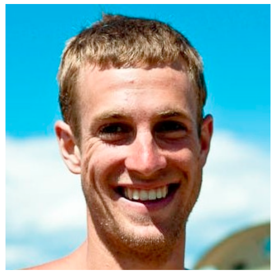
Goal-Directed Program Analysis with Jumping



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École normale supérieure
1 October 2015

PLV

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

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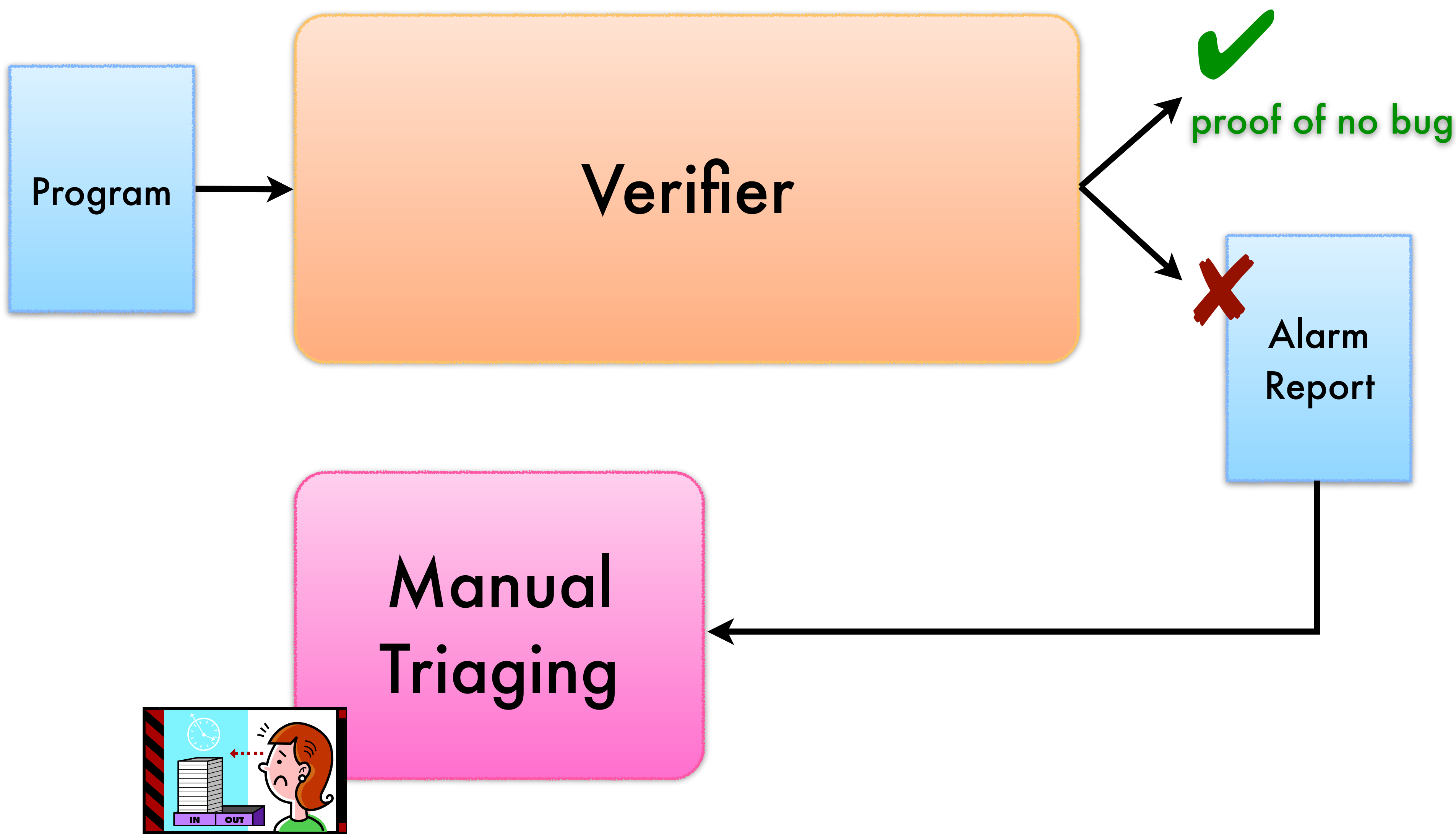

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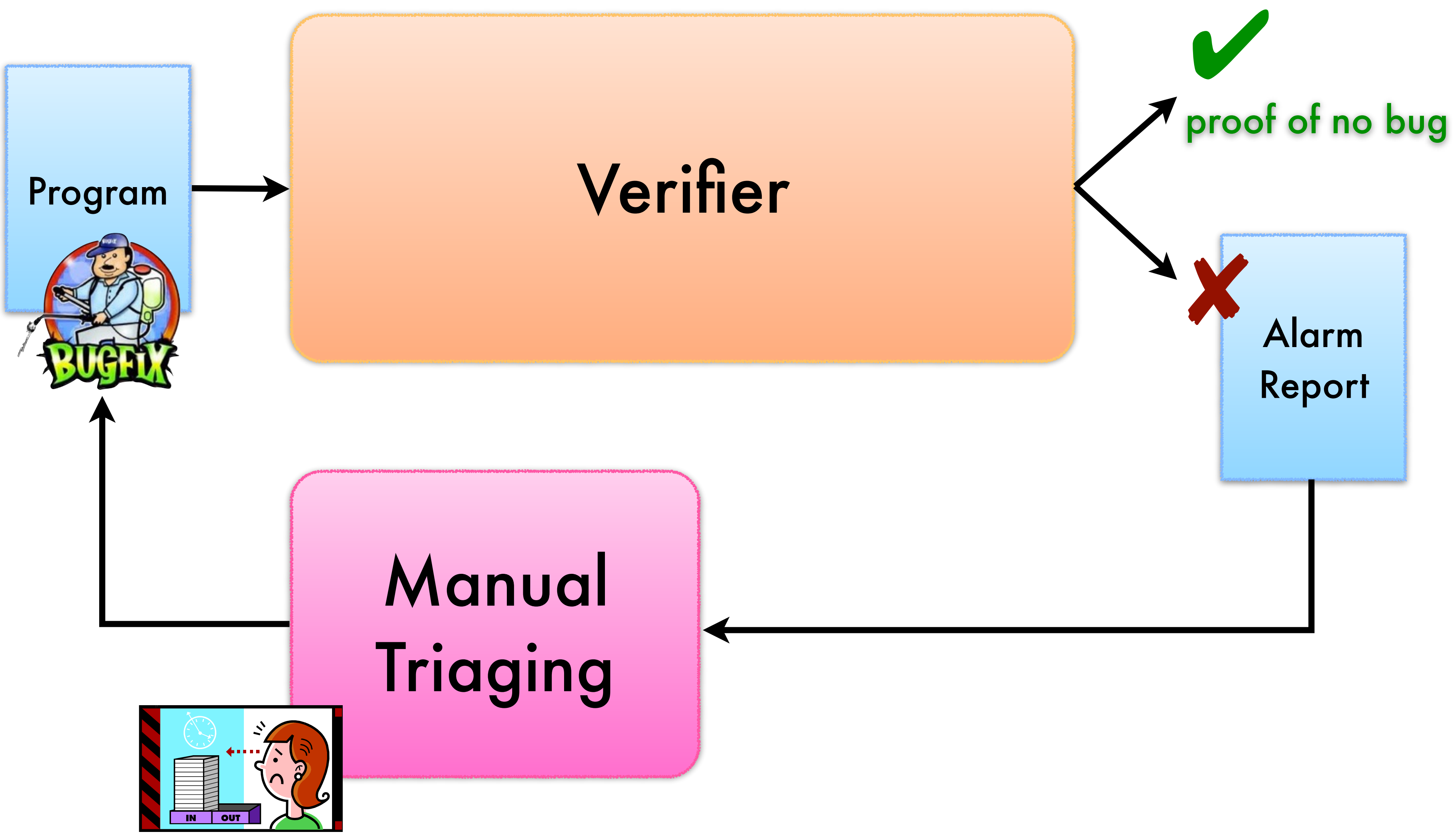

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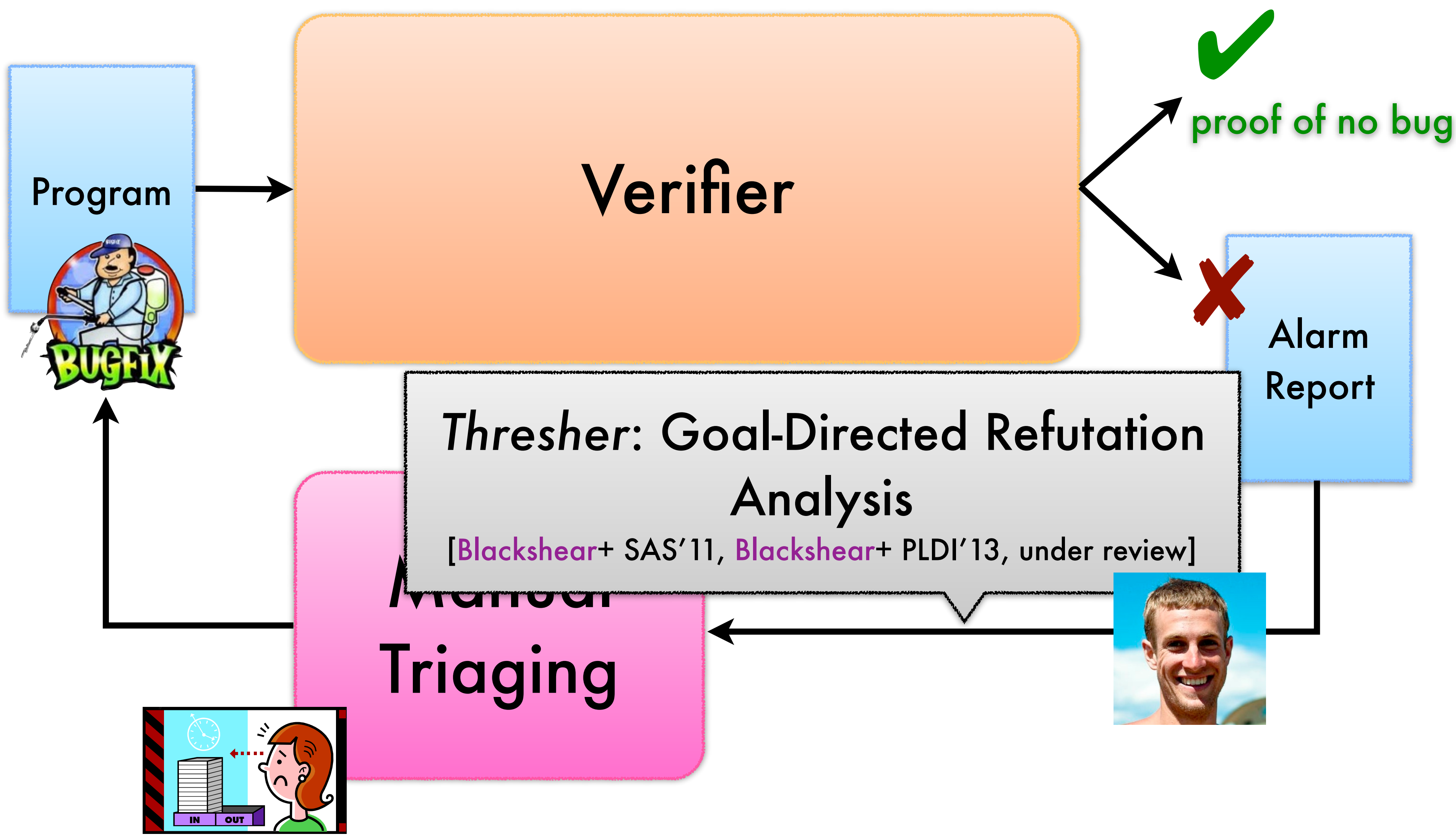

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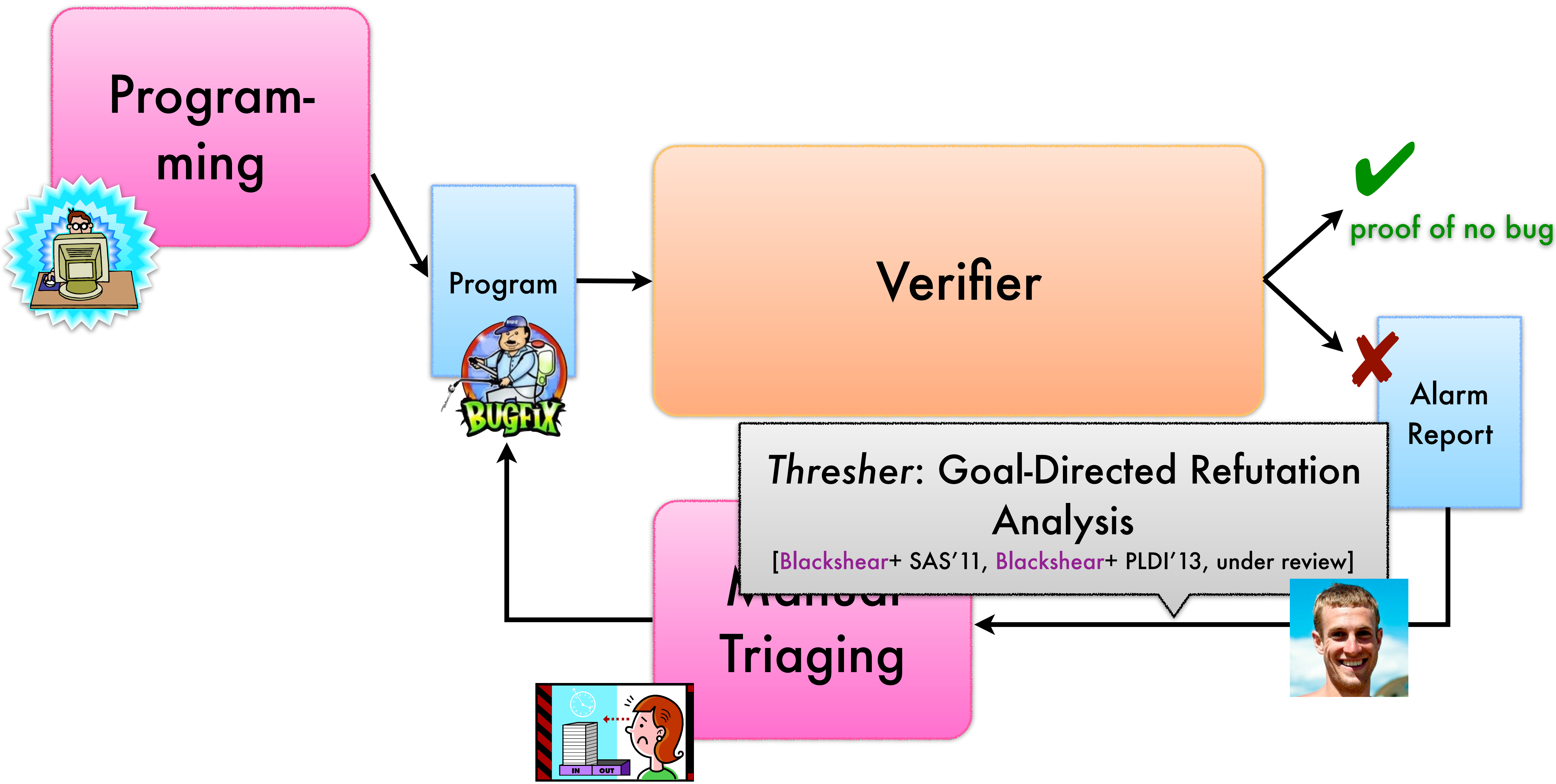

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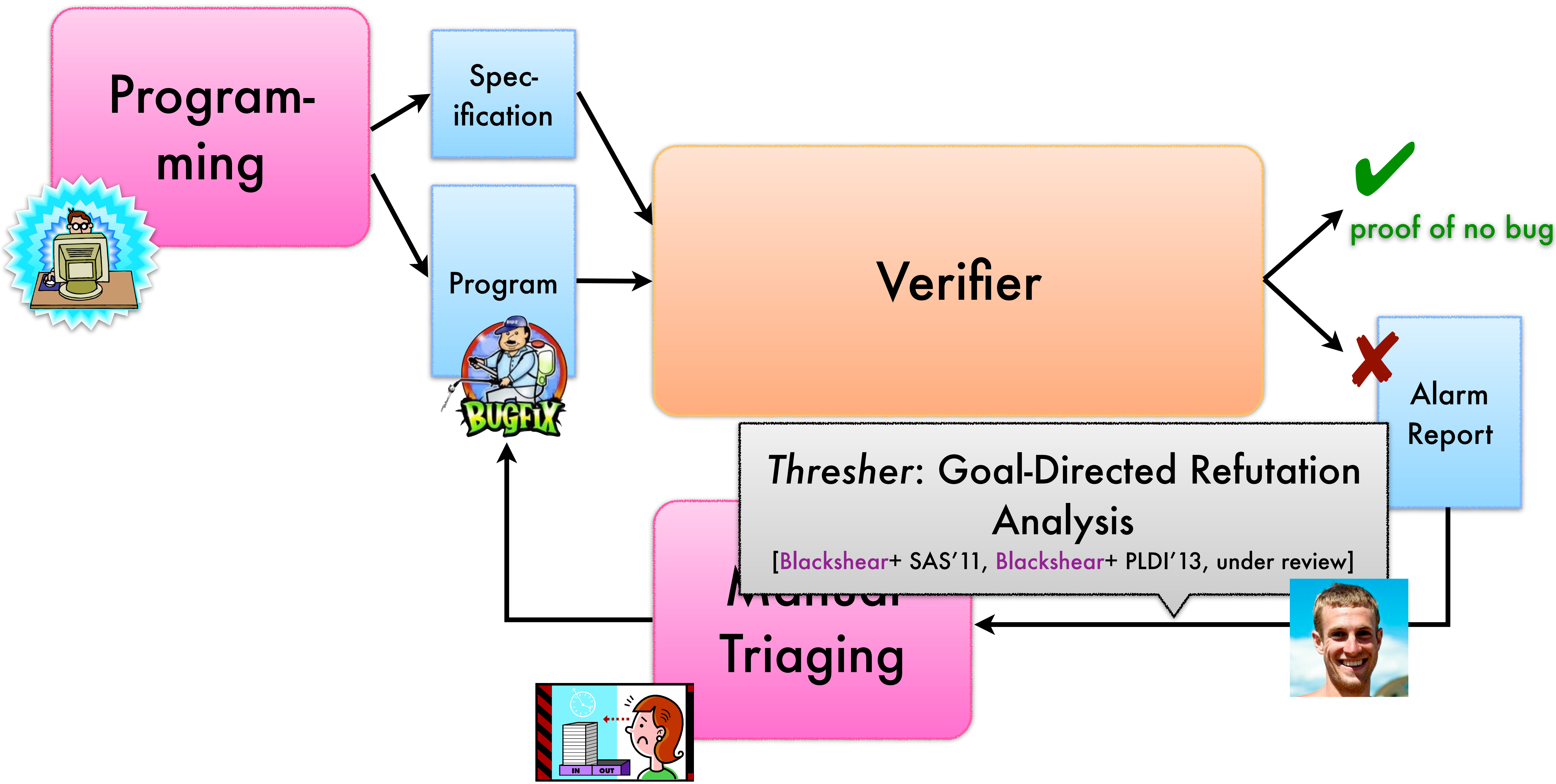


lysis in the **whole** bug mitigation **process**

Fissile Types: Checking Almost Everywhere Invariants
[Coughlin+ POPL'14, in prep]

Program-ming

Spec-ification

Program

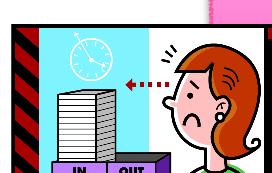
Verifier

proof of no bug

Alarm Report

Thresher: Goal-Directed Refutation Analysis
[Blackshear+ SAS'11, Blackshear+ PLDI'13, under review]

Manual Triaging



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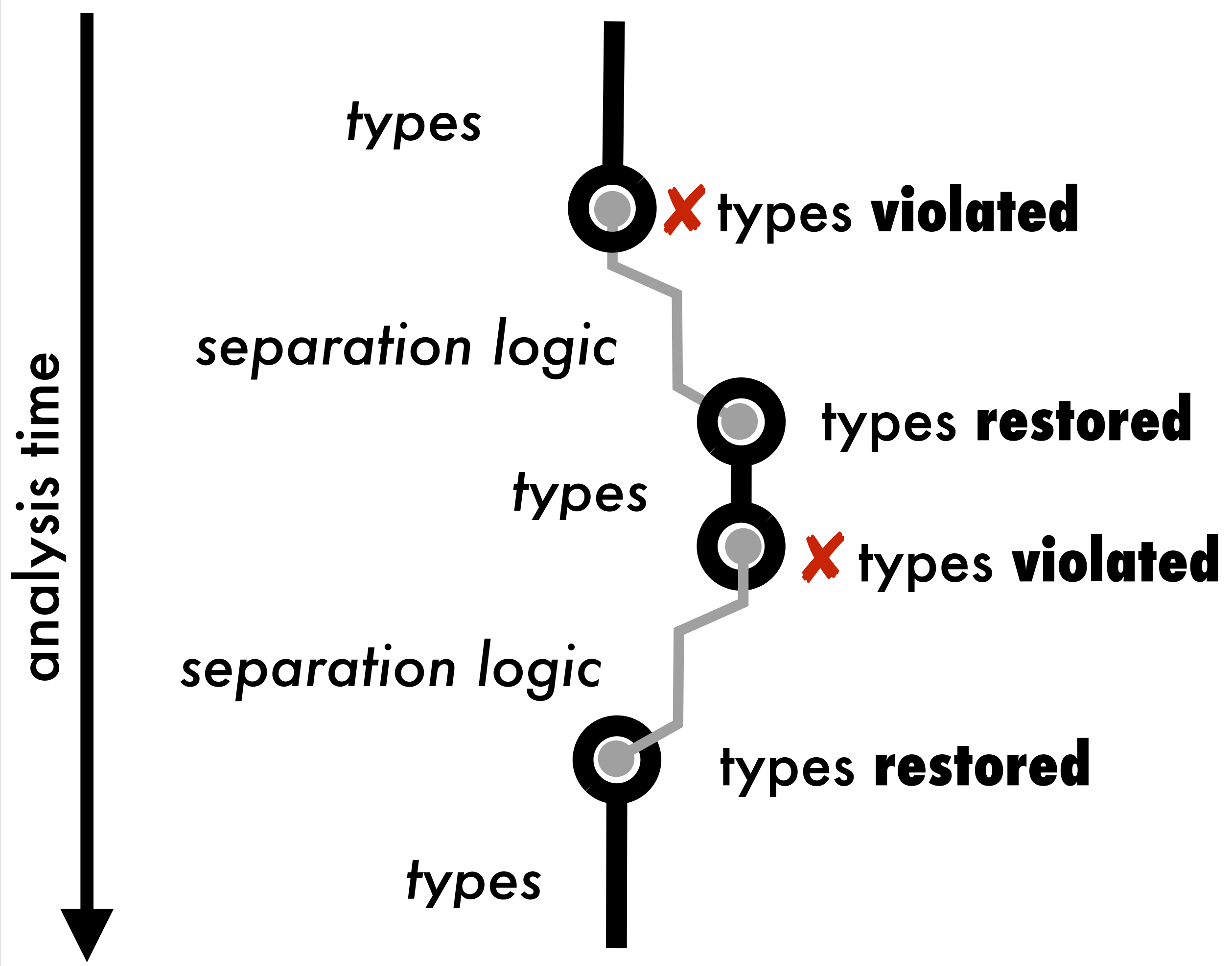
Prog
m

no bug

m
rt

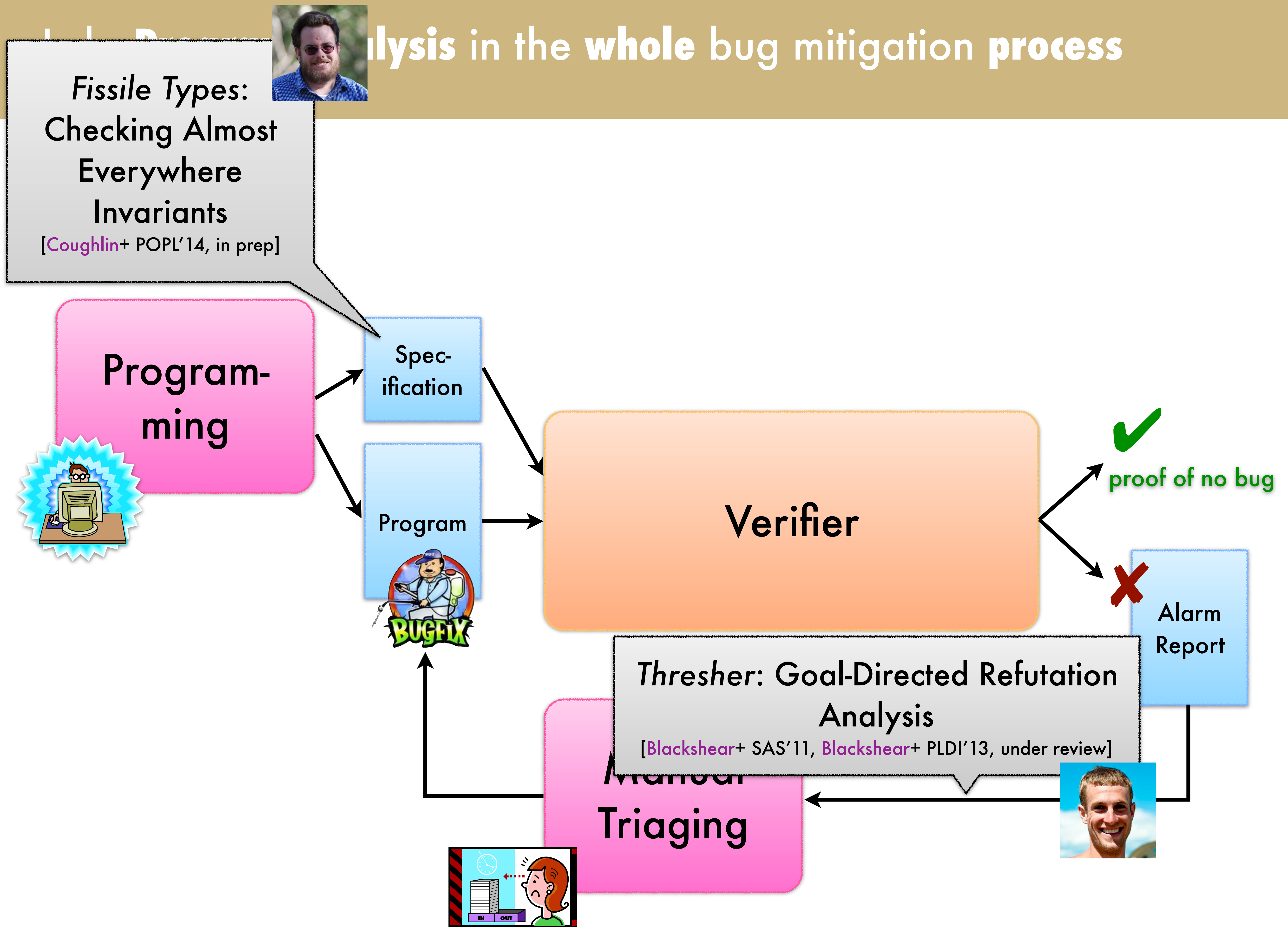


type-intertwined separation logic

Intertwine type-based and separation-based analysis to verify **almost-everywhere** invariants

Objective-C

lysis in the **whole** bug mitigation **process**



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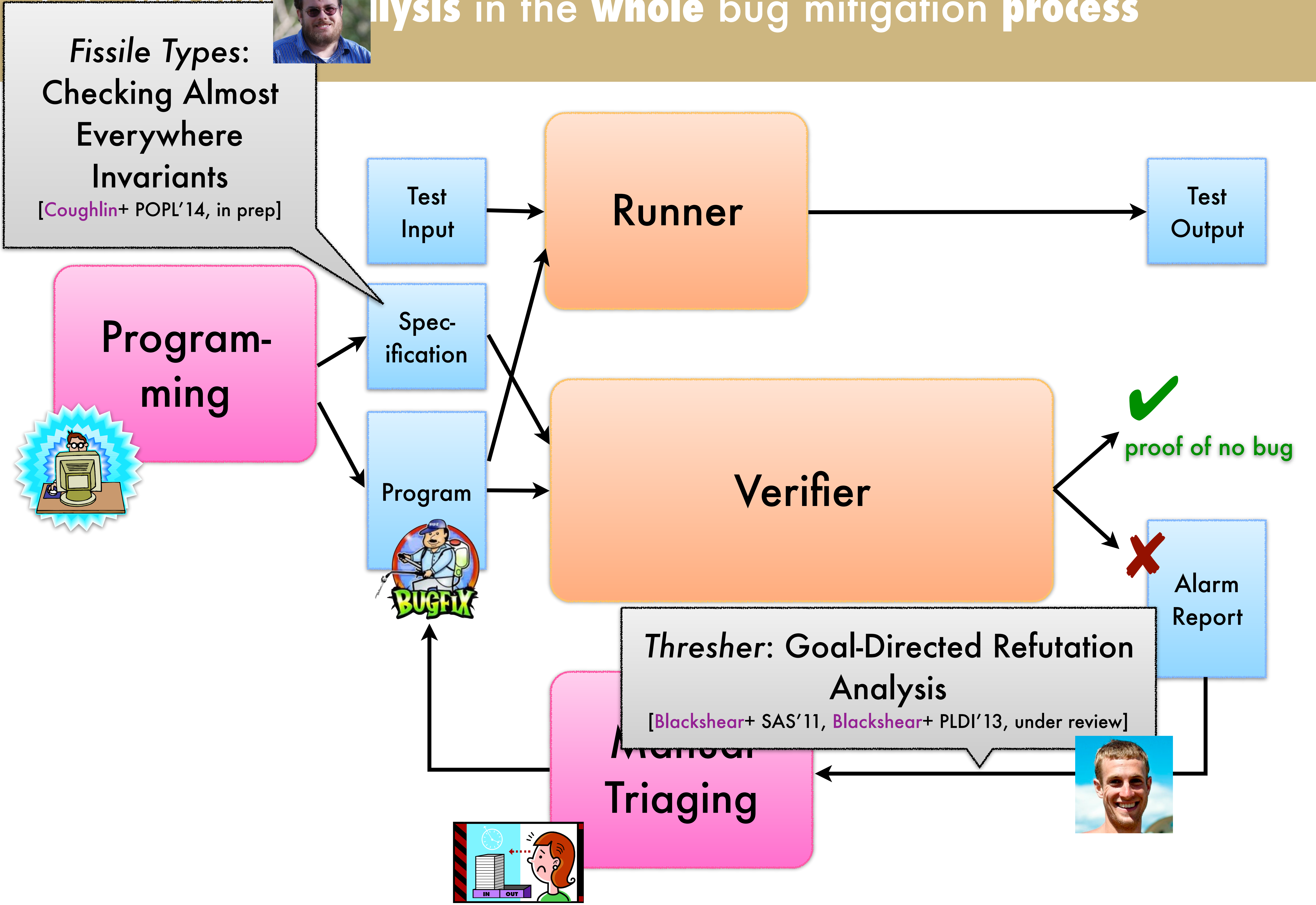

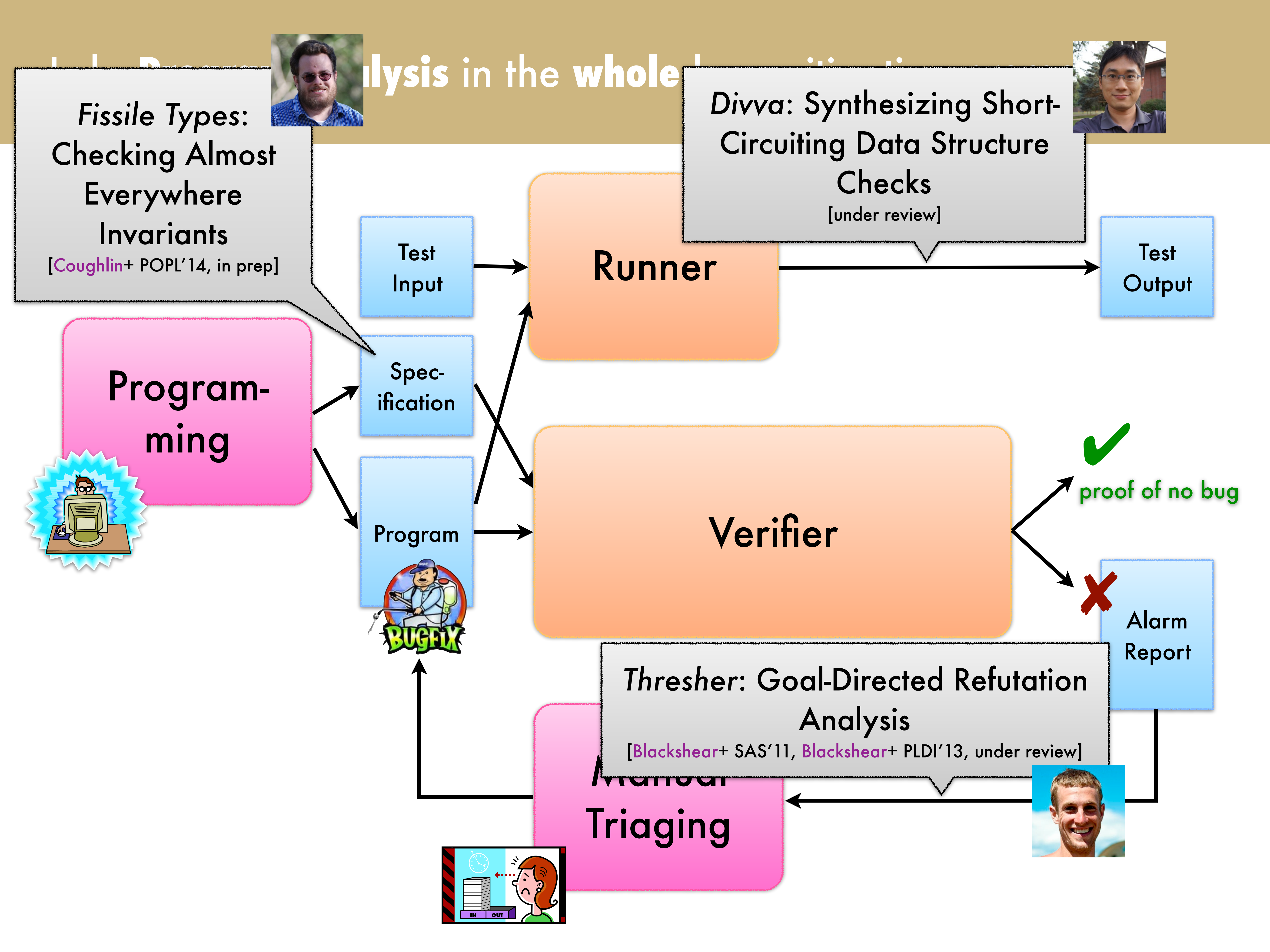
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[under review]
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IN
OUT

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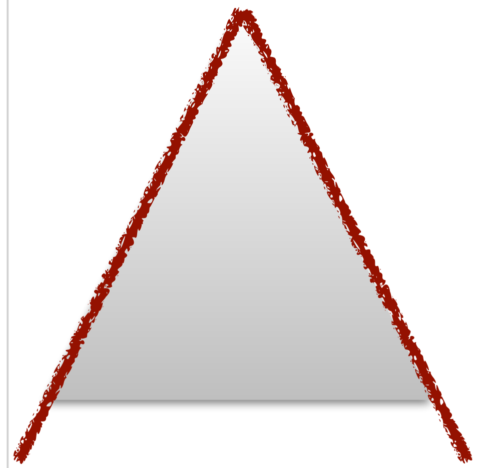

Use **static shape analysis** to **synthesize short-circuiting dynamic validation** of data structure invariants

uninterpreted inductive separation logic predicates

Alarm Report

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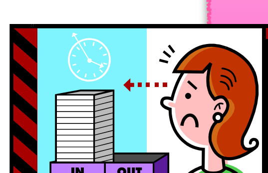
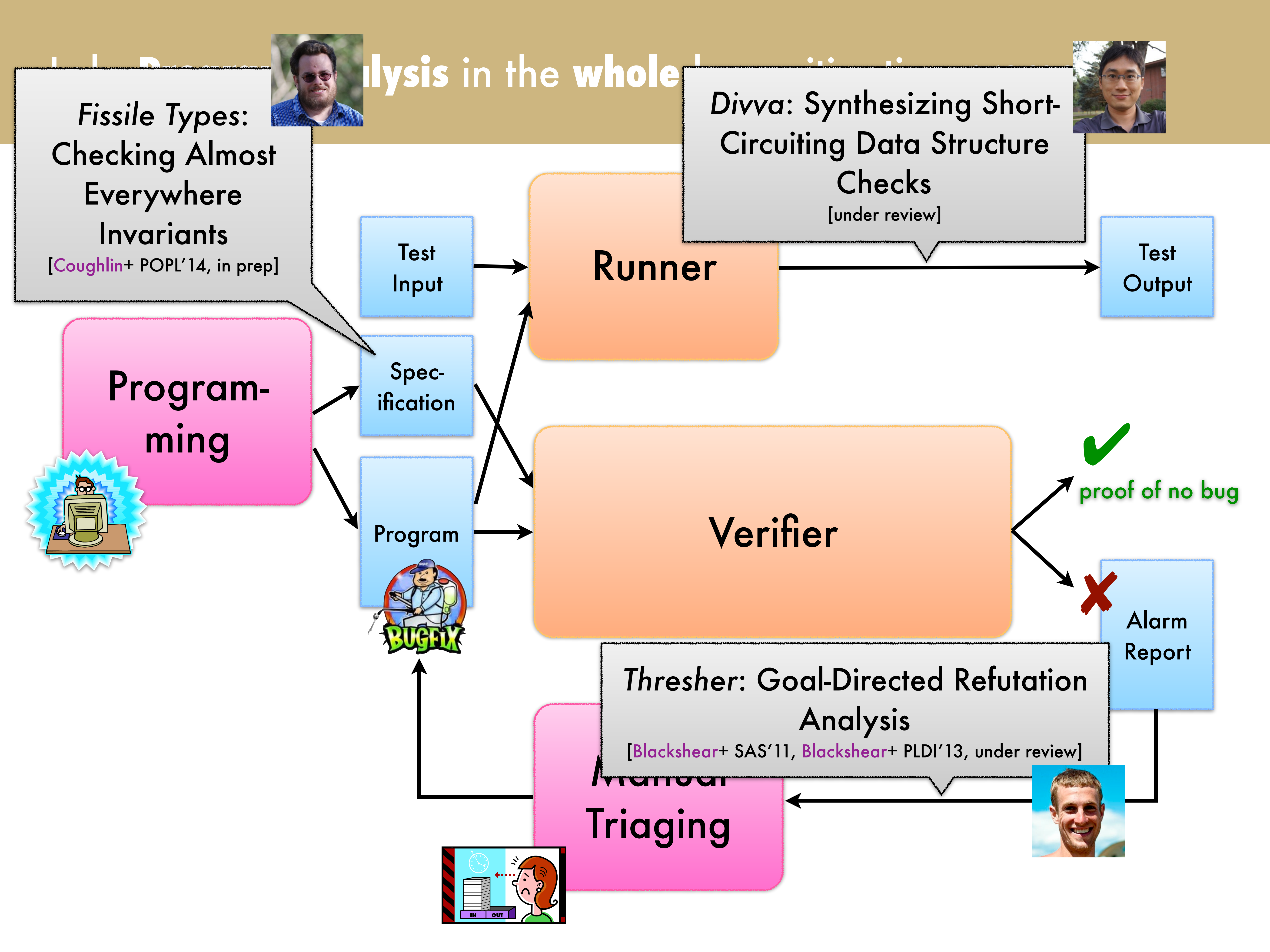
Triaging





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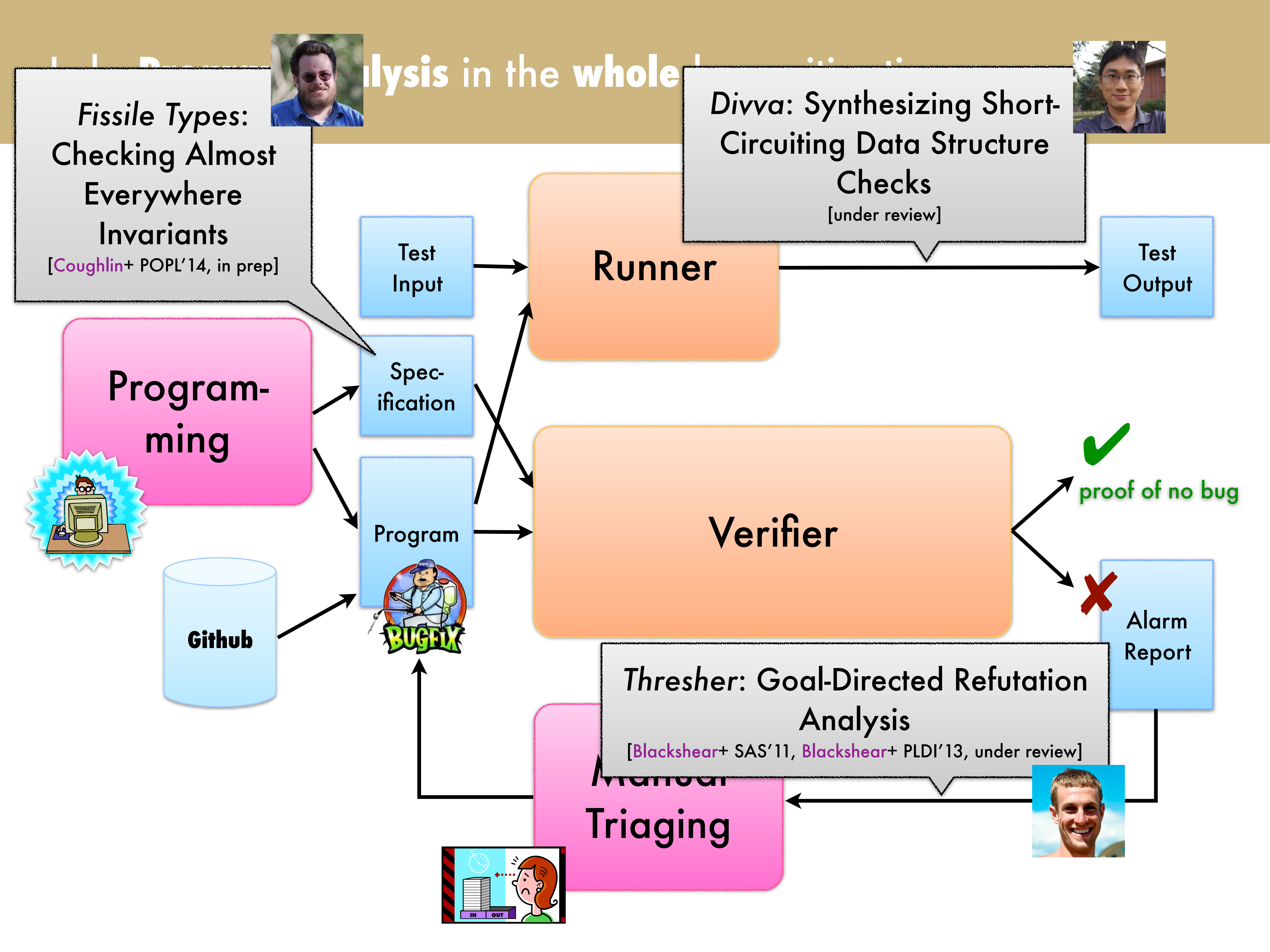

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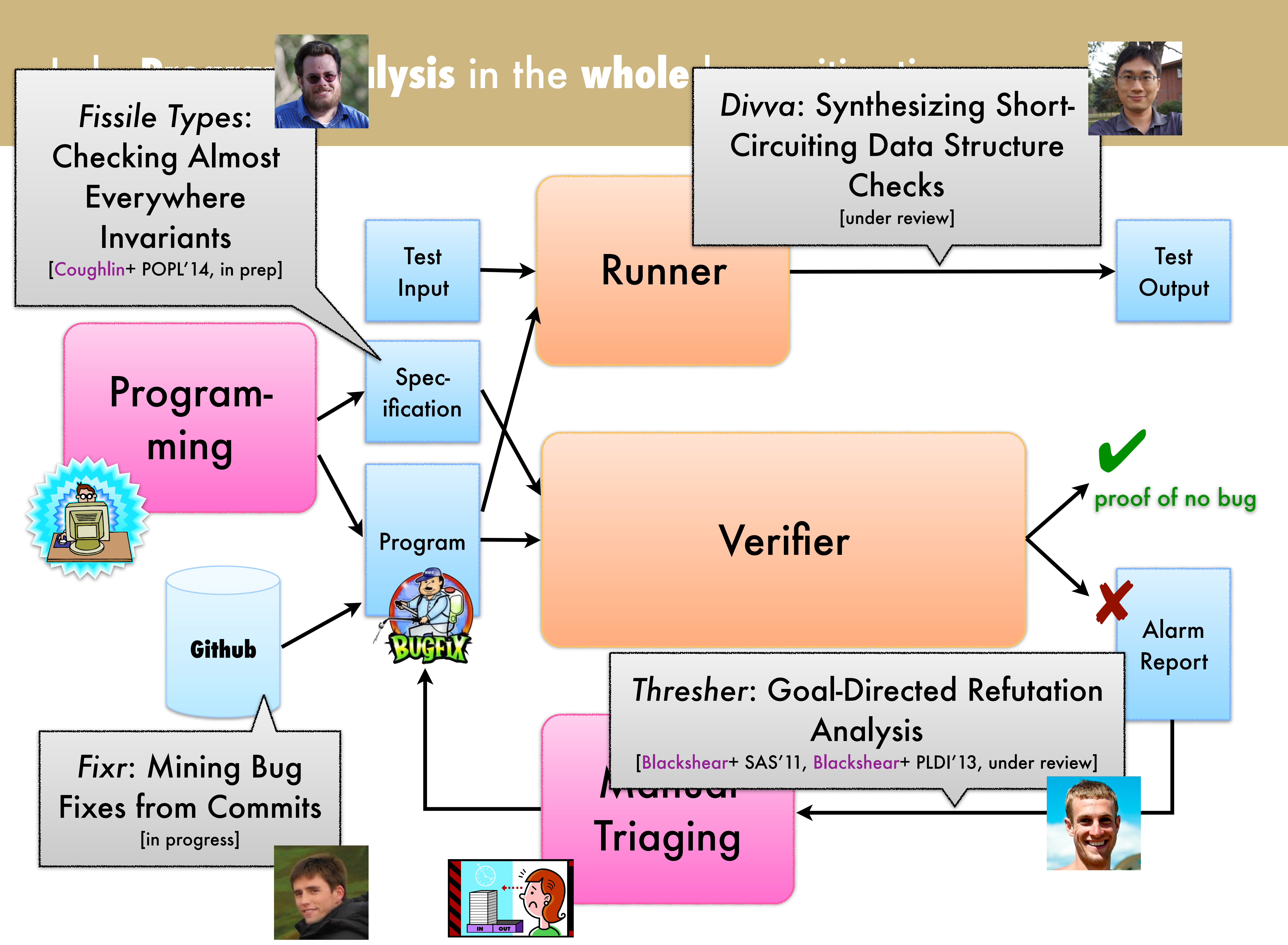
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[in progress]
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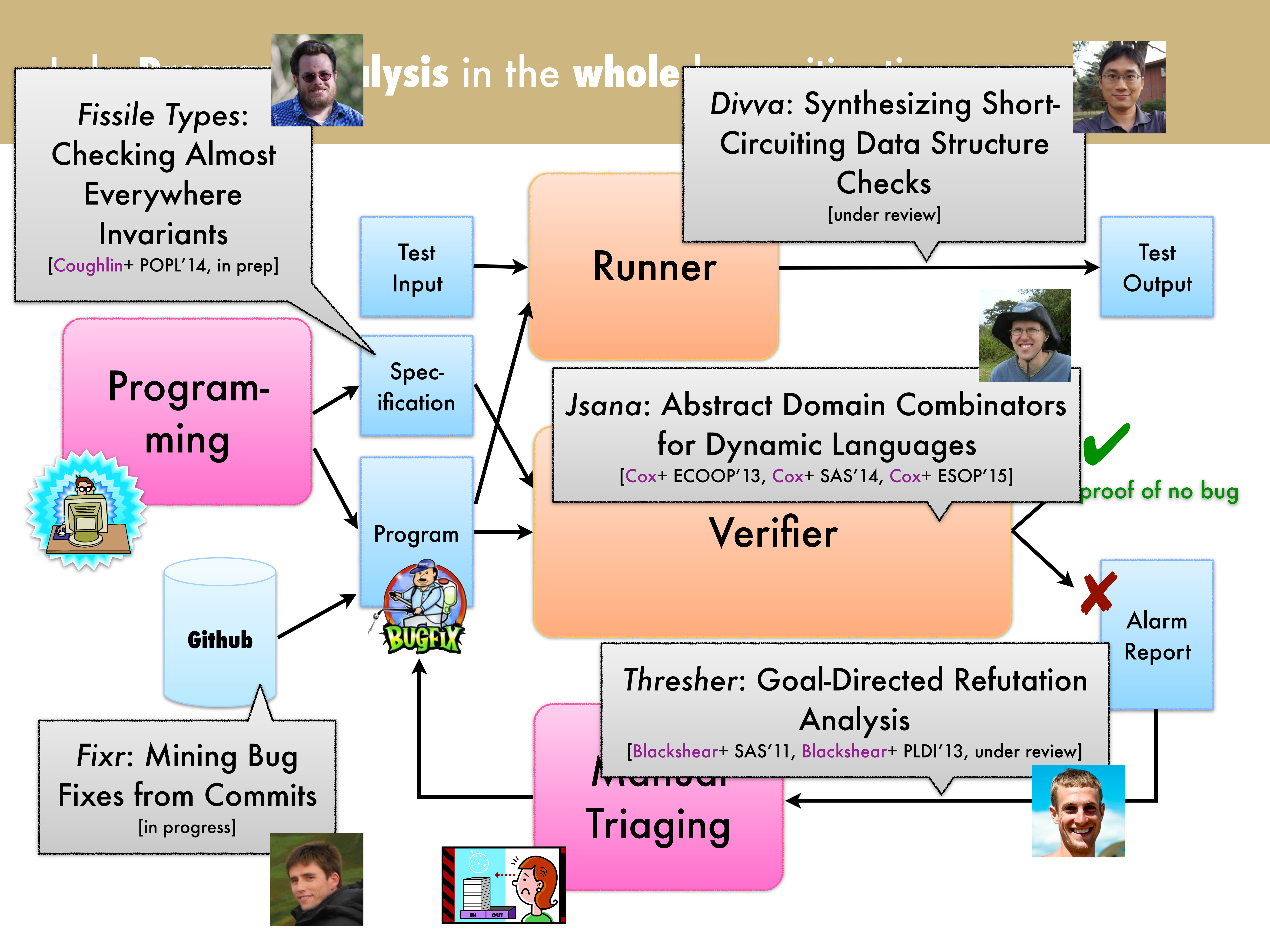
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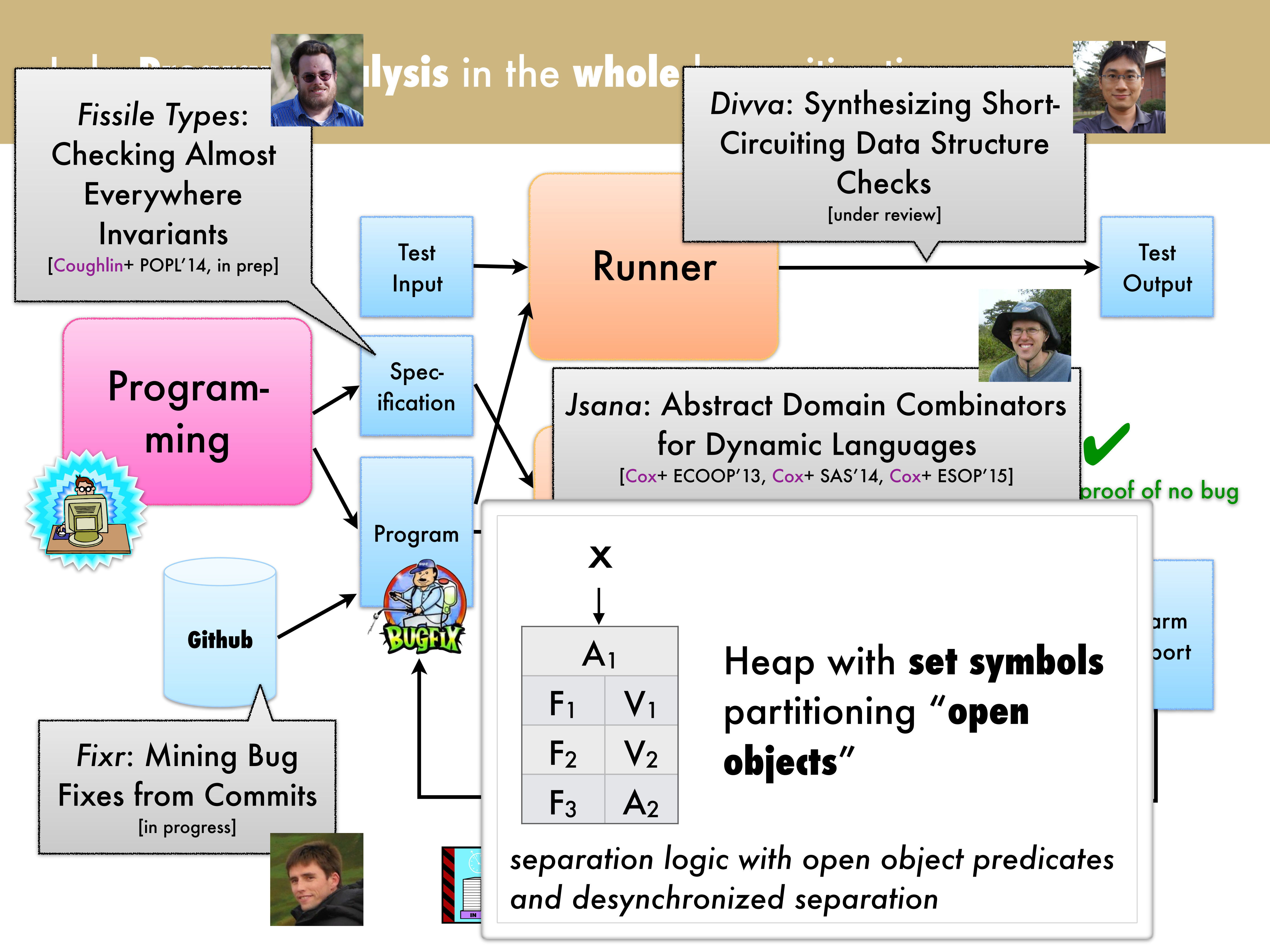
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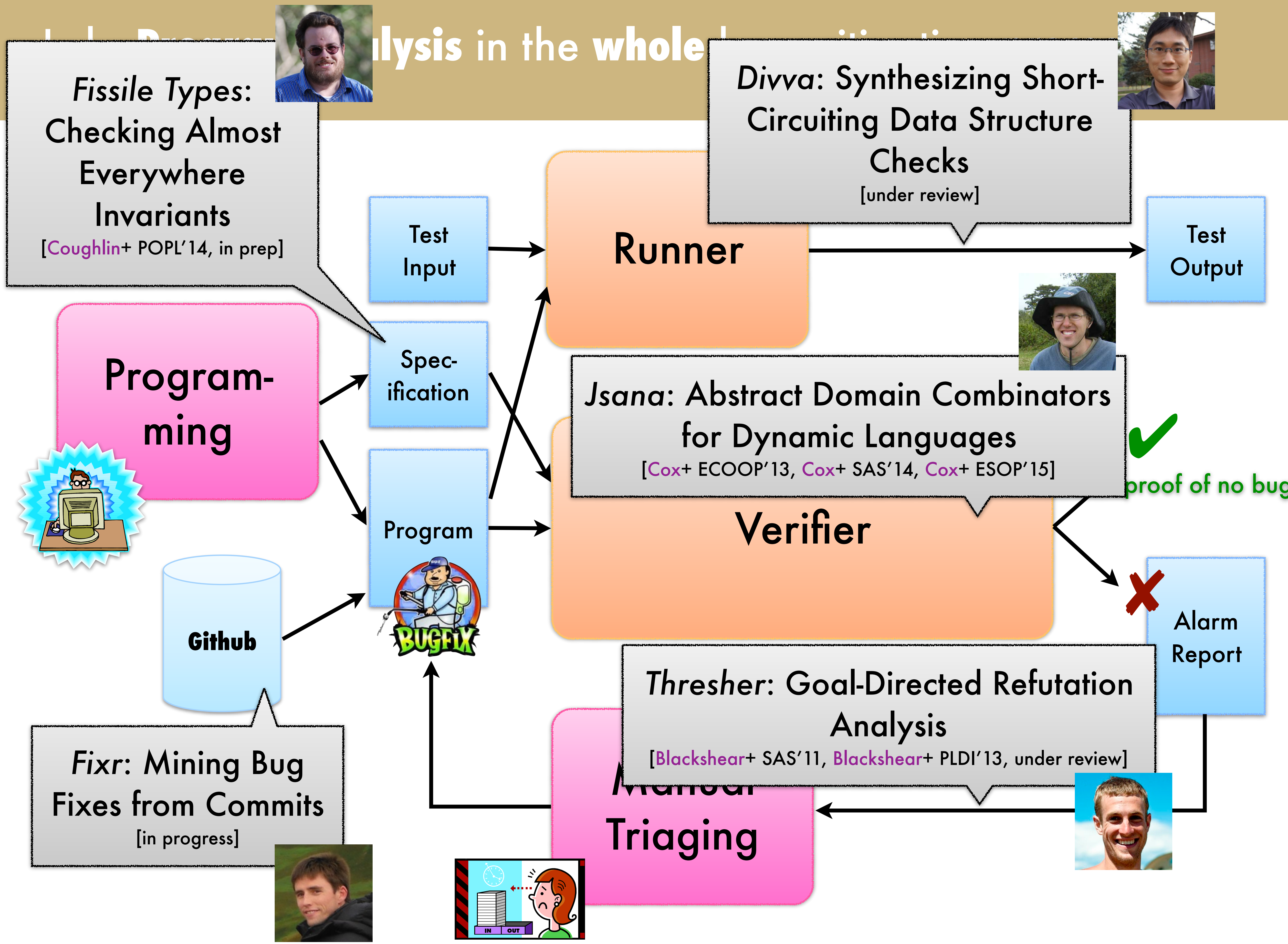
x
A1
F1 V1
F2 V2
F3 A2
Heap with set symbols partitioning "open objects"
separation logic with open object predicates and desynchronized separation

lysis in the whole



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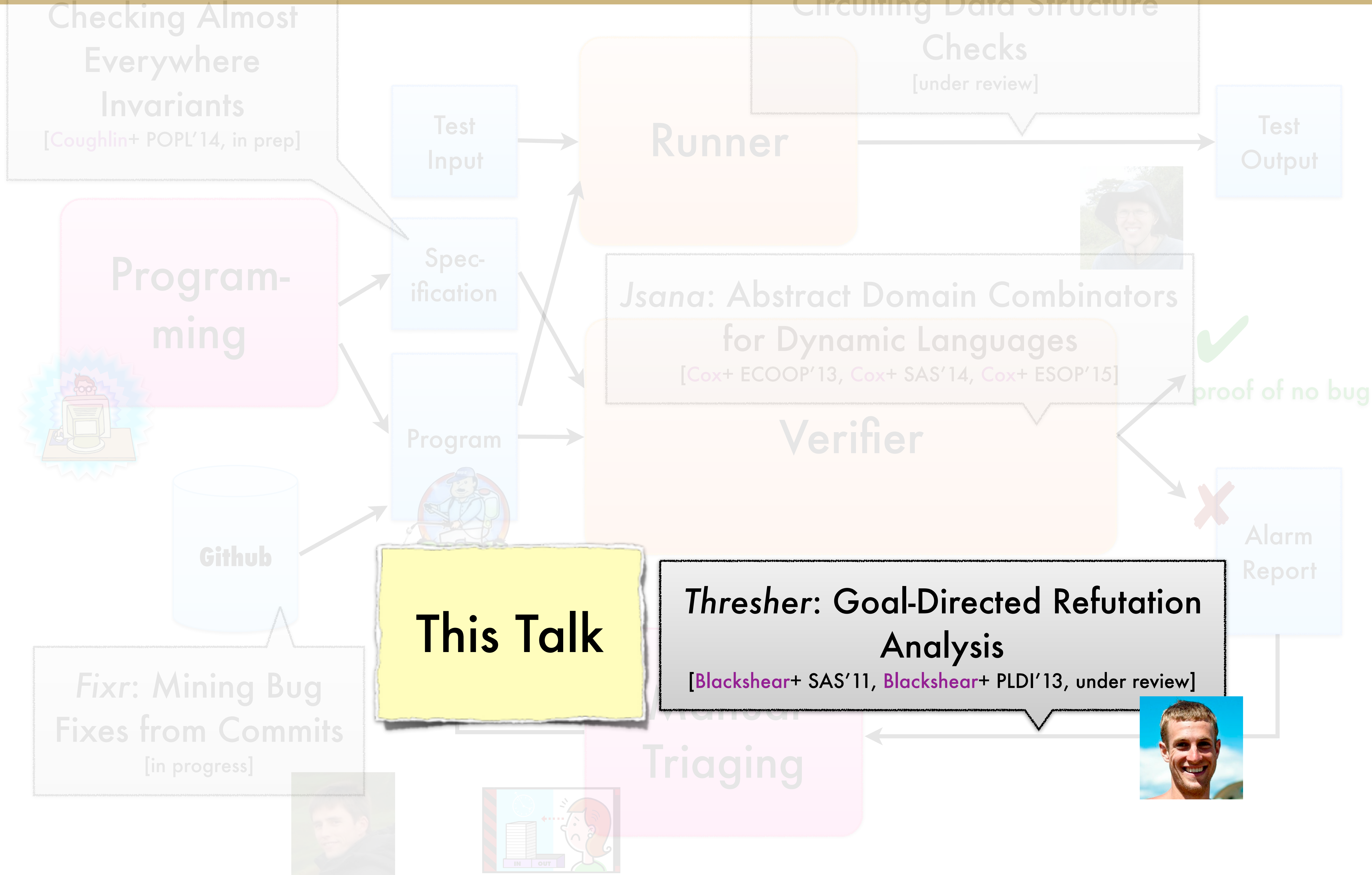

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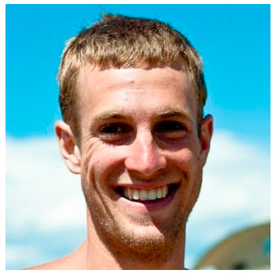

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PLV


Crash

Roughly, 3% of all commits fix NullPointerExceptions

Callback-oriented programming

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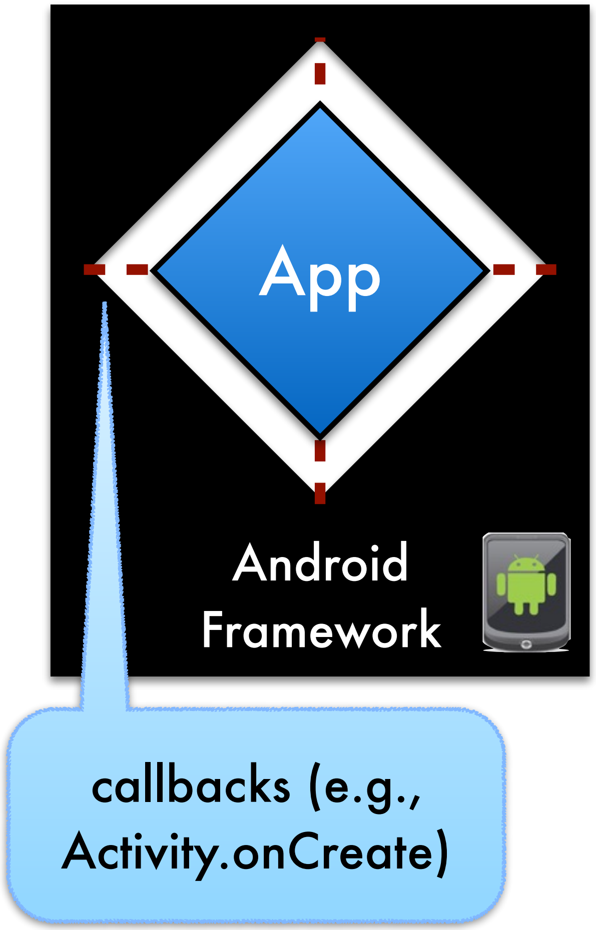
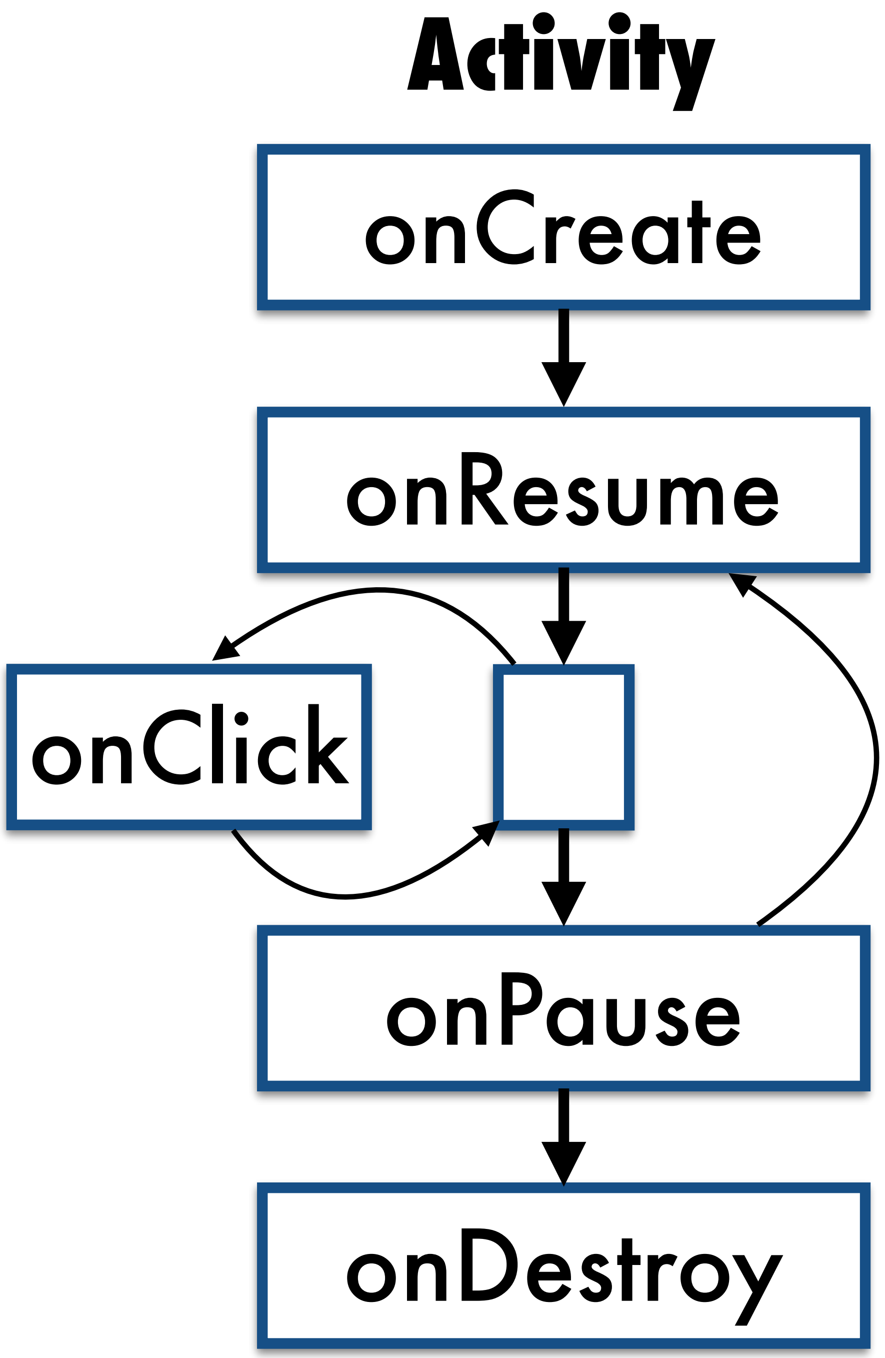
callbacks (e.g.,
Activity.onCreate)

Callback-oriented programming

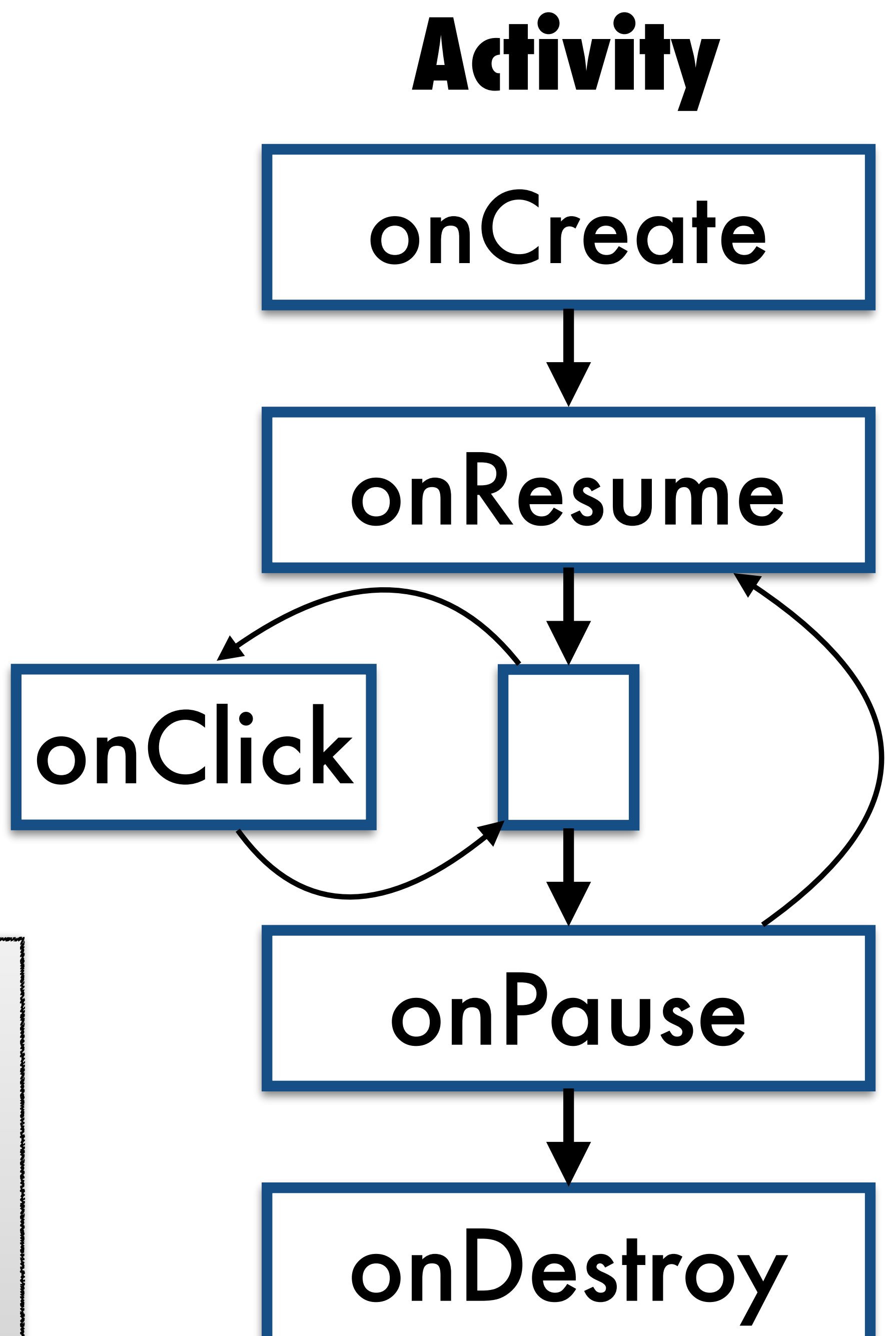




Callback-oriented programming

callbacks (e.g., Activity.onCreate)

Android components have an ordered, event-driven lifecycle



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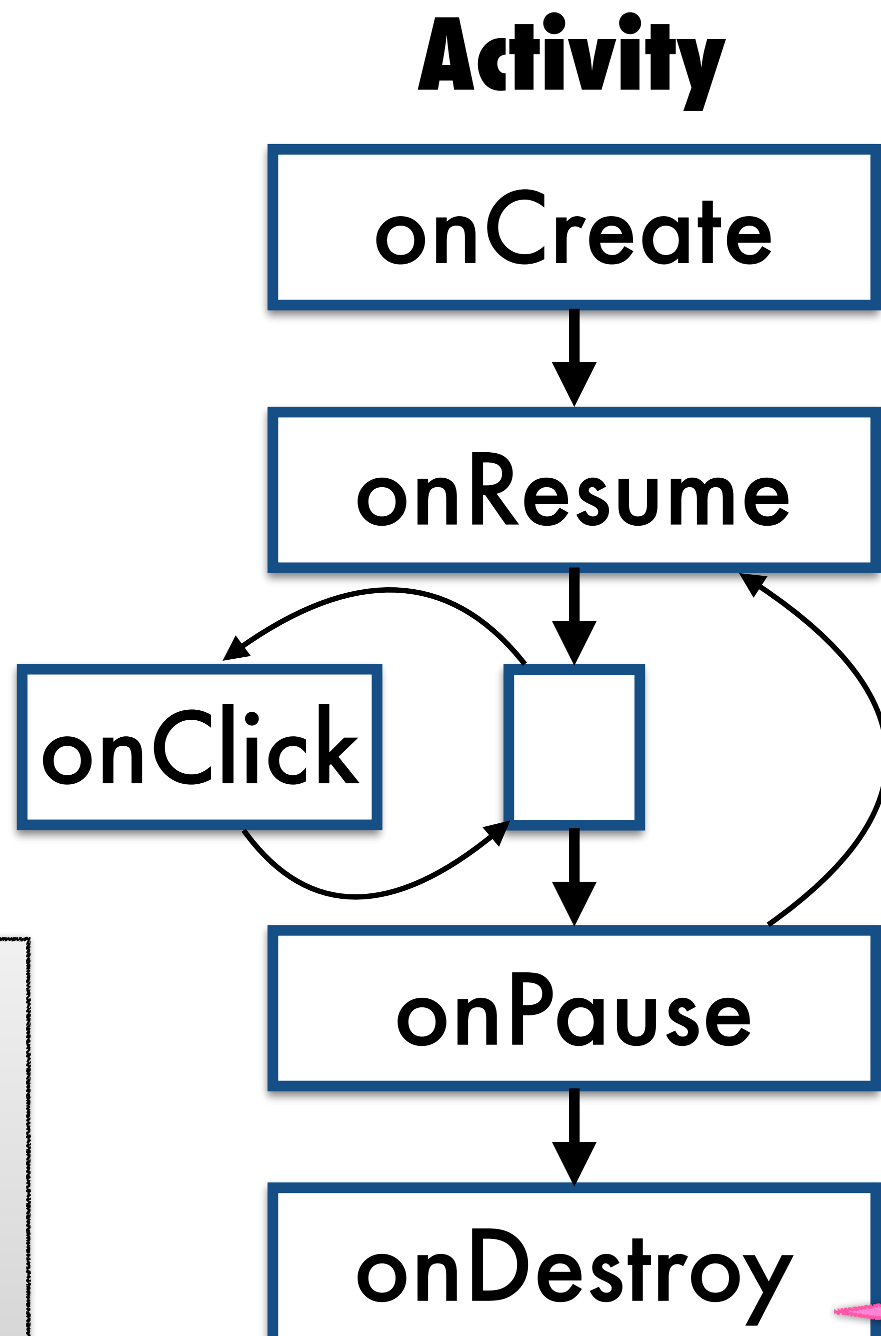


```
mHostDb = null;
mService = null;
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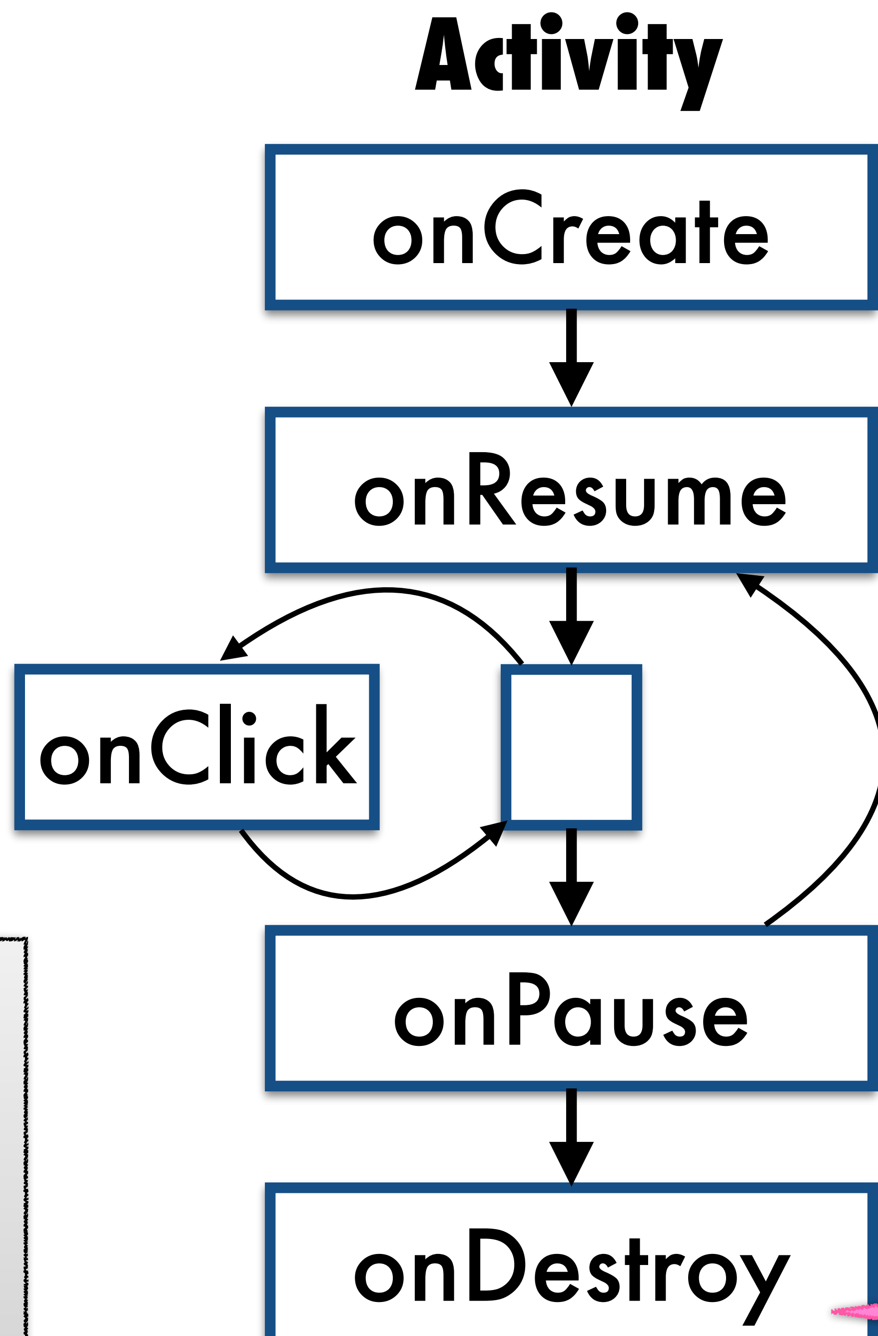


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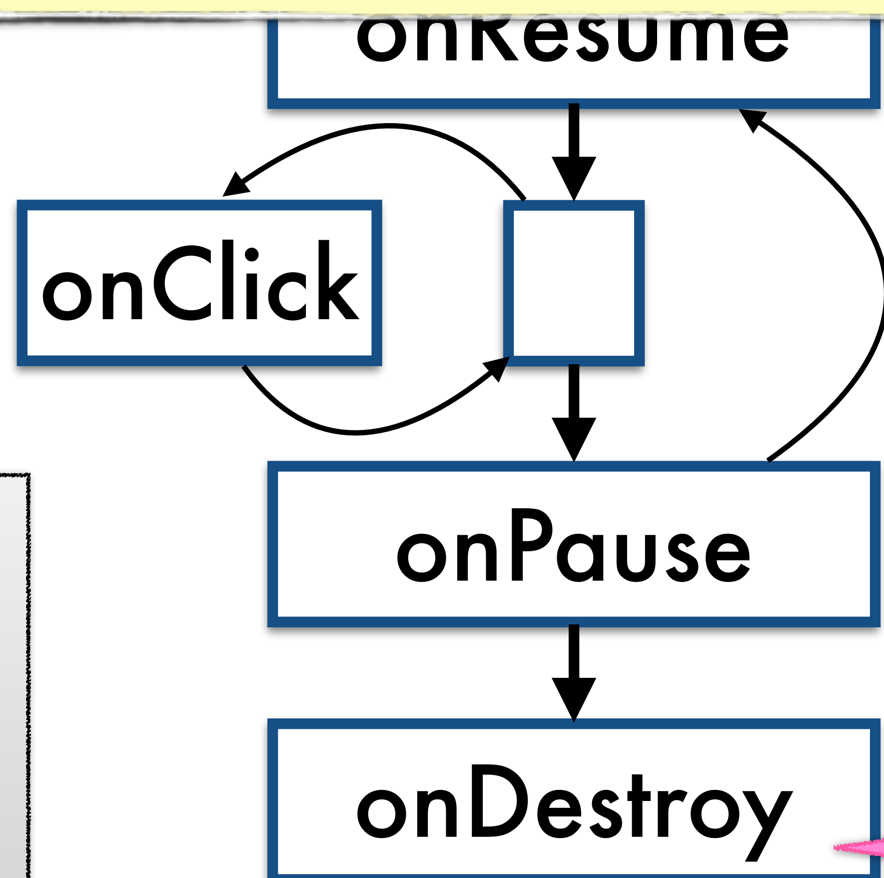
But, lifecycles of different components and other callbacks can interleave …

Callback-oriented programming

Challenge: Verifying safety (of dereferences) depends on callback interleaving

Android Framework

callbacks (e.g., Activity.onCreate)



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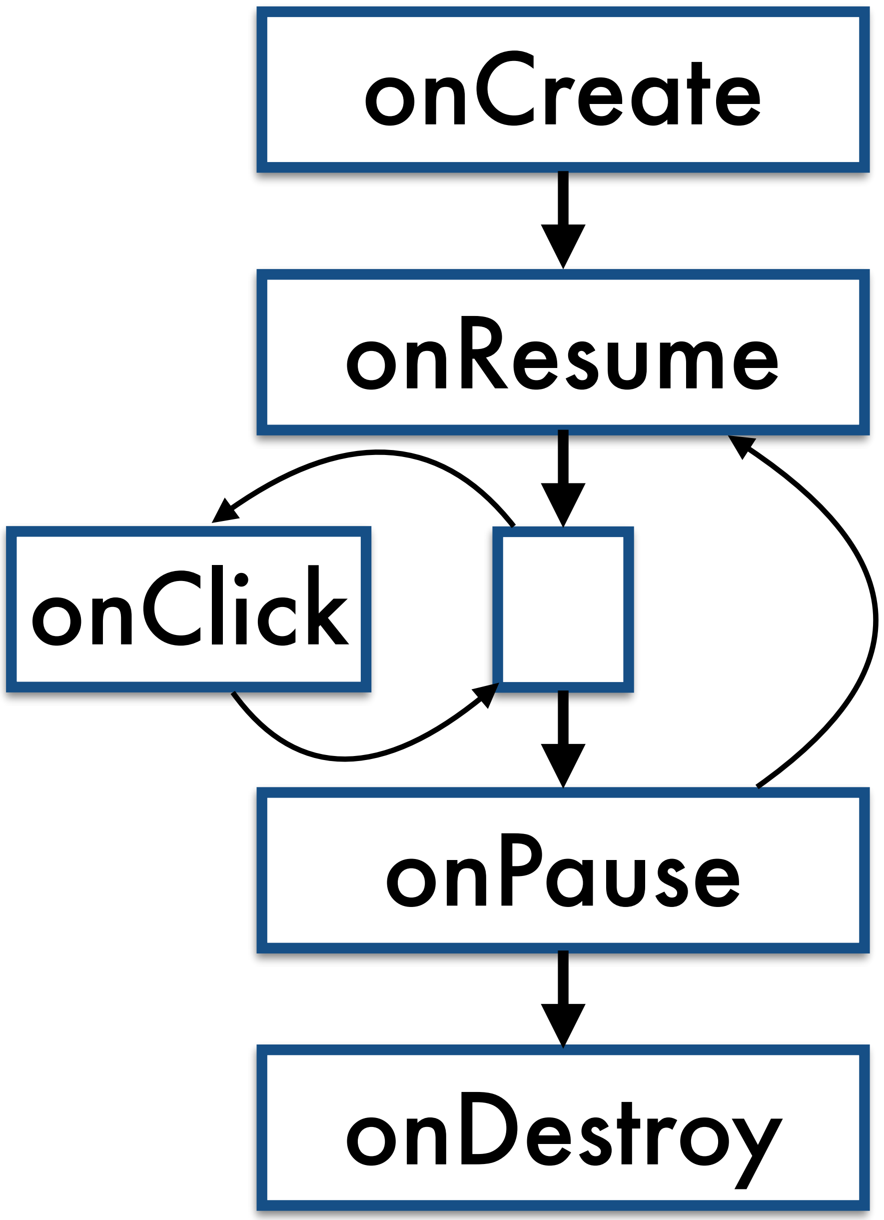

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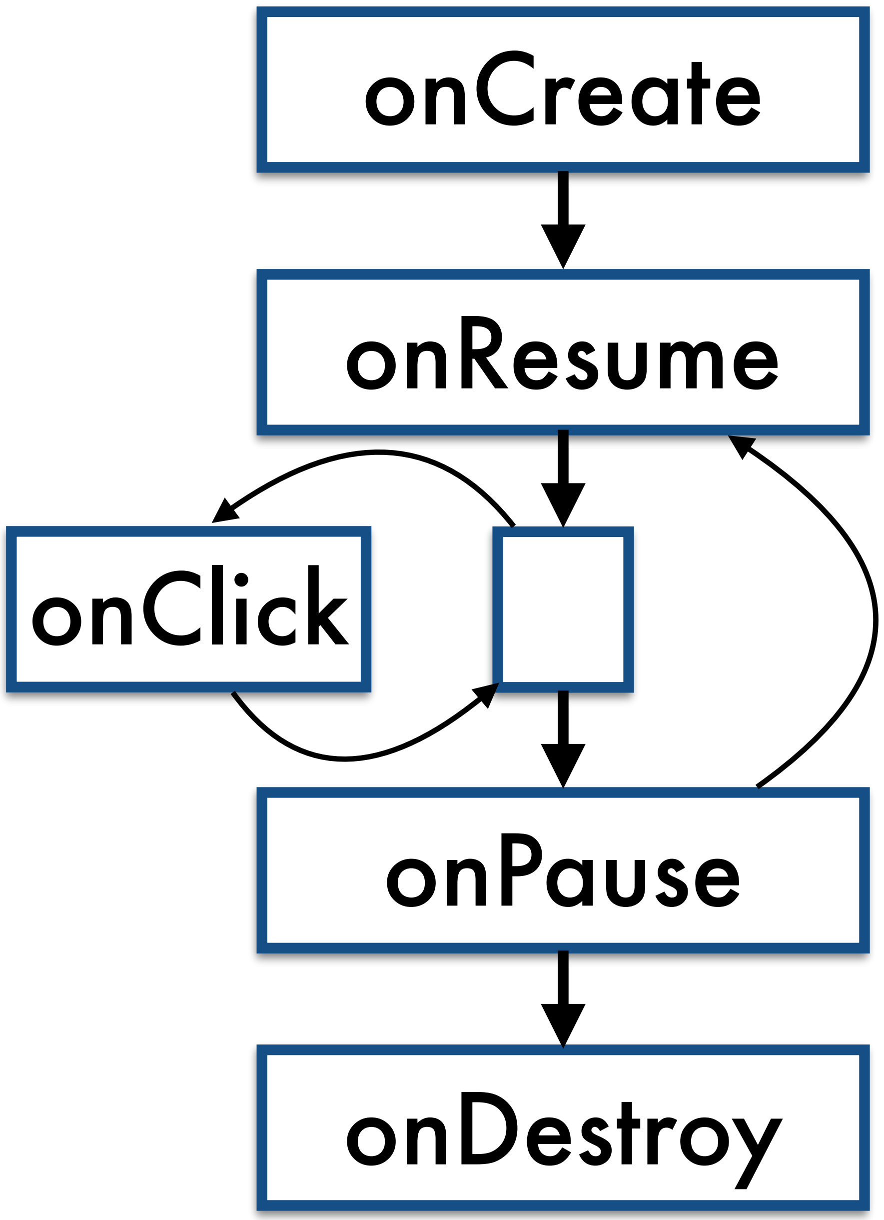

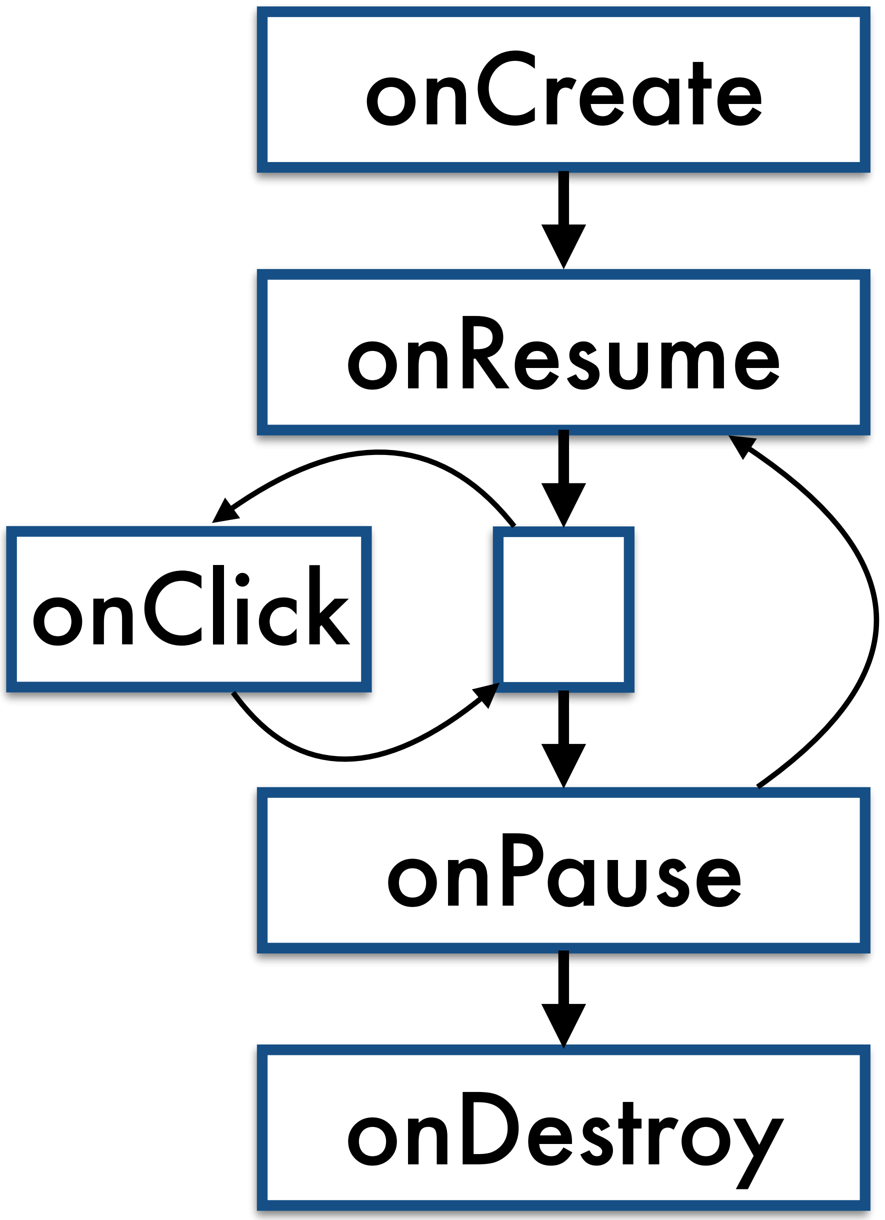

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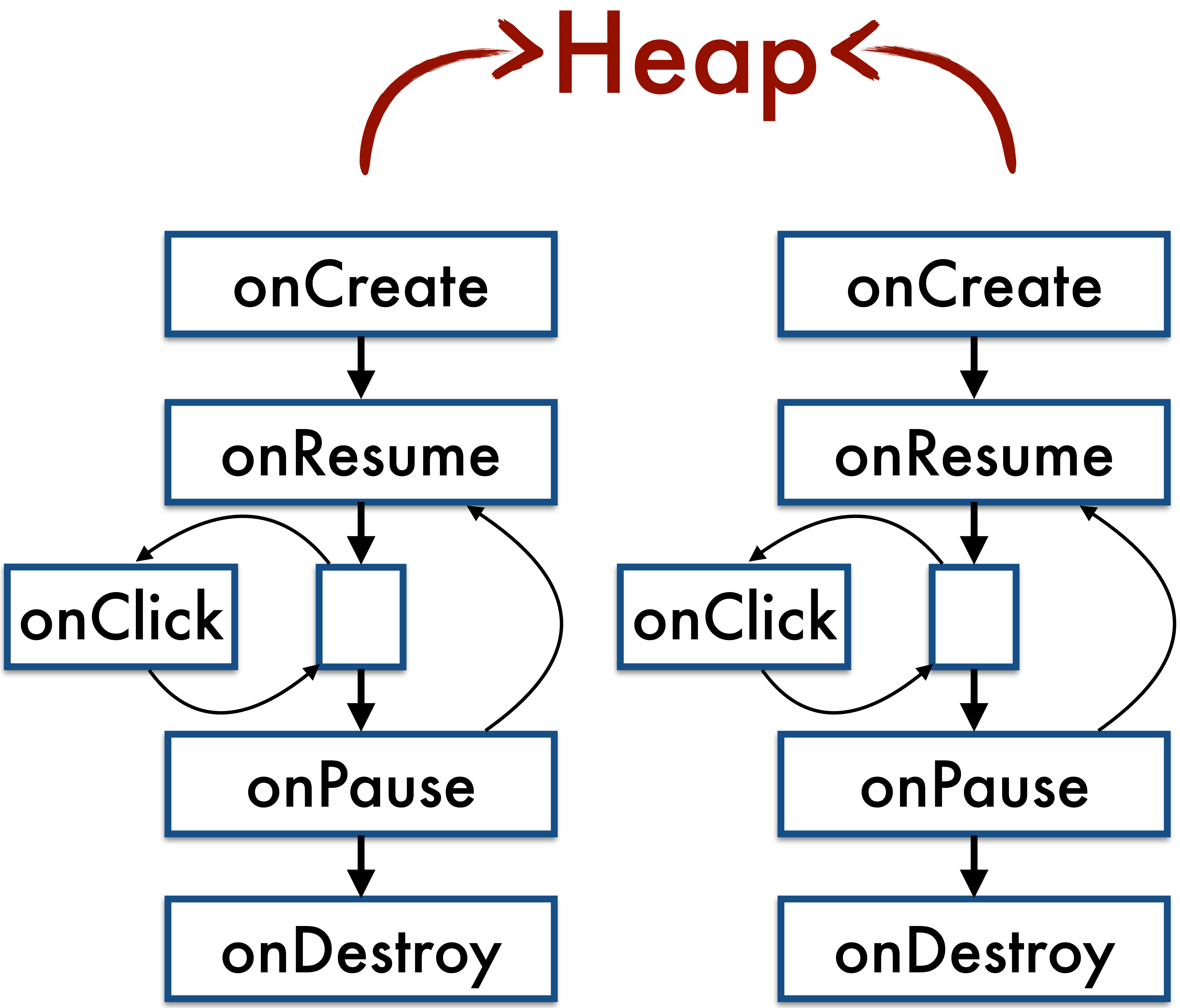

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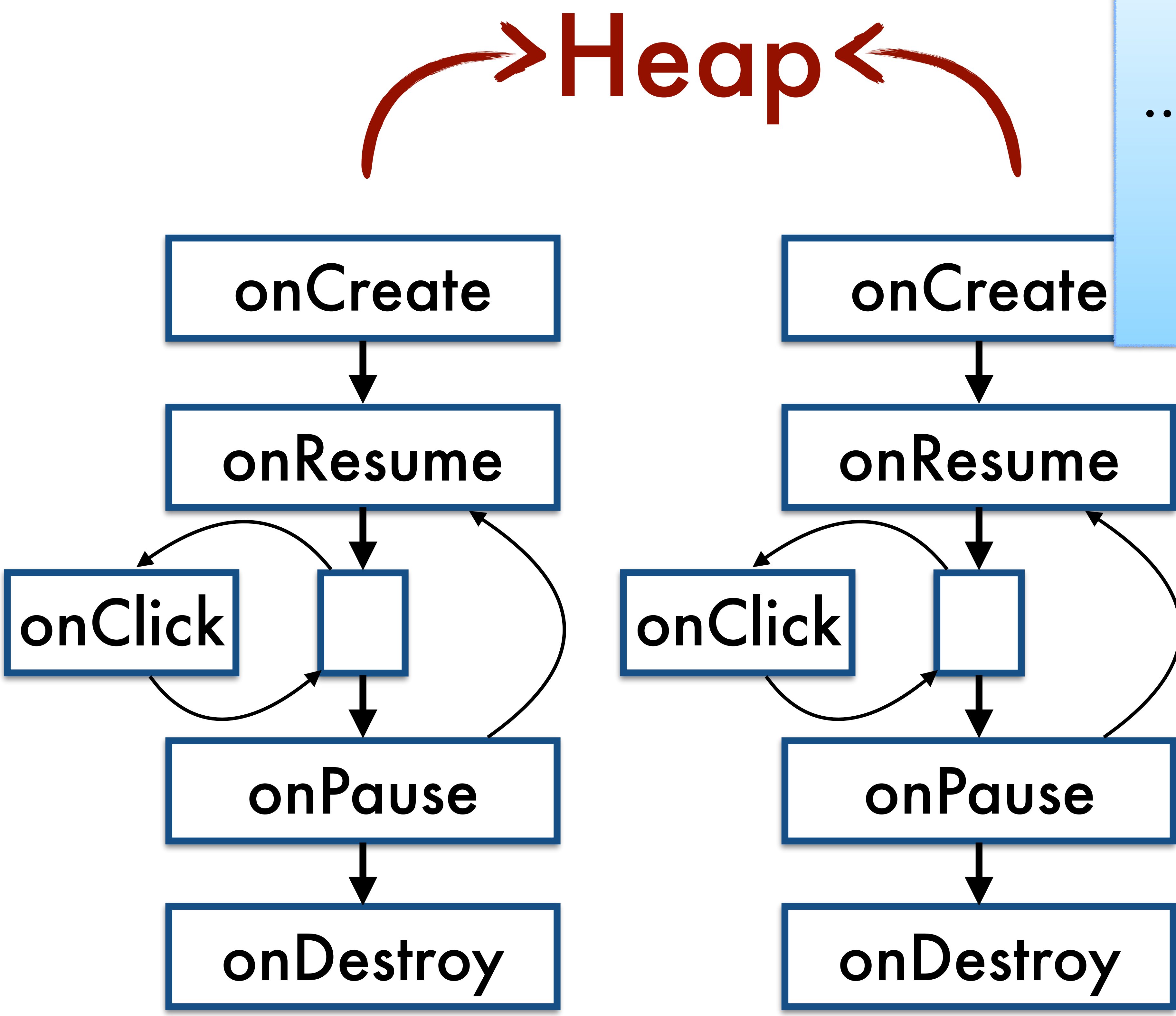
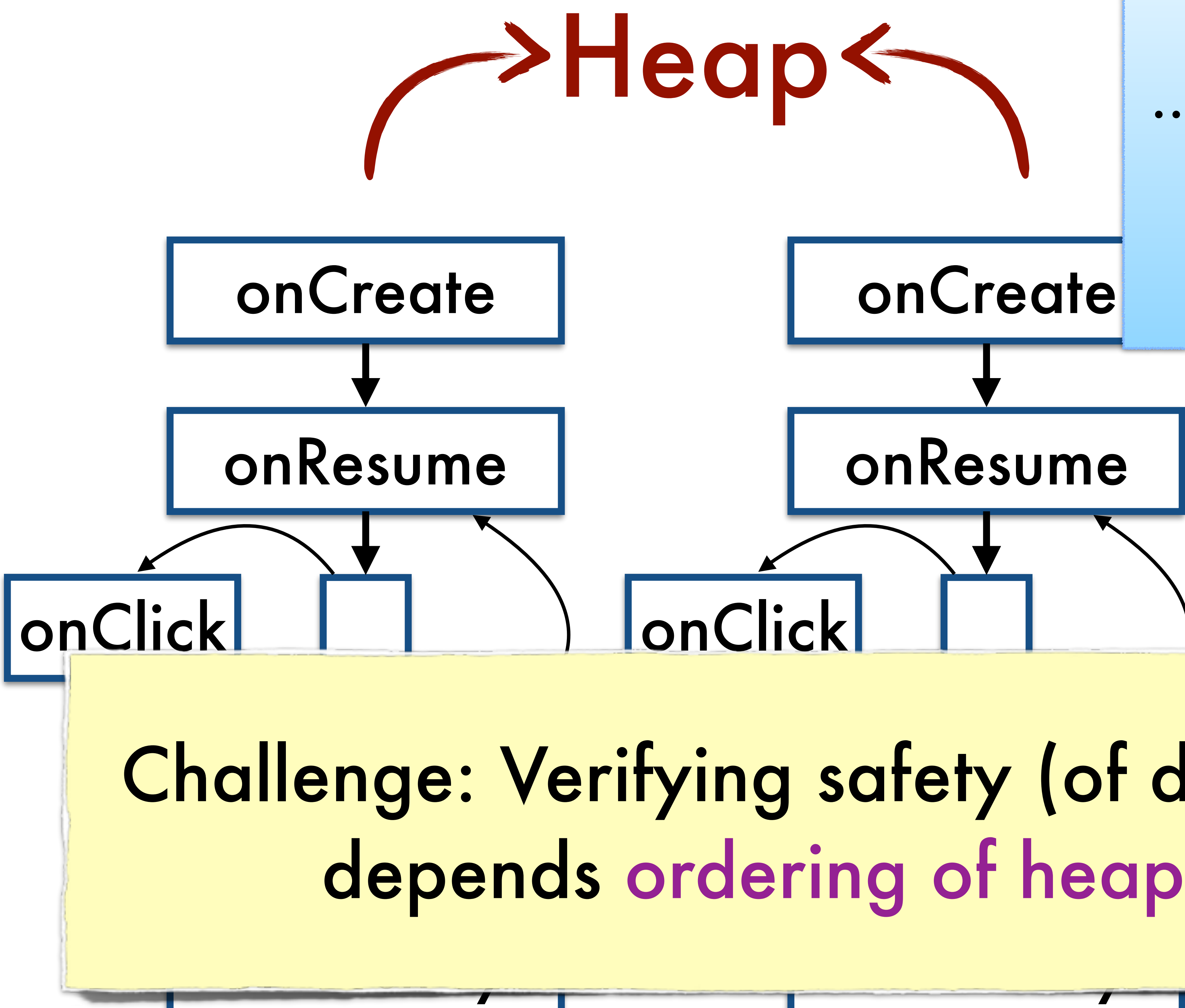


… and operates over a shared, global heap

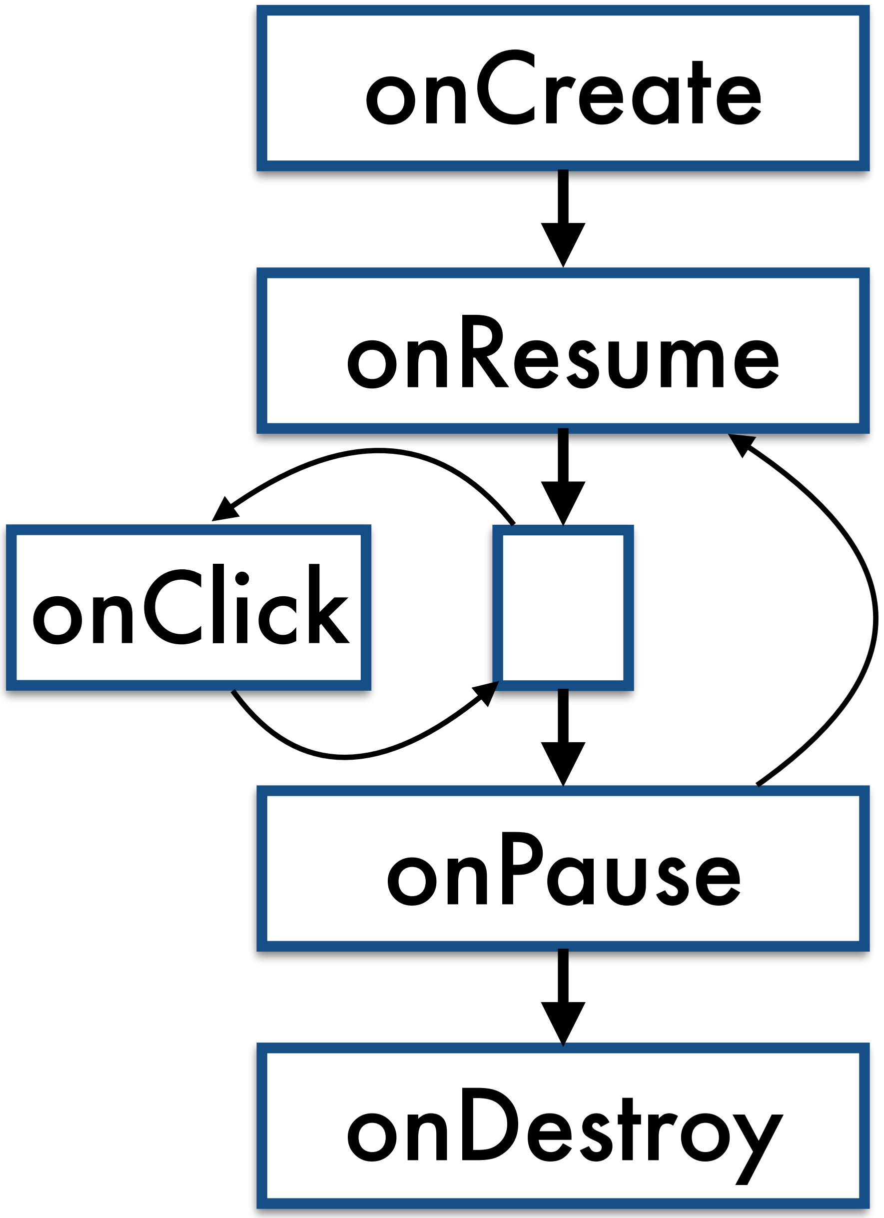
Callback-oriented programming



… and operates over a shared, global heap

Challenge: Verifying safety (of dereferences) depends ordering of heap writes

But it shouldn't be so hard ...



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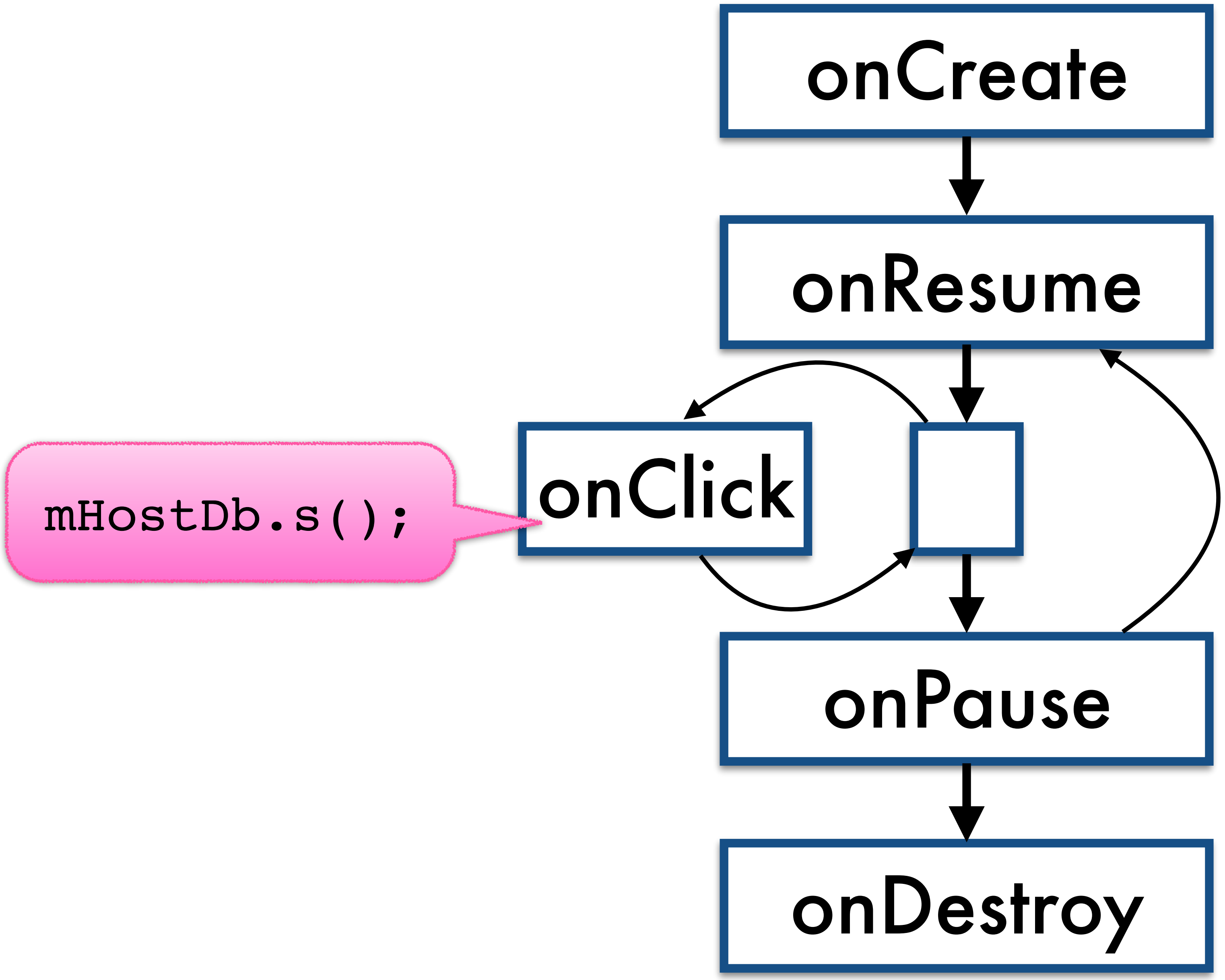

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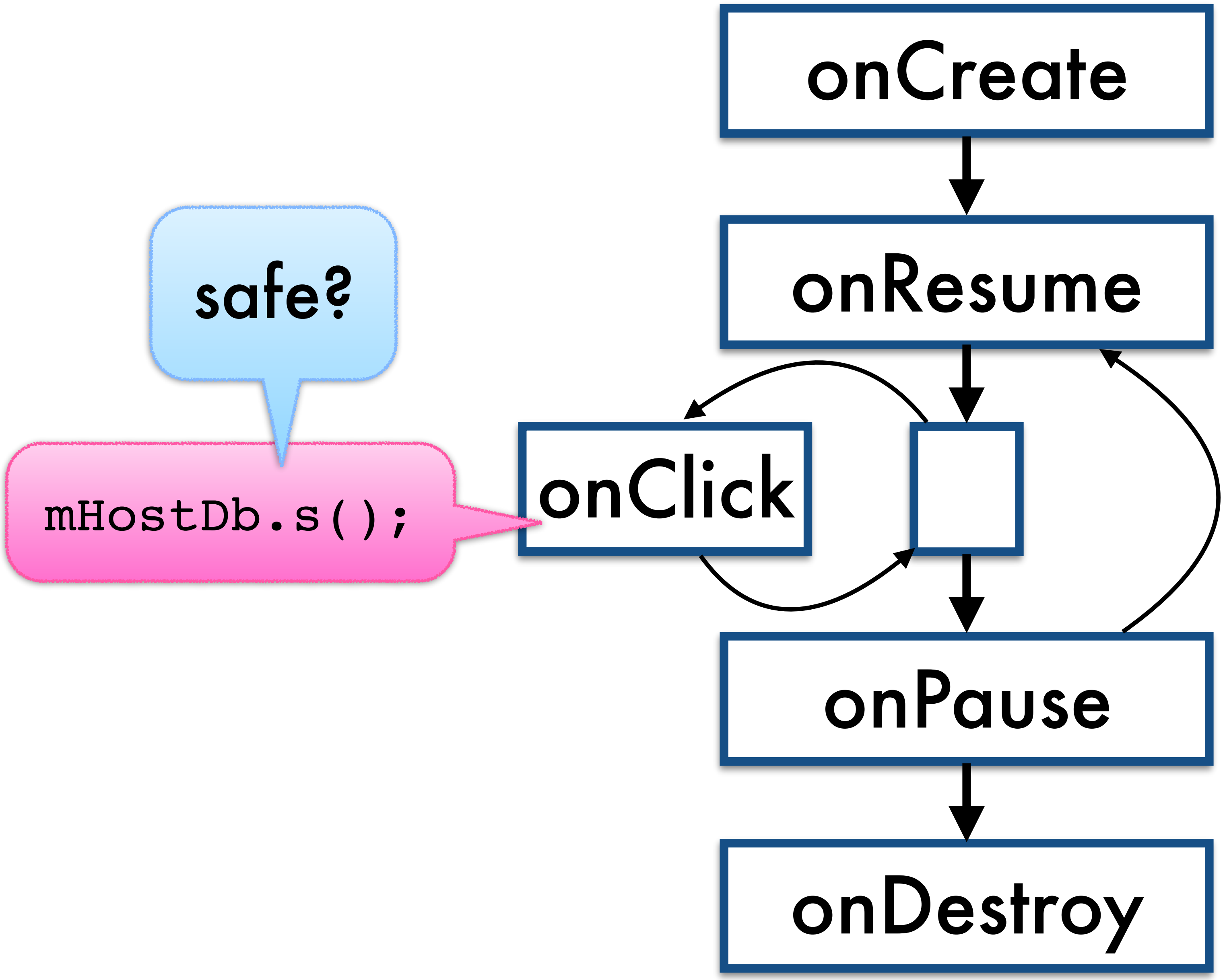

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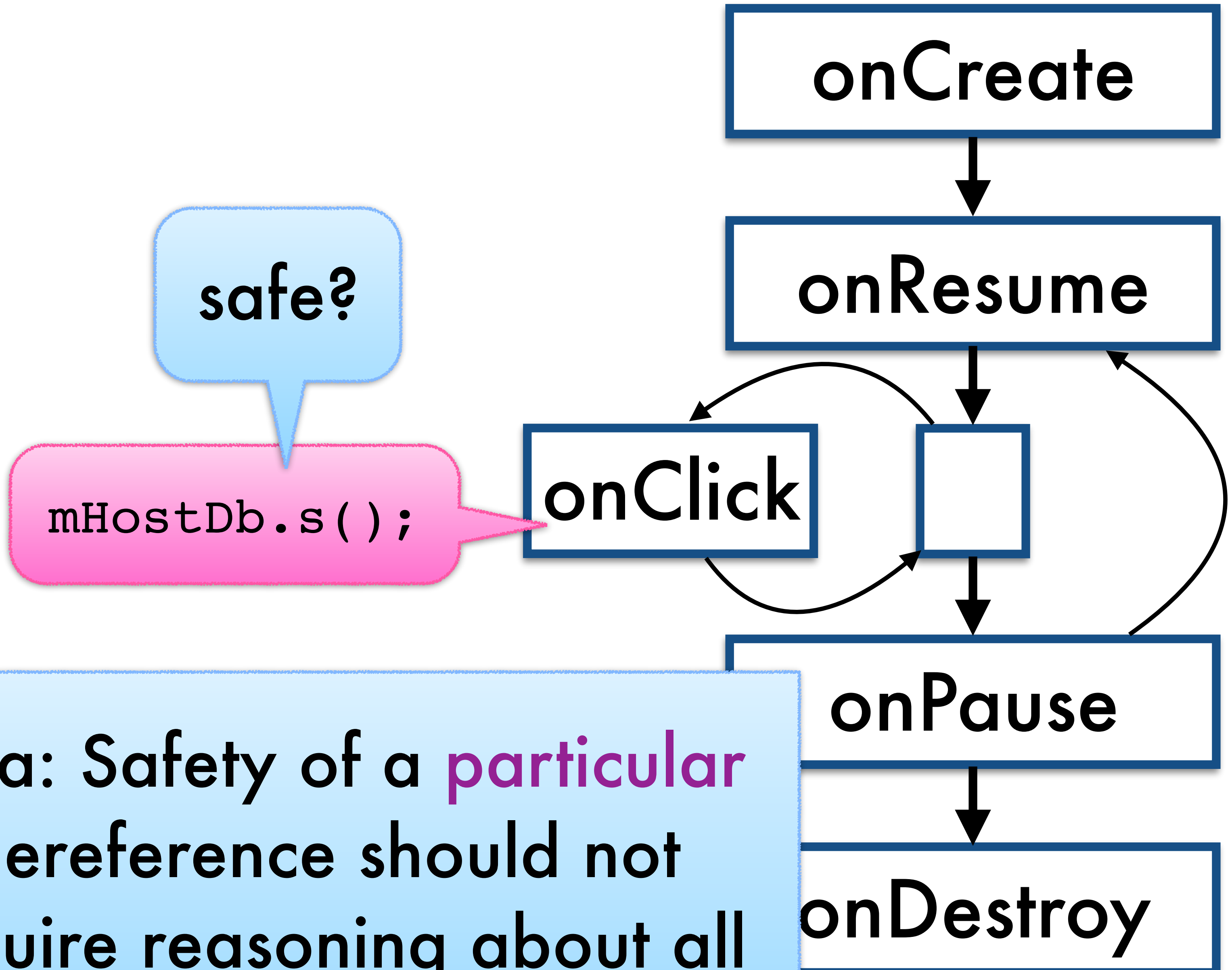
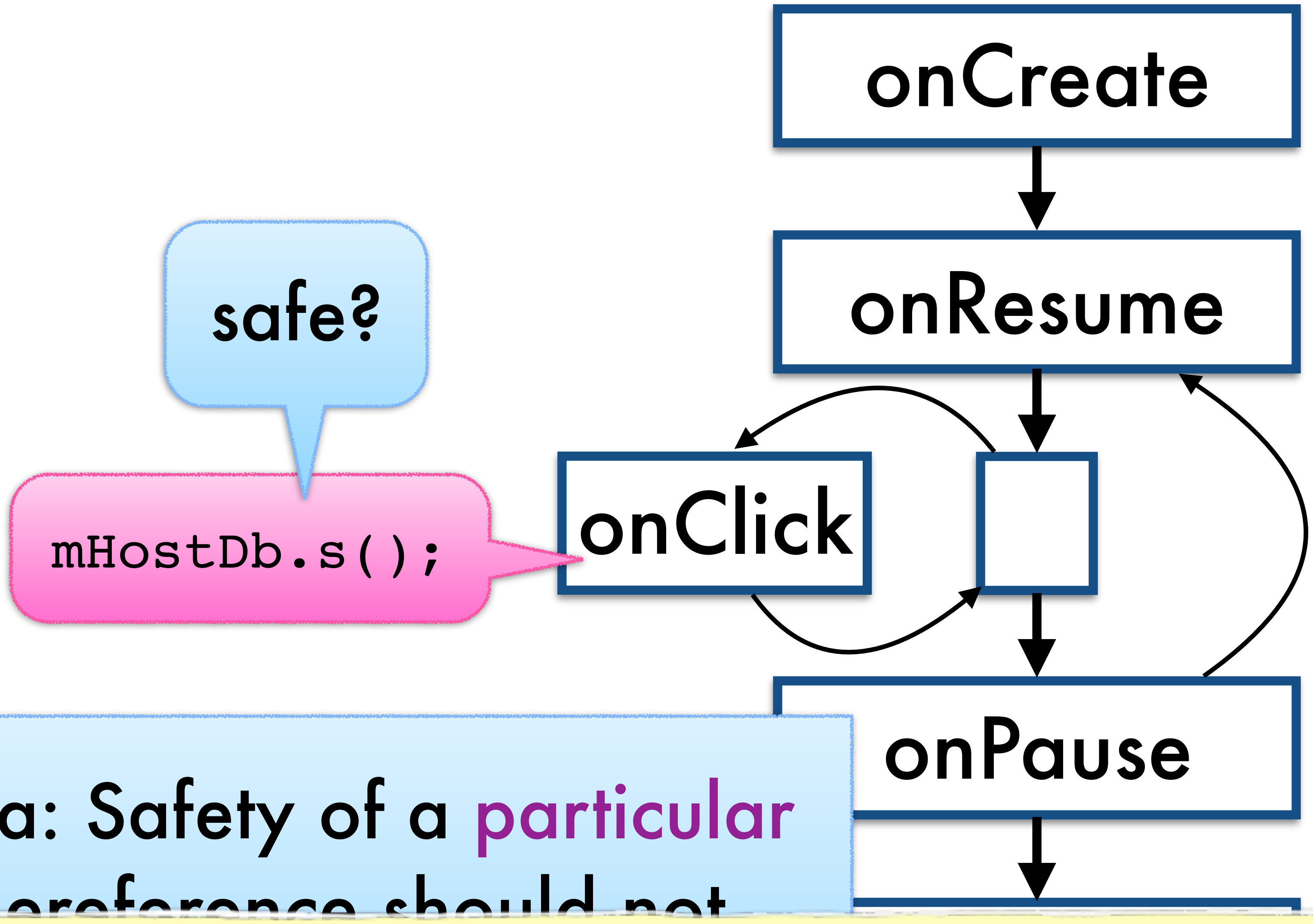


Idea: Safety of a particular dereference should not require reasoning about all callback interleavings

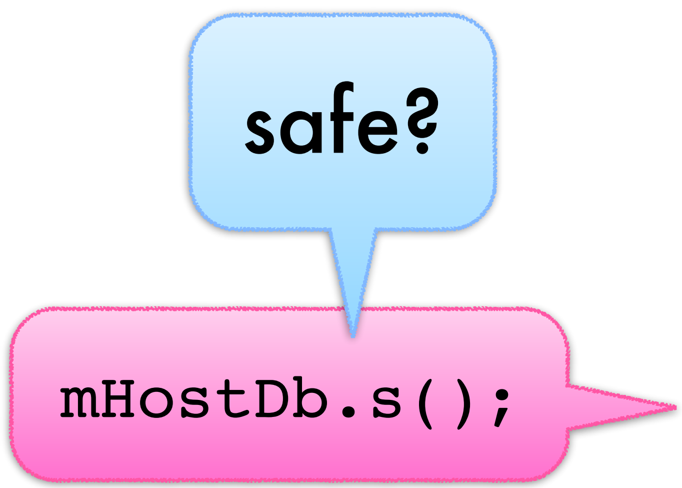
But it shouldn’t be so hard …



Idea: Safety of a particular

A “smart” goal-directed analysis could consider relevant callback orderings without considering all of them

Goal-directed program analysis



Goal-directed program analysis

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

safe?

```
mHostDb.s();
```

Goal-directed program analysis

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

safe?

`mHostDb.s();`

`mHostDb == null`

Goal-directed program analysis

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

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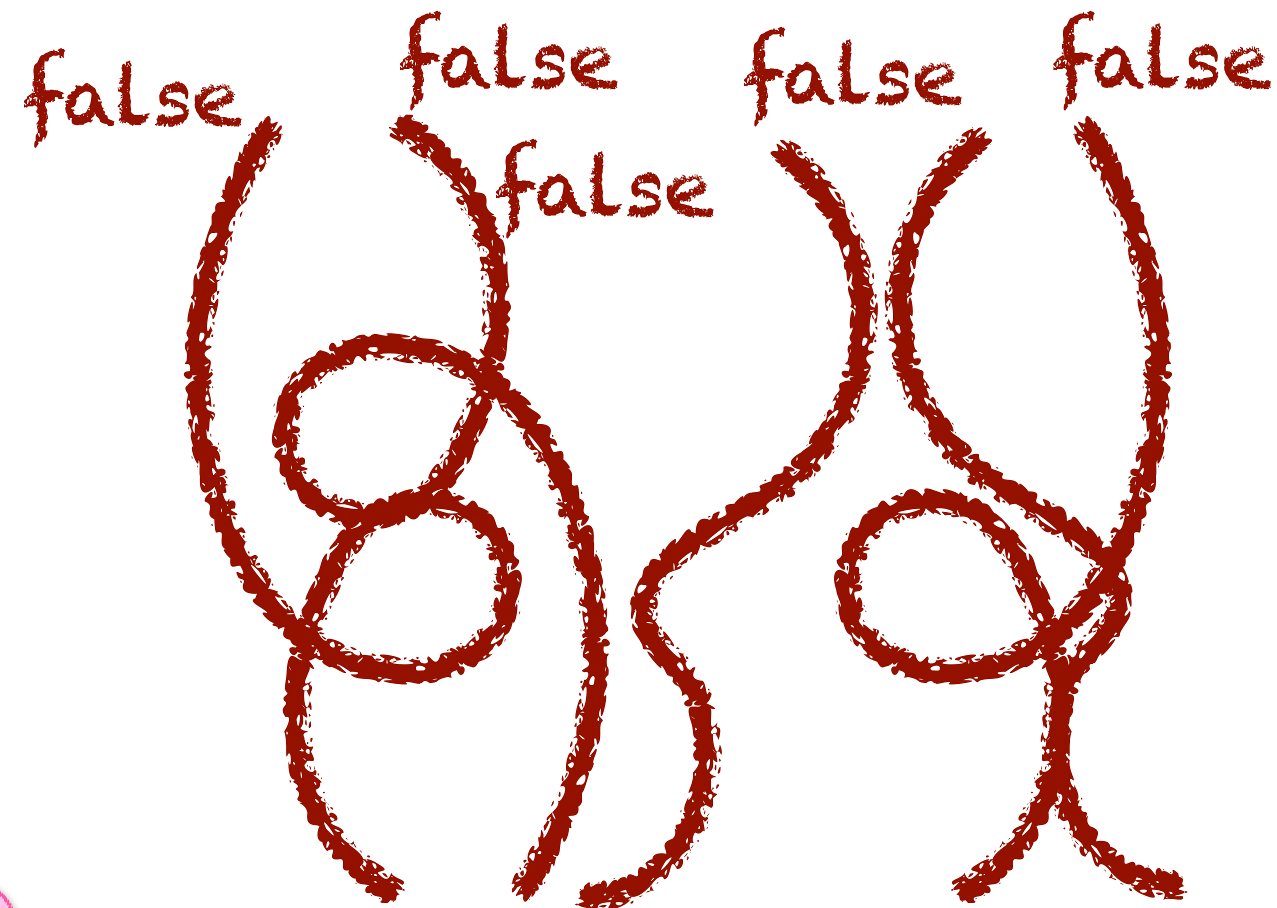
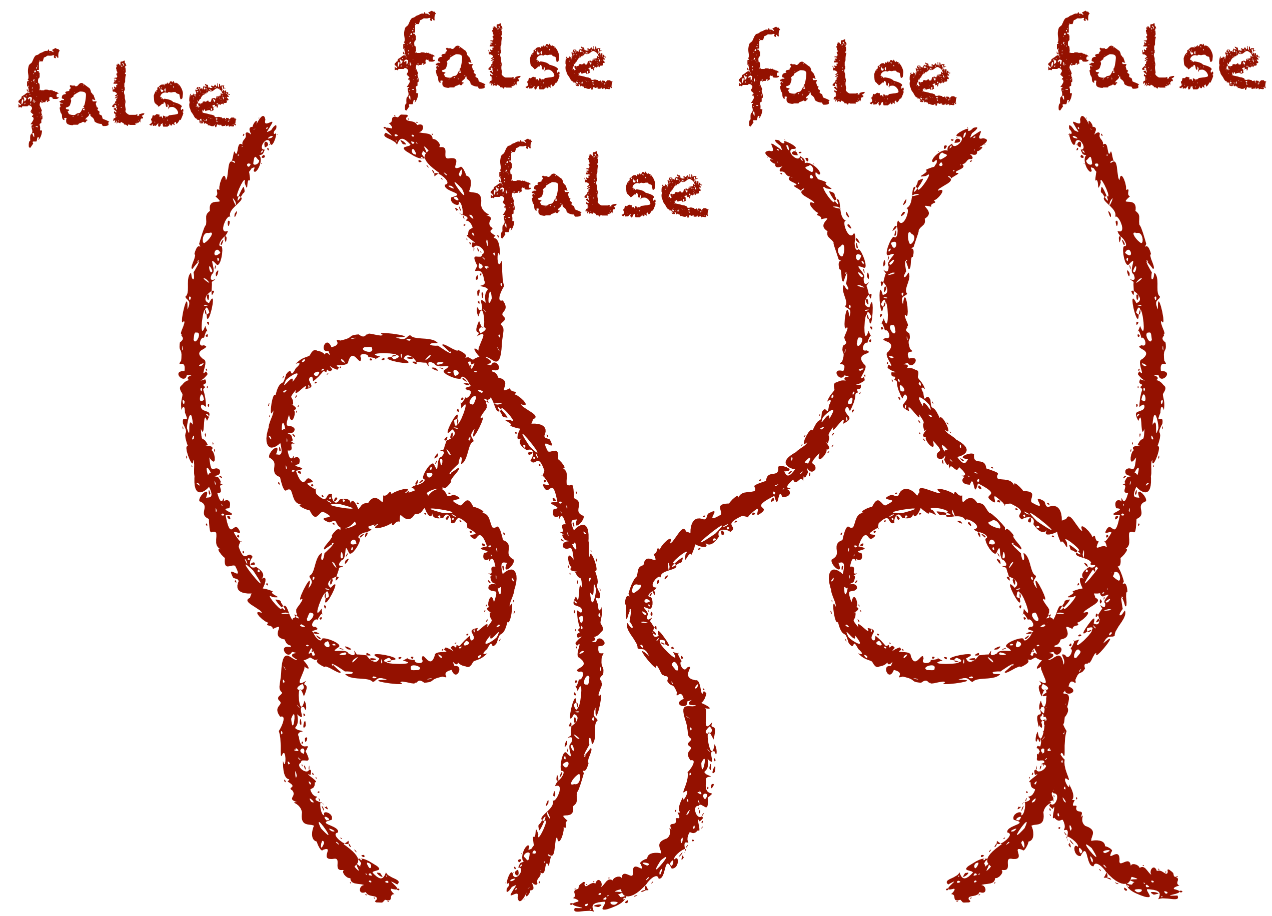


`mHostDb == null`

Goal-directed program analysis

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



$$(\mathbf{this} \mapsto \widehat{t} * \widehat{t} \cdot \texttt{mHostDb} \mapsto \widehat{a} * \mathsf{true}) \wedge \widehat{a} = \mathsf{null}$$

Goal-directed program analysis

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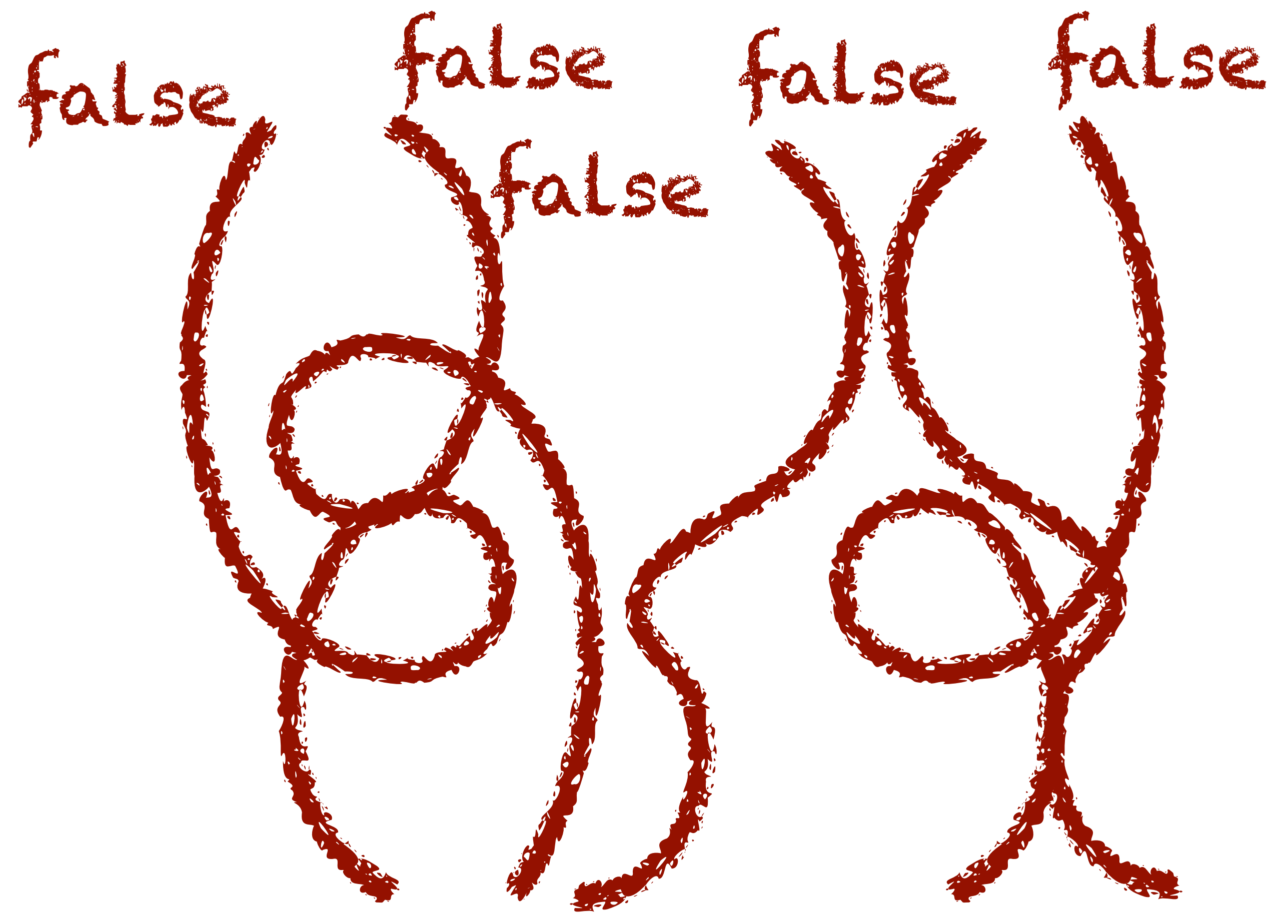
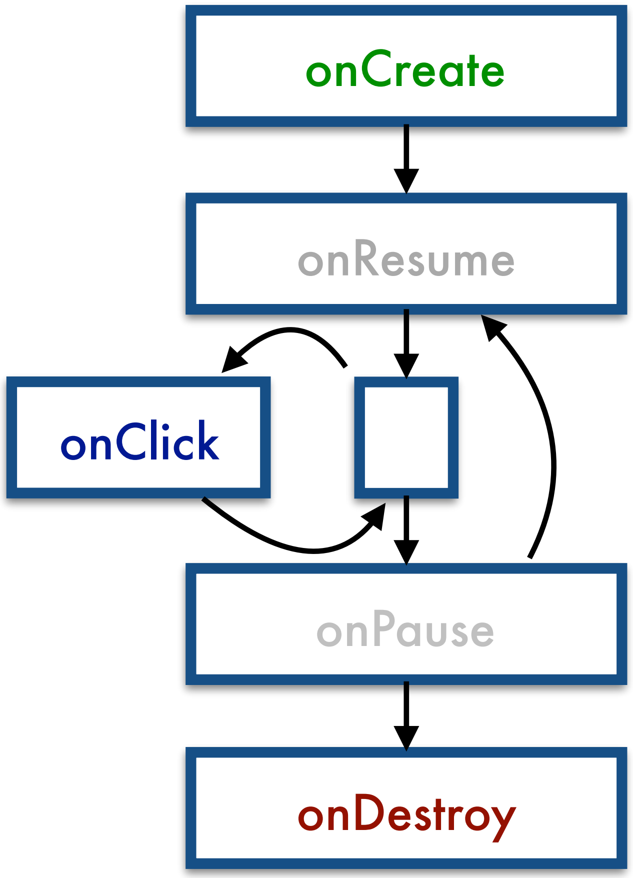


$$(\mathbf{this} \mapsto \widehat{t} * \widehat{t} \cdot \mathtt{mHostDb} \mapsto \widehat{a} * \mathsf{true}) \wedge \widehat{a} = \mathsf{null}$$

A precise backwards abstract interpretation with separation logic constraints to refute error conditions [PLDI'13]

Two dereferences: one safe and one buggy



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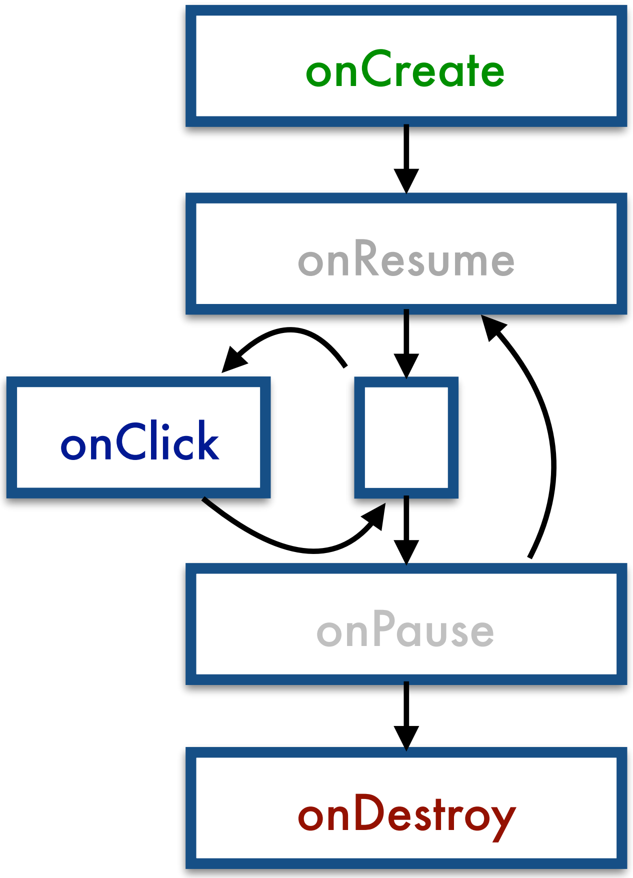
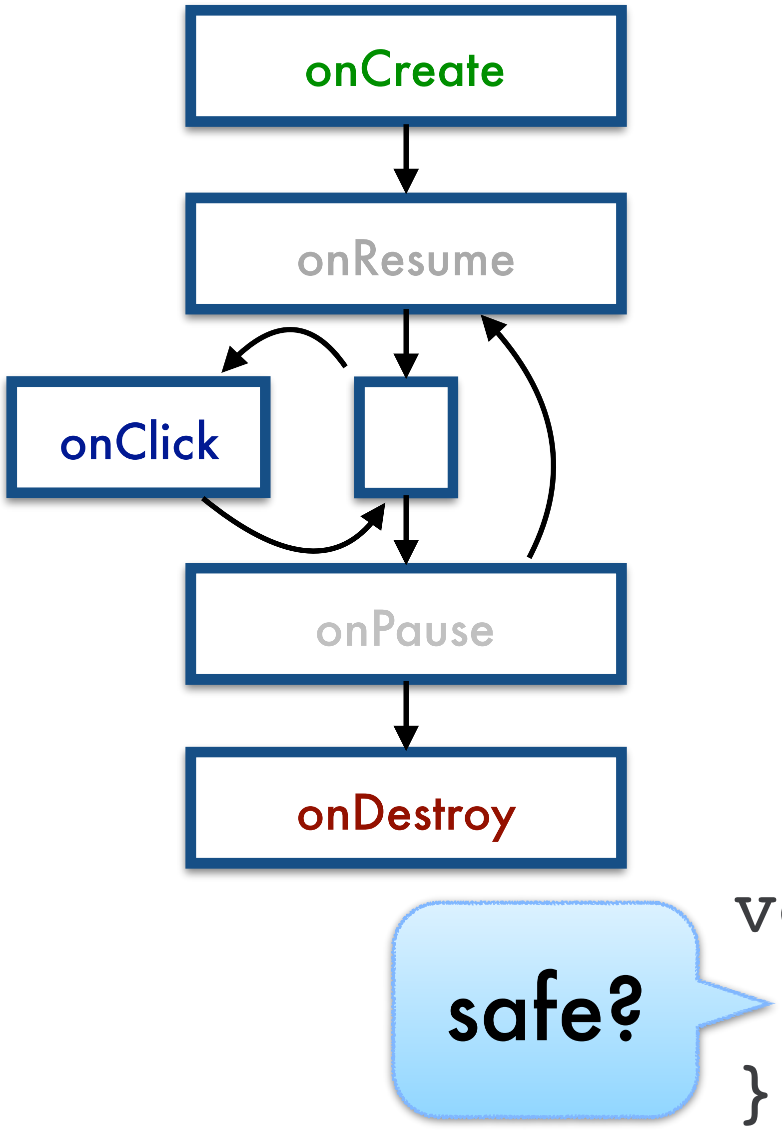



```
void onClick(…) {
  mHostDb.s(mService.g());
}
```

Two dereferences: one safe and one buggy

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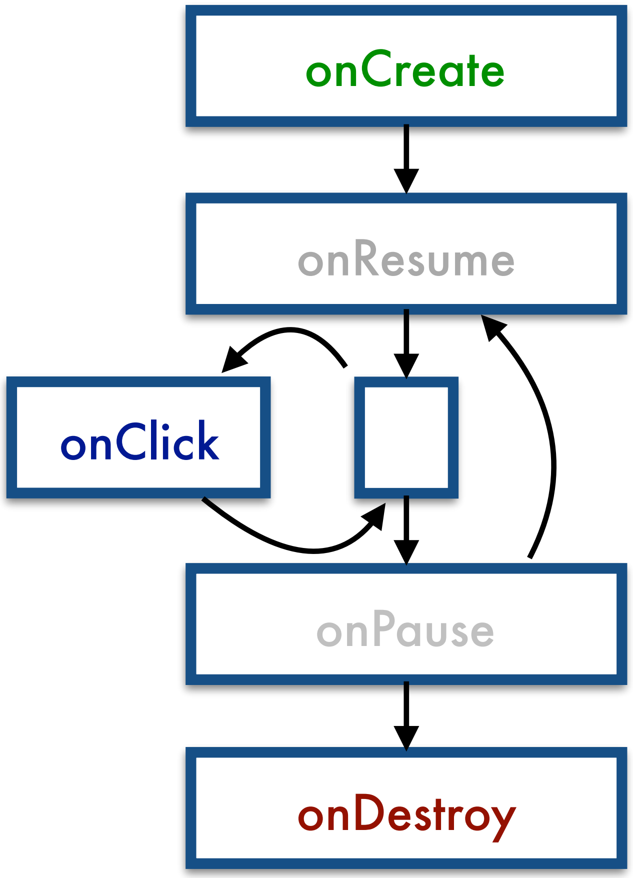

safe?

```
void onClick(…) {
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```
void onDestroy(…) {
  mHostDb = null;
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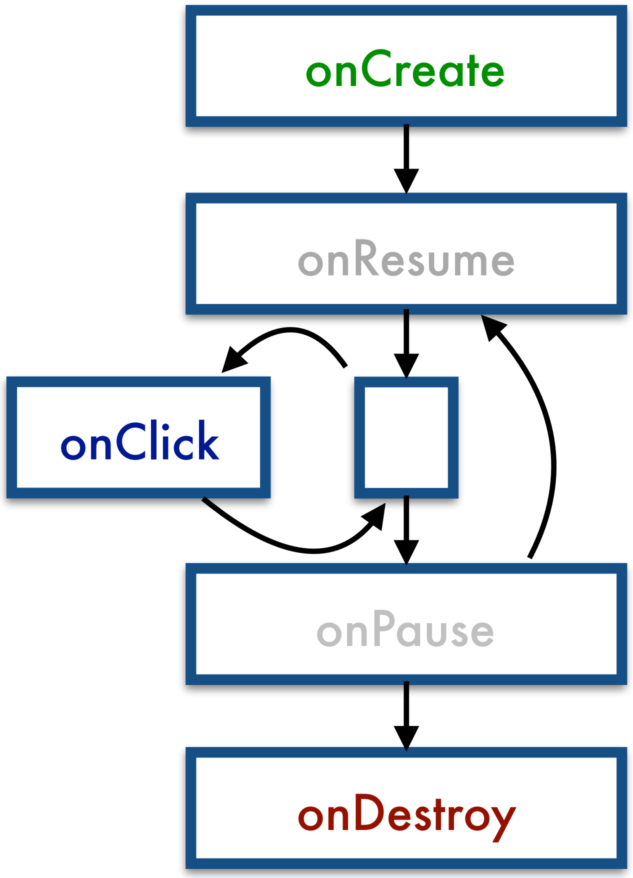
Two dereferences: one safe and one buggy



safe?

lifecycle constraints relevant

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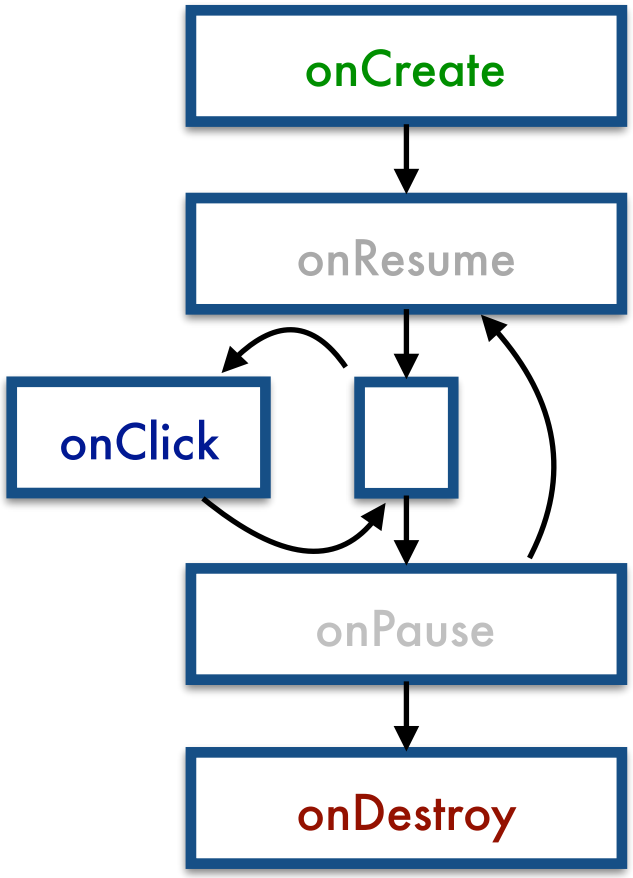


```
void onCreate() {
  bindService(…, new ServiceConn {
    void onConnected(@Nonnull Service s) {
      mService = s;
    }
  });
  mHostDb = new Db();
}
```

safe?

```
void onClick(…) {
  mHostDb.s(mService.g());
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```

1 2

lifecycle constraints relevant

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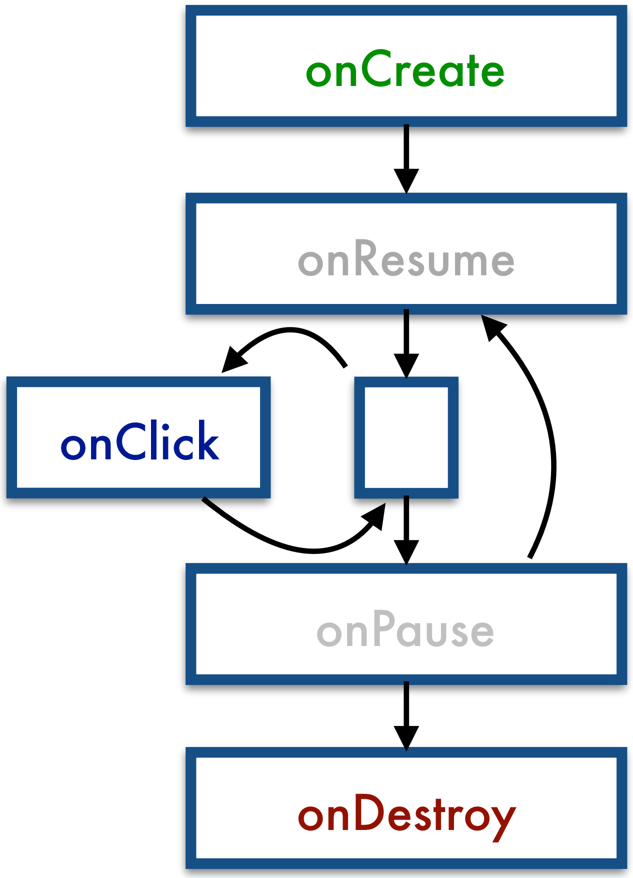


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      mService = s;
    }
  });
  mHostDb = new Db();
}
```

safe?

```
void onClick(…) {
  mHostDb.s(mService.g());
}
```

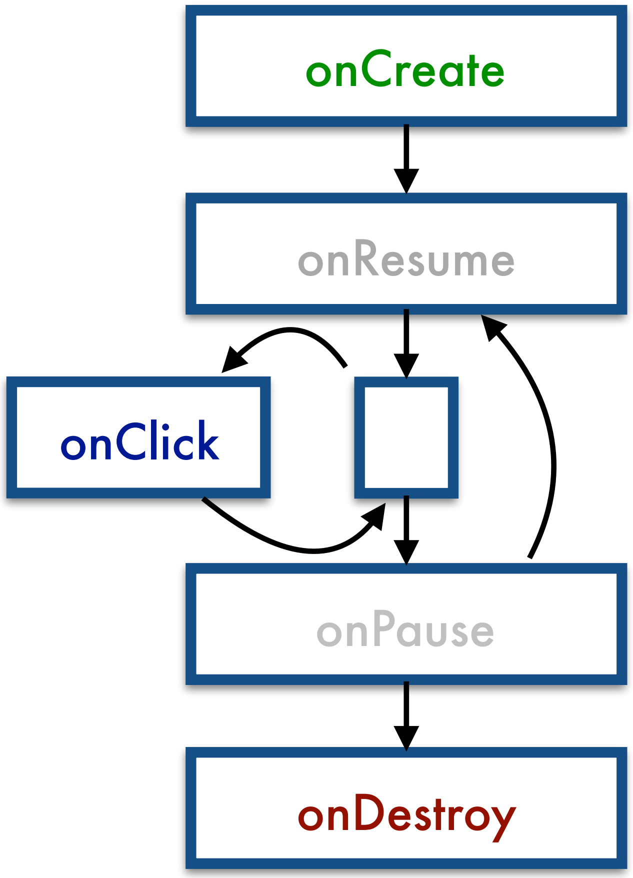
1

2

lifecycle constraints relevant

```
void onDestroy(…) {
  mHostDb = null;
  mService = null;
}
```

Two dereferences: one safe and one buggy



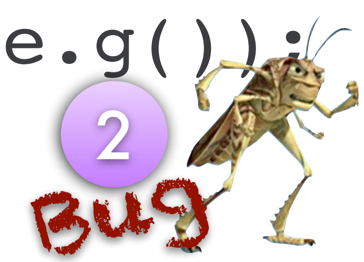

```
void onCreate() {
  bindService(…, new ServiceConn {
    void onConnected(@Nonnull Service s) {
      mService = s;
    }
  });
  mHostDb = new Db();
}

void onClick(…) {
  mHostDb.s(mService.g());
}

void onDestroy(…) {
  mHostDb = null;
  mService = null;
}
```

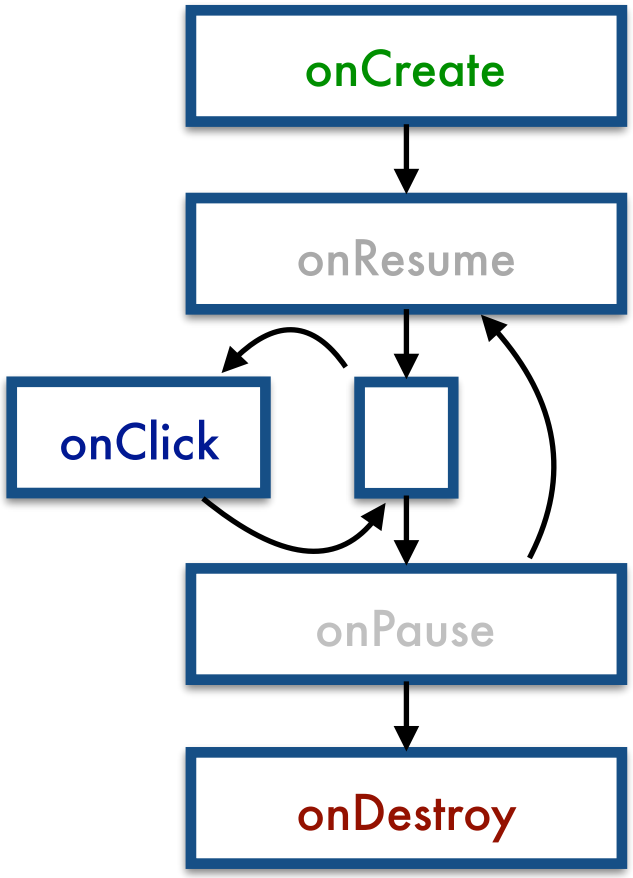
safe?

1 ✔ 2



lifecycle constraints relevant

Two dereferences: one safe and one buggy




```
void onCreate() {
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    void onConnected(@Nonnull Service s) {
      mService = s;
    }
  });
  mHostDb = new Db();
}

void onClick(…) {
  mHostDb.s(mService.g());
```
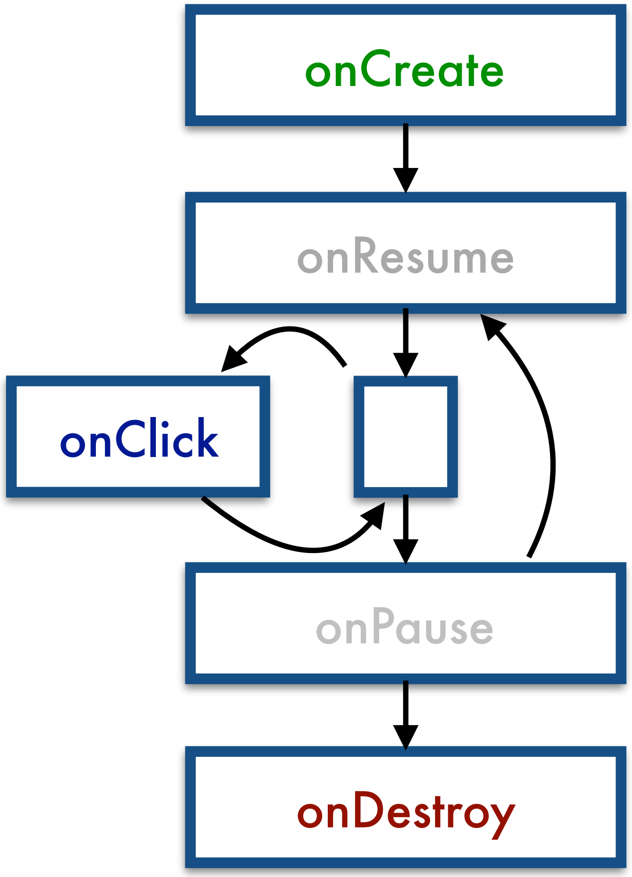

safe?

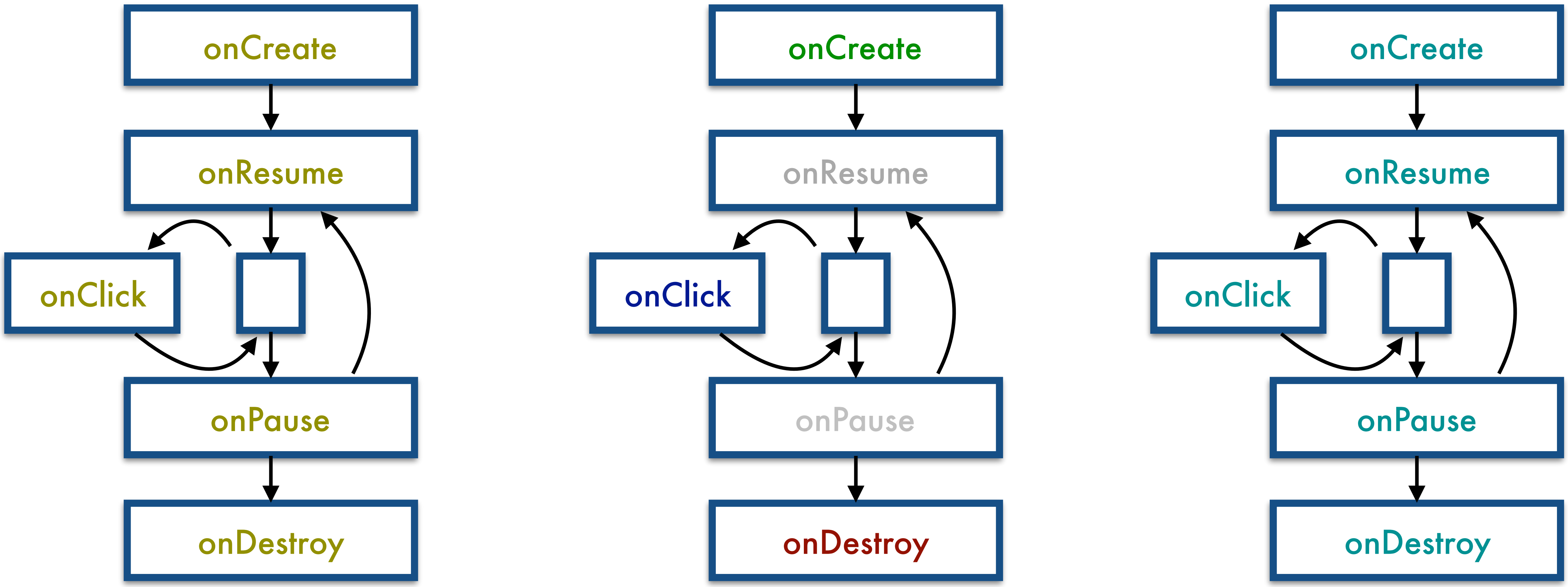
```
}
```

Need to consider some but not all callback ordering constraints

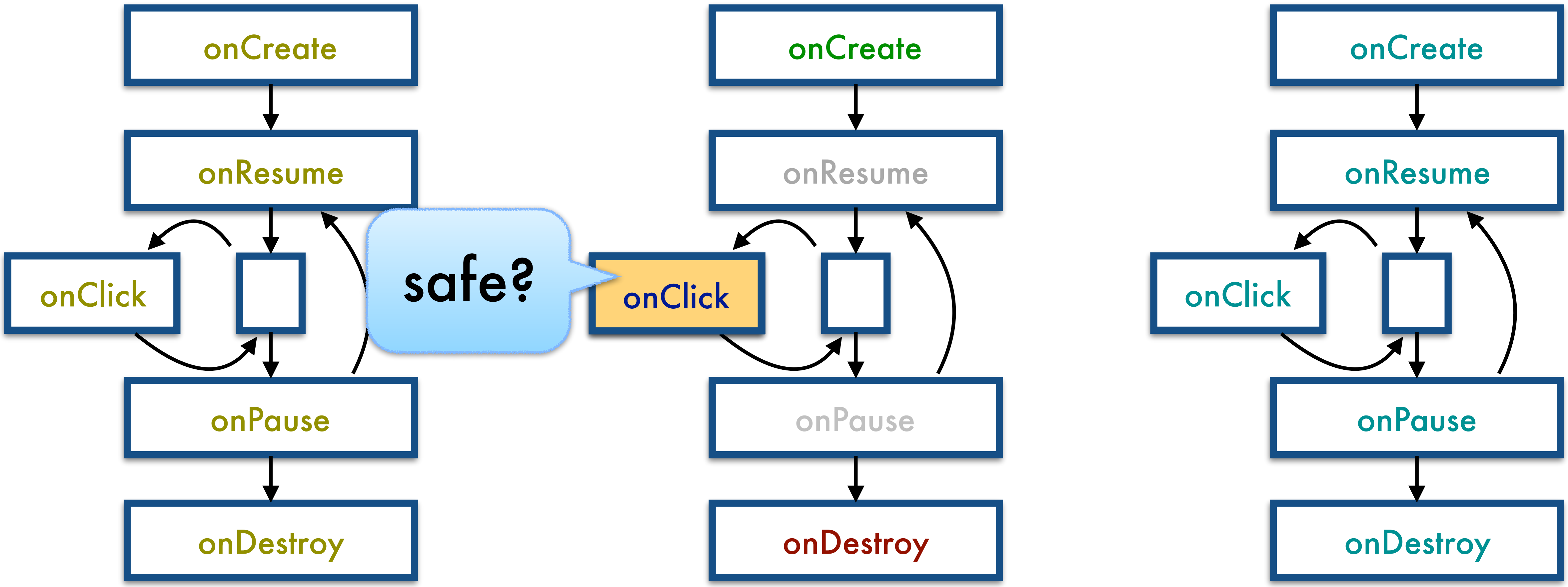
Idea: Jumping to relevant callbacks



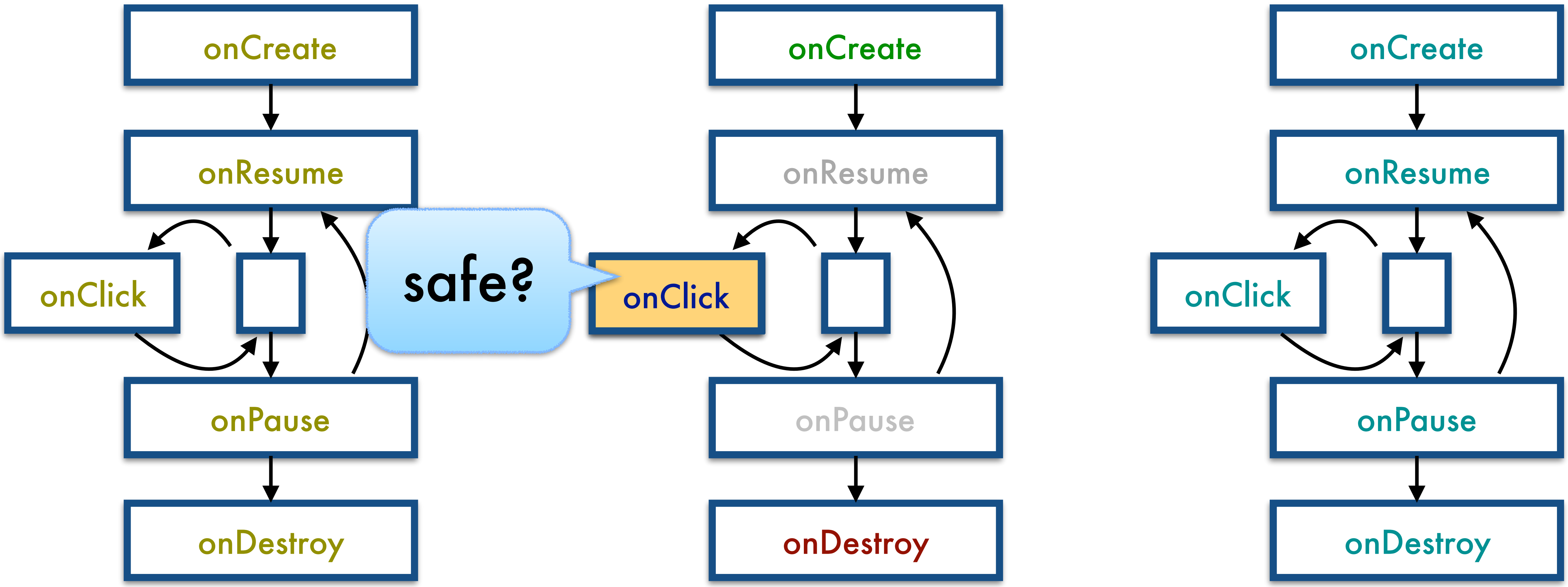
Idea: Jumping to relevant callbacks



Idea: Jumping to relevant callbacks

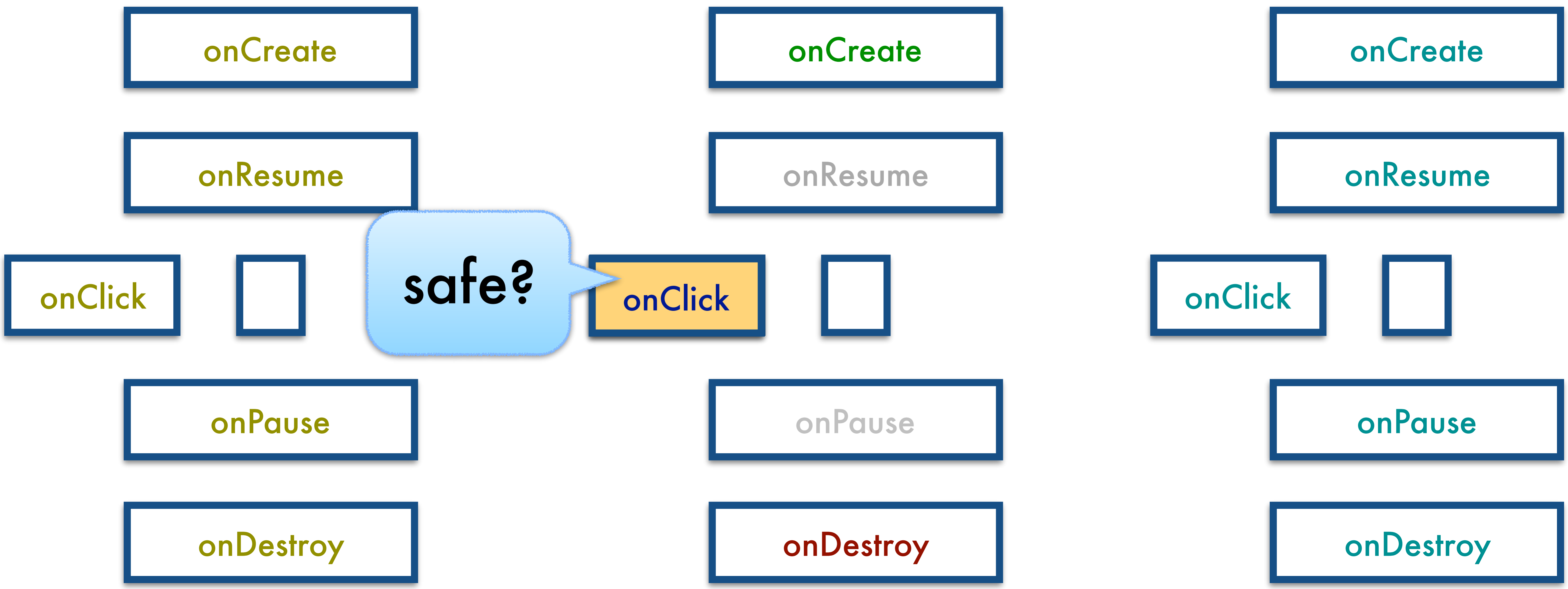


Idea: Jumping to relevant callbacks



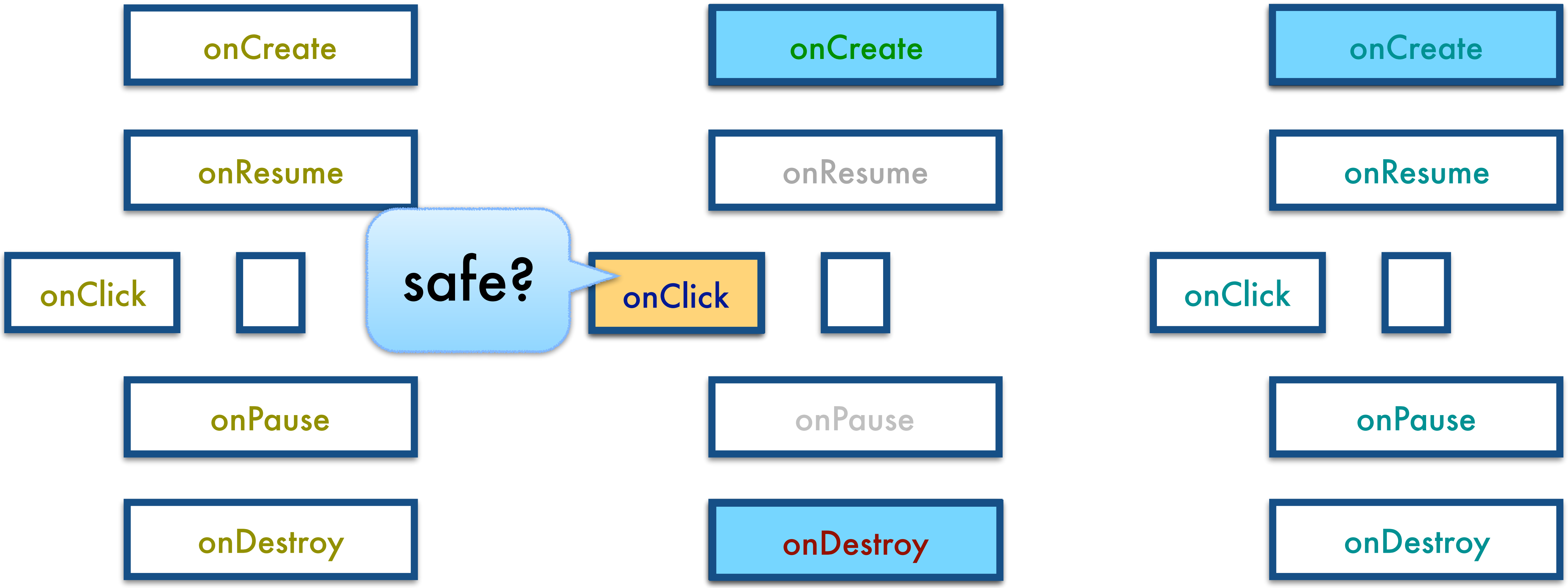
Find data relevant callbacks

Idea: Jumping to relevant callbacks



Find data relevant callbacks

Idea: Jumping to relevant callbacks



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Idea: Jumping to relevant callbacks

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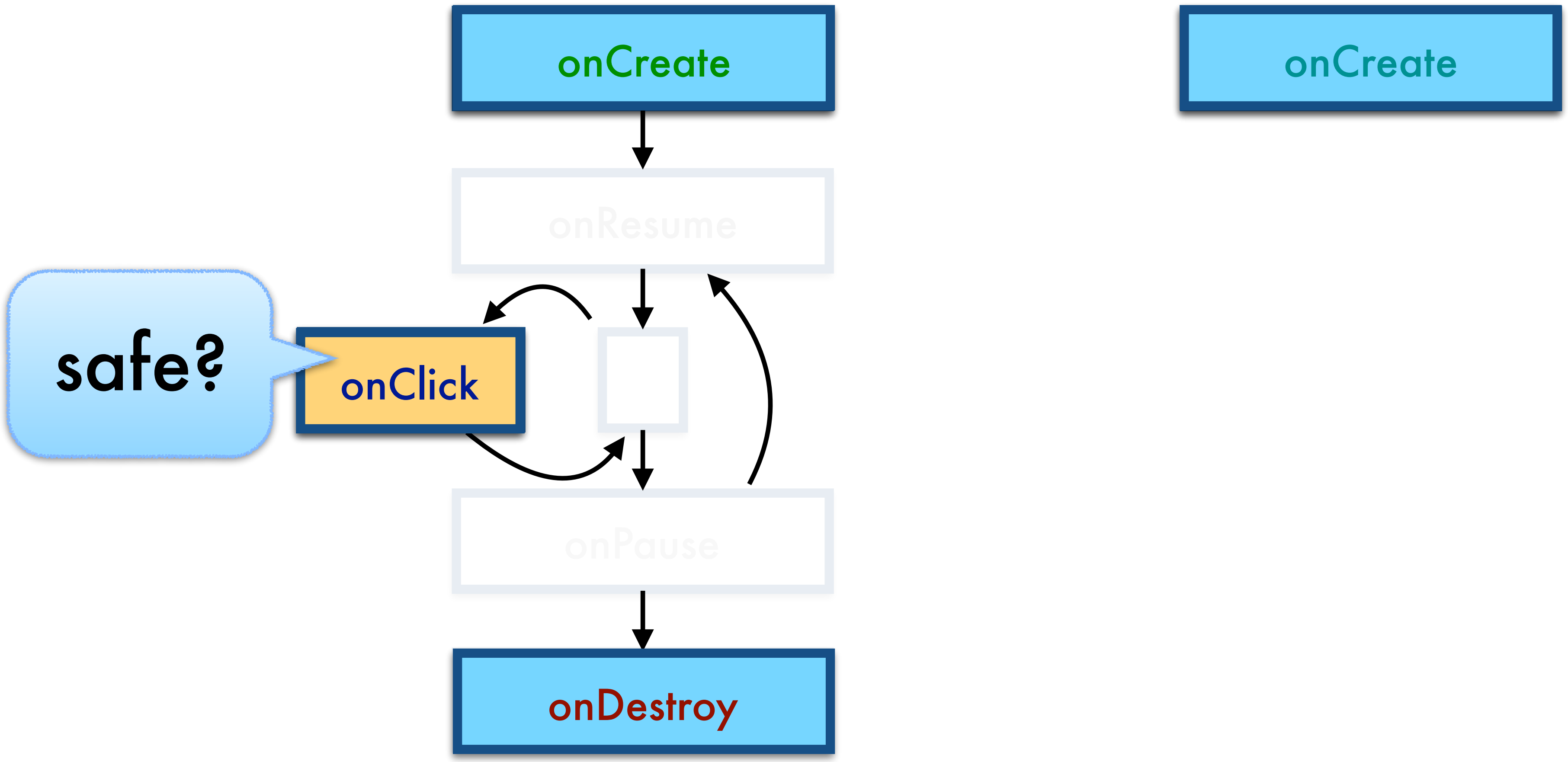
Find data relevant callbacks

Filter using control-feasibility

Idea: Jumping to relevant callbacks



Find data relevant callbacks

Filter using control-feasibility

Idea: Jumping to relevant callbacks

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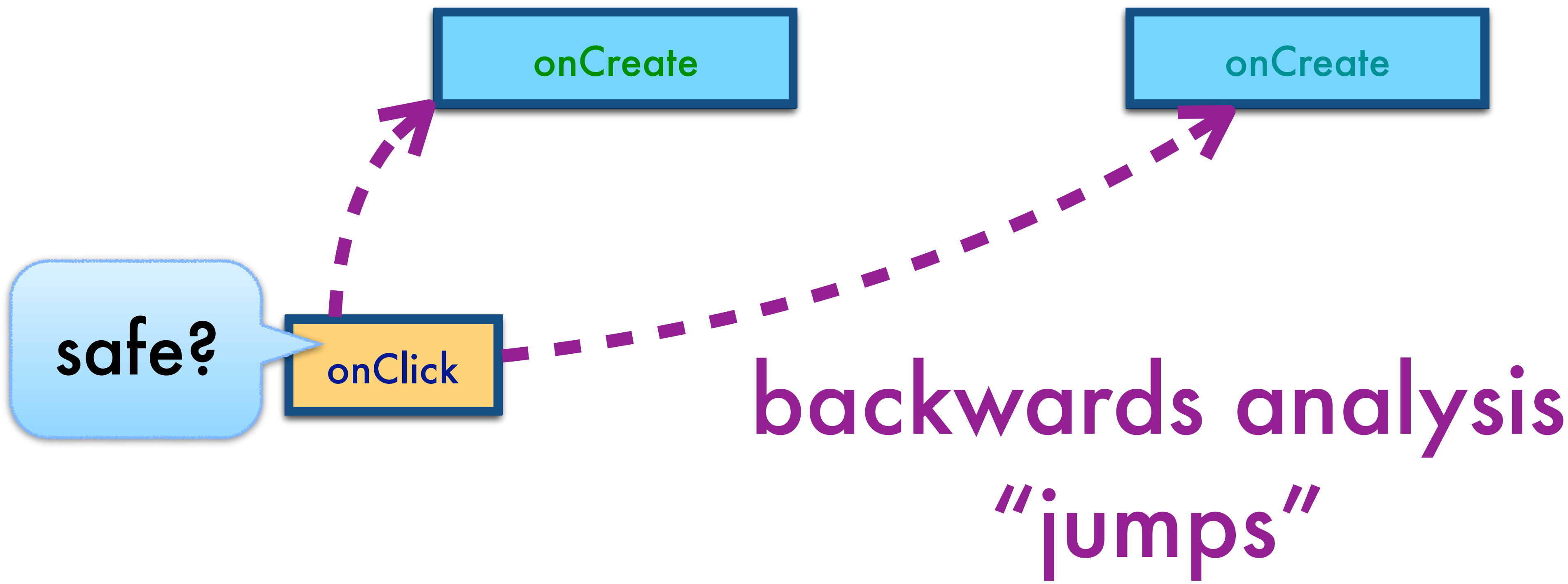
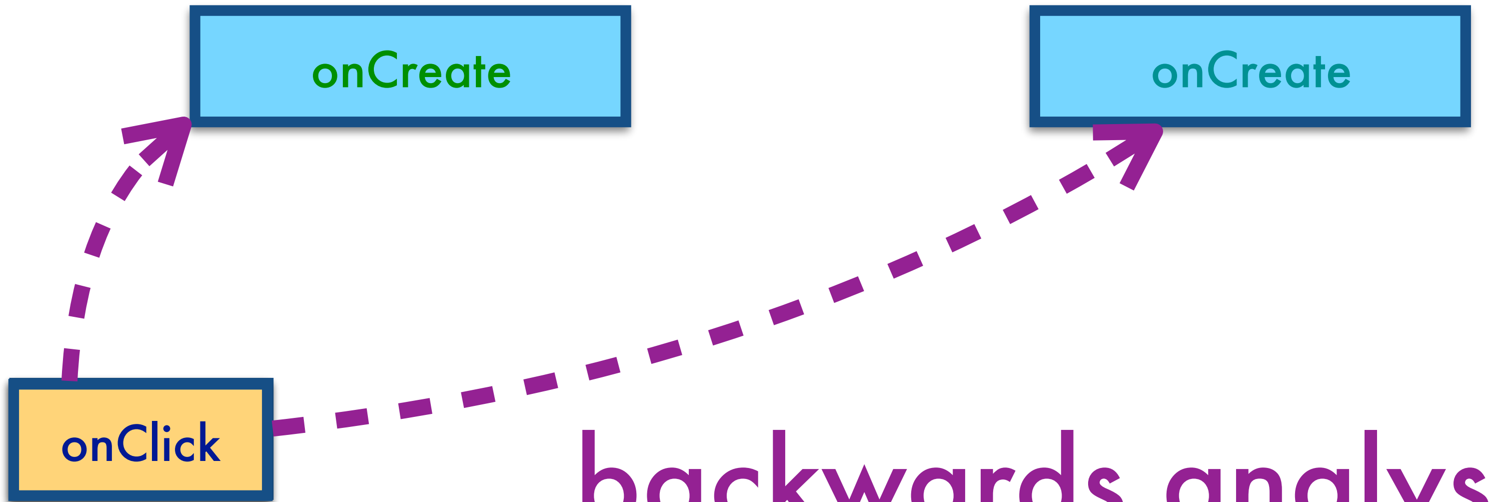
Idea: Jumping to relevant callbacks



Find data relevant callbacks

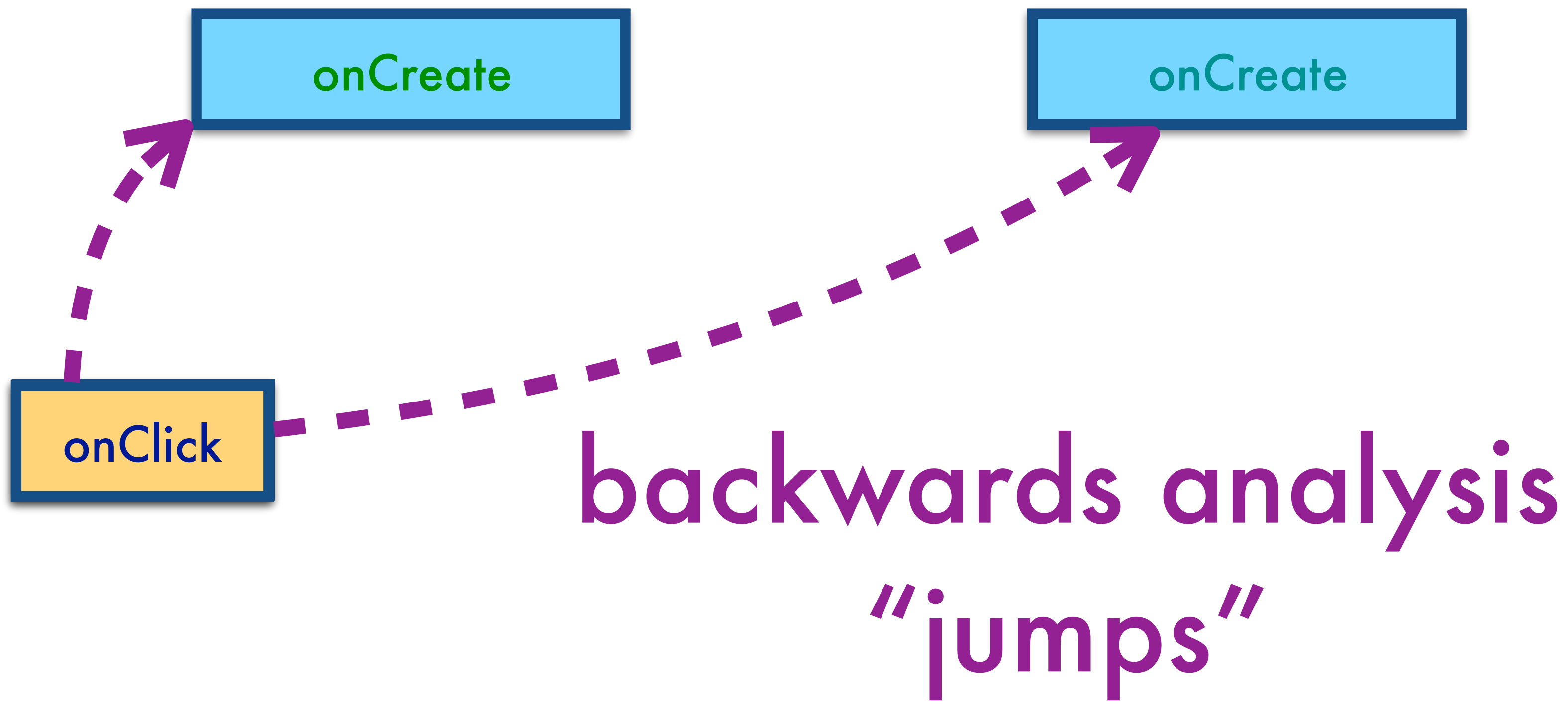
Filter using control-feasibility

Contributions



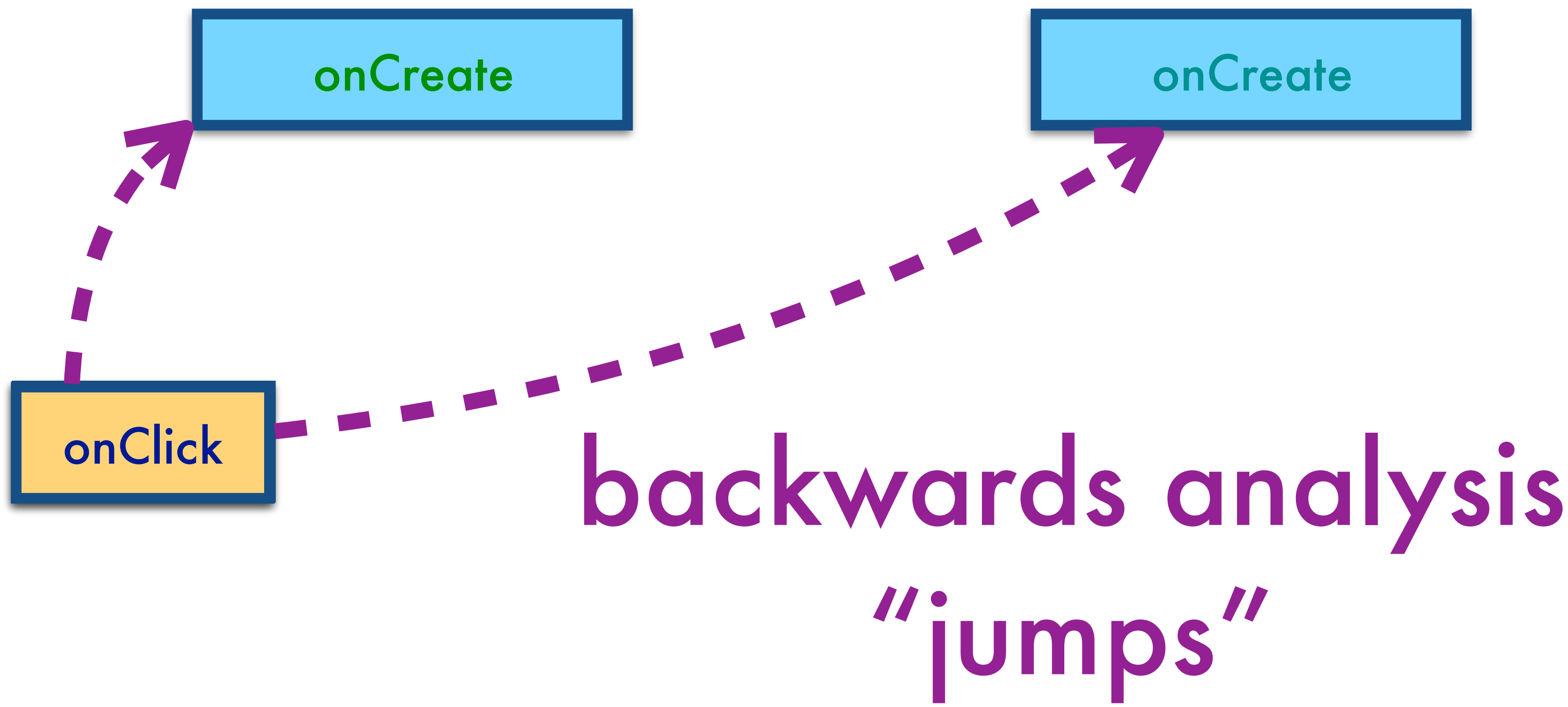
backwards analysis
"jumps"

Contributions



1 $\ell_1 \xrightarrow{[c]} \ell_2$ **Framework for jumping analyses**

Contributions



1 $\ell_1 \;\dashv\!\![c]\!\!\vdash\!\!\rightarrow\; \ell_2$ Framework for jumping analyses

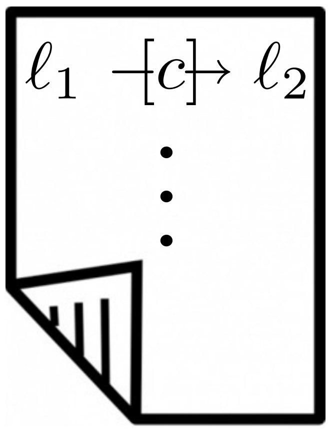
2  Applied to Android events

A program model for a jumping analysis

1 $\ell_1 \;\text{-}\!\!\left[c\right]\!\!\rightarrow \ell_2$

A program model for a jumping analysis

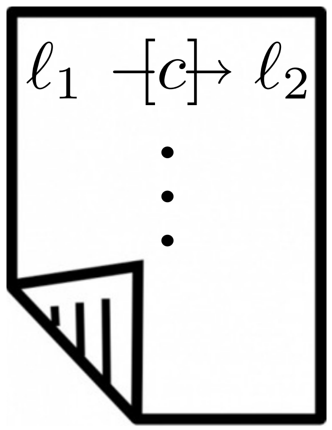
1 $\ell_1 \ \text{-}[c]\!\!\rightarrow\ \ell_2$



Program

A program model for a jumping analysis

1 $\ell_1 \;\text{-}\!\![c]\!\!\rightarrow\; \ell_2$

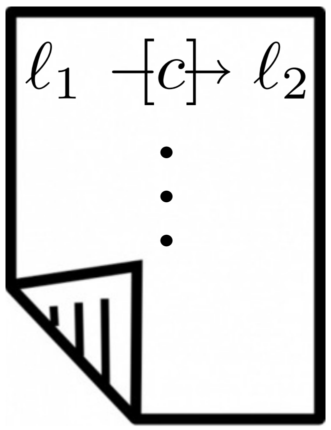


Program

Unstructured control-flow: atomic commands connected by pre/post labels

A program model for a jumping analysis

1 $\ell_1 \;\text{-}\![c]\!\!\rightarrow\; \ell_2$



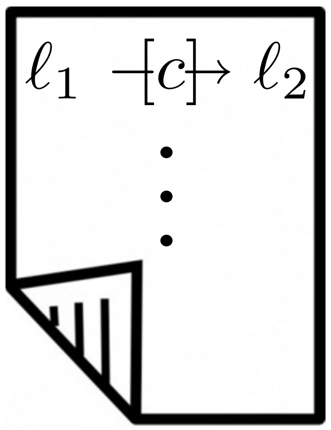
Program

Unstructured control-flow: atomic commands connected by pre/post labels

Represent conditionals with `assume`, loops with `assume` and a back edge.

A program model for a jumping analysis

1 $\ell_1 \mathrel{-\!\![c]\!\!\to} \ell_2$



Program

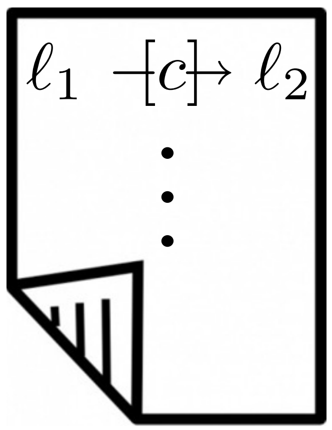
Unstructured control-flow: atomic commands connected by pre/post labels

Represent conditionals with `assume`, loops with `assume` and a back edge.

Analysis parameters

A program model for a jumping analysis

1 $\ell_1 \;{-}[c]{\rightarrow}\; \ell_2$



Program

Unstructured control-flow: atomic commands connected by pre/post labels

Represent conditionals with `assume`, loops with `assume` and a back edge.

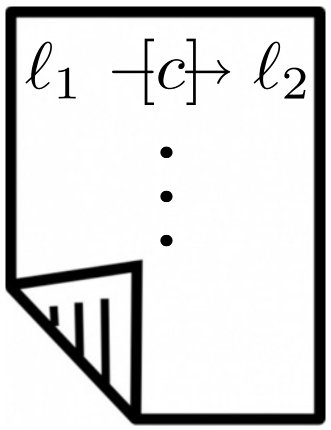
Analysis parameters

$$\{Q'\}\ c\ \{Q\}$$

Backward transfer functions

A program model for a jumping analysis

1 $\ell_1 \mathrel{-\!\![c]\!\!\rightarrow} \ell_2$



Program

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Represent conditionals with `assume`, loops with `assume` and a back edge.

Analysis parameters

$$\{Q'\}\ c\ \{Q\}$$

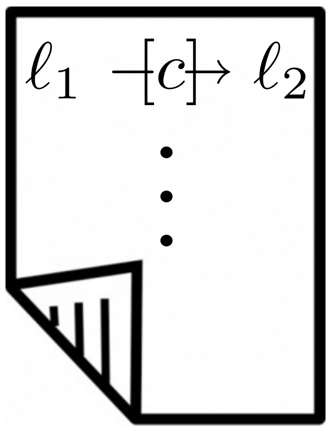
Backward transfer functions

$$\ell_{\mathrm{cur}}$$

Current location

A program model for a jumping analysis

$\ell_1 \;{-}\!\![c]\!\!\rightarrow\; \ell_2$



Program

Unstructured control-flow: atomic commands connected by pre/post labels

Represent conditionals with `assume`, loops with `assume` and a back edge.

Analysis parameters

$$\{Q'\}\; c\; \{Q\}$$

Backward transfer functions

$$\ell_{\mathrm{cur}}$$

Current location

$$Q_{\mathrm{cur}}$$

Current query

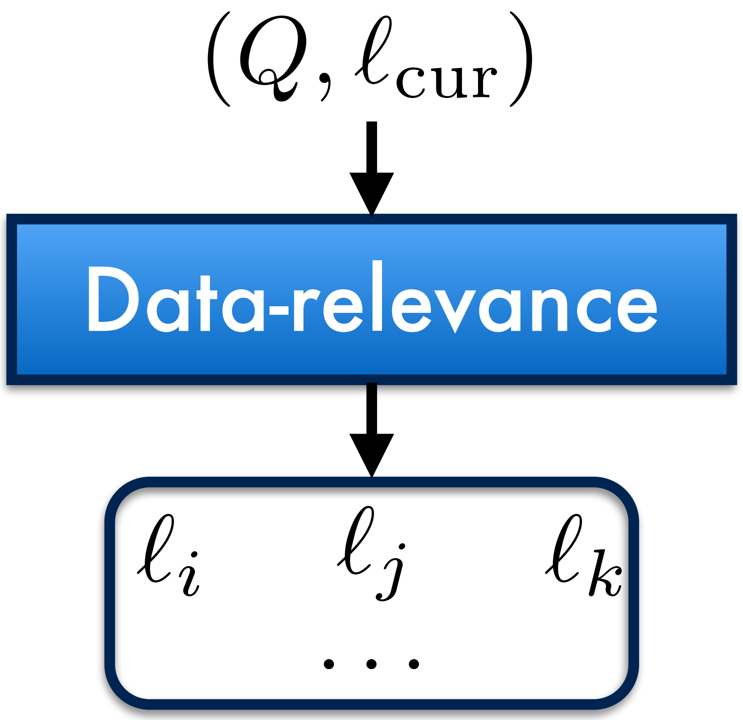
Data-relevance identifies writes

1 $\ell_1 \xrightarrow{[c]} \ell_2$

(Q, ℓ_{cur})

Data-relevance identifies writes

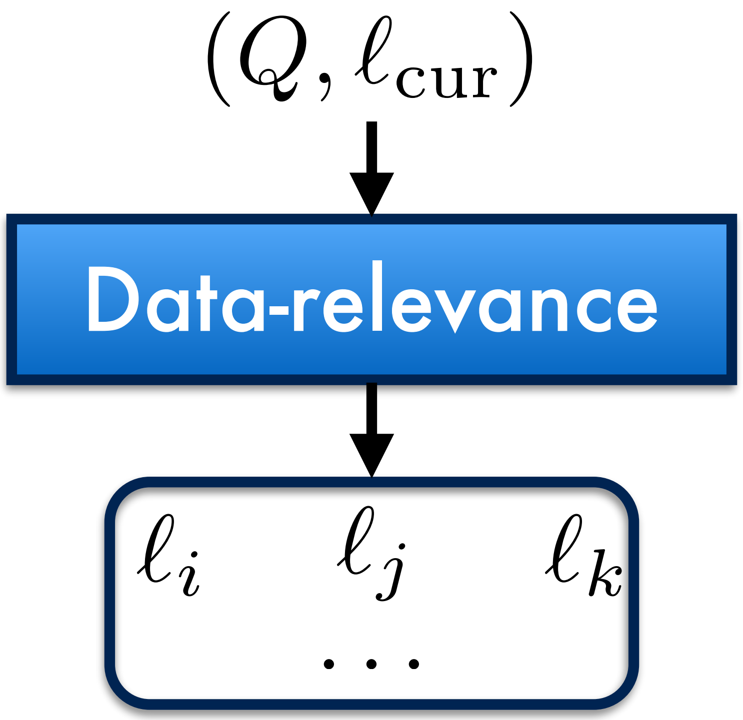
1 $\ell_1 \;-\!\![c]\!\!\rightarrow\; \ell_2$



Identify locations that can write to the query Q.

Data-relevance identifies writes

1 $\ell_1 \; \text{-}[c]\!\rightarrow \; \ell_2$



Identify locations that can write to the query Q.

Computed using pre-pass points-to analysis, types, field-based, ...

Data-relevance identifies writes

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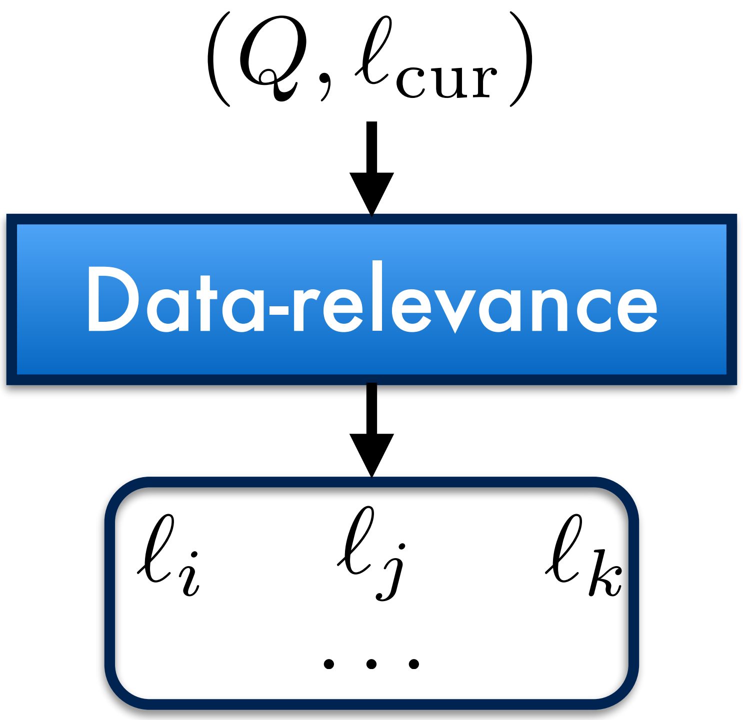


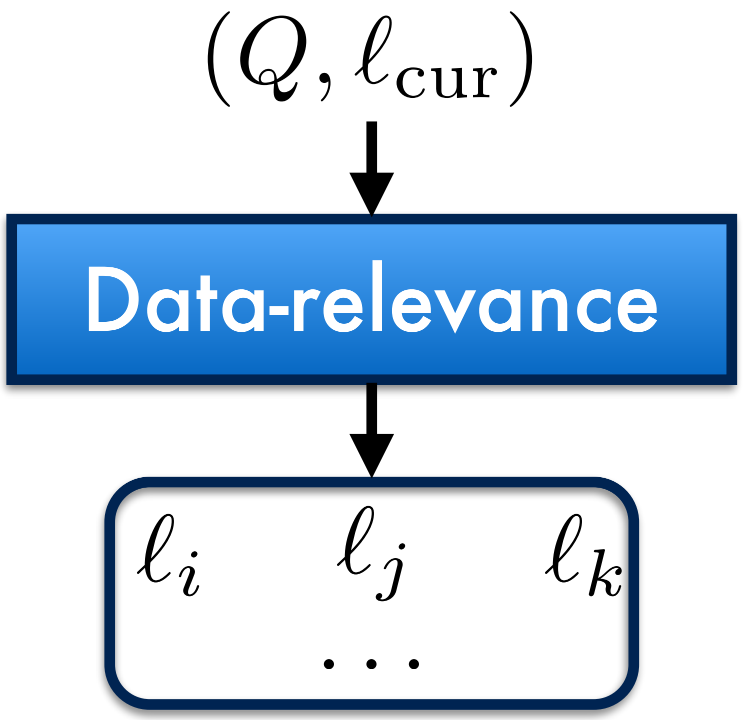
Identify locations that can write to the query Q.

Computed using pre-pass points-to analysis, types, field-based, …

Classic idea: Following data dependencies yields a sparse analysis (but, here, flow-insensitive)

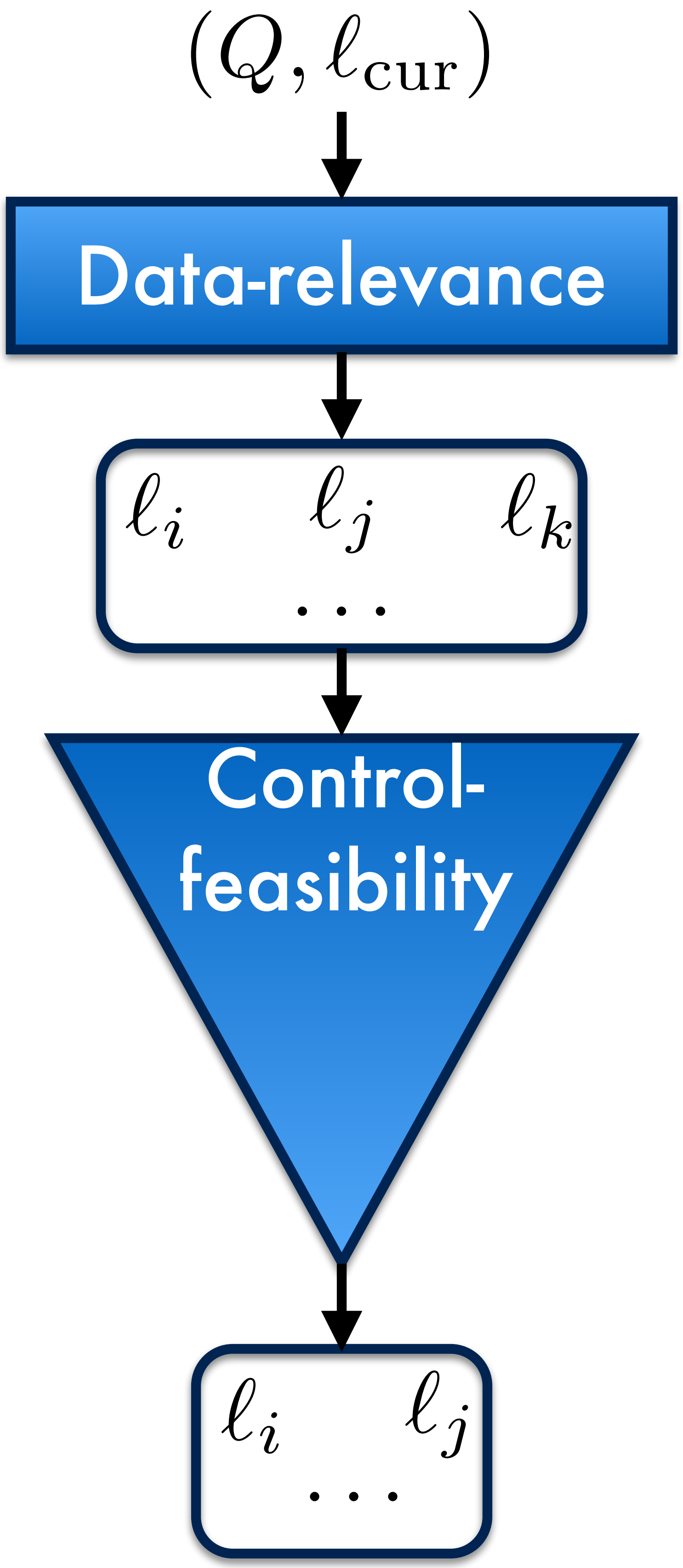
Control-feasibility **selectively** recovers flow-sensitivity

1 $\ell_1 \;\text{—}[c]\!\!\rightarrow\; \ell_2$



Control-feasibility selectively recovers flow-sensitivity

1 $\ell_1 \dashv\!\![c]\!\!\vdash\!\!\rightarrow \ell_2$



Control-feasibility selectively recovers flow-sensitivity

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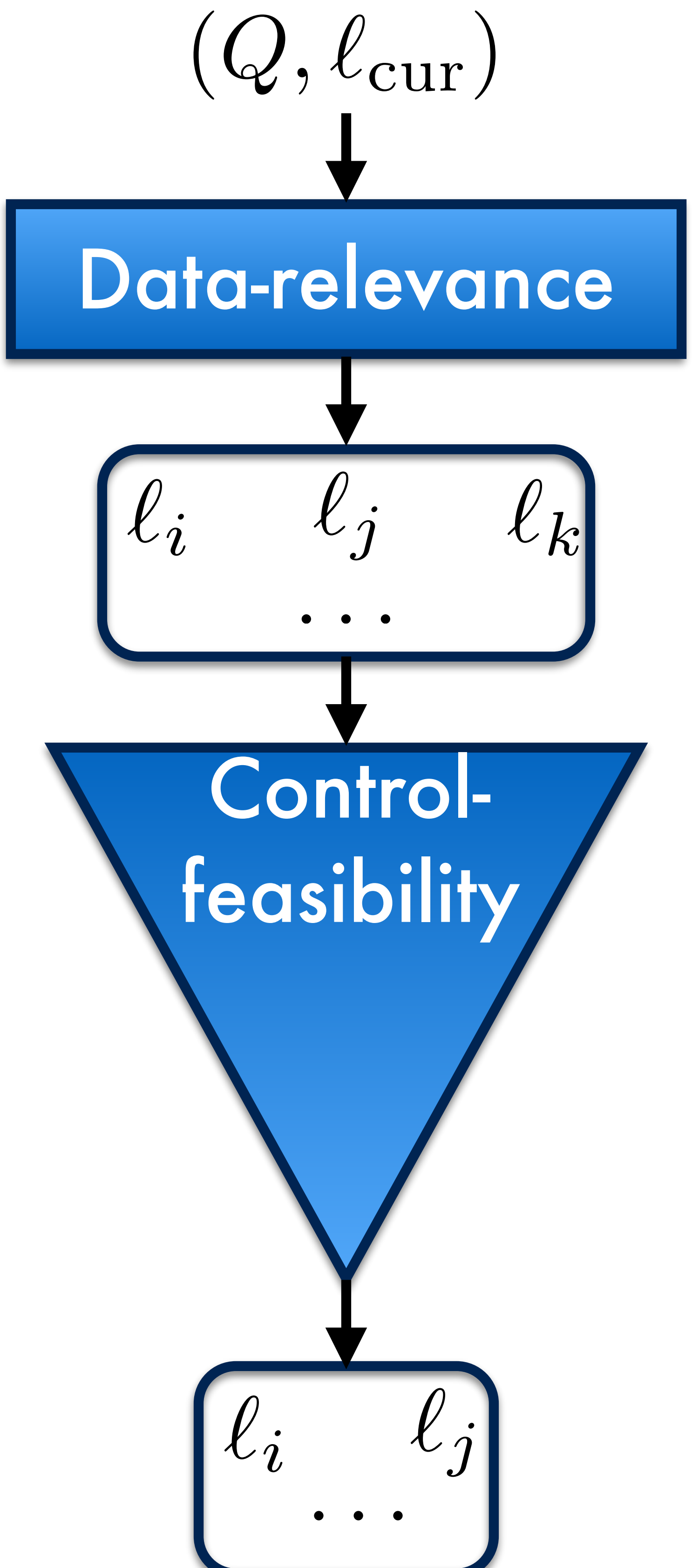
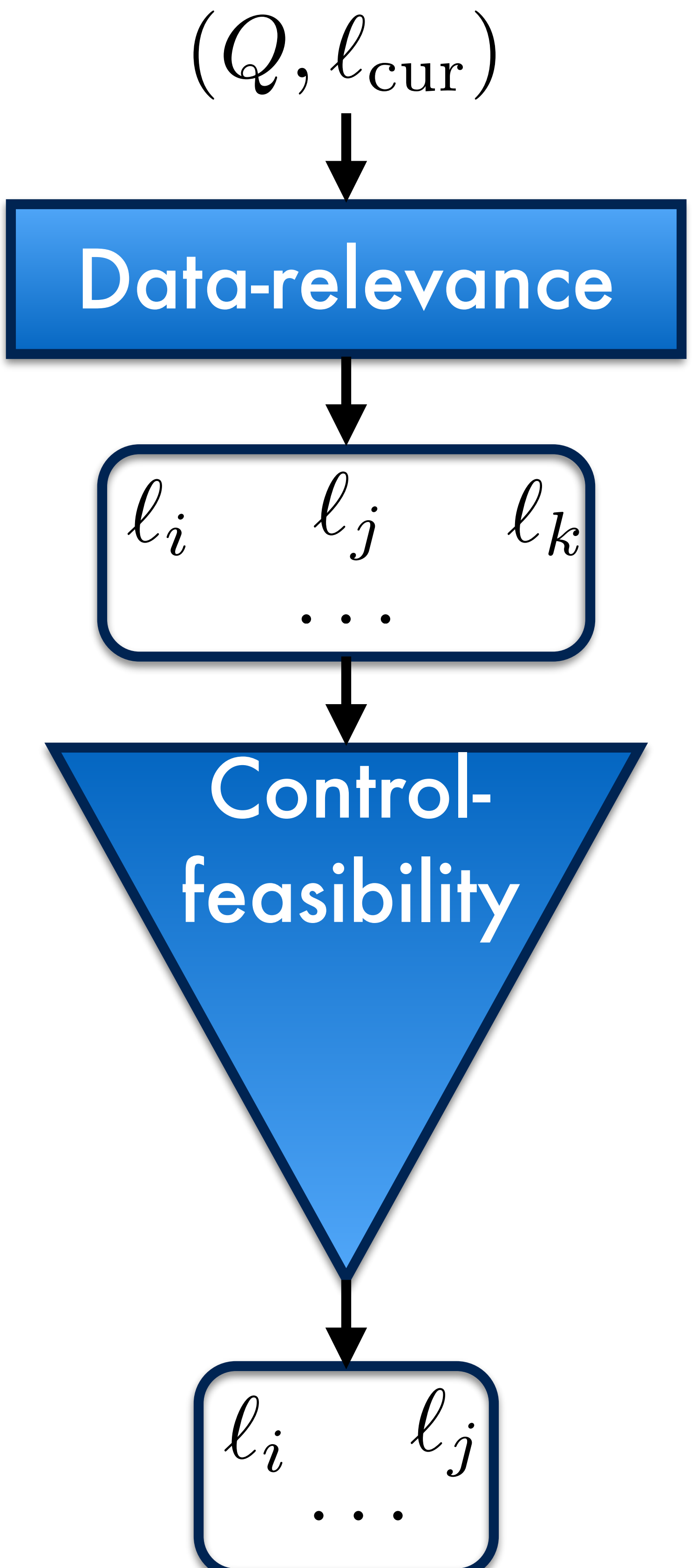


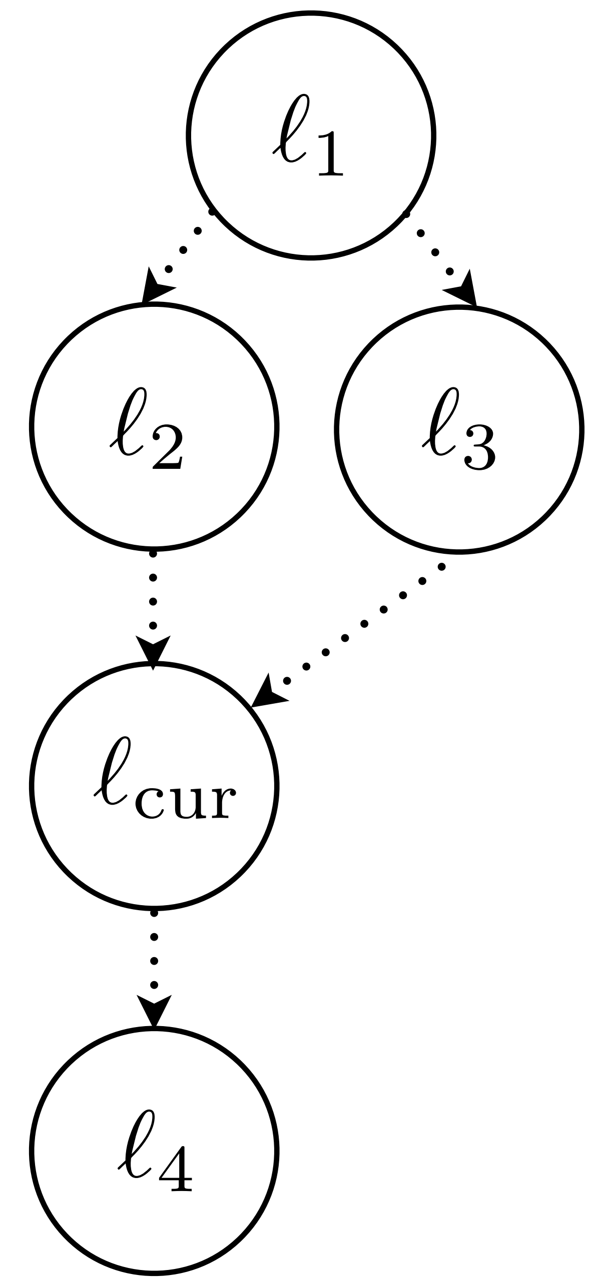
Filter the set of data-relevant locations using control flow and the current program point

Control-feasibility selectively recovers flow-sensitivity

1 $\ell_1 \xrightarrow{[c]} \ell_2$



Filter the set of data-relevant locations using control flow and the current program point



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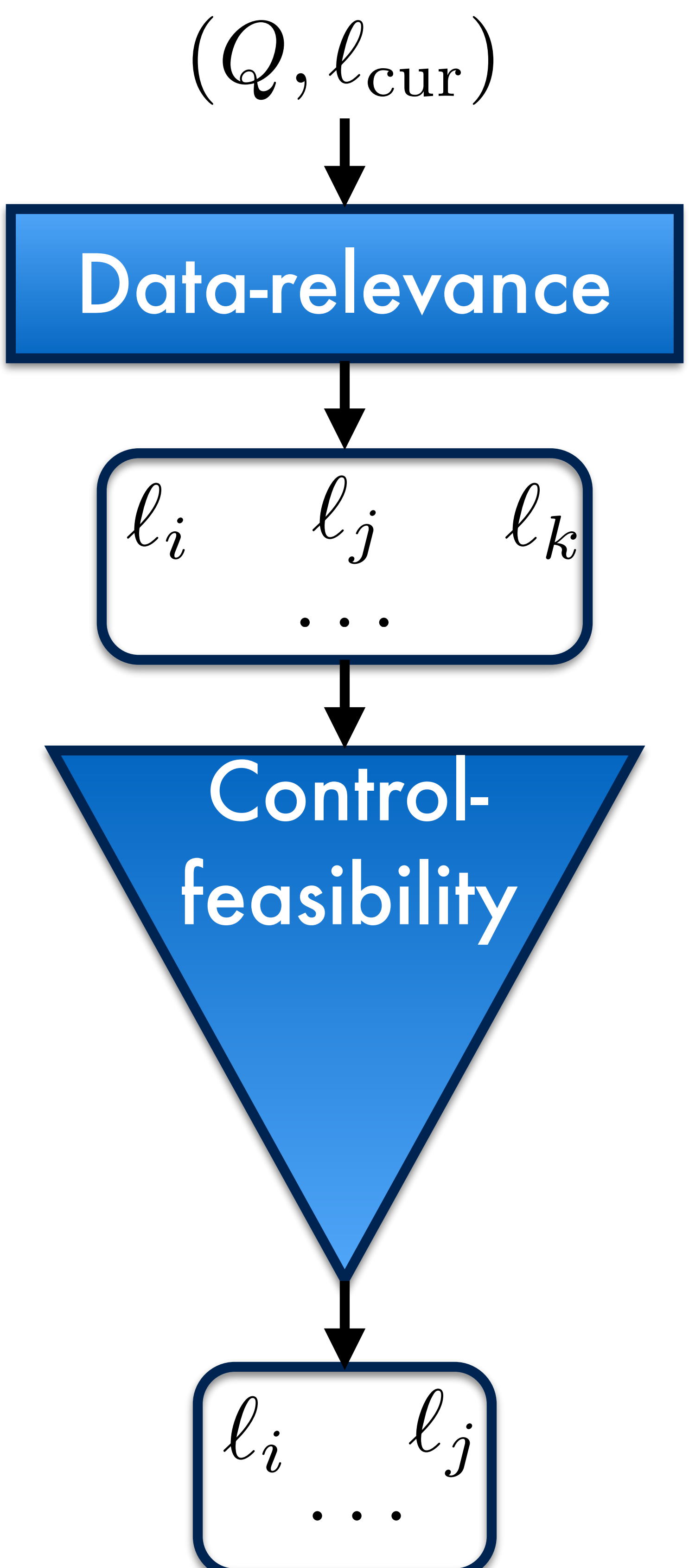
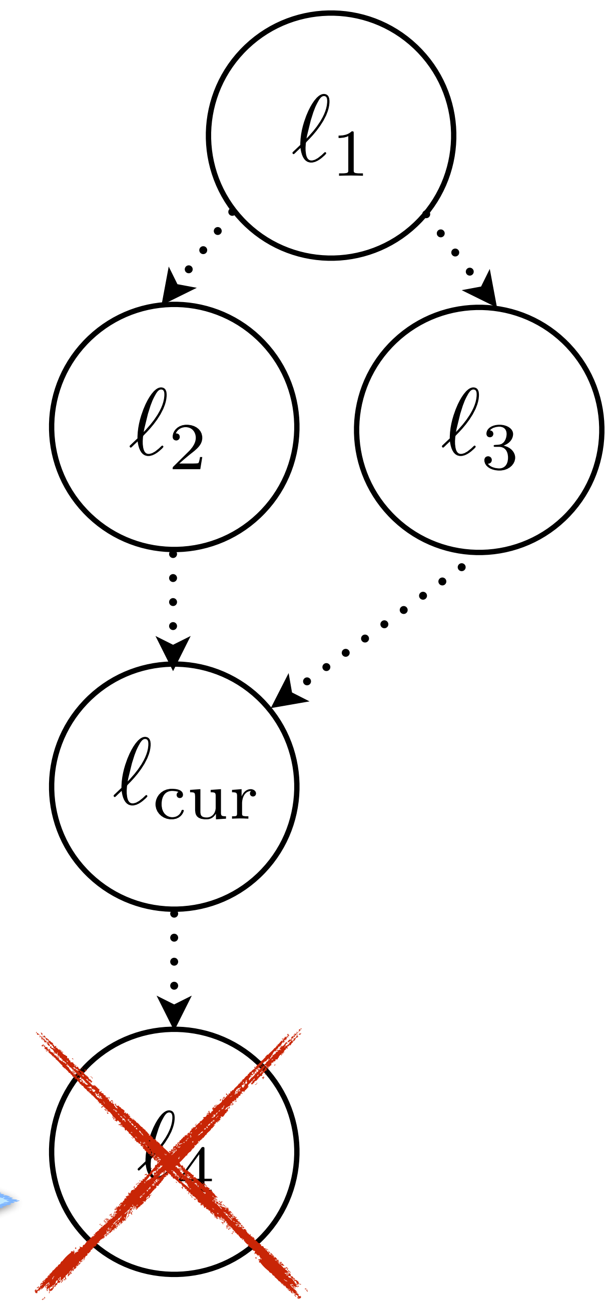


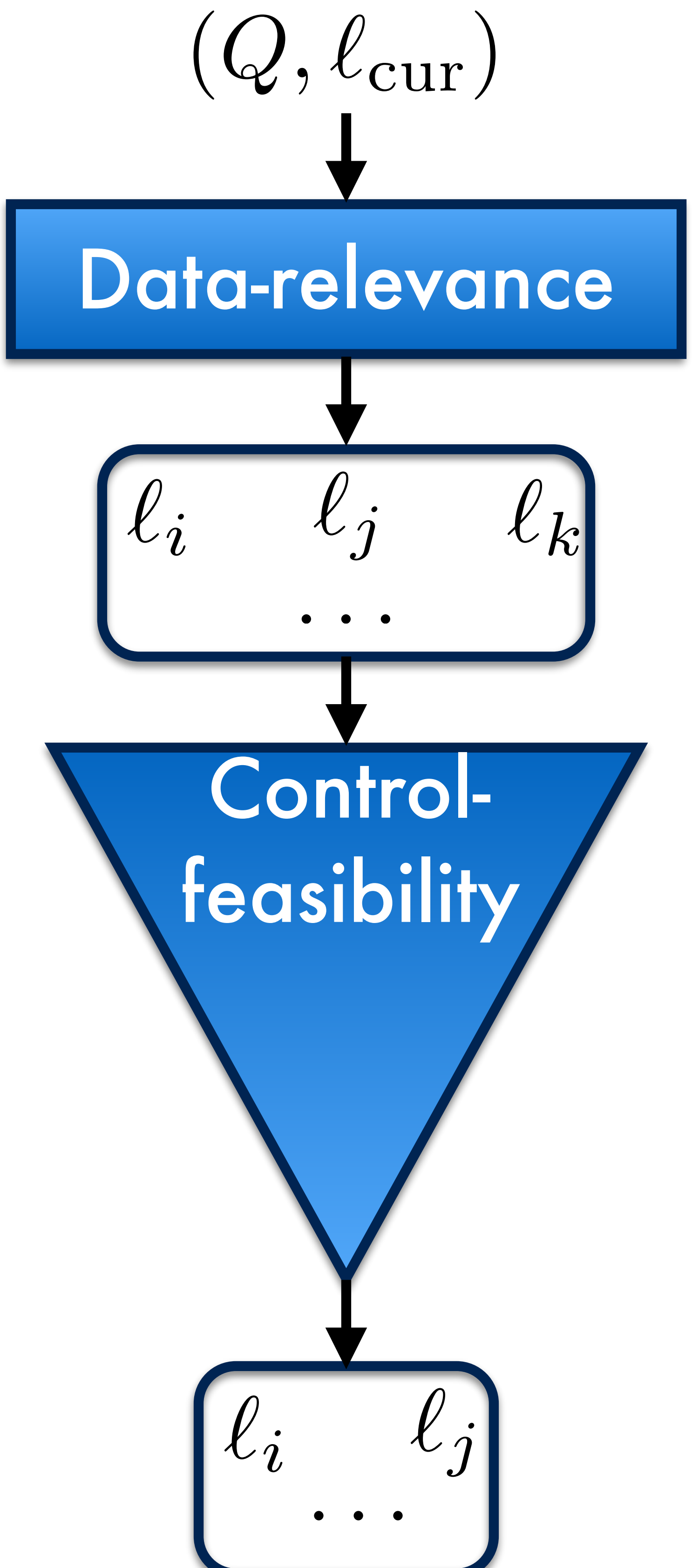
Filter the set of data-relevant locations using control flow and the current program point

Not backward-reachable from current location



Control-feasibility **selectively** recovers flow-sensitivity

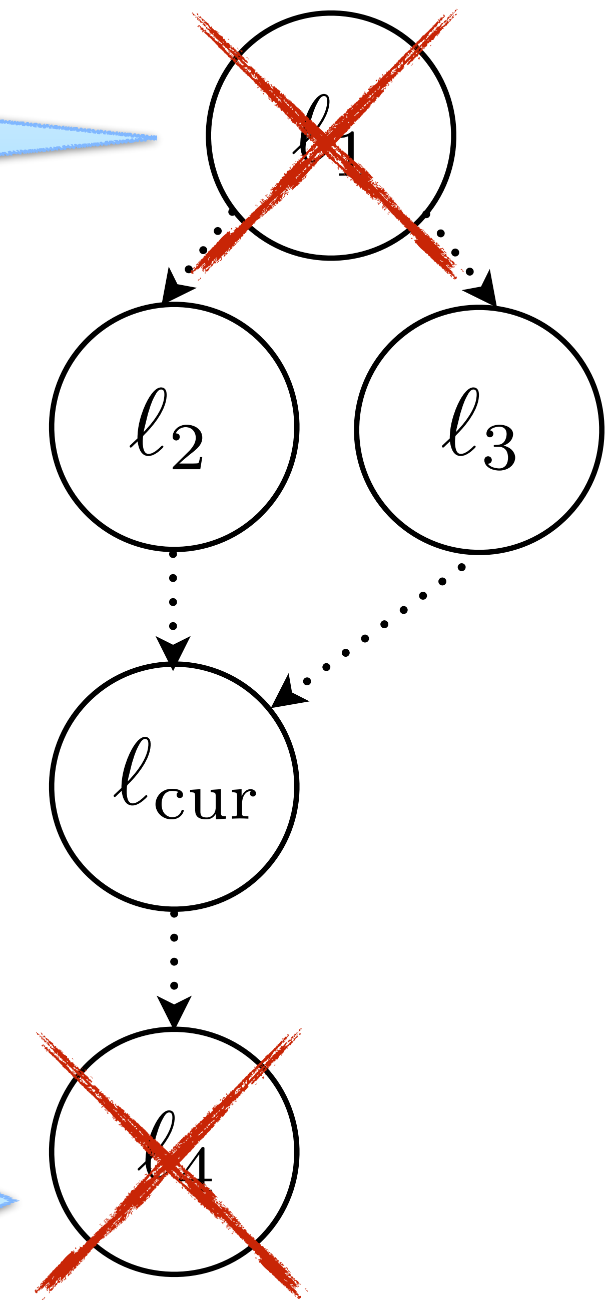
1 $\ell_1 \; \text{-}[c]\text{-}\!\!\rightarrow \; \ell_2$



Must visit another relevant location first.

Filter the set of data-relevant locations using control flow and the current program point

Not backward-reachable from current location



Jumping enables sparse, selective, on-the-fly control-flow abstraction

1

$$\ell_1 \xrightarrow{[c]} \ell_2$$

Jumping enables sparse, selective, on-the-fly control-flow abstraction

1

$$\ell_1 \xrightarrow{[c]} \ell_2$$

ℓ_{cur}

Current location

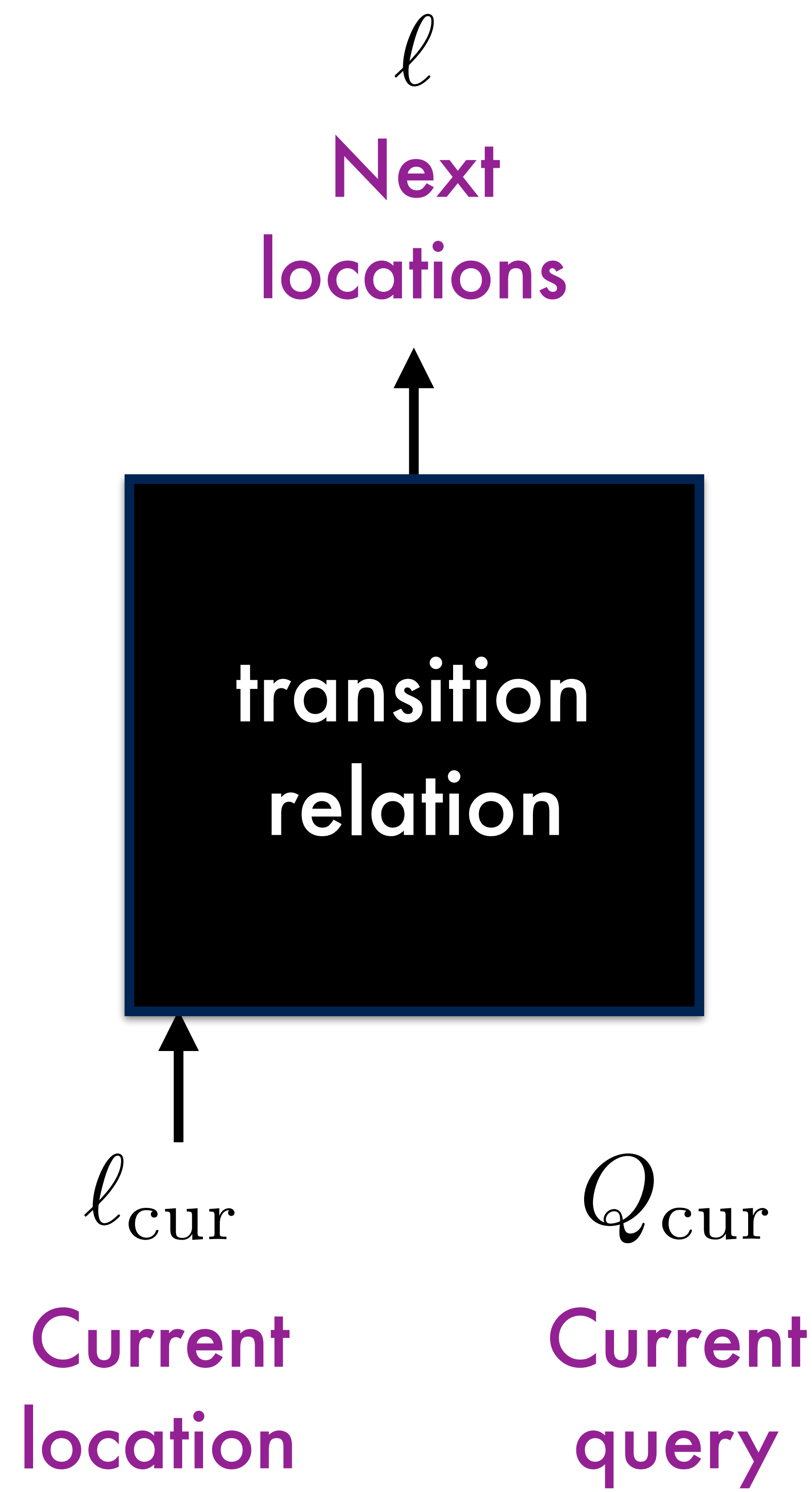
Q_{cur}

Current query

Jumping enables sparse, selective, on-the-fly control-flow abstraction

1

$\ell_1 \xrightarrow{[c]} \ell_2$



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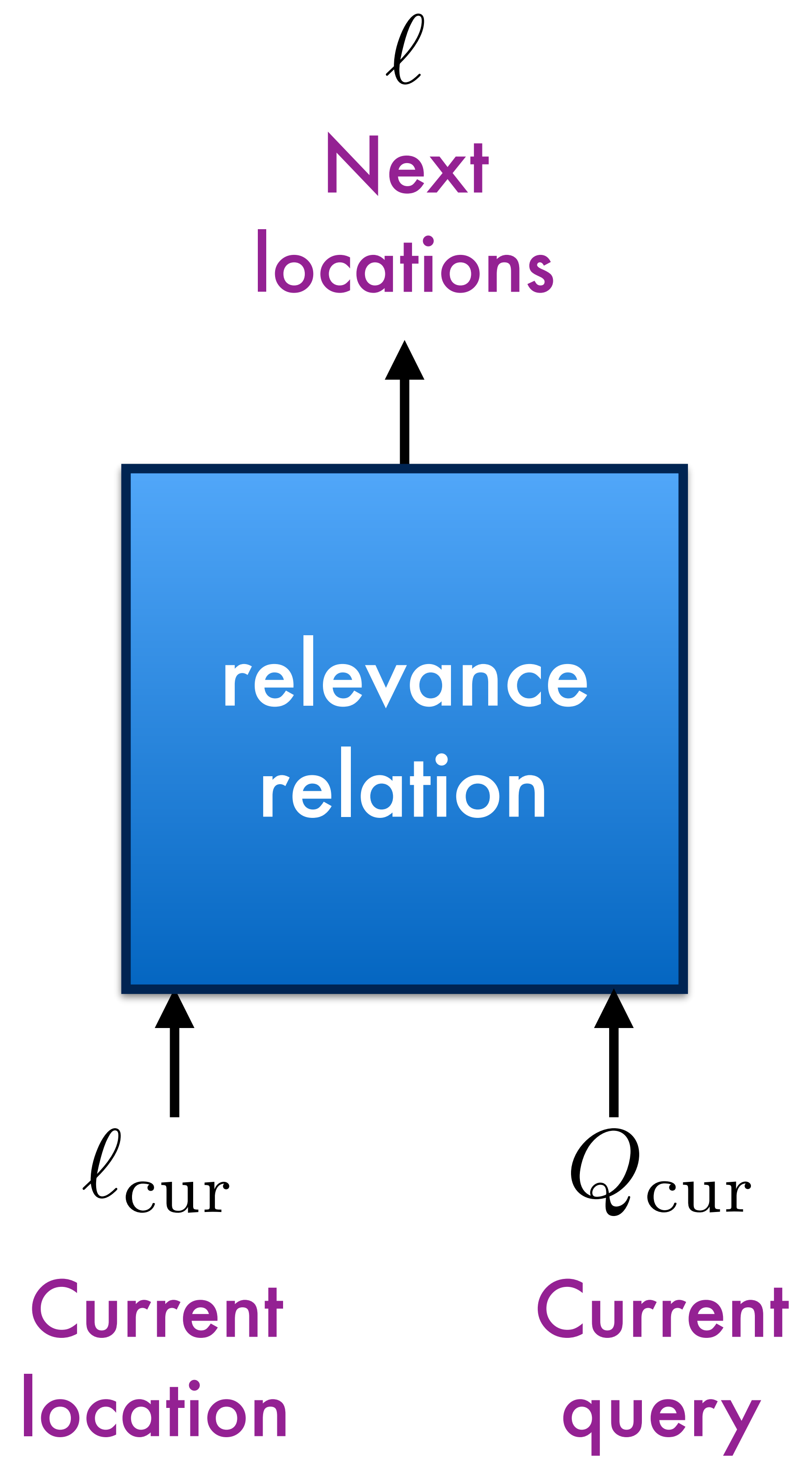
$\ell_1 \;\text{-}[c]\!\!\to \ell_2$



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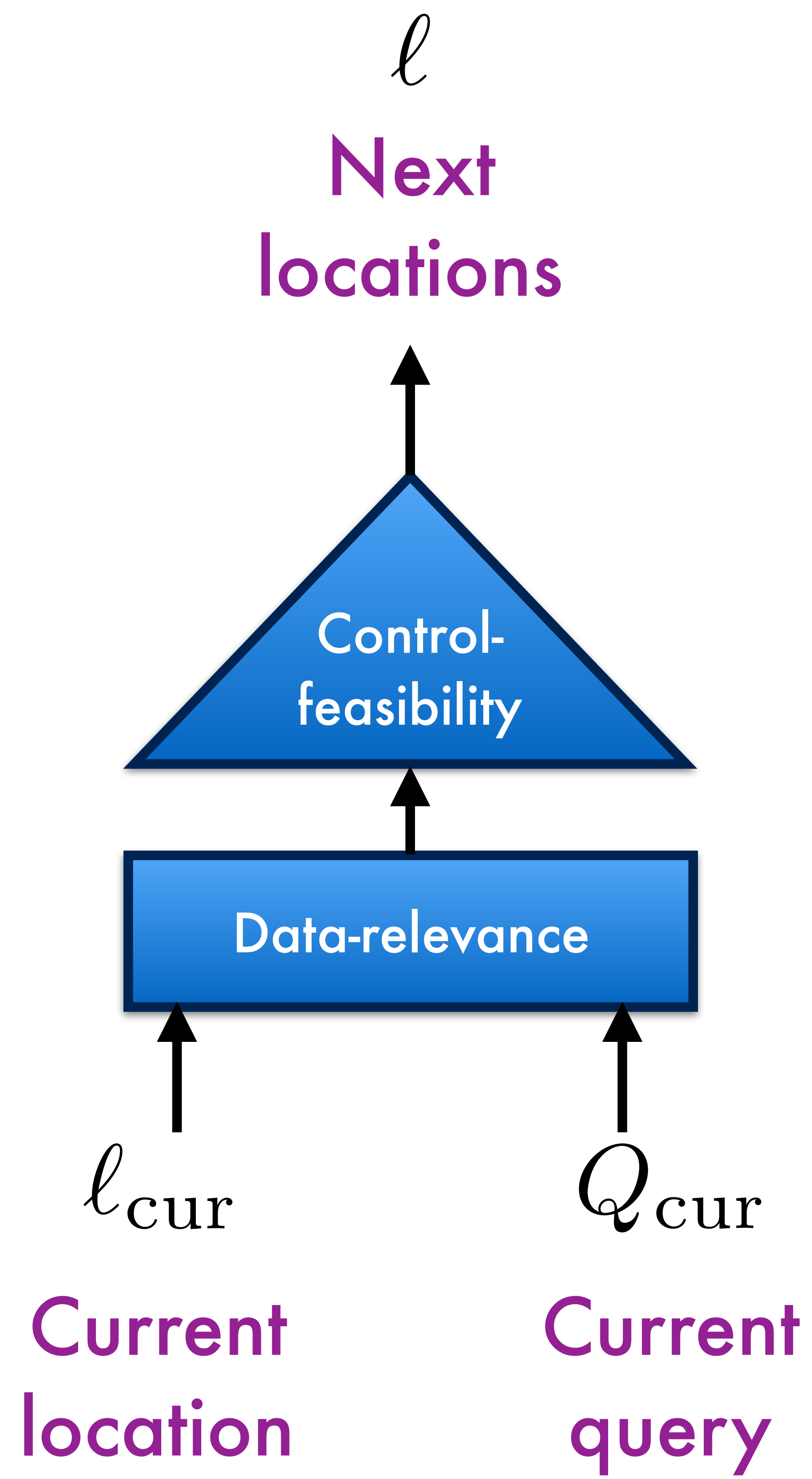
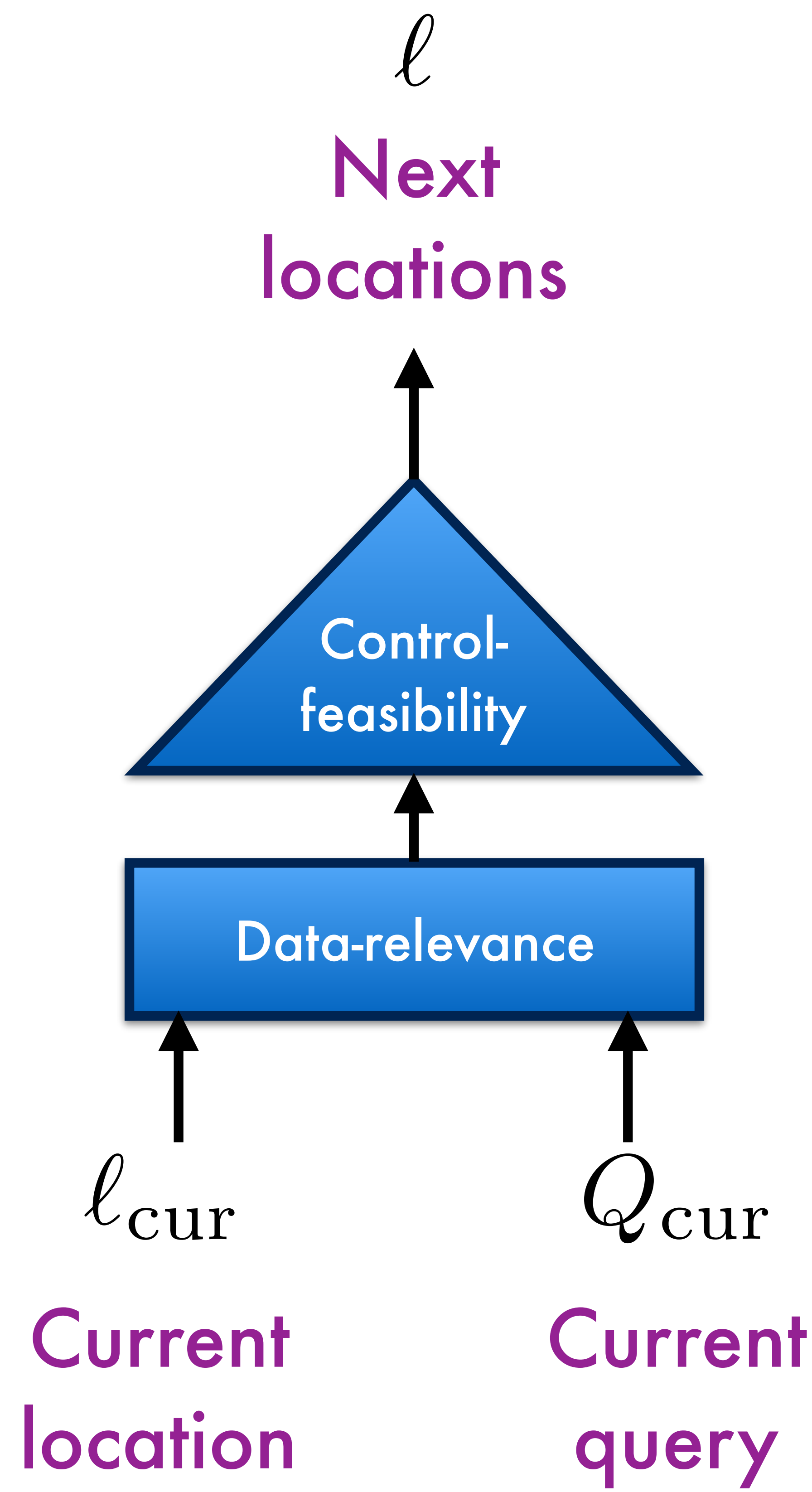
$\ell_1 \xrightarrow{[c]} \ell_2$



Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \;\text{-}[c]\!\!\rightarrow\; \ell_2$

Precision	-insensitive	-sensitive
flow		
path		
context		

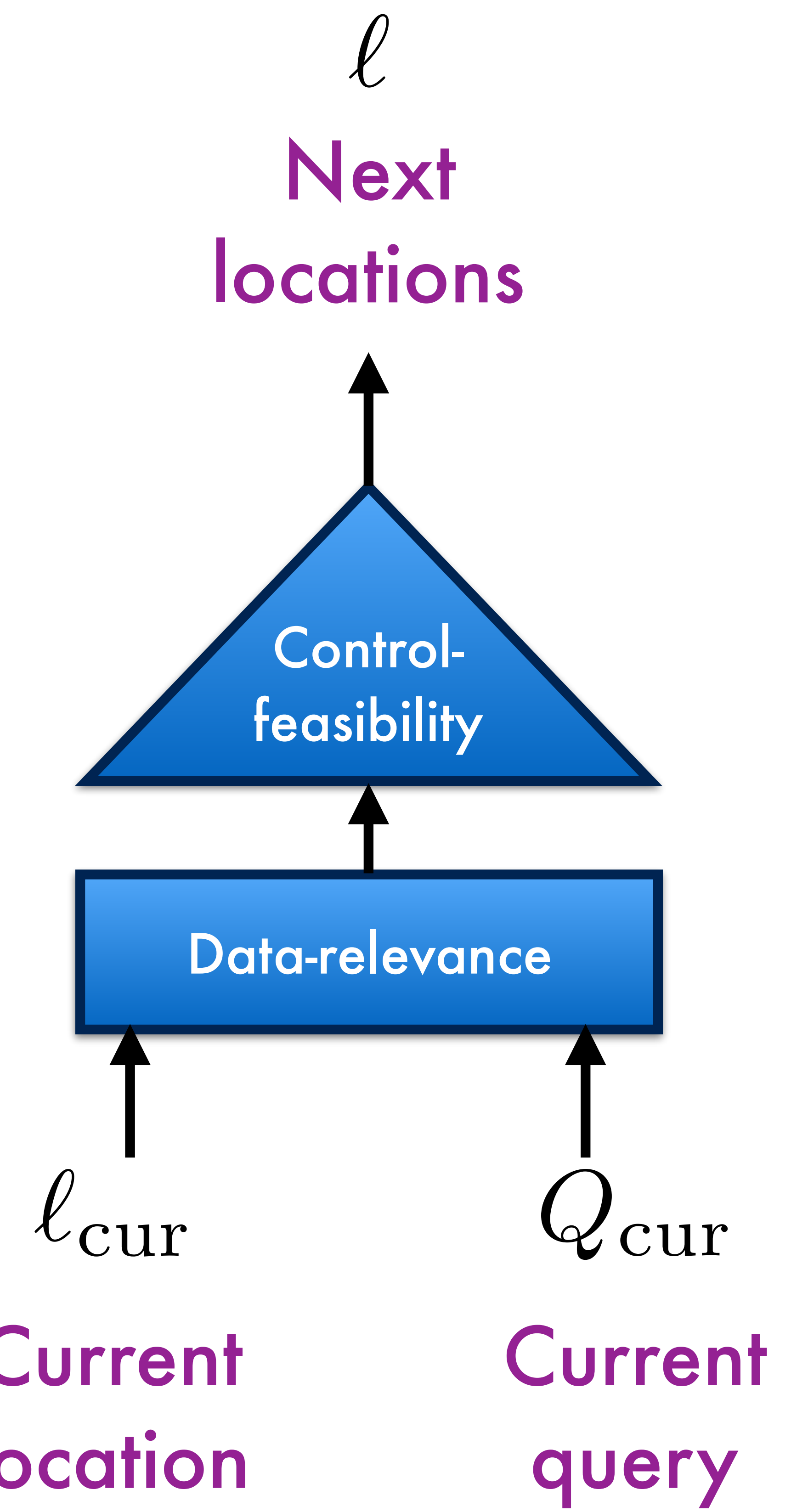


Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \;\dashv\![c]\!\vdash\!\rightarrow\; \ell_2$

Precision	-insensitive	-sensitive
flow		
path		
context		

no filter



Jumping enables sparse, selective, on-the-fly control-flow abstraction

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$\ell_1 \;\text{-}[c]\!\!\rightarrow \ell_2$

Precision	-insensitive	-sensitive
flow		
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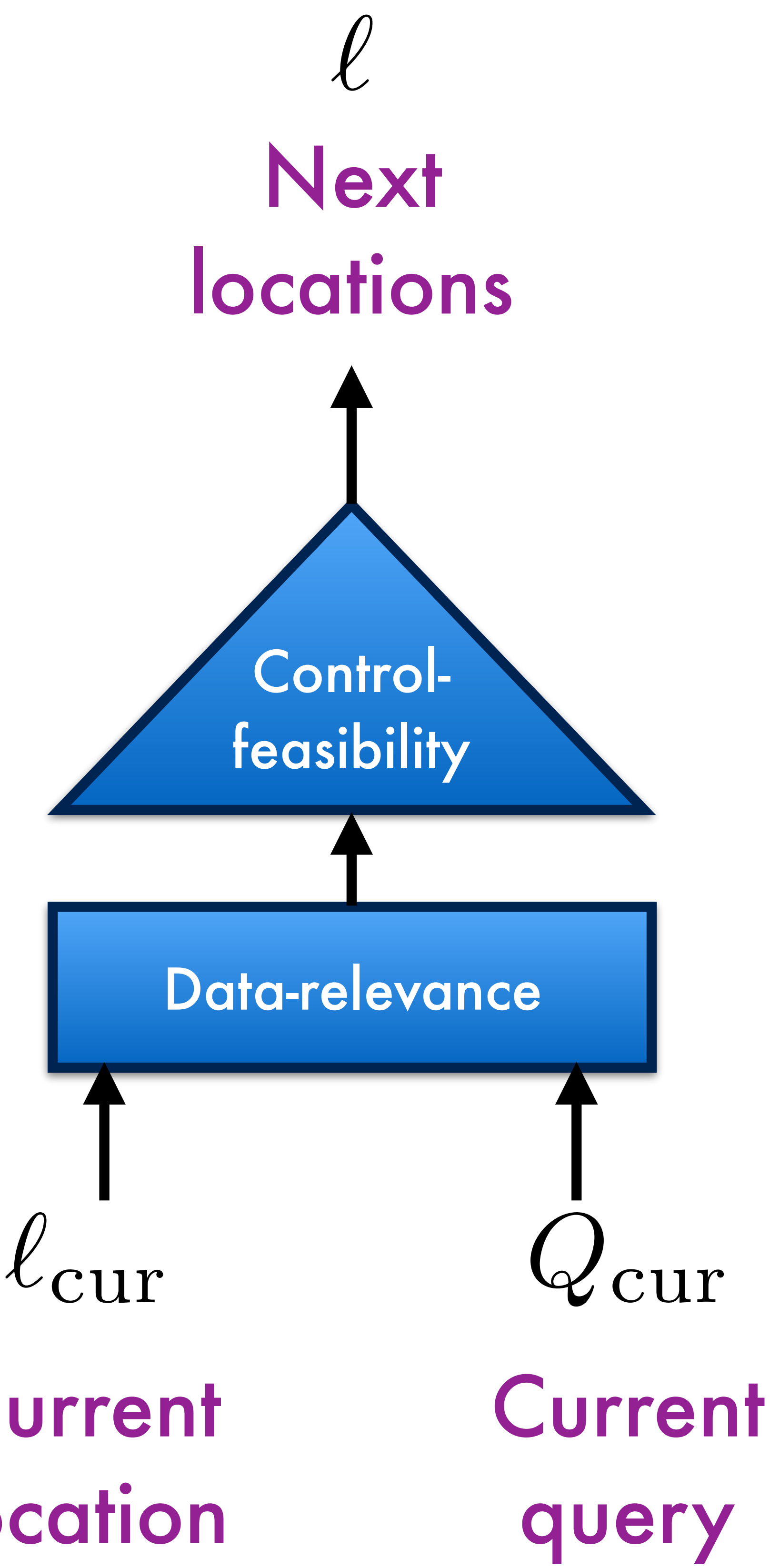
context		

no filter

all locations



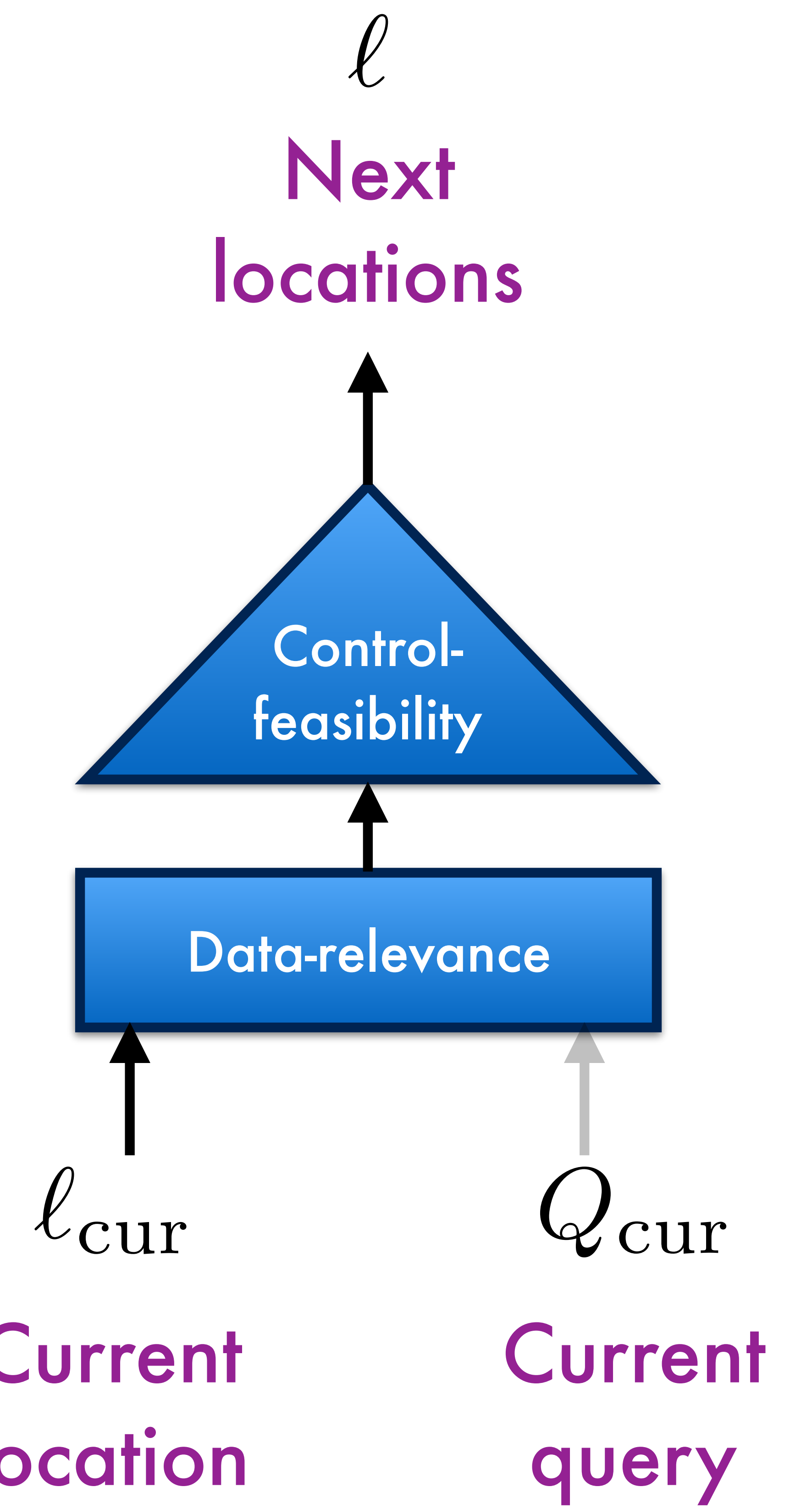
Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \dashrightarrow[c] \ell_2$

Precision	-insensitive	-sensitive
flow		
path		
context		

no filter

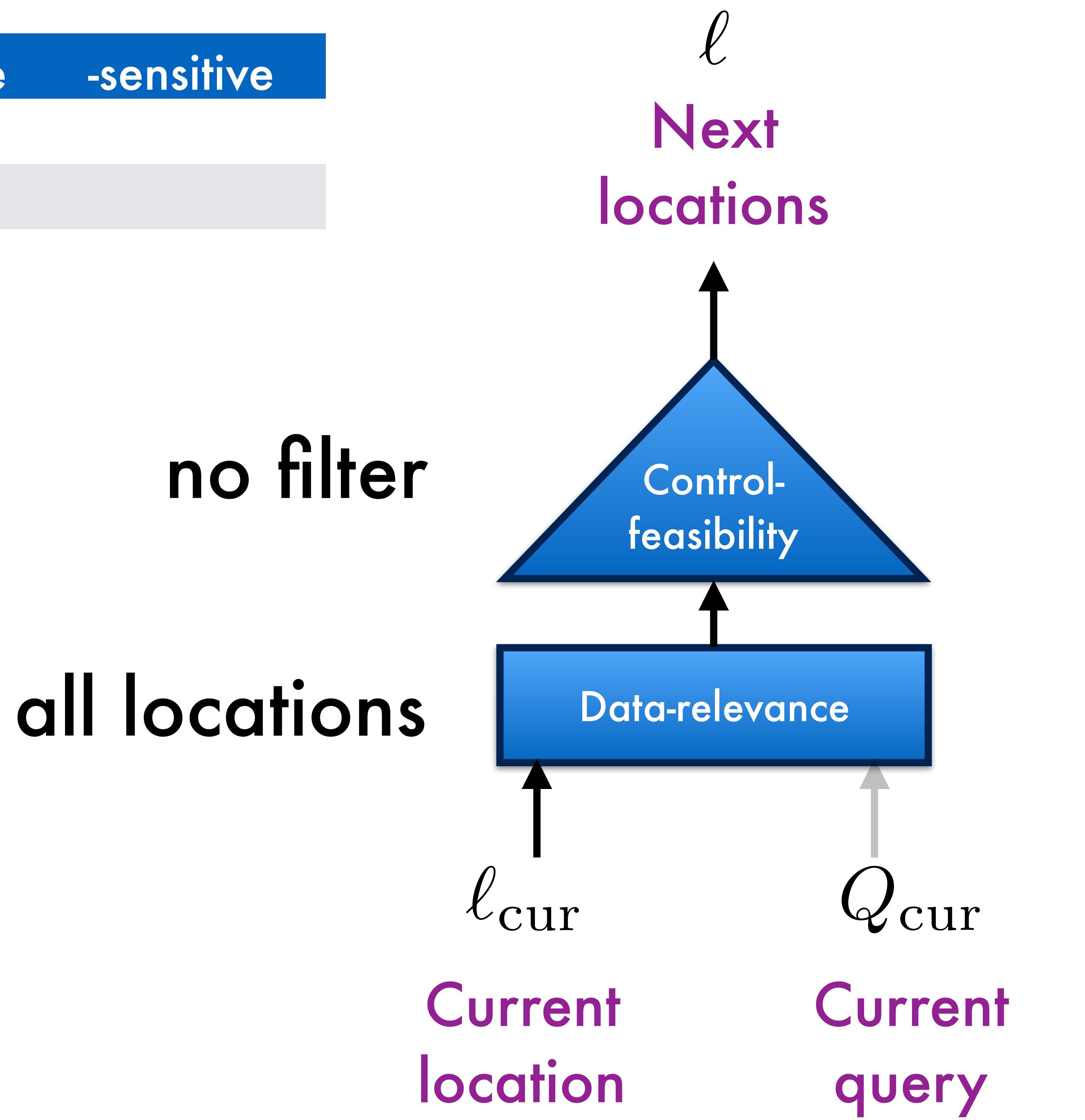
all locations



Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \;\text{-}\![c]\!\!\rightarrow \ell_2$

Precision	-insensitive	-sensitive
flow	✔	
path		
context		



Jumping enables sparse, selective, on-the-fly control-flow abstraction

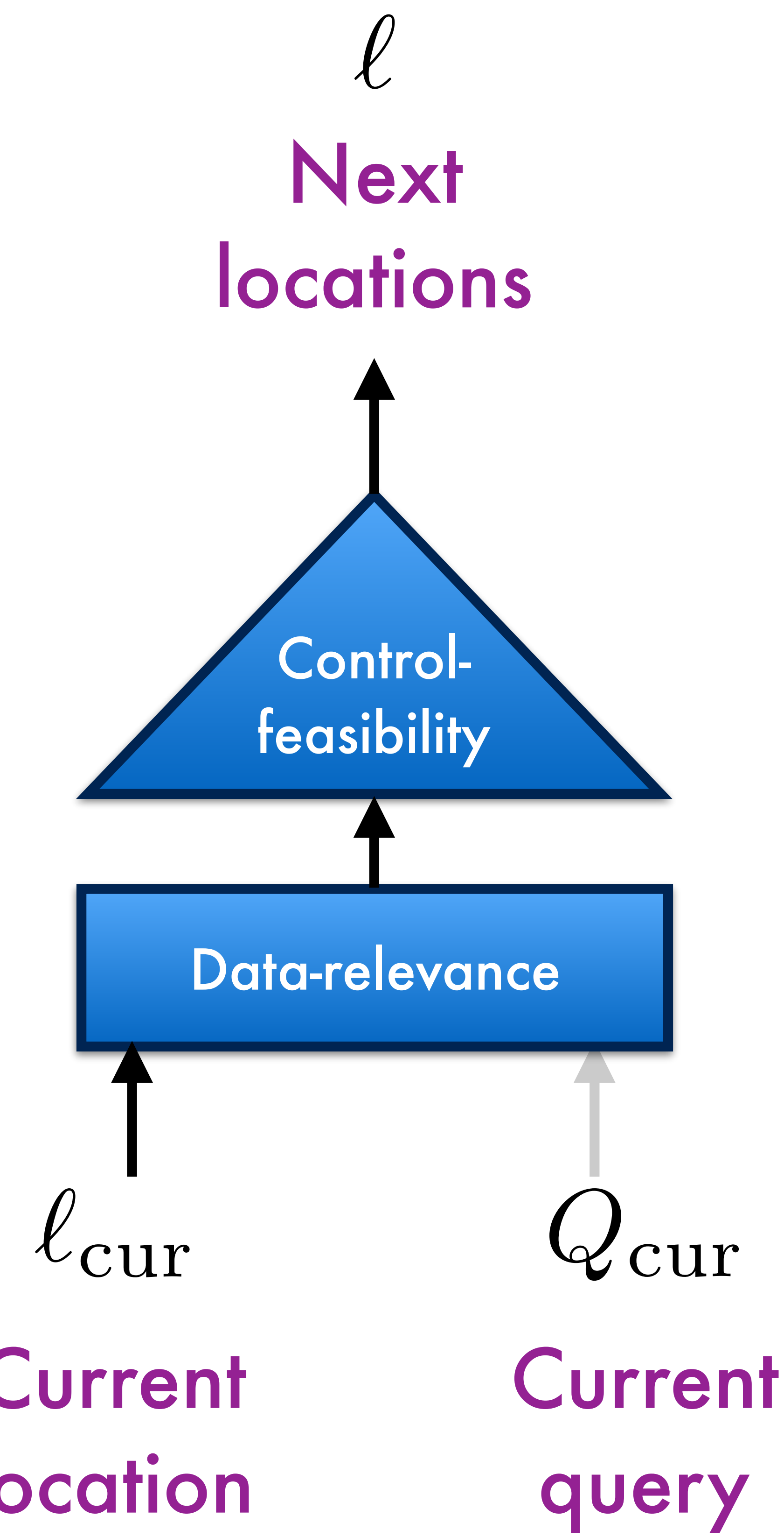
1

$\ell_1 \; \text{-}[c]\!\!\rightarrow \; \ell_2$

Precision	-insensitive	-sensitive
flow	✔	
path		
context		

only preds(ℓ_{cur})

all locations



Jumping enables sparse, selective, on-the-fly control-flow abstraction

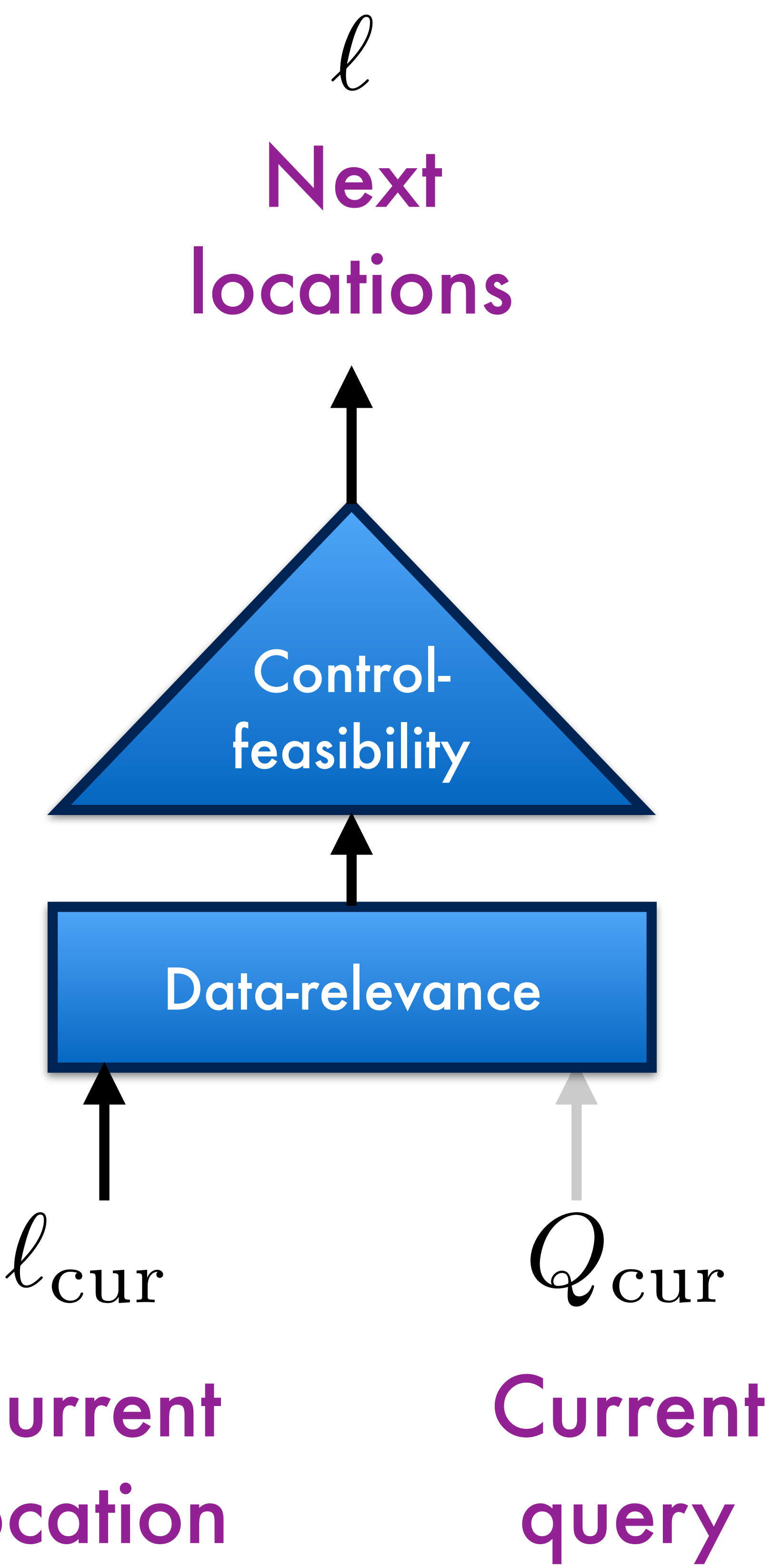
1

$$\ell_1 \xrightarrow{[c]} \ell_2$$

Precision	-insensitive	-sensitive
flow	✔	
path		
context		

only preds(ℓ_{cur})

all locations



Jumping enables sparse, selective, on-the-fly control-flow abstraction

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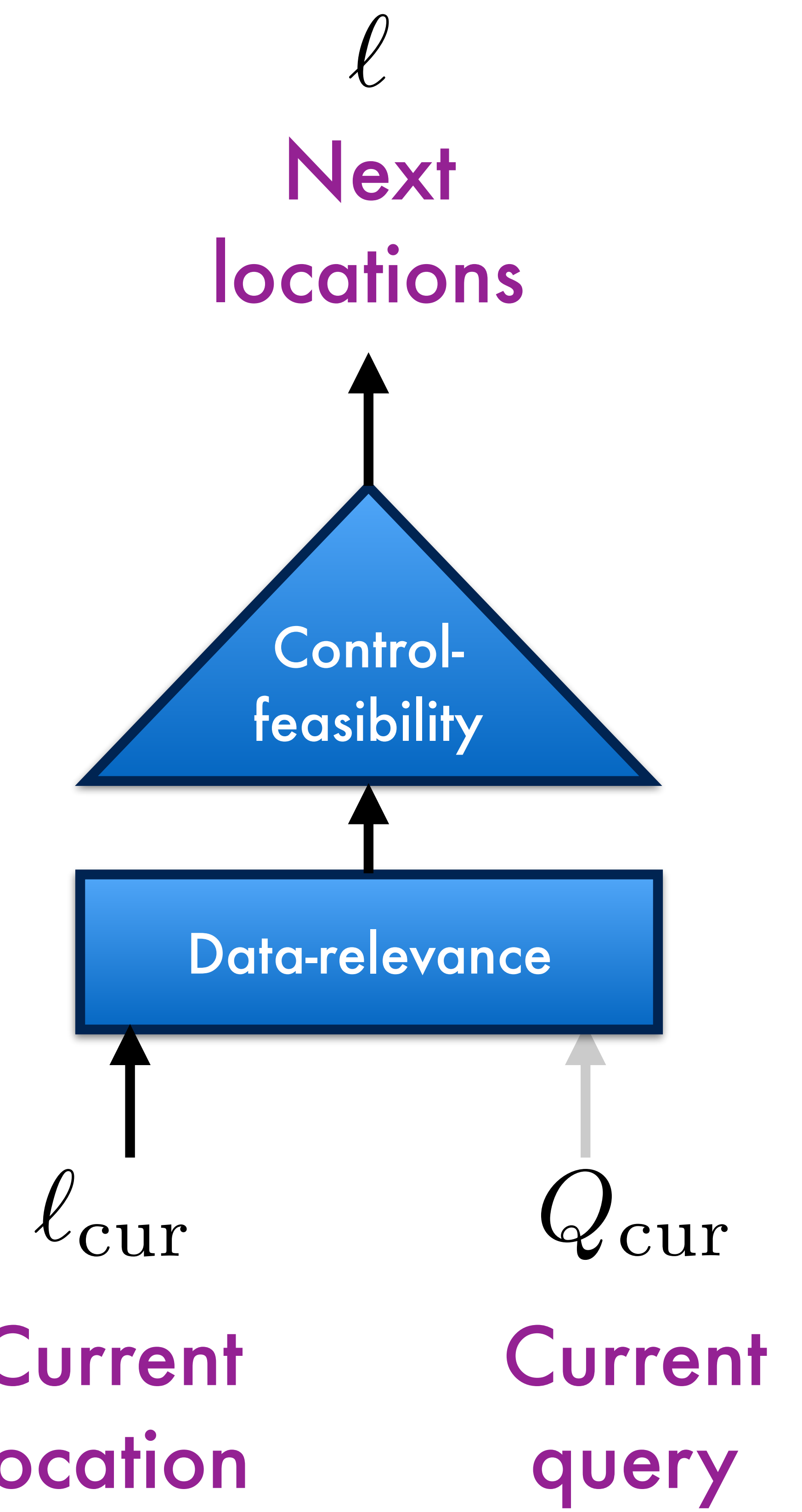
Precision	-insensitive	-sensitive
flow	✔	✔
path		✔
context	✔	

only preds(ℓ_{cur})

all locations



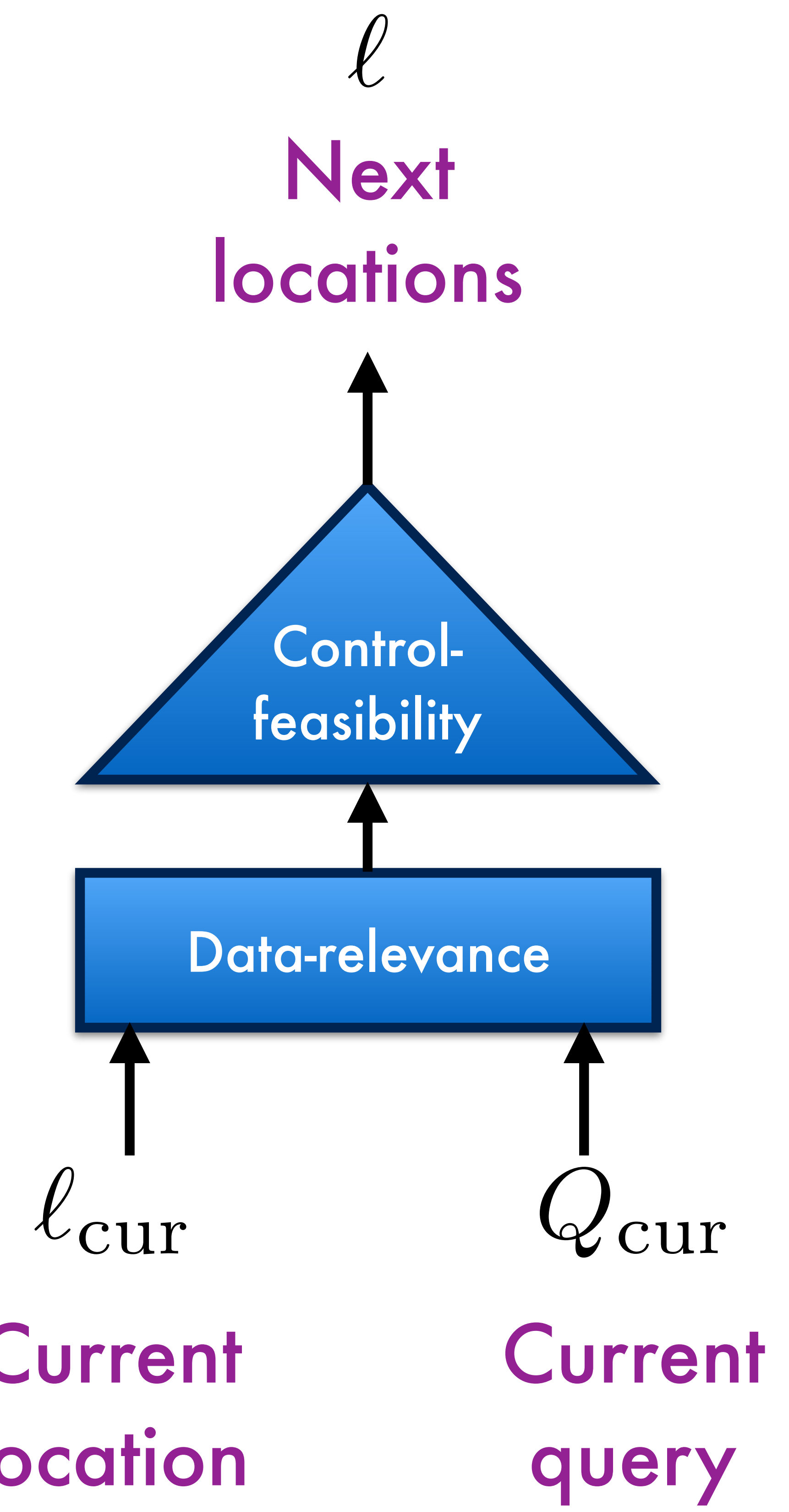
Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \overset{[c]}{\longrightarrow} \ell_2$

Precision	-insensitive	-sensitive
flow	✔	✔
path		✔
context	✔	

only feasible-preds$(\ell_{\mathrm{cur}}, Q_{\mathrm{cur}})$

all locations



Jumping enables sparse, selective, on-the-fly control-flow abstraction

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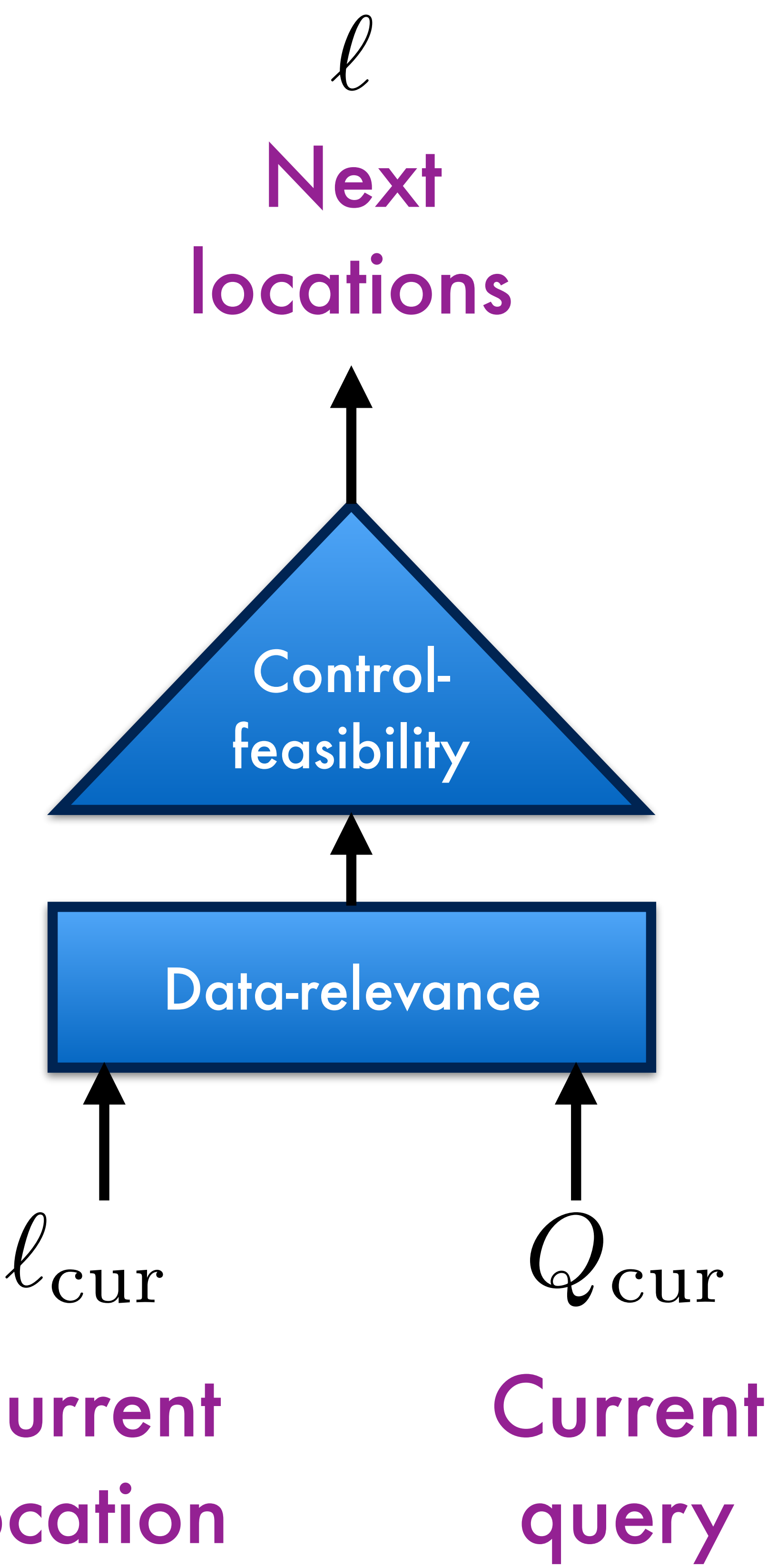
Precision	-insensitive	-sensitive
flow	✔	✔
path		✔
context	✔	

only feasible-preds($\ell_{\mathrm{cur}}, Q_{\mathrm{cur}}$)

all locations



Jumping enables sparse, selective, on-the-fly control-flow abstraction

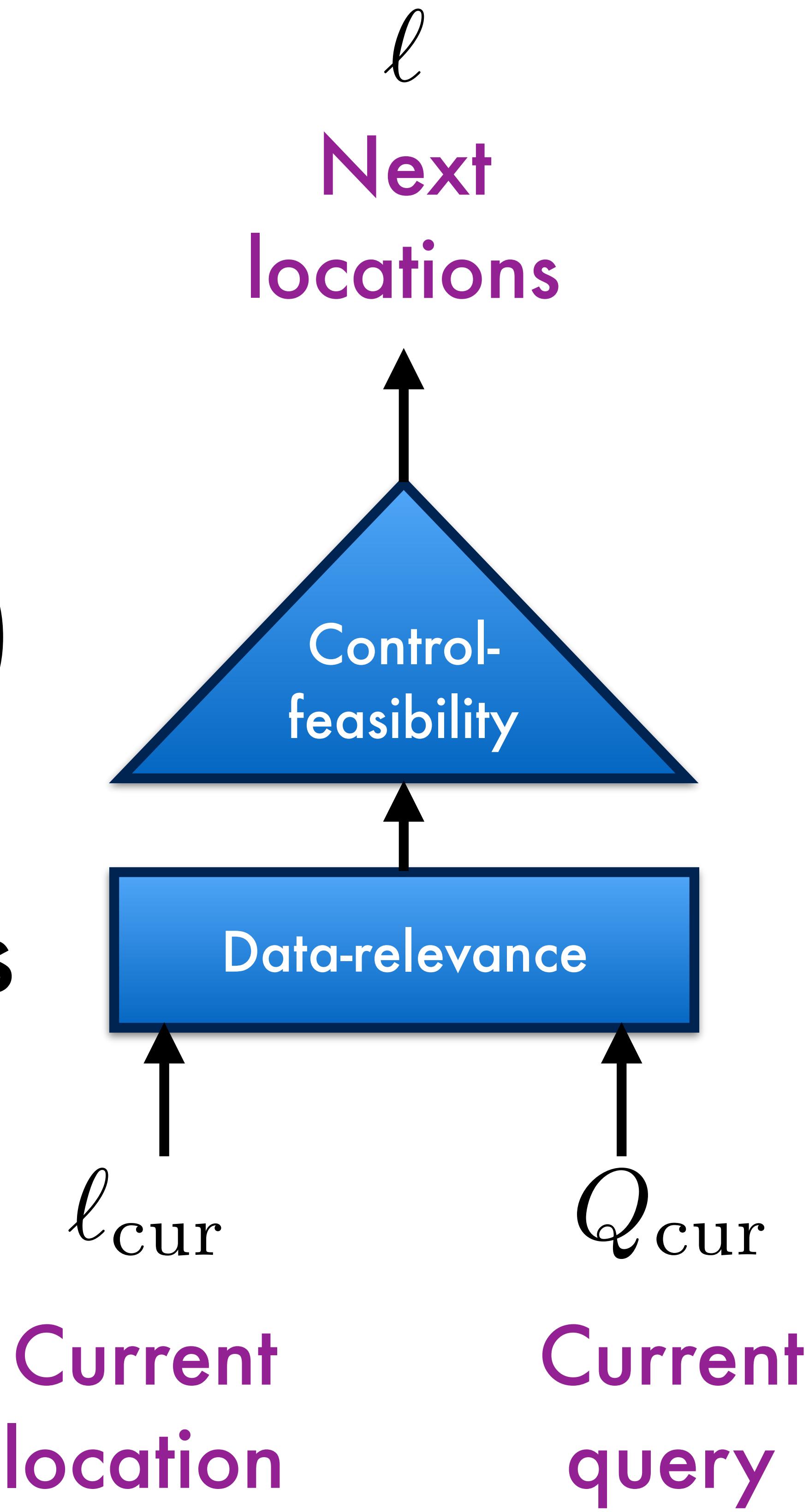
1

$\ell_1 \;\mathbin{-\!\![c]\!\!\rightarrow}\; \ell_2$

Precision	-insensitive	-sensitive
flow	✔	✔
path		✔
context	✔	✔

only feasible-preds($\ell_{\mathrm{cur}}, Q_{\mathrm{cur}}$)

all locations



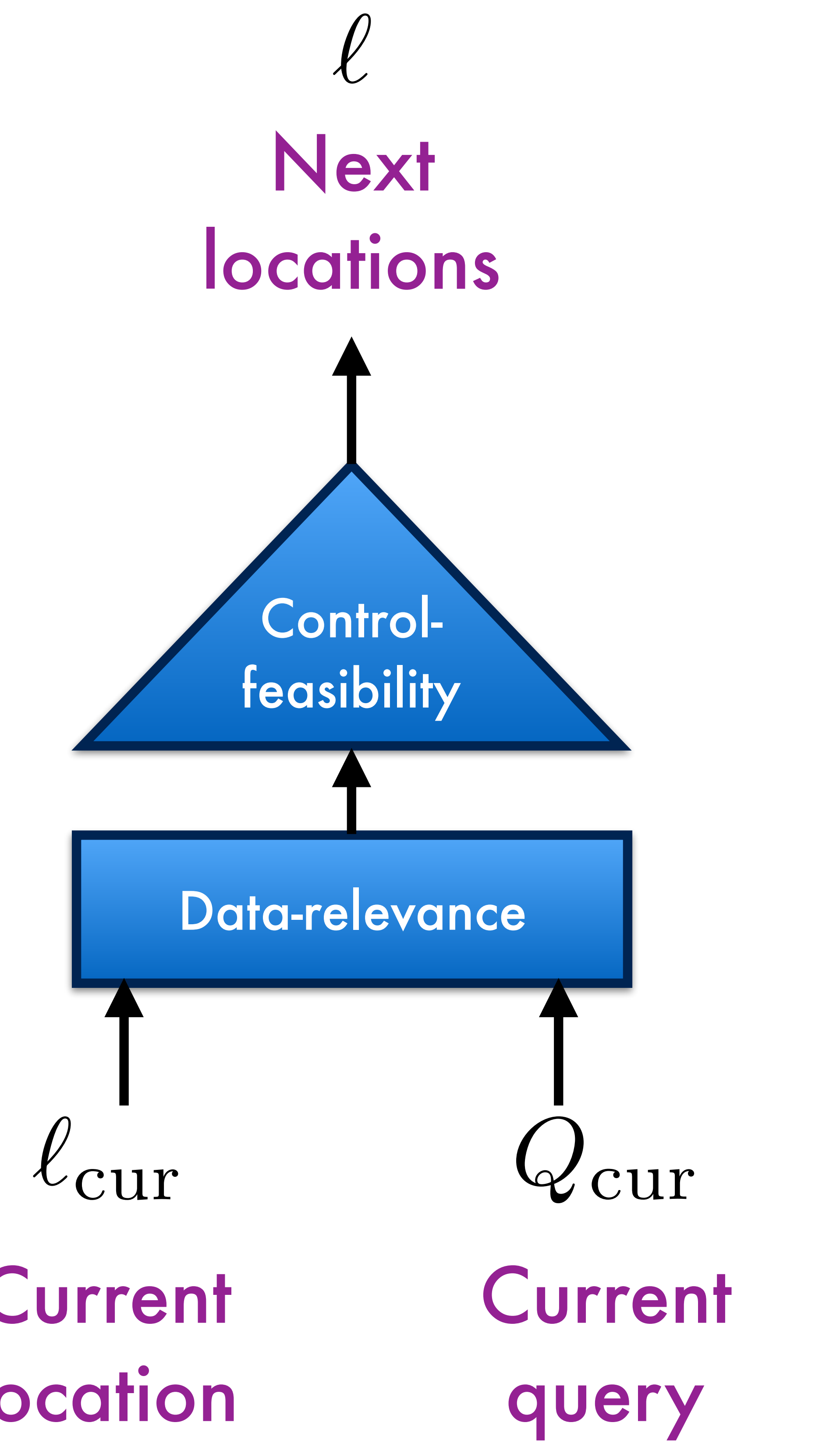
Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \; \text{-}[c]\!\!\rightarrow \; \ell_2$

Precision	-insensitive	-sensitive
flow	✔	✔
path		✔
context	✔	✔

only feasible-preds($\ell_{\mathrm{cur}}, Q_{\mathrm{cur}}$)

all locations, except `assumes`



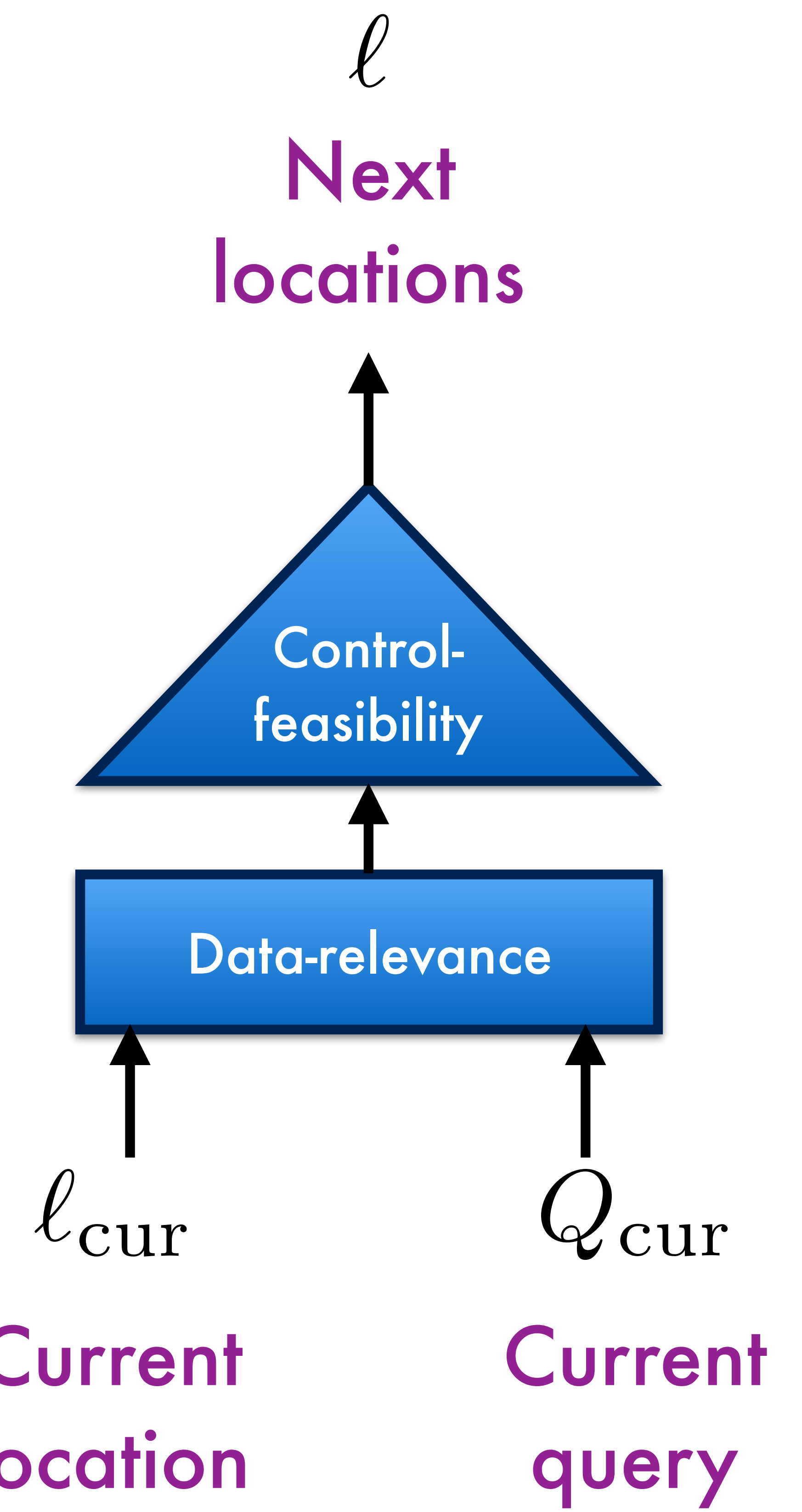
Jumping enables sparse, selective, on-the-fly control-flow abstraction

$\ell_1 \xrightarrow{[c]} \ell_2$

Precision	-insensitive	-sensitive
flow	✔	✔
path		✔
context	✔	✔

only feasible-preds($\ell_{\mathrm{cur}}, Q_{\mathrm{cur}}$)

all locations, except `assumes`



Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \xrightarrow{[c]} \ell_2$

Precision	-insensitive	-sensitive
flow	✔	✔
path	✔	✔
context	✔	✔

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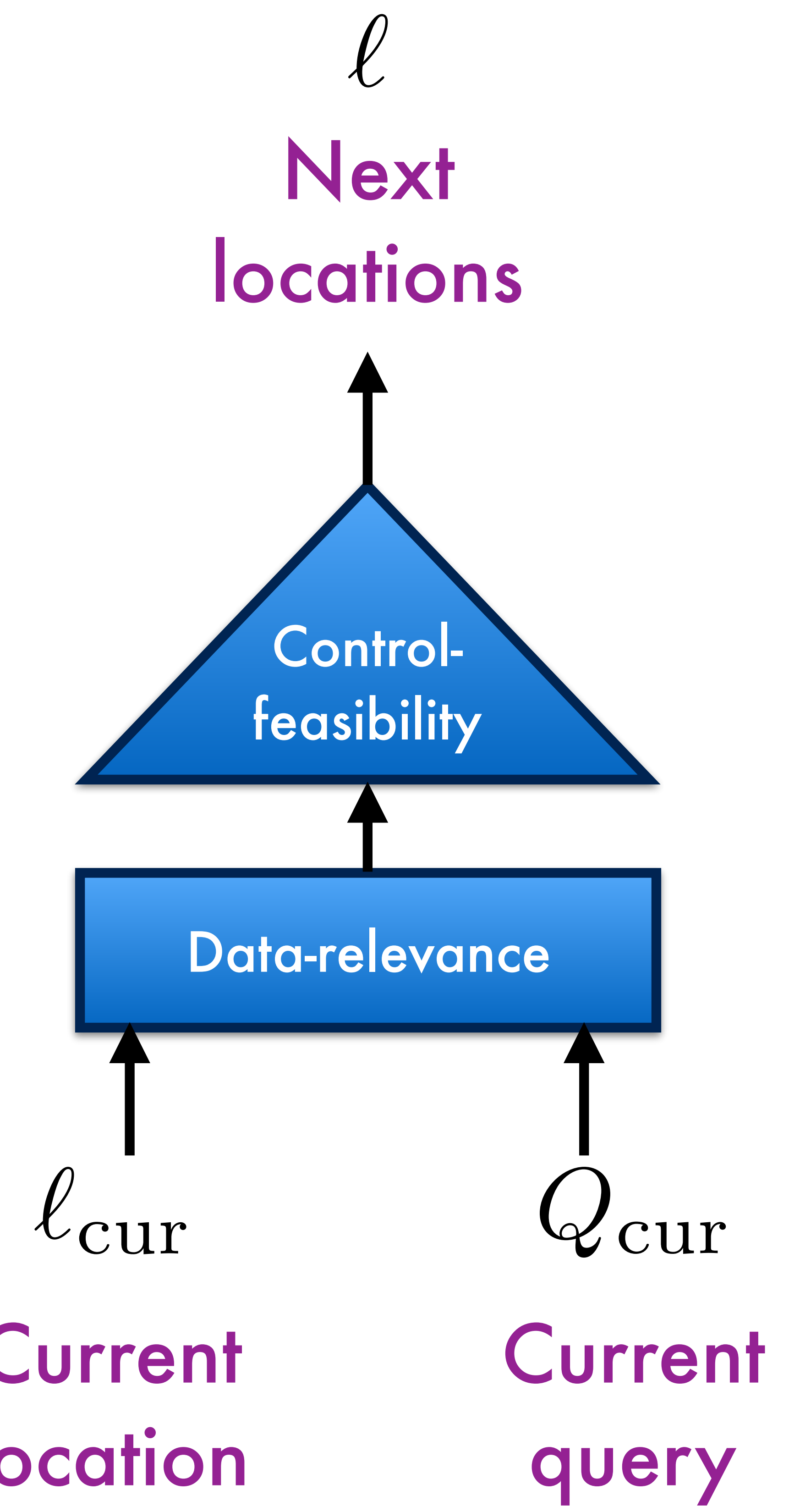

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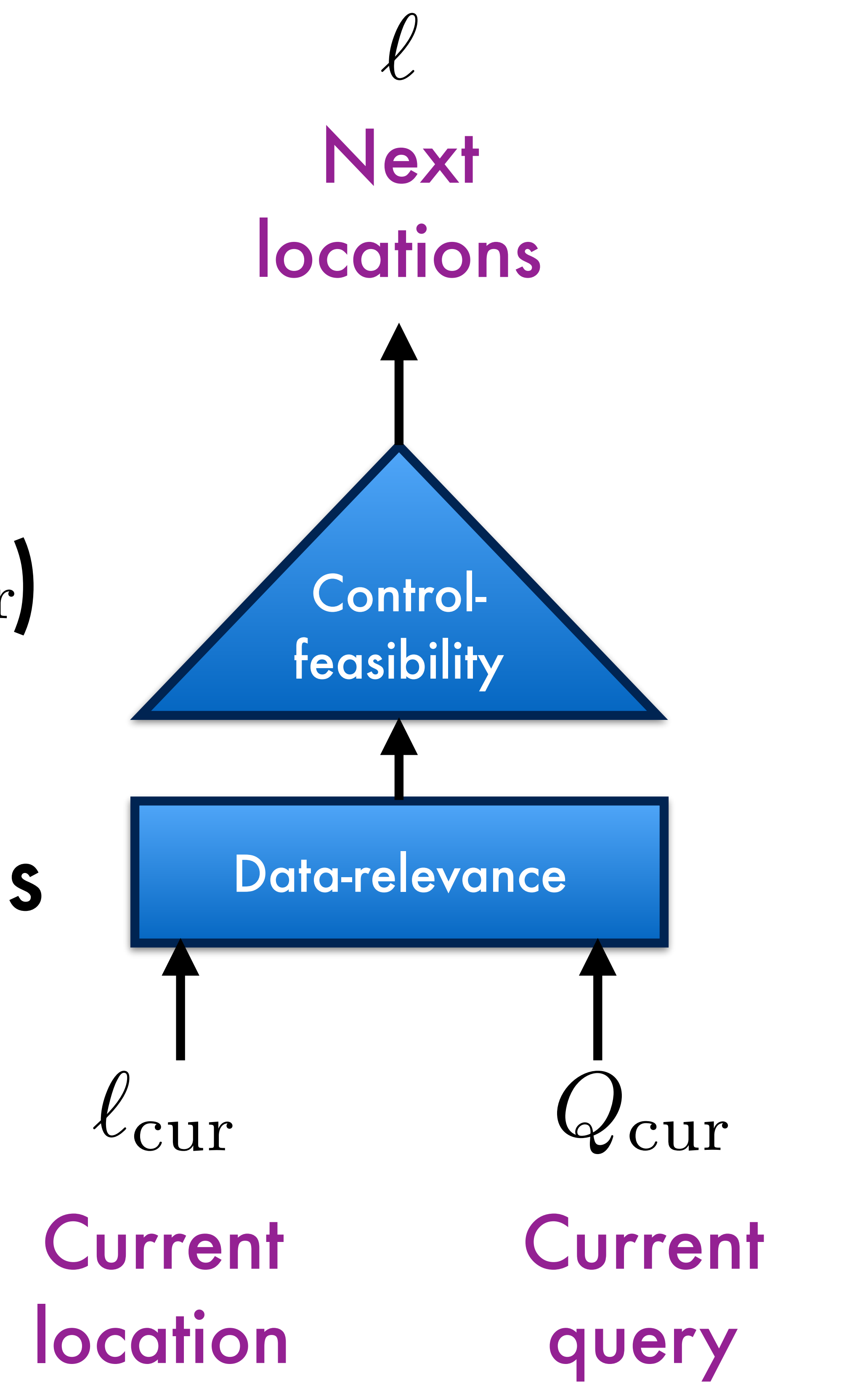

Jumping enables sparse, selective, on-the-fly control-flow abstraction

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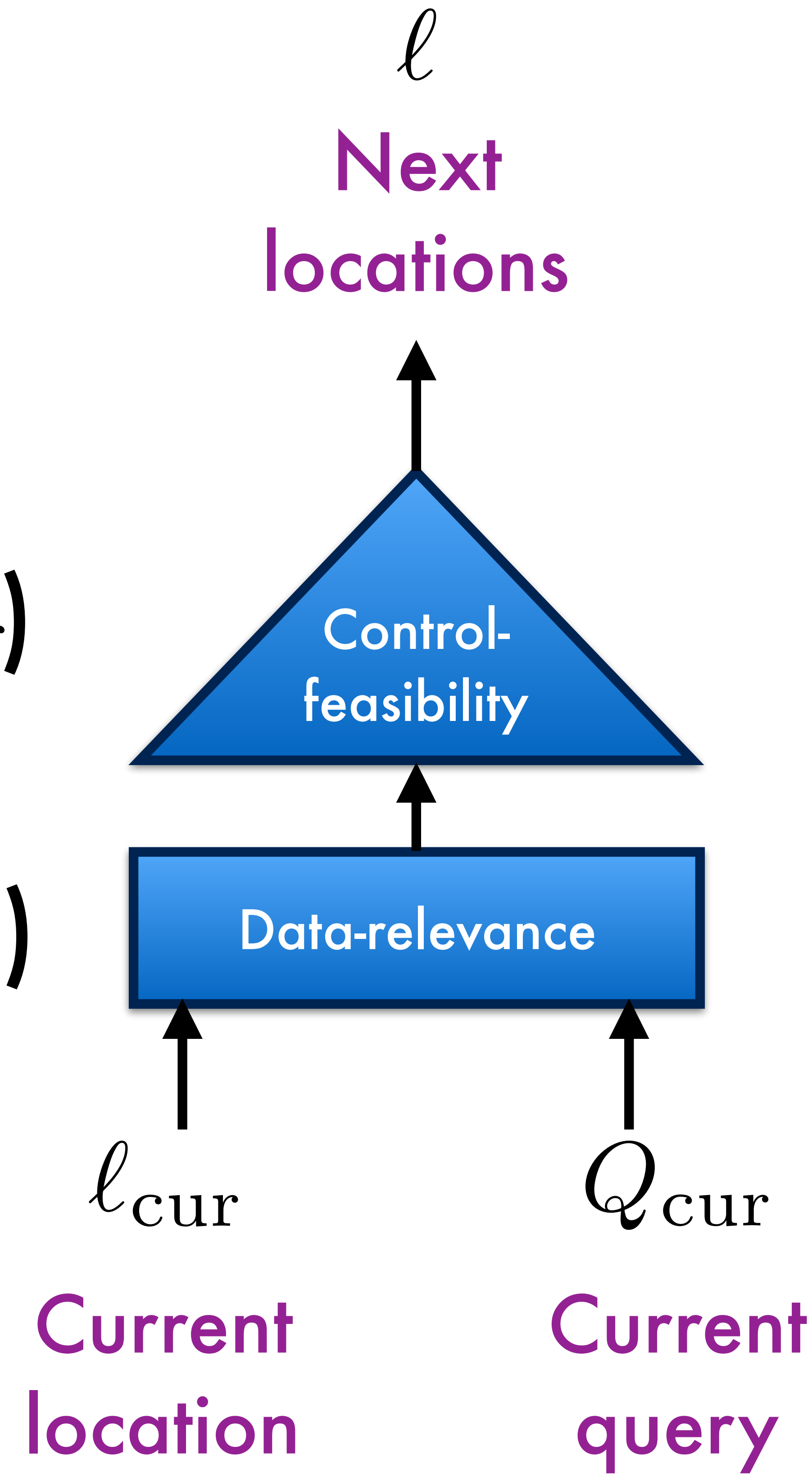

Jumping enables sparse, selective, on-the-fly (1) control-flow abstraction

$\ell_1 \;\dashv[c]\!\!\rightarrow\; \ell_2$

Be sparse by using data relevance with desired control-flow abstraction

only feasible-preds($\ell_{\mathrm{cur}}, Q_{\mathrm{cur}}$)

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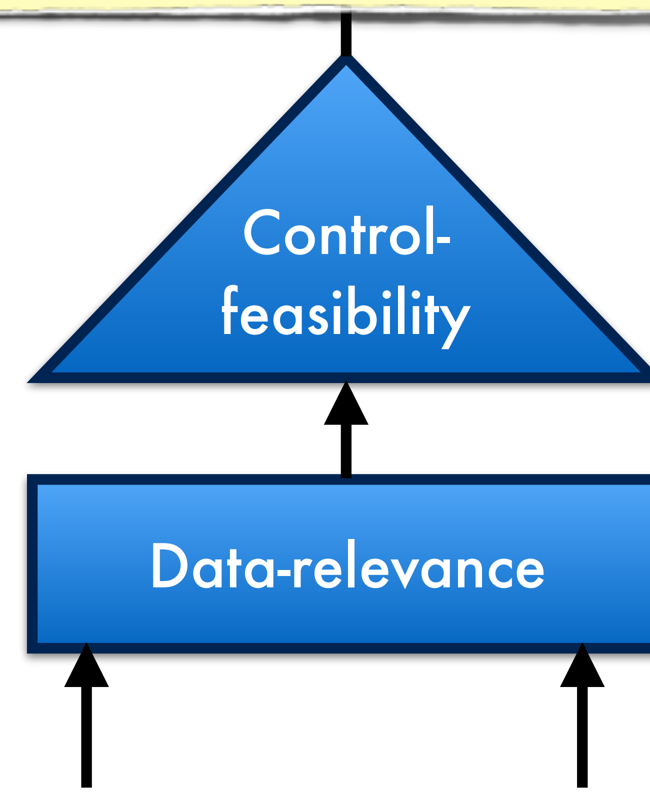

ℓ_{cur} — Current location

Q_{cur} — Current query

Jumping enables sparse, selective, on-the-fly control-flow abstraction

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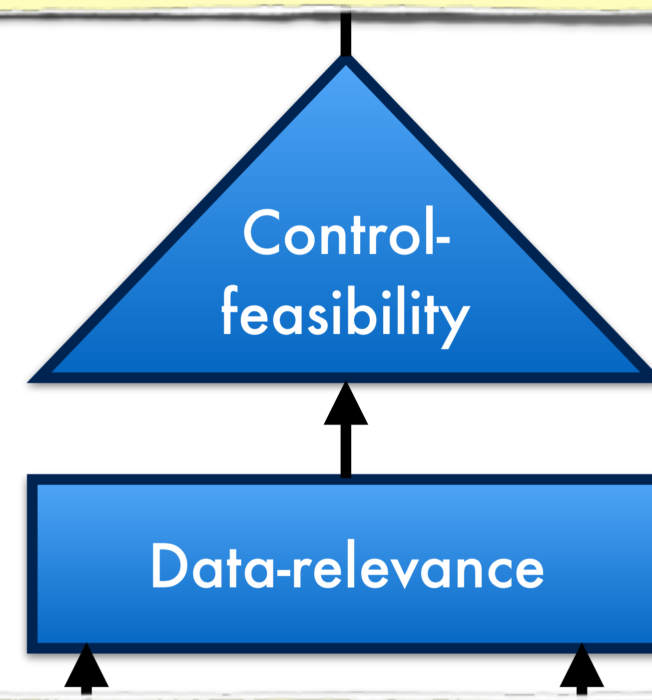
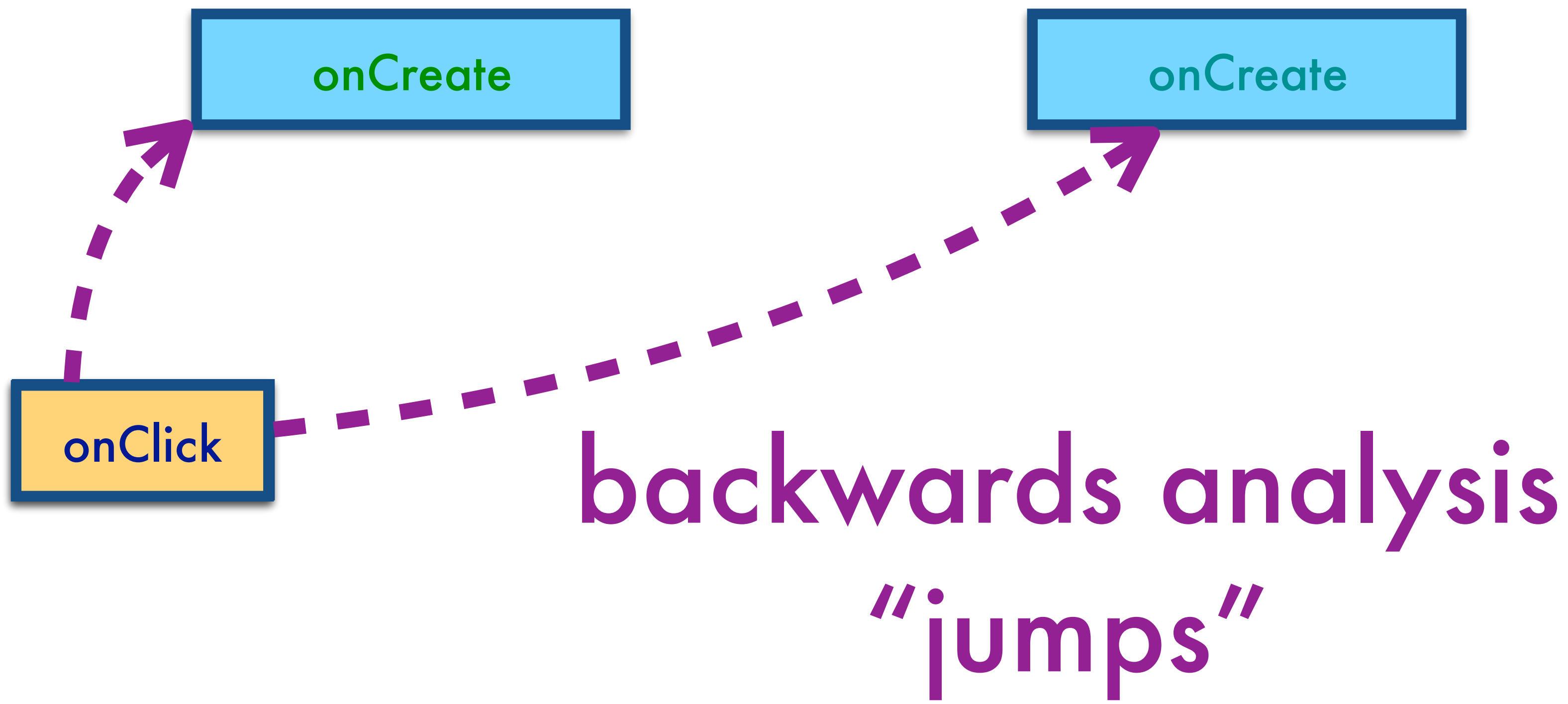


Be selective by varying the relevance relation at each analysis step

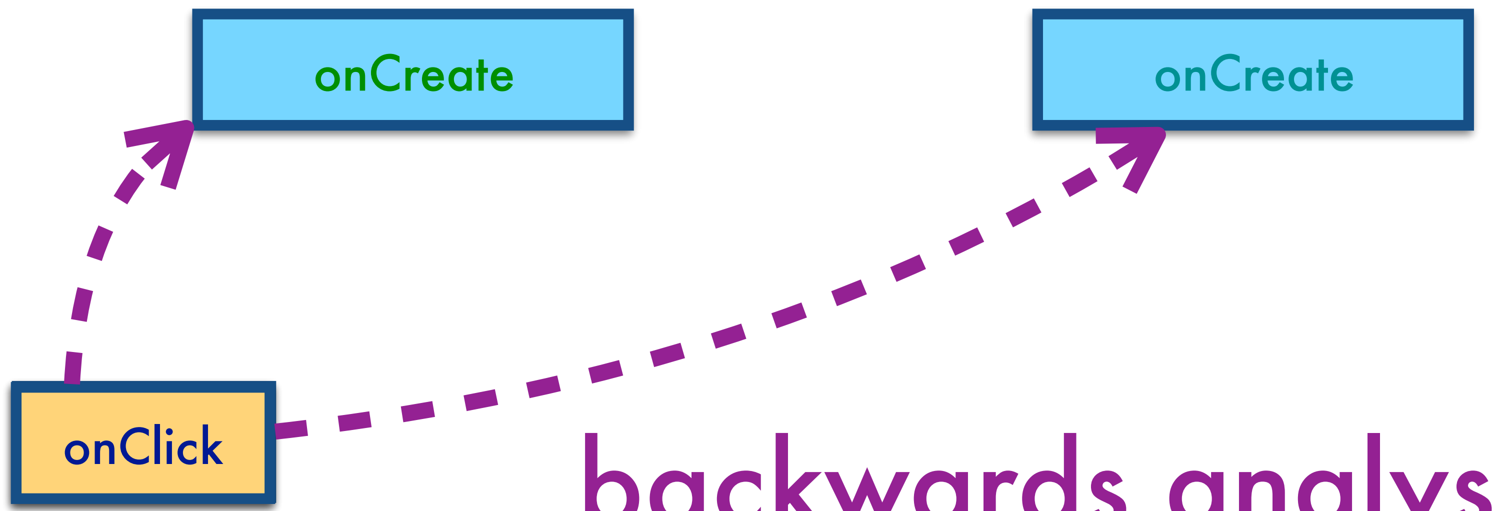
Contributions



1 $\ell_1 \;\dashv\!\![c]\!\!\rightarrow\; \ell_2$ Framework for jumping analyses

Applied to Android events

Contributions

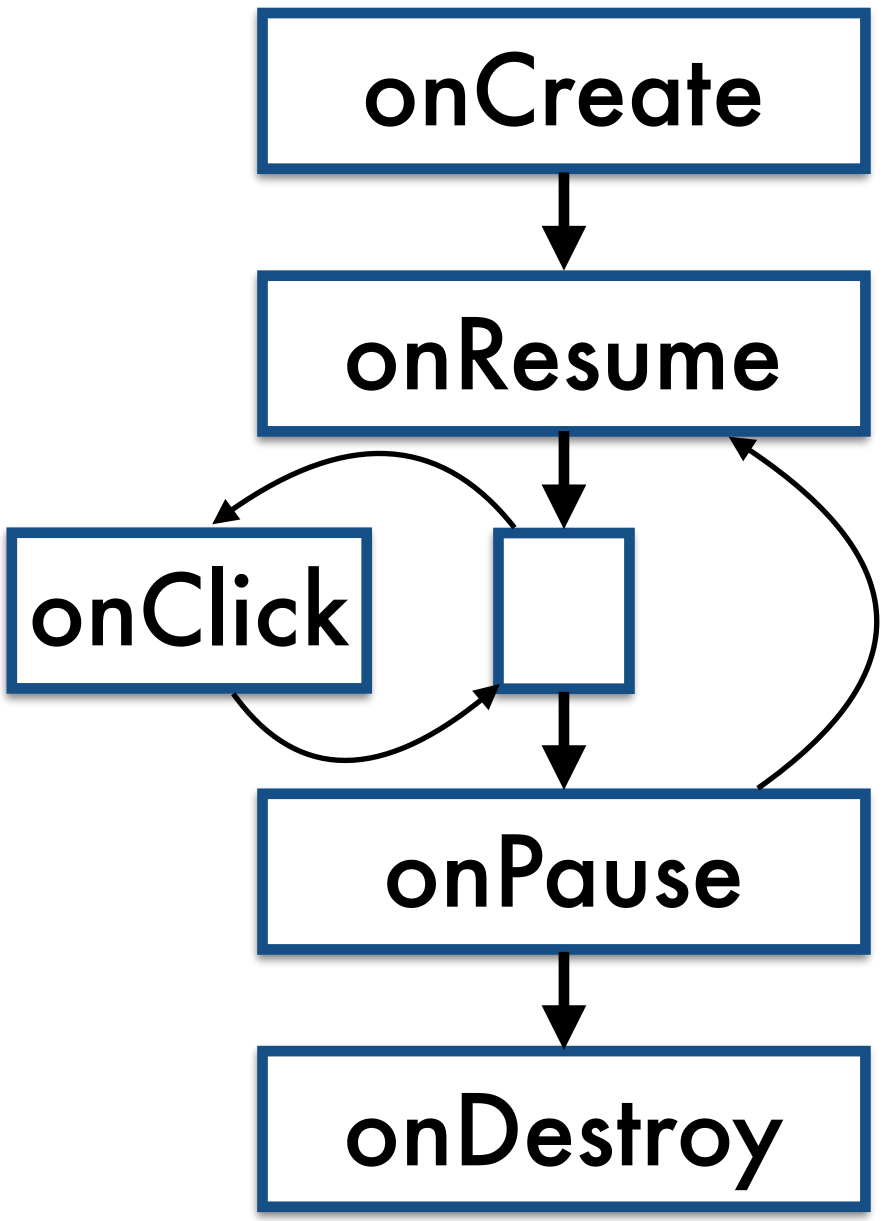


backwards analysis
"jumps"

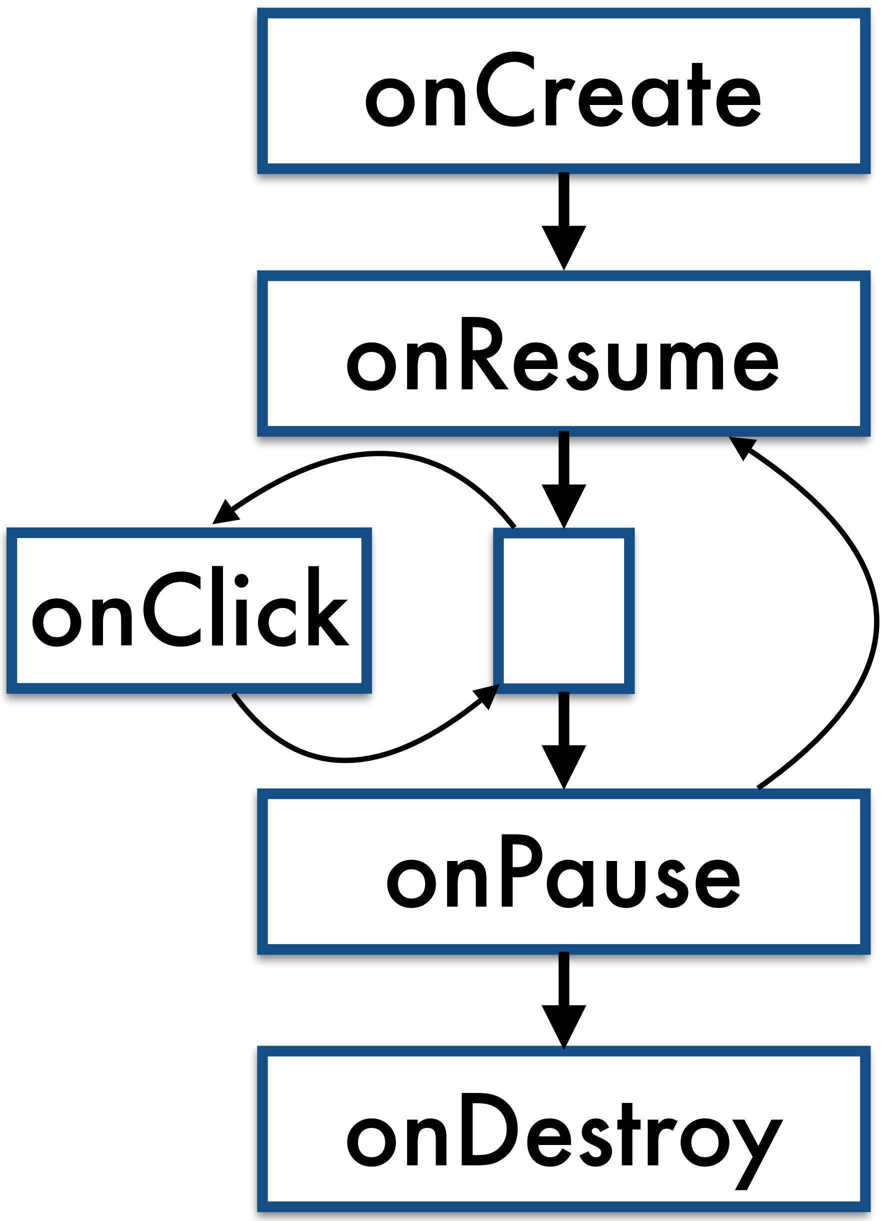
1 $\ell_1 \;{-}[c]{\rightarrow}\; \ell_2$ Framework for jumping analyses

2 Applied to Android events

Formalizing lifecycle graphs



Formalizing lifecycle graphs



"Lifecycle automata" accepts the concrete trace of callbacks projected onto its transitions

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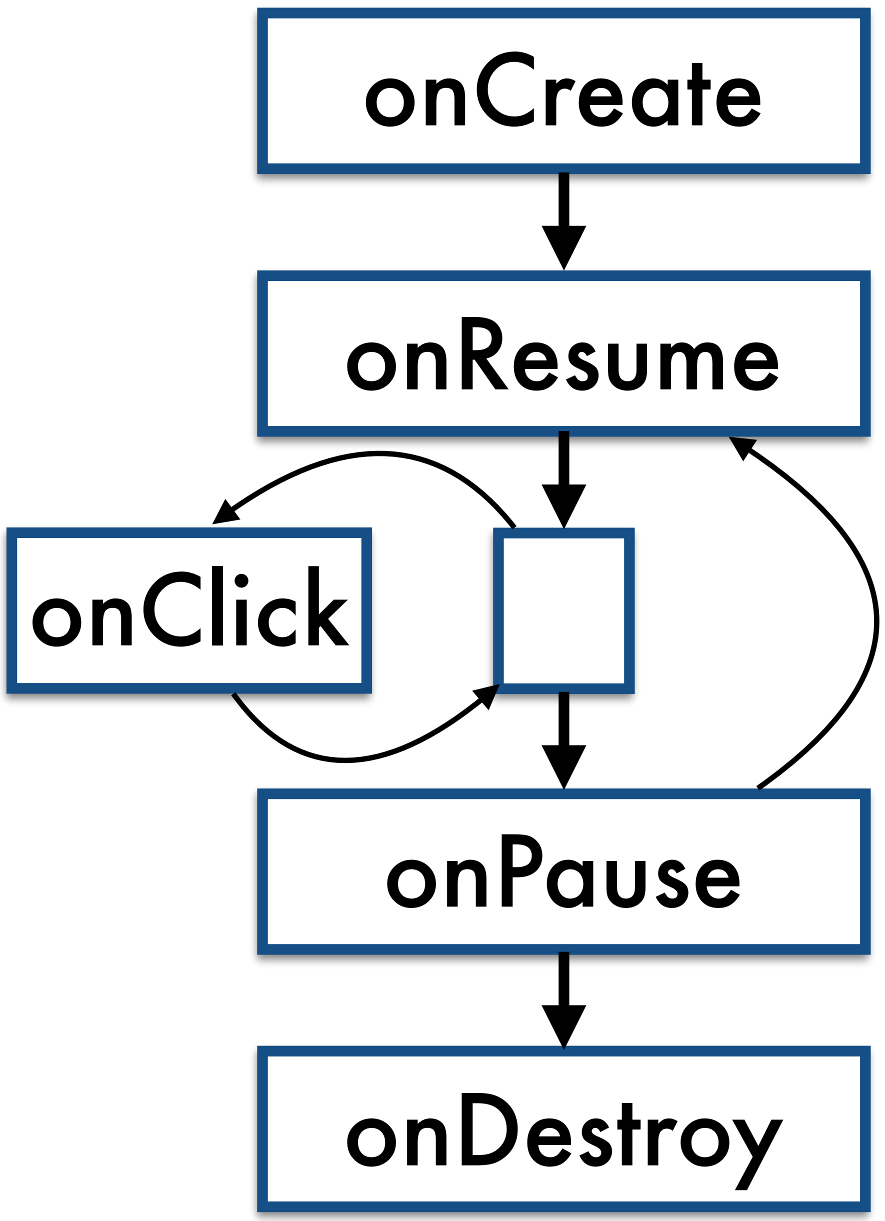

"Lifecycle automata" accepts the concrete trace of callbacks projected onto its transitions

Further scalability challenge: Lifecycle spec per class but analysis applies per object

A jumping policy for Android analysis

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Within an event-callback (intra-event), follow predecessor transitions

no jumping, path/context-sensitive

A jumping policy for Android analysis

Within an event-callback (intra-event), follow predecessor transitions

no jumping, path/context-sensitive

Between event-callbacks (inter-event), jump using lifecycle graphs for control-feasibility filtering

Hypothesis: Jumping is an effective approach to path-sensitive, inter-event analysis

Setup: Proving dereferences safe

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10 open source Android apps

- 3,000 to 55,000 lines of code
- 10 to 100 components
- 120 to 1,320 callbacks

Setup: Proving dereferences safe

10 open source Android apps

3,000 to 55,000 lines of code
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Event product graph would have 10^{10} to 10^{111} nodes (with one instance per class)

Setup: Proving dereferences safe

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Setup: Proving dereferences safe

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Compared 3 analyses

- **Nit**: flow-insensitive
- **Thr**esher: no jumping
- **Hop**per: jumping

Is jumping effective?

	KLOC	Deref	Nit	Thr	Hop (Impr %)
drupaleditor	3	928	679	179	72 (60)
npr	5	829	617	181	51 (72)
duckduckgo	11	1969	1341	518	143 (72)
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connectbot	33	2190	1562	316	74 (77)
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Thr and Hop: 10 second budget per deref

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Thresher has 74% fewer than Nit

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Hopper has 54% fewer than Thresher

Is jumping effective?

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Compare with state-of-the art NPE checking work that reports 84-91% proven on normal Java programs!

Triaging alarms to find bugs

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Triaged 200 alarms (from Hopper), 189 false

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5 bugs due to bad ordering assumptions

10/11 patches accepted

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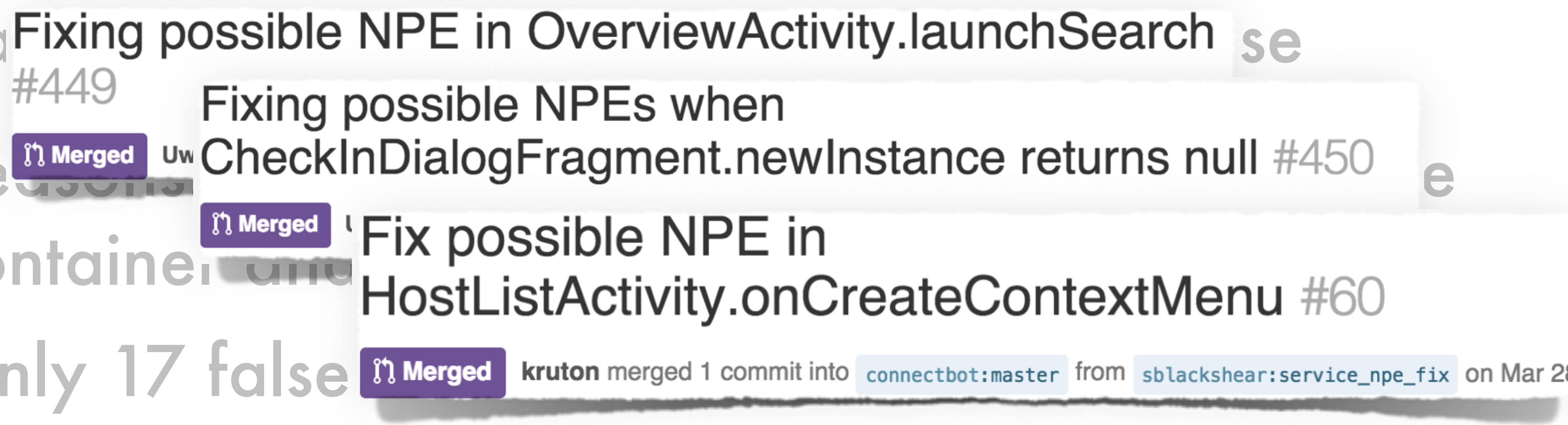

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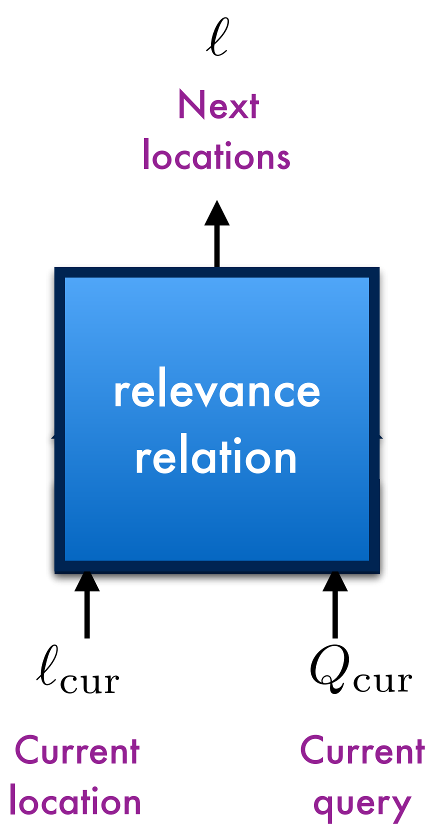
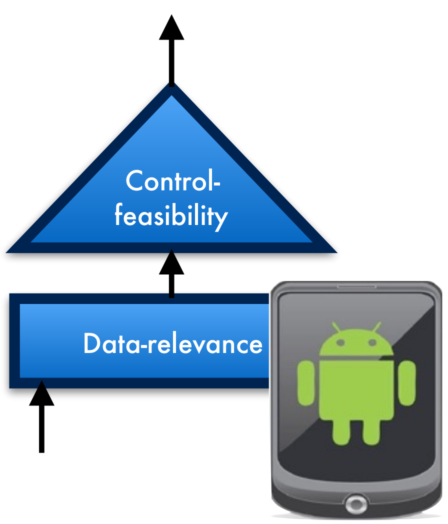


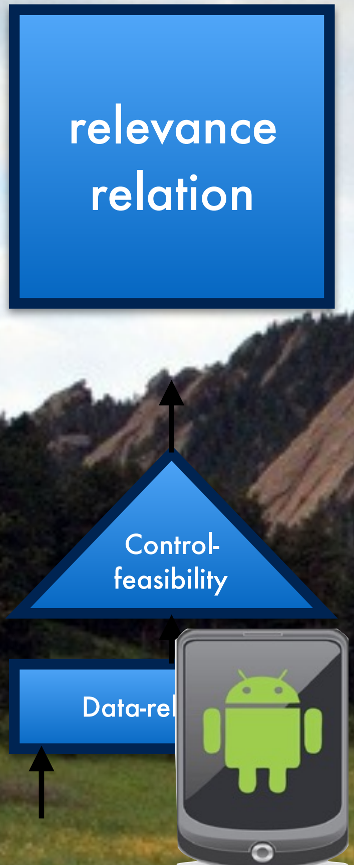
Selective control-flow abstraction via a sound relevance relation

Summary

Selective control-flow abstraction via a sound relevance relation



Effective inter-event ordering-sensitive reasoning via data-relevance and control-feasibility



Selective control-flow abstraction via a sound relevance relation

Effective inter-event ordering-sensitive reasoning via data-relevance and control-feasibility

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

PLV


Cerny


Chang


Hammer


Sankaranarayananan


Somenzi

Goal-directed:
abstraction-refinement versus abstraction-coarsening

staged abstraction refinement
(e.g., CEGAR)

on-the-fly abstraction
coarsening

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on-the-fly abstraction coarsening

Staged

Run analysis multiple times, abstraction changes only between runs.

On-the-fly

Run analysis once, abstraction changes during analysis.

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Run analysis multiple times,
abstraction changes only
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Run analysis once,
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Refinement

Start with imprecise
abstraction,
become more precise.

Coarsening

Start with precise
abstraction,
become less precise.