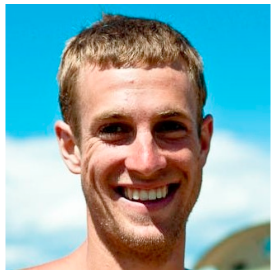
Goal-Directed Program Analysis with Jumping



Sam Blackshear
University of Colorado Boulder

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Samsung Research America

Google
July 24, 2015

PLV

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

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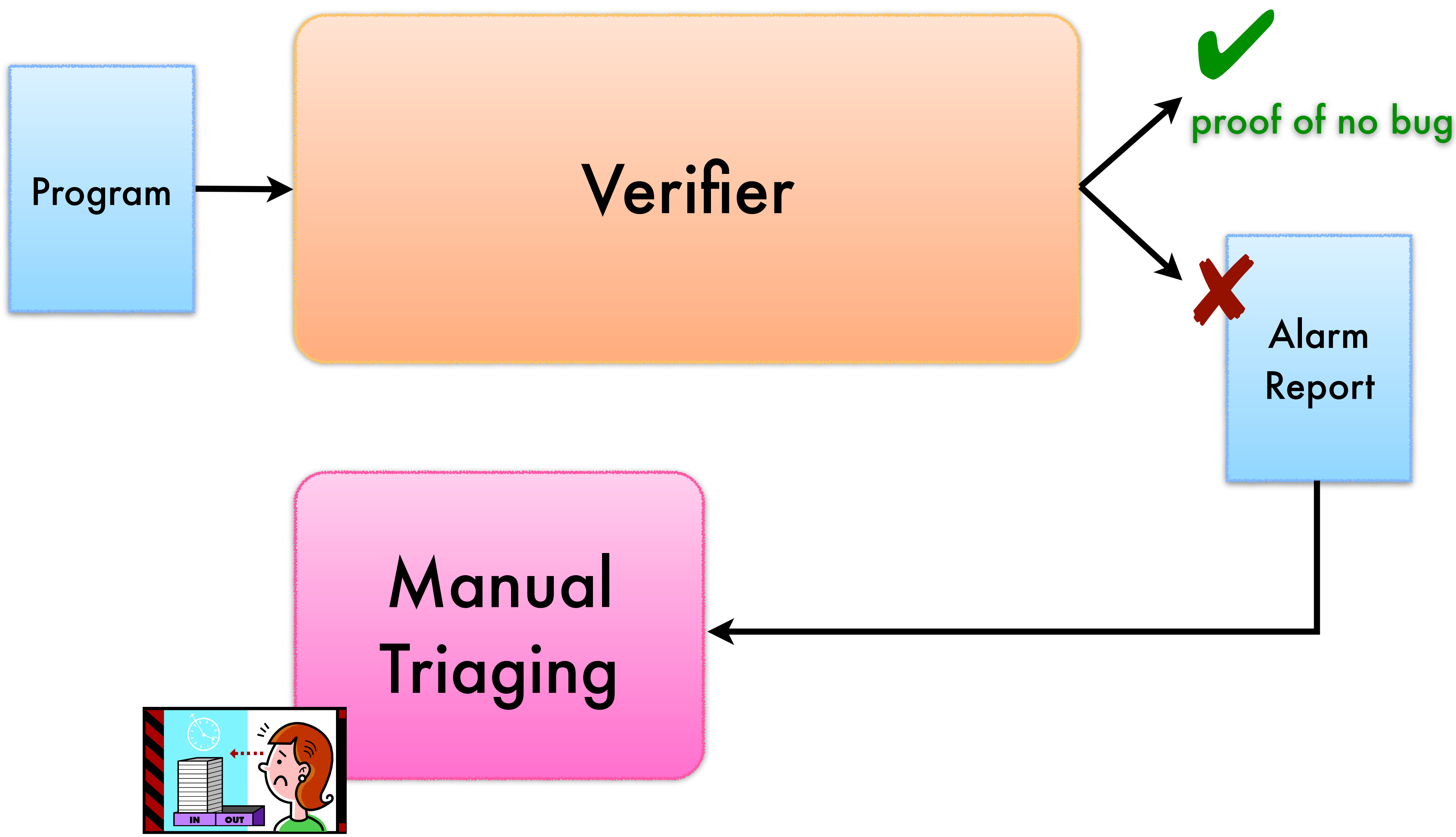

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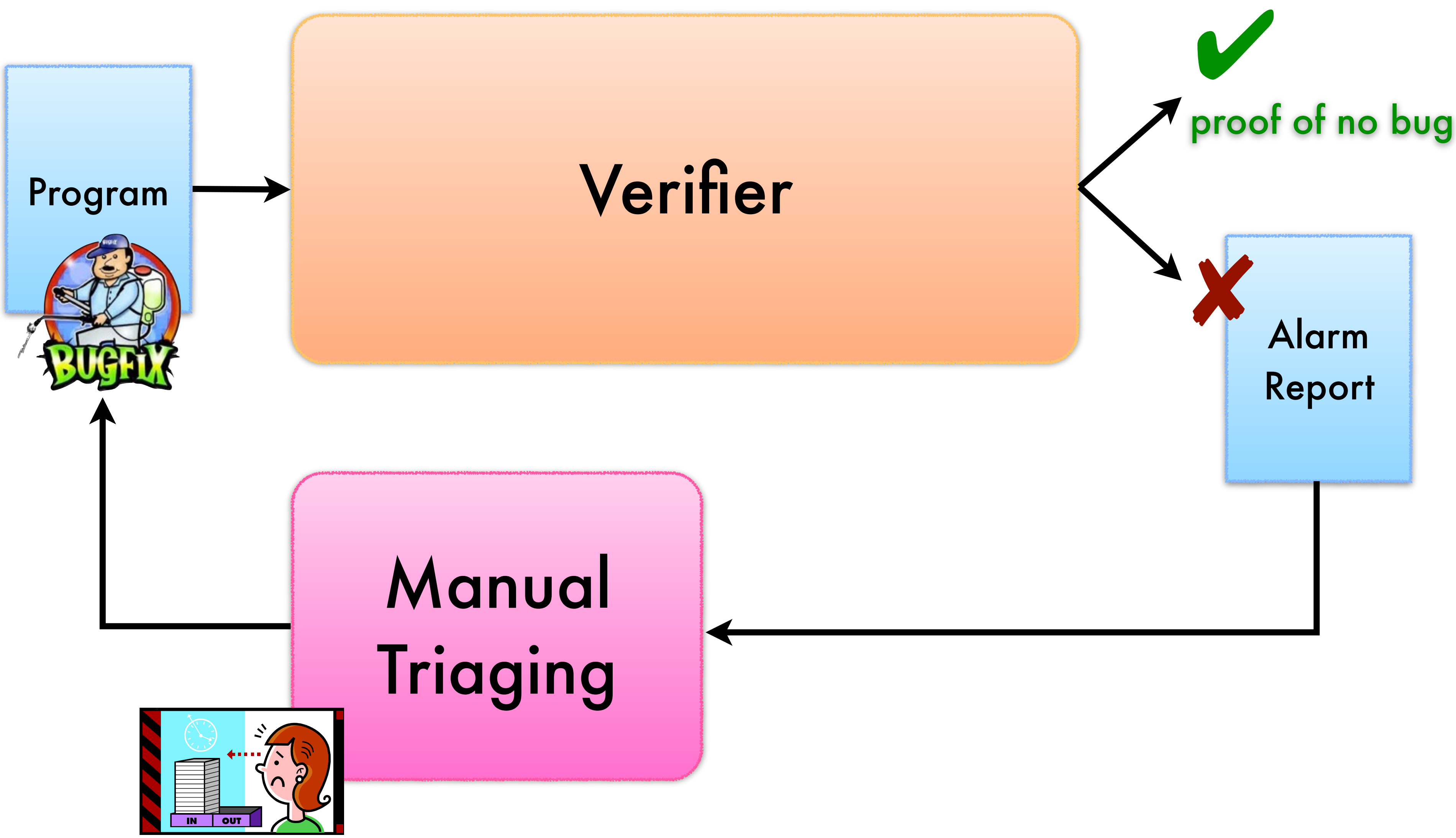

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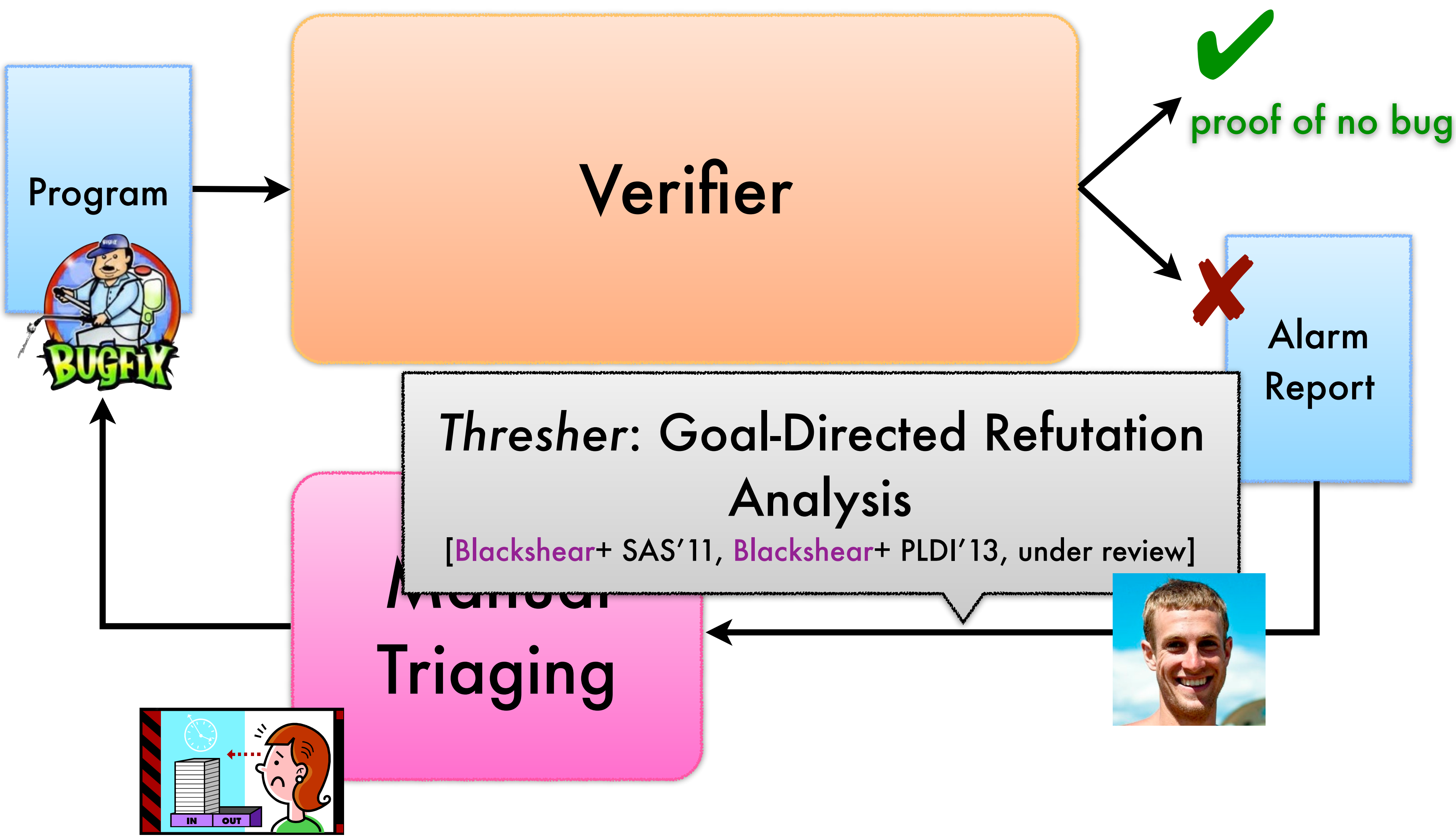

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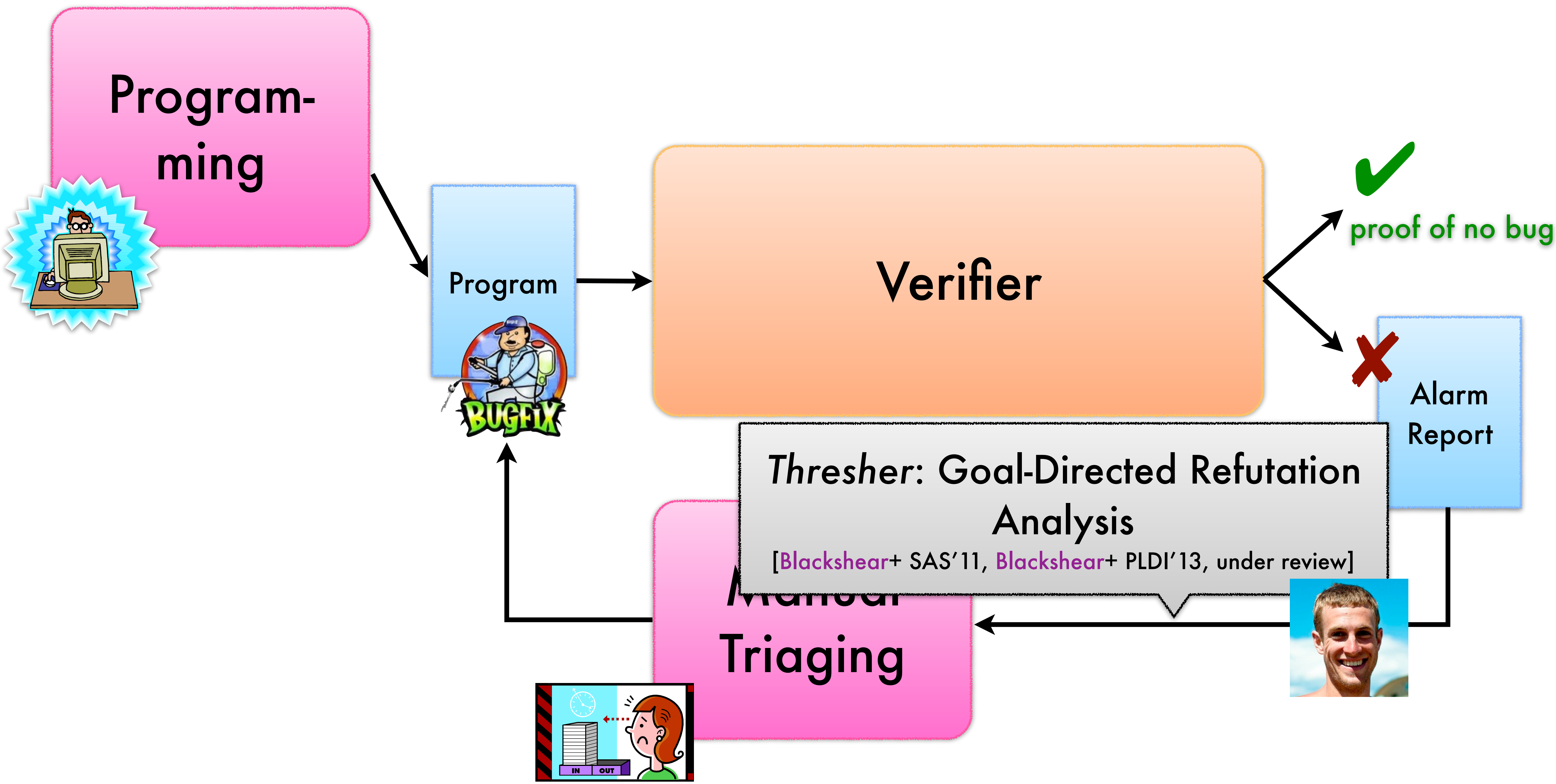

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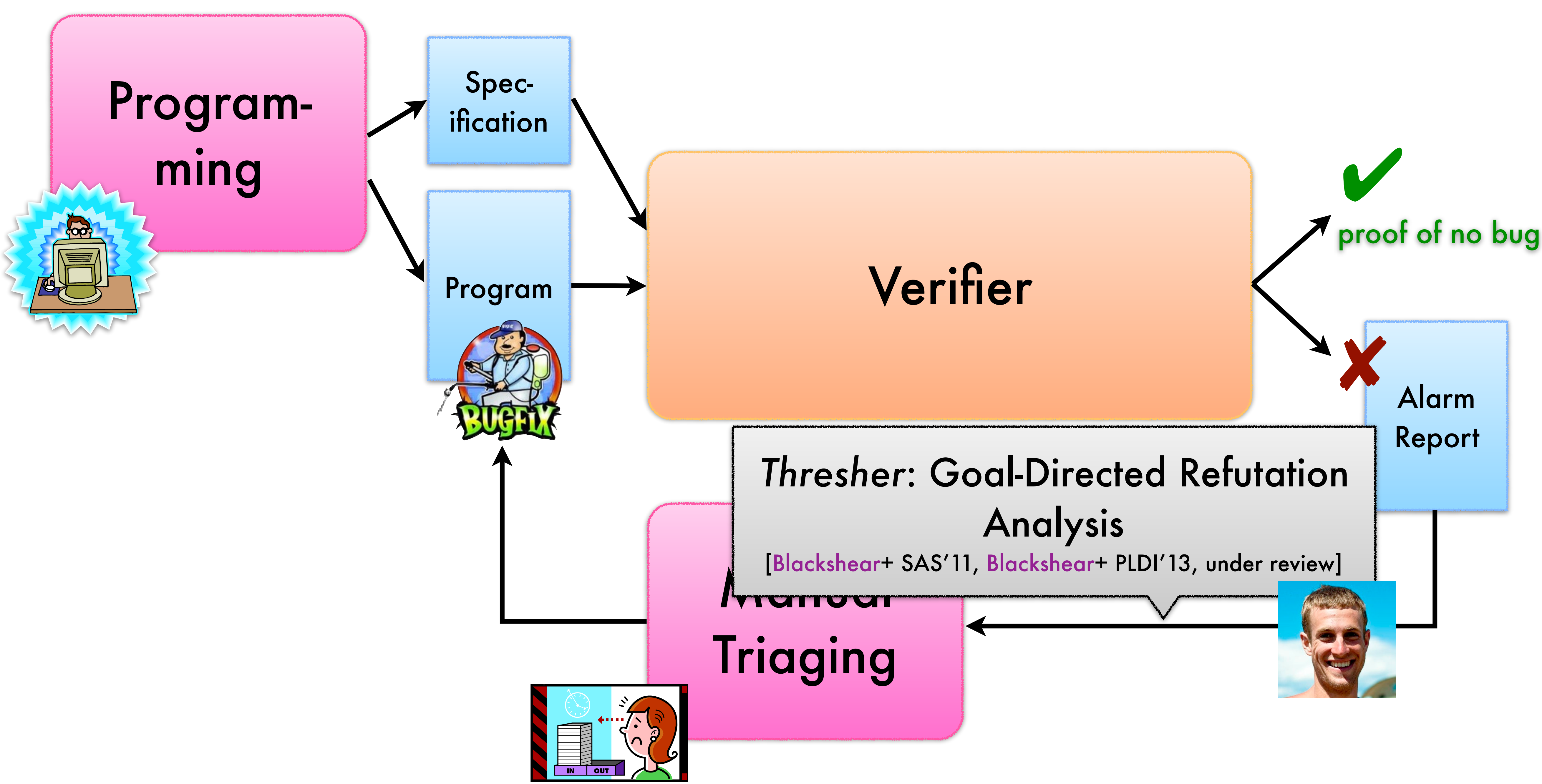

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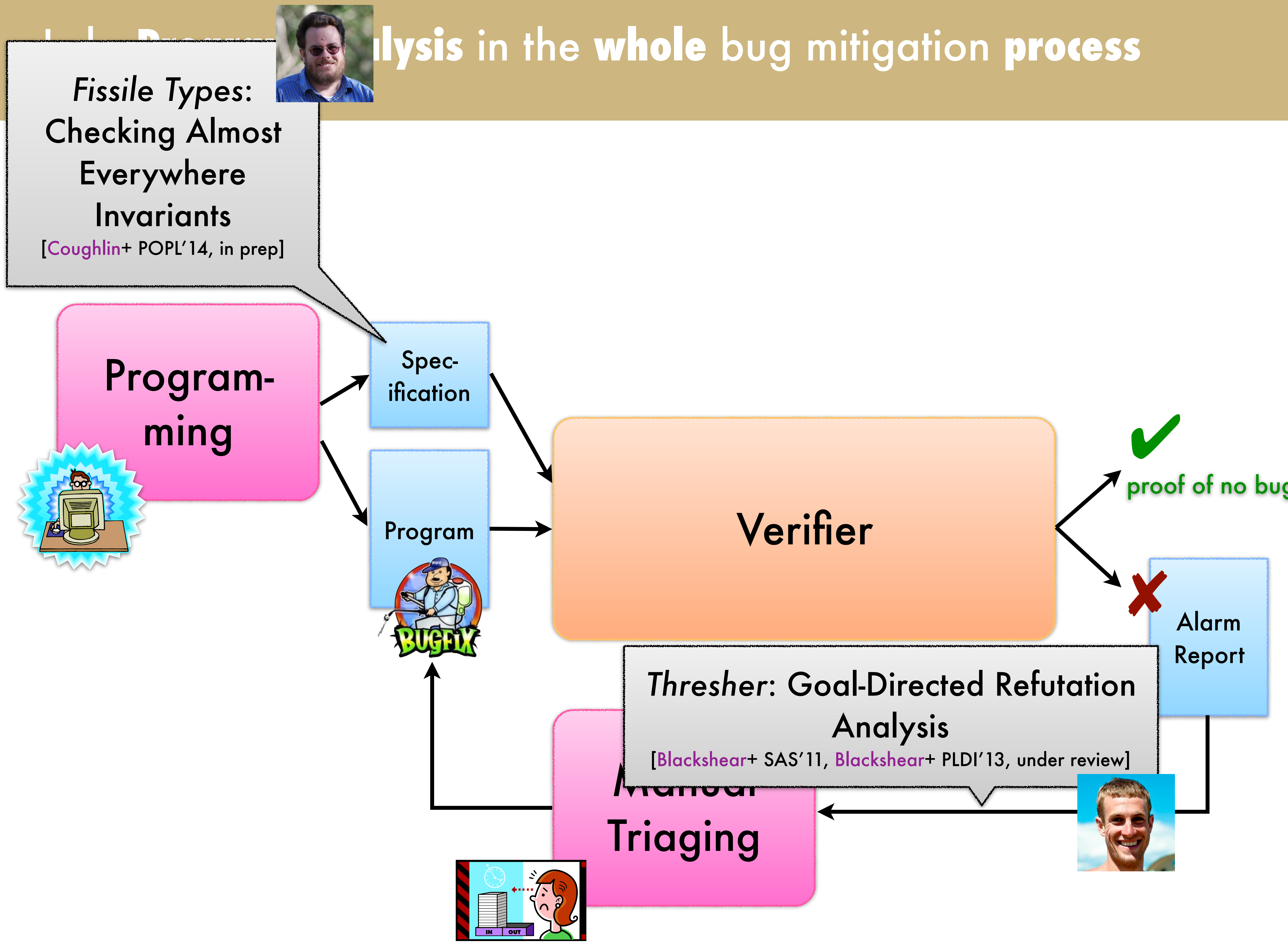
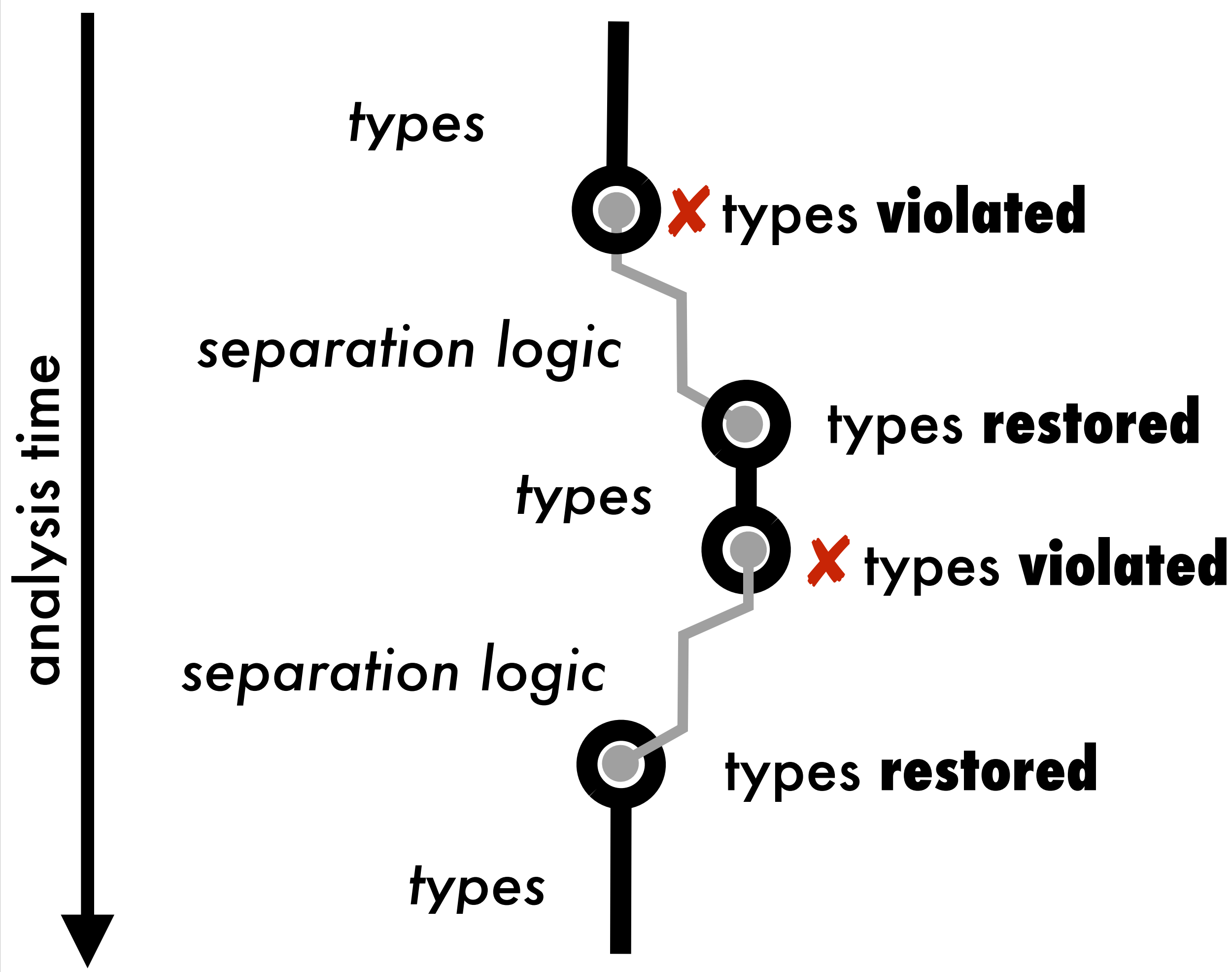


...lysis in the **whole** bug mitigation **process**

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

Prog...
m...



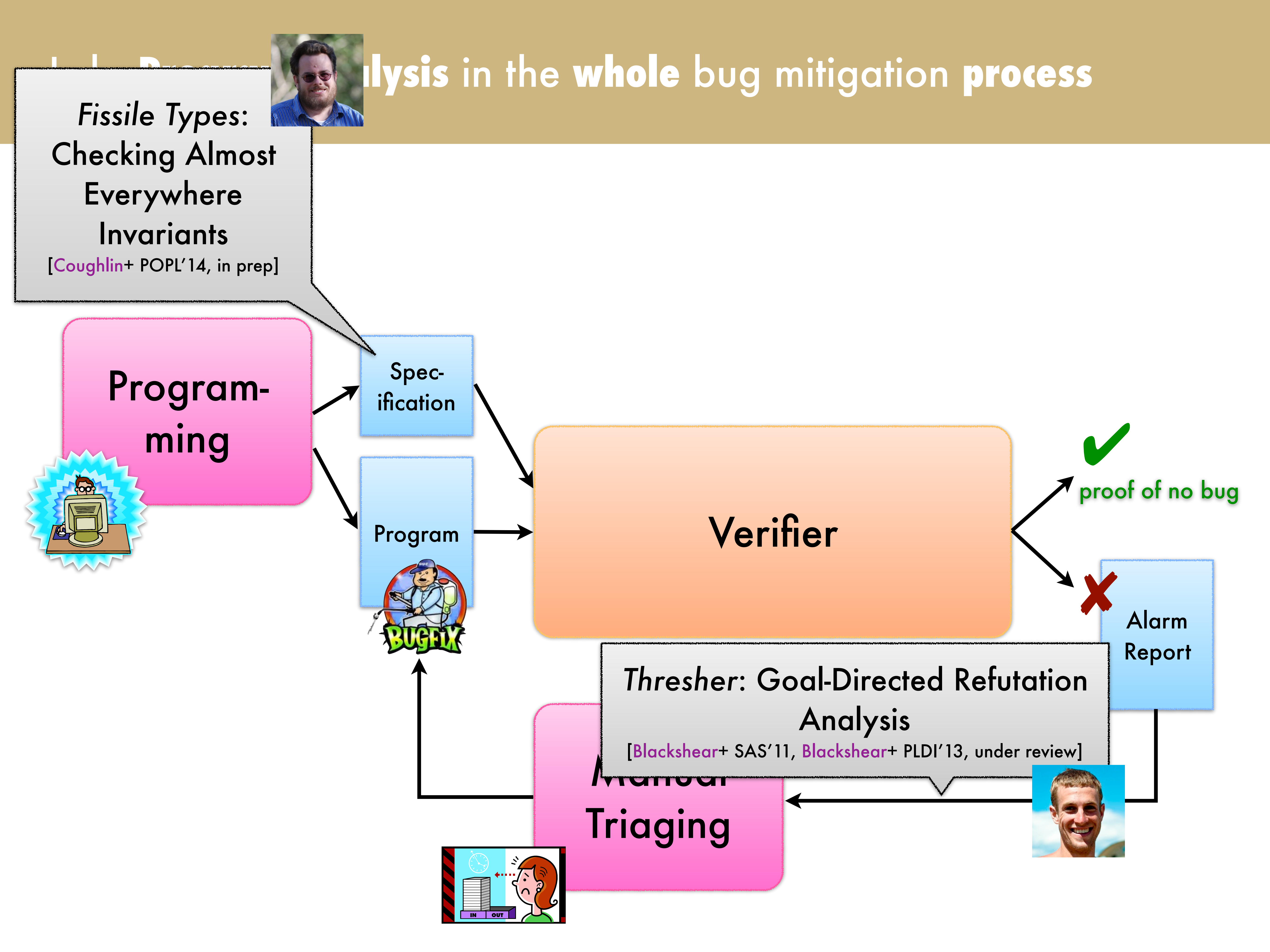
type-intertwined separation logic

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

Objective-C

...no bug

...m
...rt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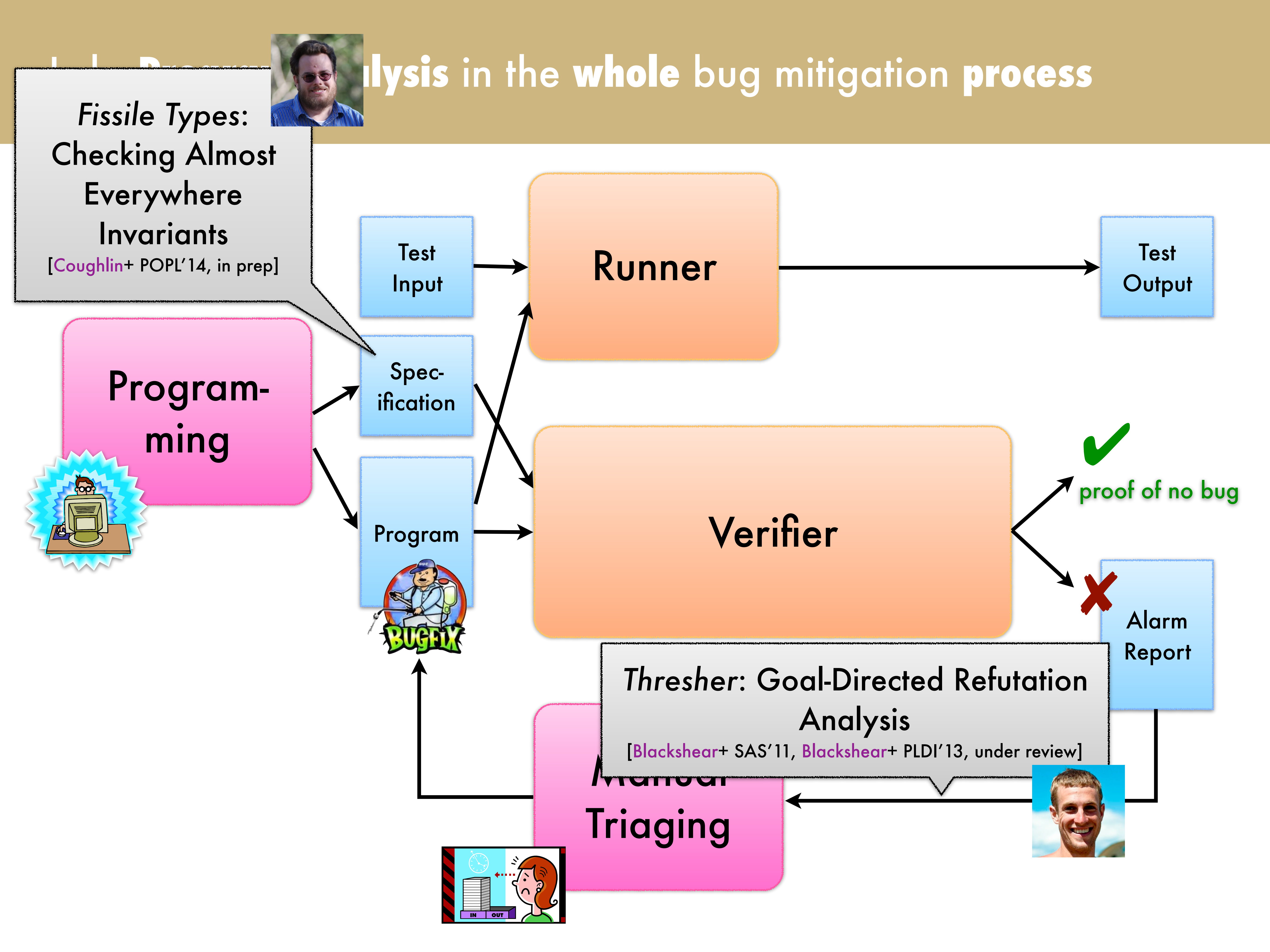
Spec-ification
Program
BUGFIX
Verifier
proof of no bug
Alarm Report
Thresher: Goal-Directed Refutation Analysis
[Blackshear+ SAS'11, Blackshear+ PLDI'13, under review]
Triaging
IN
OUT



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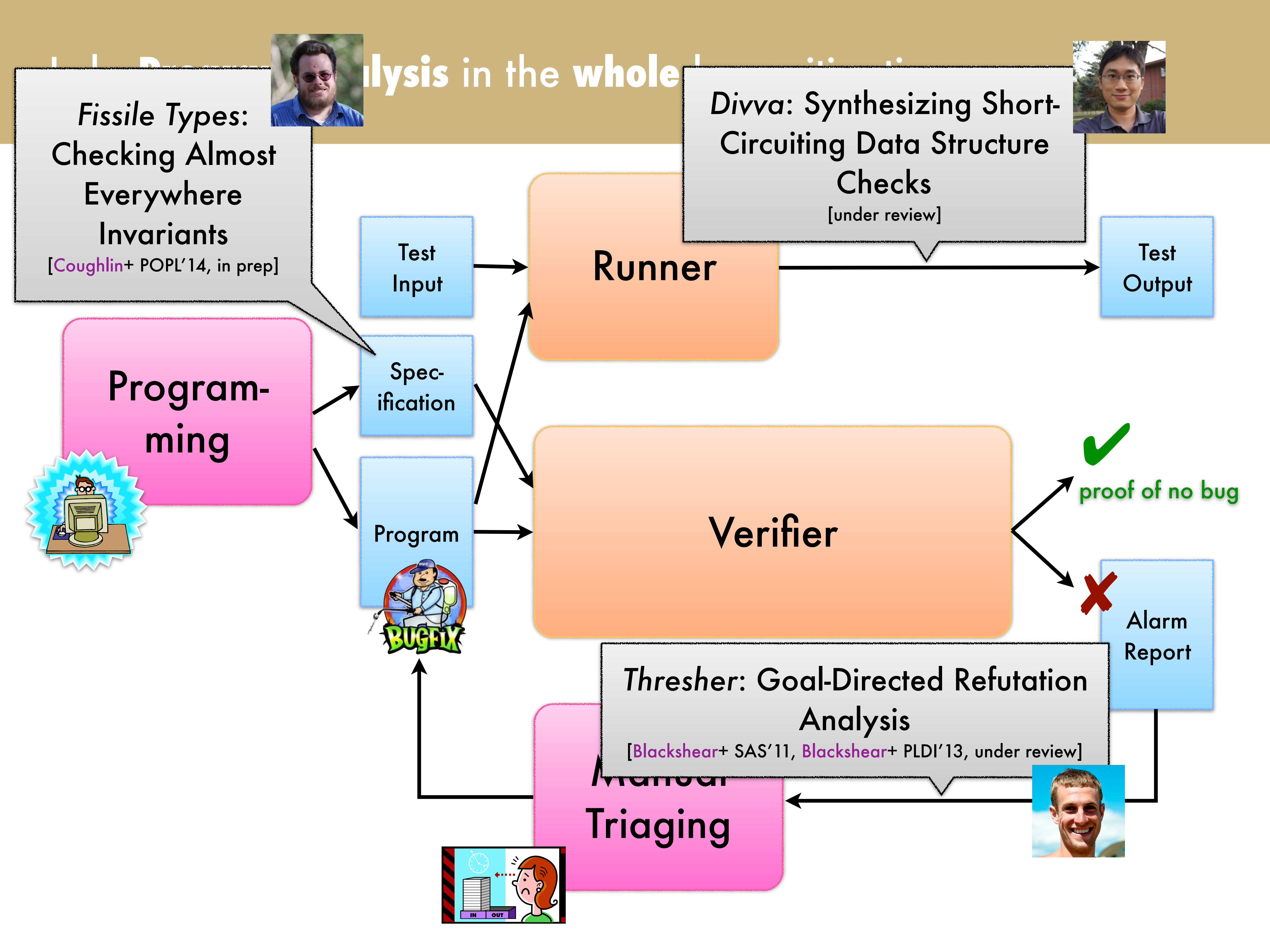

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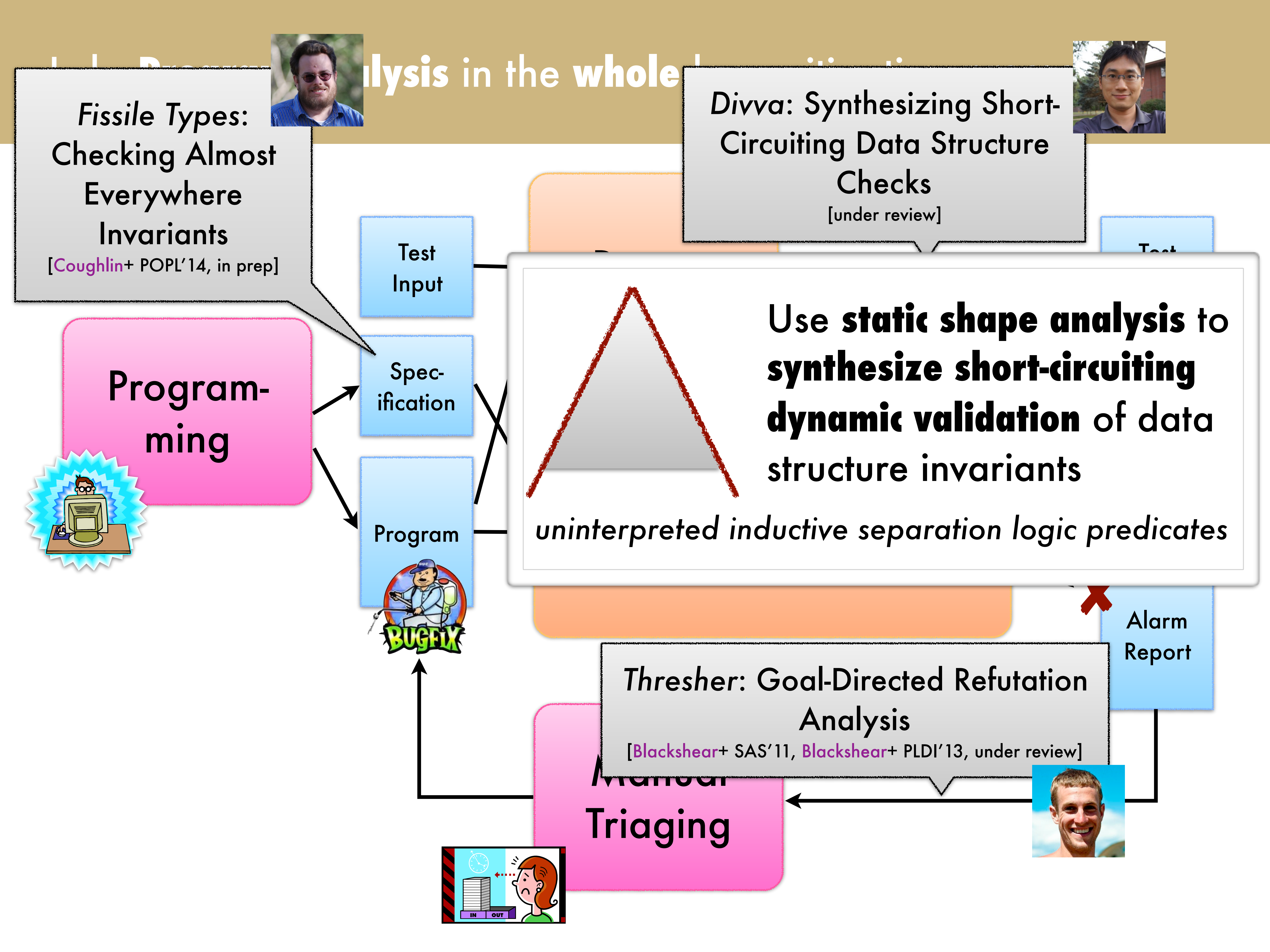

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Use static shape analysis to synthesize short-circuiting dynamic validation of data structure invariants
uninterpreted inductive separation logic predicates
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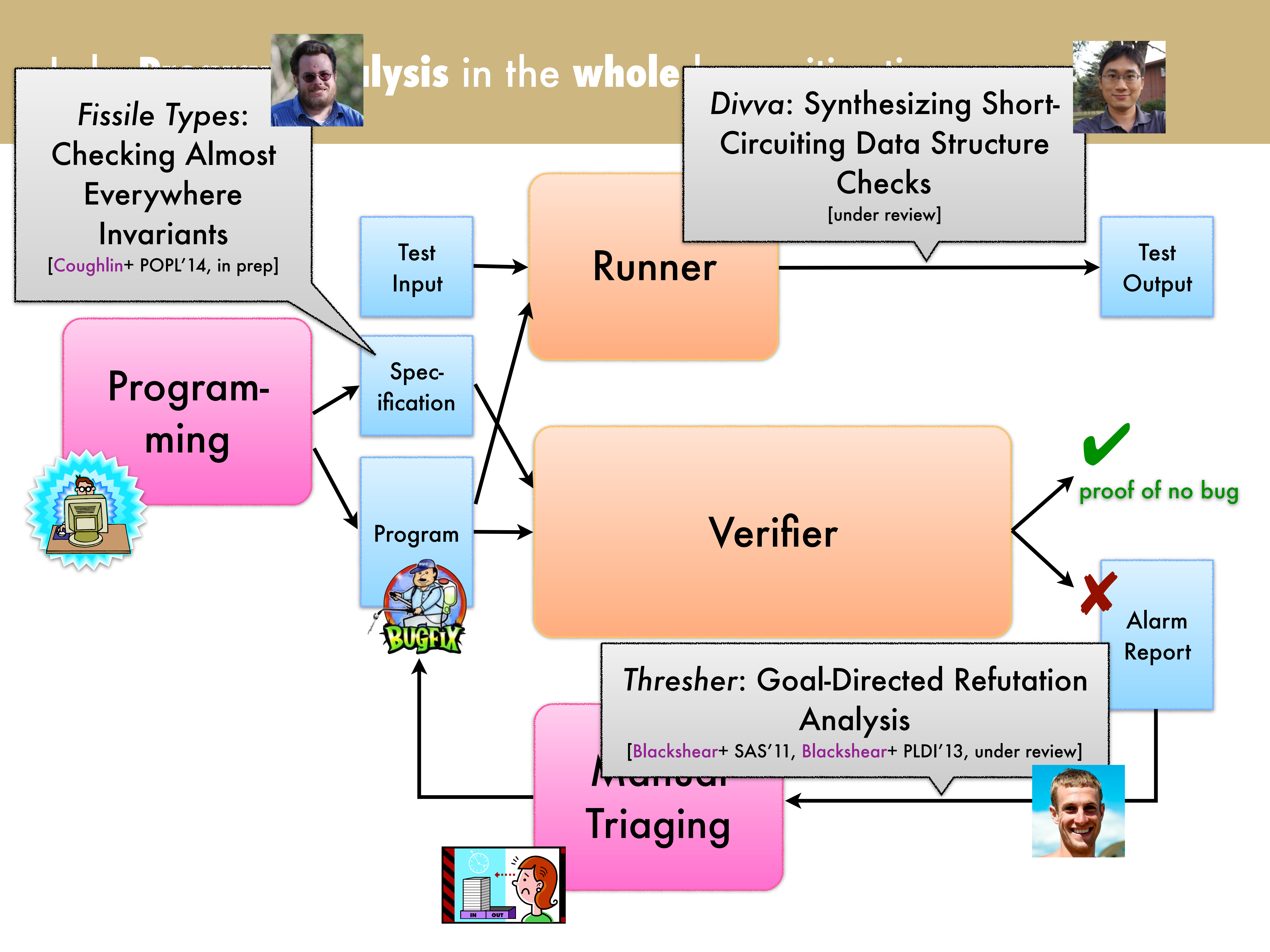

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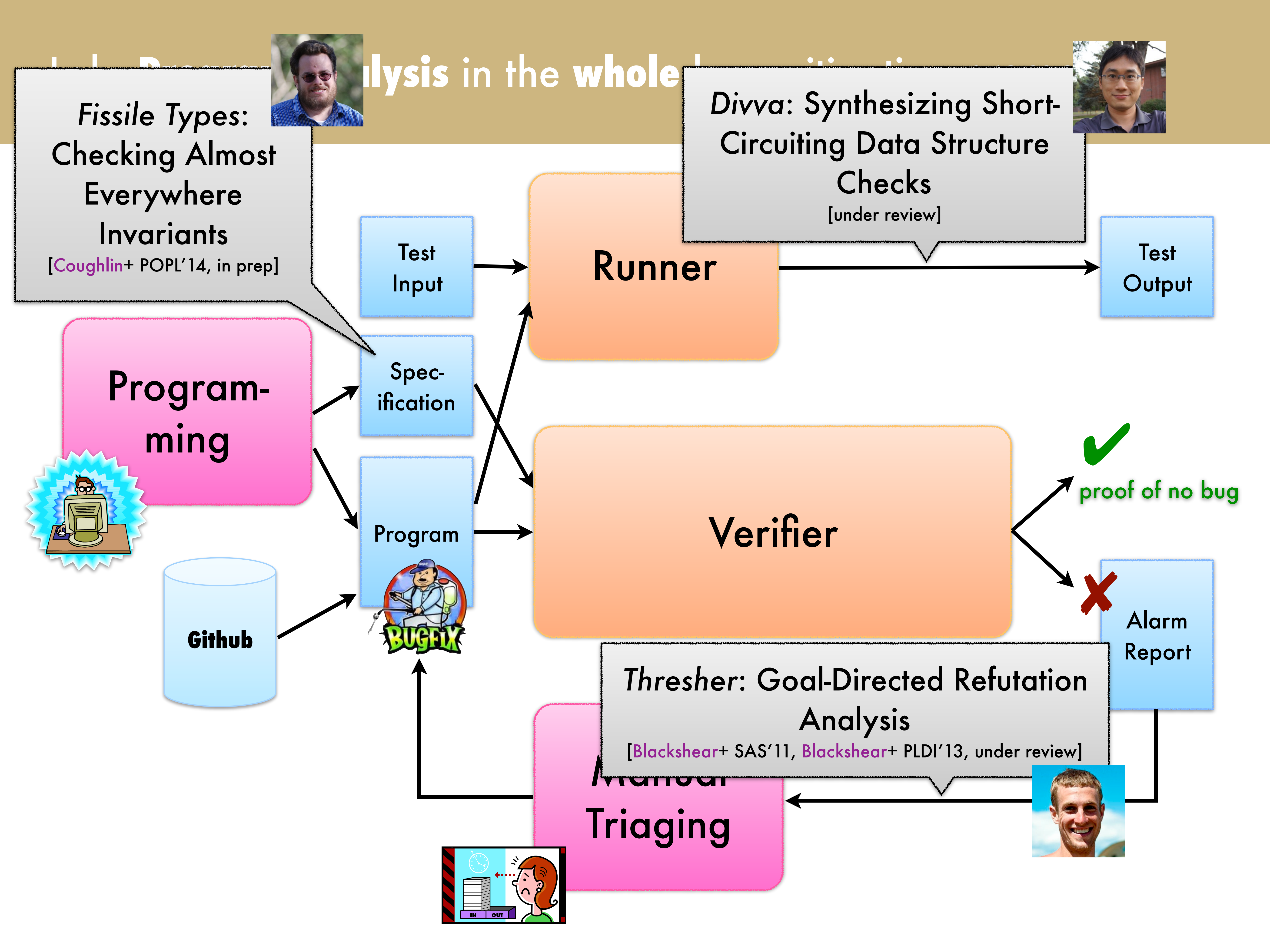

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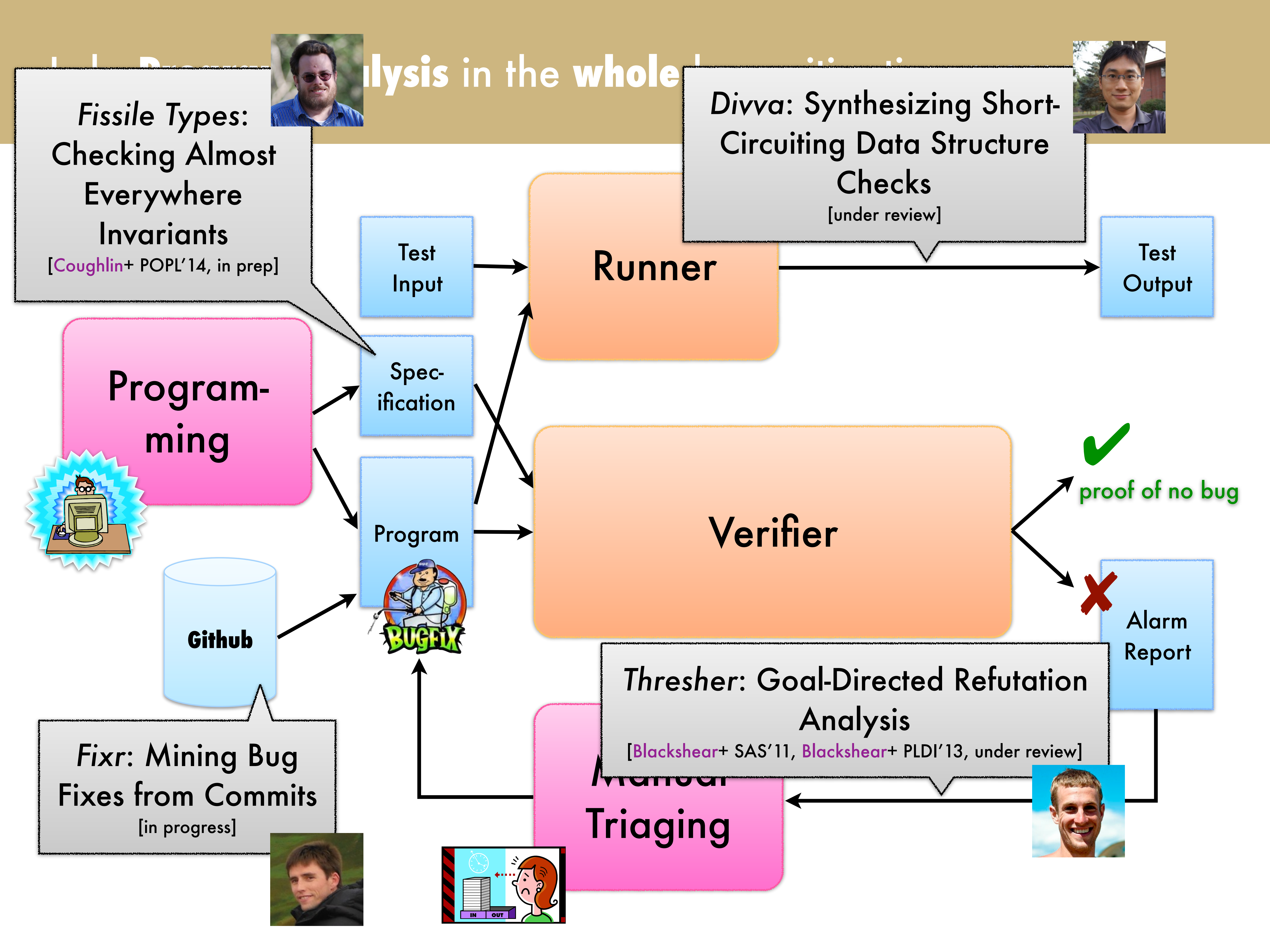

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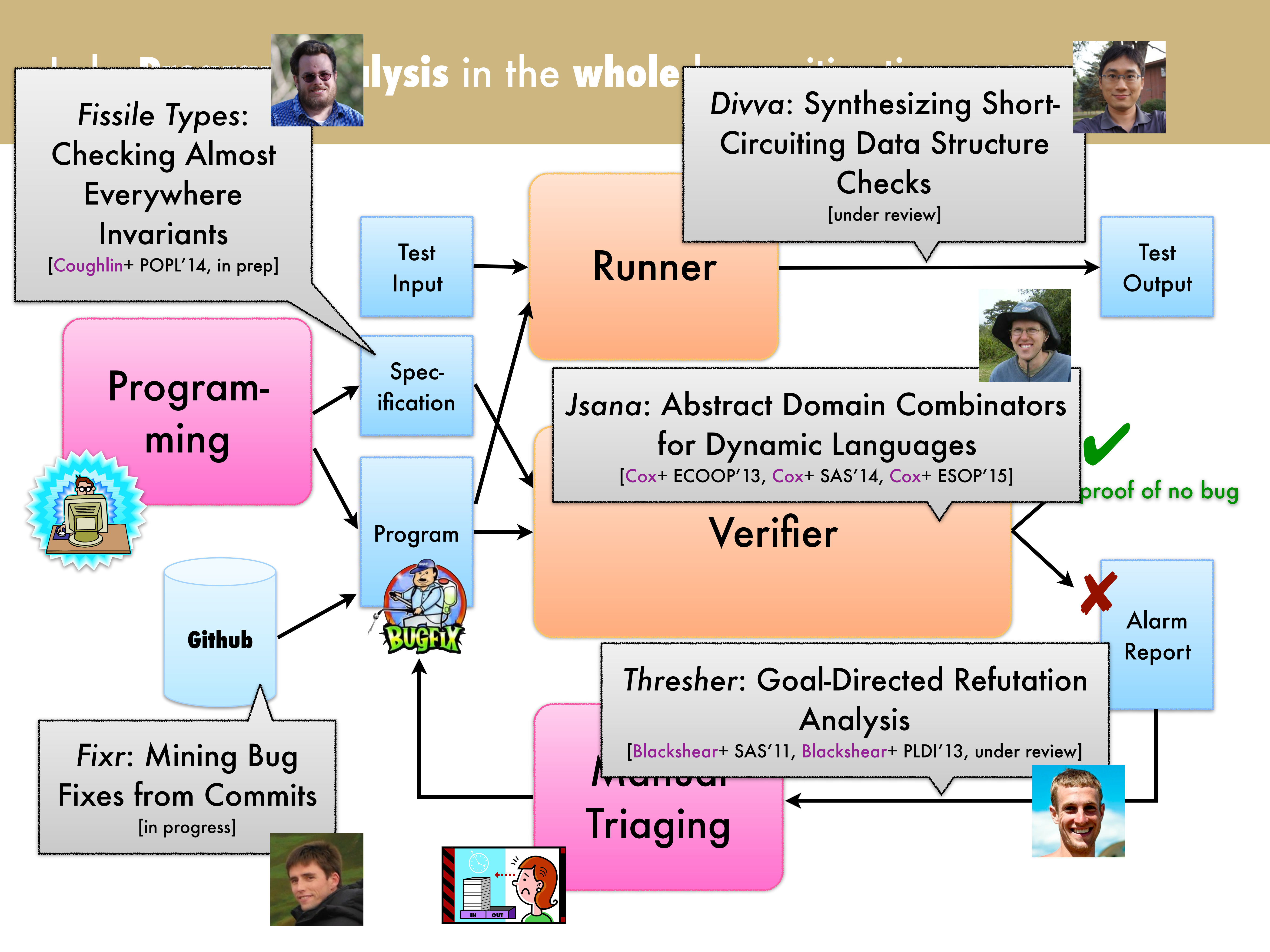

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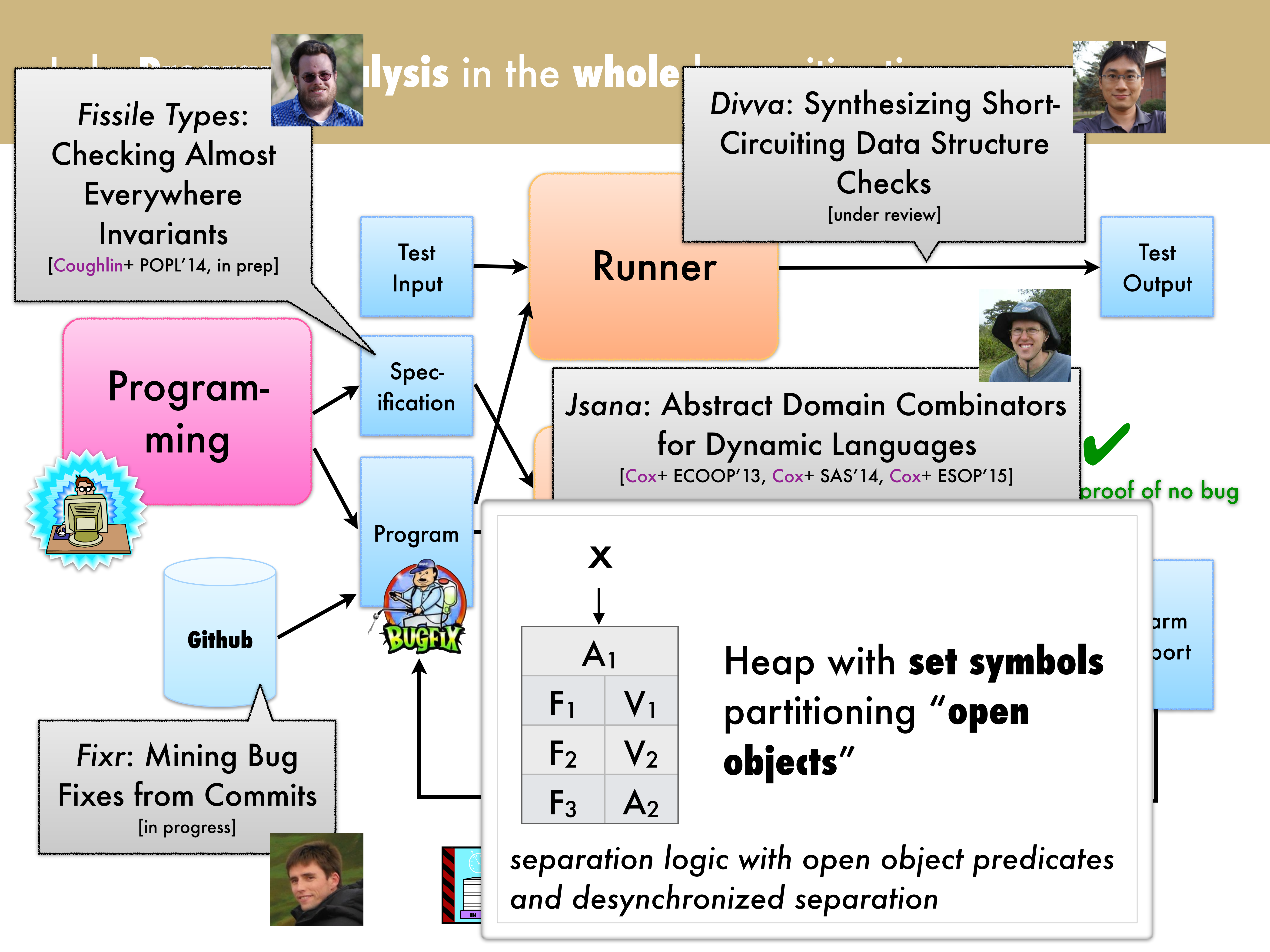

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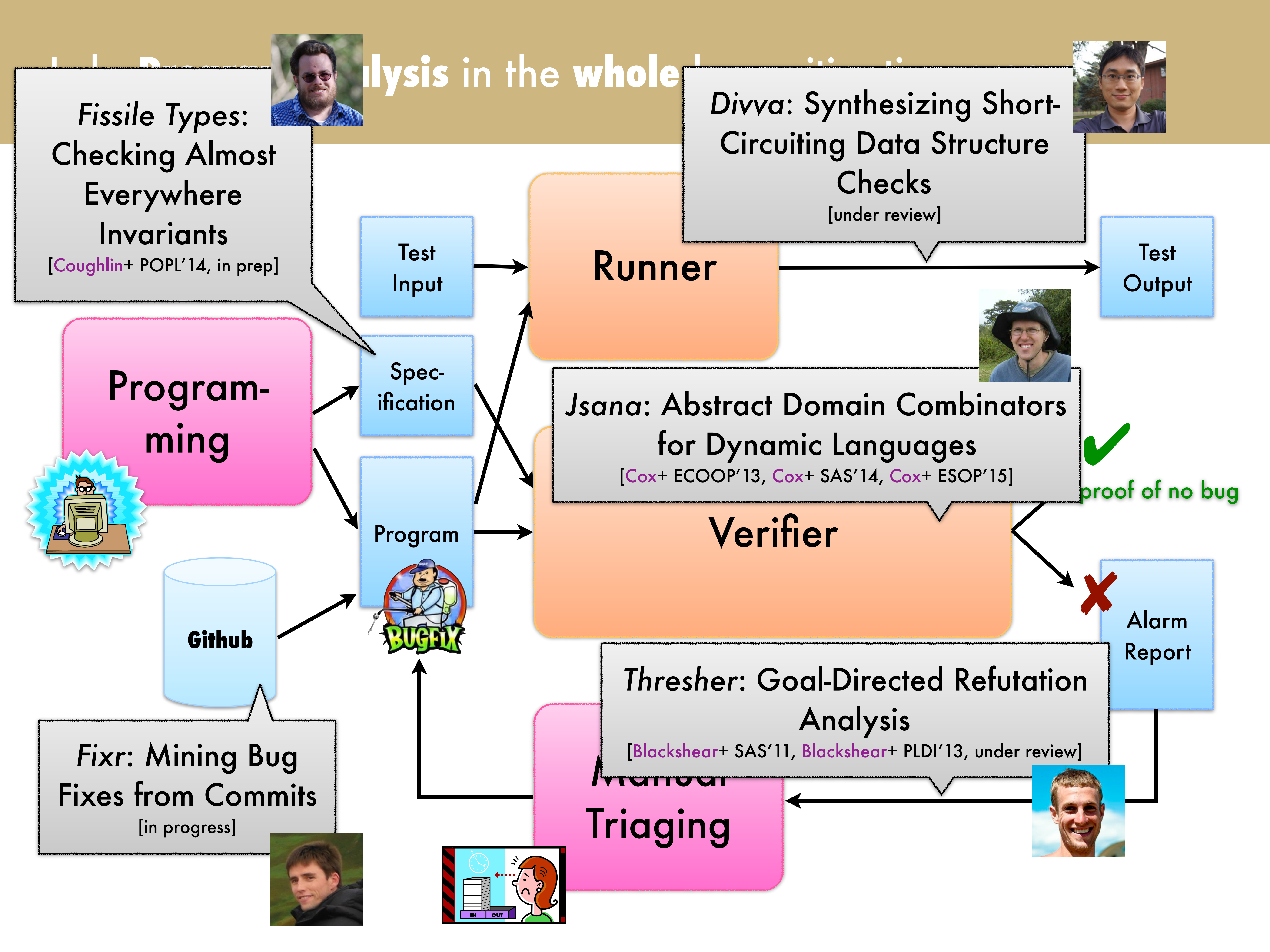
x
A1
F1 V1
F2 V2
F3 A2
Heap with set symbols partitioning "open objects"
separation logic with open object predicates and desynchronized separation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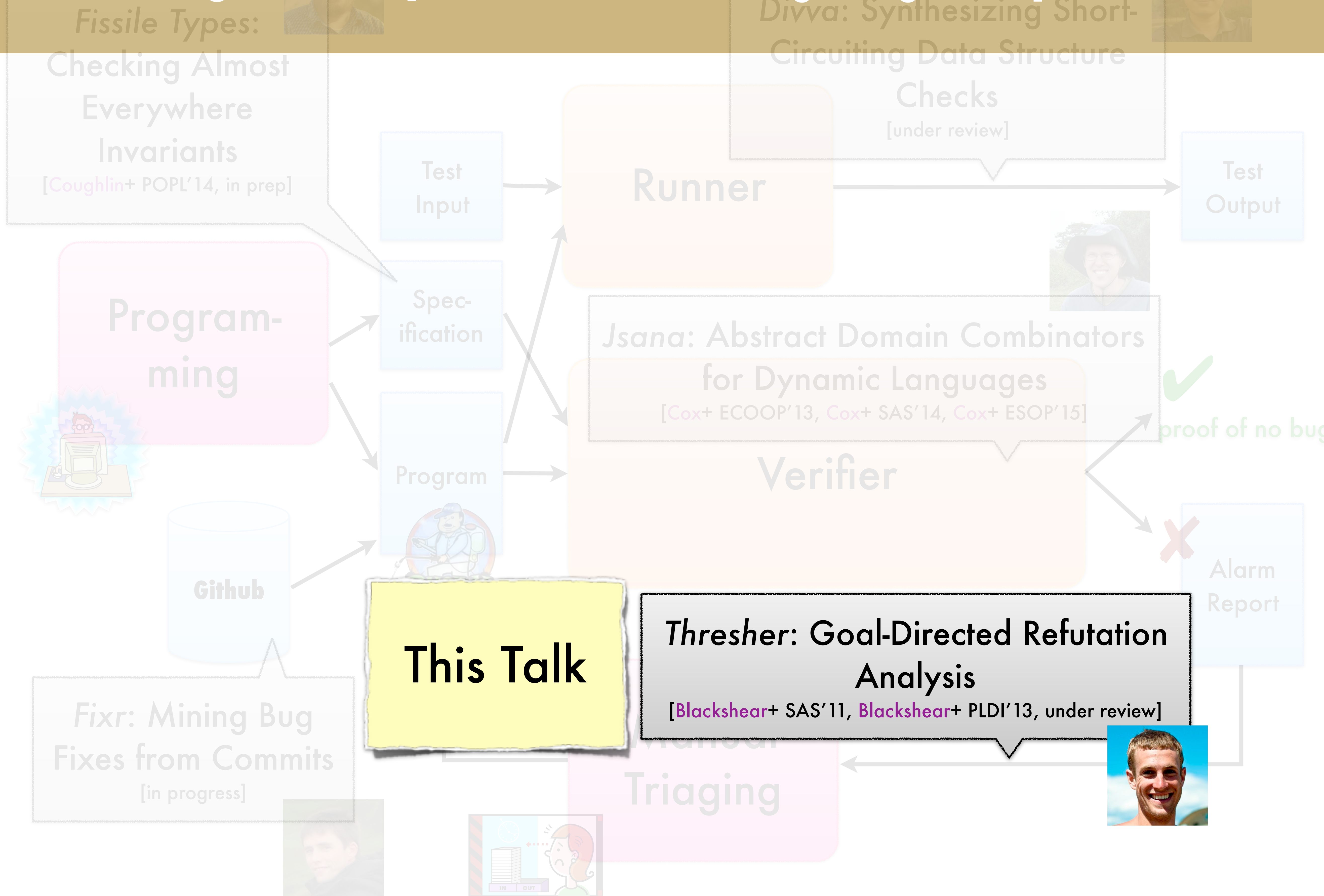

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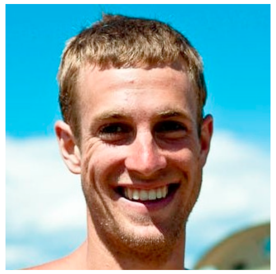

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crash

Roughly, 3% of all commits fix NullPointerExceptions

Callback-oriented programming

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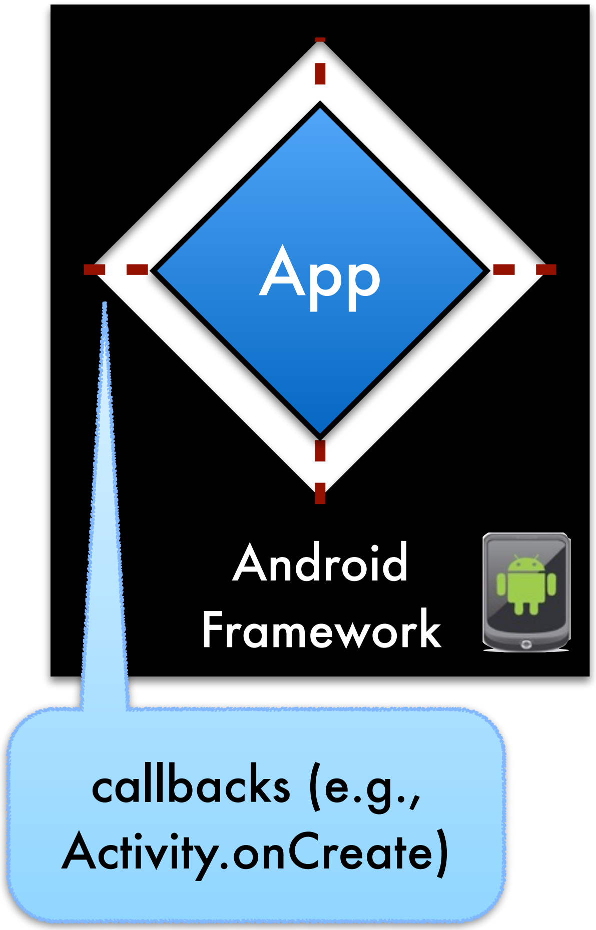
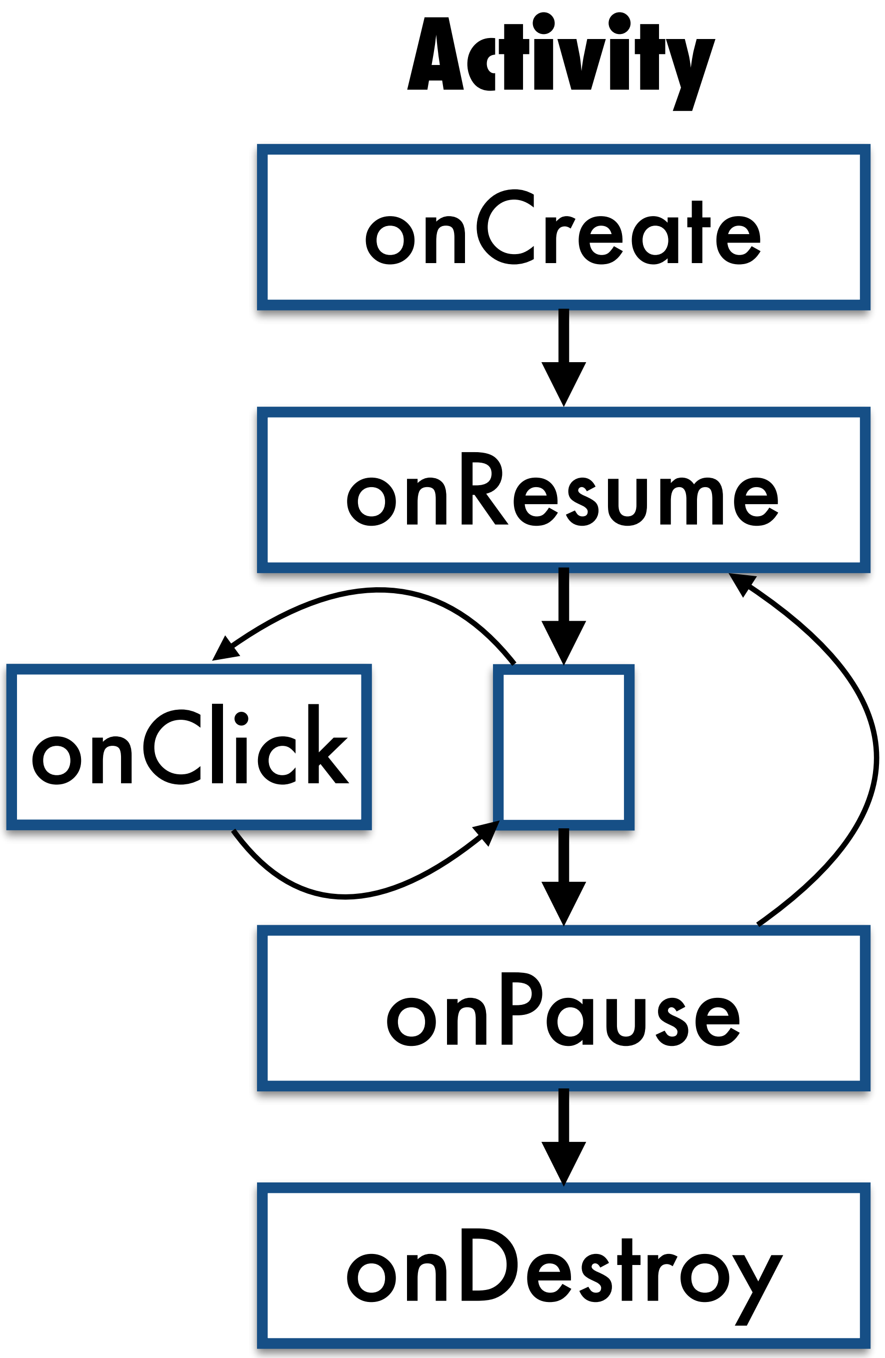
callbacks (e.g., Activity.onCreate)

Callback-oriented programming





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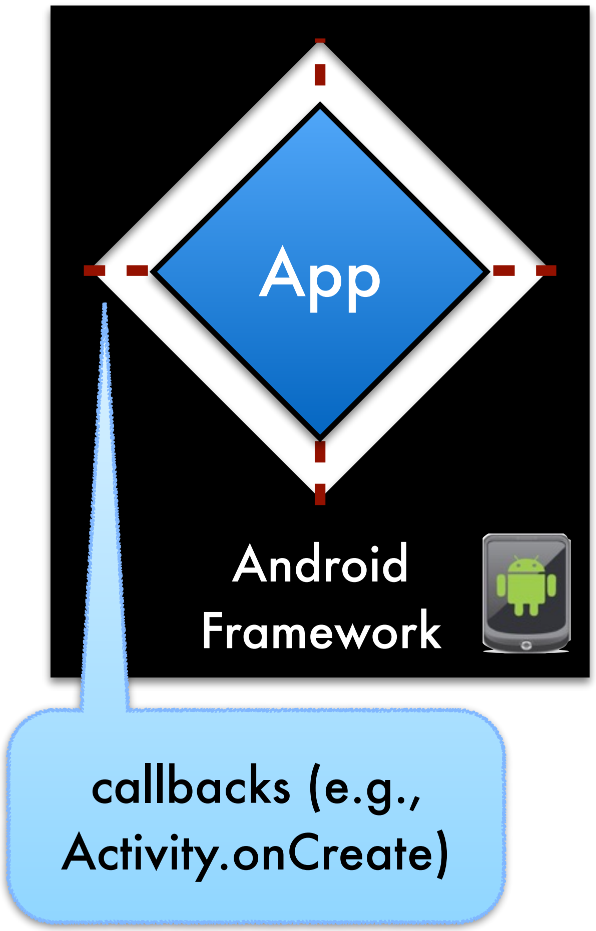

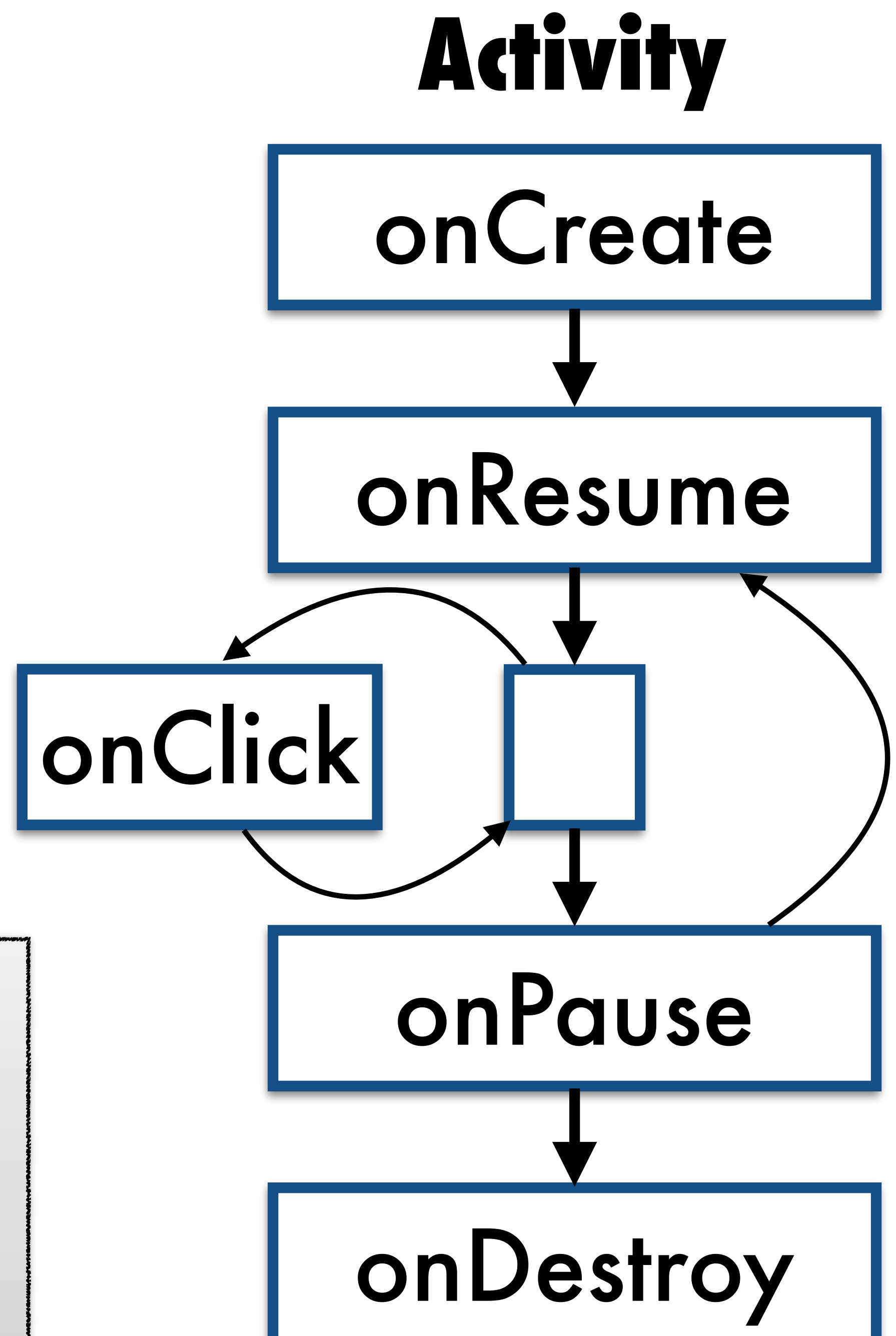

Android components have an ordered, event-driven lifecycle

Callback-oriented programming

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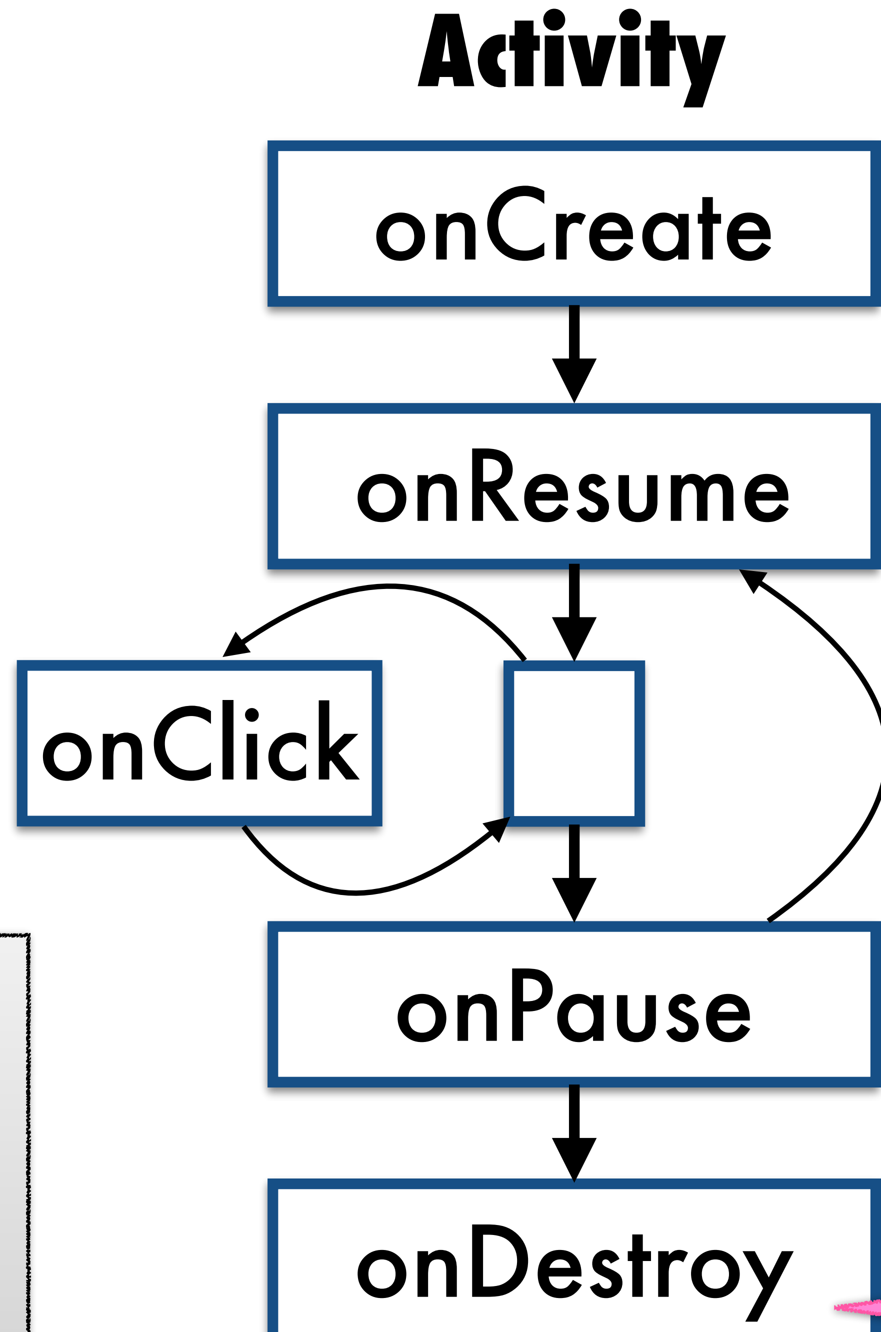


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mHostDb = null;
mService = null;
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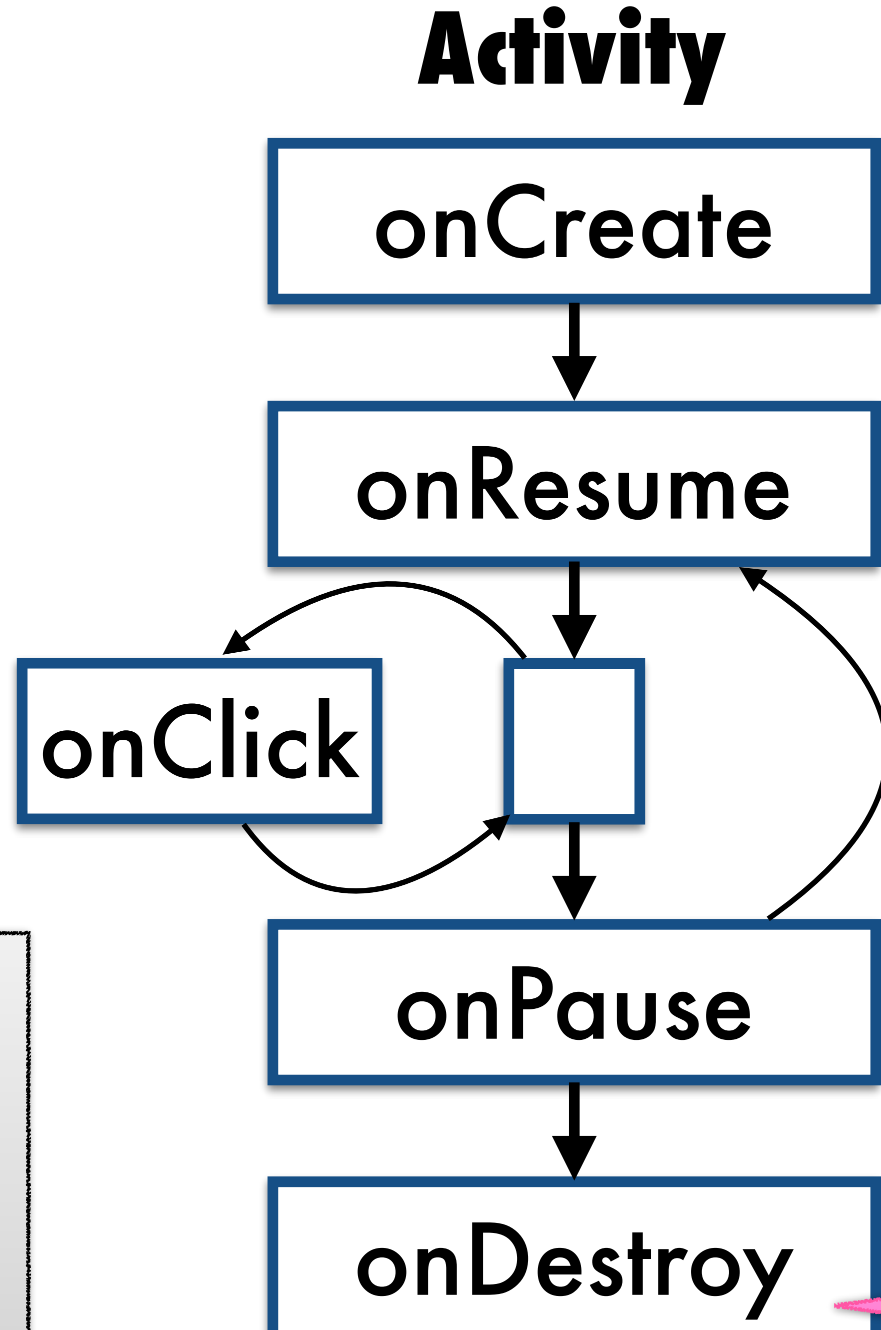

But, lifecycles of different components and other callbacks can interleave …

```
mHostDb = null;
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Callback-oriented programming

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

Android Framework

callbacks (e.g., Activity.onCreate)

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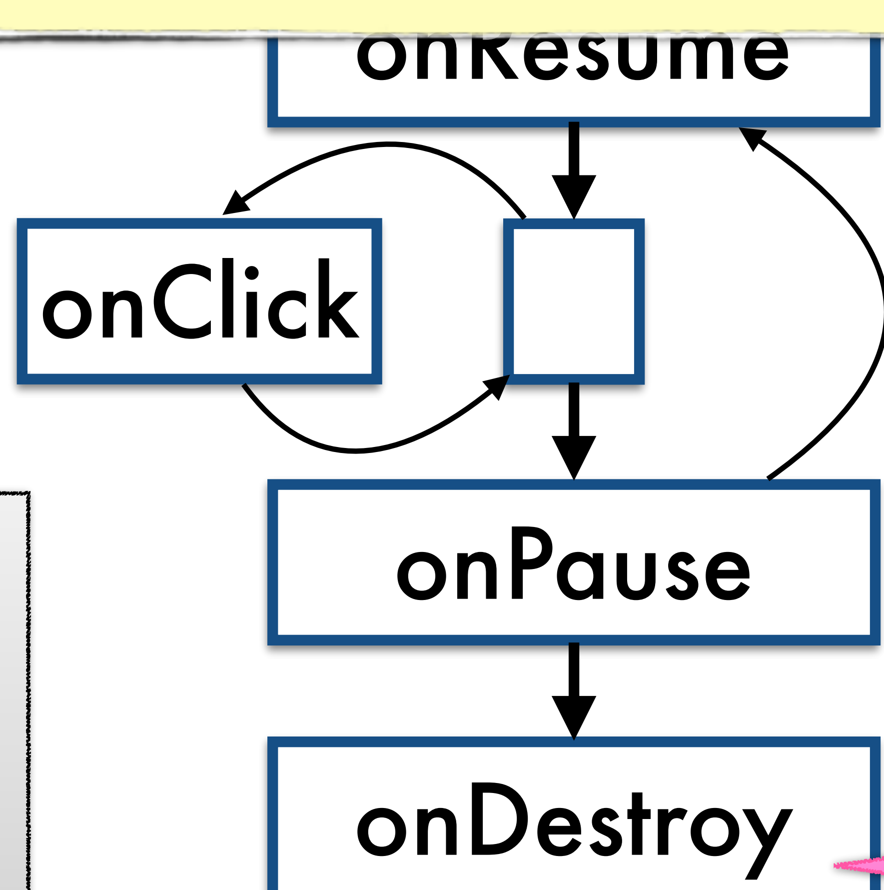

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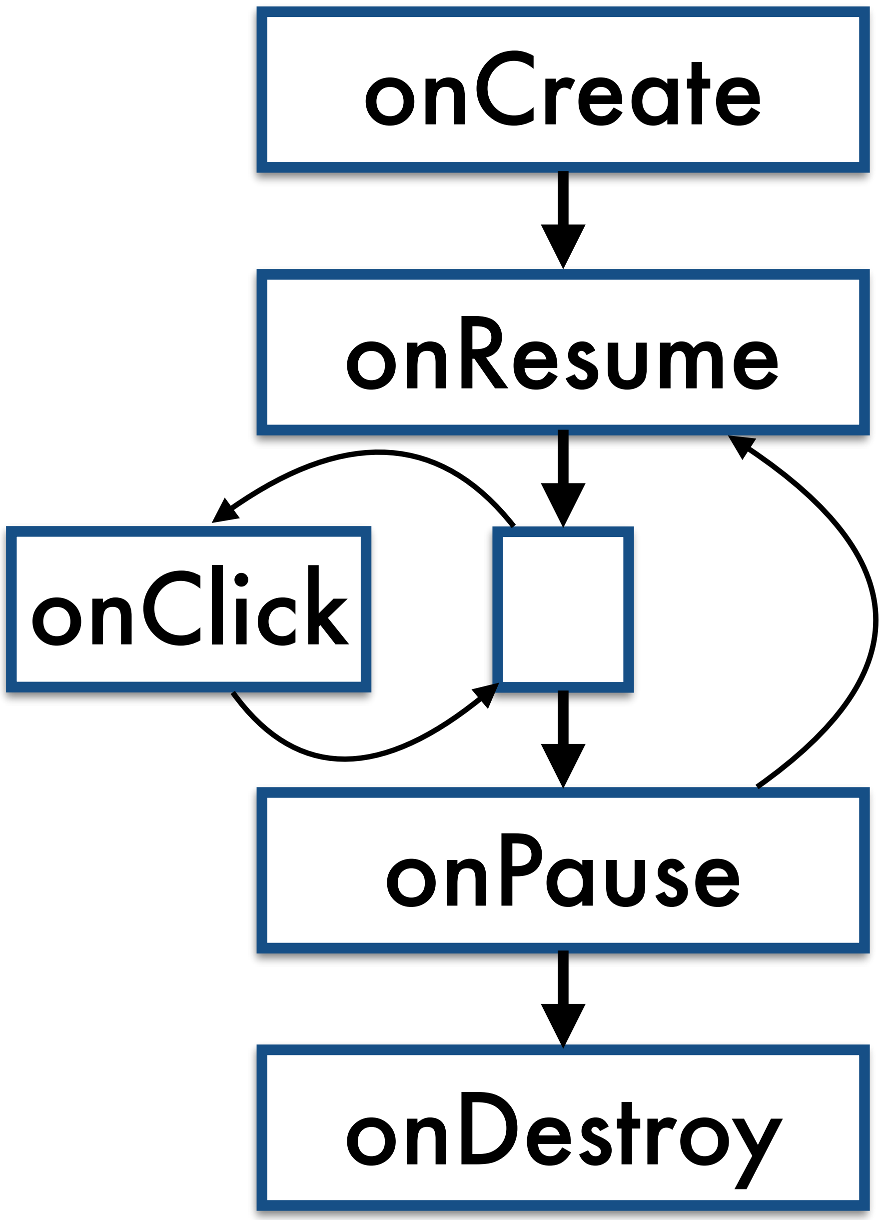

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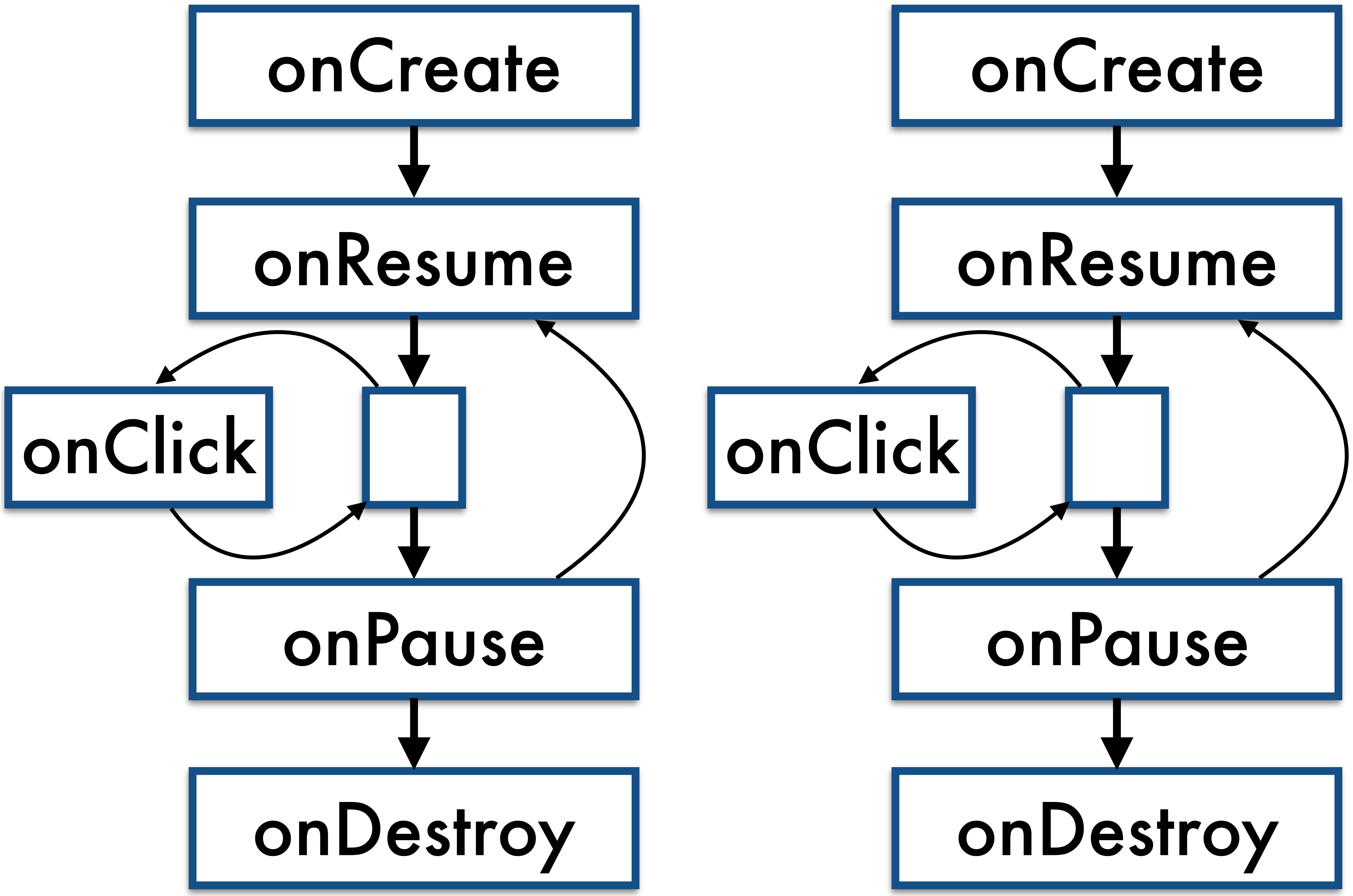

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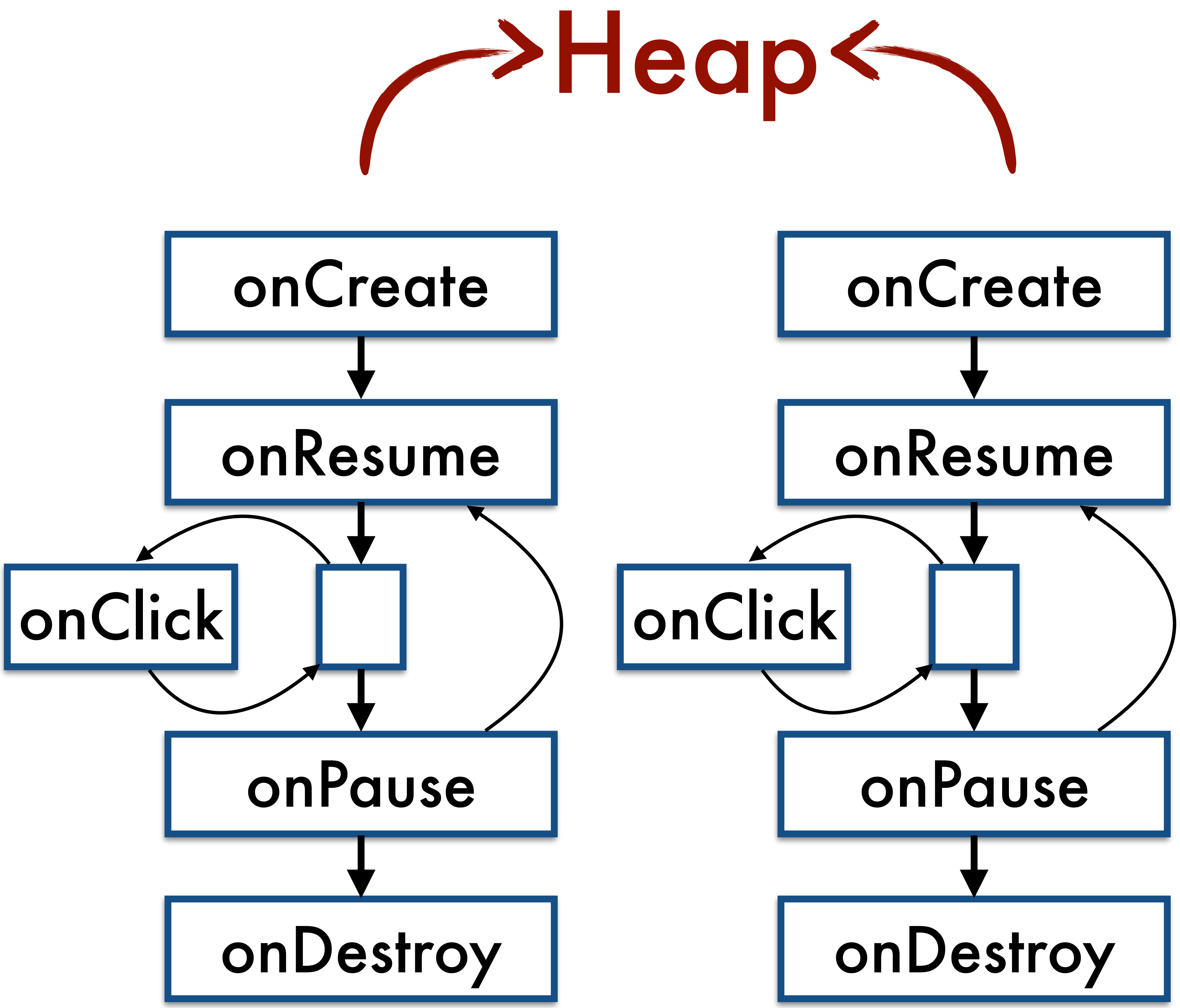

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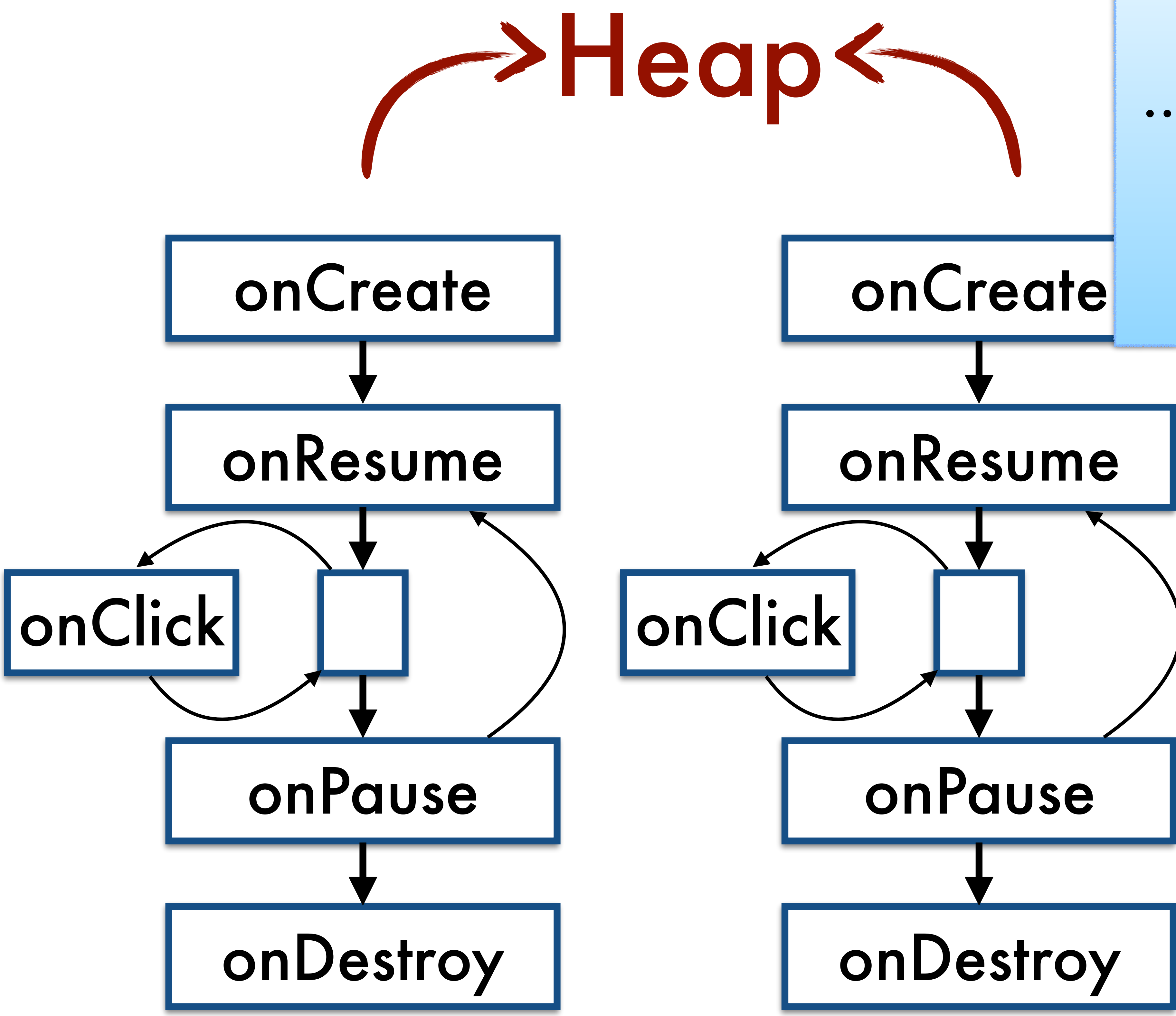
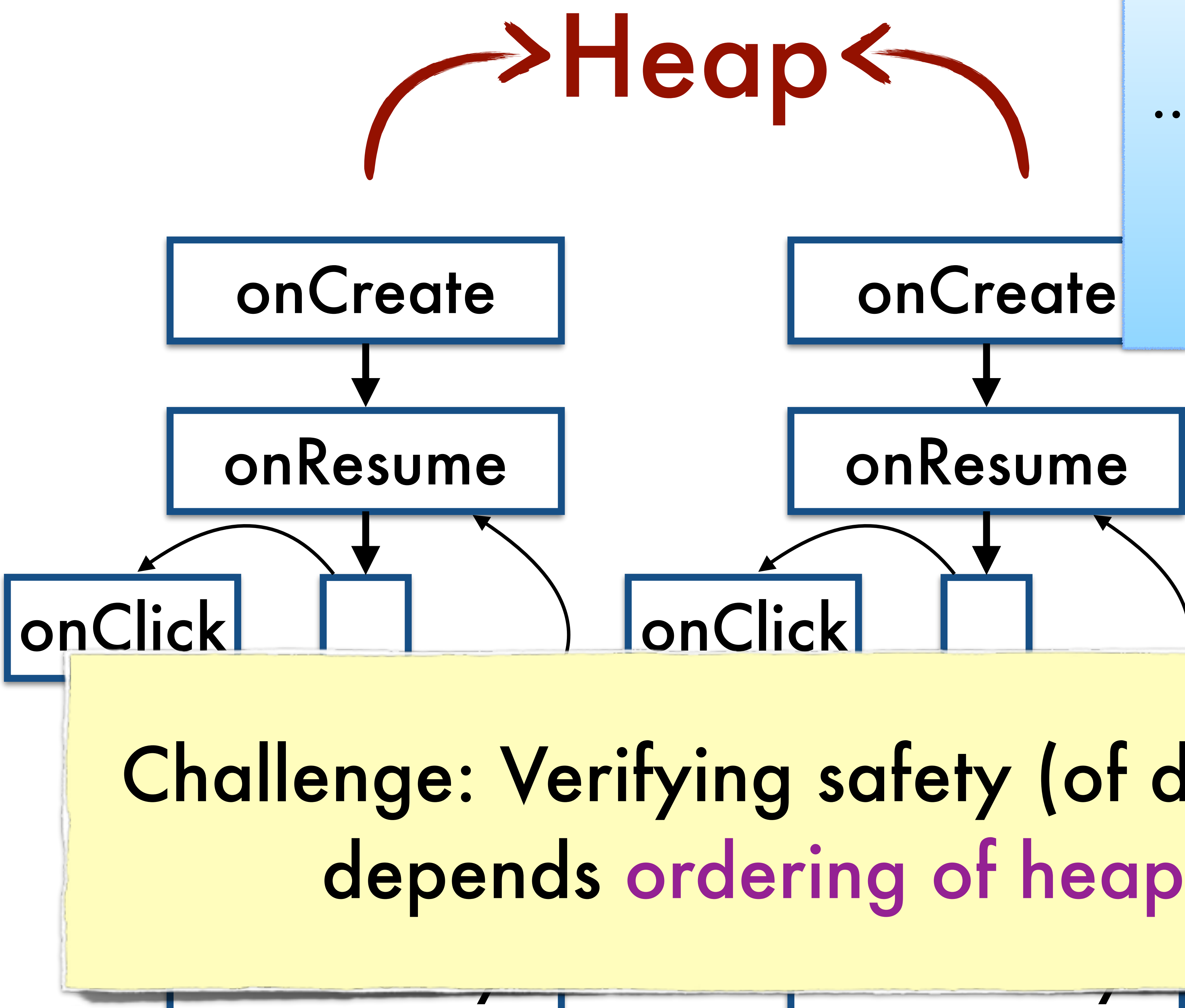


... and operates over a shared, global heap

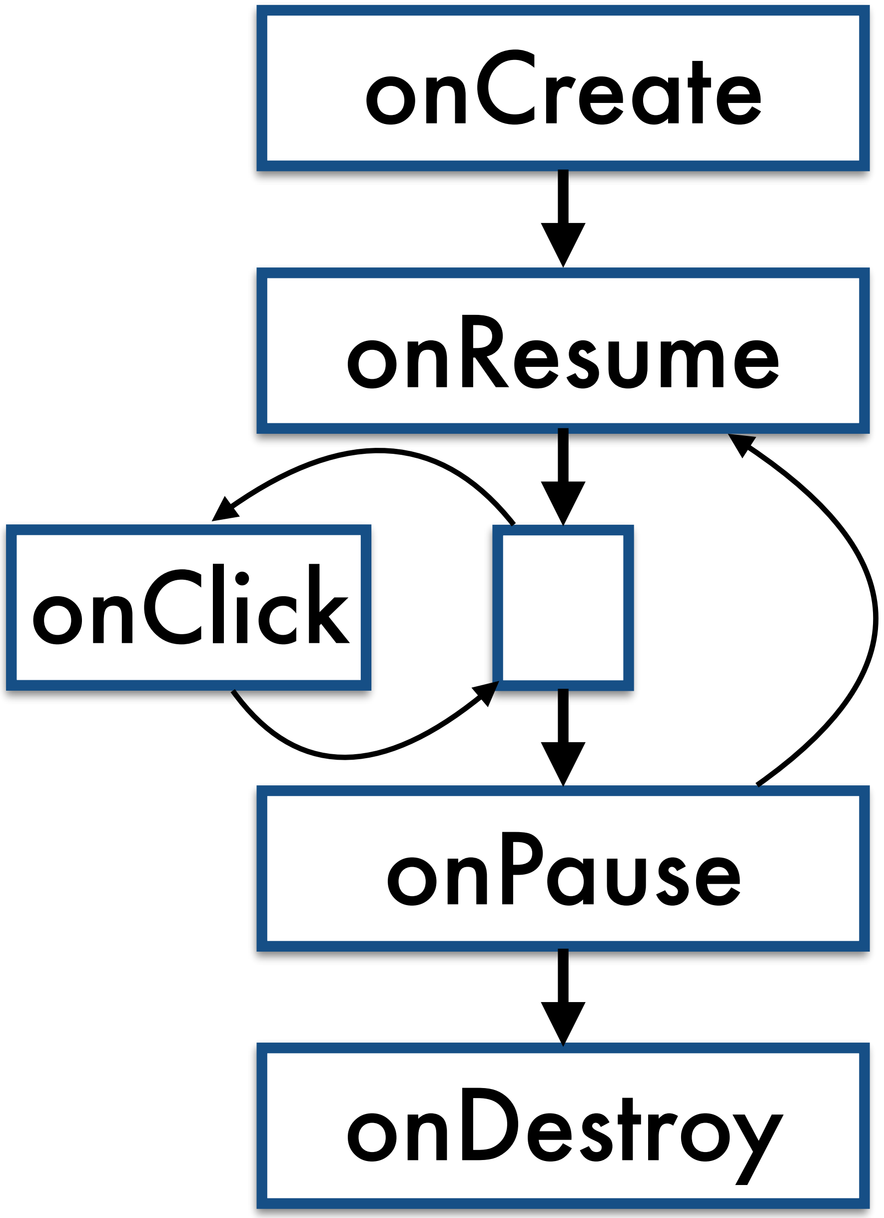
Callback-oriented programming



... 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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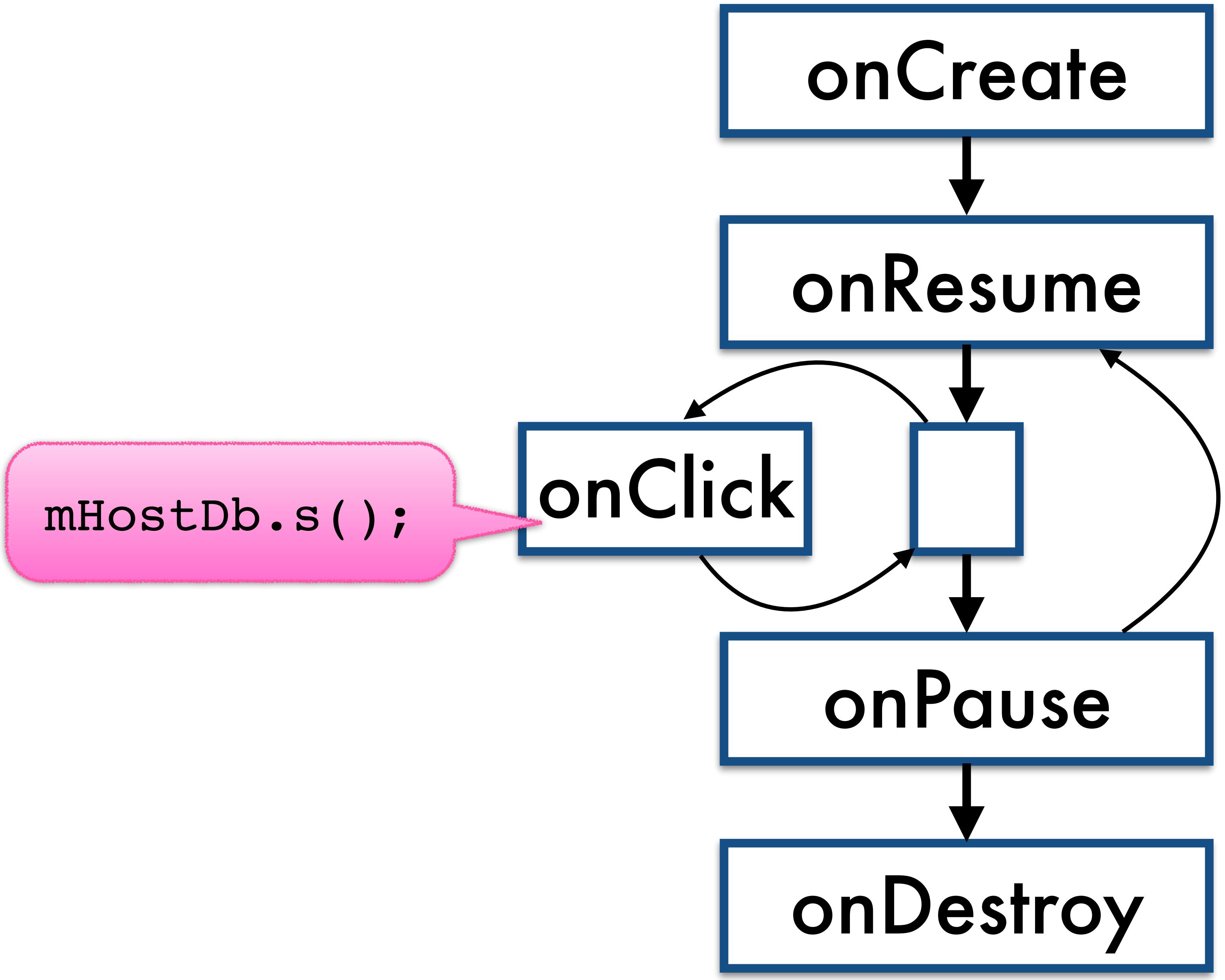

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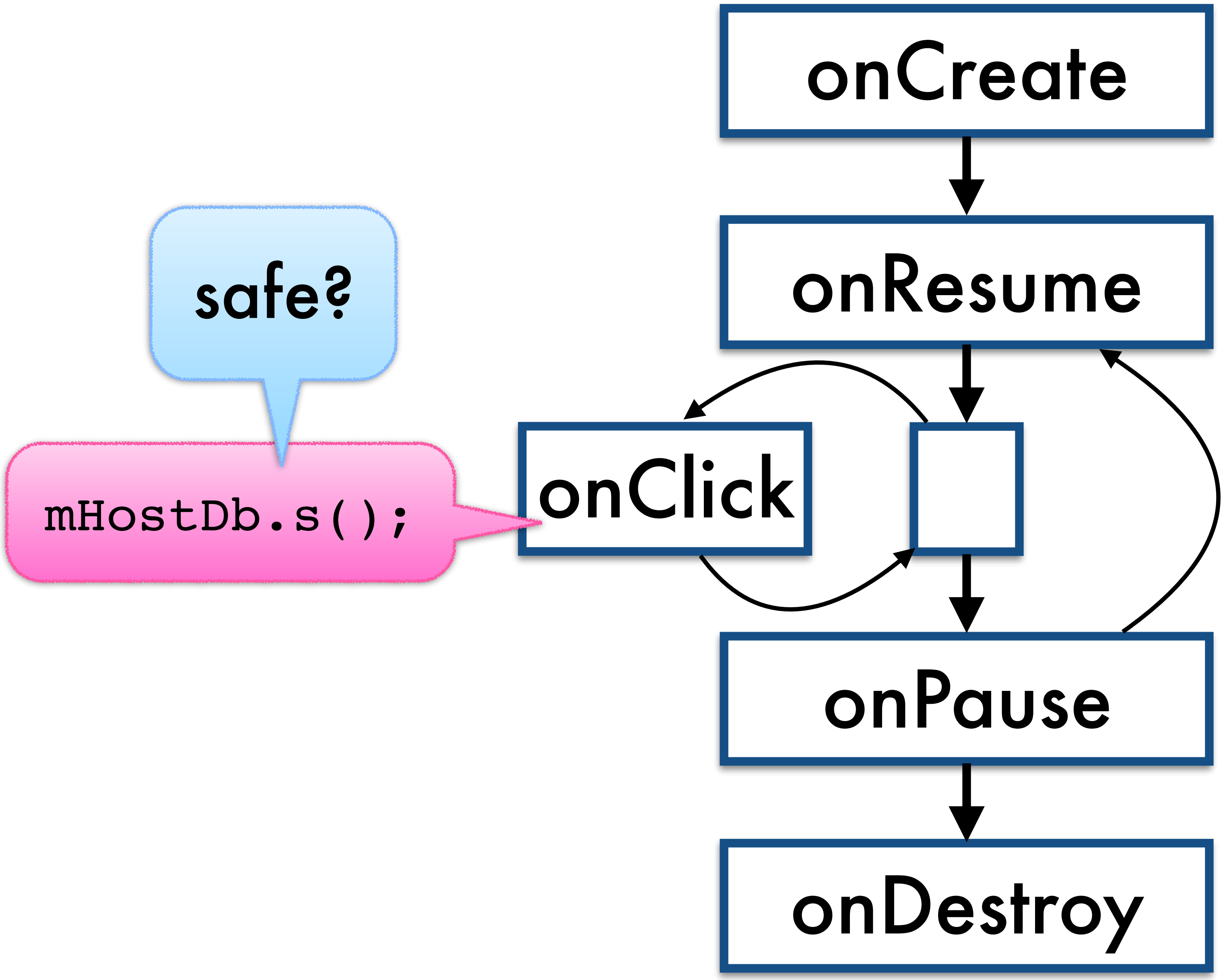

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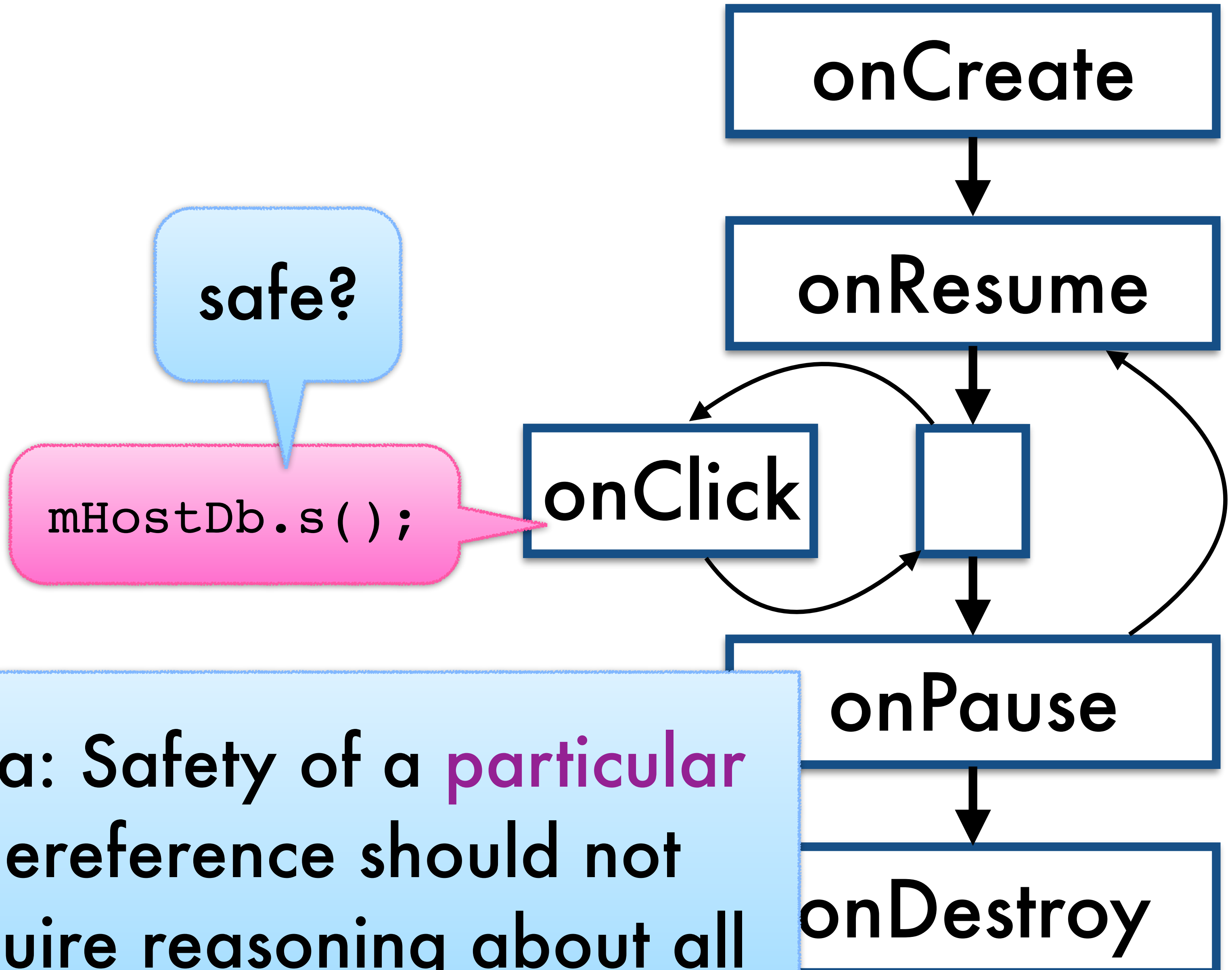
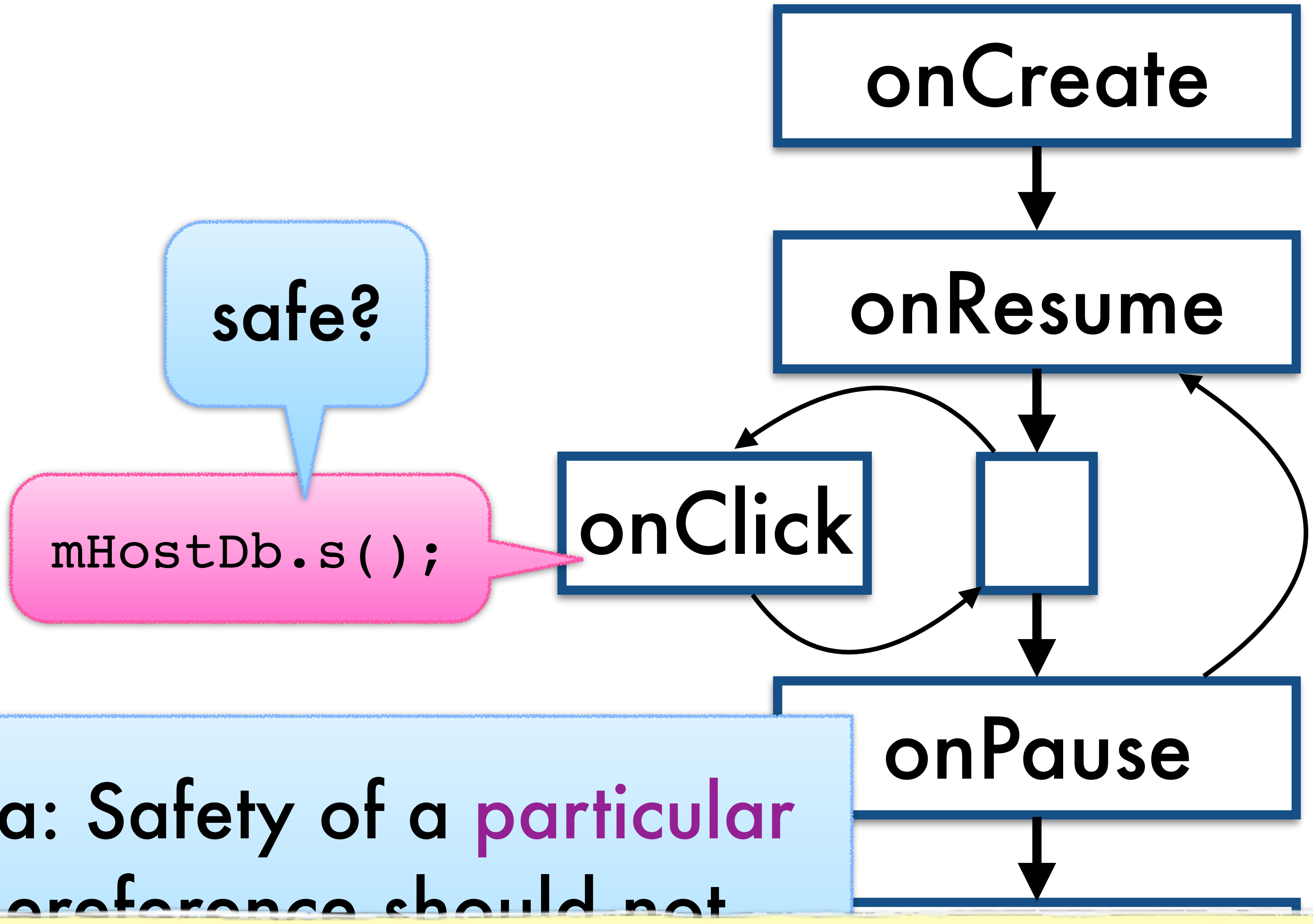


Idea: Safety of a particular dereference should not require reasoning about all callback interleavings

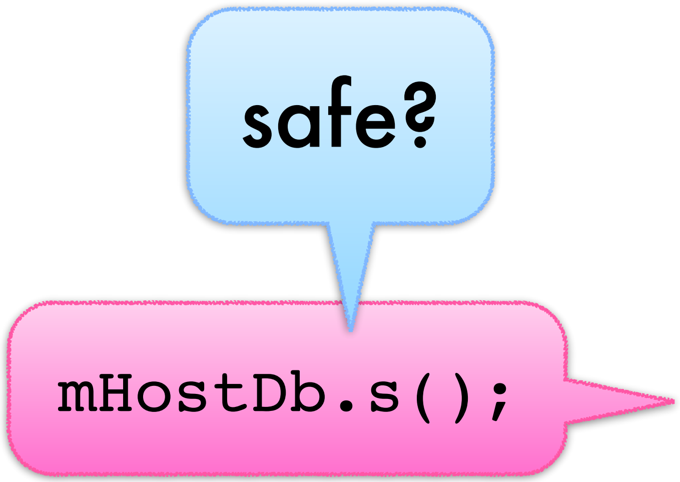
But it shouldn’t be so hard …



Idea: Safety of a particular dereference should not

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

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`mHostDb.s();`

`mHostDb == null`

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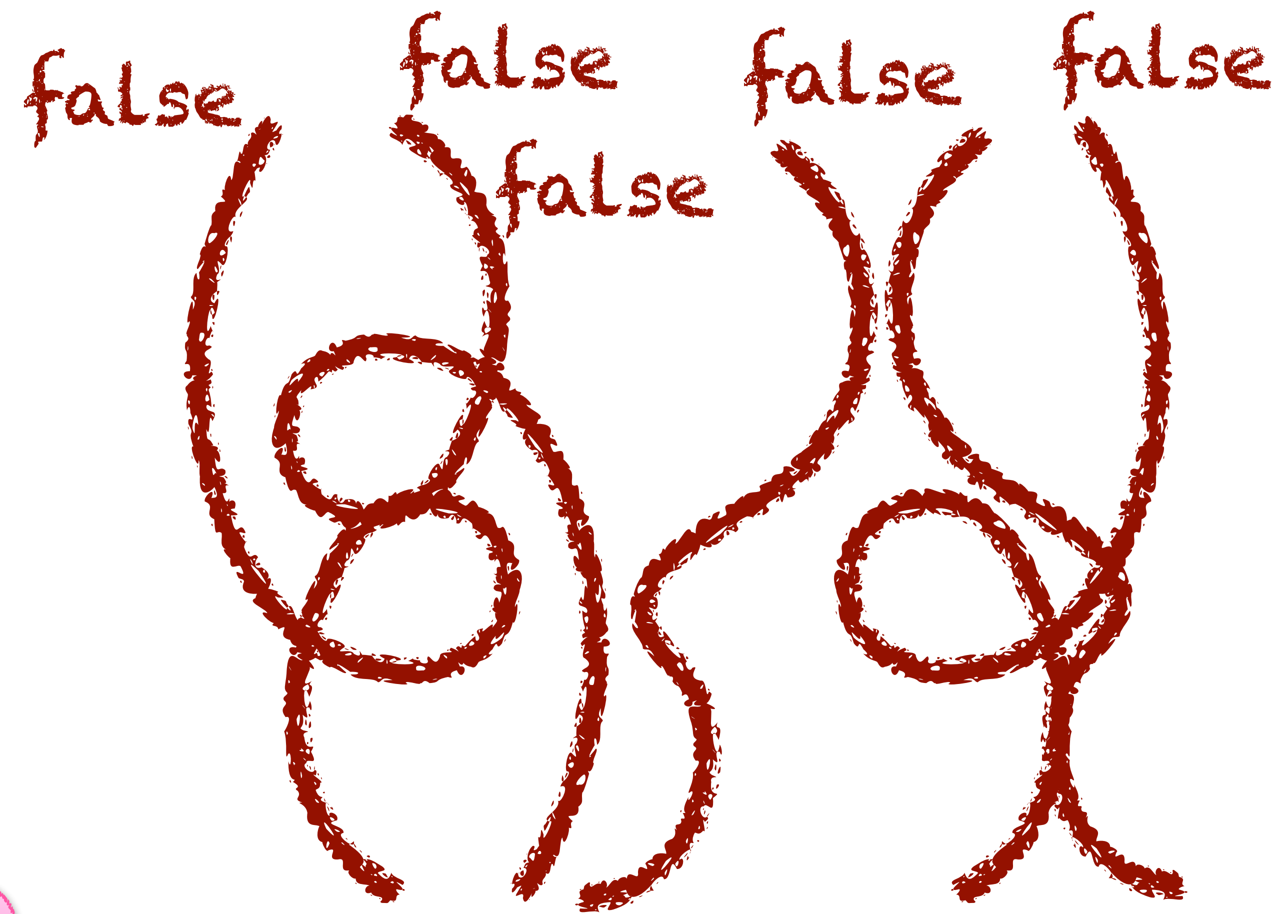

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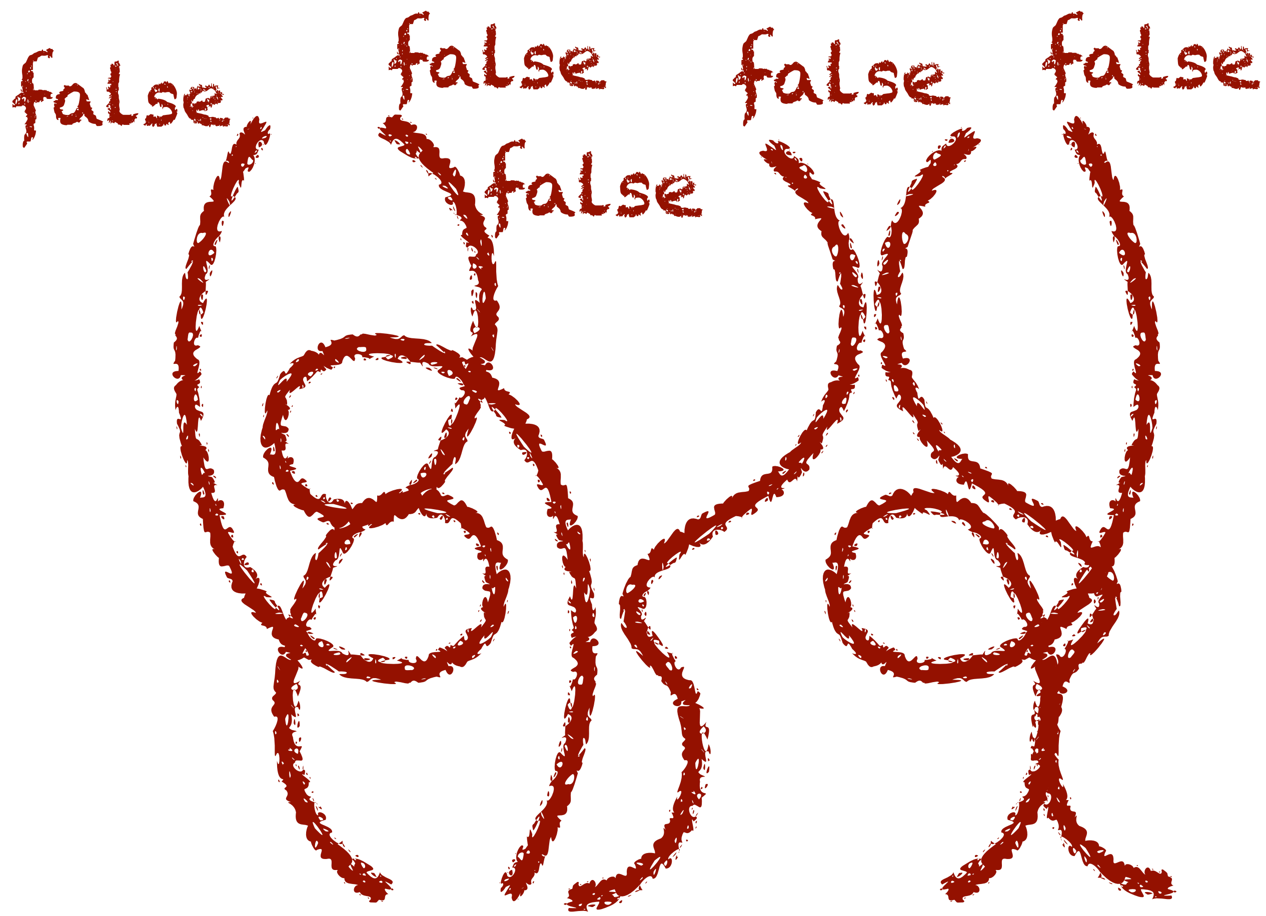

$$(\mathbf{this} \mapsto \widehat{t} * \widehat{t} \cdot \texttt{mHostDb} \mapsto \widehat{a} * \mathsf{true}) \wedge \widehat{a} = \mathsf{null}$$

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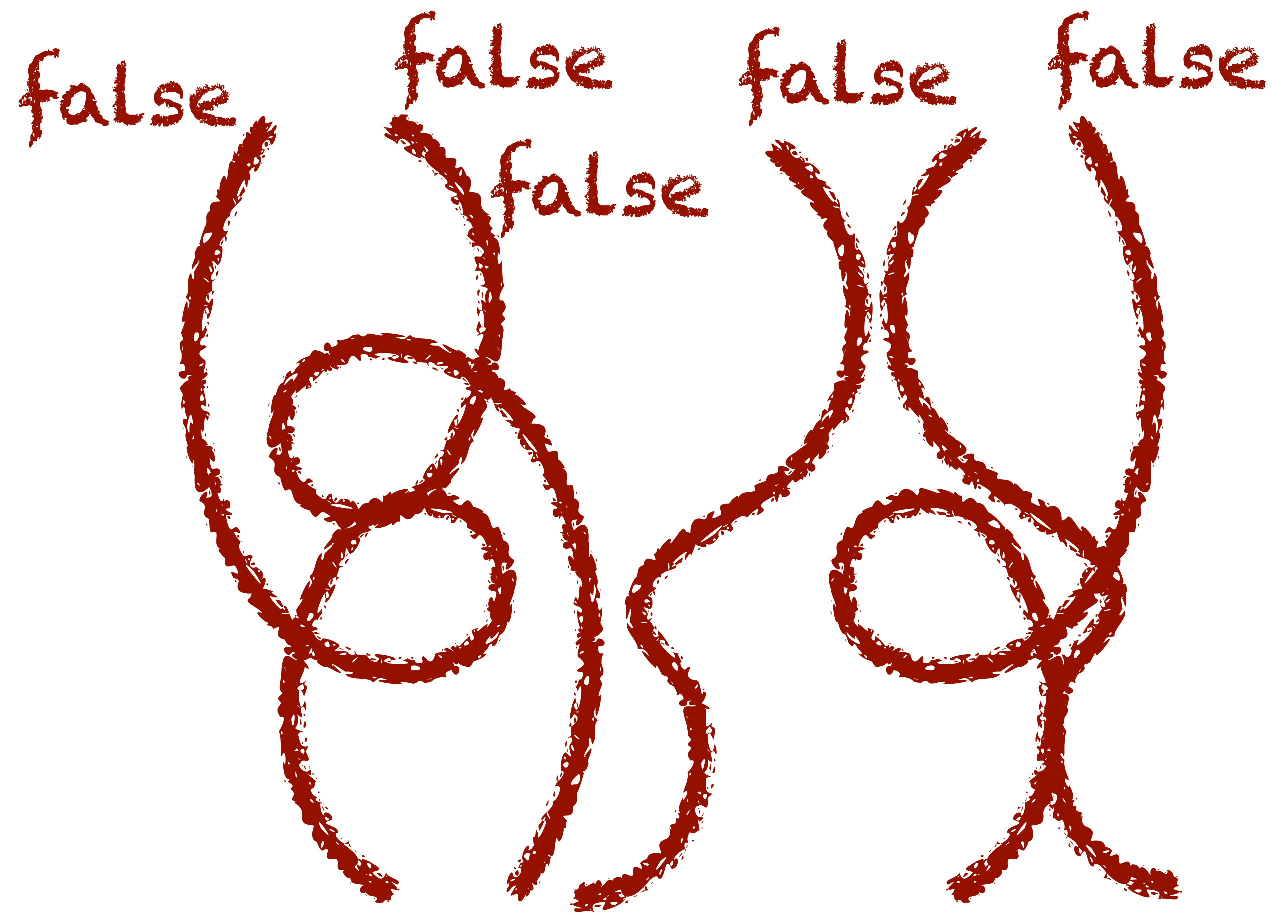
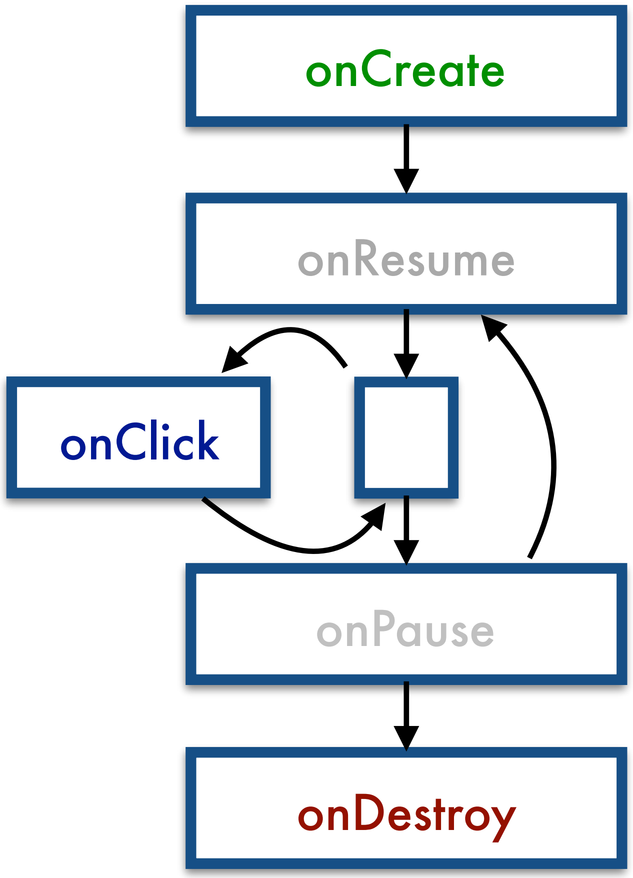
Given a program configuration **goal**, derive a **contradiction** w.r.t. its reachability



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

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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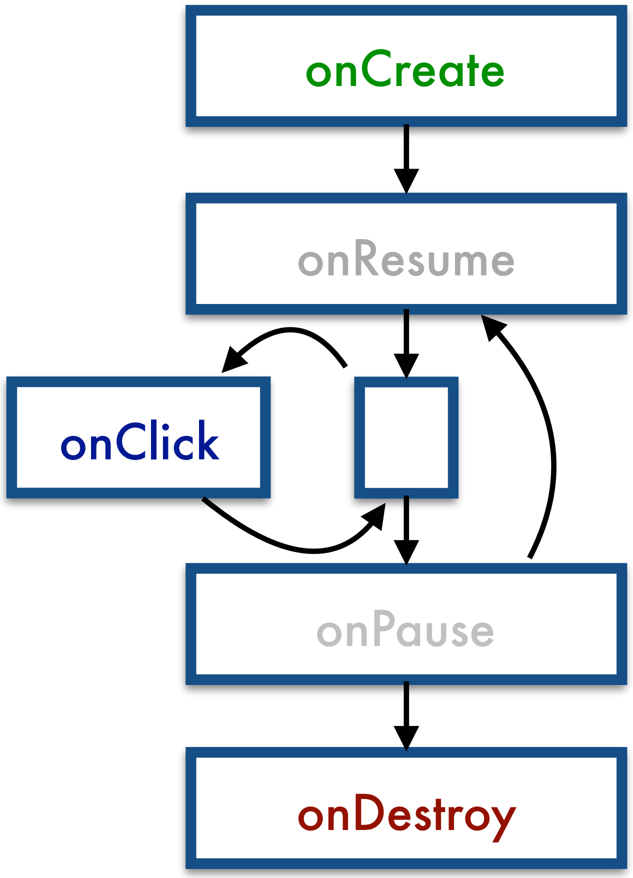
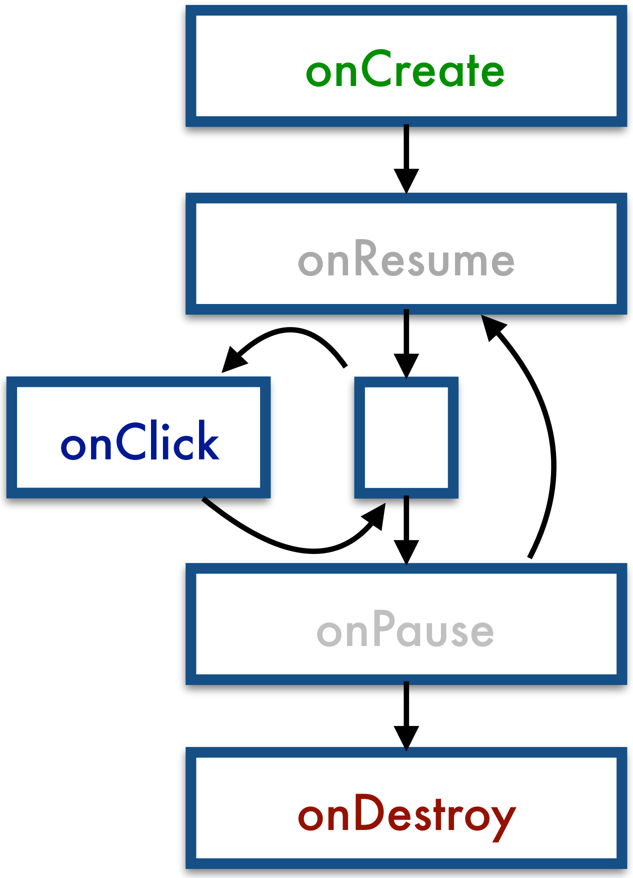



```
void onClick(…) {
  mHostDb.s(mService.g());
}
```

Two dereferences: one safe and one buggy

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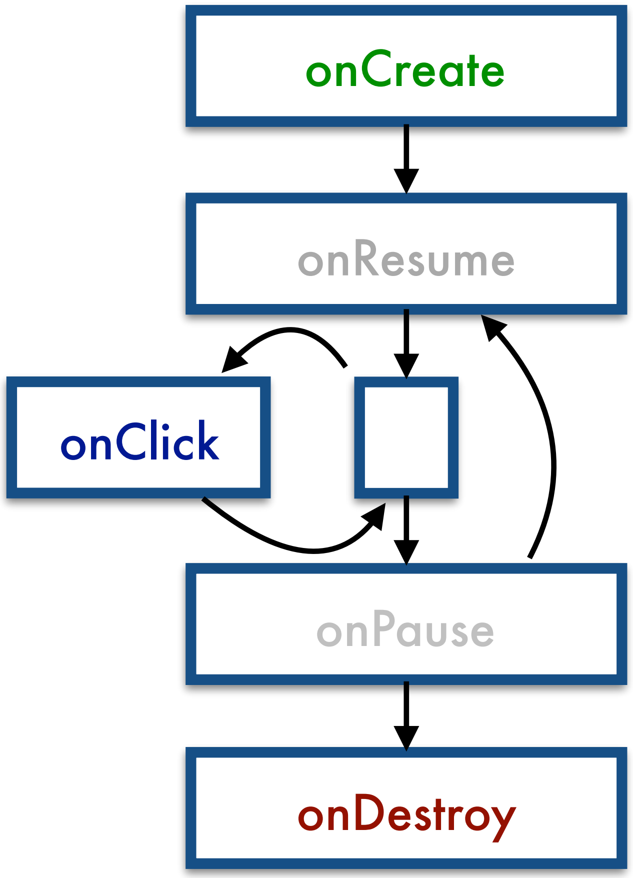

safe?

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void onClick(…) {
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```

1 2

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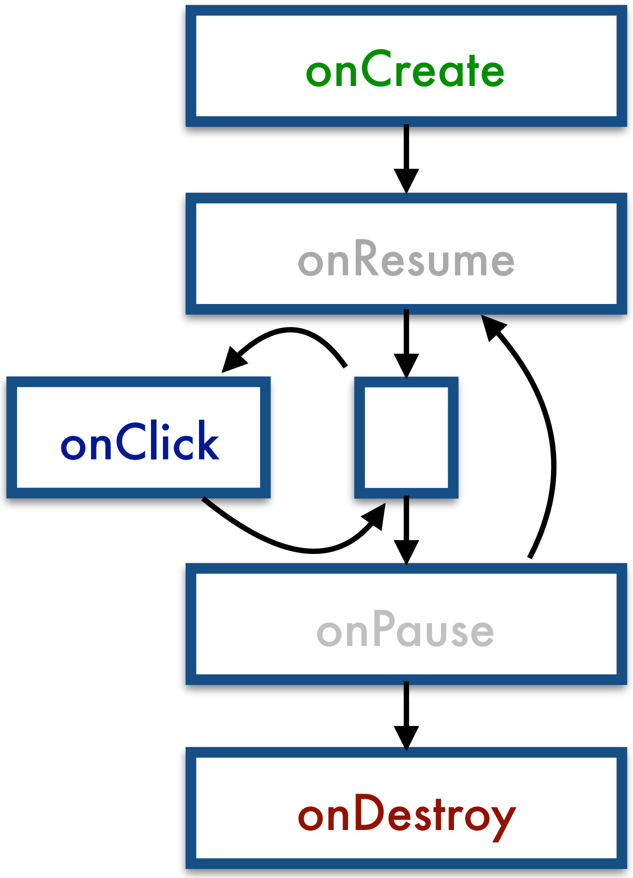
```

Two dereferences: one safe and one buggy



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1 2

lifecycle constraints relevant

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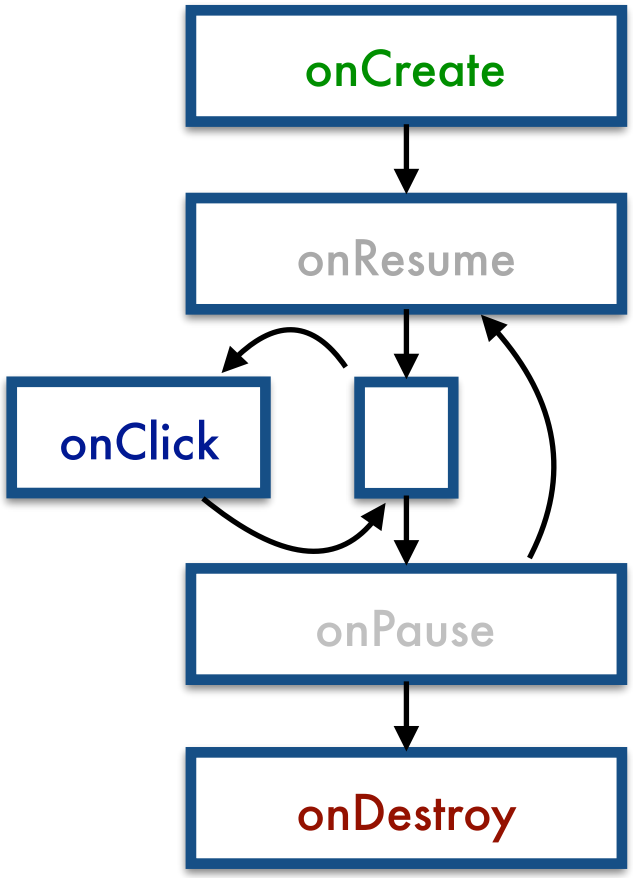



```
void onCreate() {
  bindService(…, new ServiceConn {
    void onConnected(@Nonnull Service s) {
      mService = s;
    }
  });
  mHostDb = new Db();
}
```

safe?

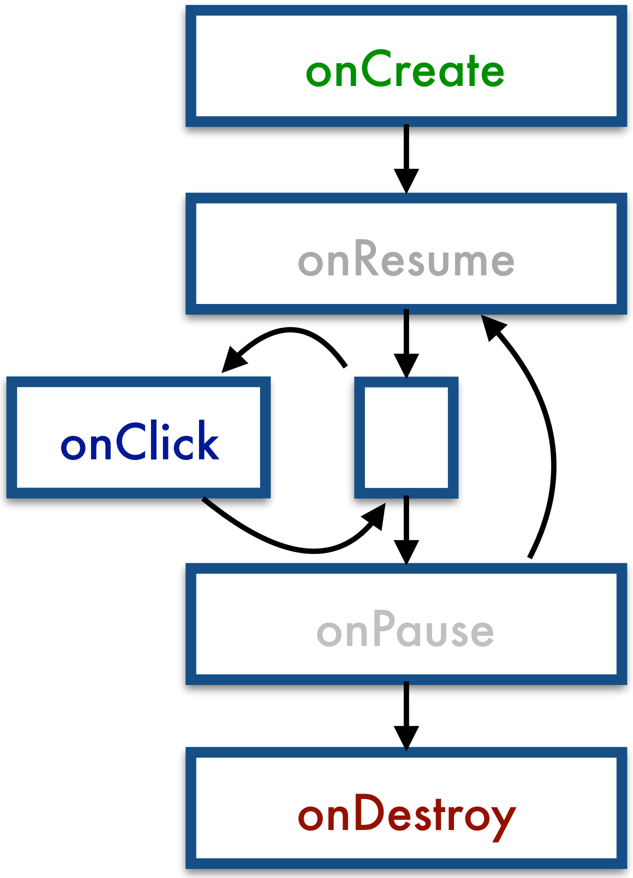
```
void onClick(…) {
  mHostDb.s(mService.g());
}
```

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();
}
```

safe?

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1 ✔ 2

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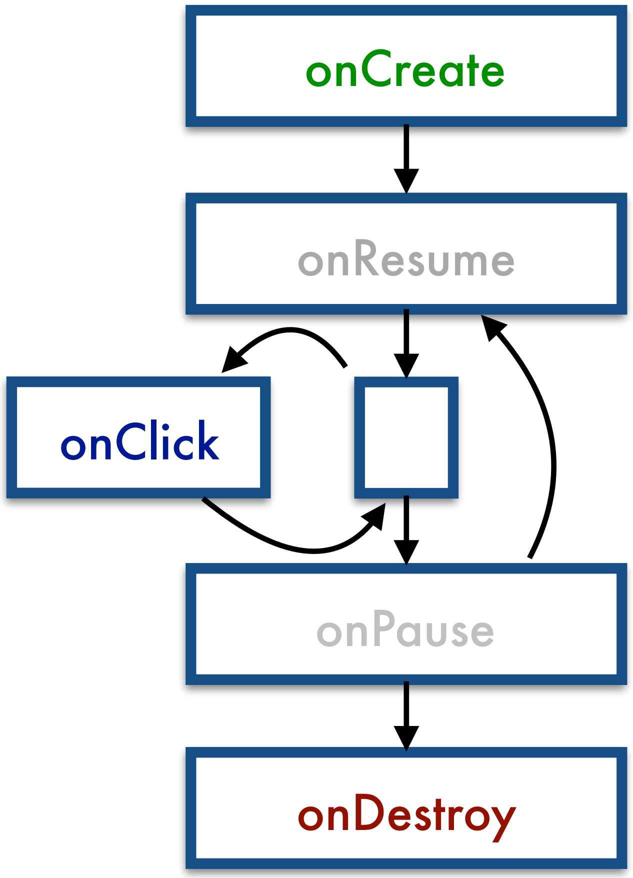


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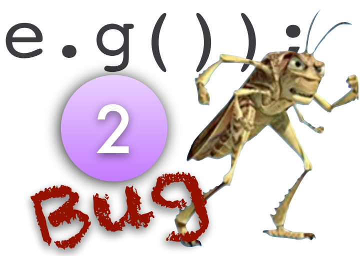
1 ✔ 2



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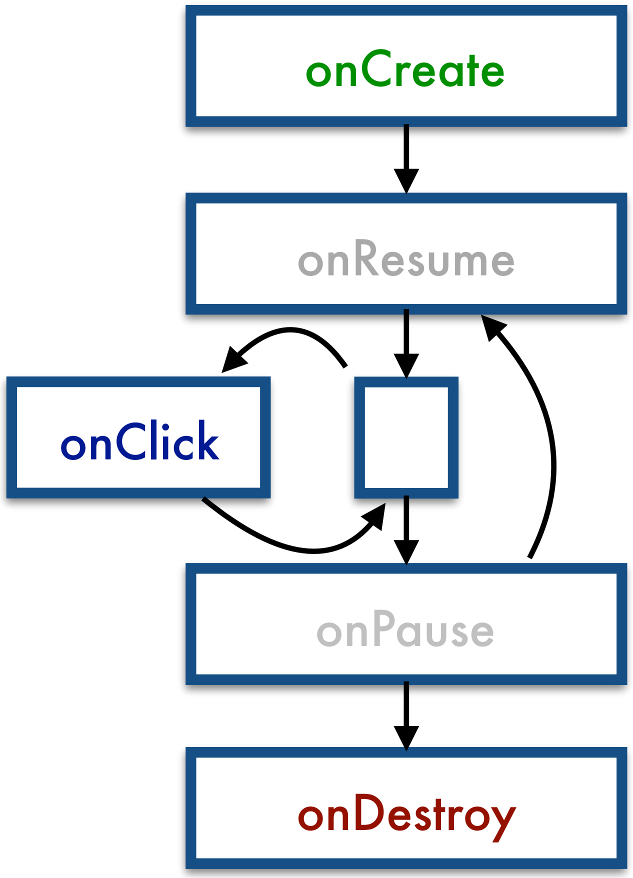


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      mService = s;
    }
  });
  mHostDb = new Db();
}

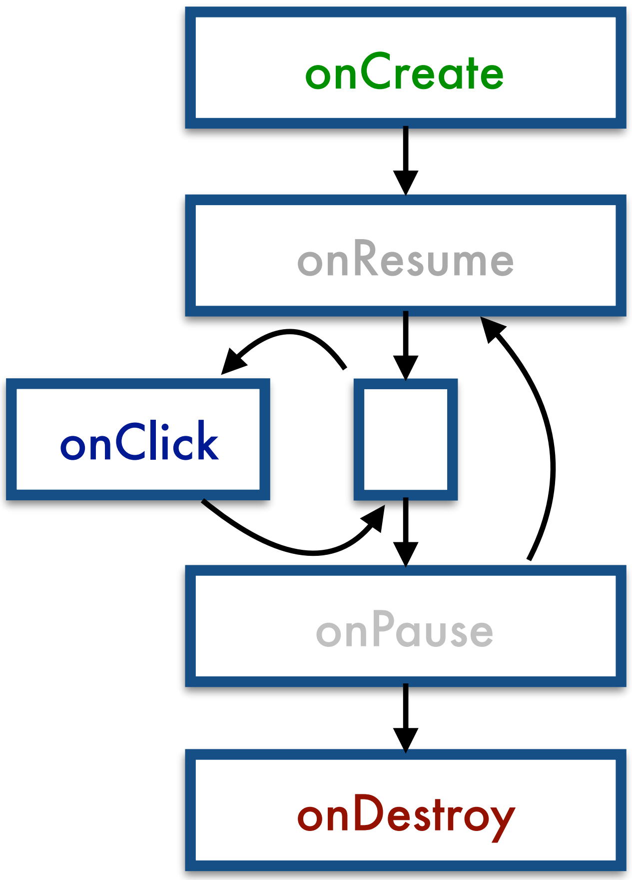
void onClick(…) {
  mHostDb.s(mService.g());
```

```
}
```

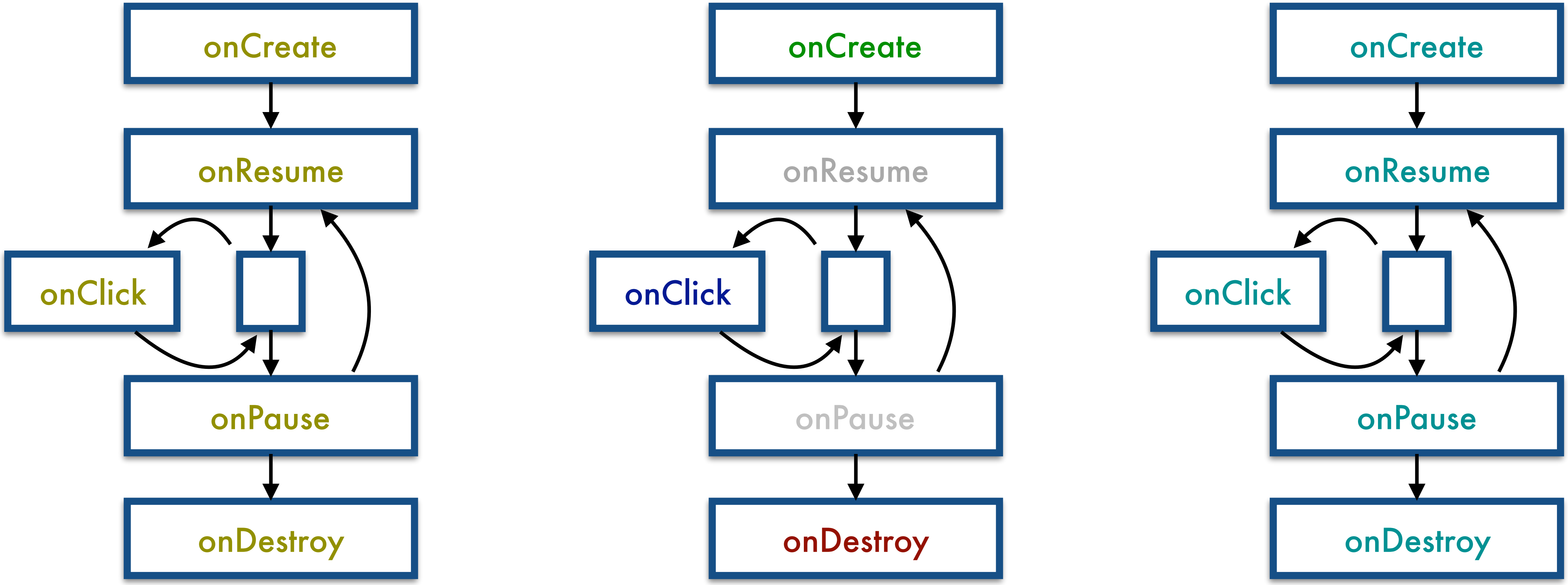
safe?

Need to consider some but not all callback ordering constraints

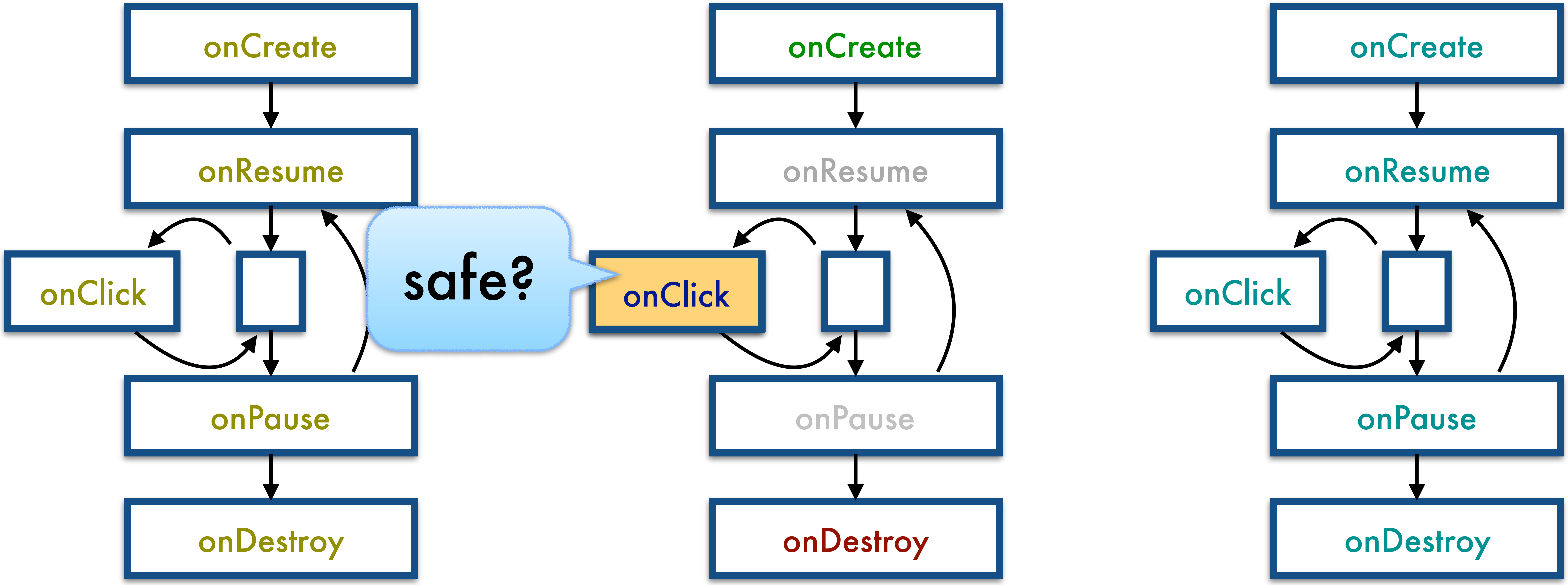
Idea: Jumping to relevant callbacks



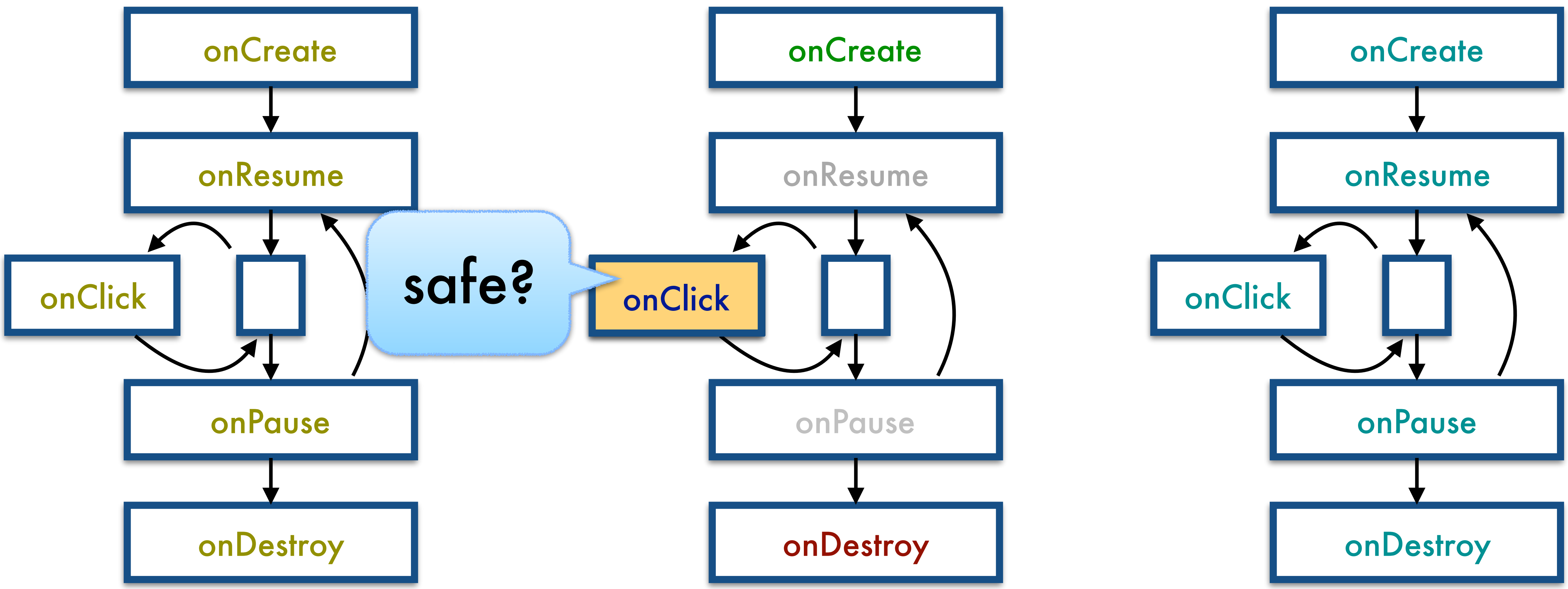
Idea: Jumping to relevant callbacks



Idea: Jumping to relevant callbacks

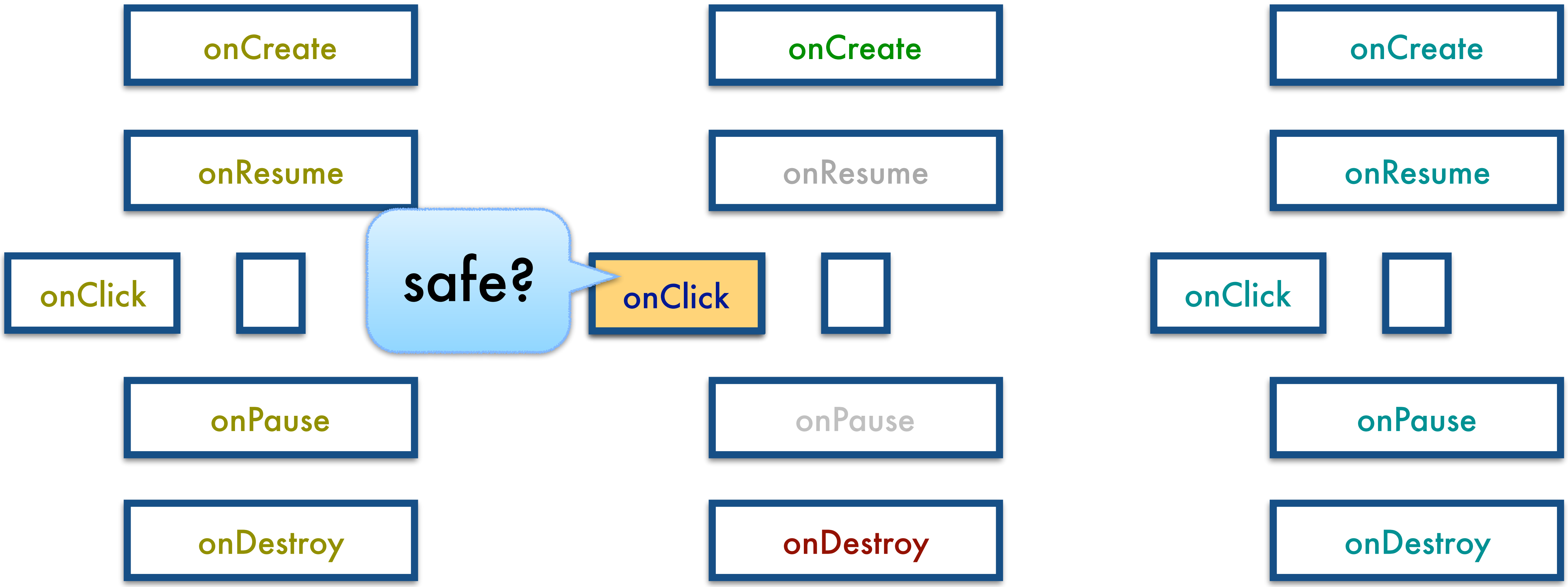


Idea: Jumping to relevant callbacks



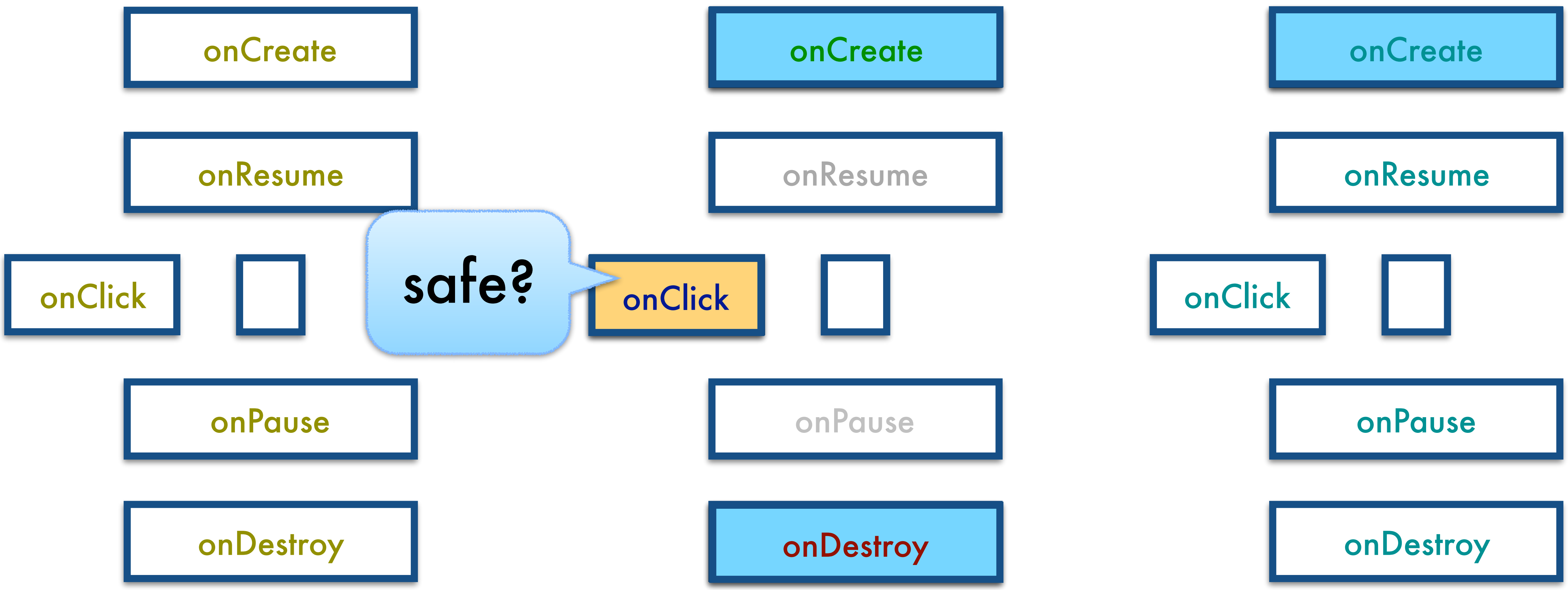
Find data relevant callbacks

Idea: Jumping to relevant callbacks



Find data relevant callbacks

Idea: Jumping to relevant callbacks



Find data relevant callbacks

Idea: Jumping to relevant callbacks

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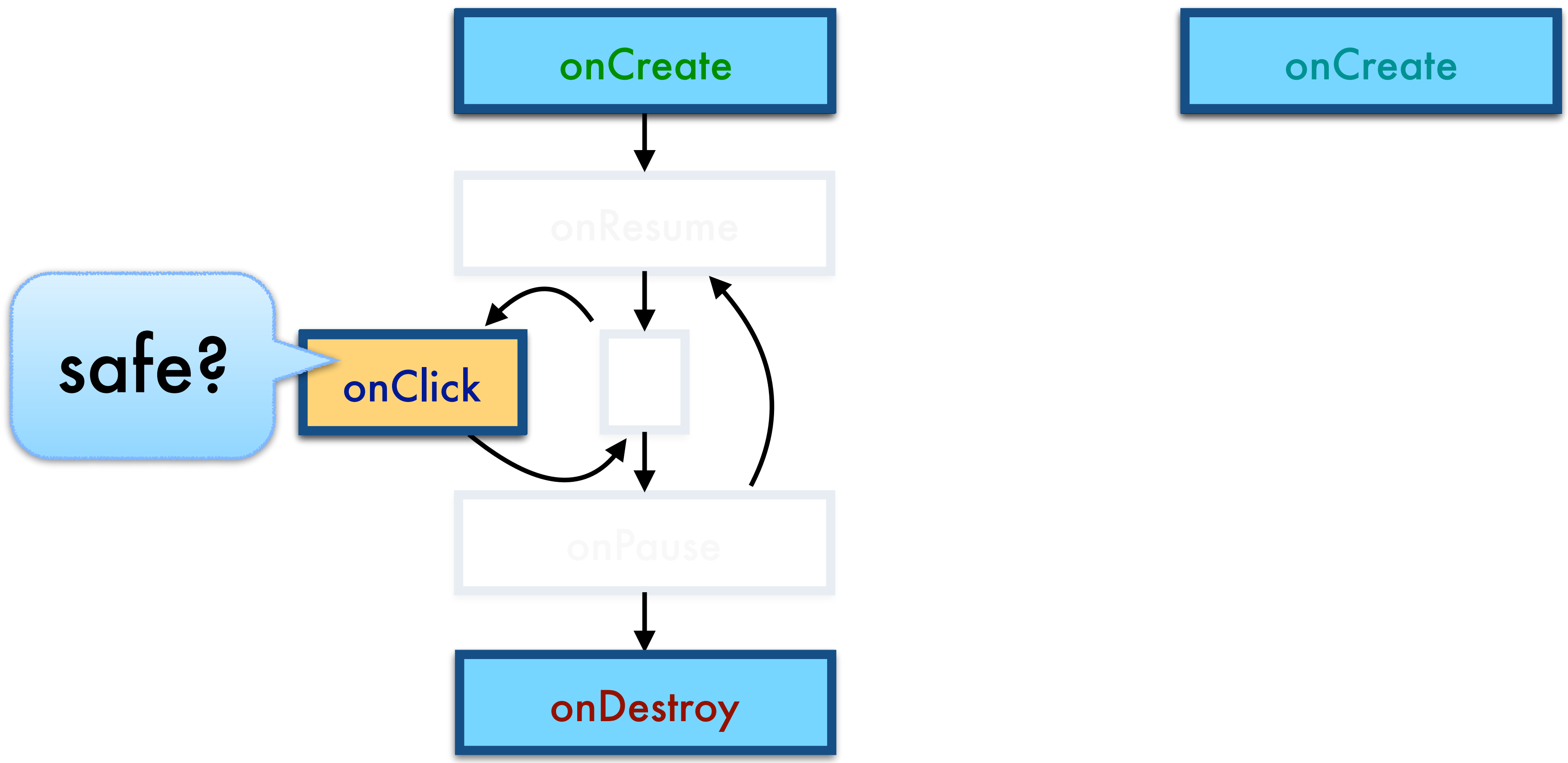
Find data relevant callbacks

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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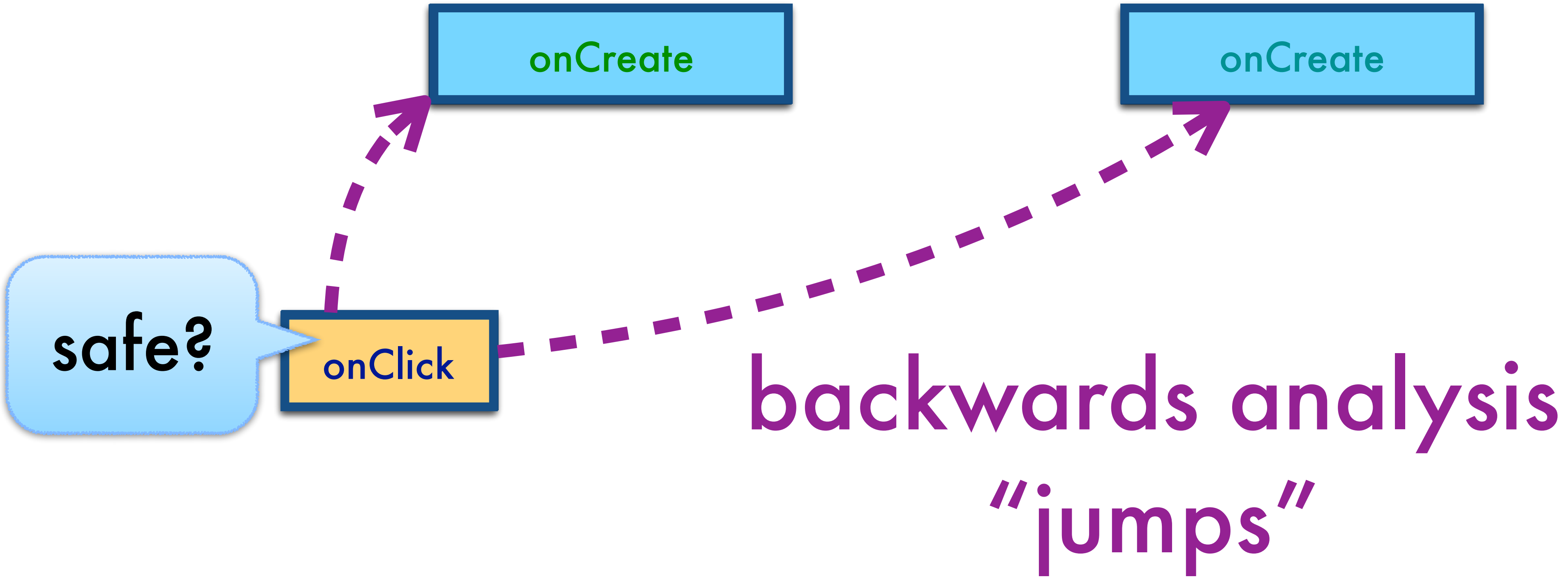
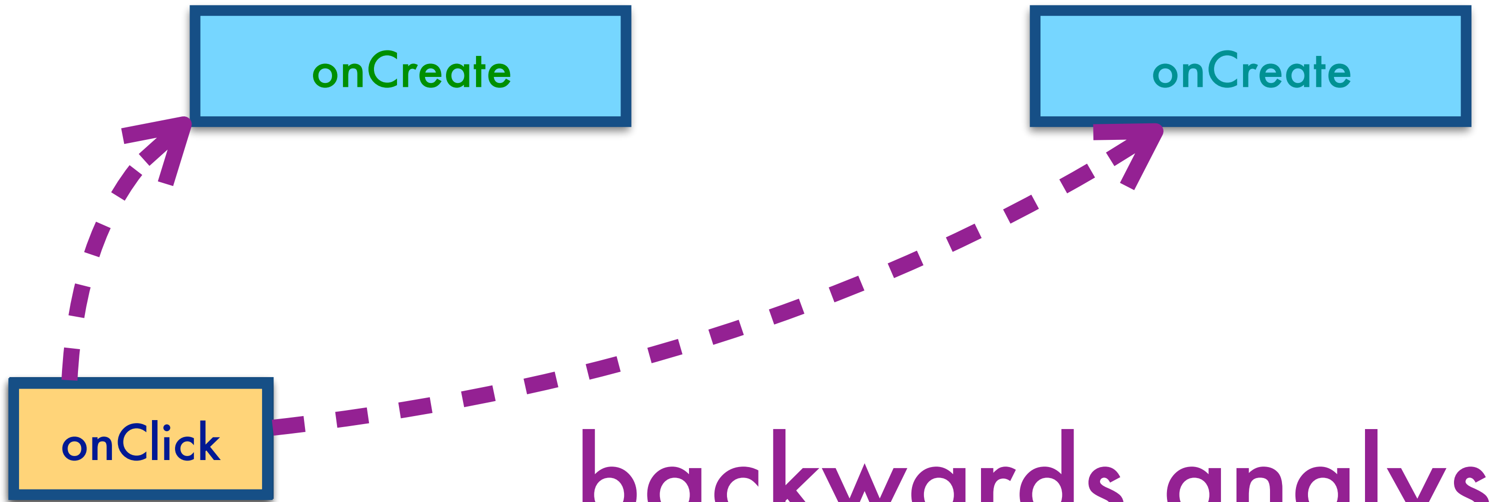


Find data relevant callbacks

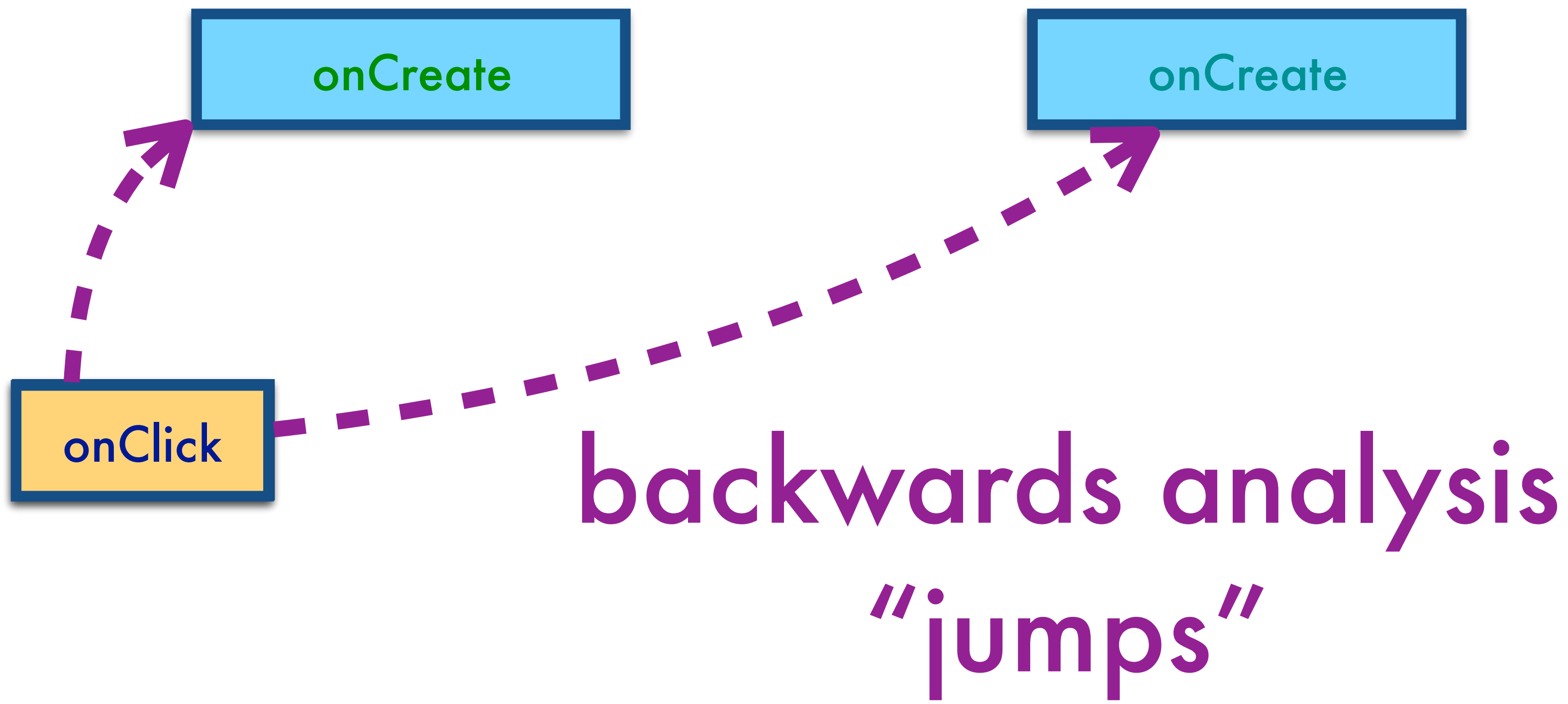
Filter using control-feasibility

Contributions



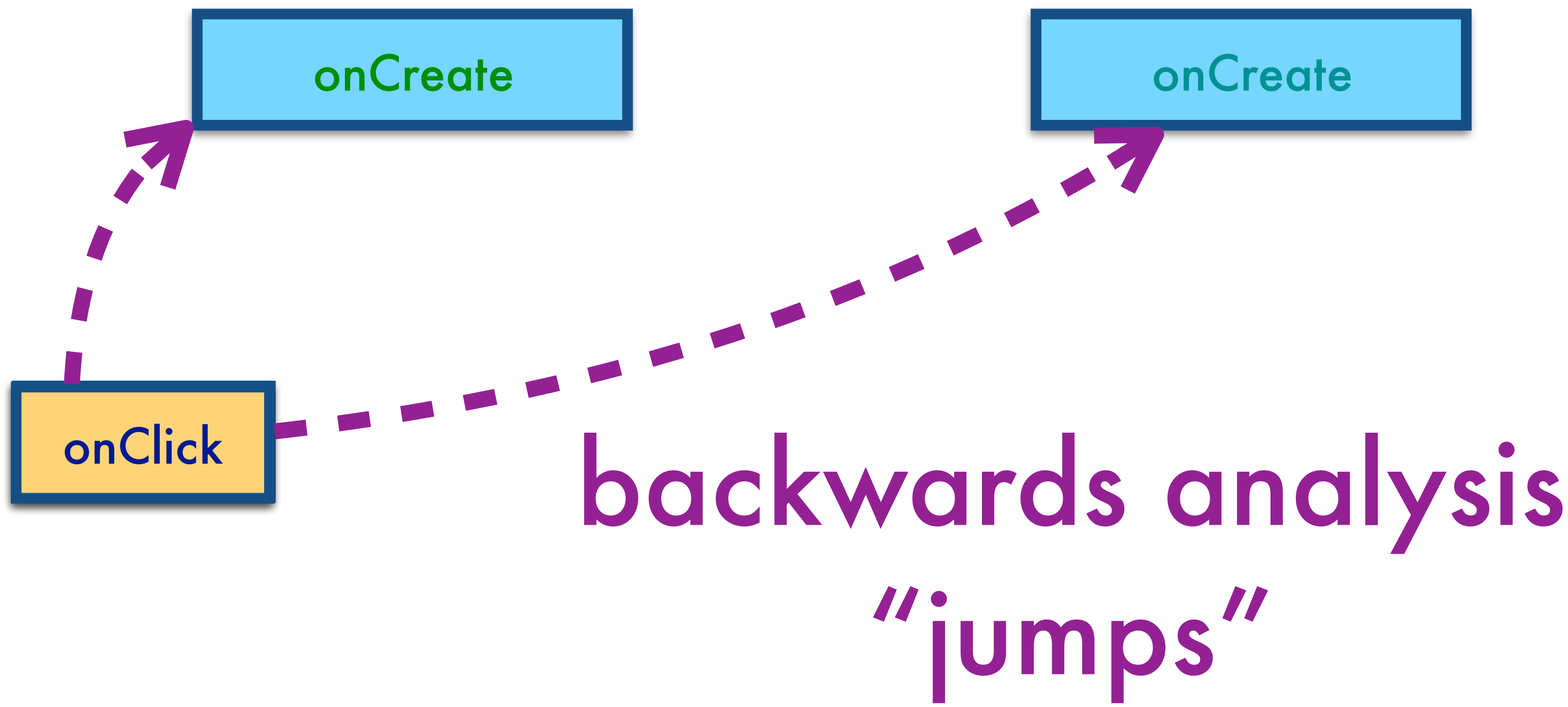
backwards analysis
"jumps"

Contributions



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

Contributions



1 $\ell_1 \;\text{—}[c]\!\rightarrow\; \ell_2$ **Framework for jumping analyses**

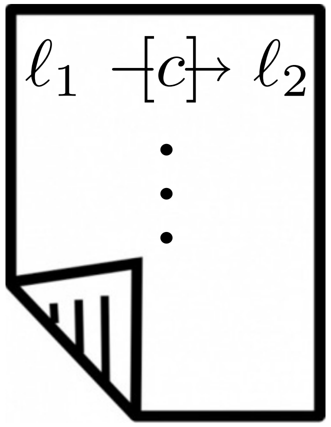
2 **Applied to Android events**

A program model for a jumping analysis

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

A program model for a jumping analysis

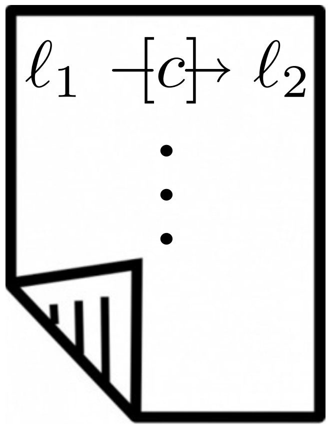
1 $\ell_1 \xrightarrow{[c]} \ell_2$



Program

A program model for a jumping analysis

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

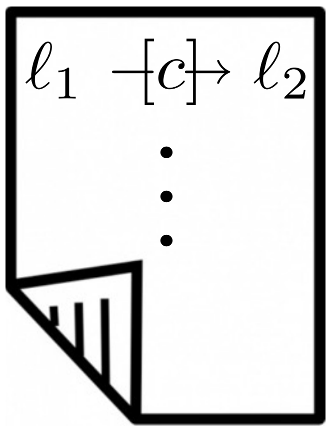


Program

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

A program model for a jumping analysis

1 $\ell_1 \;\dashv\!\![c]\!\!\mapsto\; \ell_2$



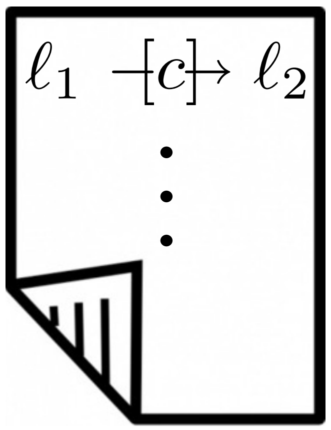
Program

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 $\ell_1 \dashv [c] \mapsto \ell_2$



Program

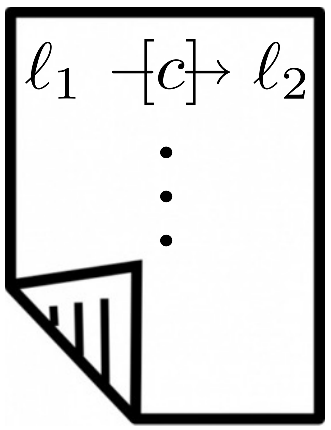
Unstructured control-flow: atomic commands connected by pre/post labels

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

Analysis parameters

A program model for a jumping analysis

1 $\ell_1 \;\dashv\!c\!\mapsto\; \ell_2$



Program

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

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

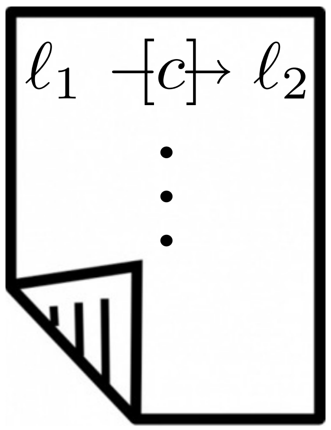
Analysis parameters

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

Backward transfer functions

A program model for a jumping analysis

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



Program

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

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

Analysis parameters

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

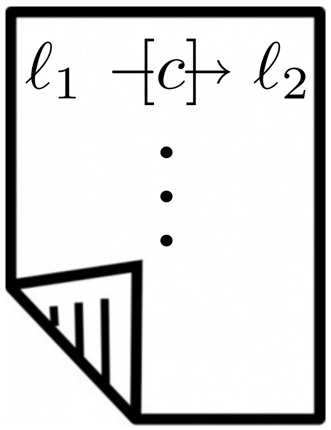
Backward transfer functions

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

Current location

A program model for a jumping analysis

$\ell_1 \;\dashv c \vdash\!\!\rightarrow\; \ell_2$



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

$$\ell_{\text{cur}}$$

Current location

$$Q_{\text{cur}}$$

Current query

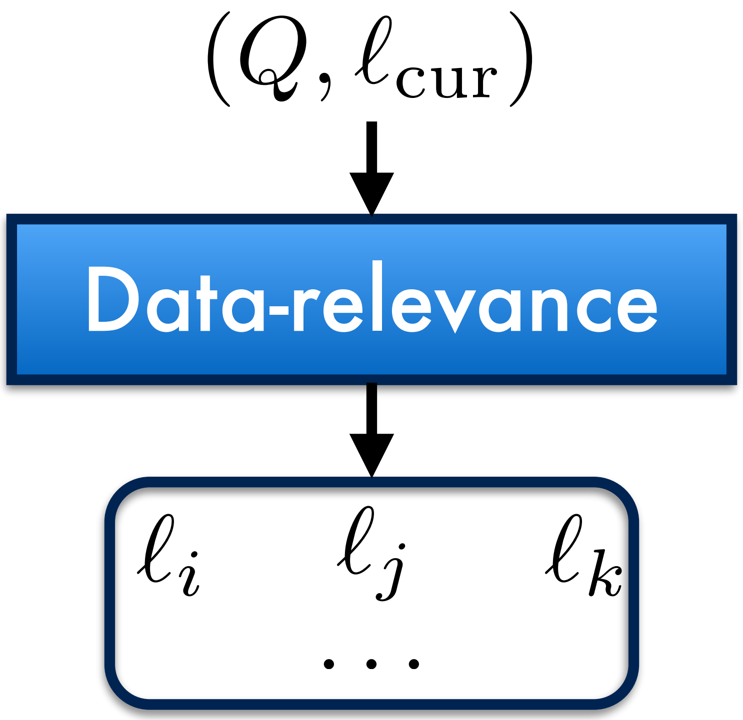
Data-relevance identifies writes

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

(Q, ℓ_{cur})

Data-relevance identifies writes

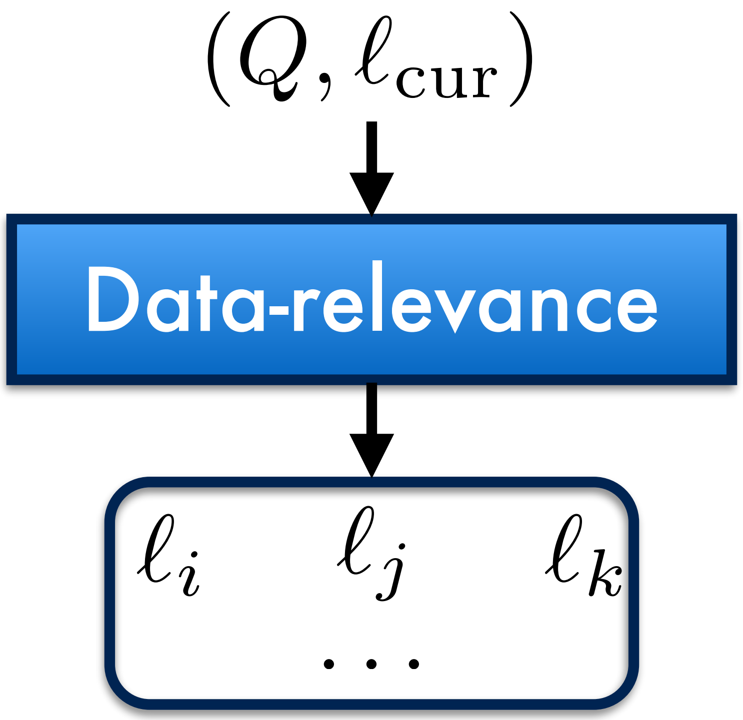
1 $\ell_1 \;\dashv\!\![c]\!\!\rightarrow\; \ell_2$



Identify locations that can write to the query Q.

Data-relevance identifies writes

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

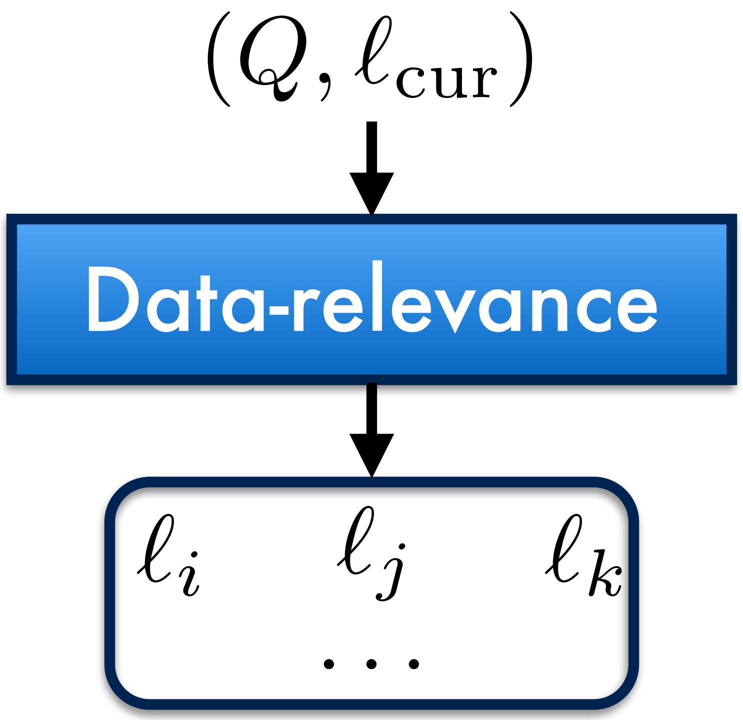


Identify locations that can write to the query Q.

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

Data-relevance identifies writes

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



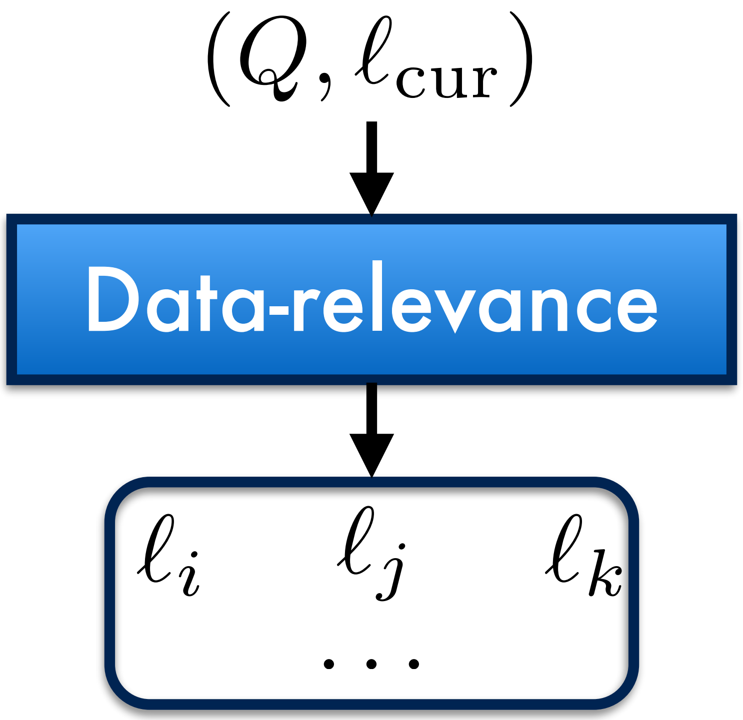
Identify locations that can write to the query Q.

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

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

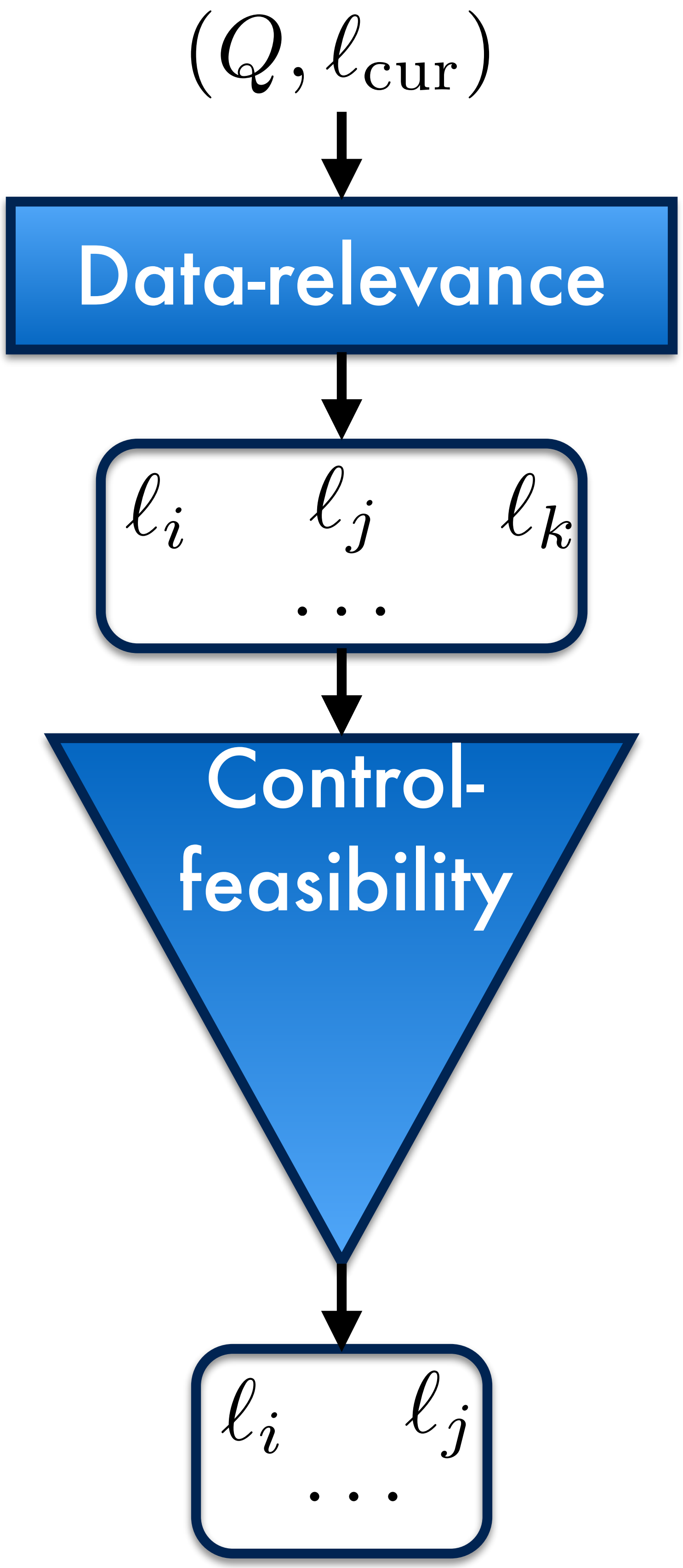
Control-feasibility selectively recovers flow-sensitivity

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



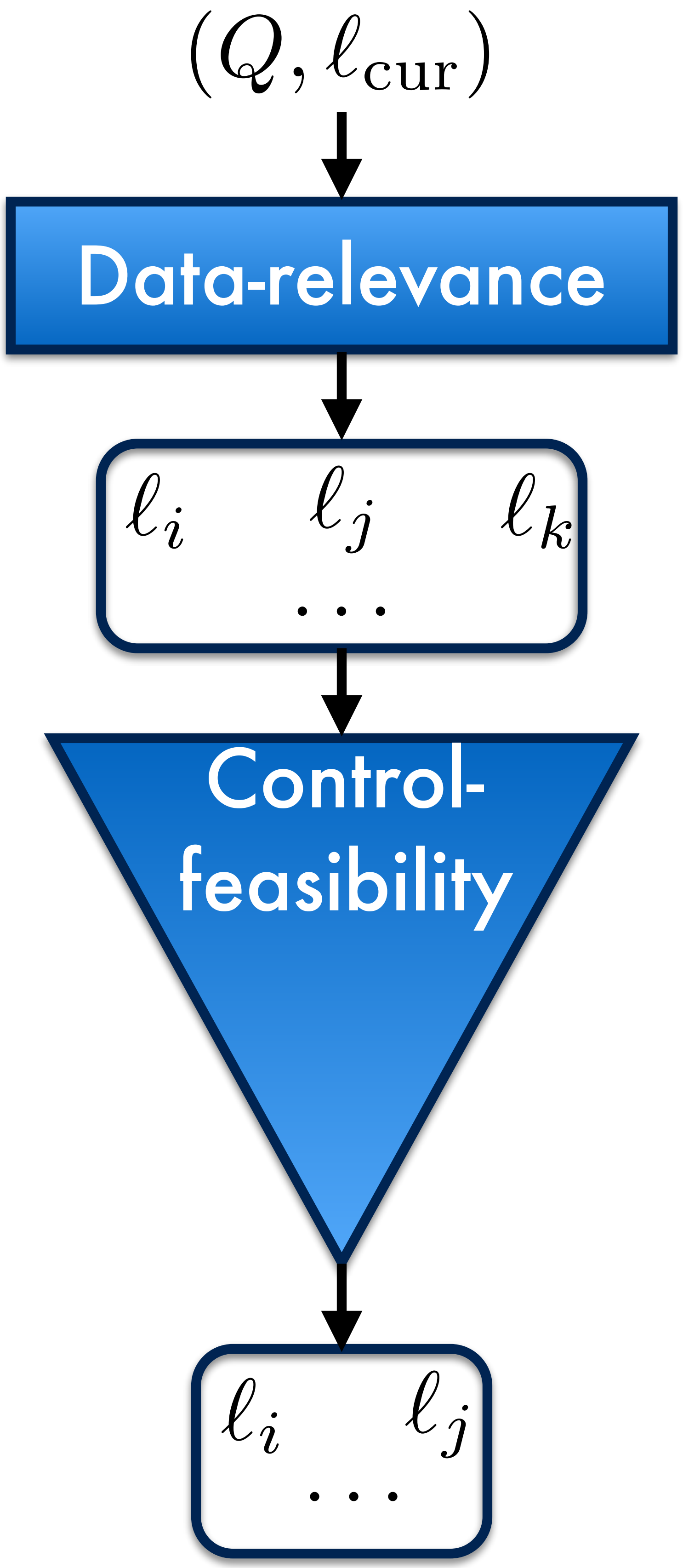
Control-feasibility selectively recovers flow-sensitivity

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



Control-feasibility selectively recovers flow-sensitivity

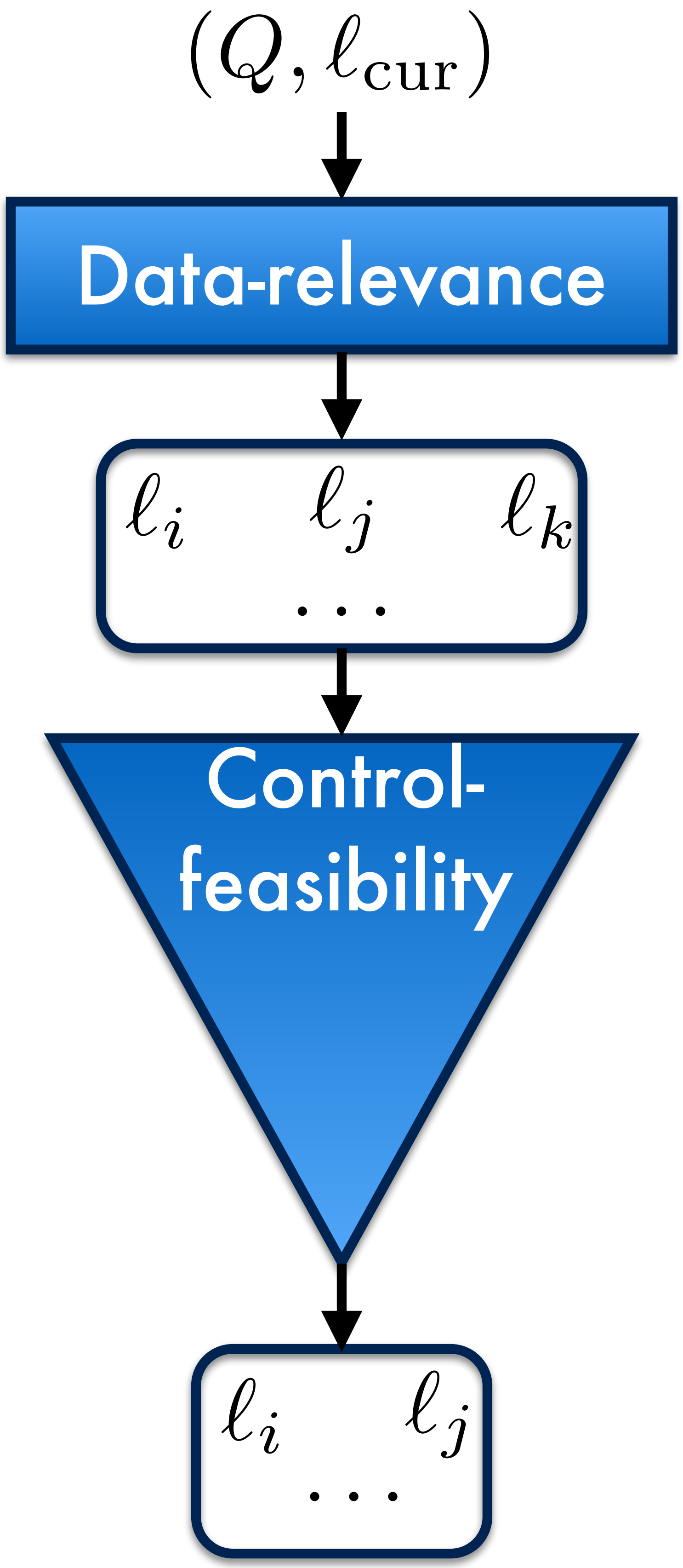
1 $\ell_1 \dashv\!\! [c] \!\!\rightarrow \ell_2$



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

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

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



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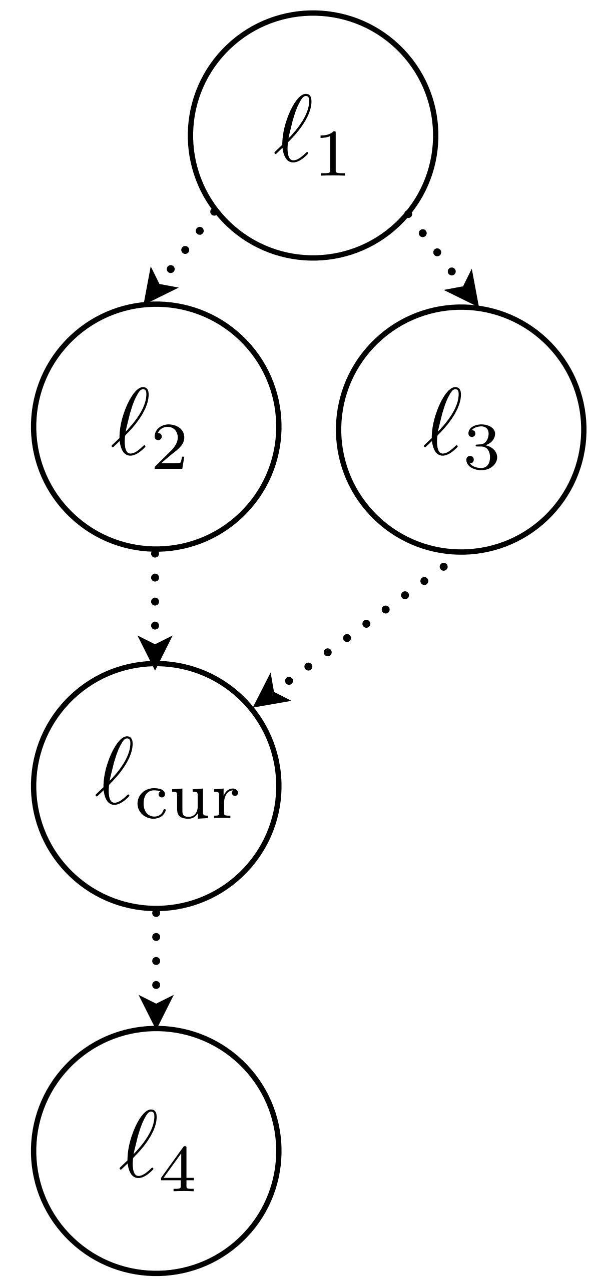
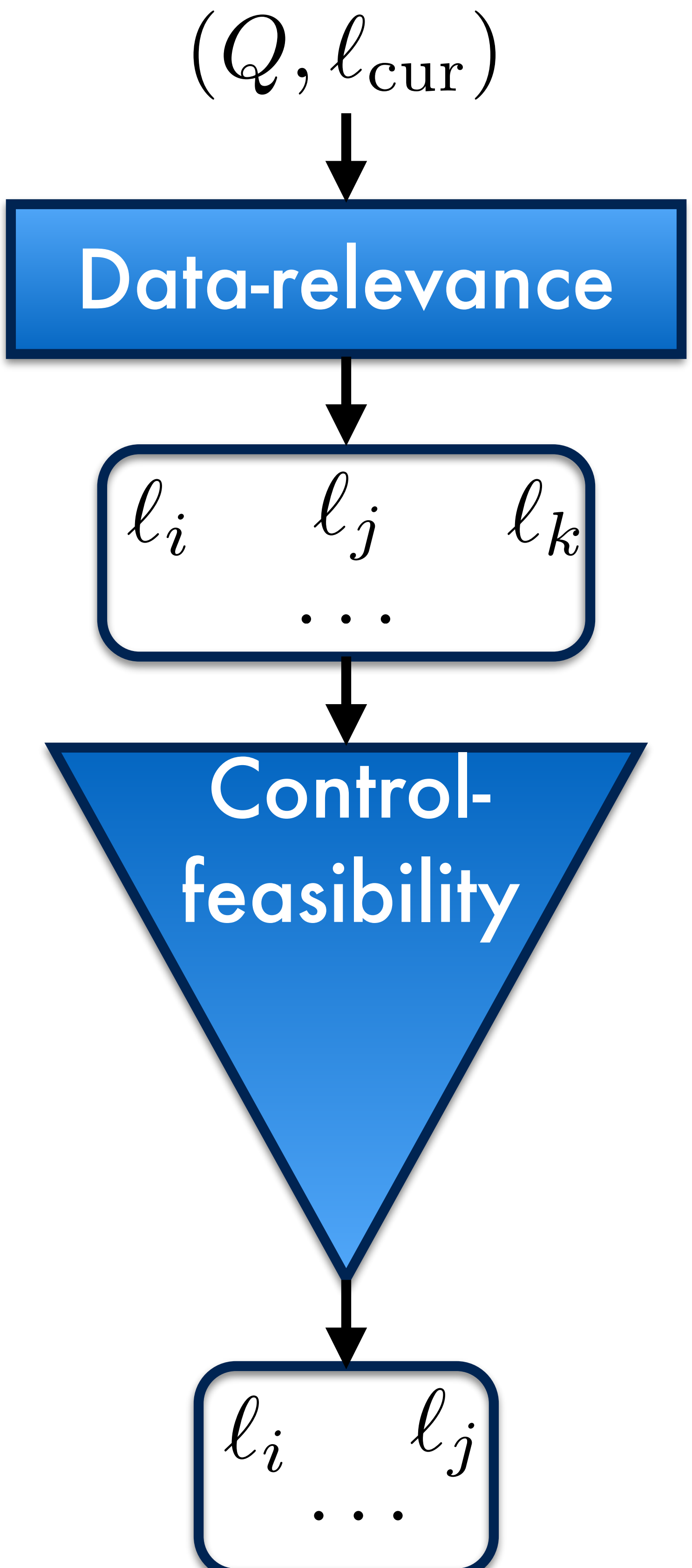


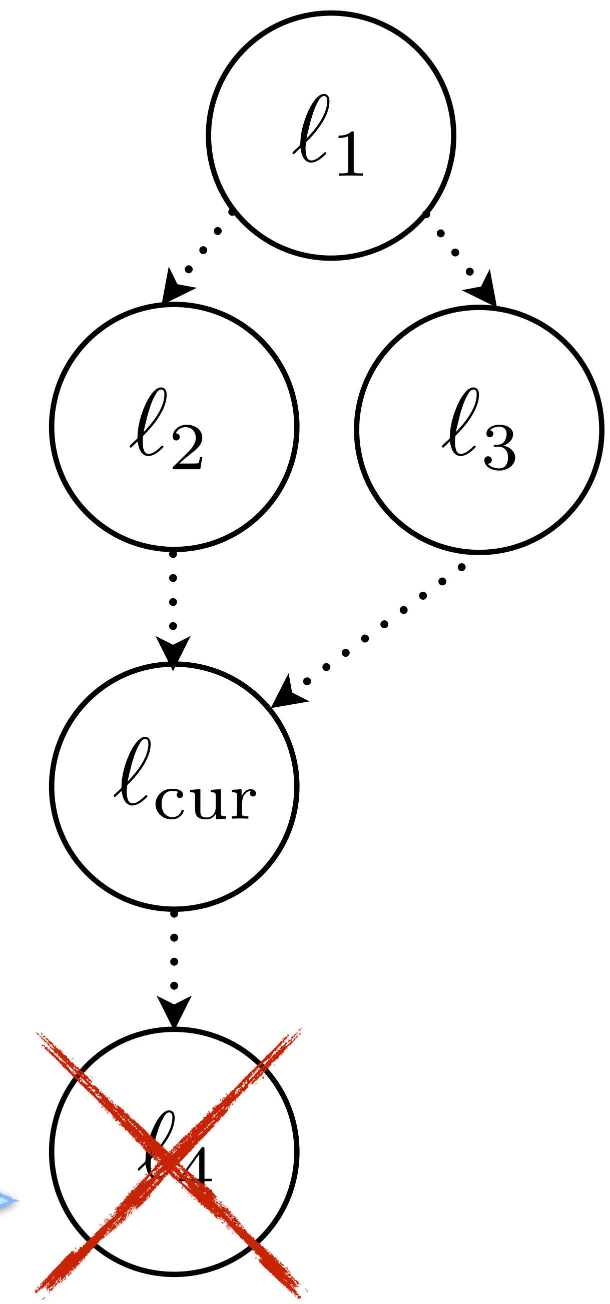
Control-feasibility selectively recovers flow-sensitivity

1 $\ell_1 \dashv[c]\!\!\to \ell_2$



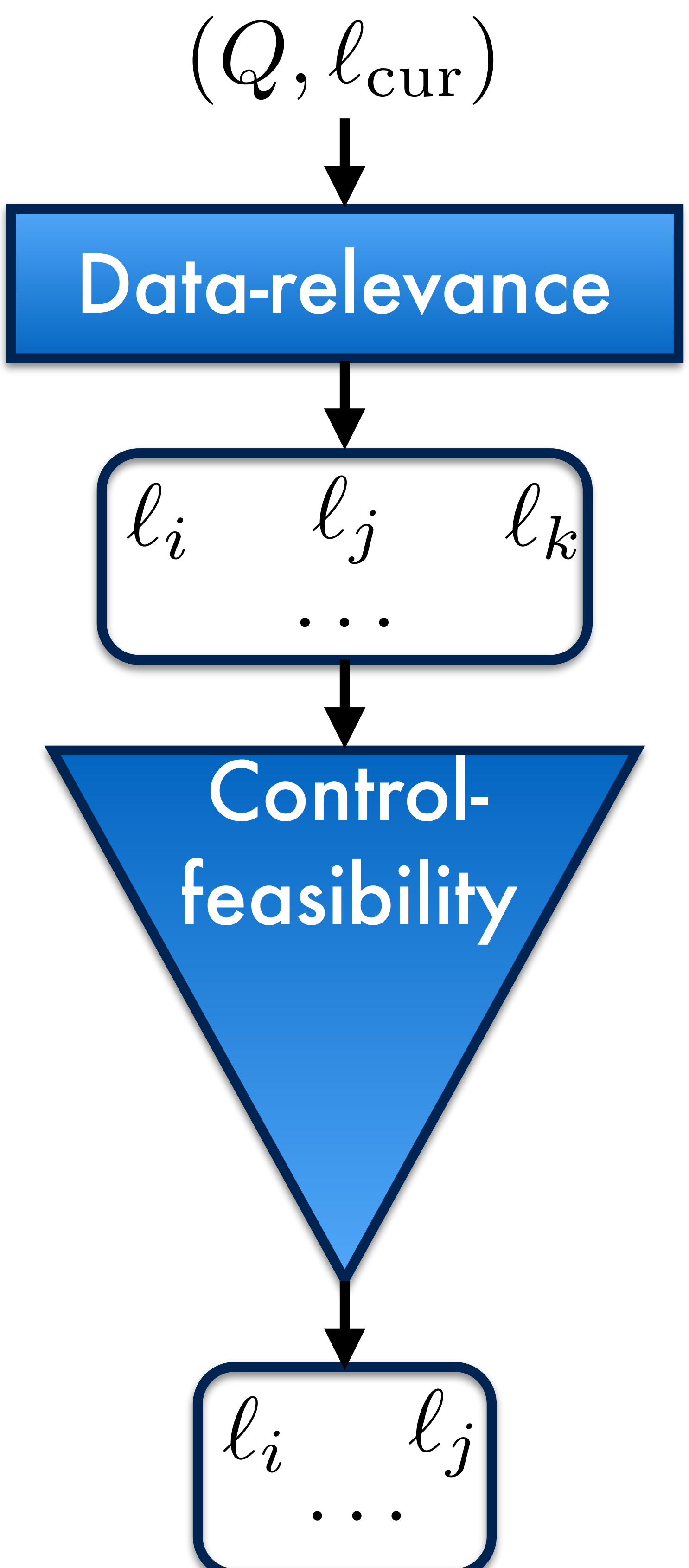
Filter the set of data-relevant locations using control flow and the current program point

Not backward-reachable from current location



Control-feasibility selectively recovers flow-sensitivity

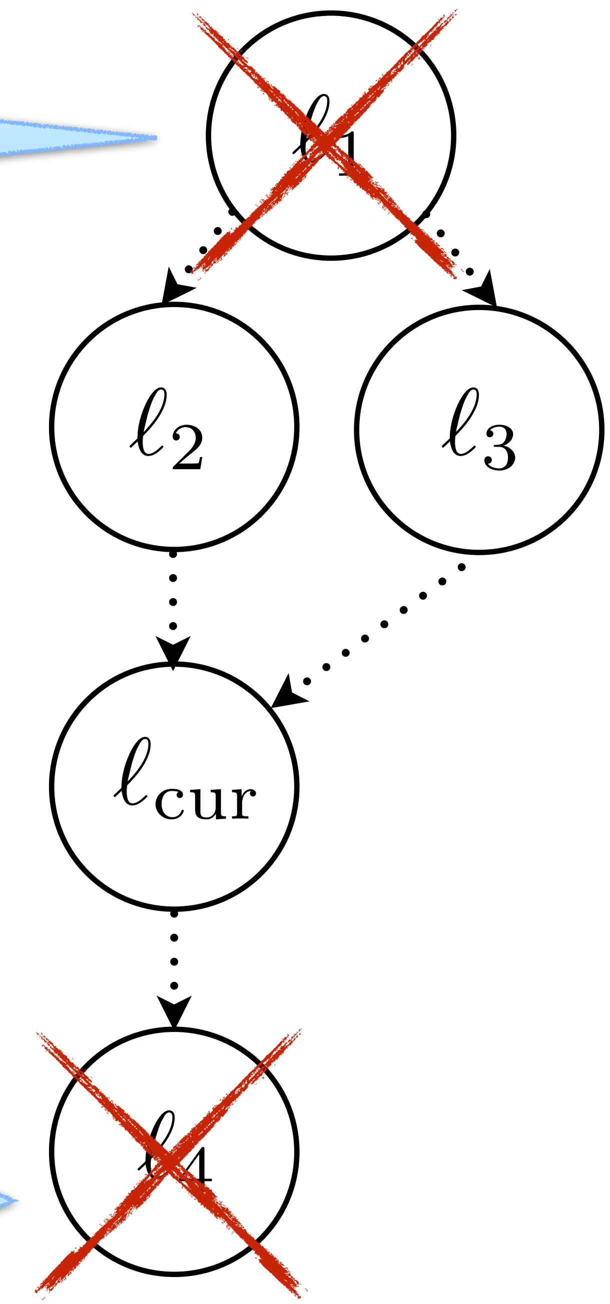
1 $\ell_1 \dashv\!\!\![c]\!\!\!\rightarrow \ell_2$



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

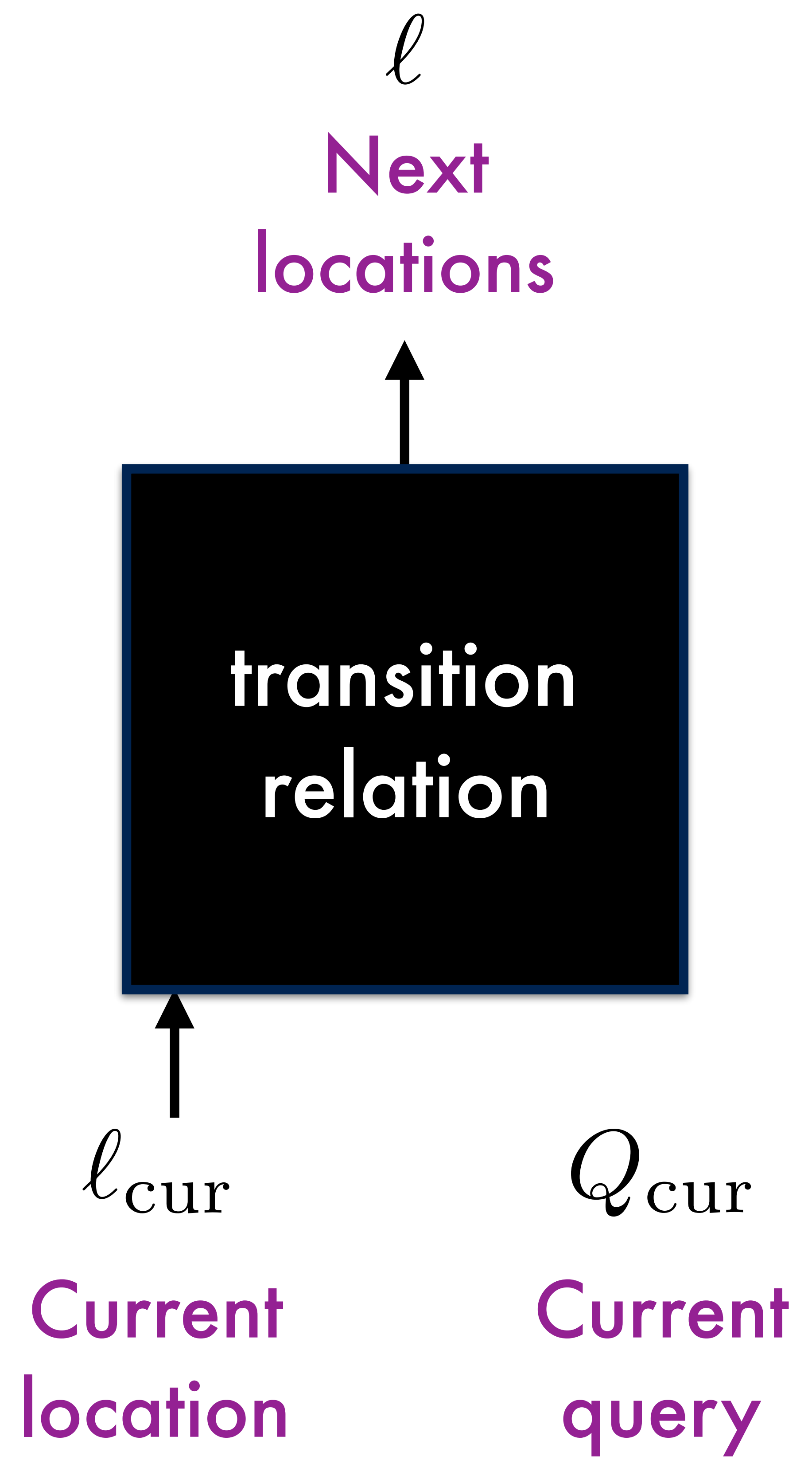
Q_{cur}

Current query

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

1

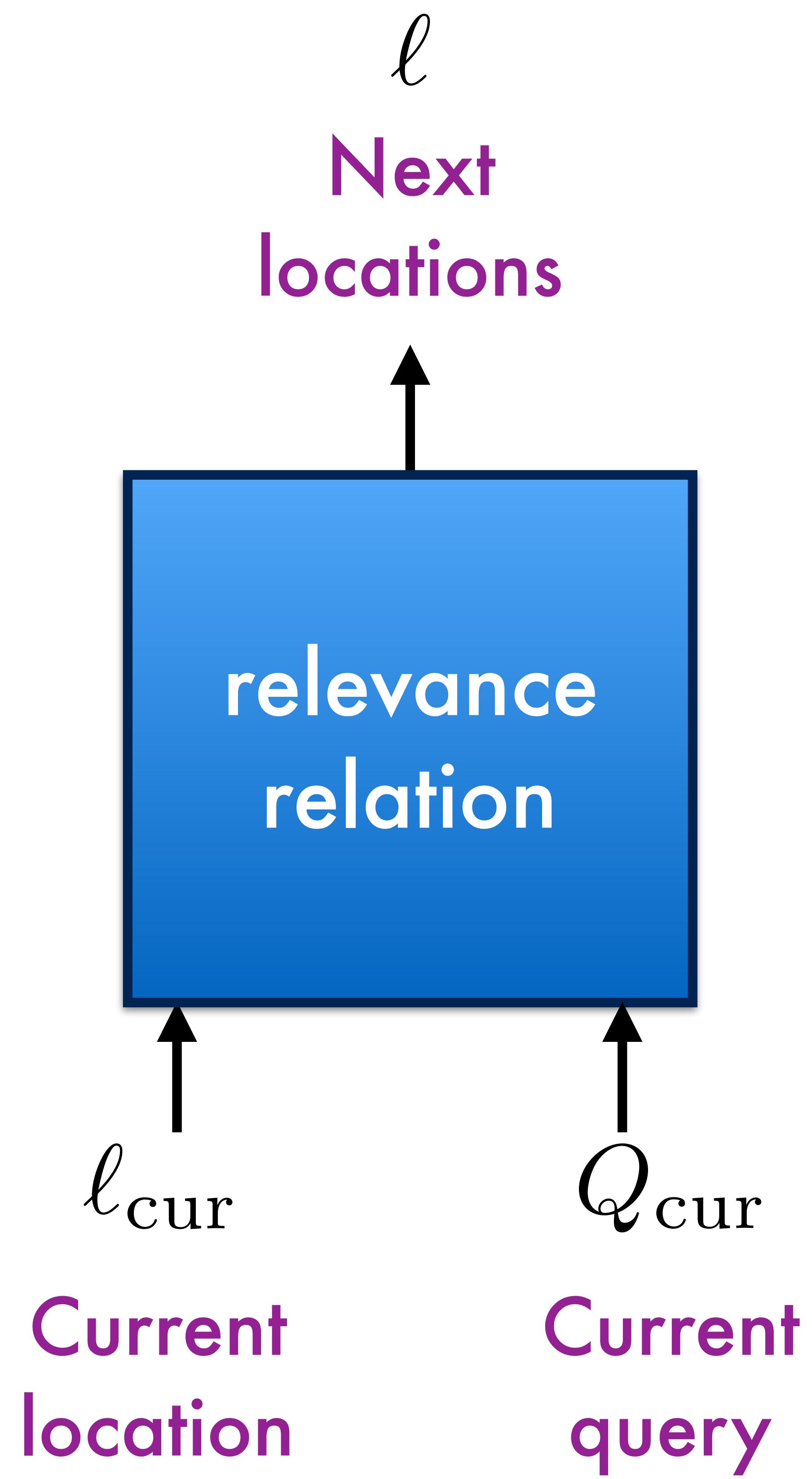
$\ell_1 \ \text{-}[c]\!\!\rightarrow\ \ell_2$



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

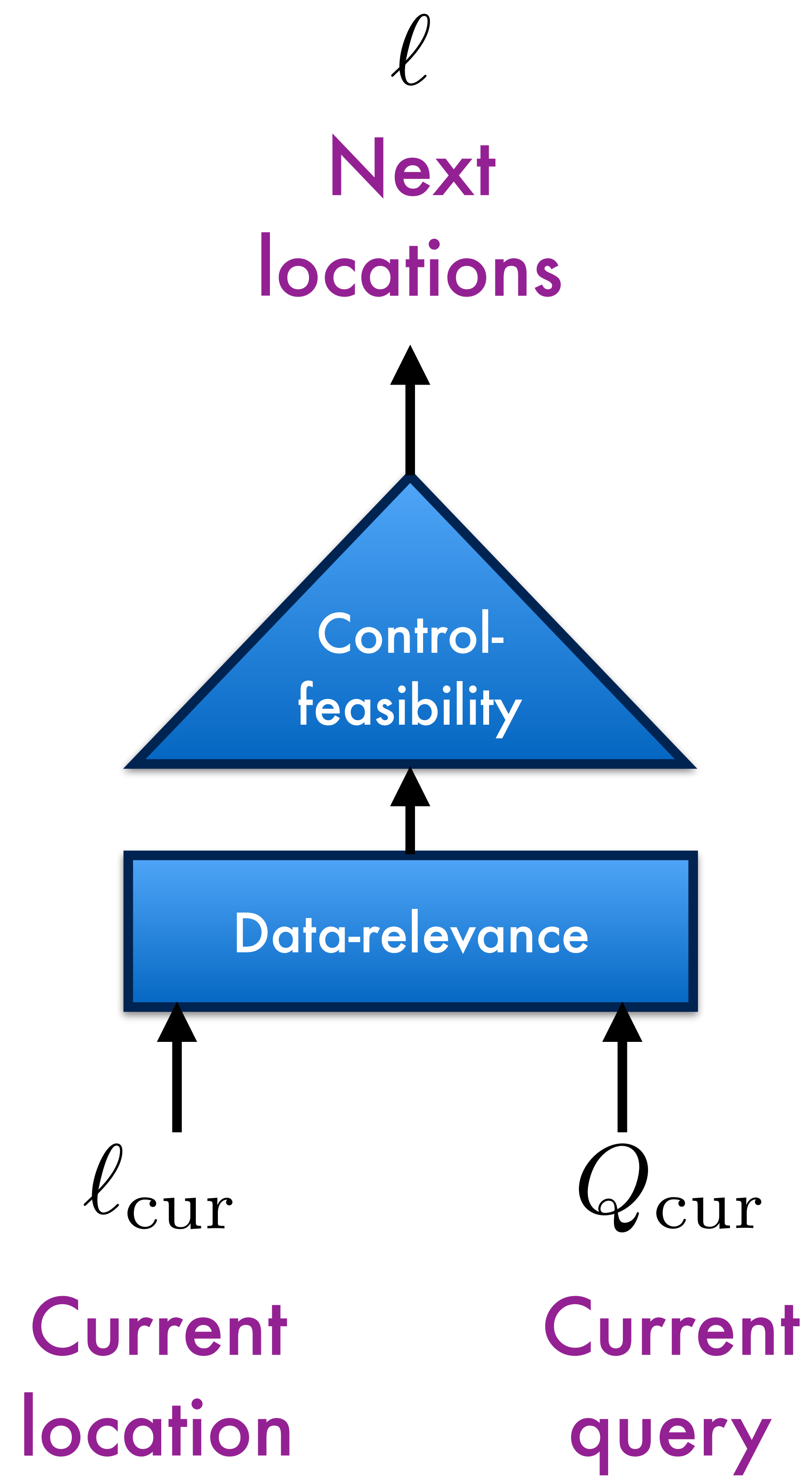
1

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



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

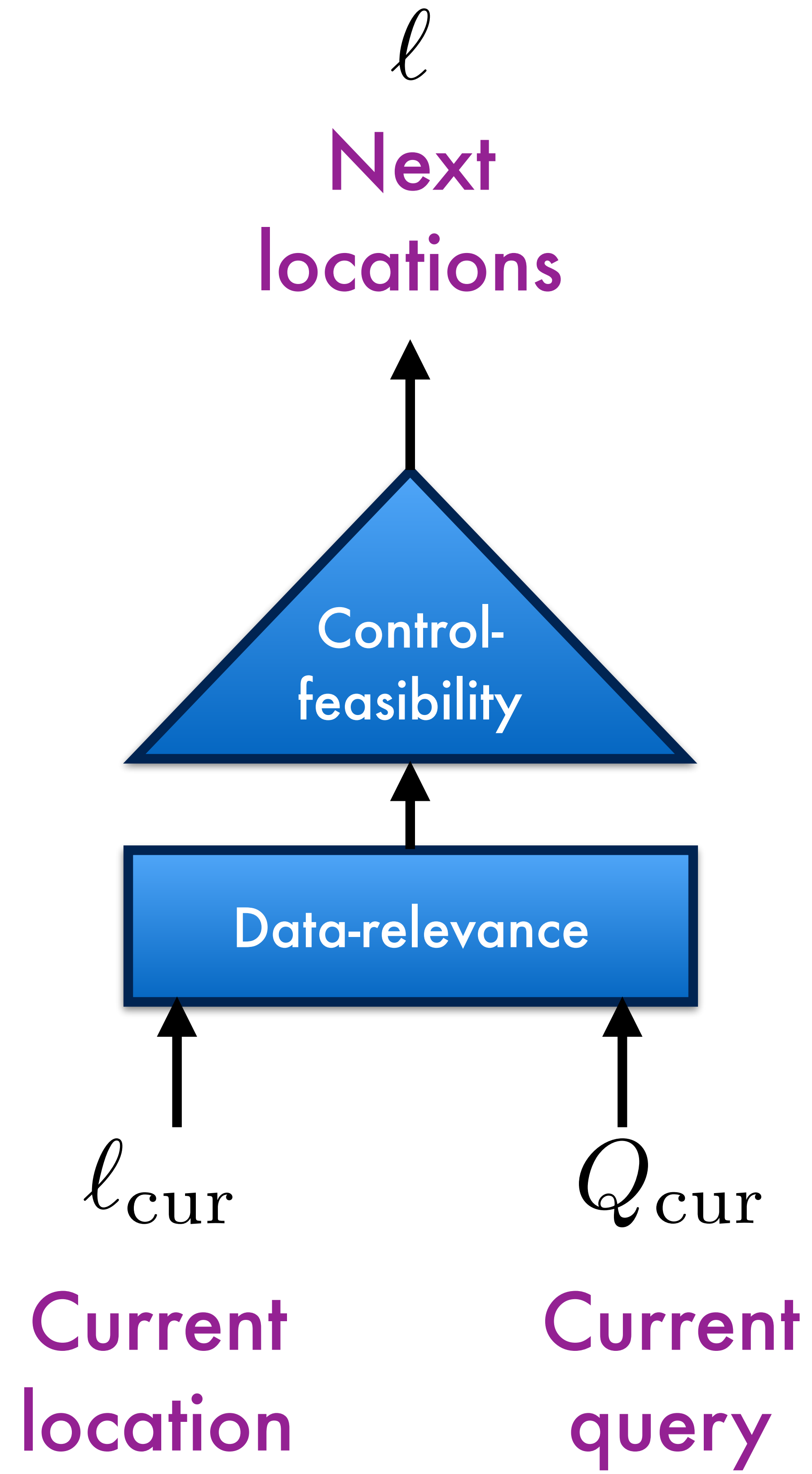
$\ell_1 \xrightarrow{[c]} \ell_2$



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

1 $\ell_1 \dashv[c]\mapsto \ell_2$

Precision	-insensitive	-sensitive
flow		
path		
context		

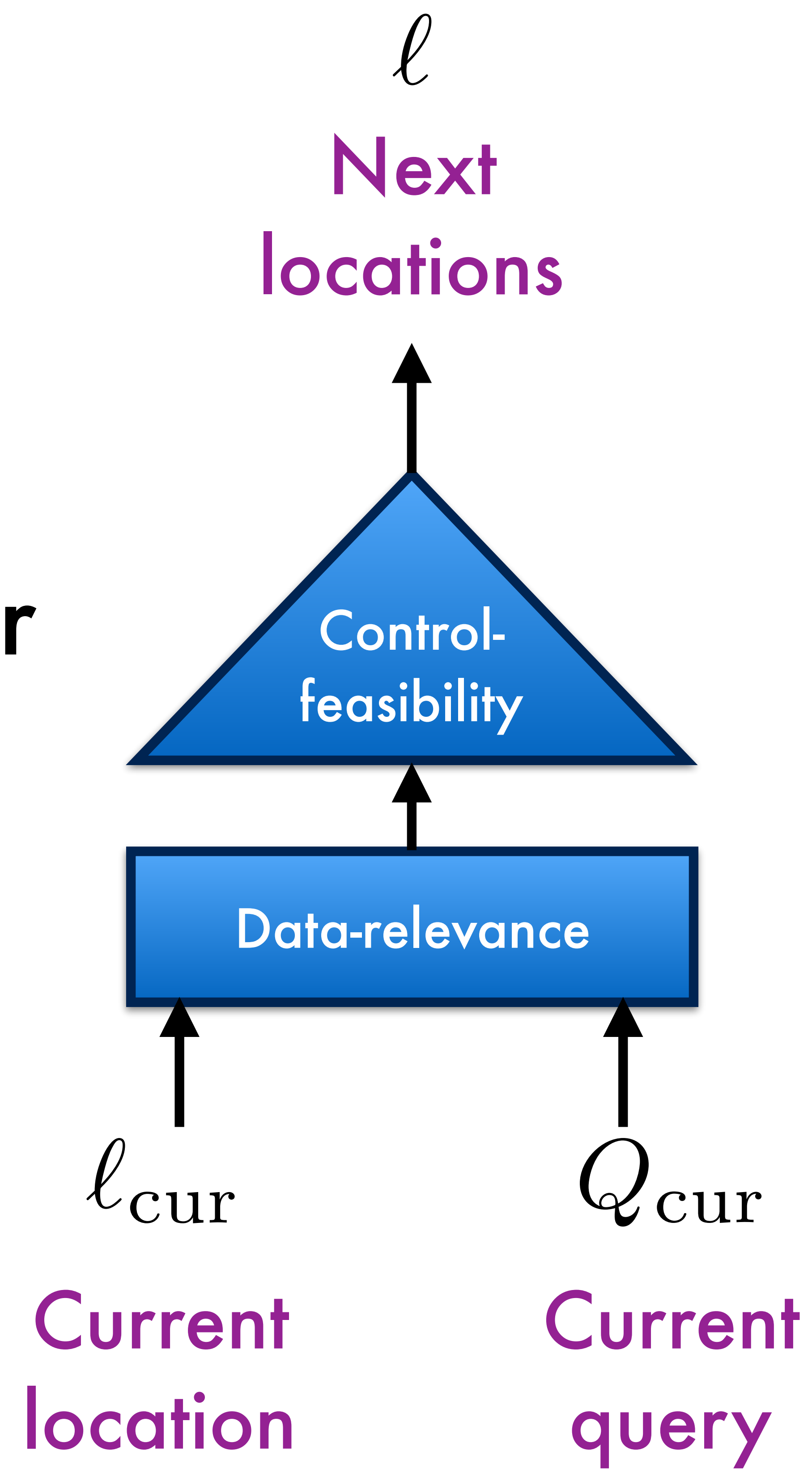


Jumping enables sparse, selective, on-the-fly control-flow abstraction

$\ell_1 \dashv[c]\mapsto \ell_2$

Precision	-insensitive	-sensitive
flow		
path		
context		

no filter



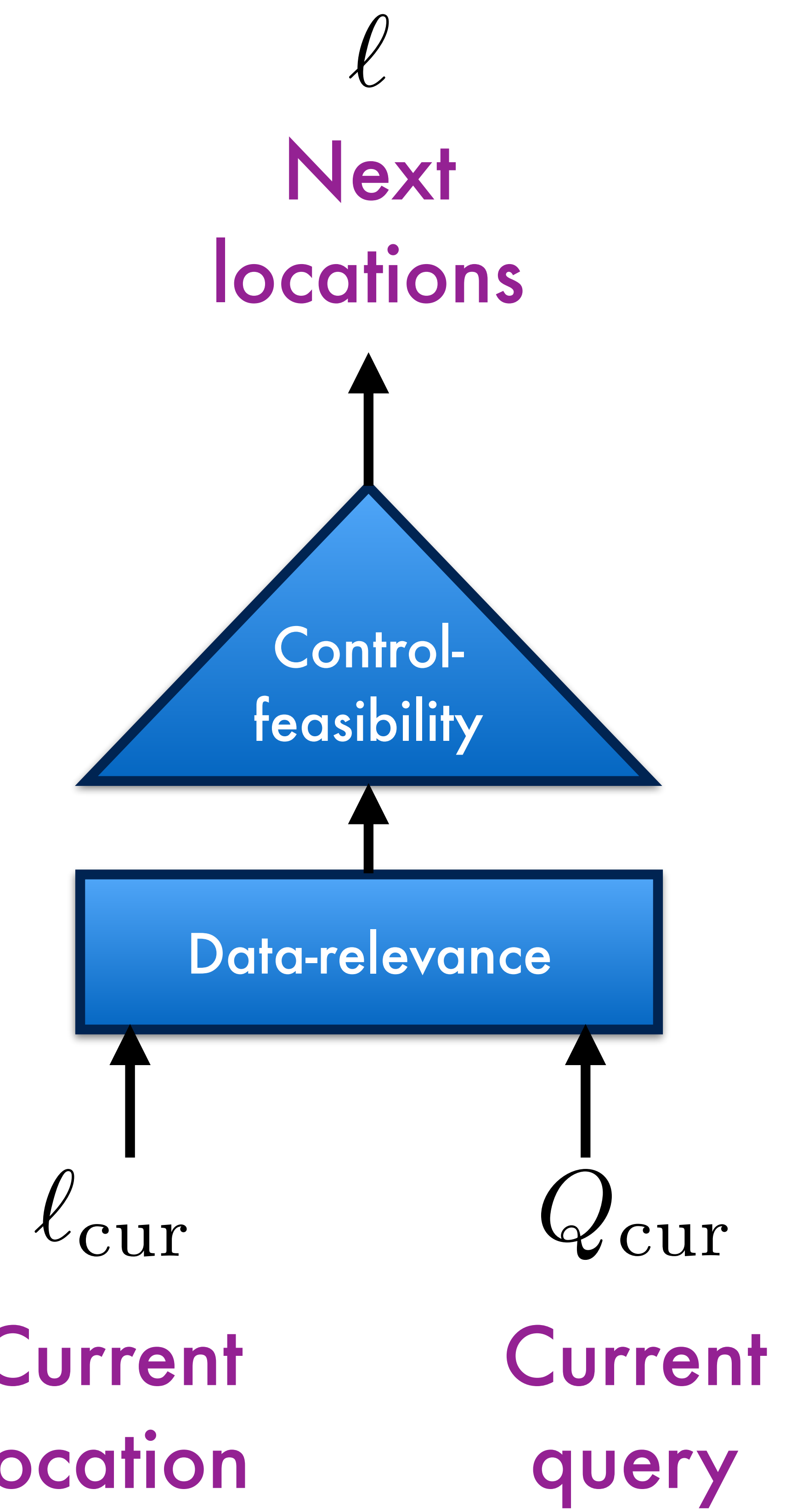
Jumping enables sparse, selective, on-the-fly control-flow abstraction

1 $\ell_1 \dashv[c]\mapsto \ell_2$

Precision	-insensitive	-sensitive
flow		
path		
context		

no filter

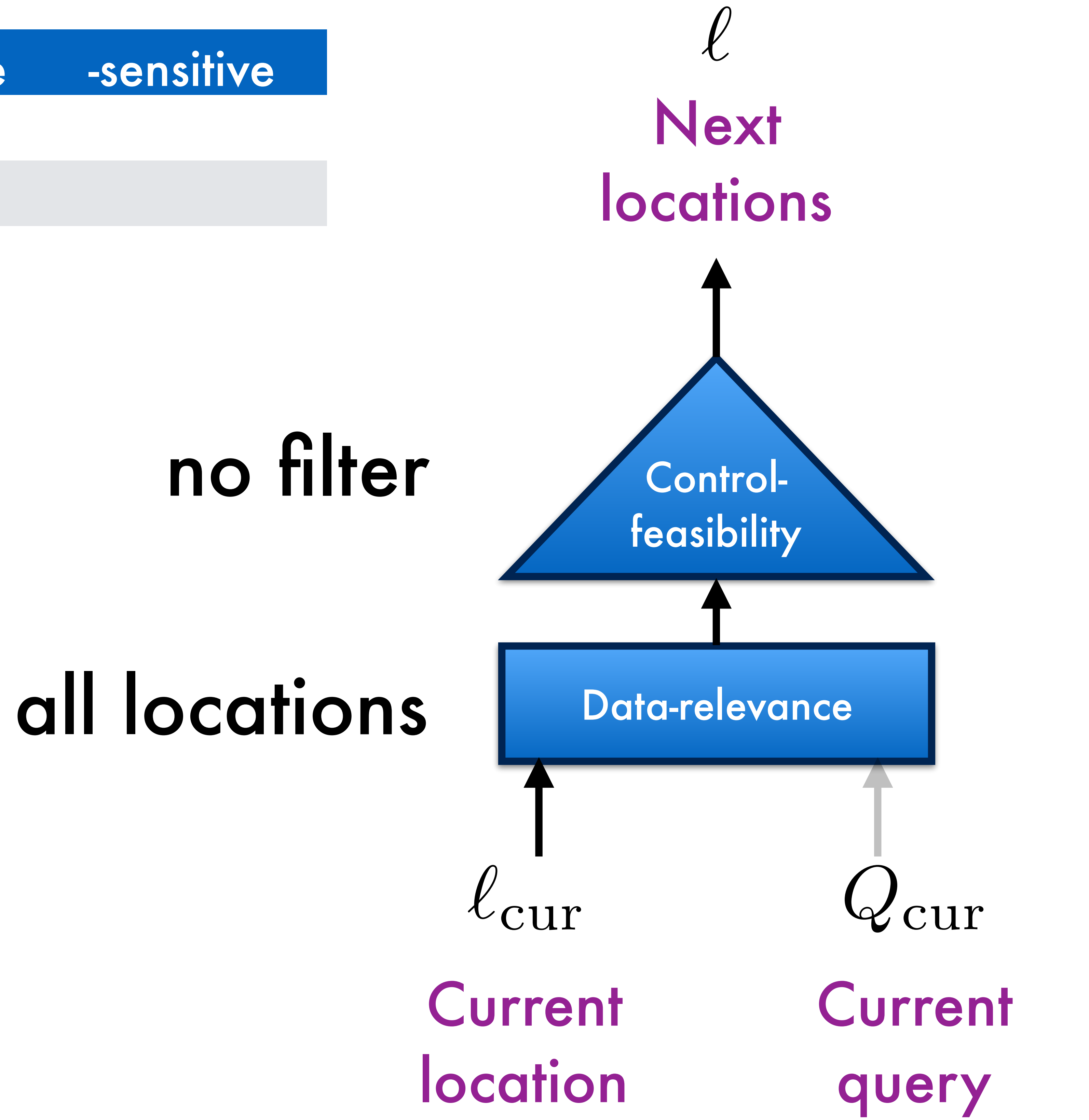
all locations



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

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

Precision	-insensitive	-sensitive
flow		
path		
context		



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

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

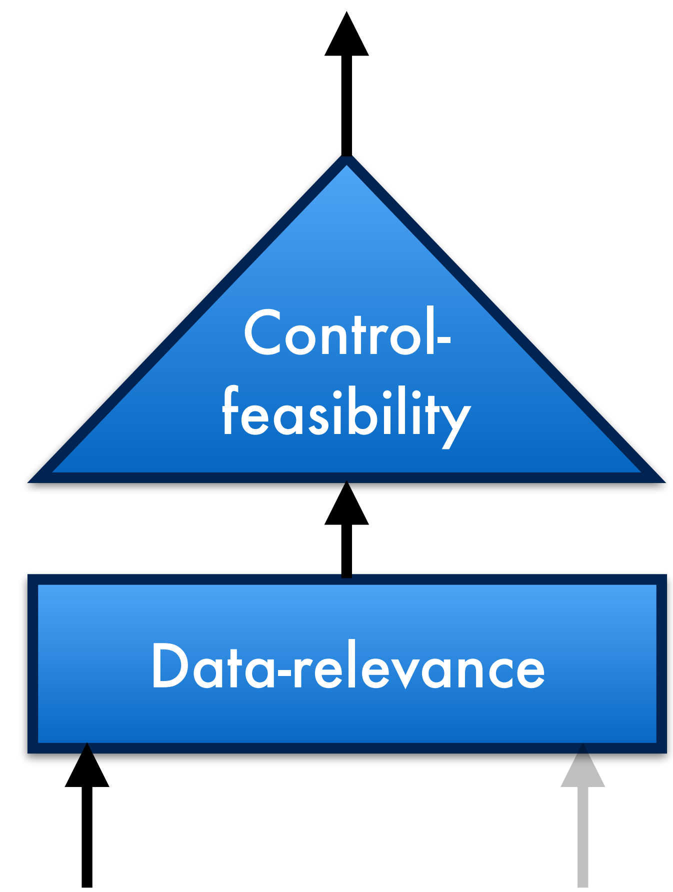
Precision	-insensitive	-sensitive
flow	✔	
path		
context		

ℓ

Next locations

no filter

all locations



ℓ_{cur} Q_{cur}

Current location

Current query

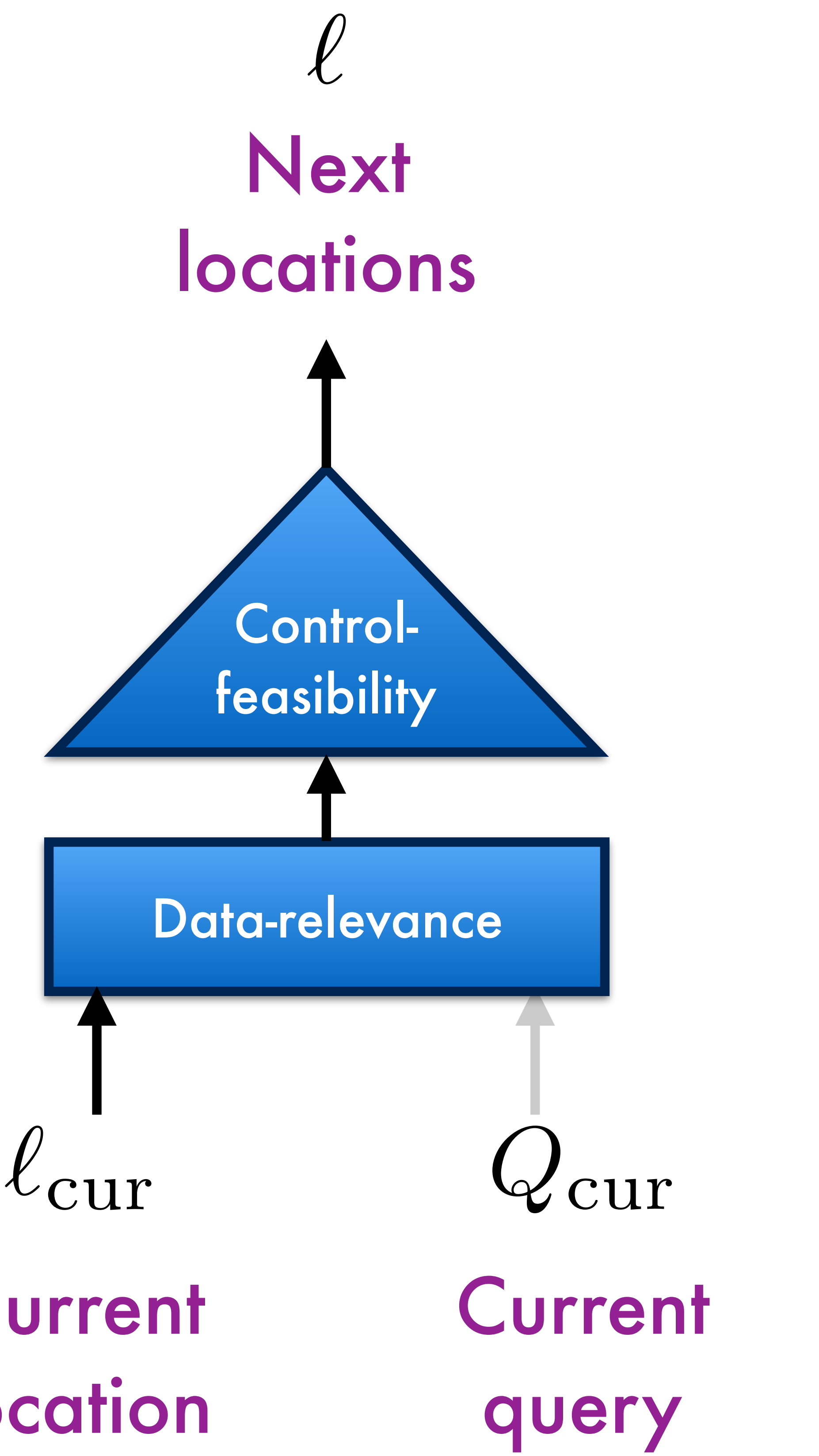
Jumping enables sparse, selective, on-the-fly ① control-flow abstraction

$$\ell_1 \dashv\!\![c]\!\!\to \ell_2$$

Precision	-insensitive	-sensitive
flow	✔	
path		
context		

only preds(ℓ_{cur})

all locations



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

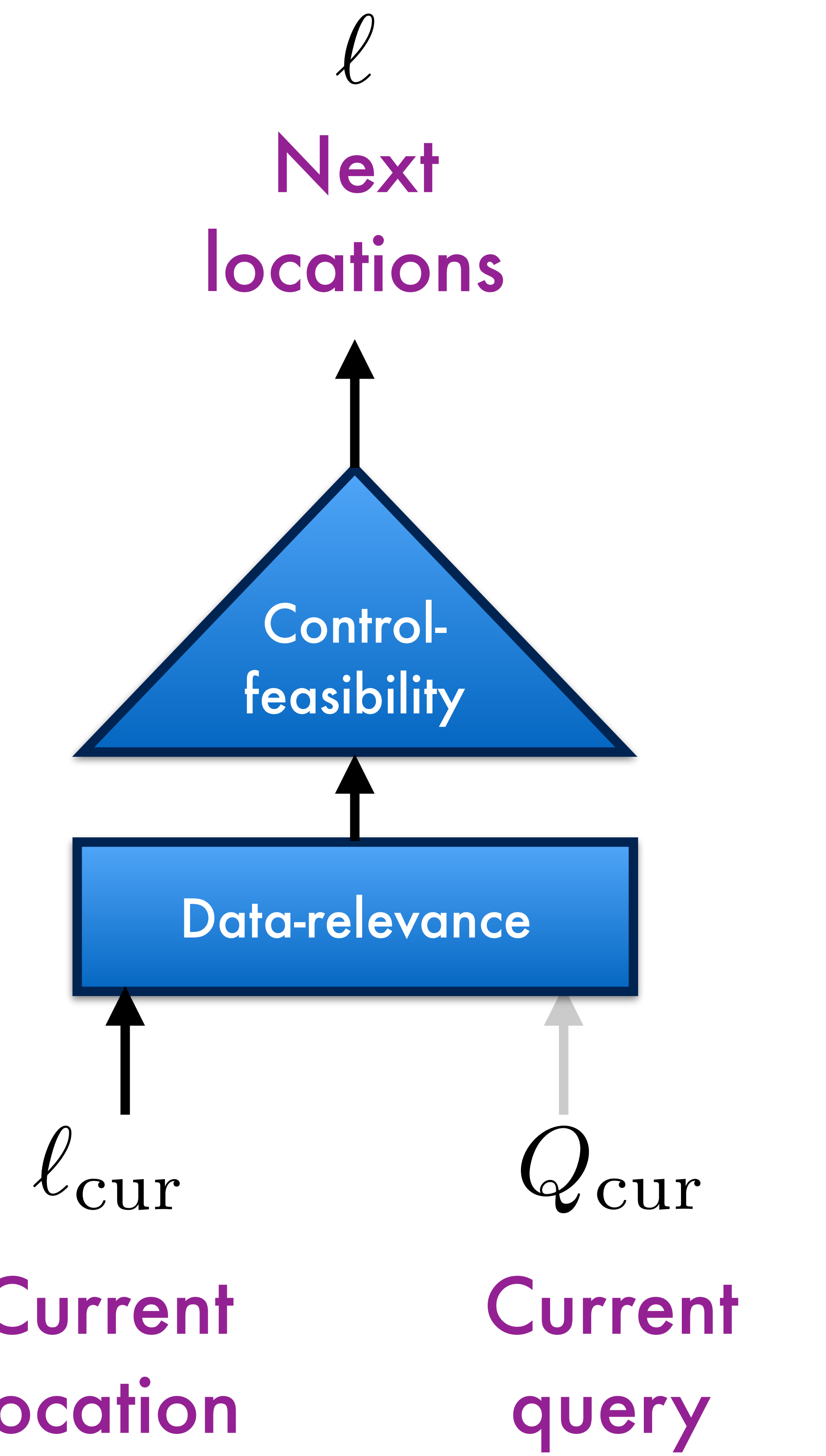
1

$\ell_1 \dashrightarrow[c] \ell_2$

Precision	-insensitive	-sensitive
flow	✔	
path		
context		

only preds(ℓ_{cur})

all locations



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

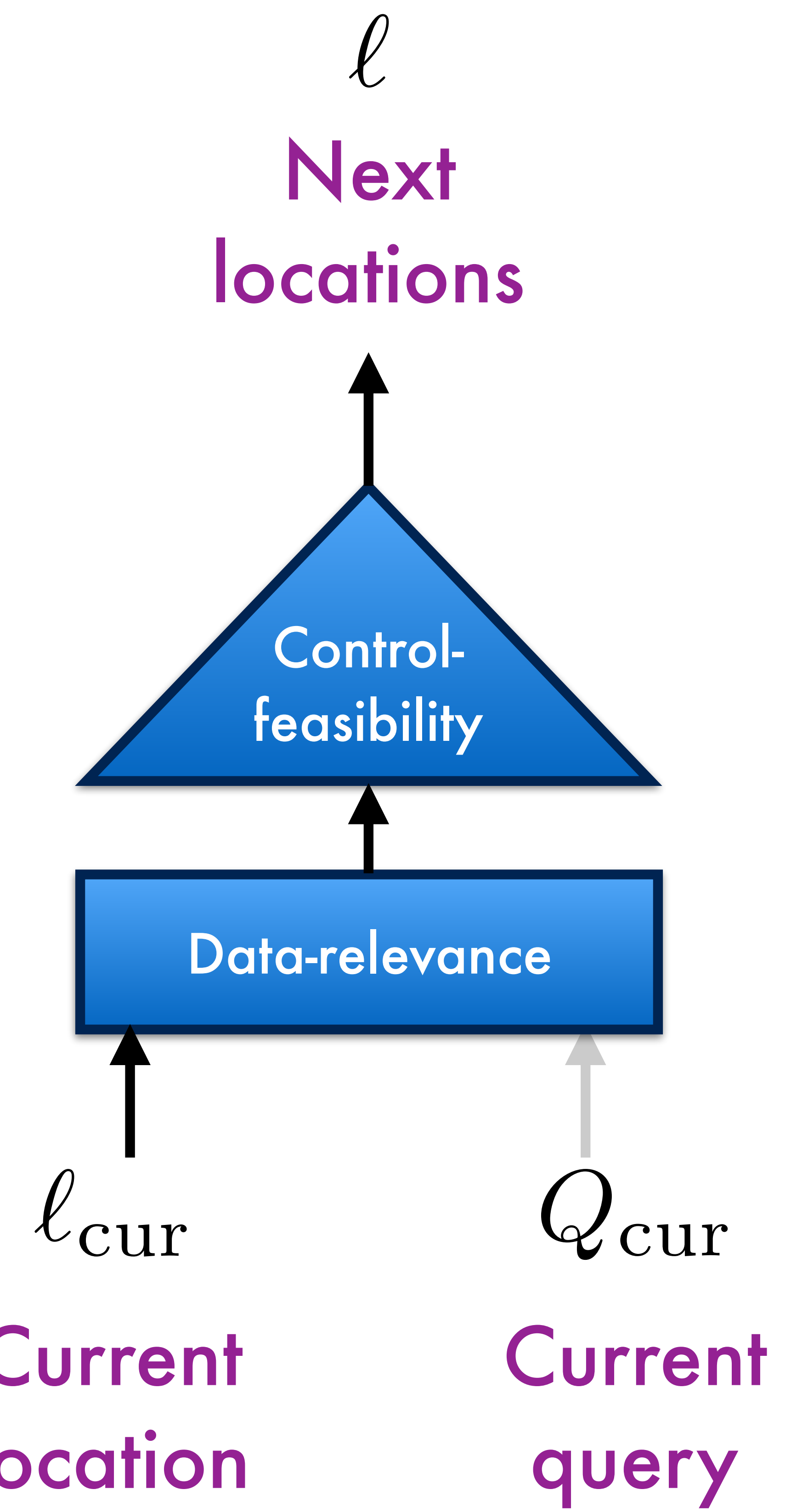
1

$$\ell_1 \dashv\!\![c]\!\!\mapsto \ell_2$$

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

only preds(ℓ_{cur})

all locations



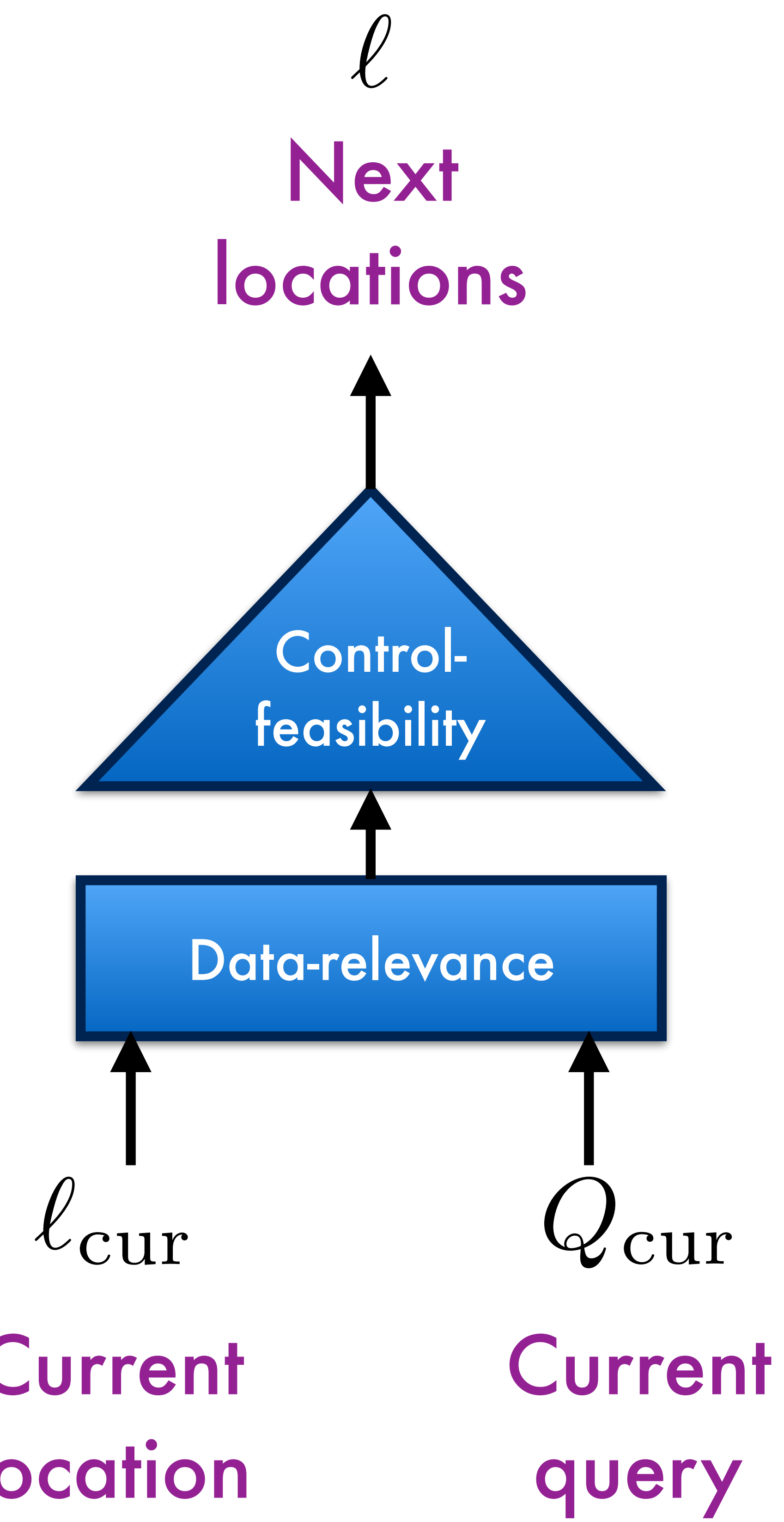
Jumping enables sparse, selective, on-the-fly control-flow abstraction

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

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

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

all locations



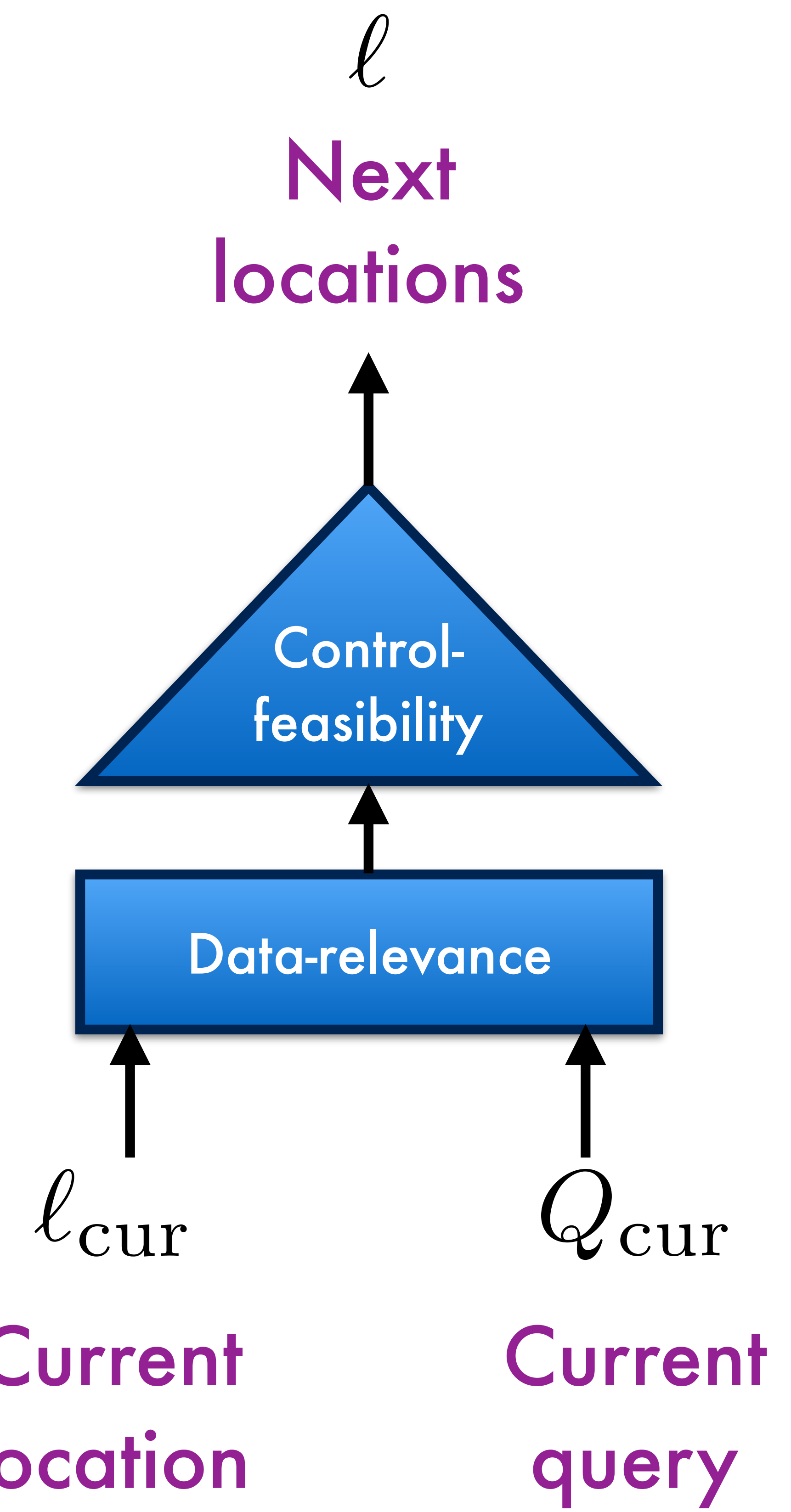
Jumping enables sparse, selective, on-the-fly control-flow abstraction

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

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

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

all locations



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

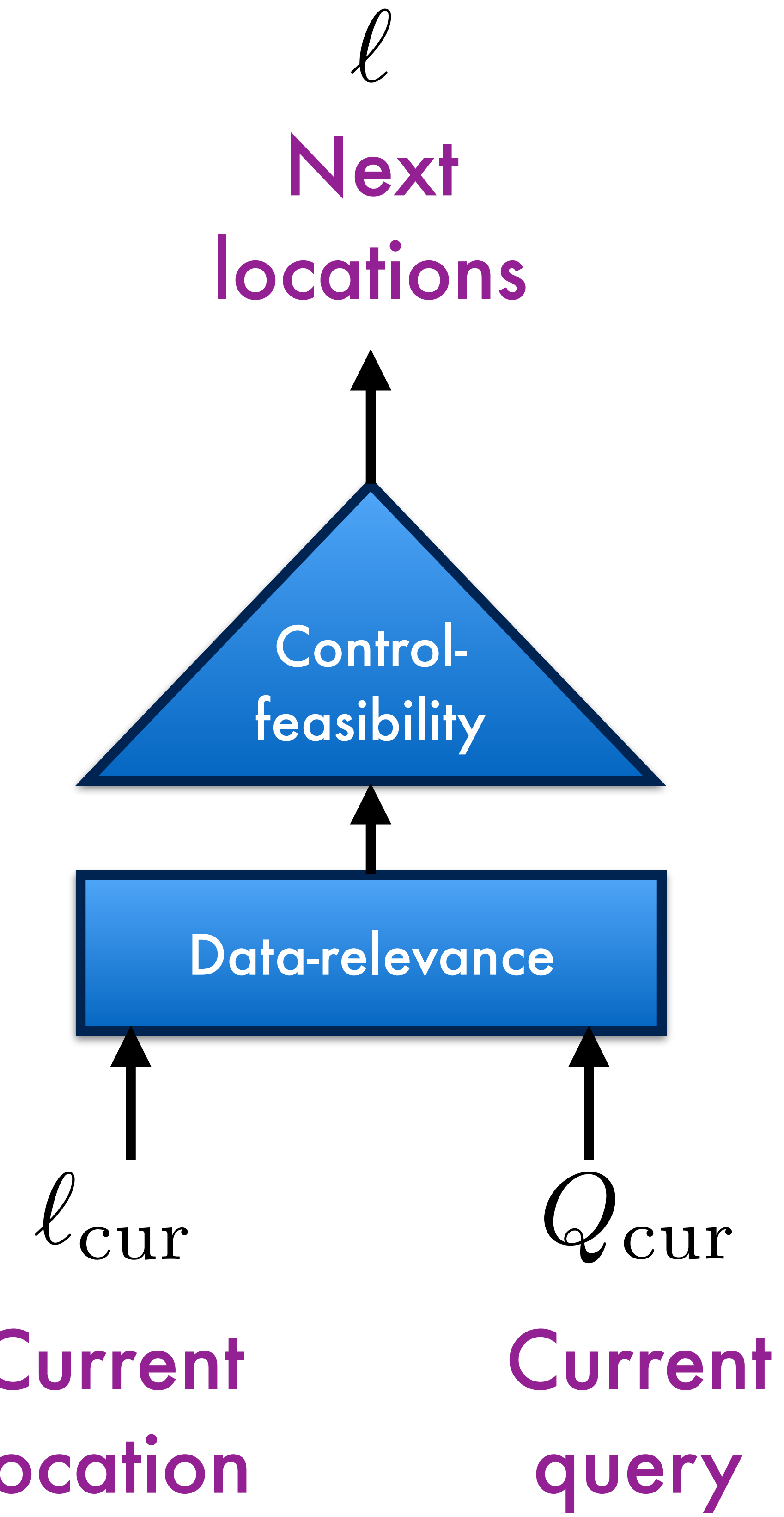
1

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

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

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

all locations



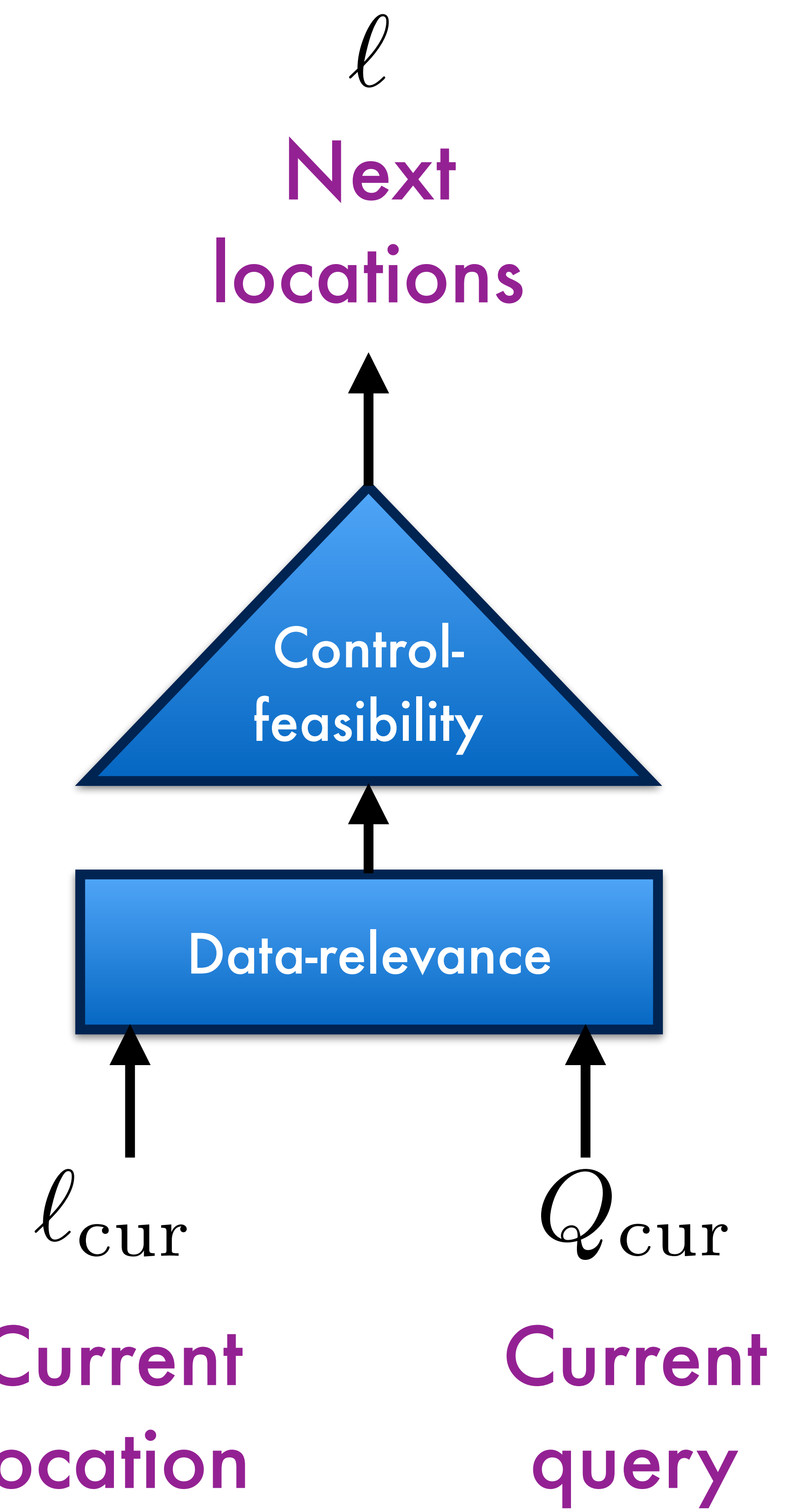
Jumping enables sparse, selective, on-the-fly control-flow abstraction

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

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

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

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

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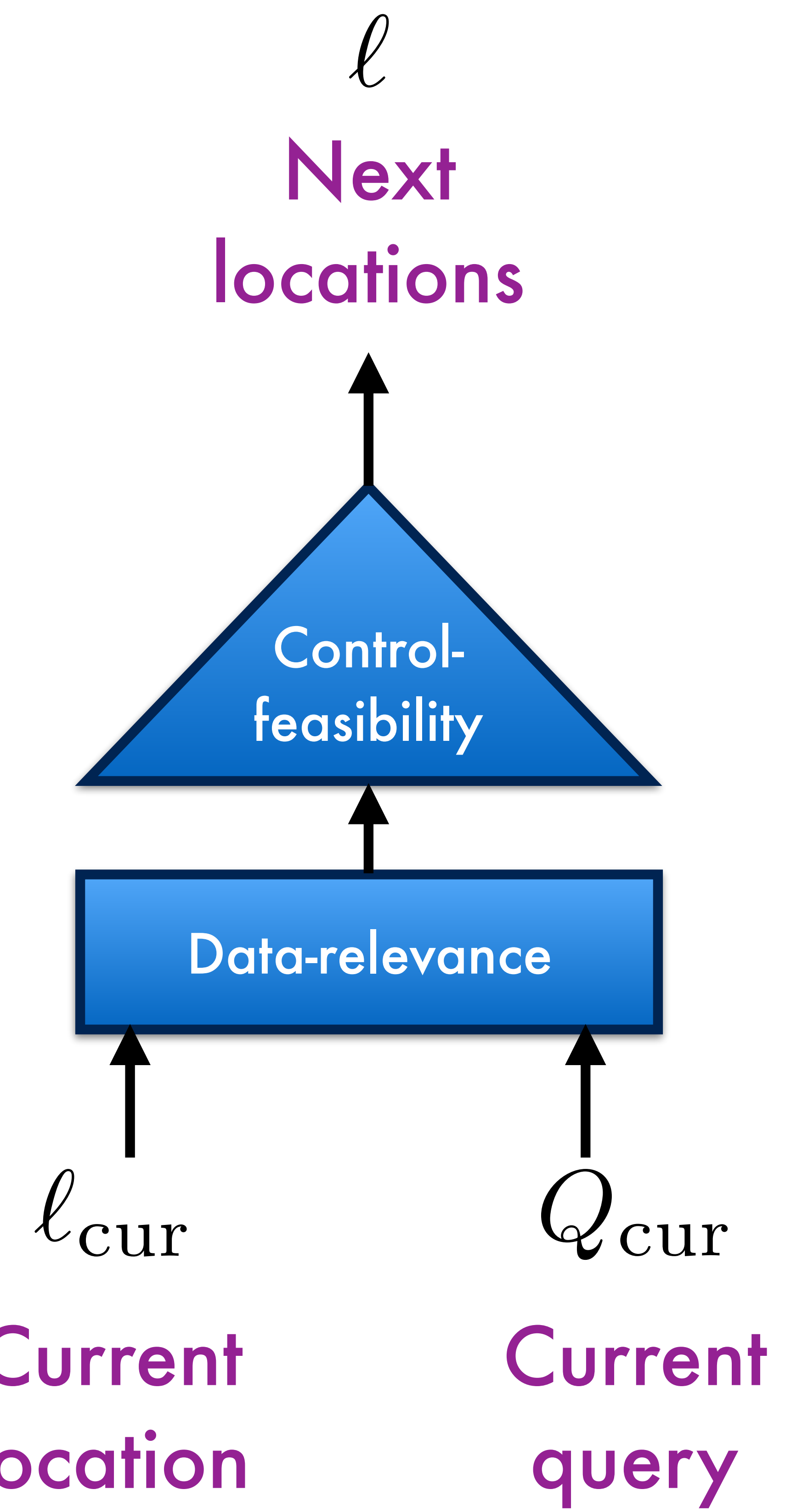

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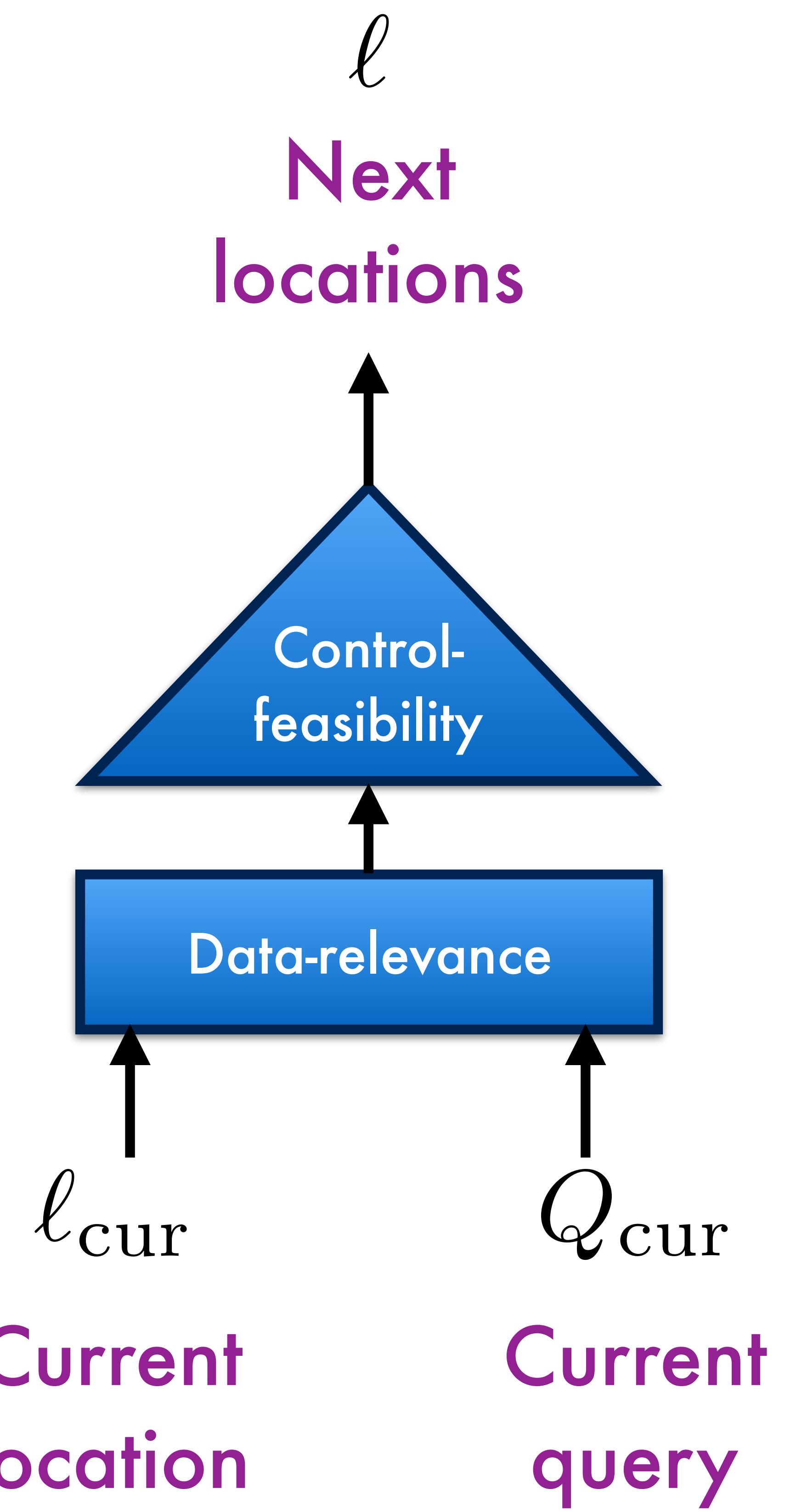


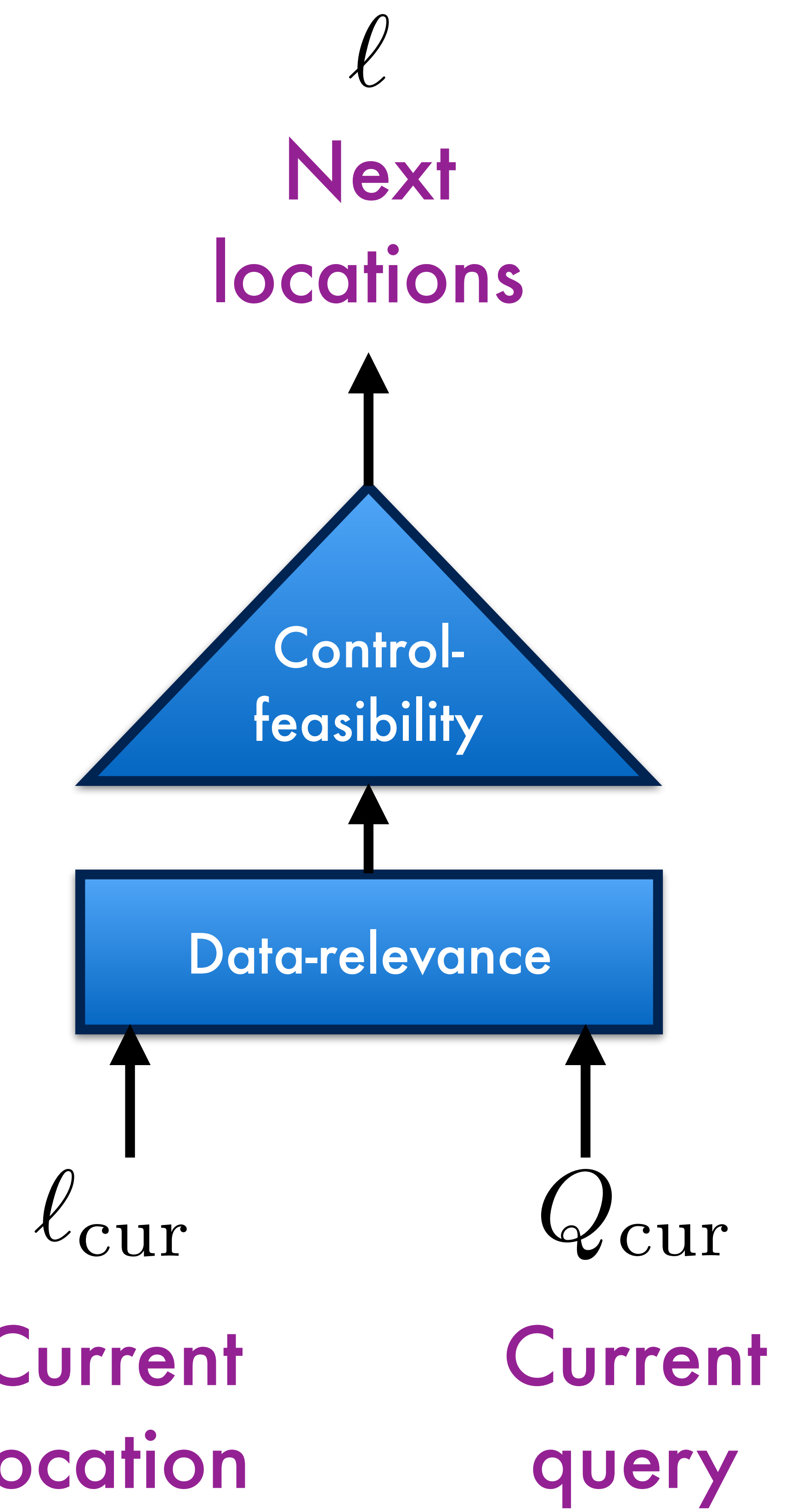
Jumping enables sparse, selective, on-the-fly control-flow abstraction

1

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

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

all locations



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

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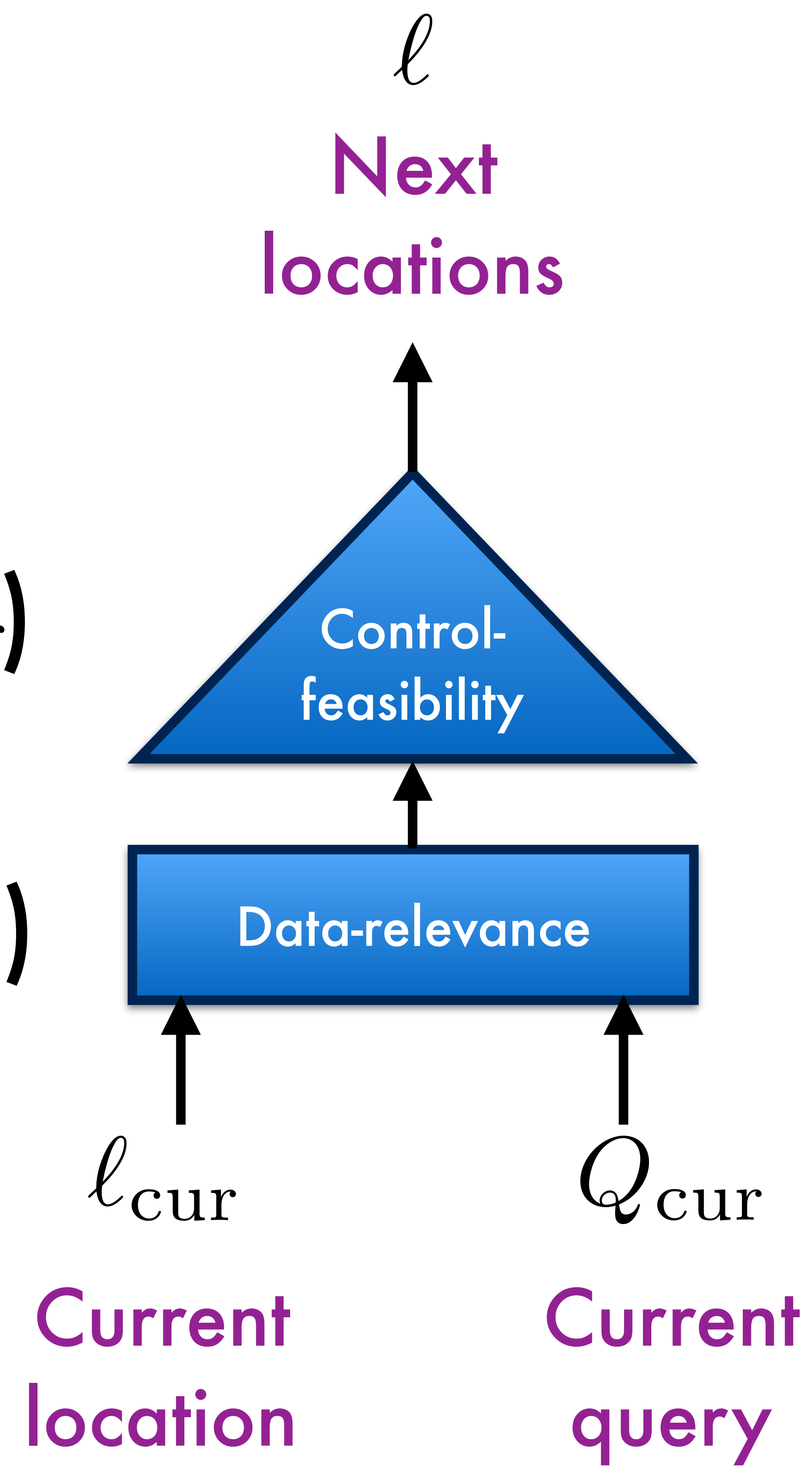
only feasible-preds($\ell_{\mathrm{cur}}, Q_{\mathrm{cur}}$)

all mods(Q_{cur})



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

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

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

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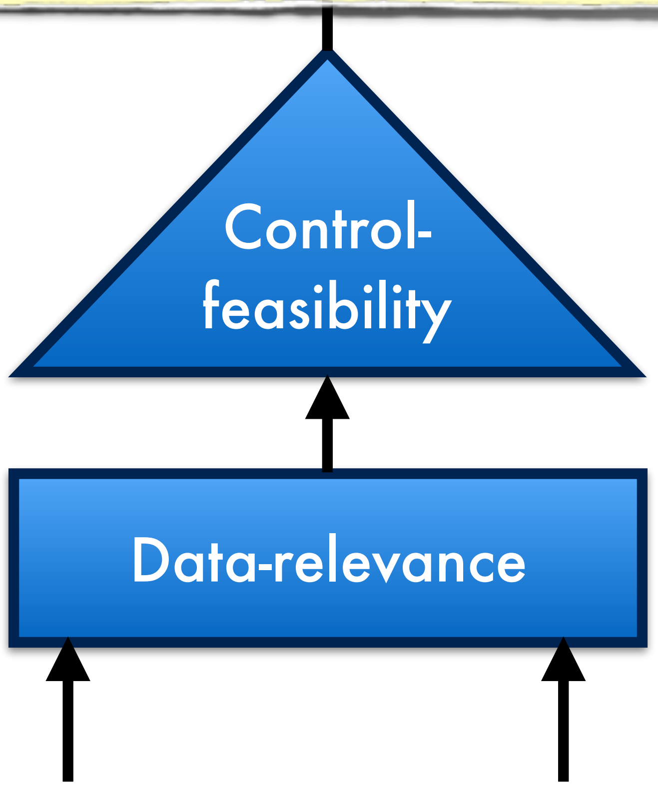
all mods(Q_{cur})



ℓ_{cur} Current location

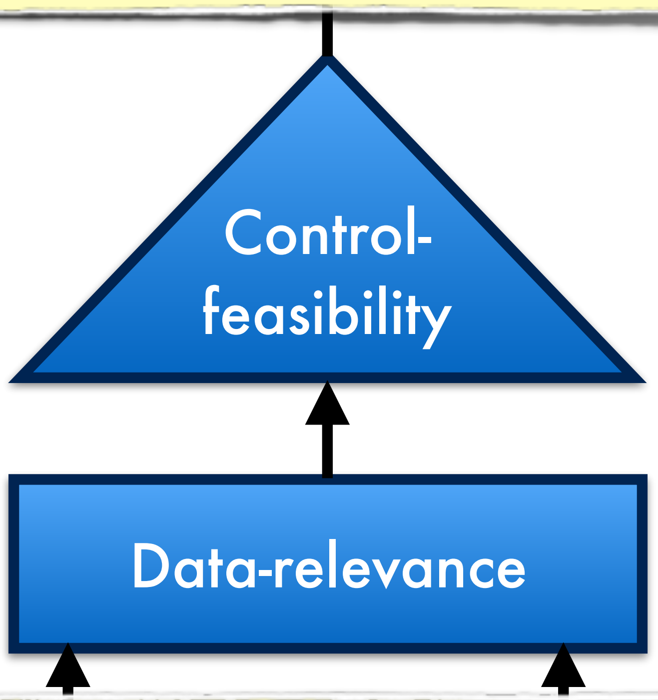
Q_{cur} Current query

Jumping enables sparse, selective, on-the-fly (1) control-flow abstraction $\ell_1 \dashrightarrow[c] \ell_2$

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

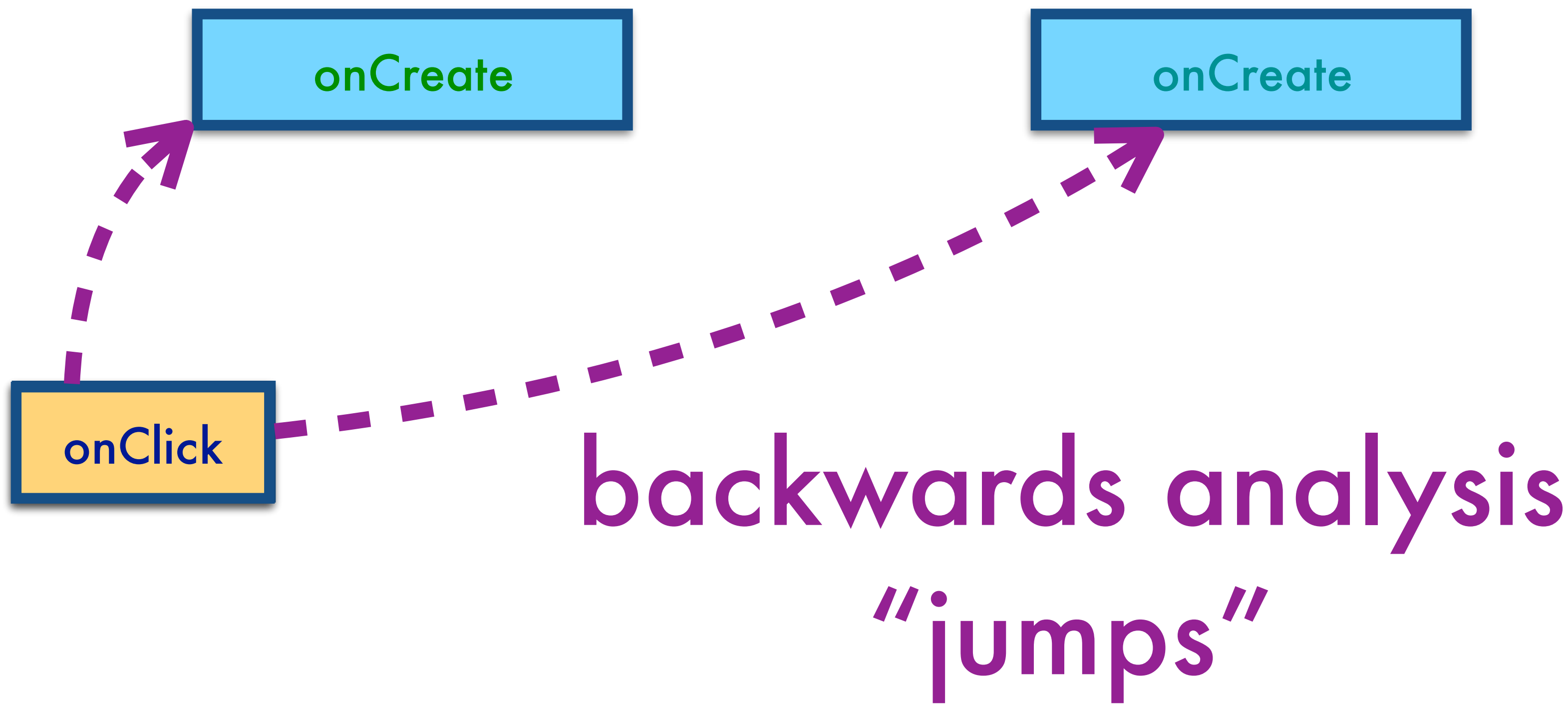
only feasible-preds($\ell_{\mathrm{cur}}, Q_{\mathrm{cur}}$)

all mods(Q_{cur})



Be **selective** by varying the relevance relation at each an analysis step

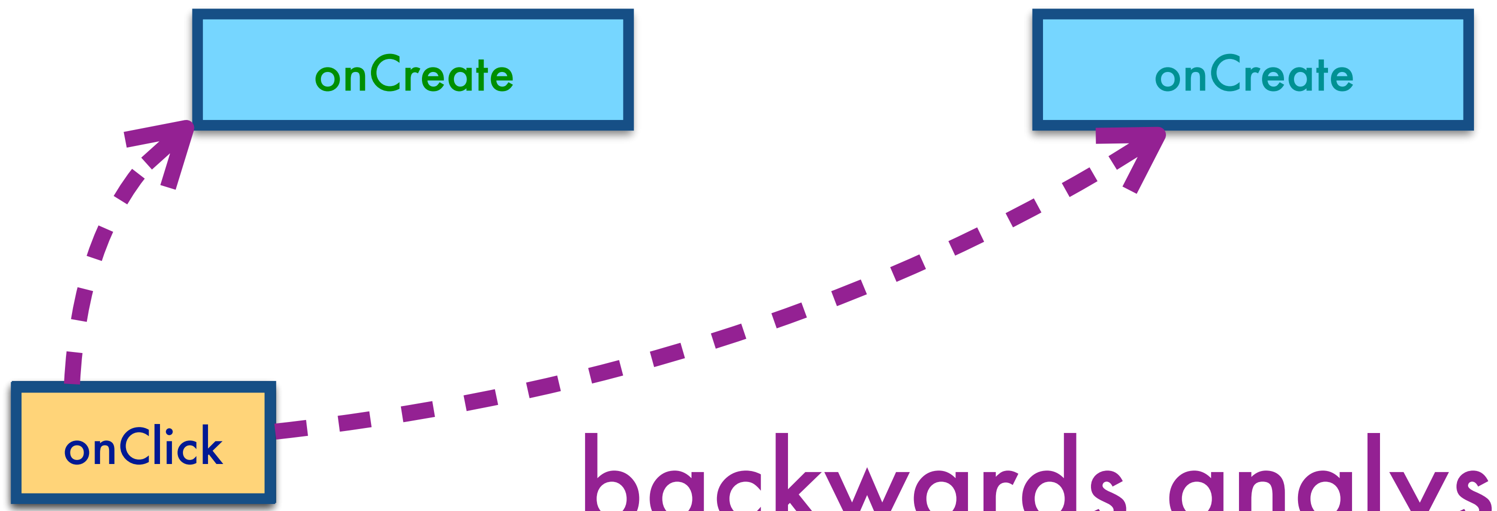
Contributions



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

2  Applied to Android events

Contributions

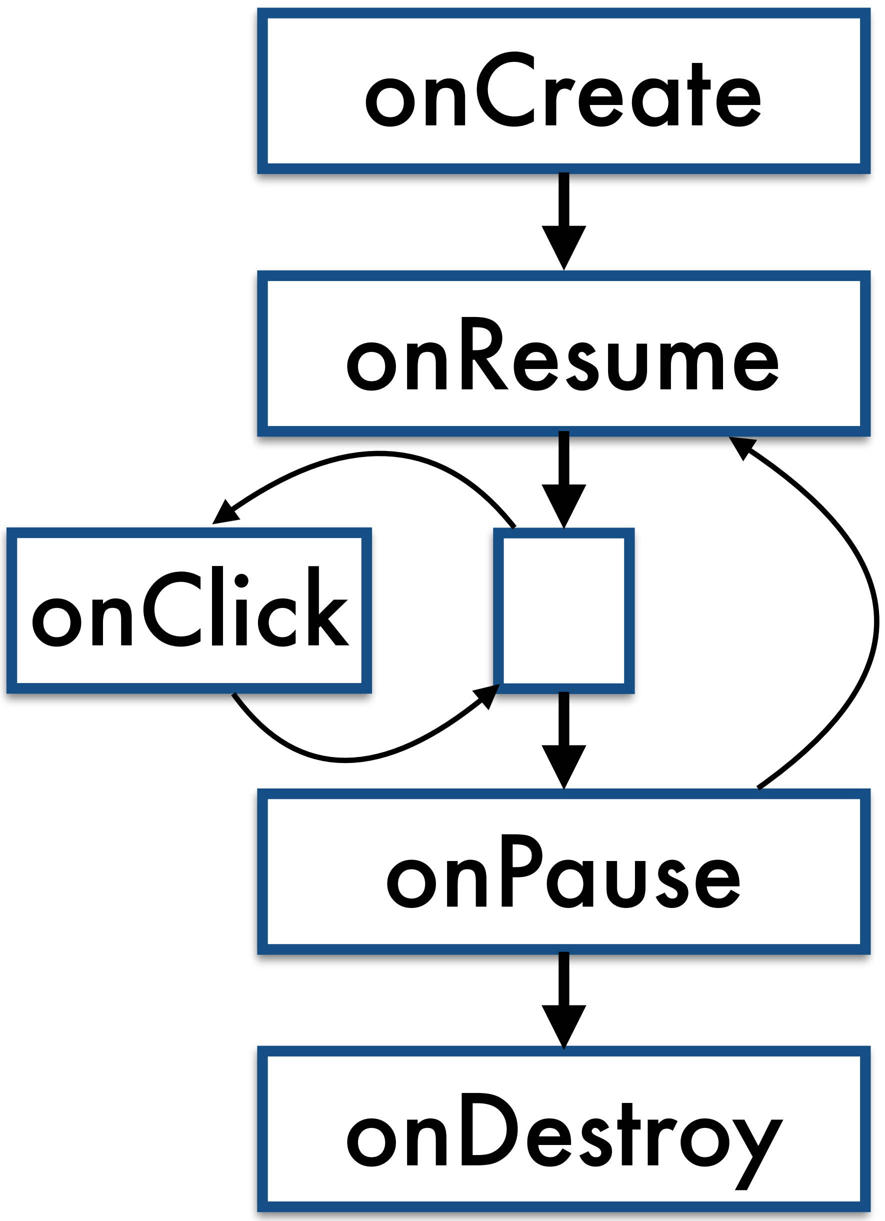


backwards analysis
"jumps"

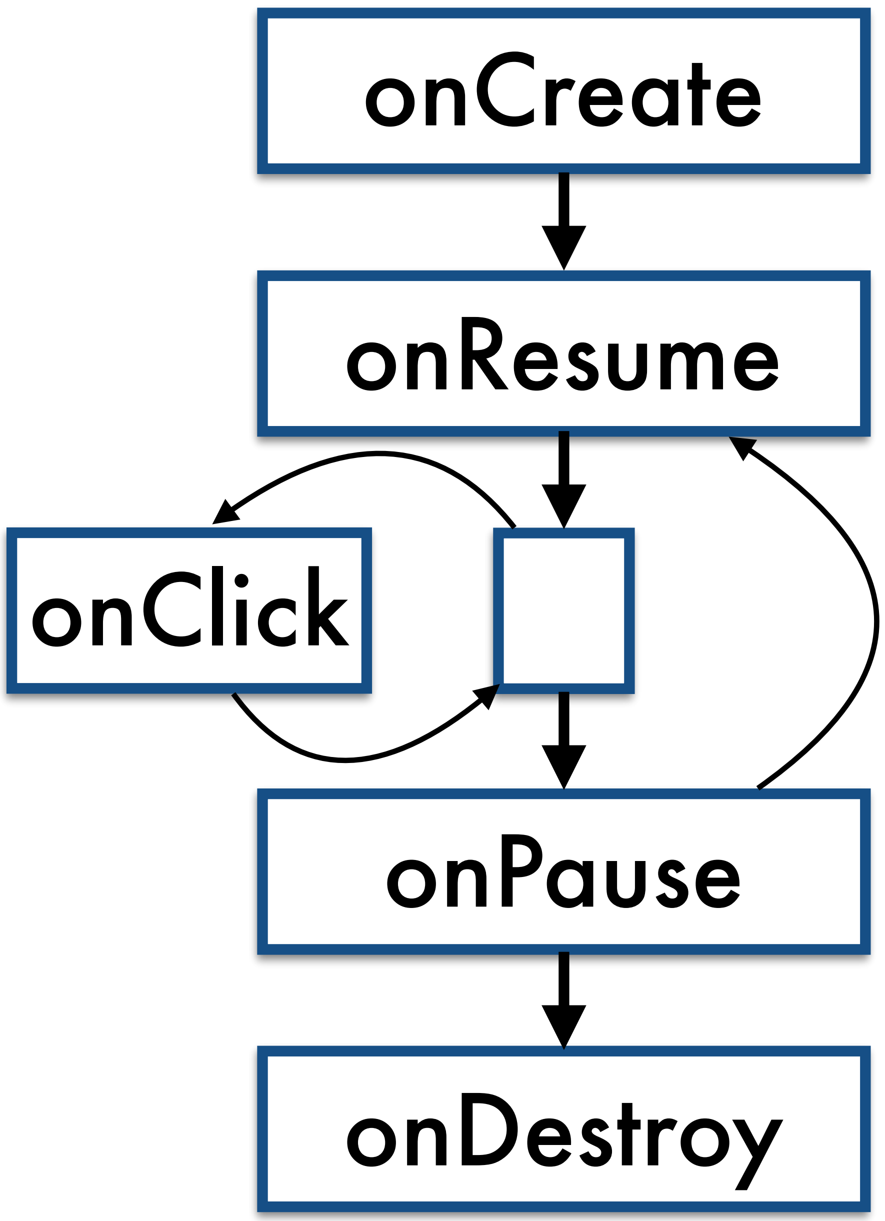
1 $\ell_1 \mathrel{-[c]\!\!\rightarrow} \ell_2$ Framework for jumping analyses

2 Applied to Android events

Formalizing lifecycle graphs

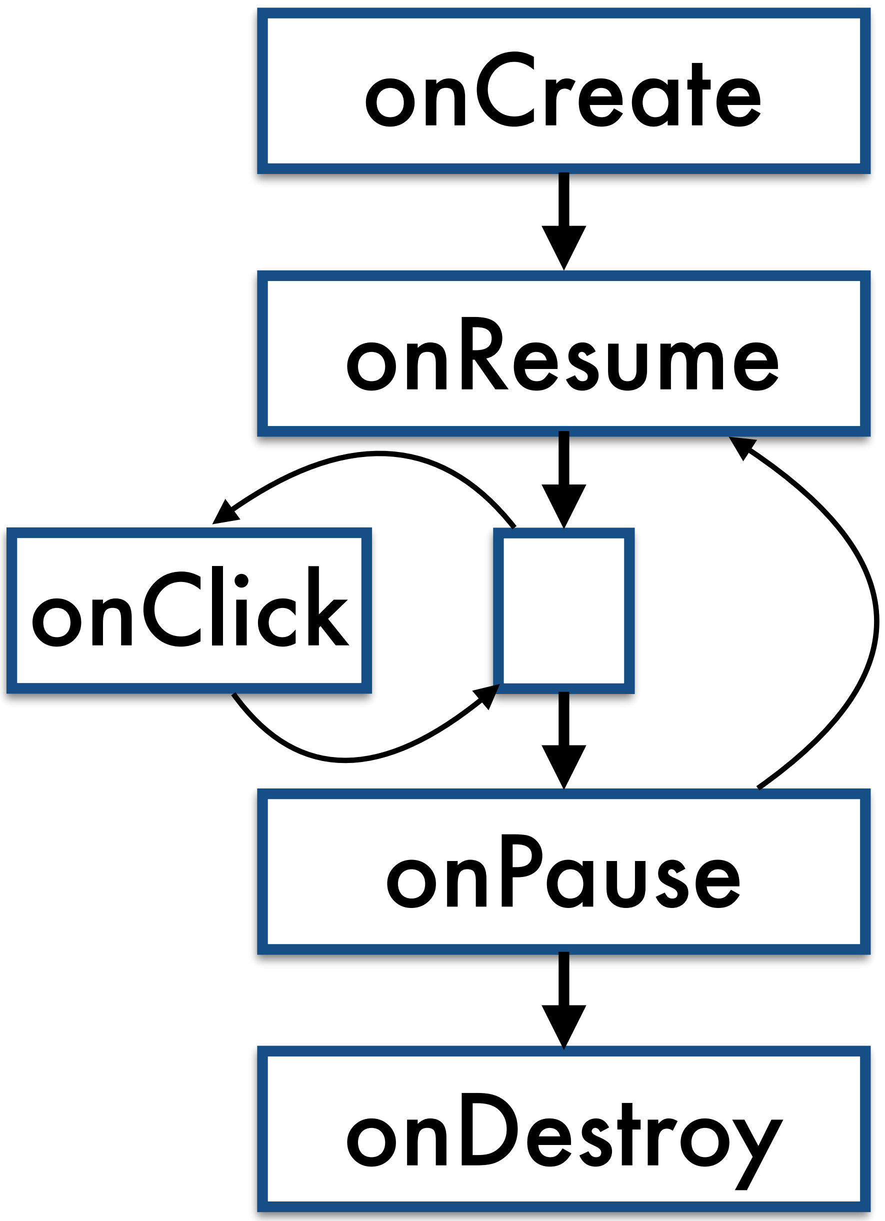


Formalizing lifecycle graphs



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

Formalizing lifecycle graphs



"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

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Event product graph would have 10^{10} to 10^{111} nodes (with one instance per class)

Setup: Proving dereferences safe

10 open source Android apps

- 3,000 to 55,000 lines of code
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Setup: Proving dereferences safe

10 open source Android apps

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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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Total	**266**	**62562**	**41071**	**9968**	**5412 (54)**

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Many derefs

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Flow-insensitive

No jumping

Jumping

unproven derefs

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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?

	KLOC	unproven derefs: Deref	Nit	Thr	Hop (Impr %)	% Proven
drupaleditor	3	928	679	179	72 (60)	92
npr	5	829	617	181	51 (72)	94
duckduckgo	11	1969	1341	518	143 (72)	93
lastfm	13	4840	3528	954	477 (50)	90
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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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Found 11 bugs in 4 apps
(lastfm, seriesguide, connectbot, wordpress)

5 bugs due to bad ordering assumptions

10/11 patches accepted

Triaging alarms to find bugs

Fixing possible NPE in OverviewActivity.launchSearch #449

Merged

Fixing possible NPEs when CheckInDialogFragment.newInstance returns null #450

Merged

Fix possible NPE in HostListActivity.onCreateContextMenu #60

Merged **kruton** merged 1 commit into `connectbot:master` from `sblackshear:service_npe_fix` on Mar 28

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(lastfm, seriesguide, connectbot, wordpress)

5 bugs due to bad ordering assumptions

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Summary

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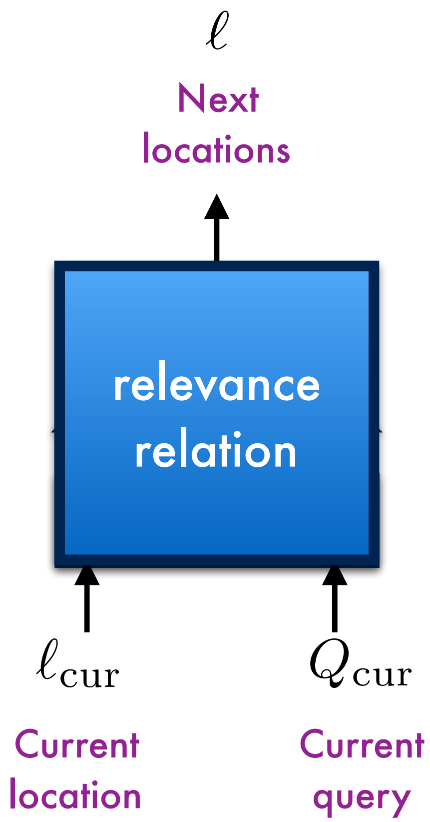
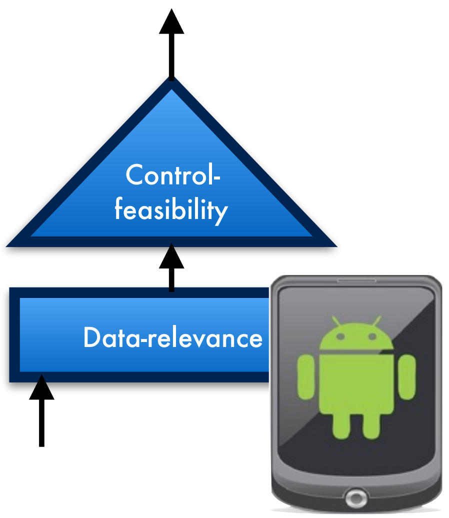


Selective control-flow abstraction via a sound relevance relation

Summary

Selective control-flow abstraction via a sound relevance relation



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

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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Staged

Run analysis multiple times, abstraction changes only between runs.

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Run analysis once, abstraction changes during analysis.

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Run analysis multiple times, abstraction changes only between runs.

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Run analysis once, abstraction changes during analysis.

Refinement

Start with imprecise abstraction, become more precise.

Coarsening

Start with precise abstraction, become less precise.