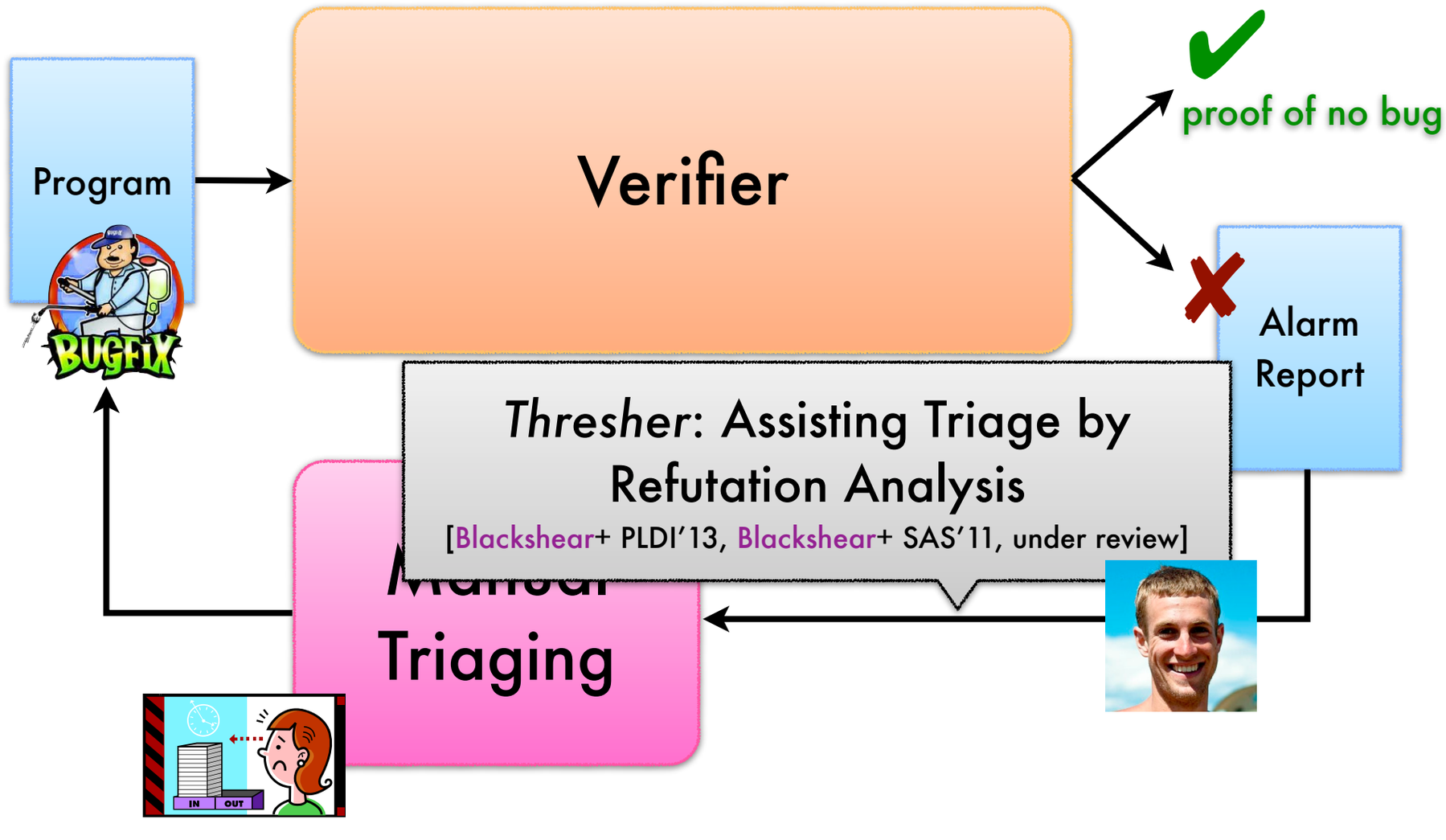

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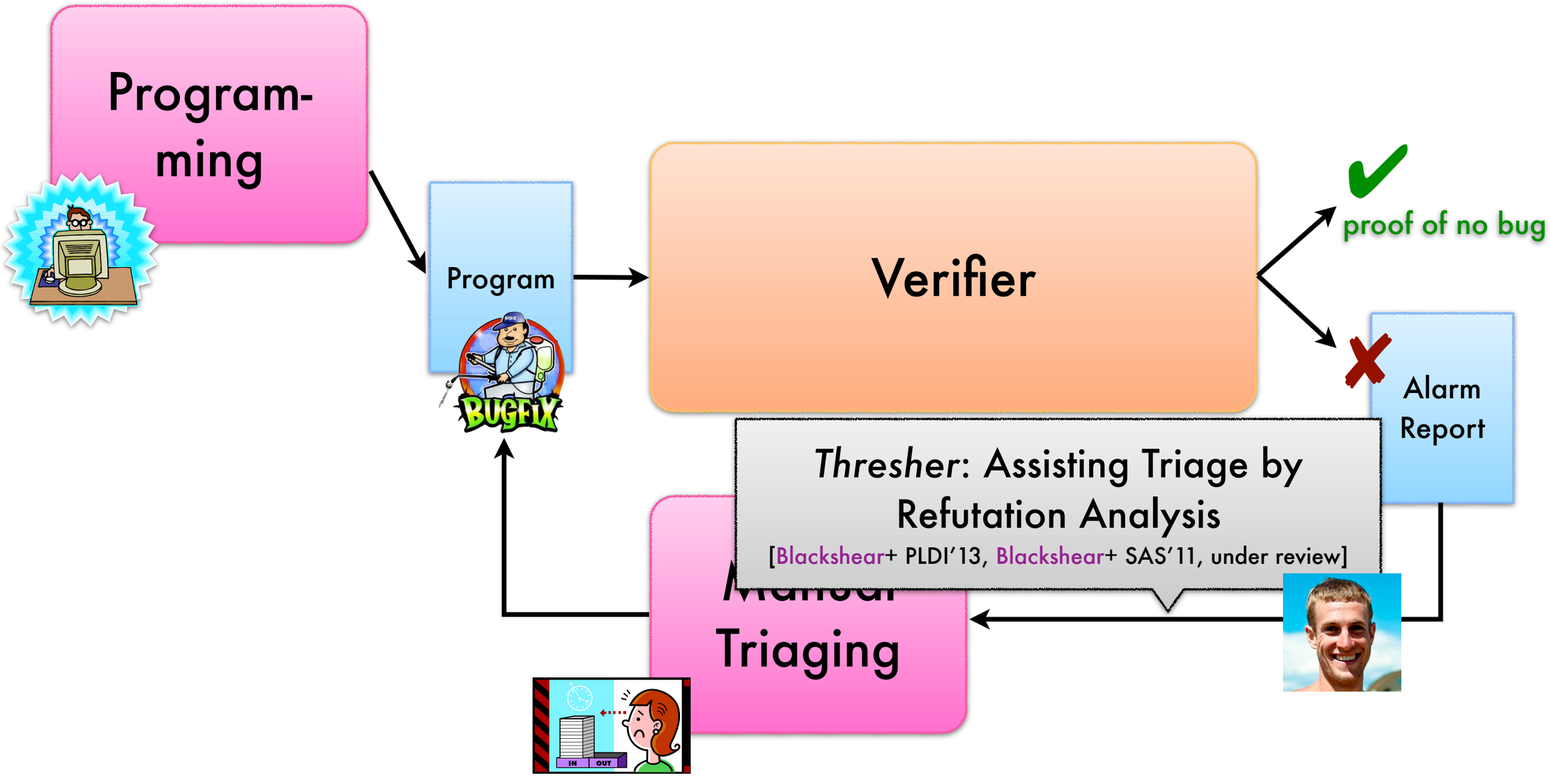

Thresher: Assisting Triage by Refutation Analysis

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

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Enforcement Windows: Measuring Bug Avoidance
[Coughlin+ ISSTA'12]

Program-ming

Program

Verifier

✔ proof of no bug

✘ Alarm Report

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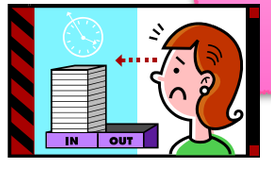
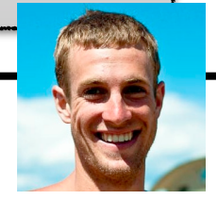
Manual Triaging





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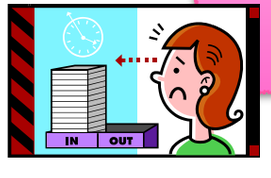

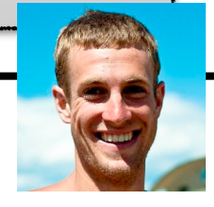

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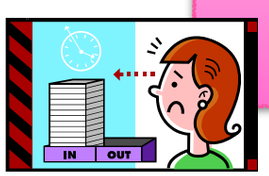

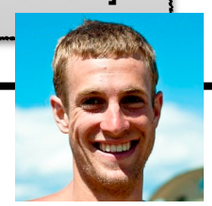

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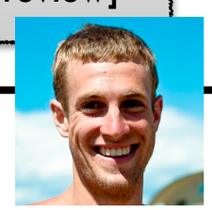

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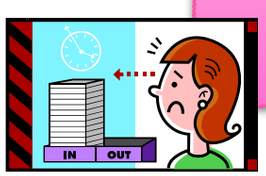

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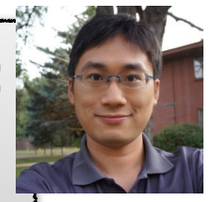
Static Incrementalization of Data Structure Checks
[under review]



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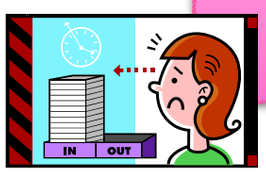

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Jsana: Abstract Domain Combinators for Dynamic Languages
[Cox+ ECOOP'13, Cox+ SAS'14, under review]

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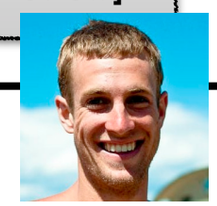

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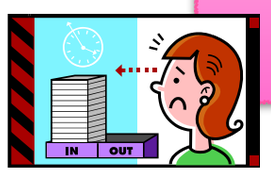

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This Talk

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Fissile Type Analysis:

Types and Separation Logic, Better Together

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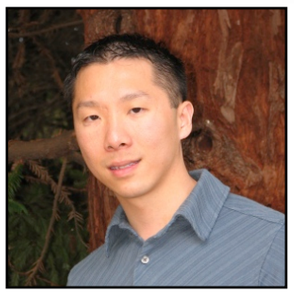

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How to **type check** a program that is **almost** well-typed?

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]()
```

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

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

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

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class Callback
 var sel : Str
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def call()
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```

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

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

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

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class Callback
  var sel : Str
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def call()
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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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“static” folks

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

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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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object.[string]()
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“static” folks

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

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

“web 2.0” developers

“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]()
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“static” folks

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Wha
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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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class Callback
 var sel : Str
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Ensure reflection safety with **dependent-refinement type** expressing required **relationship**

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class Callback
 var sel : Str
 var obj : Obj | r2 sel
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`obj` must "respond to" `sel`

```
def call()
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Ensure reflection safety with **dependent-refinement type** expressing required **relationship**

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

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

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

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

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

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

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

Updating relationship causes **type error**

```
class Callback
  var sel : Str
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```

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

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$\Gamma \vdash \cdots$

Flow-Insensitive Type Systems

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Flow-Insensitive Type Systems

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

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Flow-Insensitive Type Systems

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

$\gamma(\cdot) = \cdots$

Abstract Interpretation/ Flow Analysis/ Model Checking

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

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

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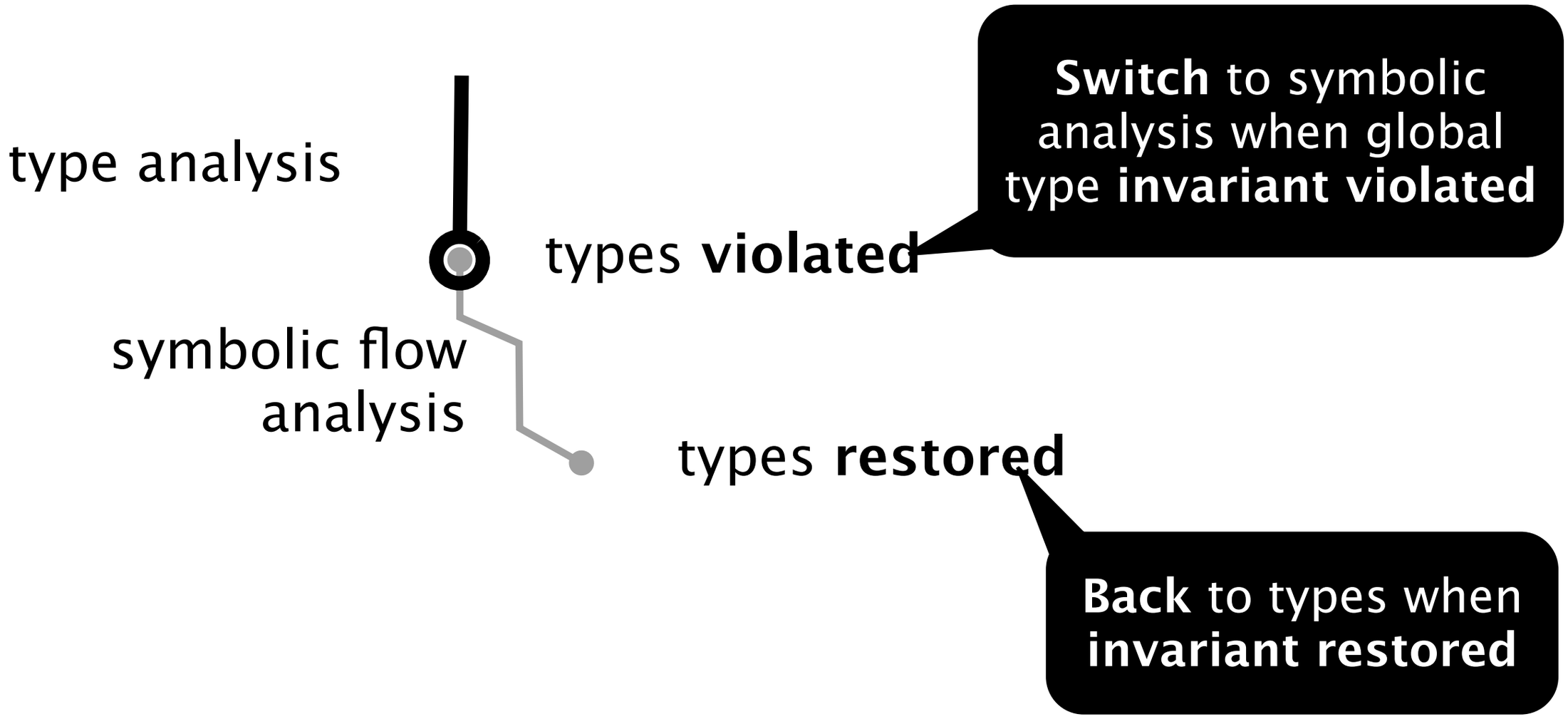

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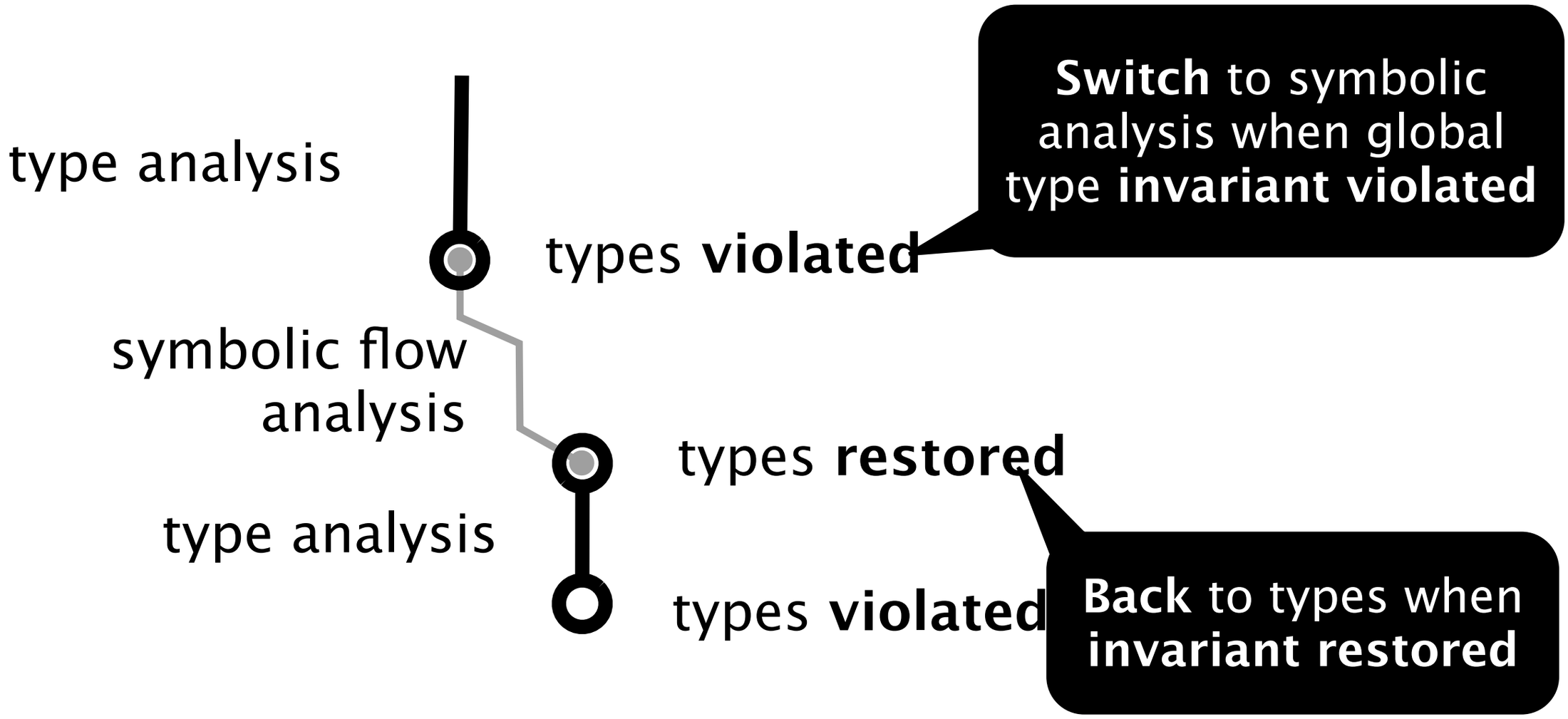

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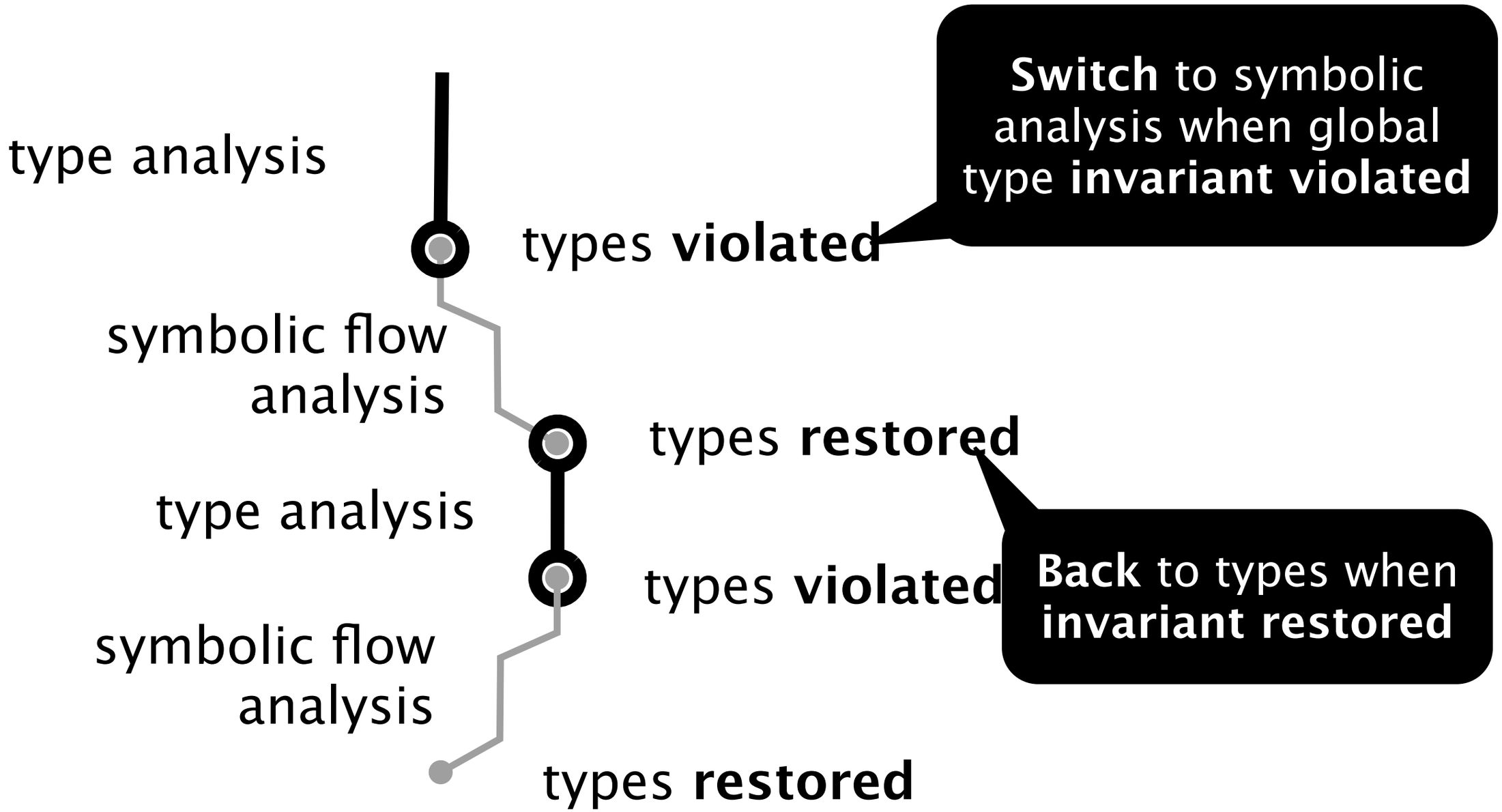

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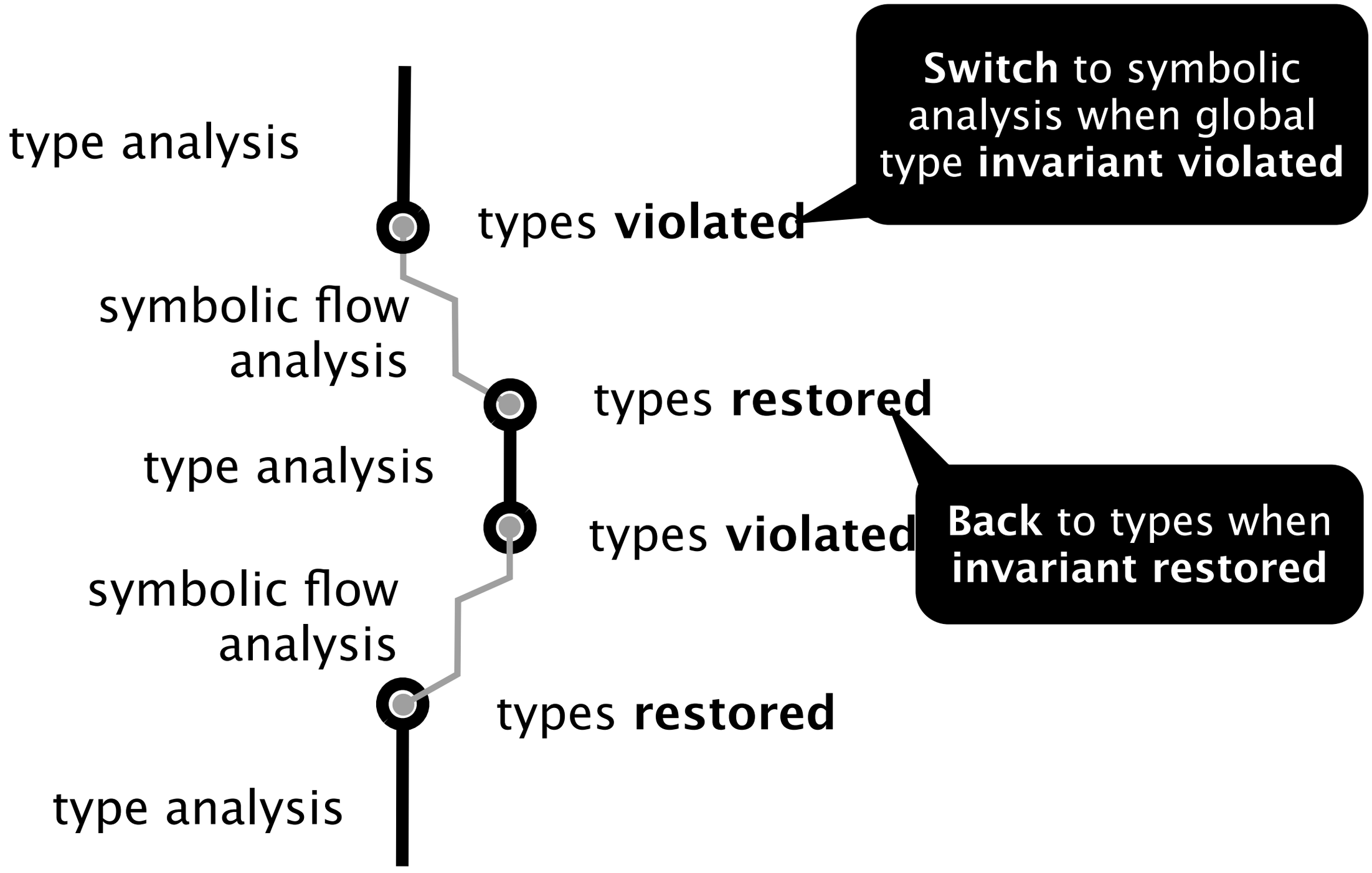

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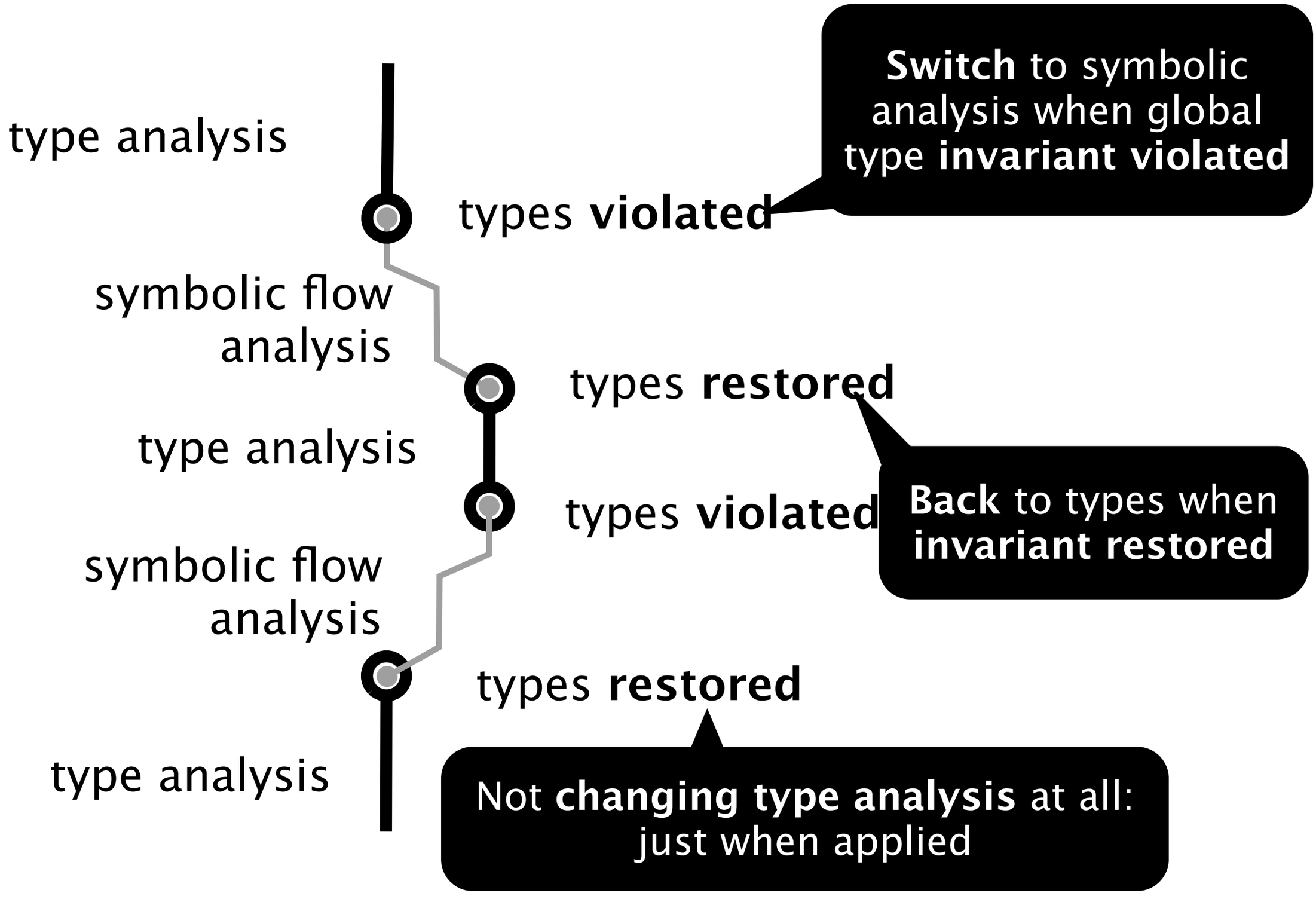
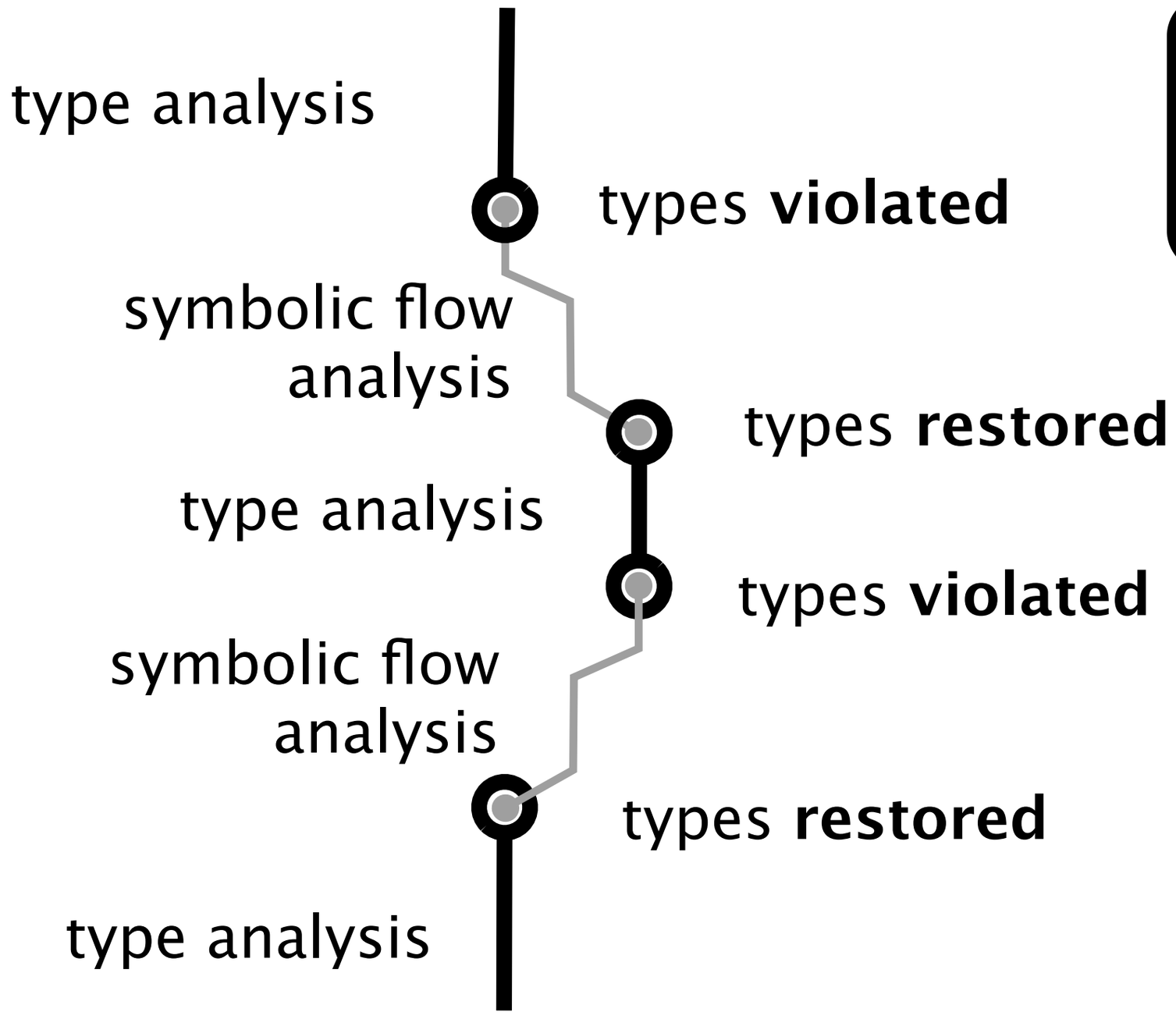


Verification of **almost-everywhere invariants** with **intertwined** type and flow analysis

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



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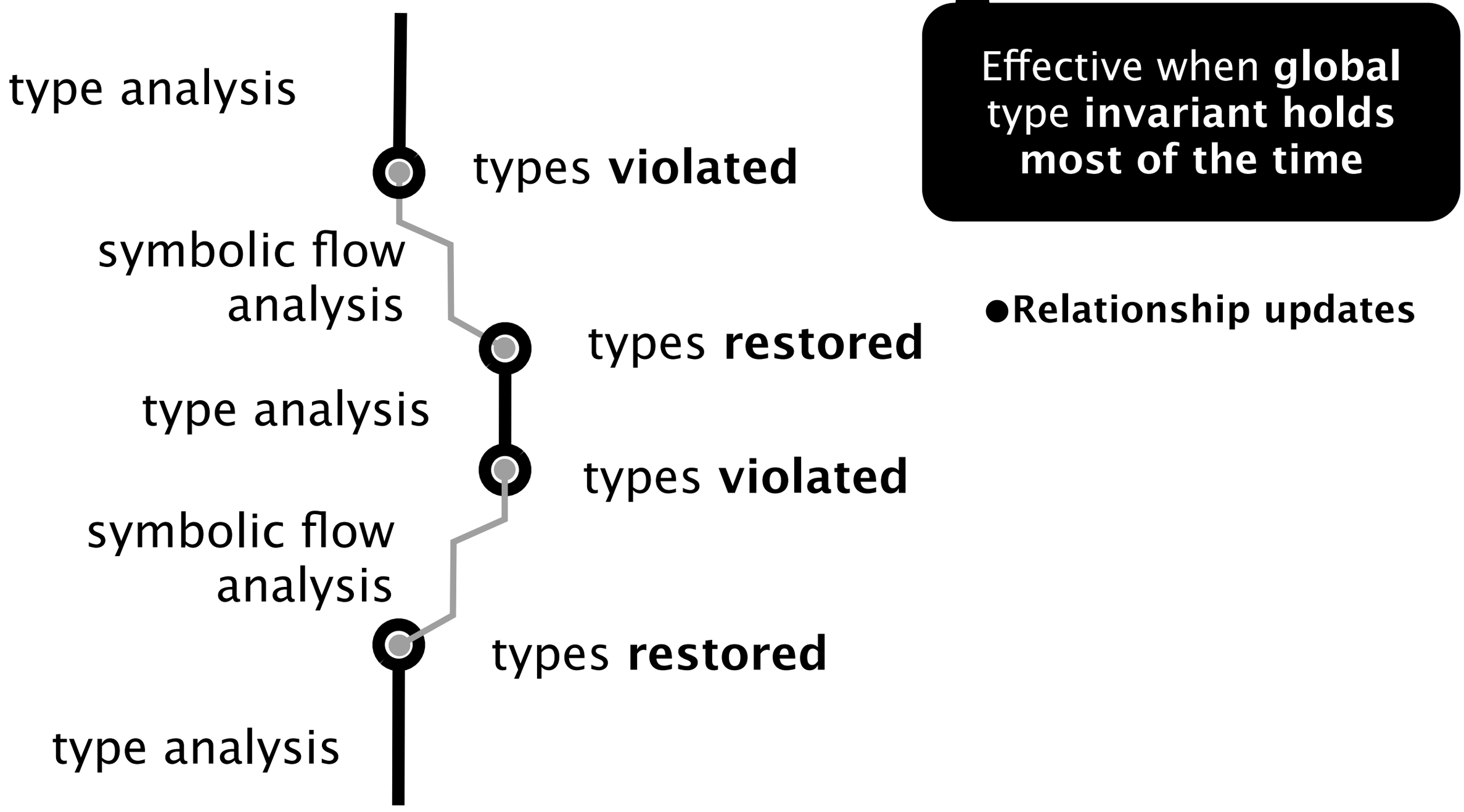
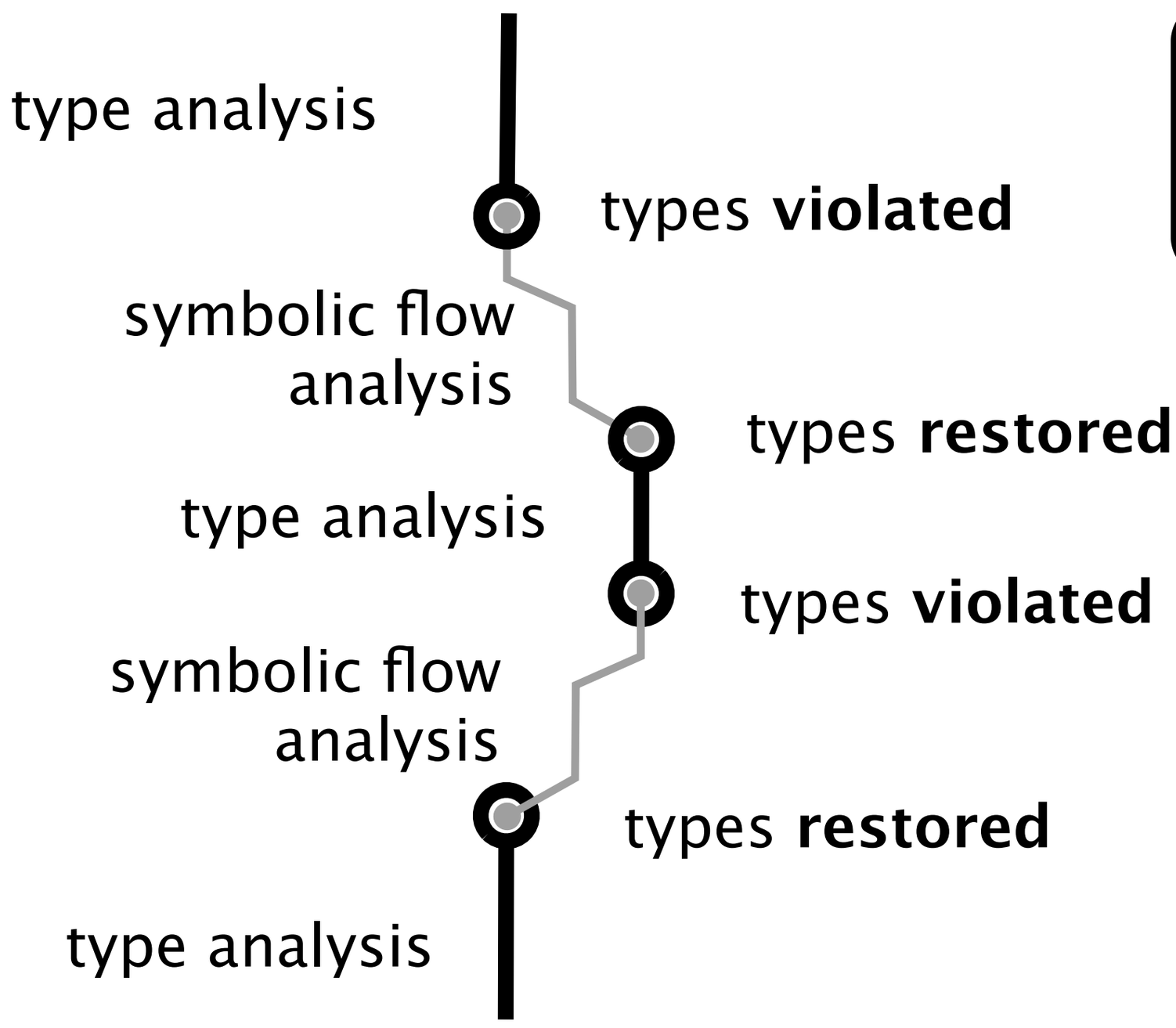


Verification of **almost-everywhere invariants** with **intertwined** type and flow analysis



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

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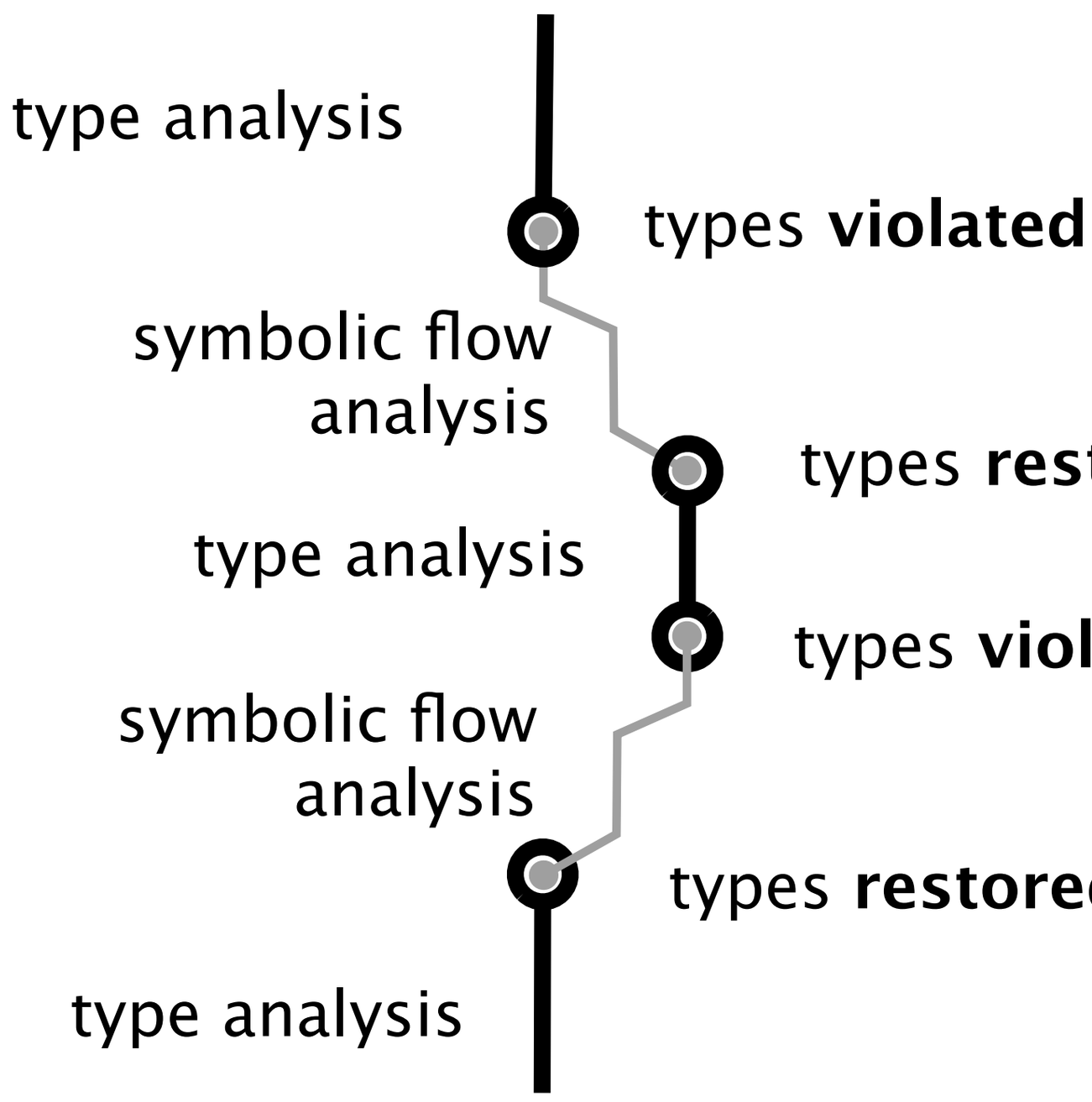

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- **Relationship updates**
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- **Tagged unions**

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

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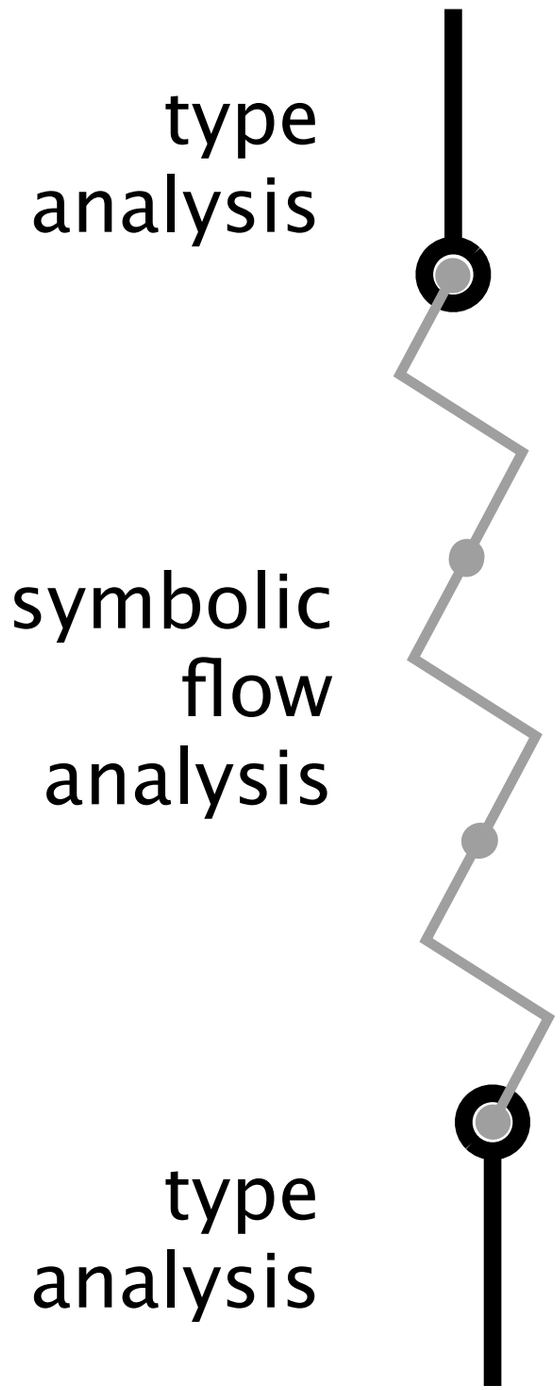
Complexity lies in **handoff** between analyses and in **symbolic analysis**

Key Contributions



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

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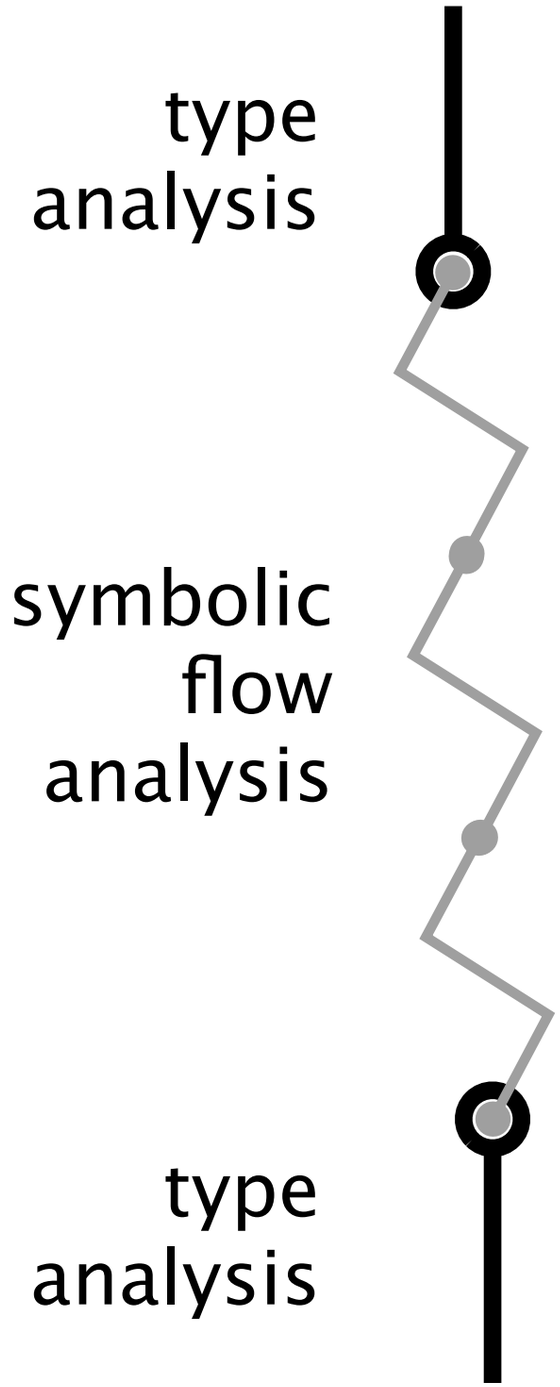

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Reason precisely only **when** type invariant violated

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Key Contributions

type analysis

symbolic flow analysis

type analysis

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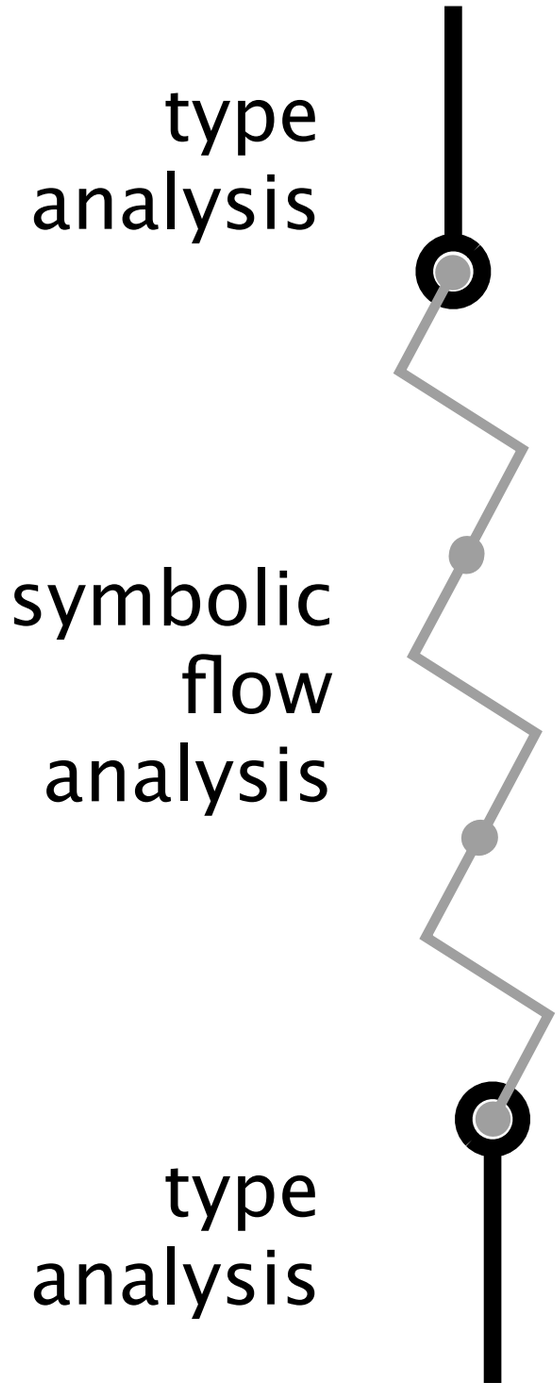

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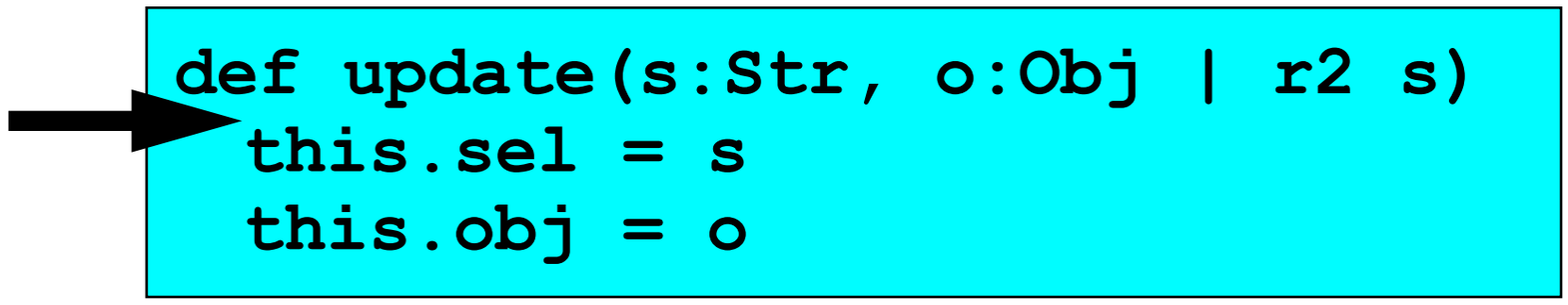

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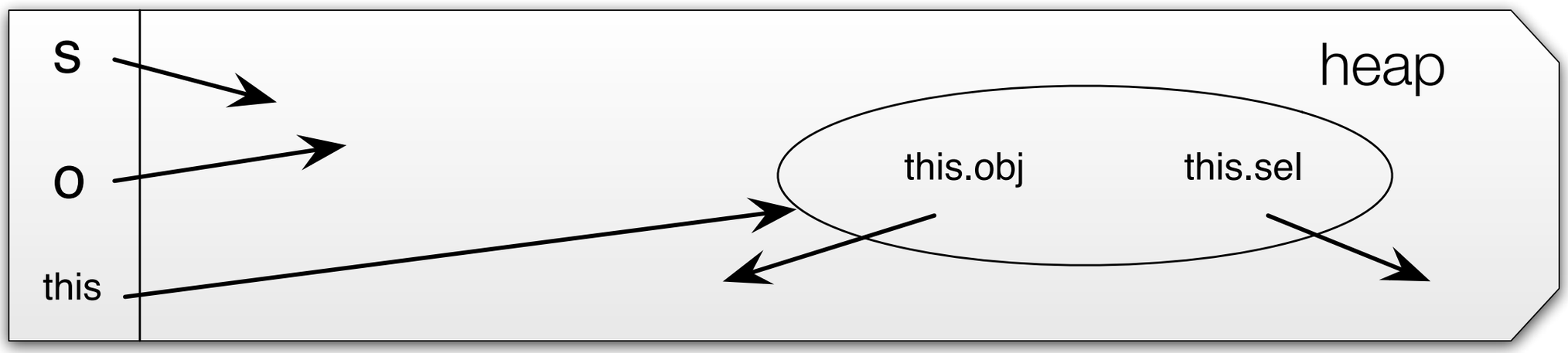

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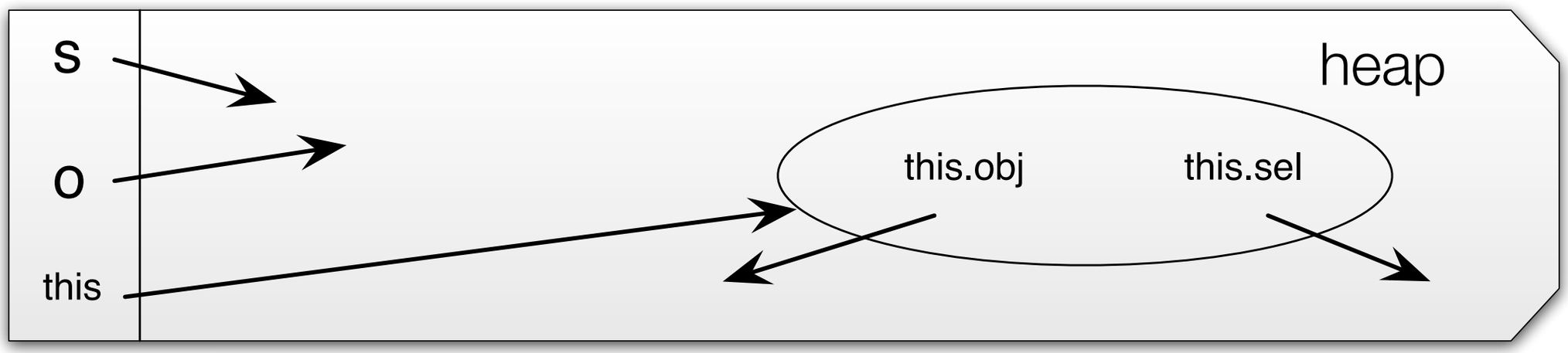

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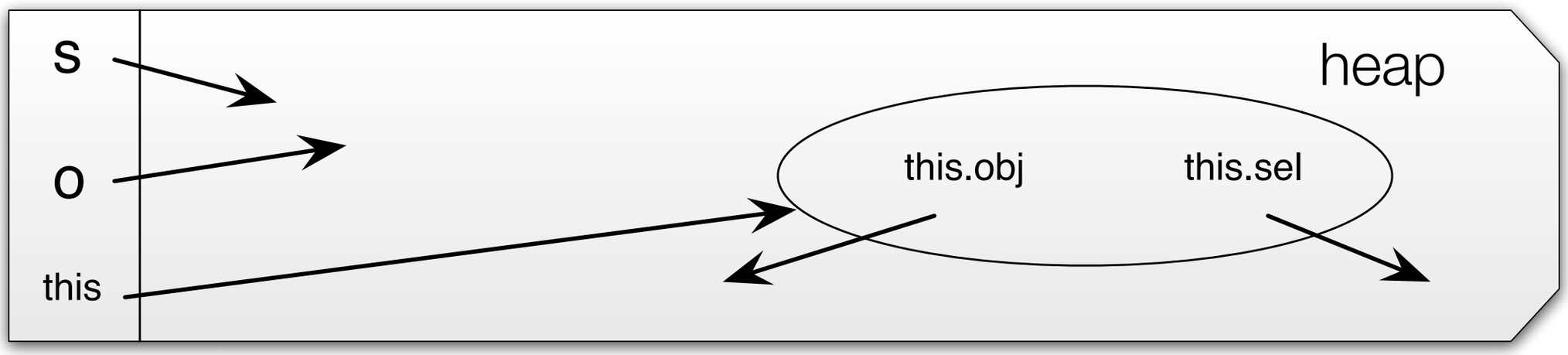

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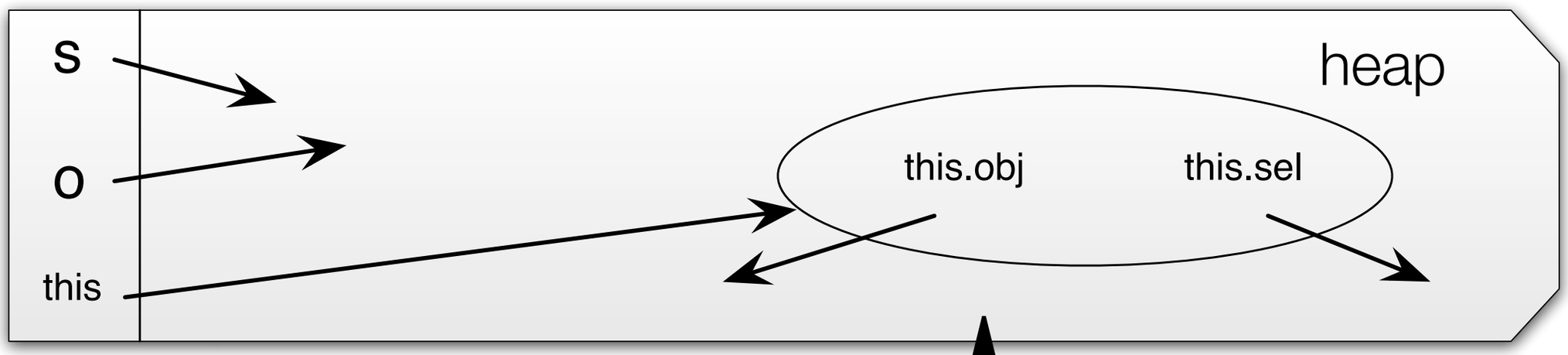

This picture captures the **fully type-consistent concrete** state

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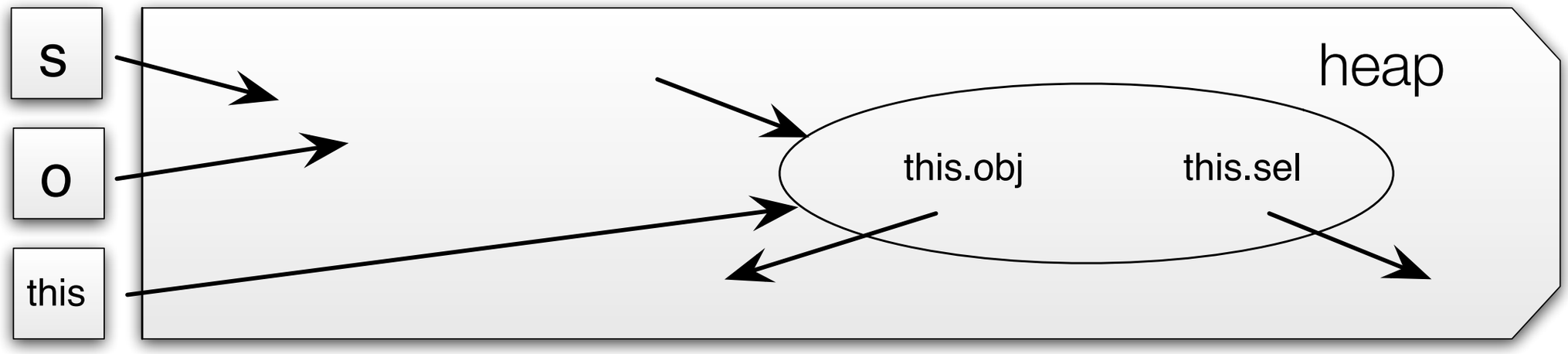

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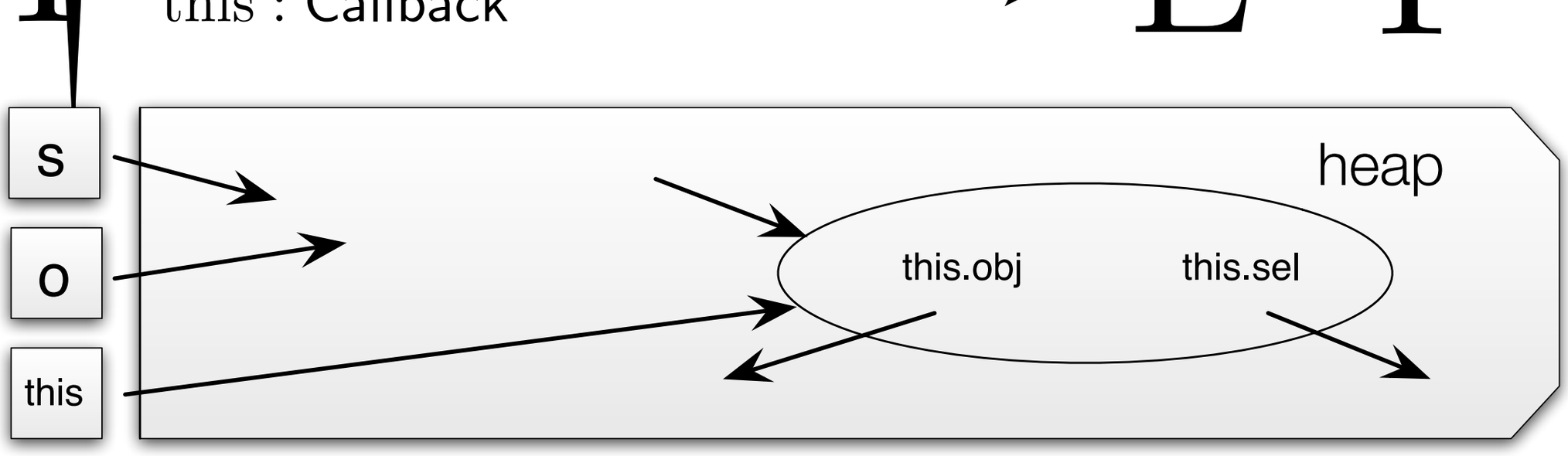

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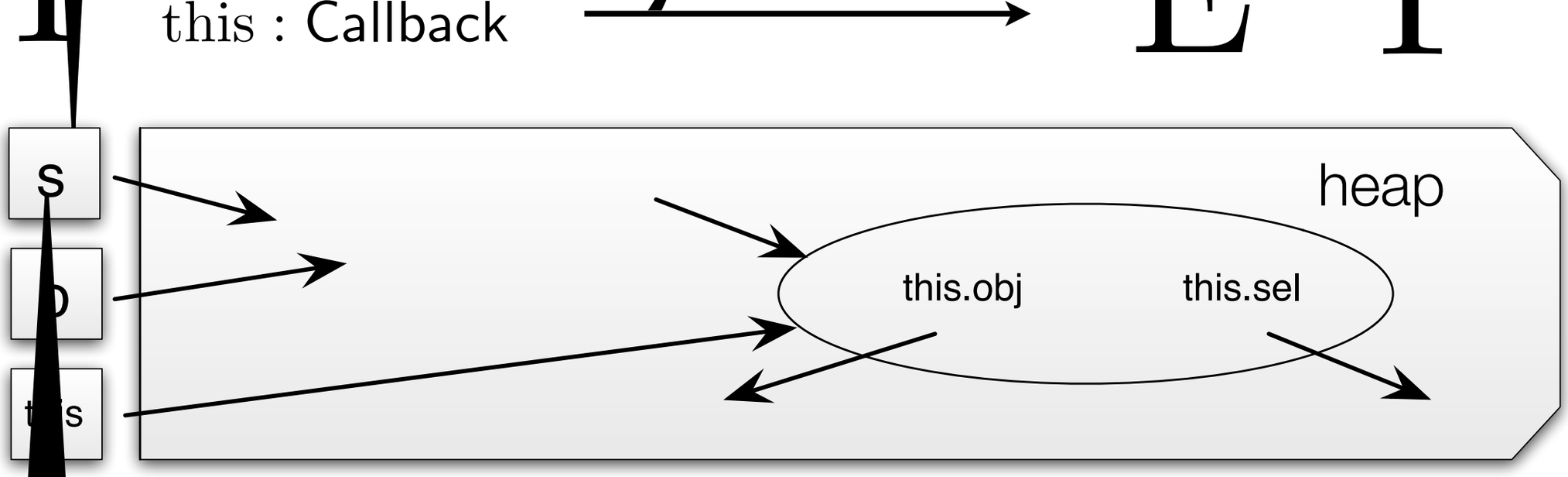

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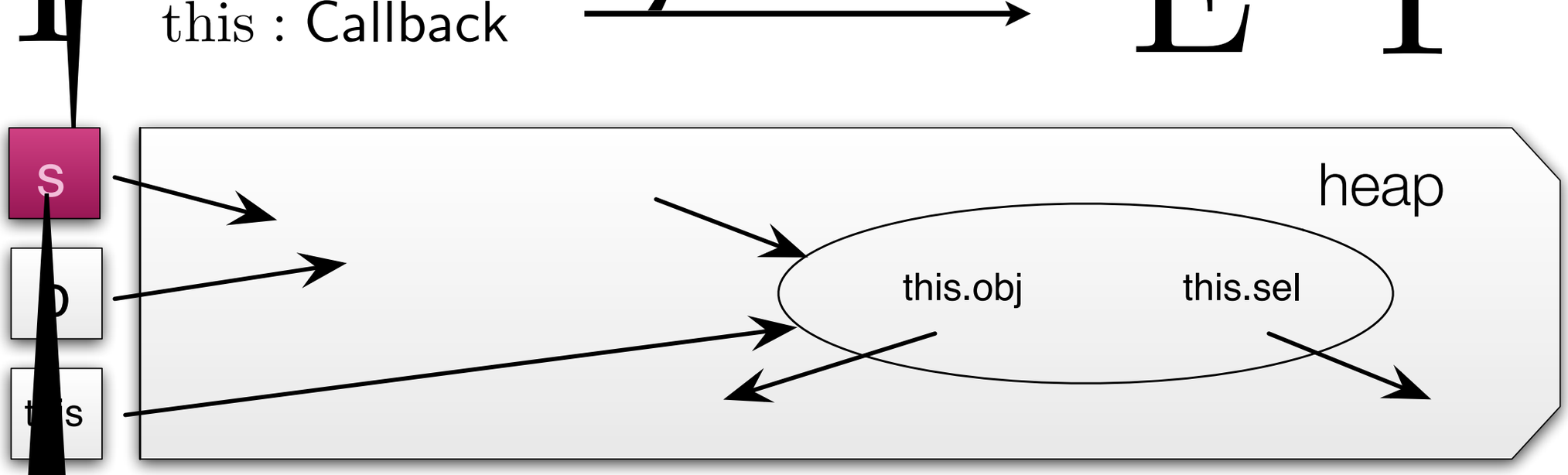

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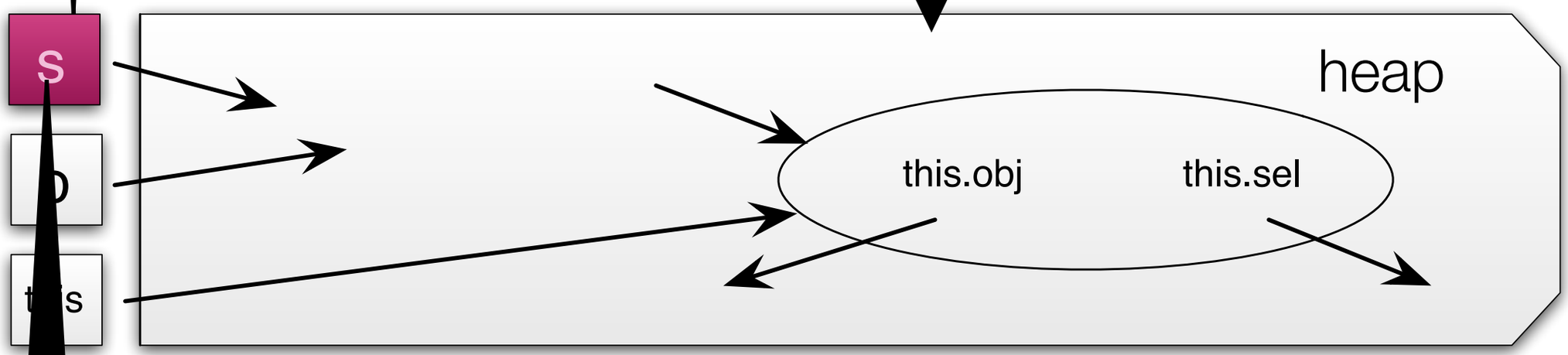
Grey indicates storage that is **not immediately type-inconsistent**



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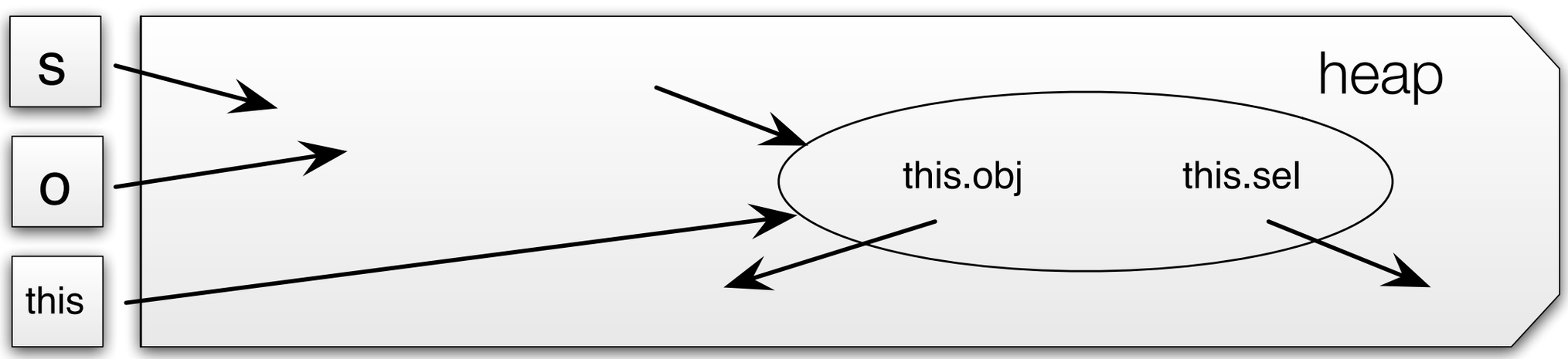

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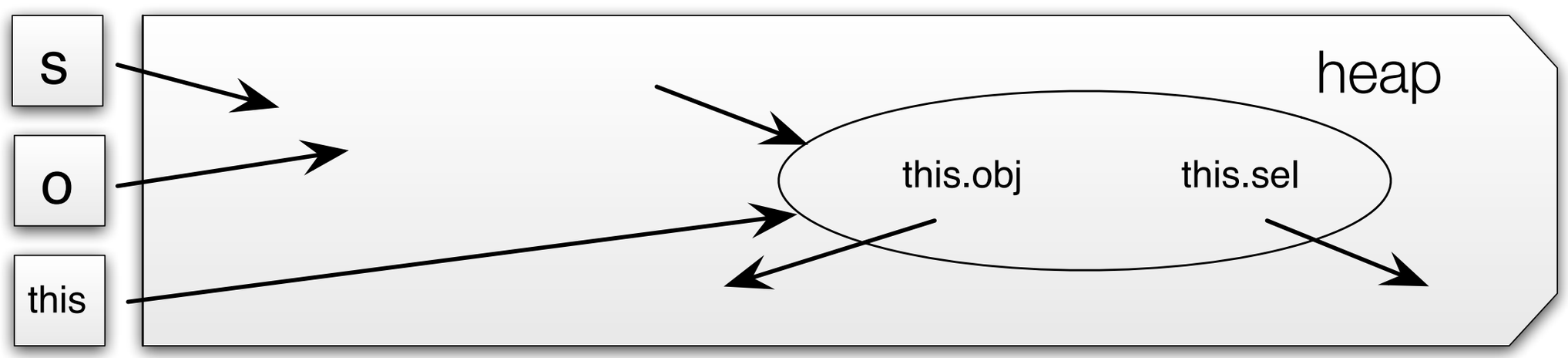

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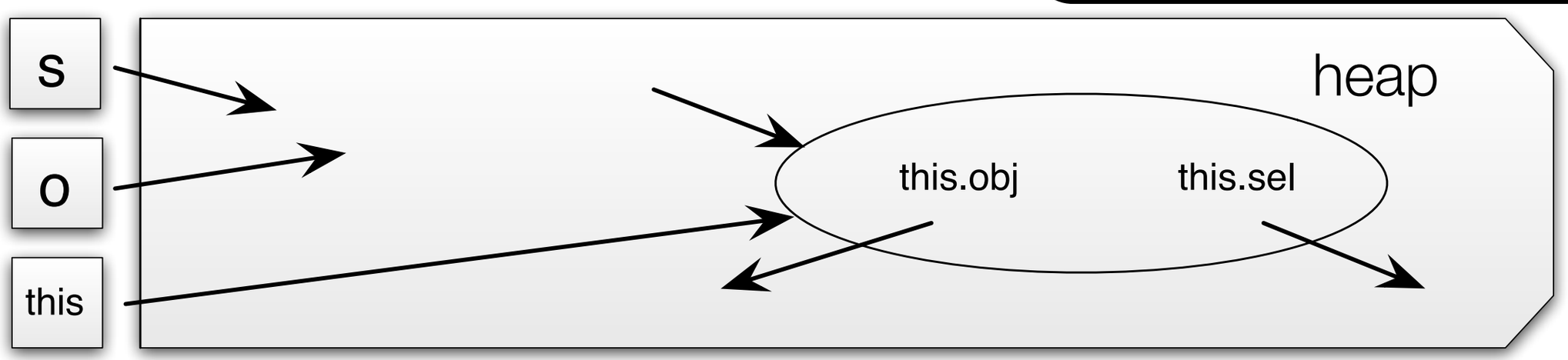
$$\mathsf{Callback} \triangleq \{\mathrm{sel} : \mathsf{Str}, \mathrm{obj} : \mathsf{Obj} \mid \mathsf{r2}\ \mathrm{sel}\}$$

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



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

Symbolic Heap

$\widetilde{H}$ okheap

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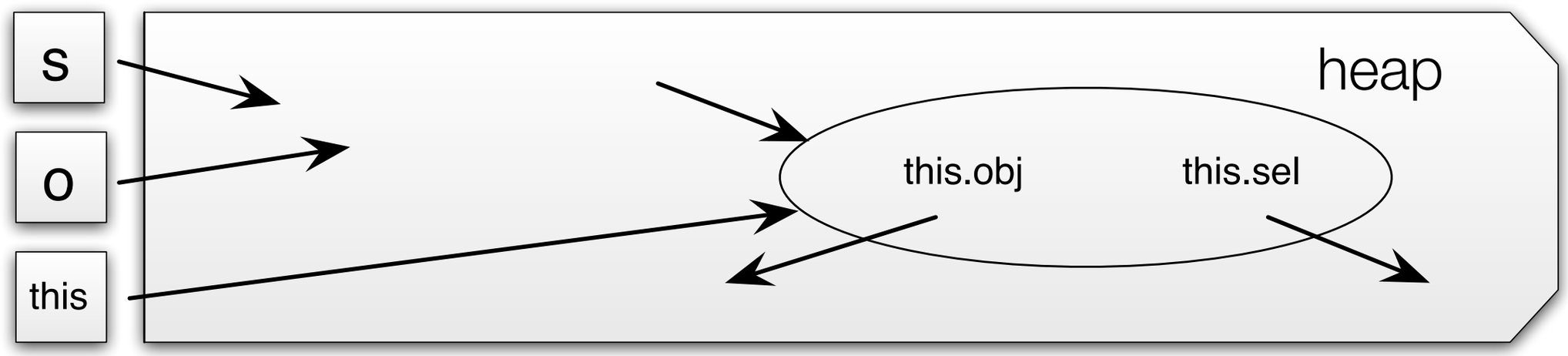
Concrete State



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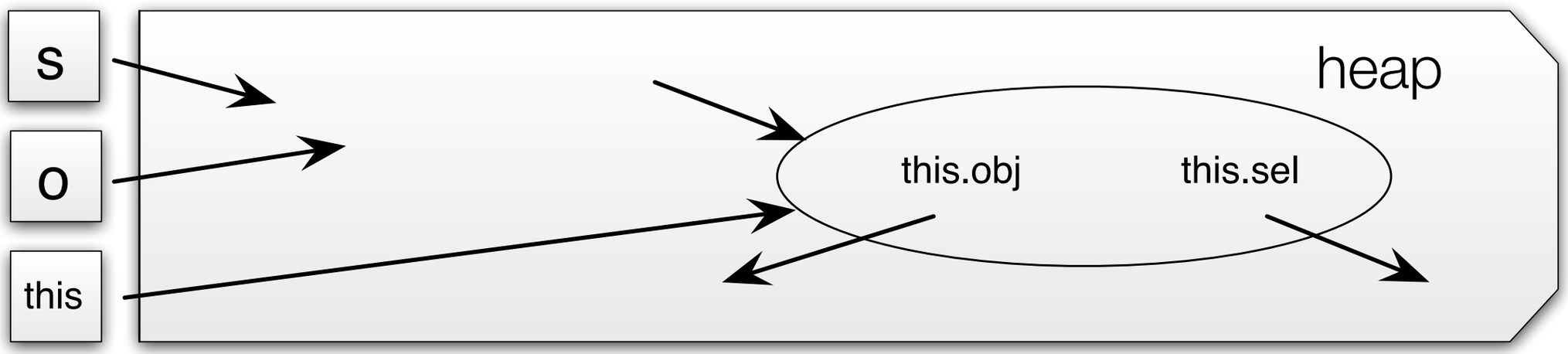

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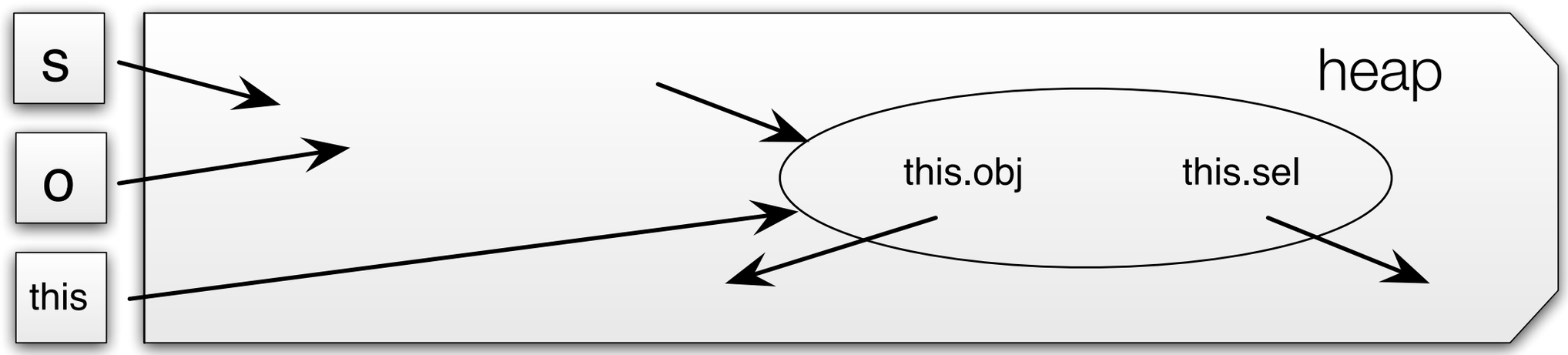

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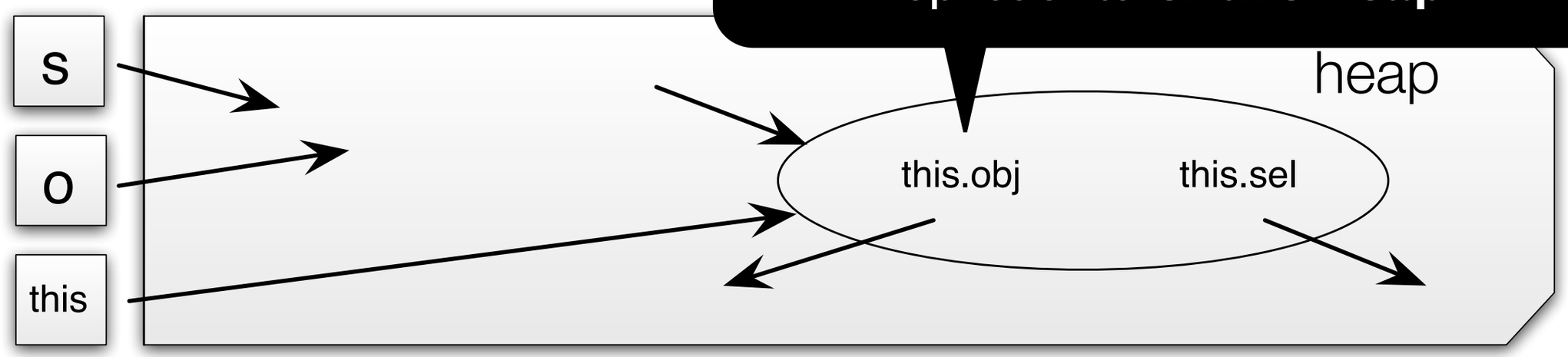
Concrete State

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



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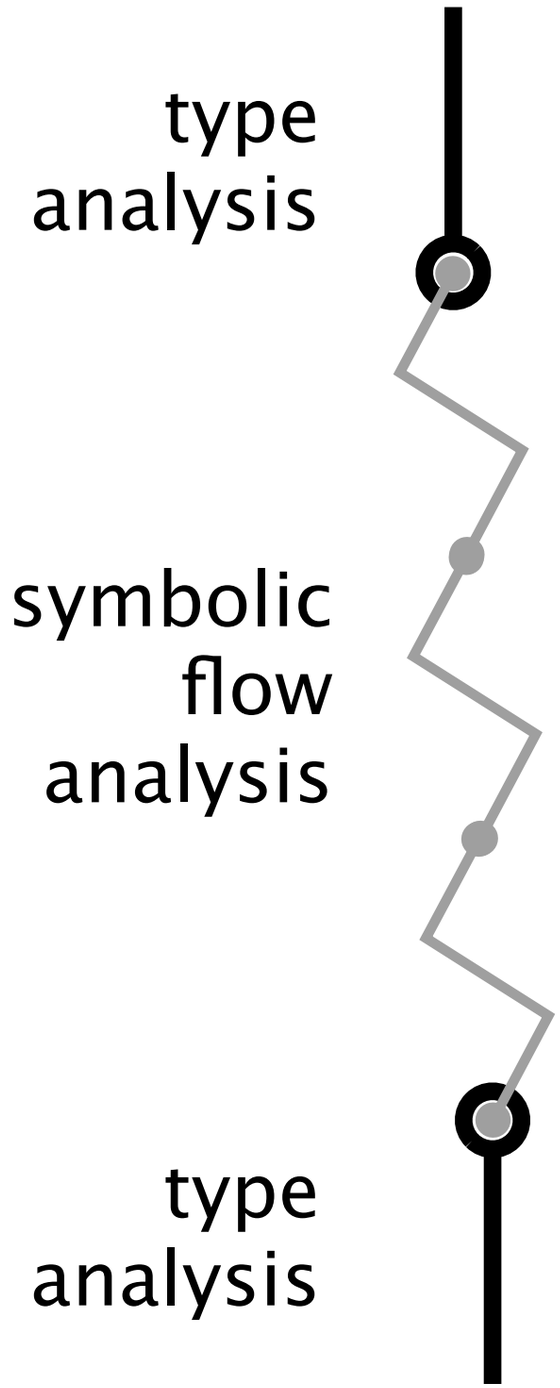

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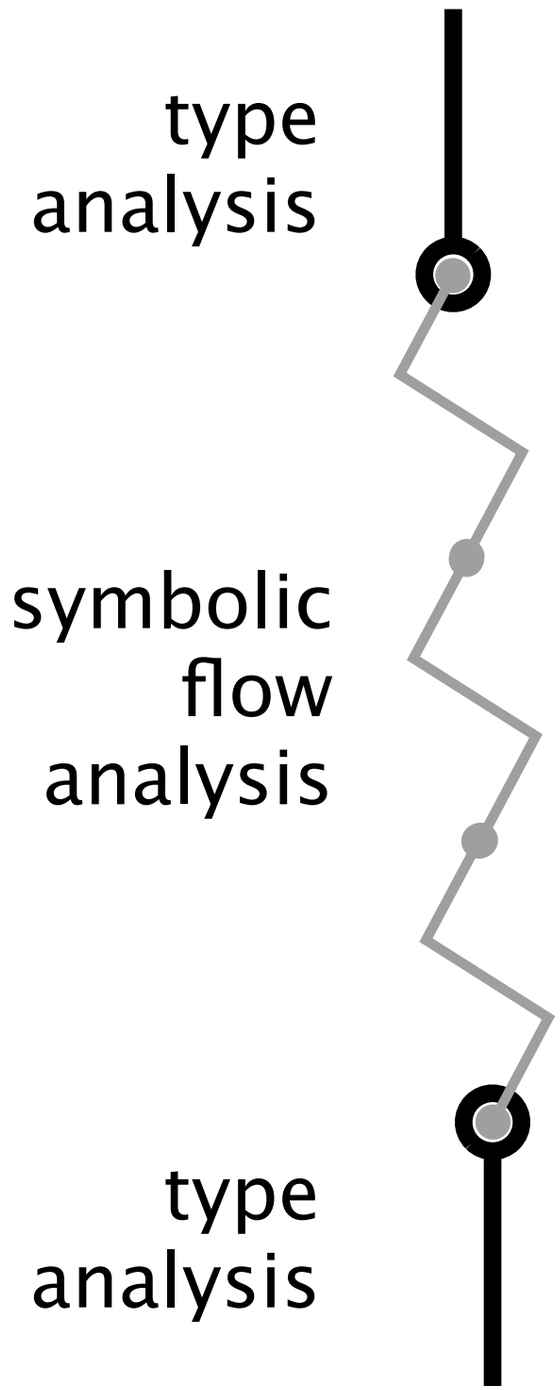

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Leverage **heap type invariant** via **type-consistent materialization**

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Symbolic State

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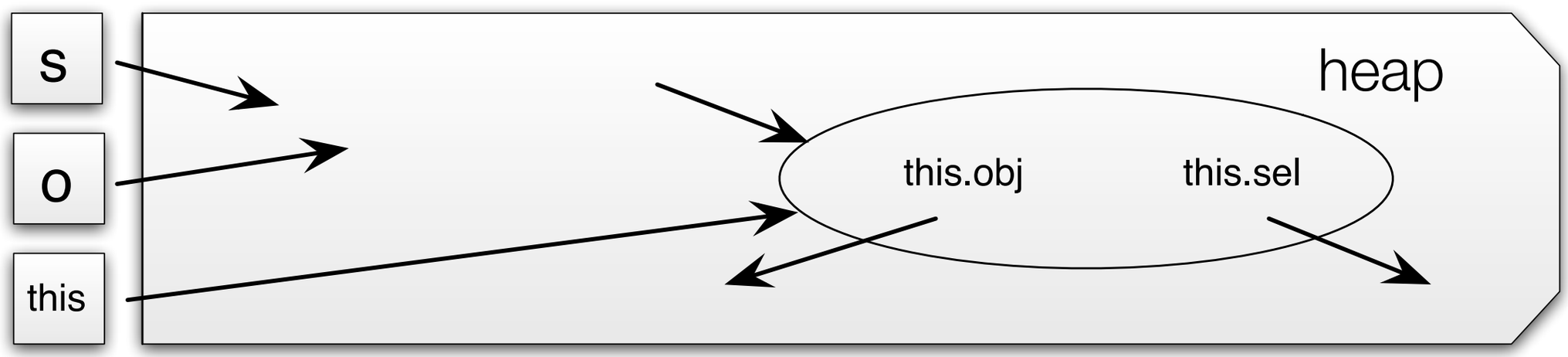
Concrete State



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

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

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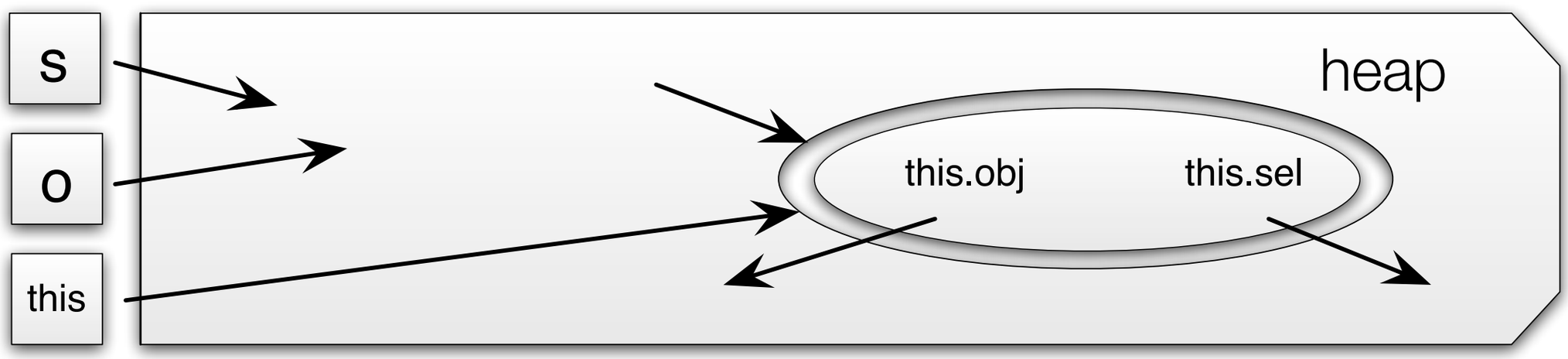

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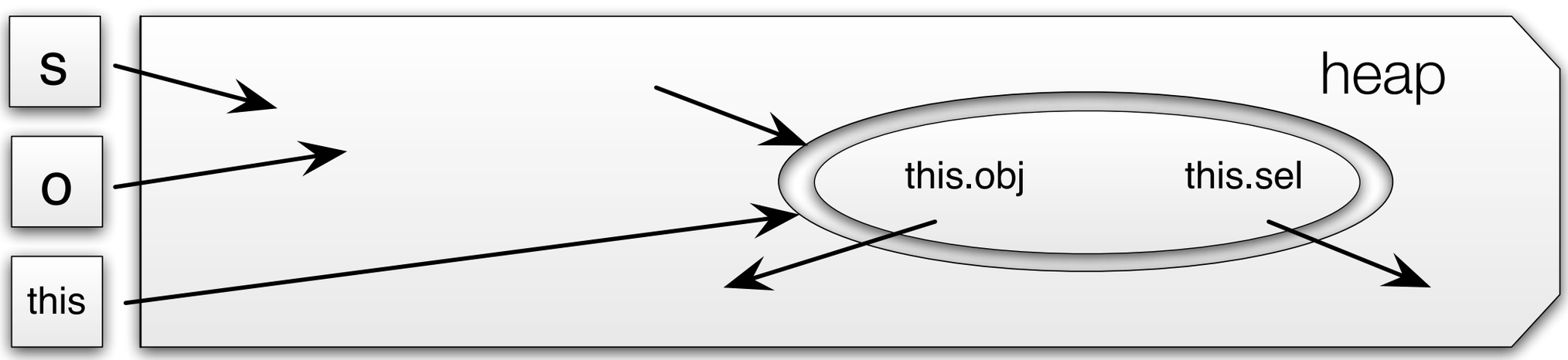

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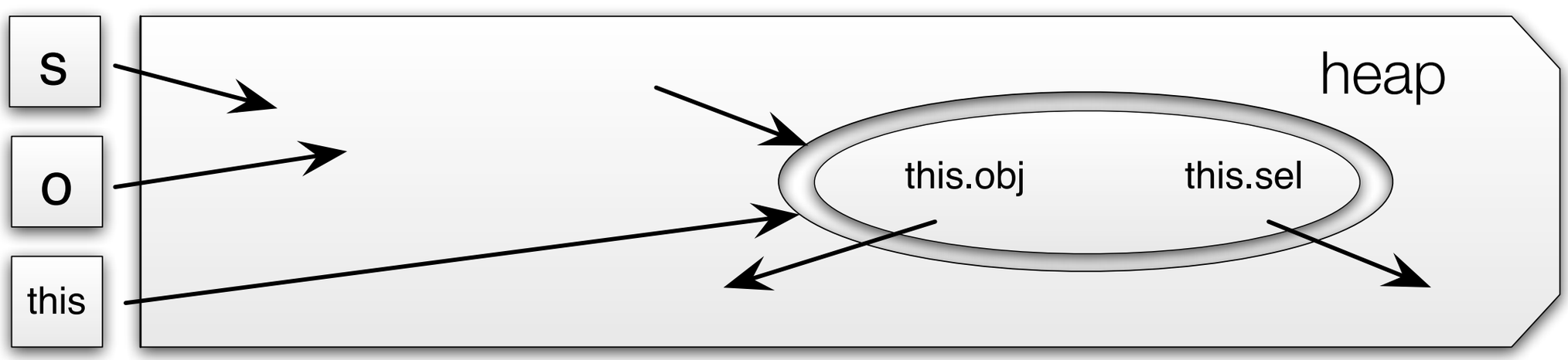

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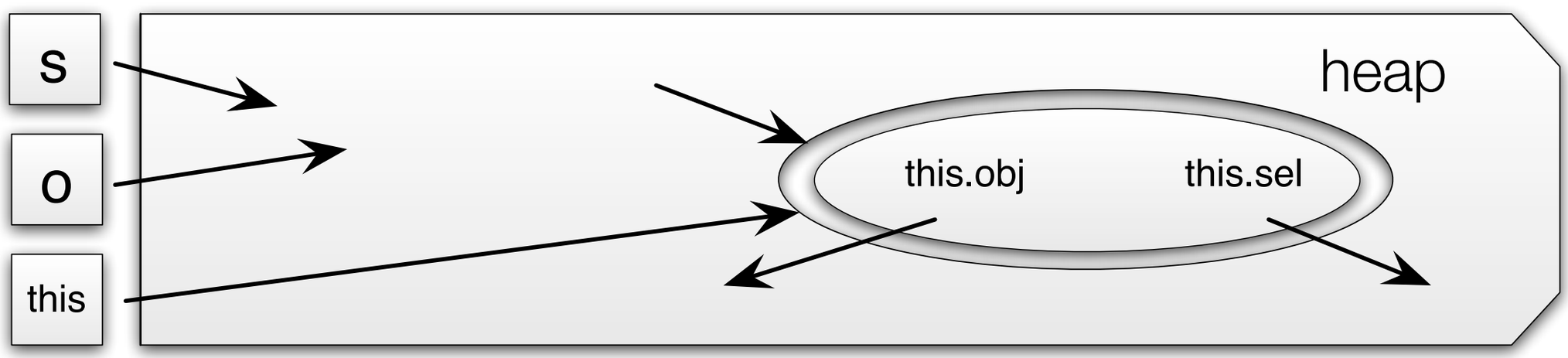

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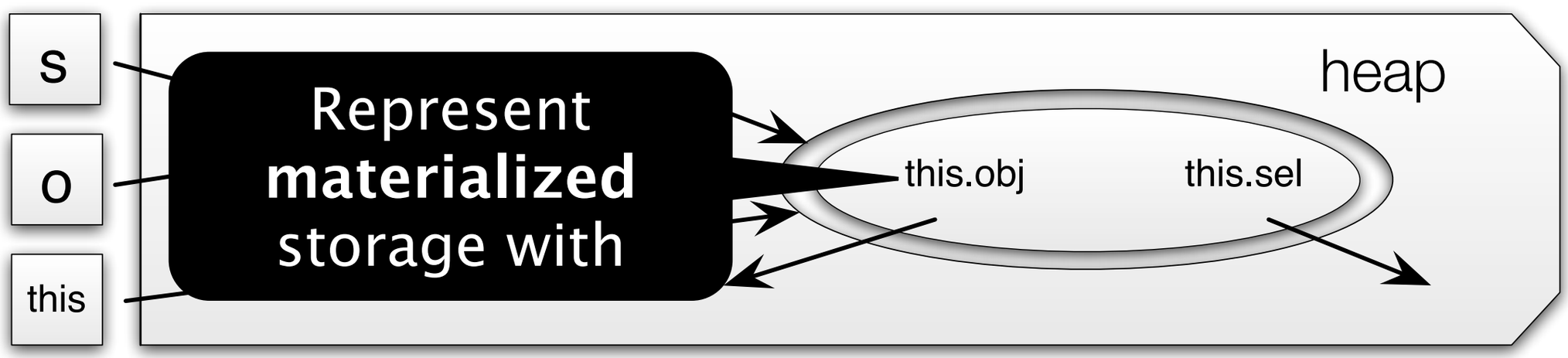

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Concrete State

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

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

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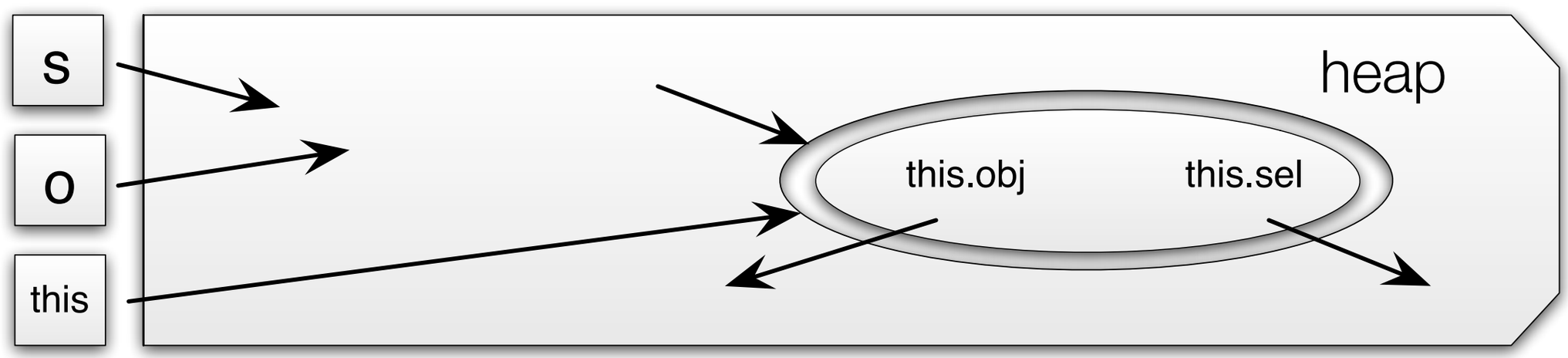

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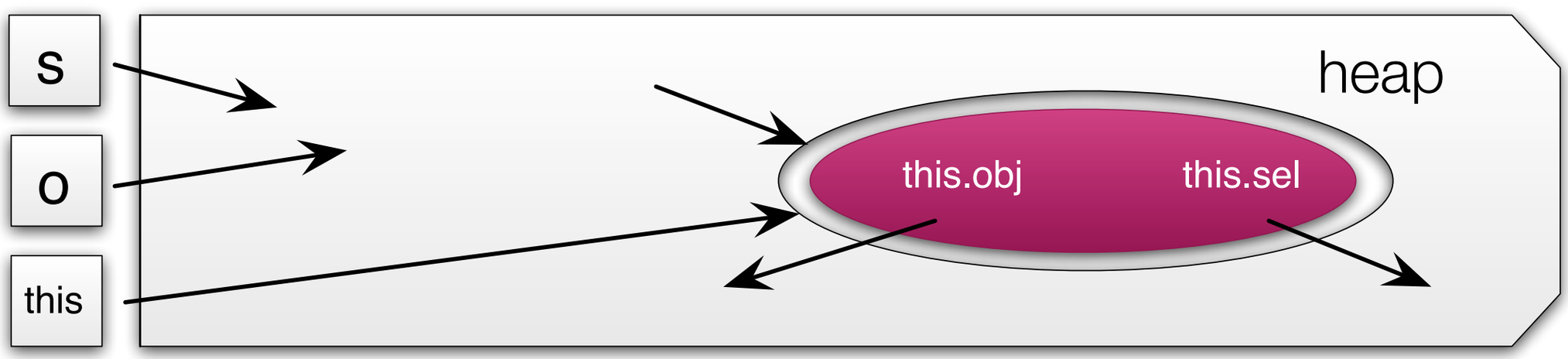

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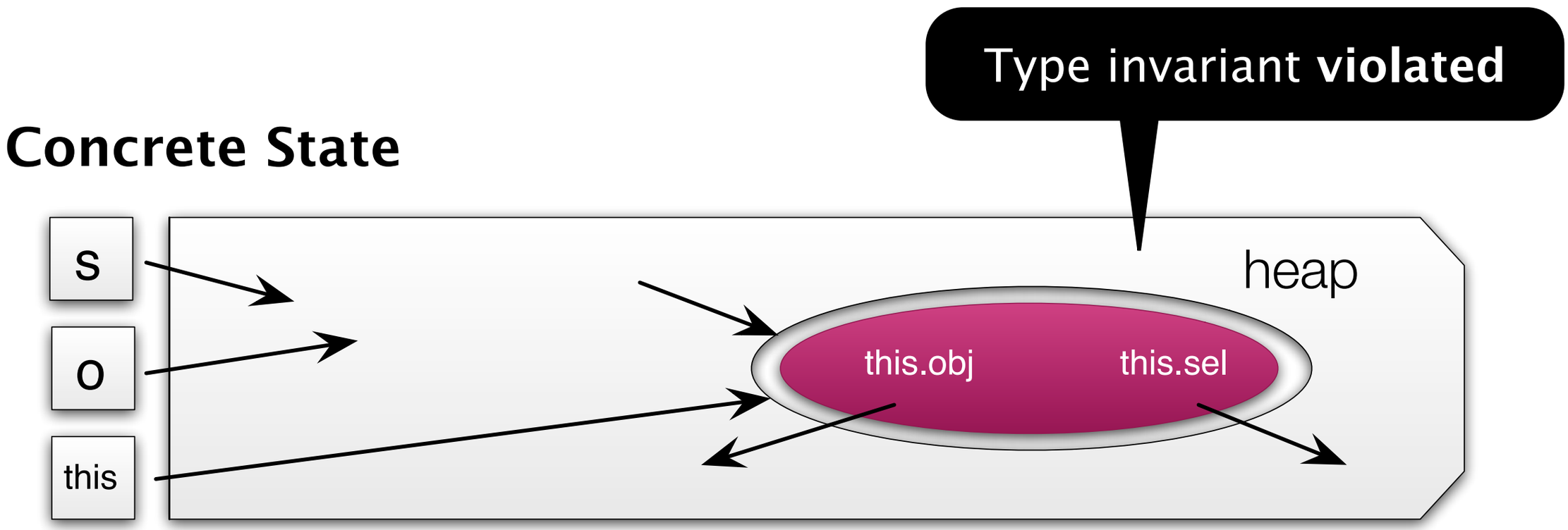

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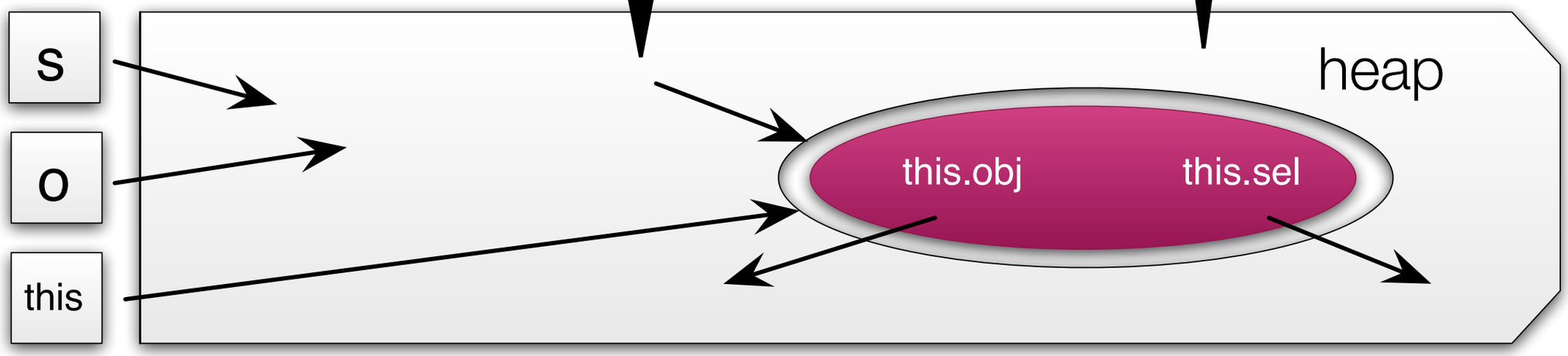
Surprising: can **soundly** permit **pointers in** and **out** of the region that is **not immediately type-inconsistent**

Type invariant **violated**



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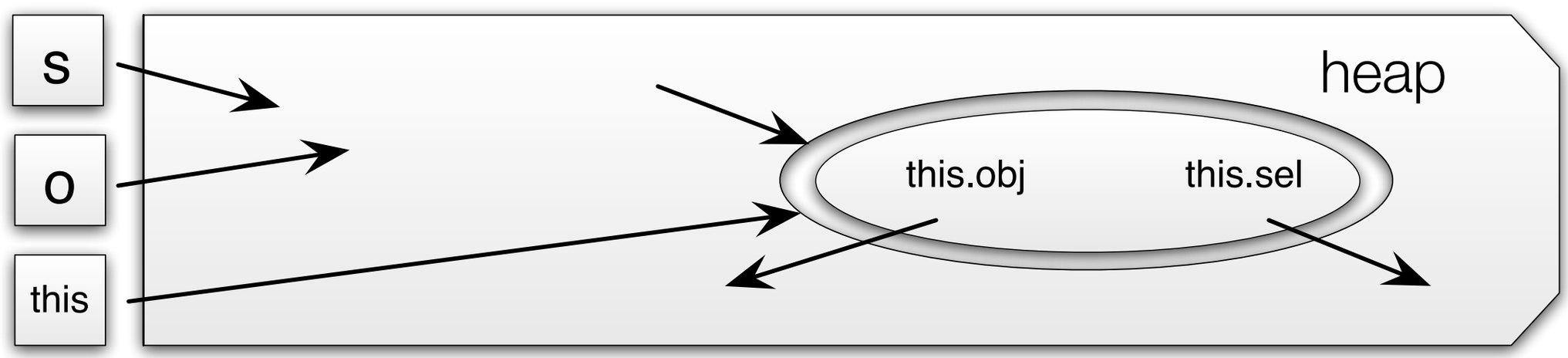

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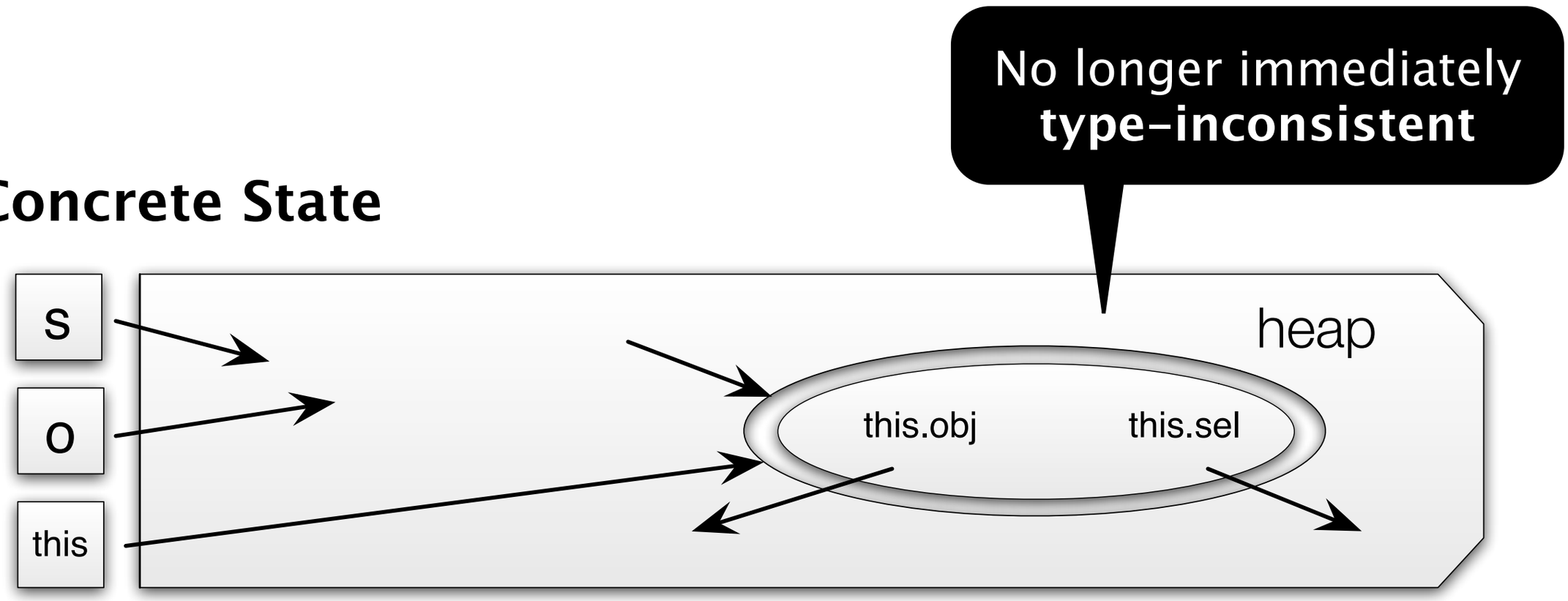

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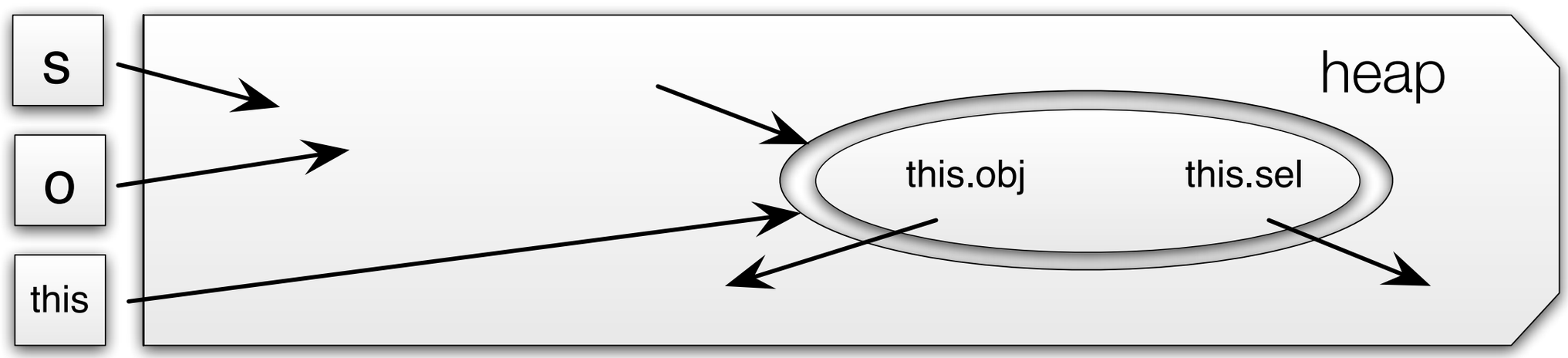

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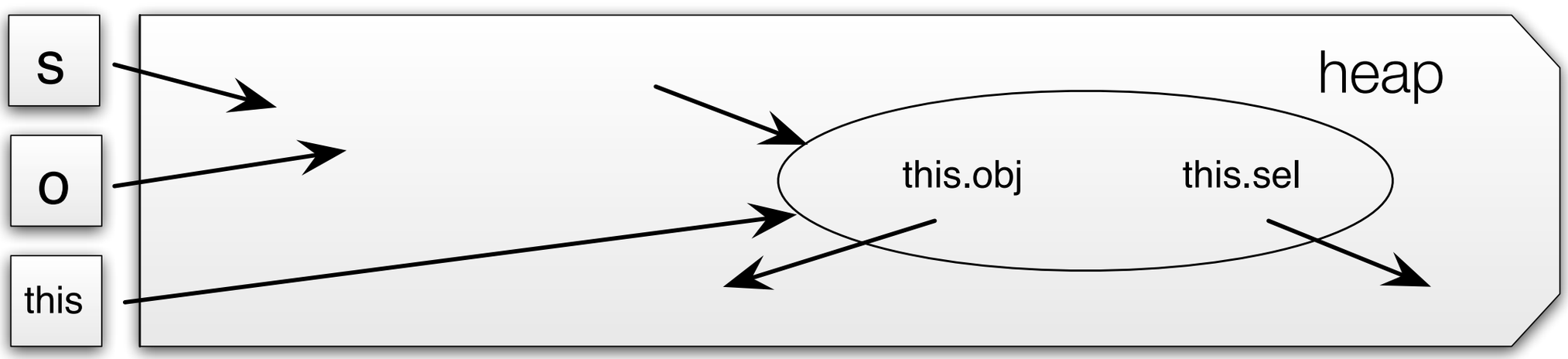

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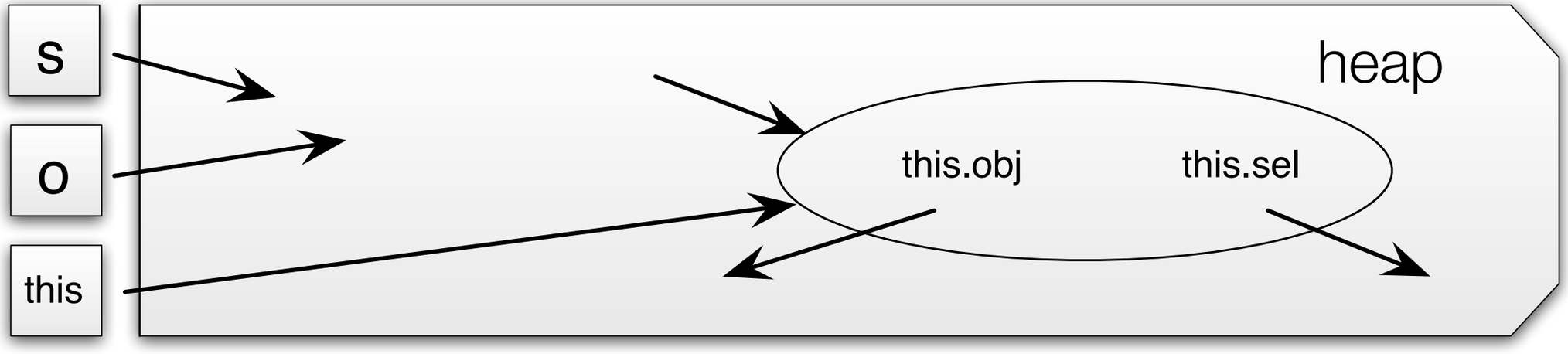

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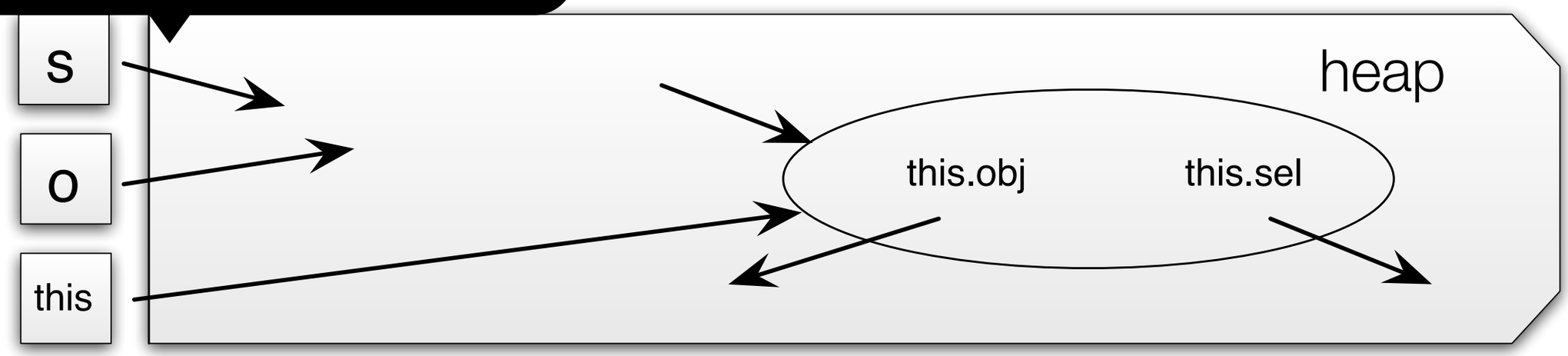

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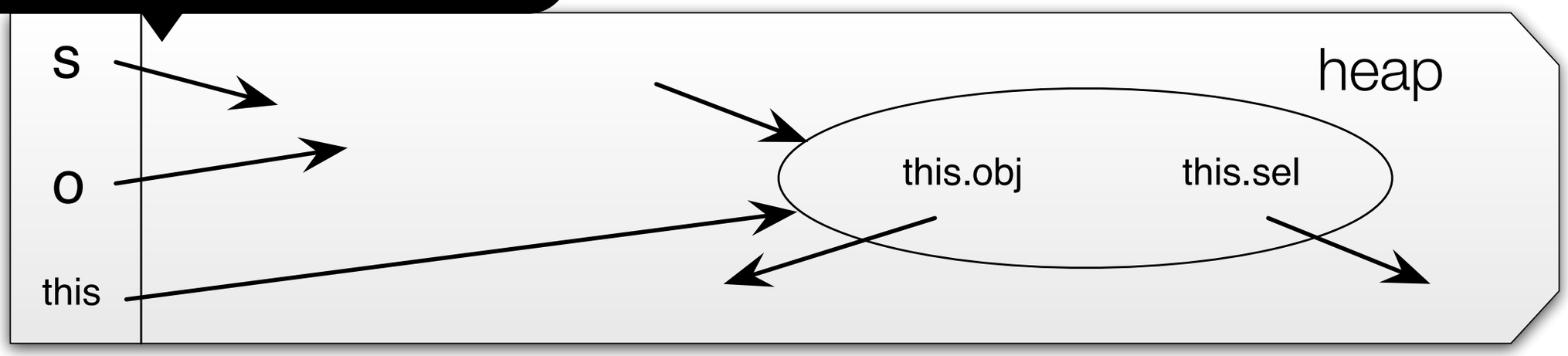

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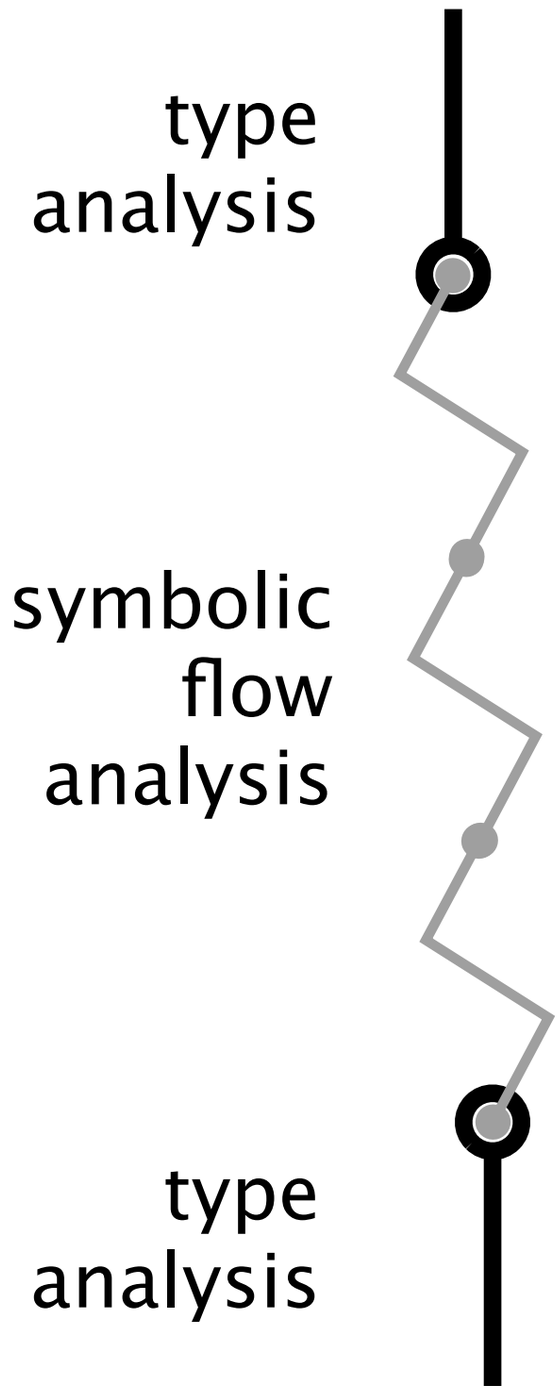

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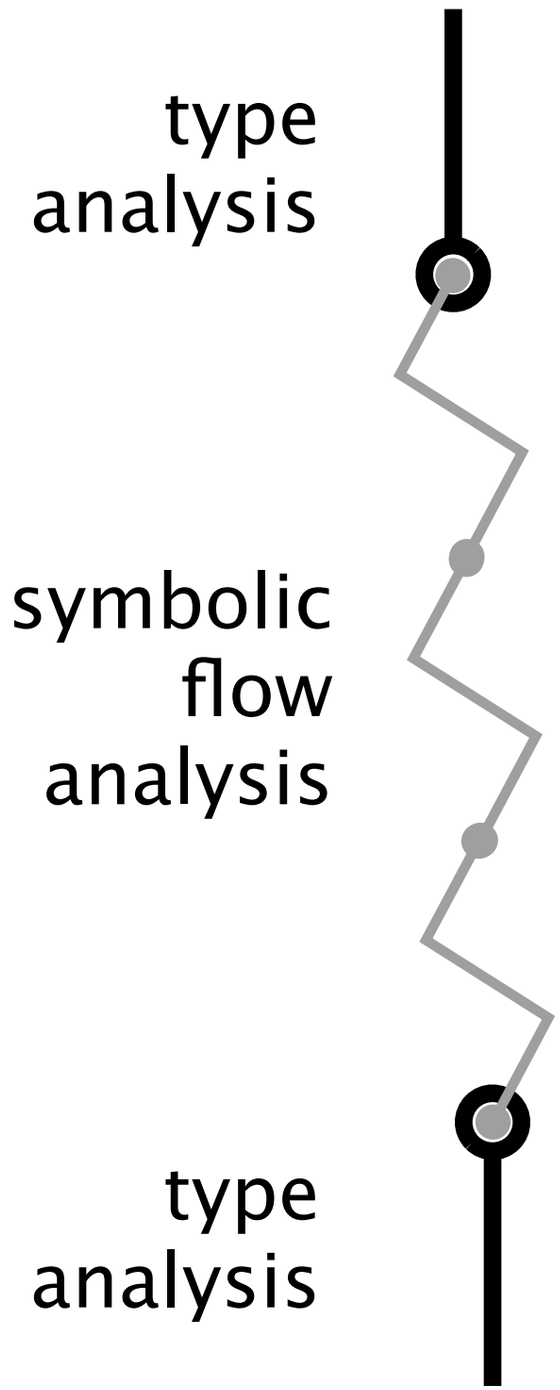

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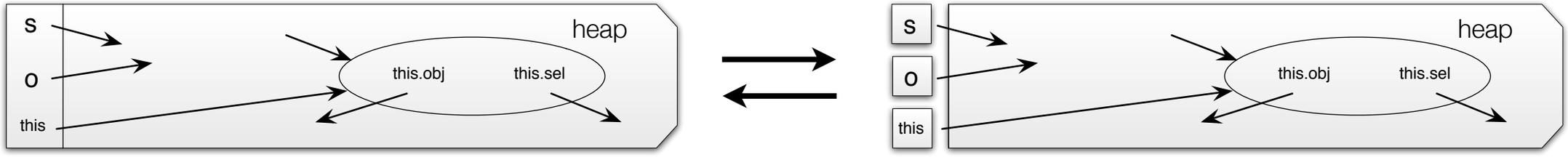

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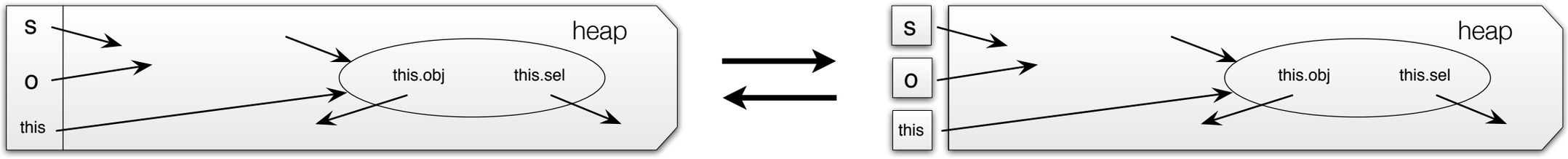
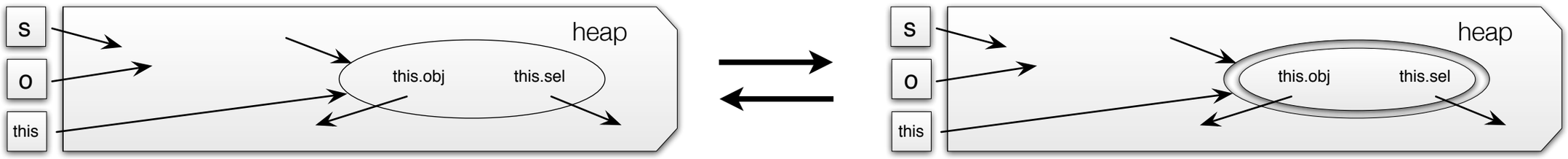


Theorem (Soundness of Materialization/Summarization).

Storage that is **not immediately type-inconsistent** can be safely materialized and summarized into **okheap**.



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
ZipKit	3301	0	0
Sparkle	5289	3	1
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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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SCRecorder	2716	12	2	0 (–100%)
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OmniFrameworks	160769	192	82	74 (–10%)
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Baseline: standard, **flow-insensitive** type analysis - no sw

Almost everywhere techniques show **29% improvement** in false alarms

Precision

	size		false alarms	
benchmark	(loc)	reflective call sites	flow-insensitive	almost-everywhere
OAuth	1248	7	7	2 (-71%)
	2716	12	2	0 (-100%)
	3301	28	0	0 (-)
	5289	40	4	1 (-75%)
	14620	68	50	10 (-80%)
	160769	192	82	74 (-10%)
Vienna	37327	186	59	38 (-36%)
Skim	60211	207	43	43 (-0%)
Adium	176629	587	87	70 (-20%)
combined	461080	1327	334	238 (-29%)

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	
benchmark	**(loc)**	**Time**	**Rate (kloc/s)**
OAuth	1248	0.24s	5.3
SCRecorder	2716	0.28s	10.8
ZipKit	3301	0.10s	33.0
Sparkle	5289	0.67s	7.9
ASIHTTPRequest	14620	0.50s	27.2
OmniFrameworks	160769	4.25s	37.8
Vienna	37327	2.79s	13.4
Skim	60211	2.49s	24.1
Adium	176629	8.79s	20.1
combined	461080	20.09s	23.0

Cost: Analysis **time**

	size	analysis time	
benchmark	**(loc)**	**Time**	**Rate (kloc/s)**
OAuth	1248	0.24s	5.3
SCRecorder	2[illegible]	0.28s	10.8
ZipKit	3301	0.10s	33.0
[illegible]	5289	0.67s	7.9
[illegible]	14620	0.50s	27.2
[illegible]	160769	4.25s	37.8
[illegible]	37327	2.79s	13.4
Skim	60211	2.49s	24.1
Adium	176629	8.79s	20.1
combined	461080	20.09s	23.0

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

Cost: Analysis **time**

	size	analysis time	
	(loc)	Time	Rate (kloc/s)
	1248	0.24s	5.3
	2716	0.28s	10.8
	3301	0.10s	33.0
	5289	0.67s	7.9
	14620	0.50s	27.2
	160769	4.25s	37.8
	37327	2.79s	13.4
SKIM	60211	2.49s	24.1
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combined	461080	20.09s	23.0

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

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

Cost: Analysis **time**

	size	analysis time	
benchmark	**(loc)**	**Time**	**Rate (kloc/s)**
OAuth	1248	0.24s	5.3
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ZipKit	3301	0.10s	33.0
Sparkle	5289	0.67s	7.9
ASIHTTPRequest	14620	0.50s	27.2
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Fast: 5 to 38 kloc/s with most time spent **analyzing system headers**

Cost: Analysis **time**

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benchmark	**(loc)**	**Time**	**Rate (kloc/s)**
OAuth	1248	0.24s	5.3
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Fast: 5 to 38 kloc/s with most time spent **analyzing system headers**

Interactive speeds

Cost: Analysis **time**

	size	analysis time	
benchmark	**(loc)**	**Time**	**Rate (kloc/s)**
OAuth	1248	0.24s	5.3
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ZipKit	3301	0.10s	33.0
Sparkle	5289	0.67s	7.9
ASIHTTPRequest	14620	0.50s	27.2
OmniFrameworks	160769	4.25s	37.8
Vienna	37327	2.79s	13.4
Skim	60211	2.49s	24.1
Adium	176629	8.79s	20.1
combined	461080	20.09s	23.0

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

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

Cost: Analysis **time**

	size	analysis time	
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OAuth	1248	0.24s	5.3
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combined	461080	20.09s	23.0

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

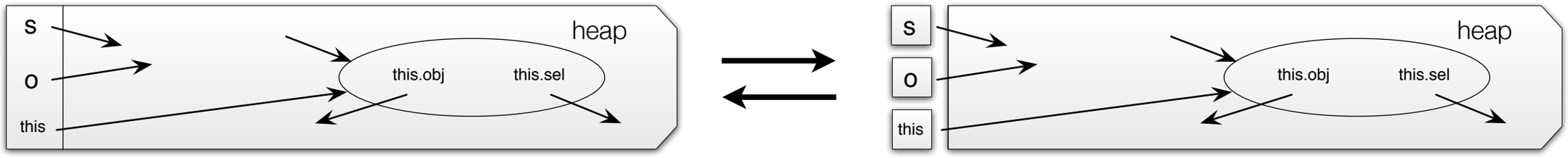
Maintains key benefit of flow-insensitive analyses: **speed**

tion

Reiteration: Fissile Type Analysis is sound

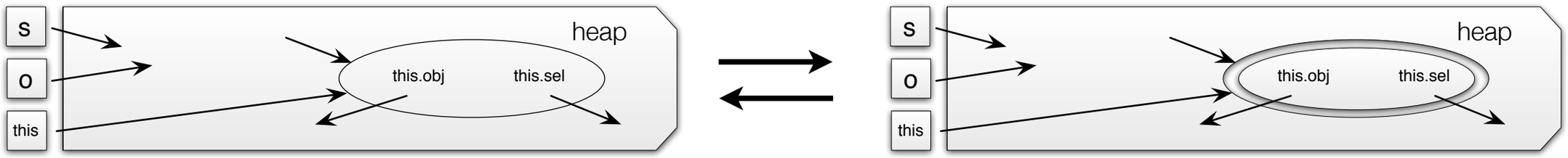
Theorem (Soundness of Handoff).

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



Theorem (Soundness of Materialization/Summarization).

Storage that is **not immediately type-inconsistent** can be safely materialized and summarized into **okheap**.



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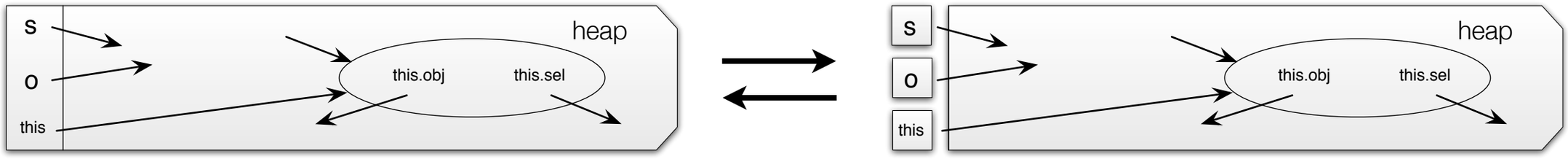

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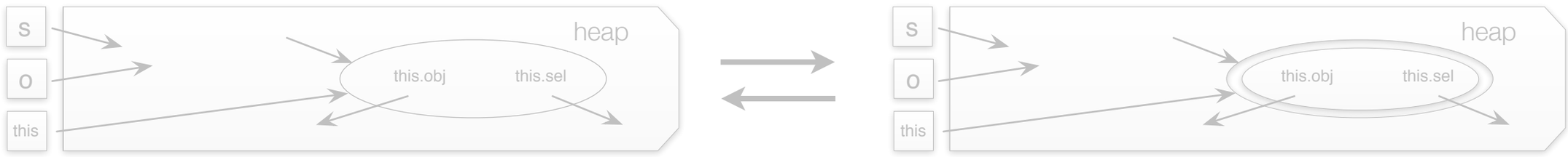

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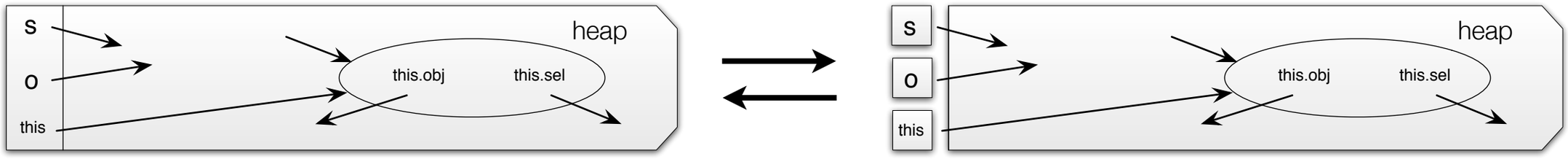

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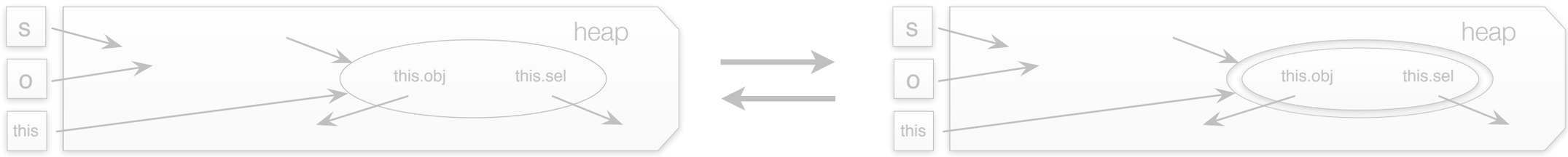

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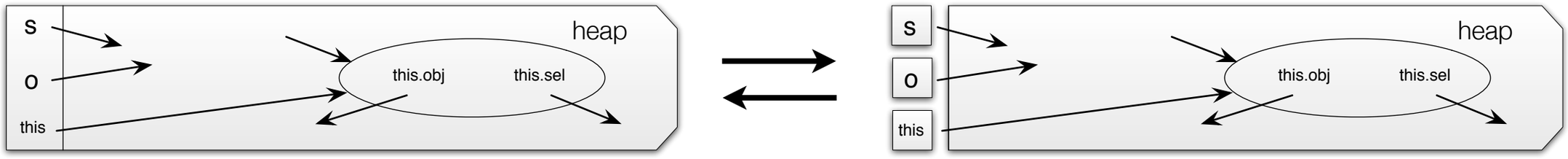
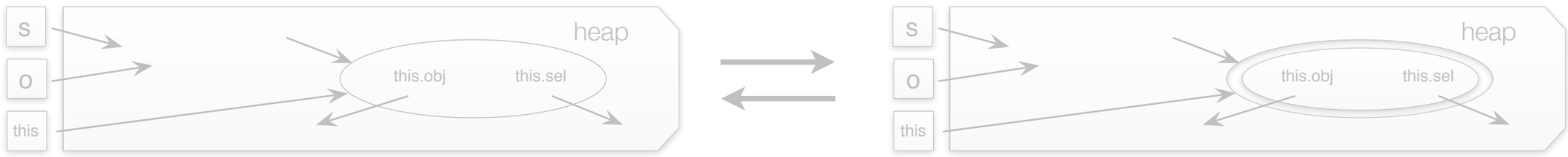
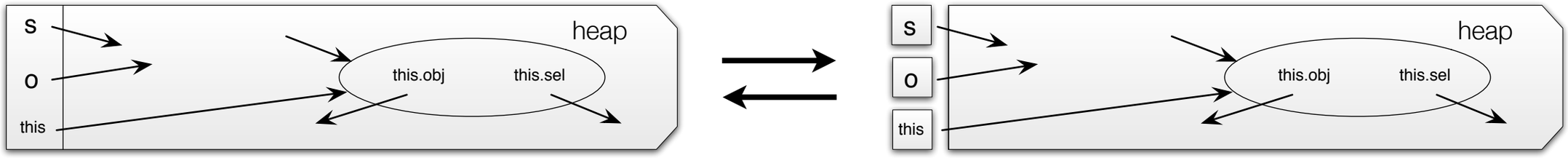


No locality or **framing**



Next Steps: Gated Separation

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



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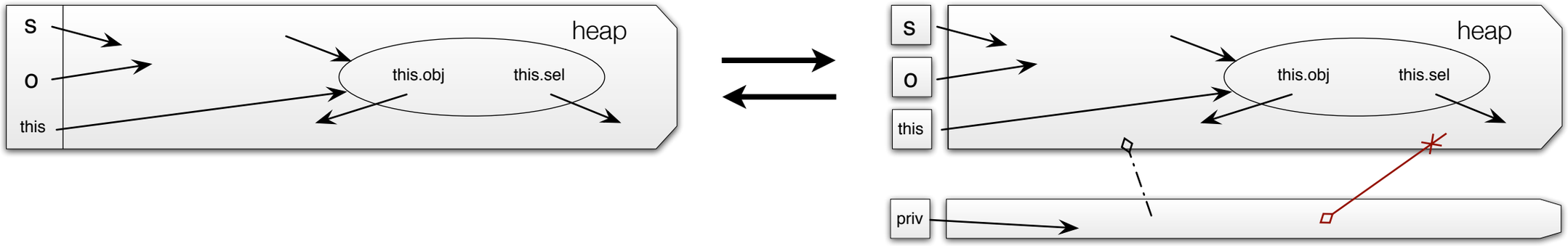
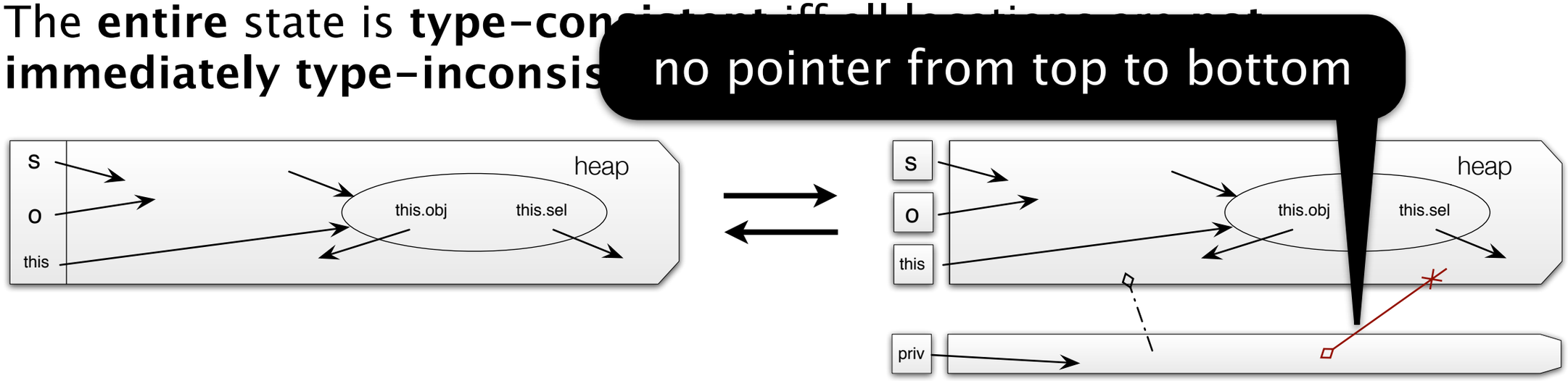


Next Steps: Gated Separation

The **entire** state is **type-con** **immediately type-inconsis**



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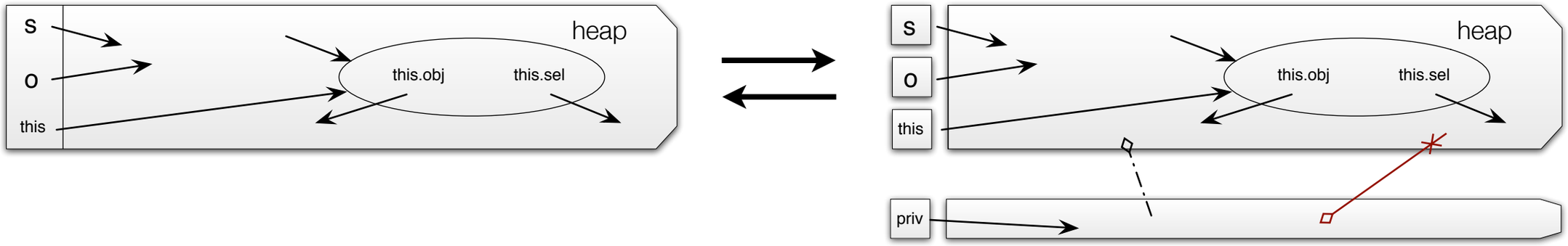

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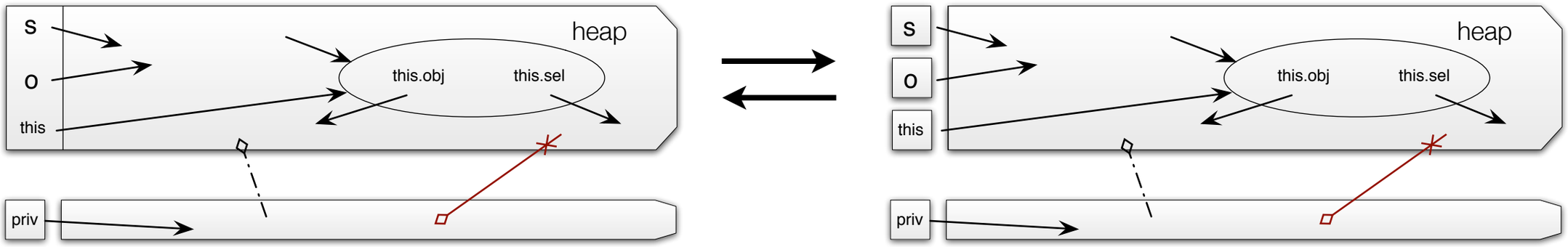

Next Steps: Gated Separation ⋆

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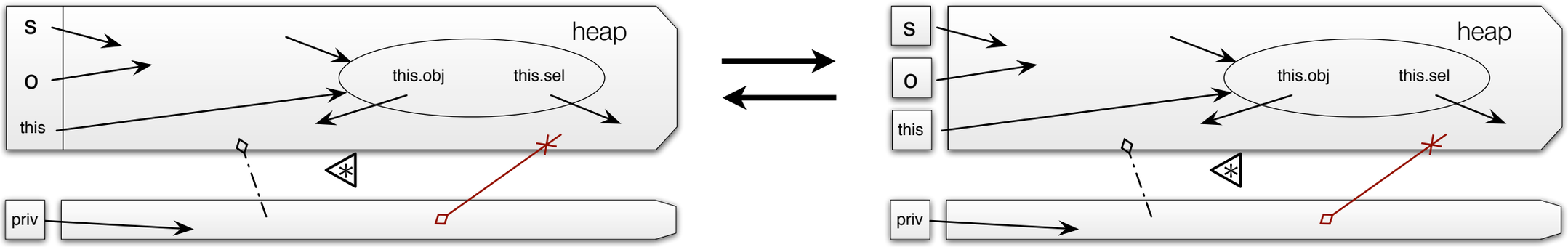

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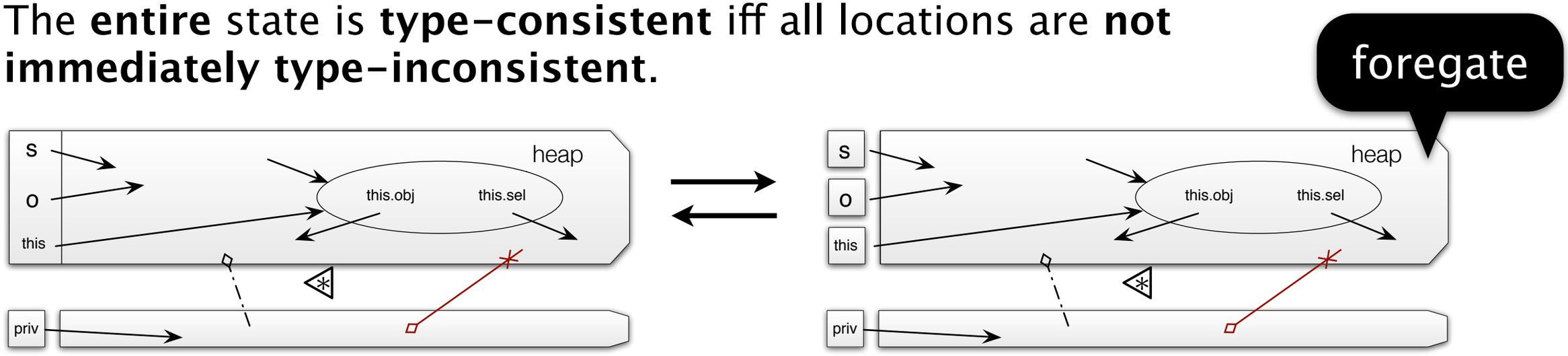

Next Steps: Gated Separation ⊲*

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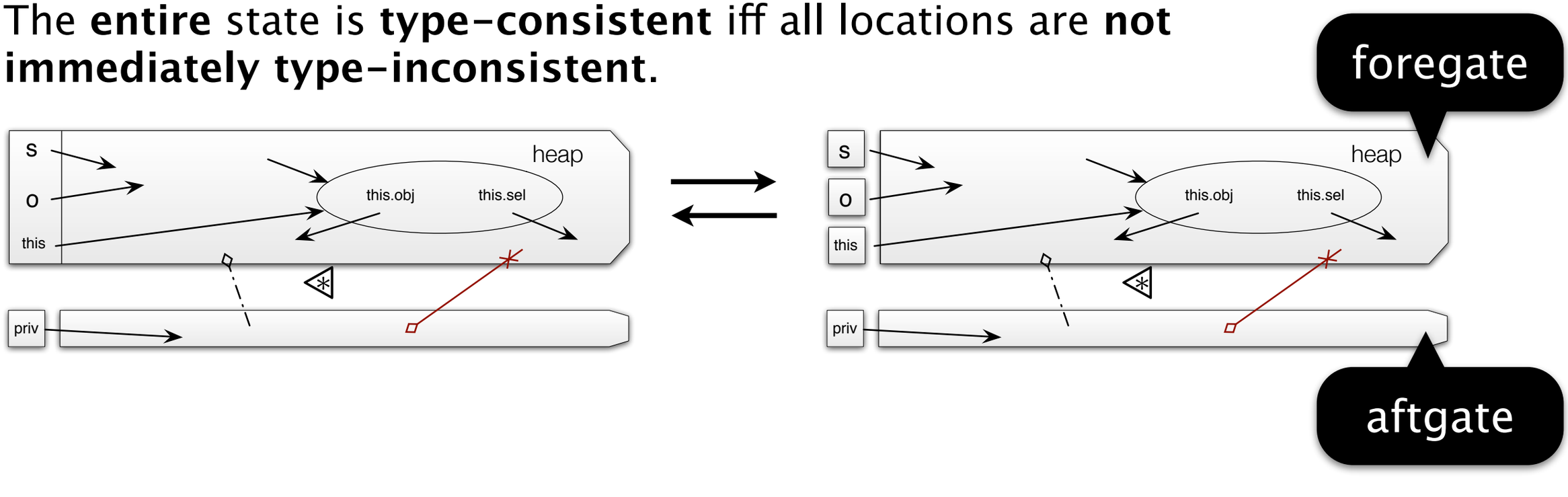

Next Steps: Gated Separation ⋆

“foregate”

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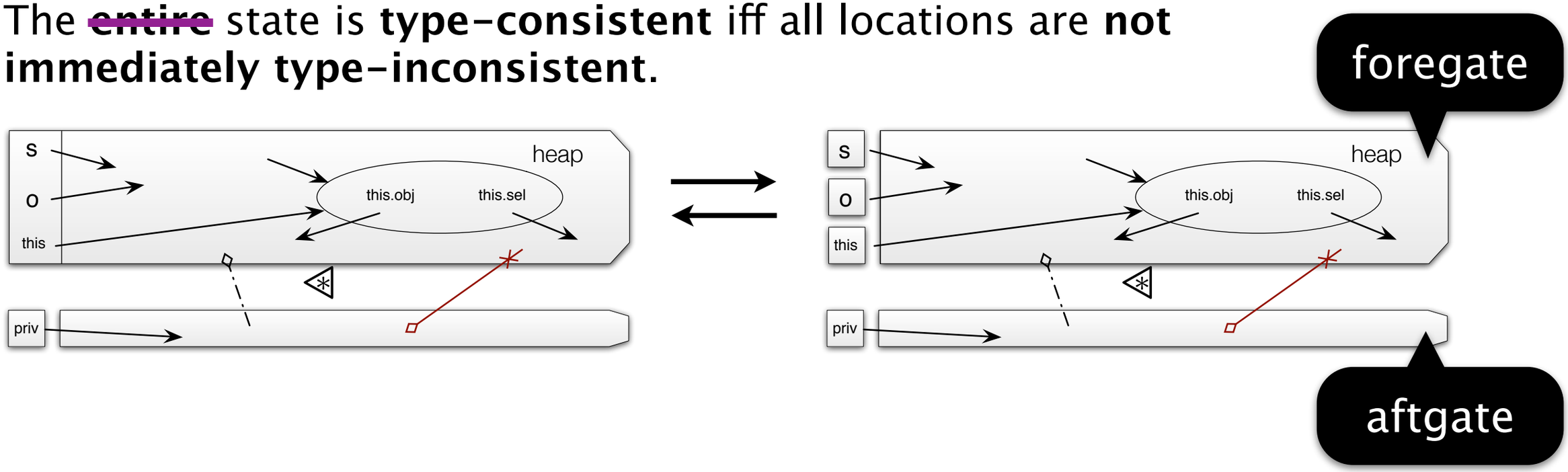

Next Steps: Gated Separation ⋪

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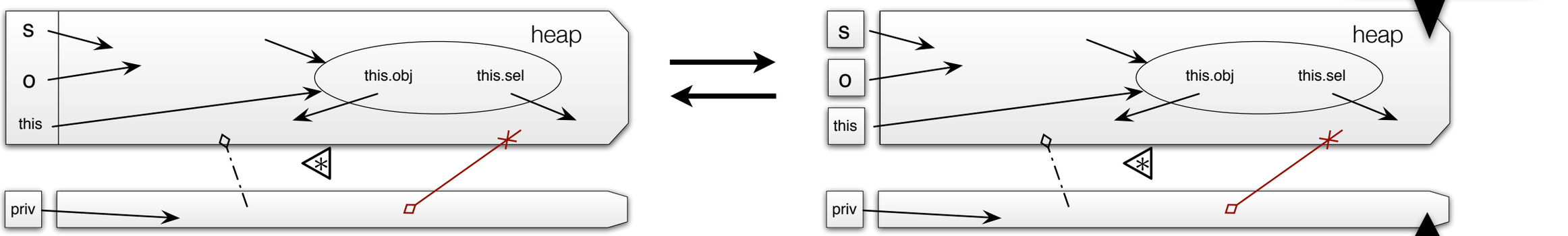
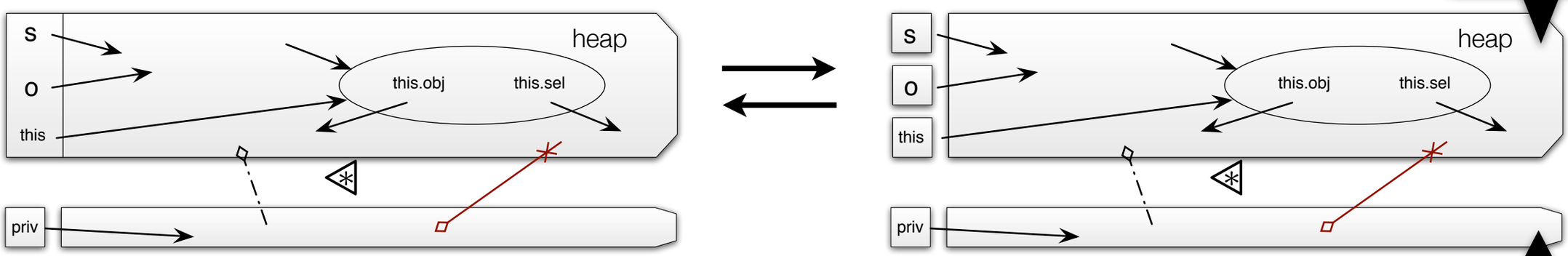


$$\sigma \vdash_V M_1 \not\triangleleft M_2 \quad \text{iff} \quad \sigma = \sigma_1 \cup \sigma_2 \text{ for some } \sigma_1, \sigma_2$$
$$\text{where } \sigma_1 \vdash_V M_1 \text{ and } \sigma_2 \vdash_V M_2$$
$$\text{and } \mathrm{dom}(\sigma_1) \cap \mathrm{dom}(\sigma_2) = \emptyset$$
$$\text{and } \mathrm{rng}(\sigma_1) \cap \mathrm{dom}(\sigma_2) = \emptyset$$

Next Steps: Gated Separation ⋪

“foregate”

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



foregate

aftgate

concrete

$$\sigma \vdash_V M_1 \mathrel{⋪} M_2 \quad \text{iff} \quad \sigma = \sigma_1 \cup \sigma_2 \text{ for some } \sigma_1, \sigma_2$$
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Next Steps: Gated Separation ⋪

“foregate”

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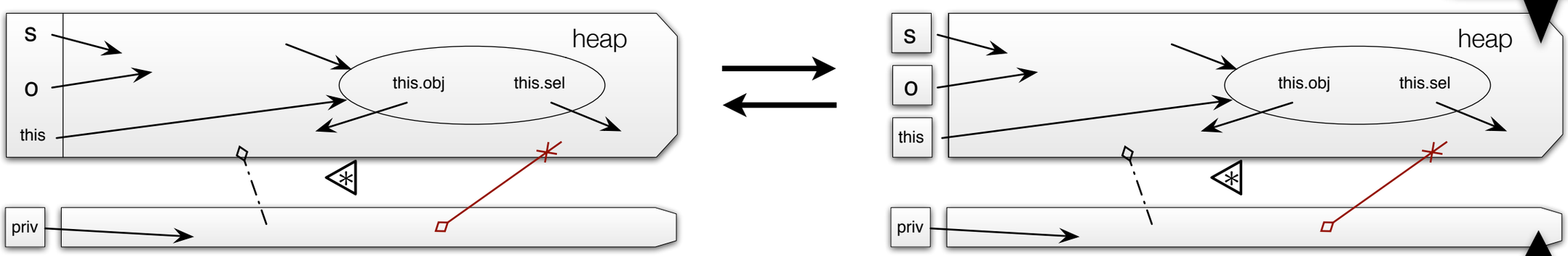

foregate

aftgate

concrete

abstract

$$\sigma \vDash_V M_1 \mathrel{⋪} M_2 \quad \text{iff} \quad \sigma = \sigma_1 \cup \sigma_2 \text{ for some } \sigma_1, \sigma_2$$
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Next Steps: Gated Separation ⋖*

“foregate”

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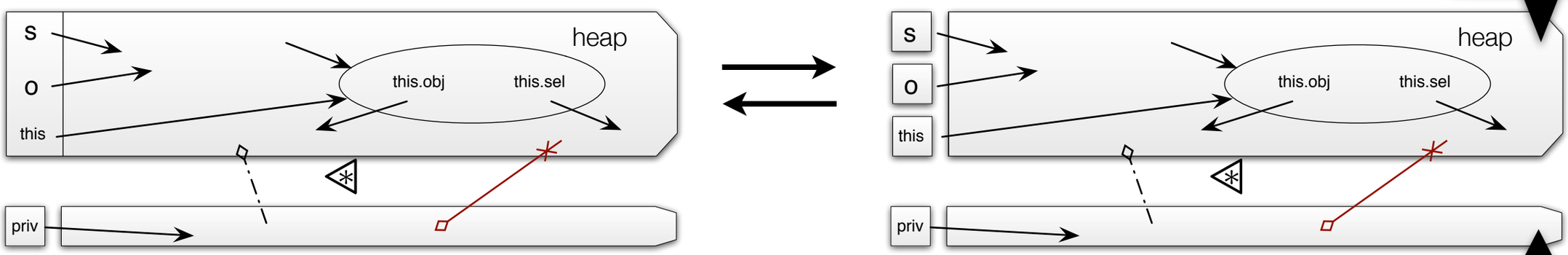

$$\sigma \vDash_V M_1 \lhd\!\!* M_2 \quad \text{iff} \quad \sigma = \sigma_1 \cup \sigma_2 \text{ for some } \sigma_1, \sigma_2$$

concrete abstract separated

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Next Steps: Gated Separation ⋪

"foregate"

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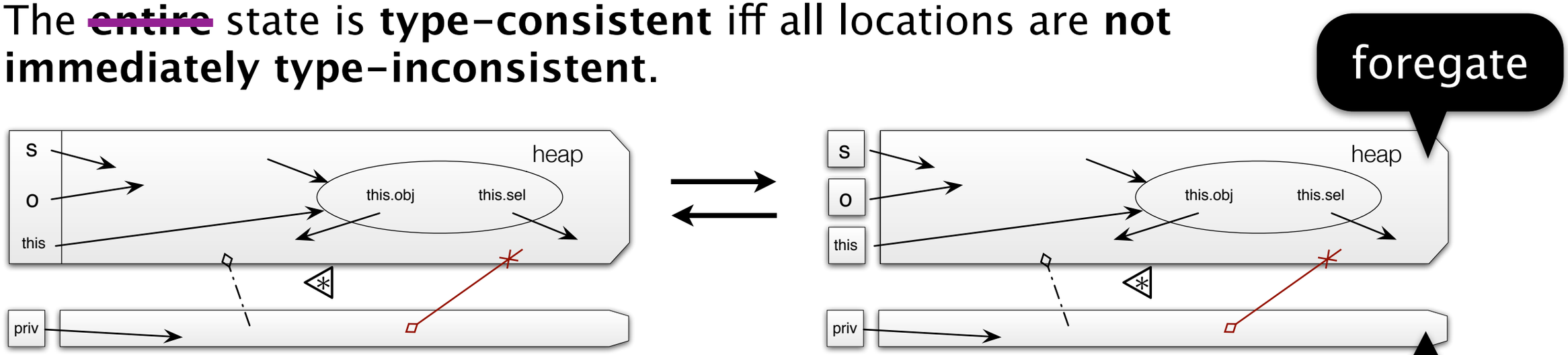

$$\sigma \vdash_V M_1 \mathrel{⋪} M_2 \quad \text{iff} \quad \sigma = \sigma_1 \cup \sigma_2 \text{ for some } \sigma_1, \sigma_2$$

concrete abstract separated

where $\sigma_1 \vdash_V M_1$ and $\sigma_2 \vdash_V M_2$

and $\mathrm{dom}(\sigma_1) \cap \mathrm{dom}(\sigma_2) = \emptyset$

and $\mathrm{rng}(\sigma_1) \cap \mathrm{dom}(\sigma_2) = \emptyset$

Next Steps: Gated Separation ⋪

"foregate"

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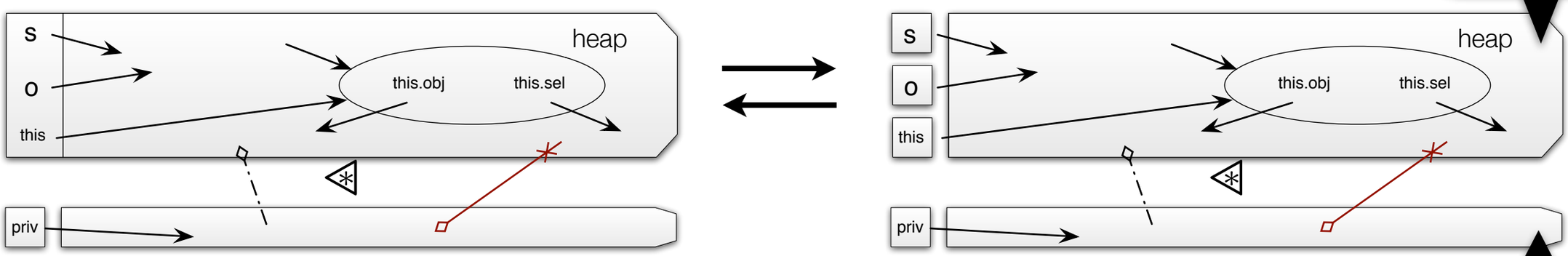

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Slightly stronger than ✻ :
No **direct** pointers from "foregate" to "aftgate"

Next Steps: Type-Intertwined Framing

“foregate”

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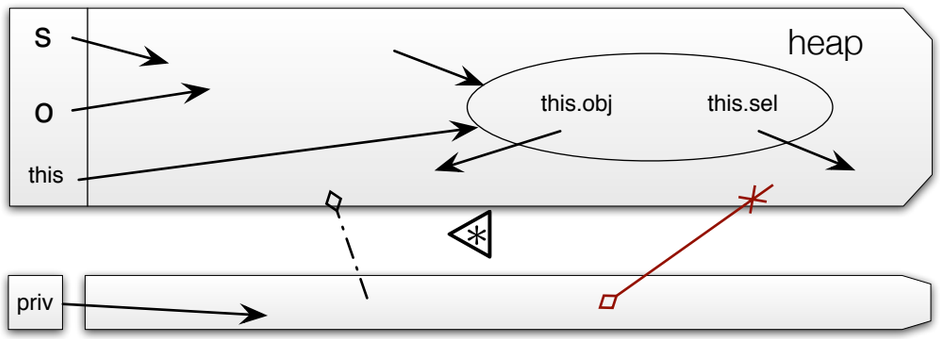

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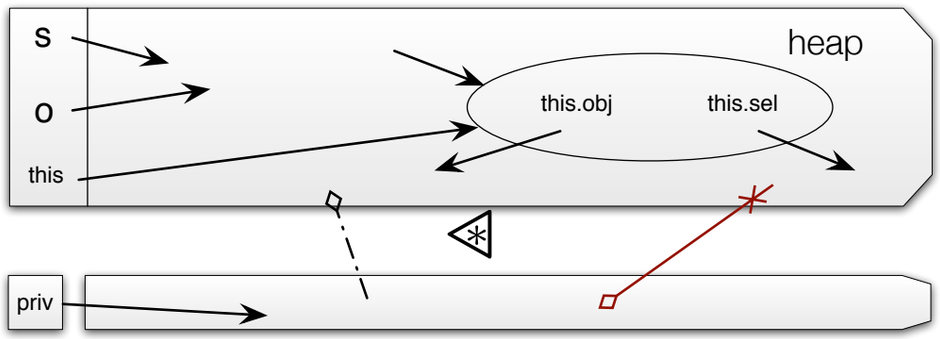
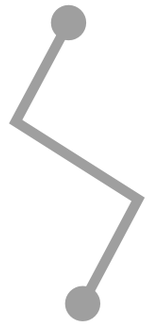


symbolic flow analysis



Next Steps: Type-Intertwined Framing

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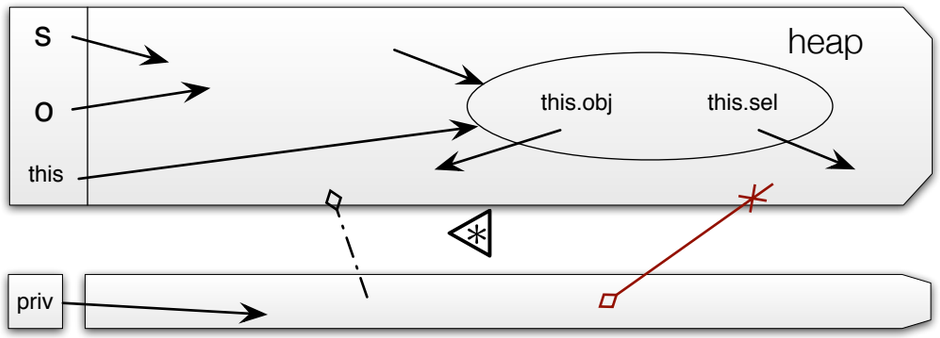

symbolic flow analysis

type analysis

Next Steps: Type-Intertwined Framing

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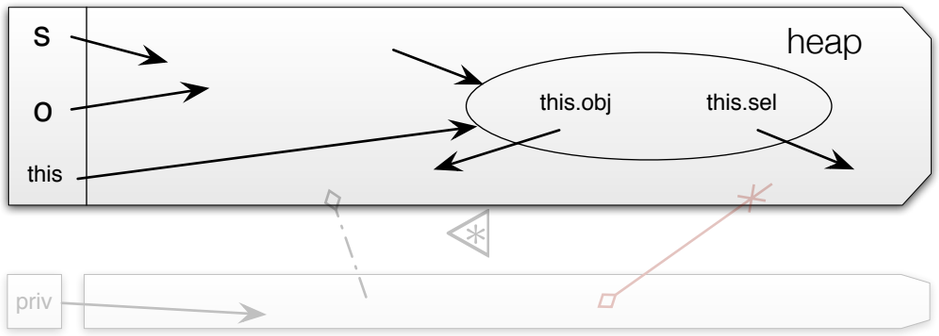

symbolic flow analysis

type analysis

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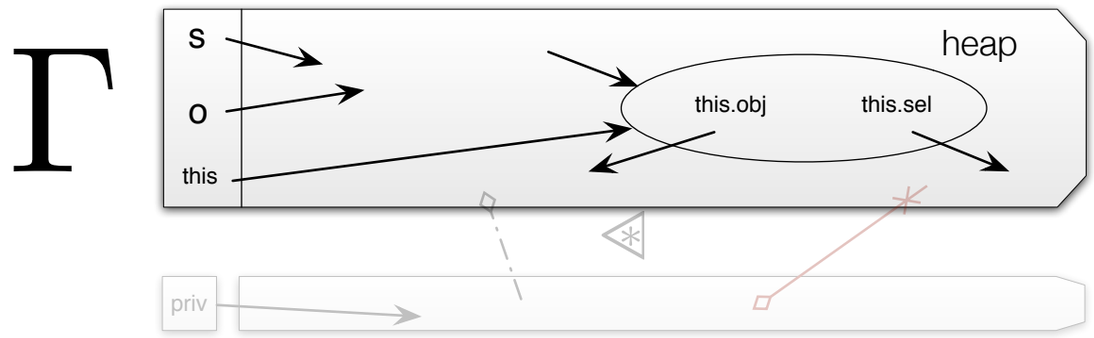

symbolic flow analysis

type analysis

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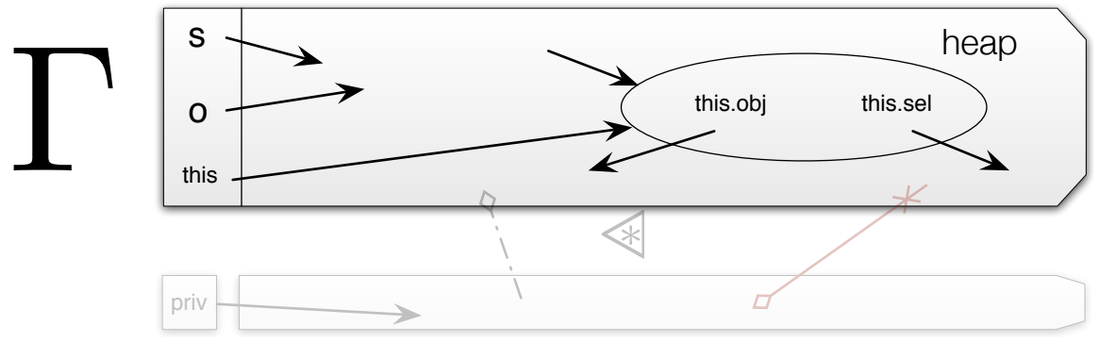

symbolic flow analysis

type analysis

Next Steps: Type-Intertwined Framing

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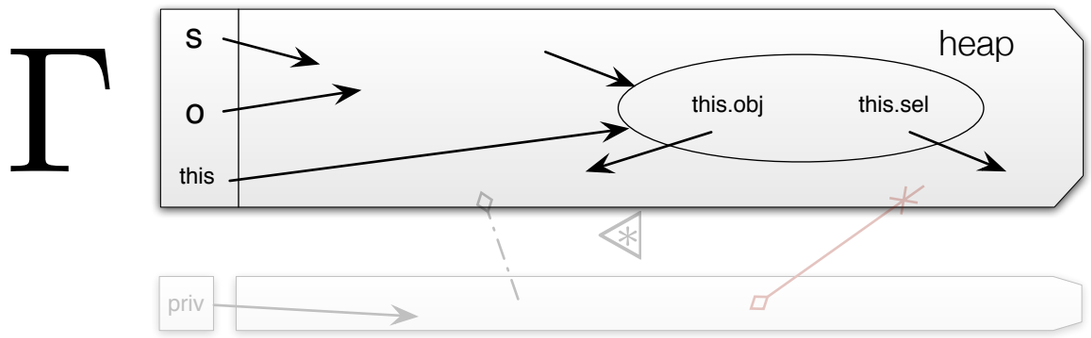

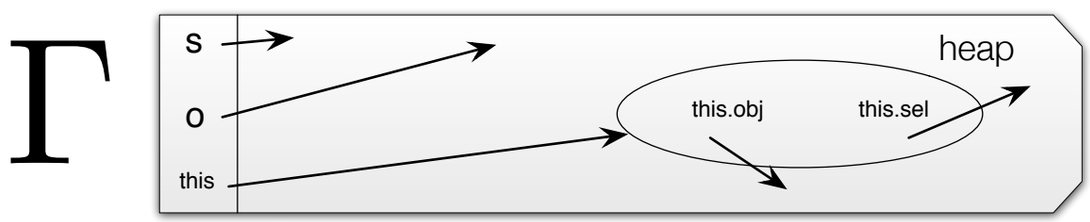

symbolic flow analysis

type analysis

Next Steps: Type-Intertwined Framing

“foregate”

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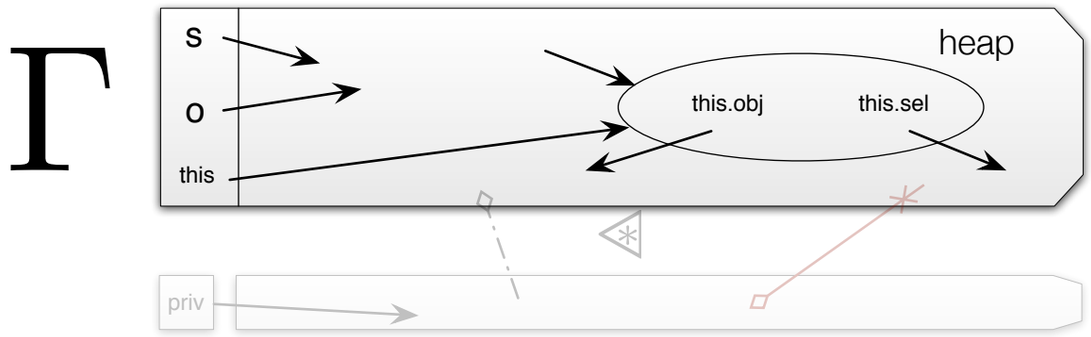

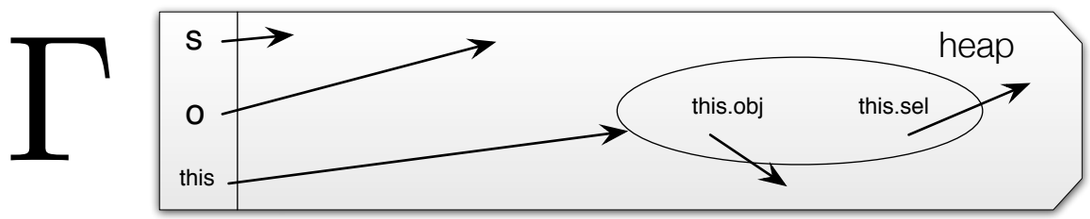

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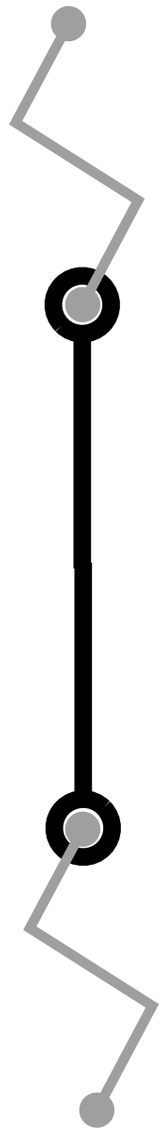

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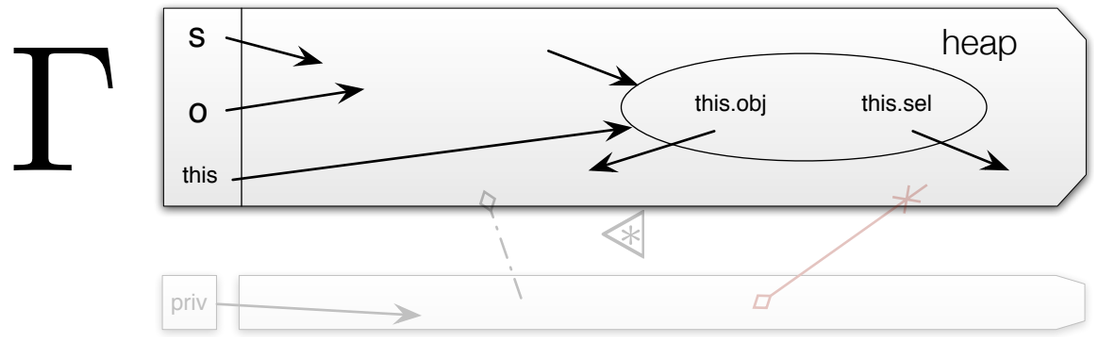

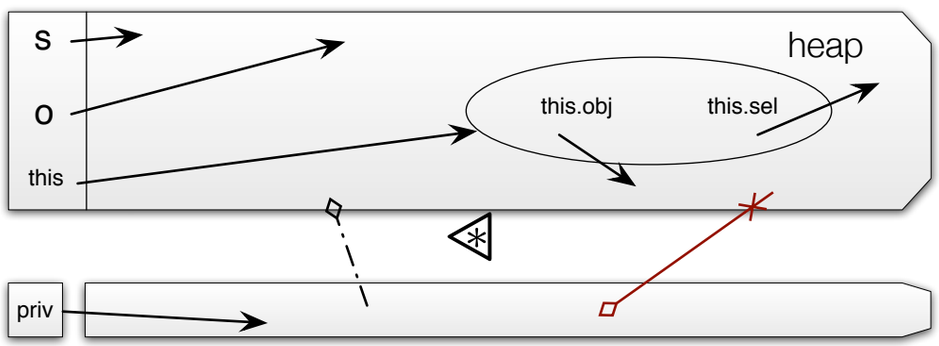

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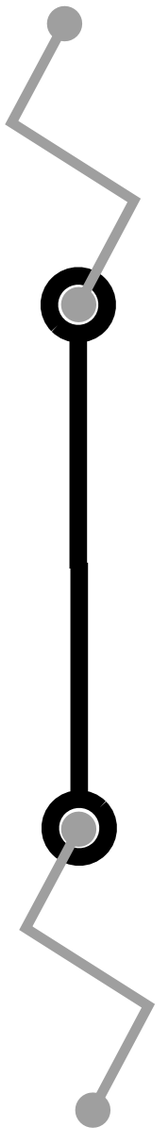

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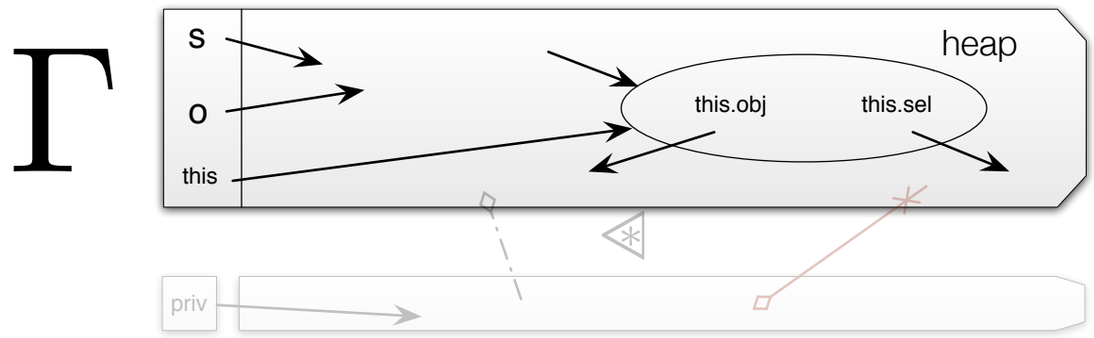

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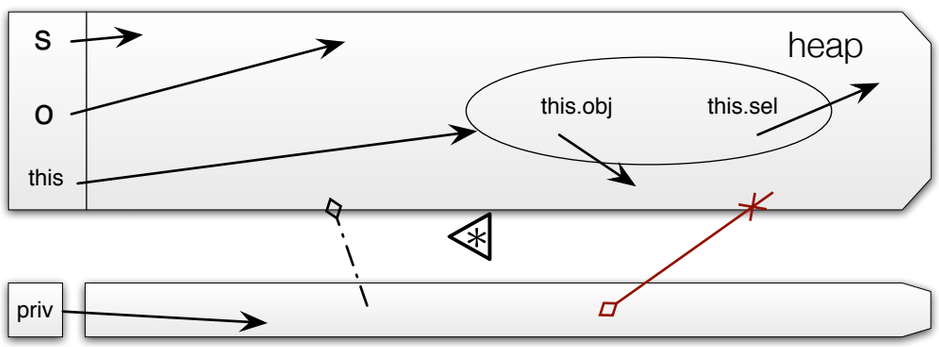

Type-intertwined framing is sound because “aftgate” is not reachable.

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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Cerny


Chang

www.cs.colorado.edu/~bec
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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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in-between for **applications** and large frameworks (which do both)

application code

```
class MyButton {
  var cb : Callback = ...

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

  def draw()
      cb.call()
  end

  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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