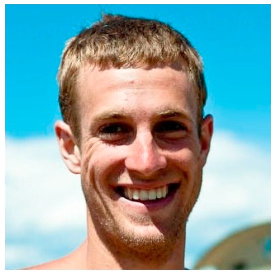
Goal-Directed Program Analysis with Jumping



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Samsung Research America

MPI-SWS
3 October 2015

To appear at OOPSLA 2015

PLV


Crash
T··Mobile·

Roughly, 3% of all commits fix NullPointerExceptions

Callback-oriented programming

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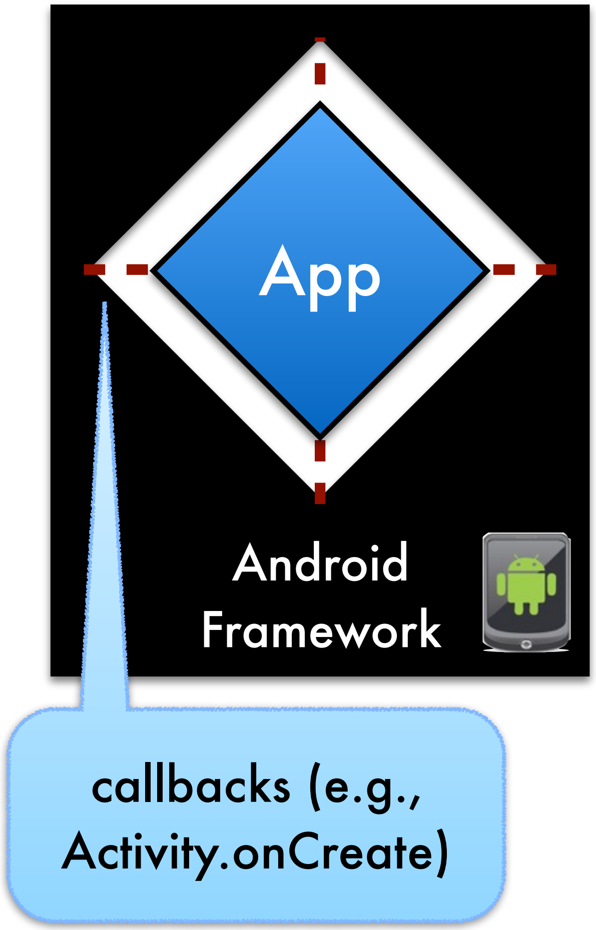

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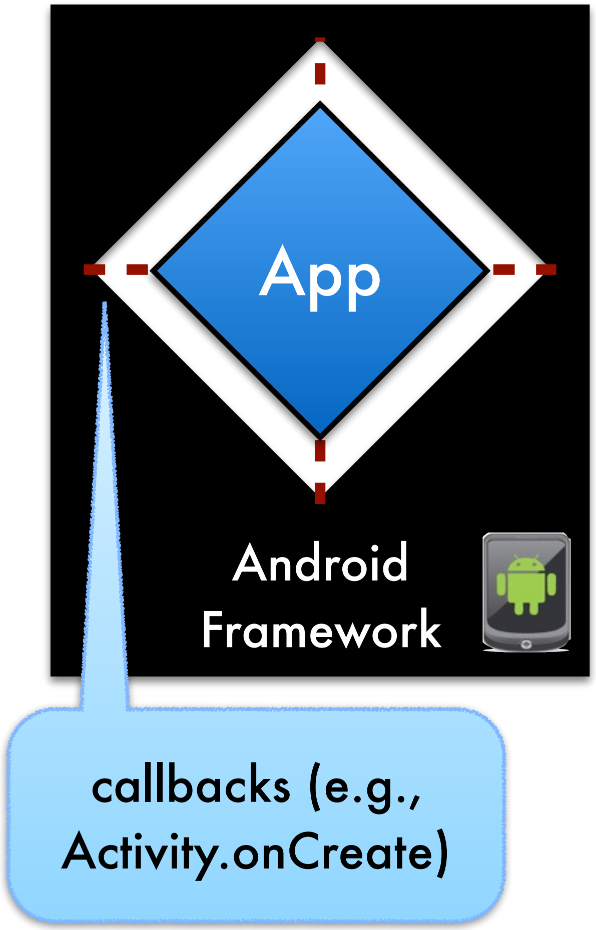

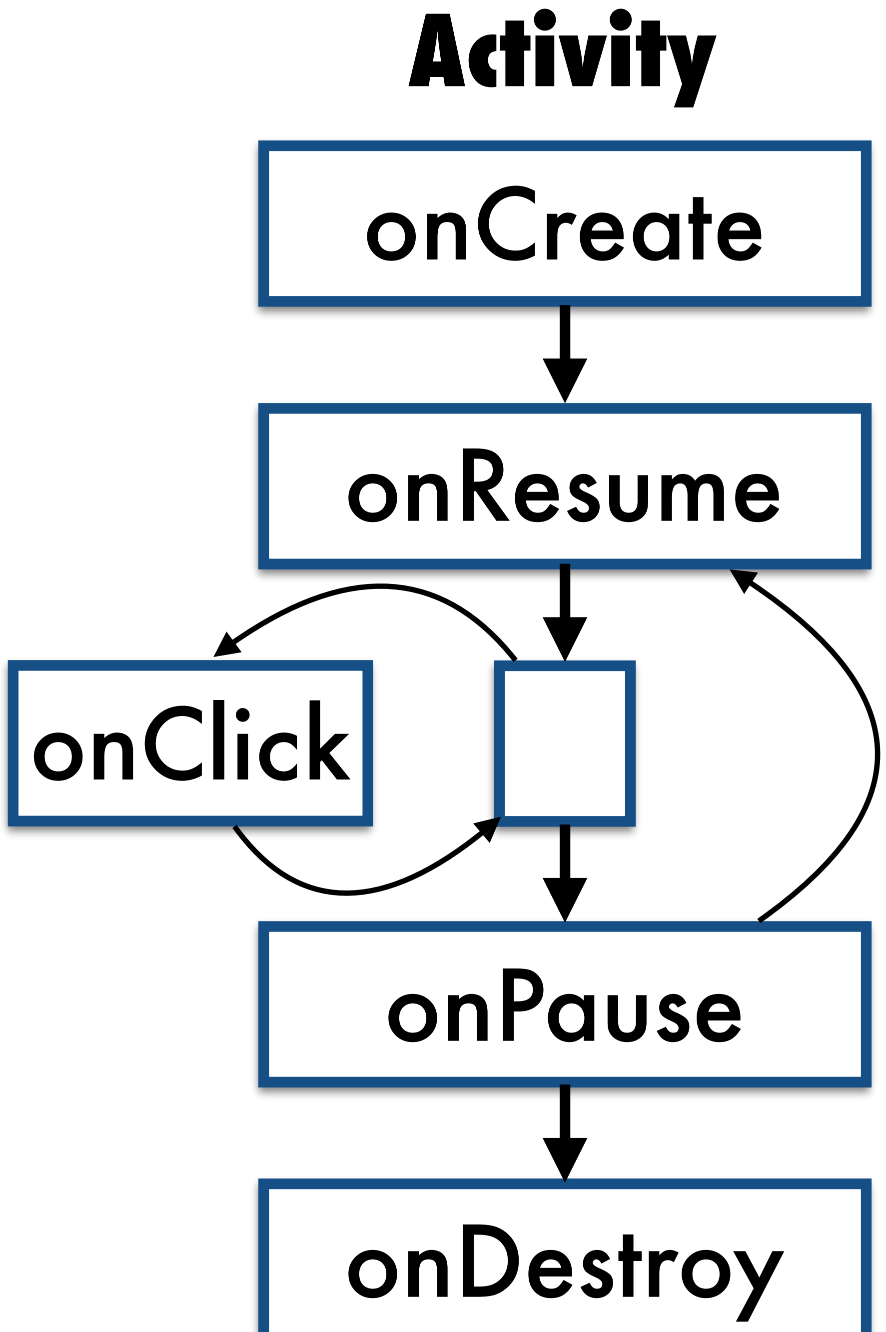

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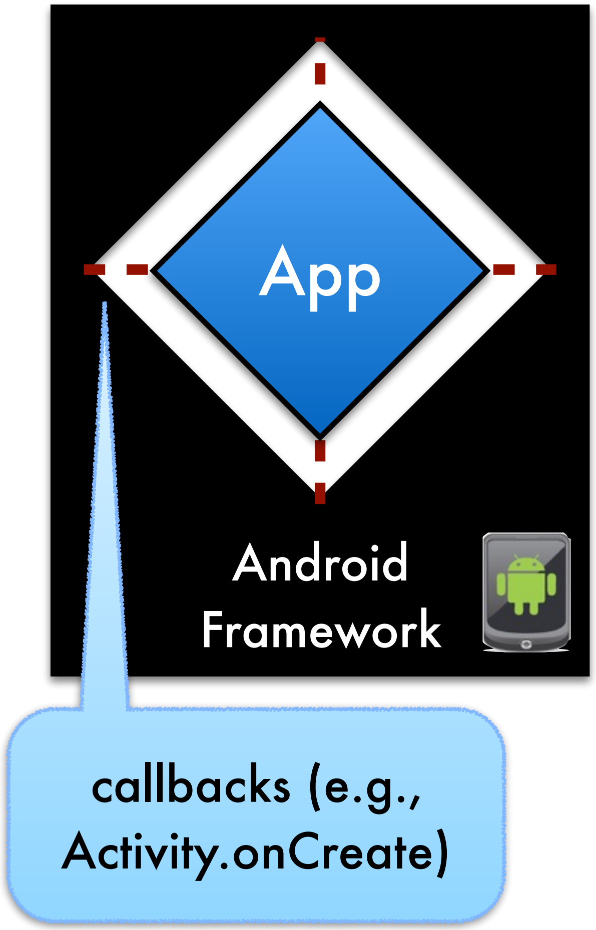
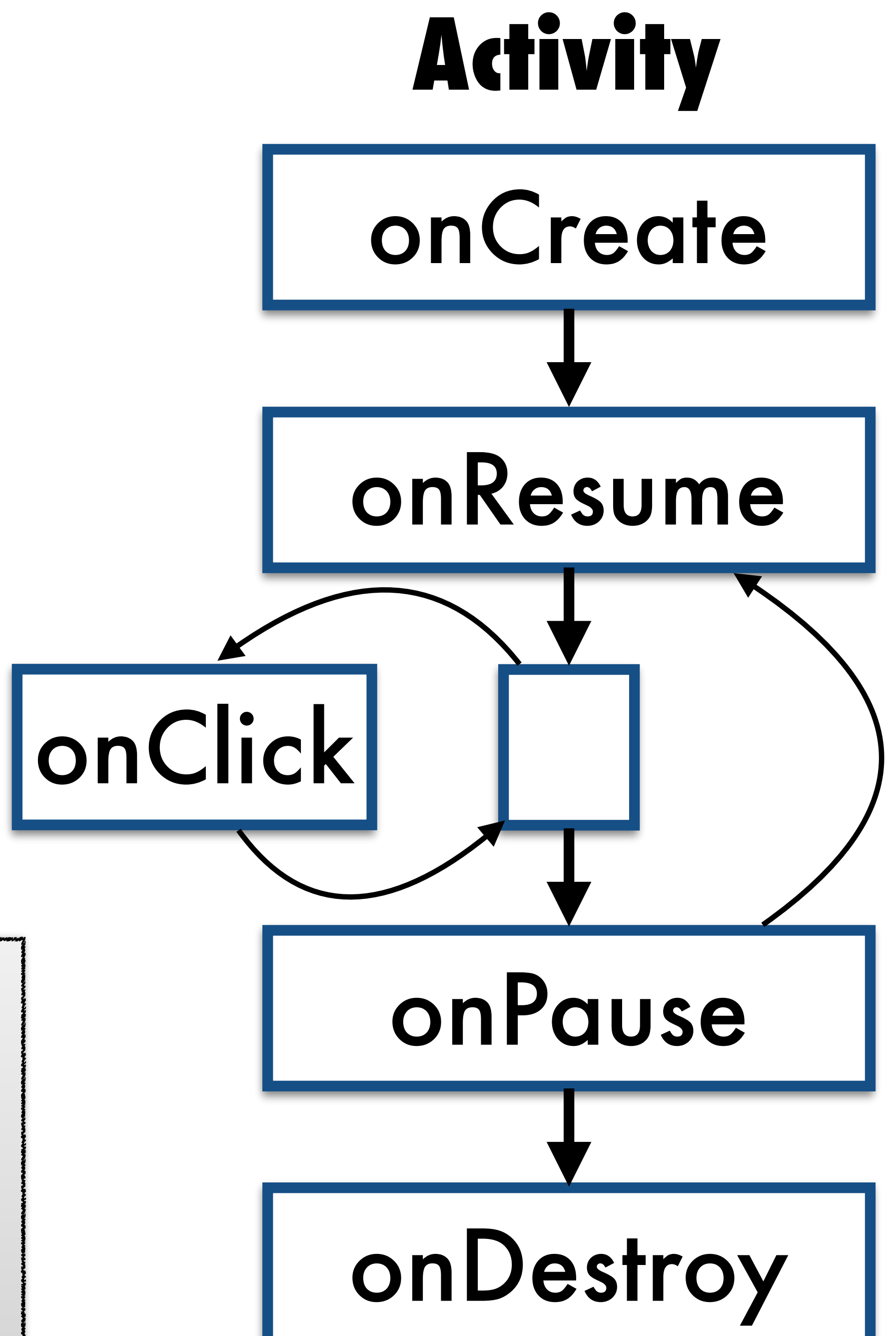


Android components have an ordered, event-driven lifecycle



Callback-oriented programming

callbacks (e.g.,
Activity.onCreate)

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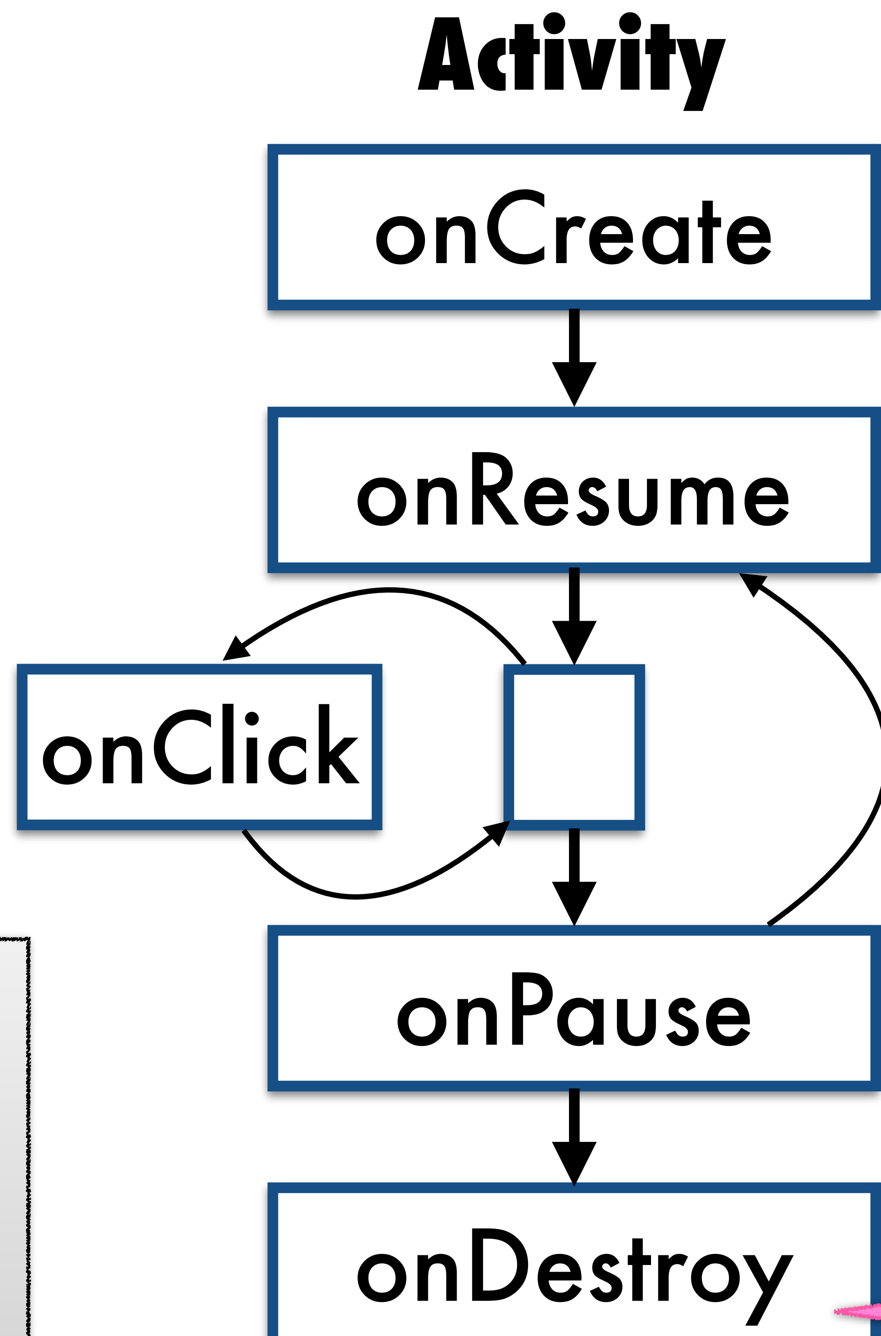


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Callback-oriented programming

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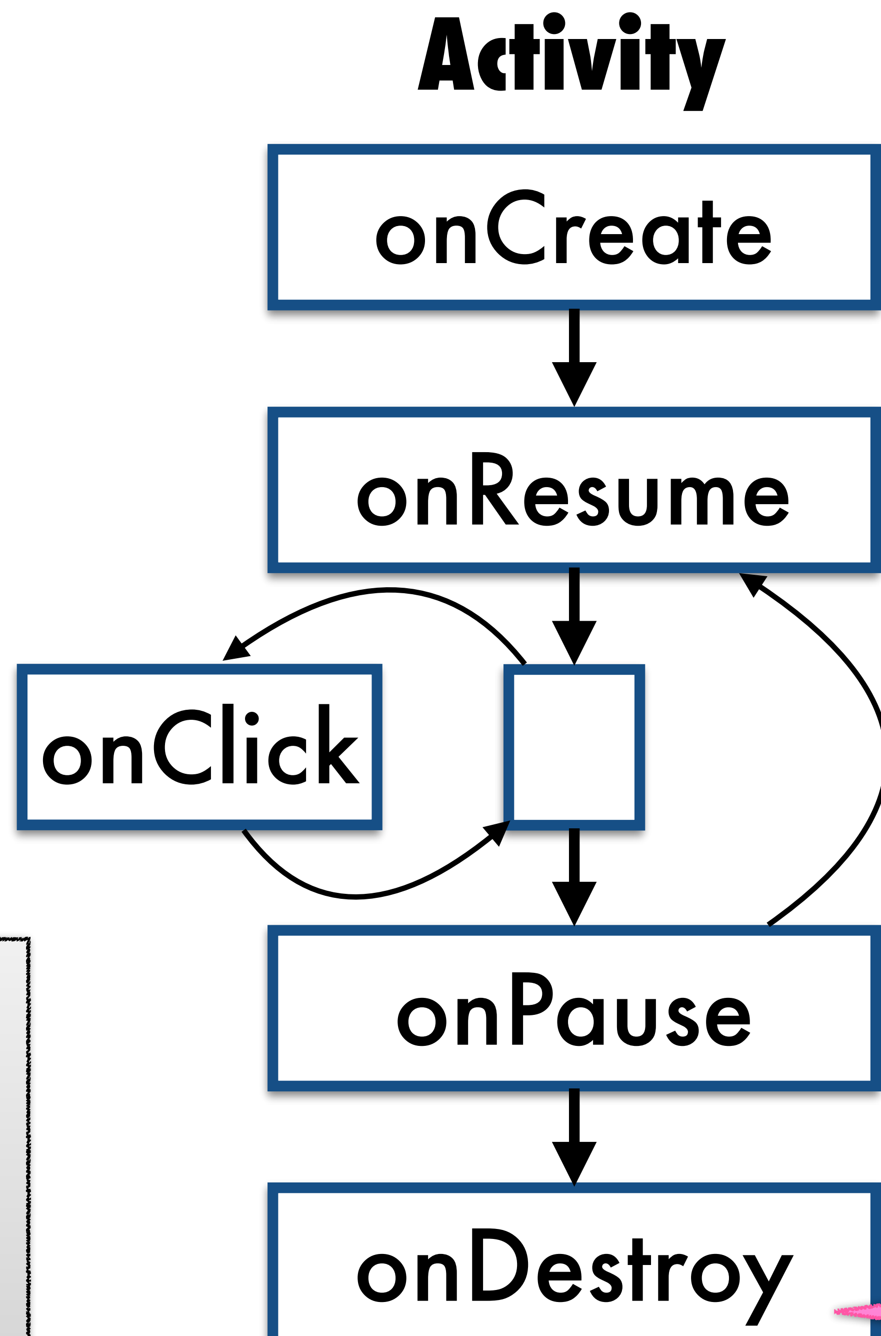

But, lifecycles of different components and other callbacks can interleave …

```
mHostDb = null;
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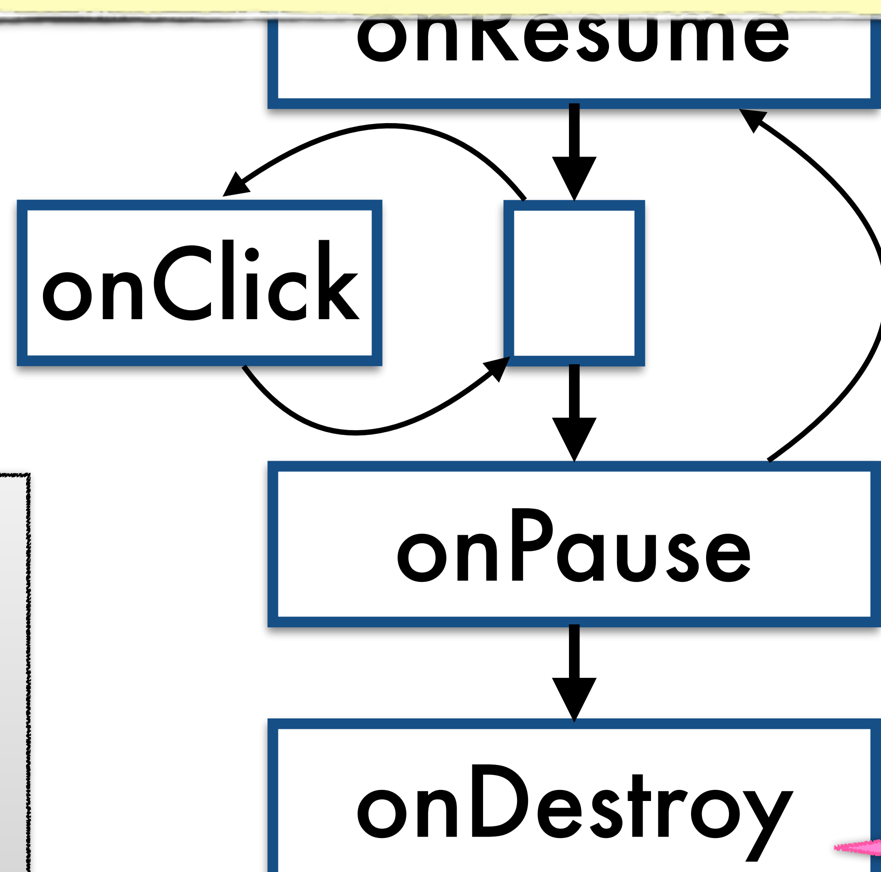
Callback-oriented programming

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

Android Framework

callbacks (e.g., Activity.onCreate)

Android components have an ordered, event-driven lifecycle



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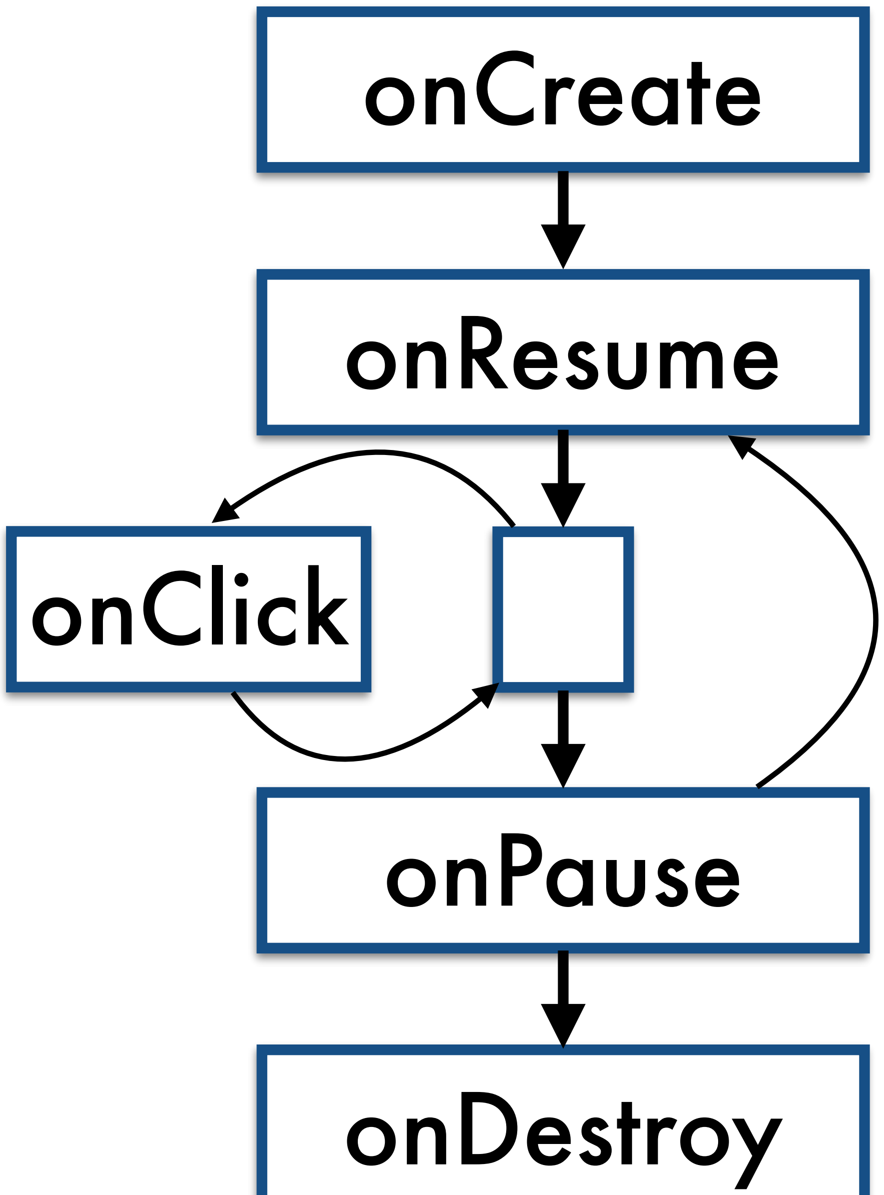
Callback-oriented programming



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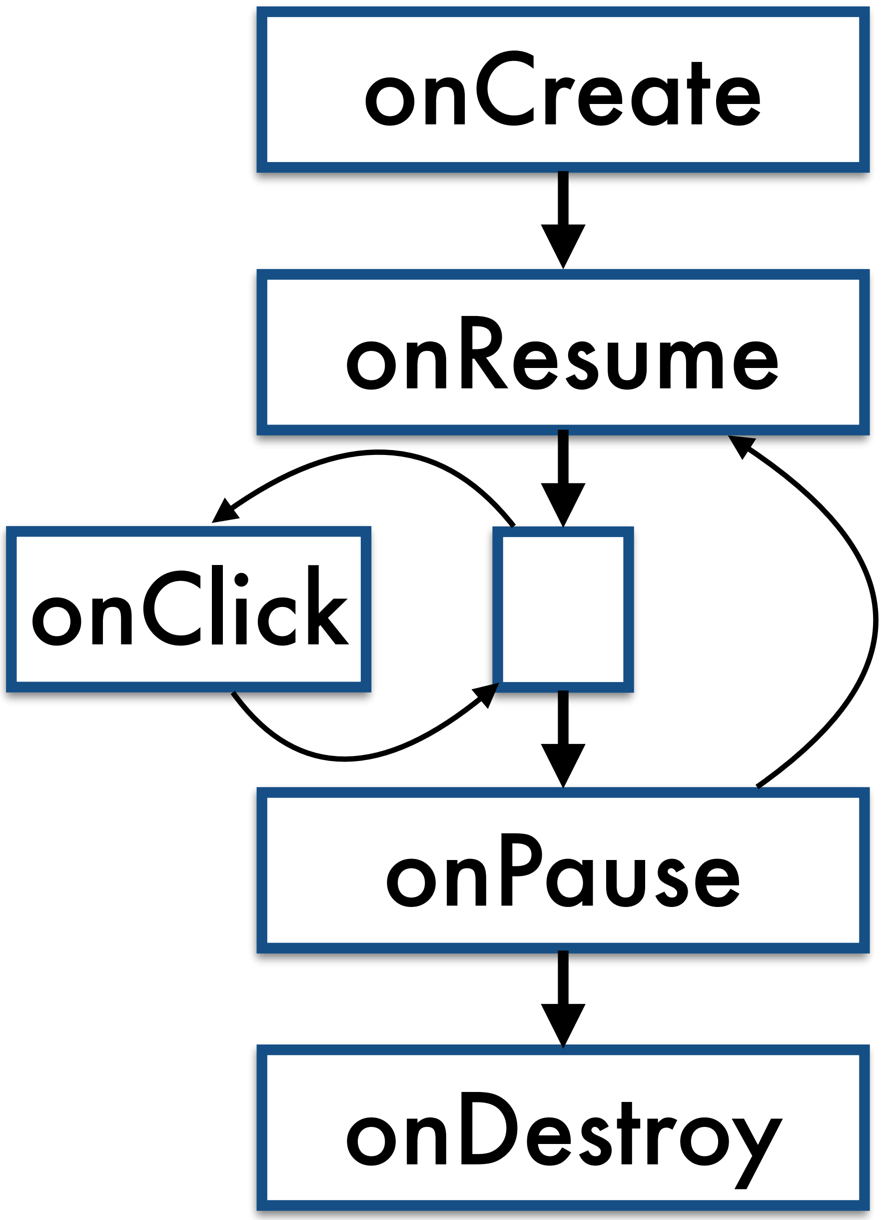

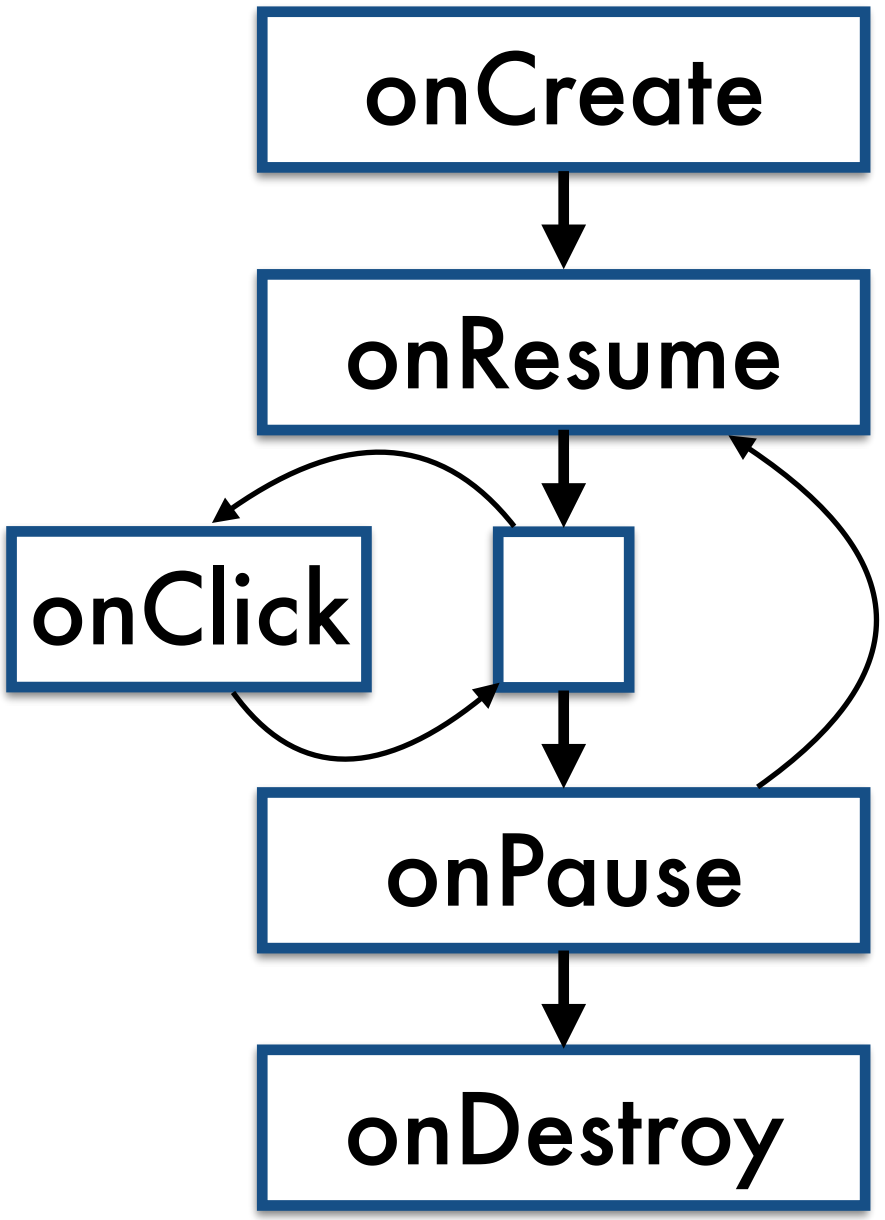

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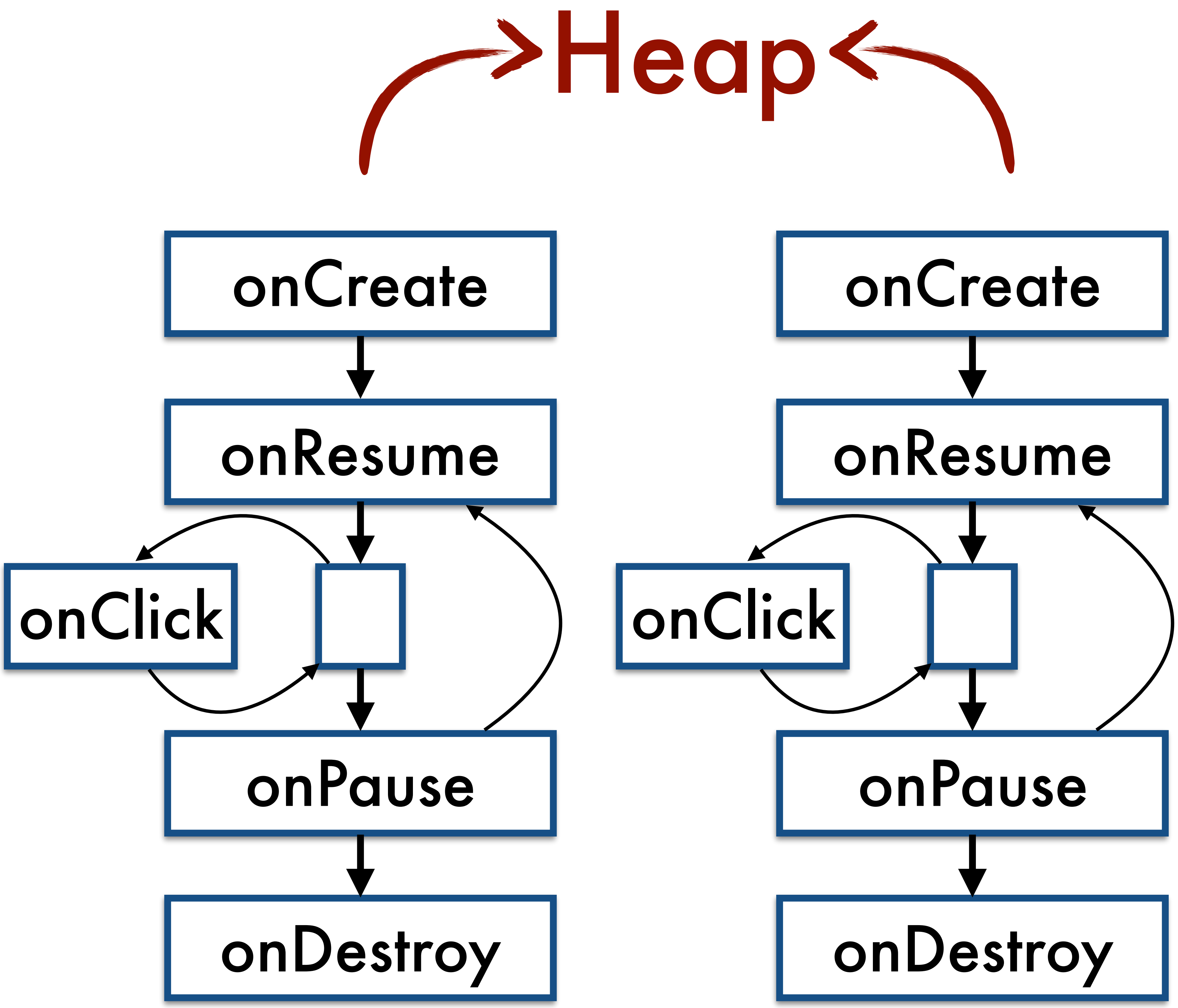

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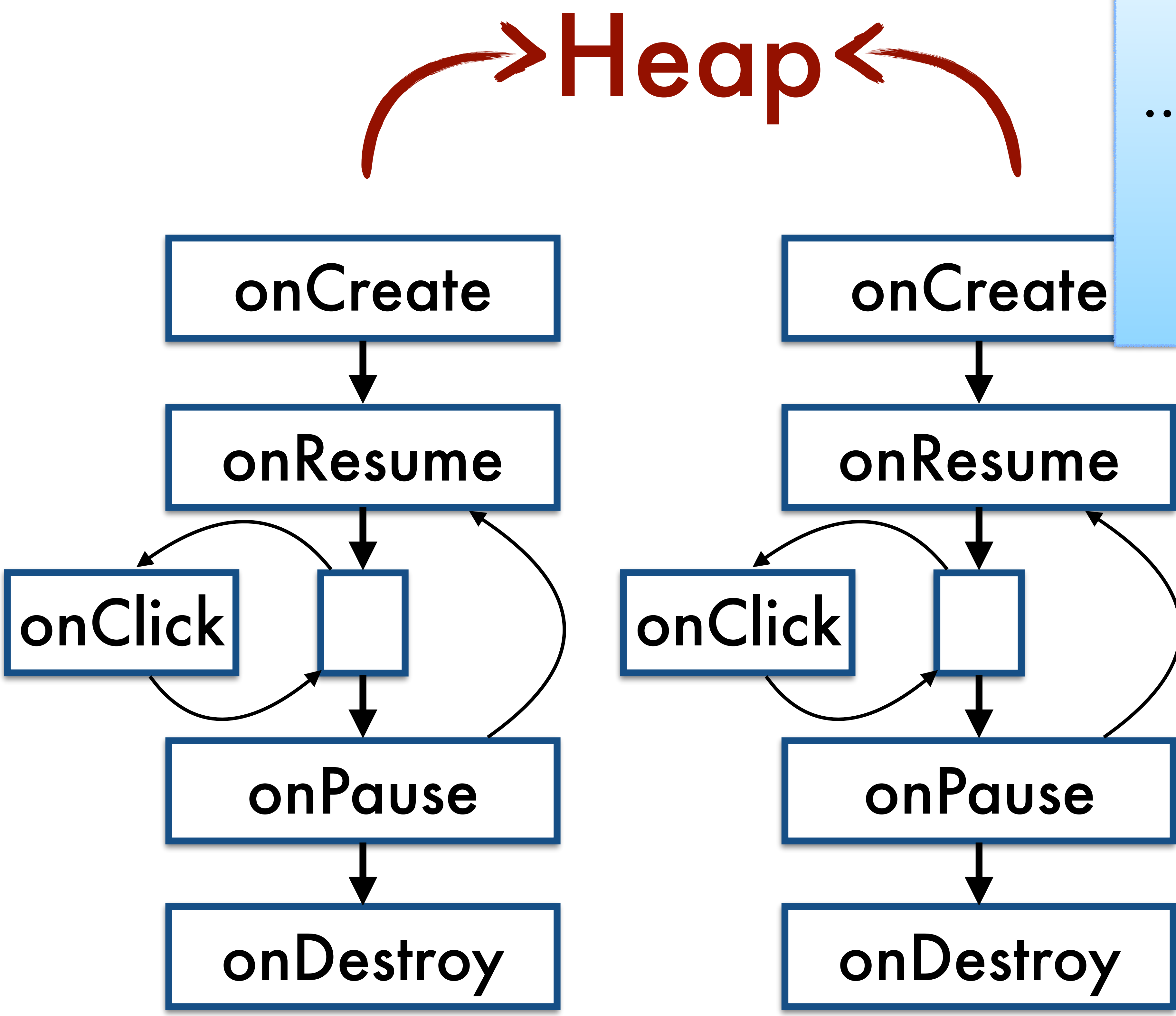

… and operates over a shared, global heap

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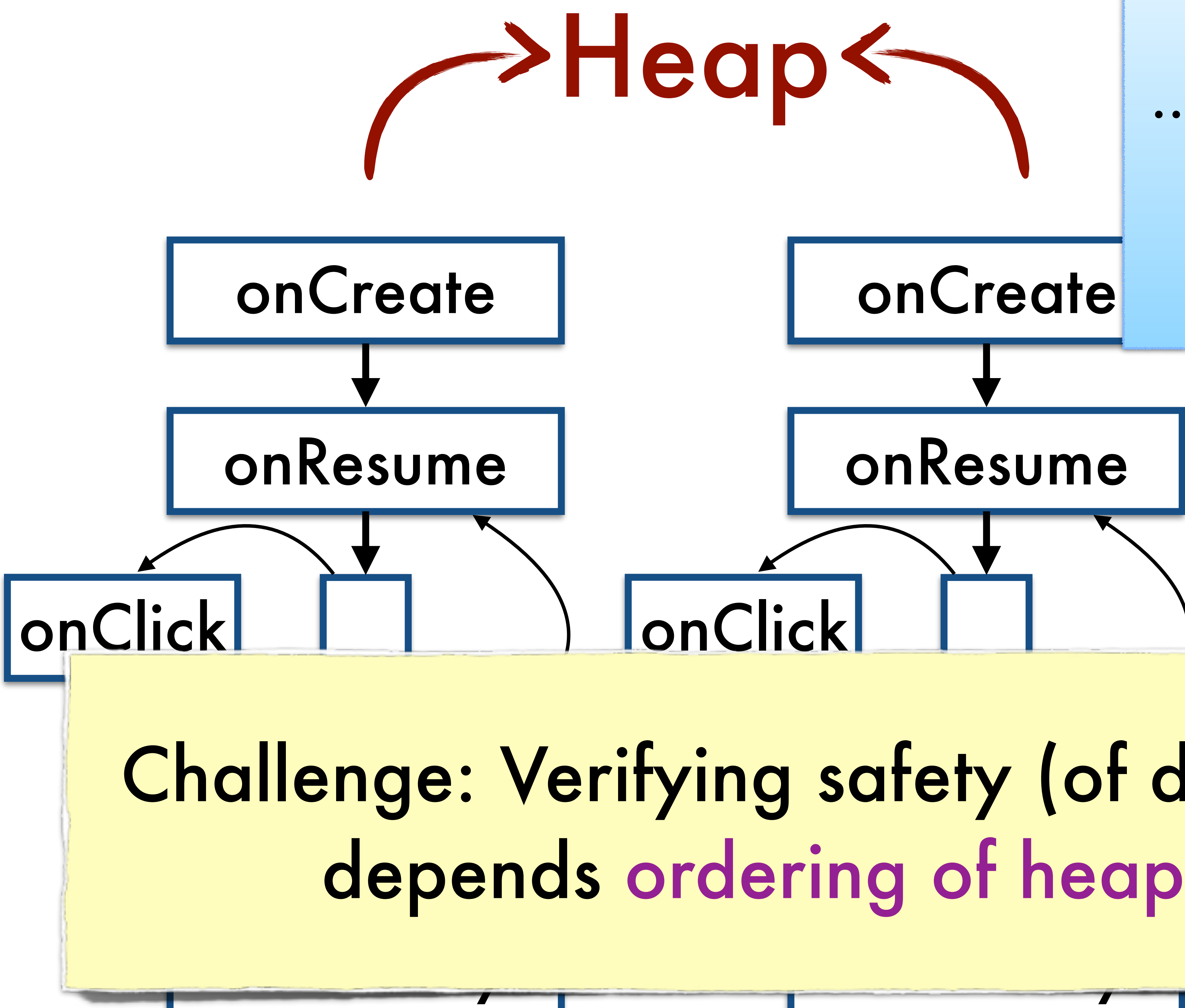
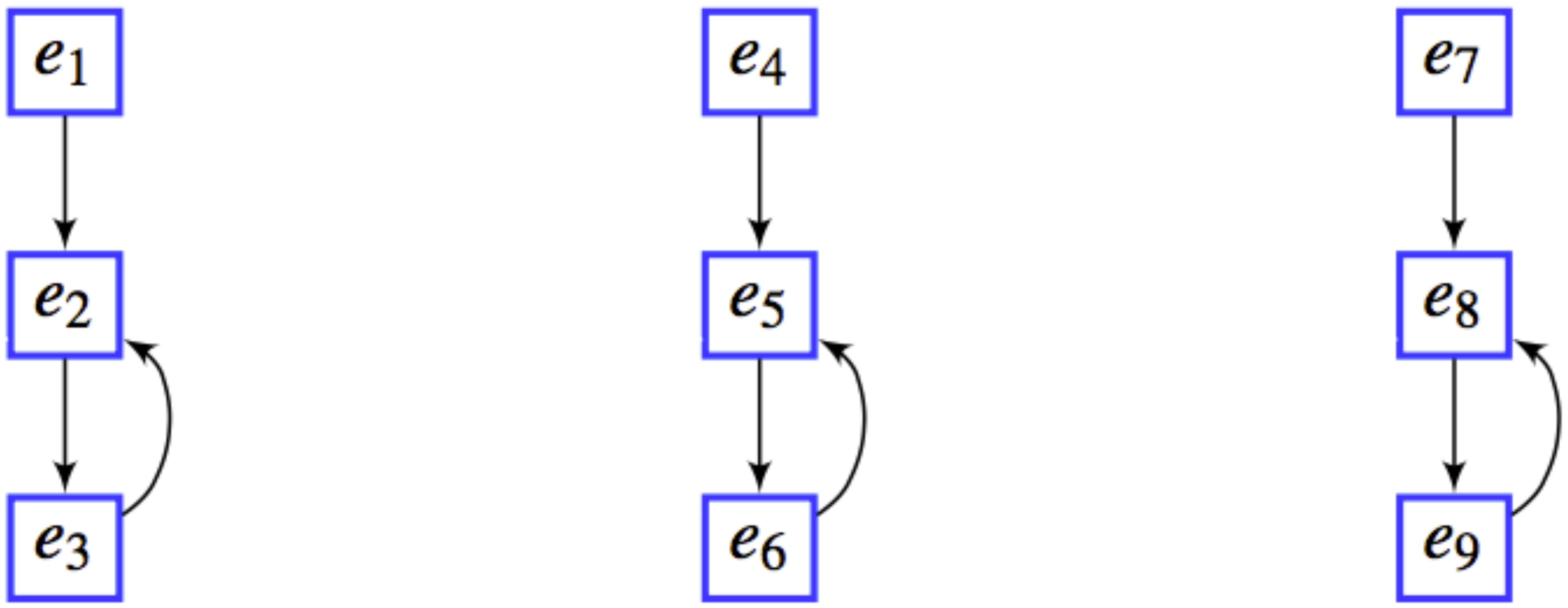


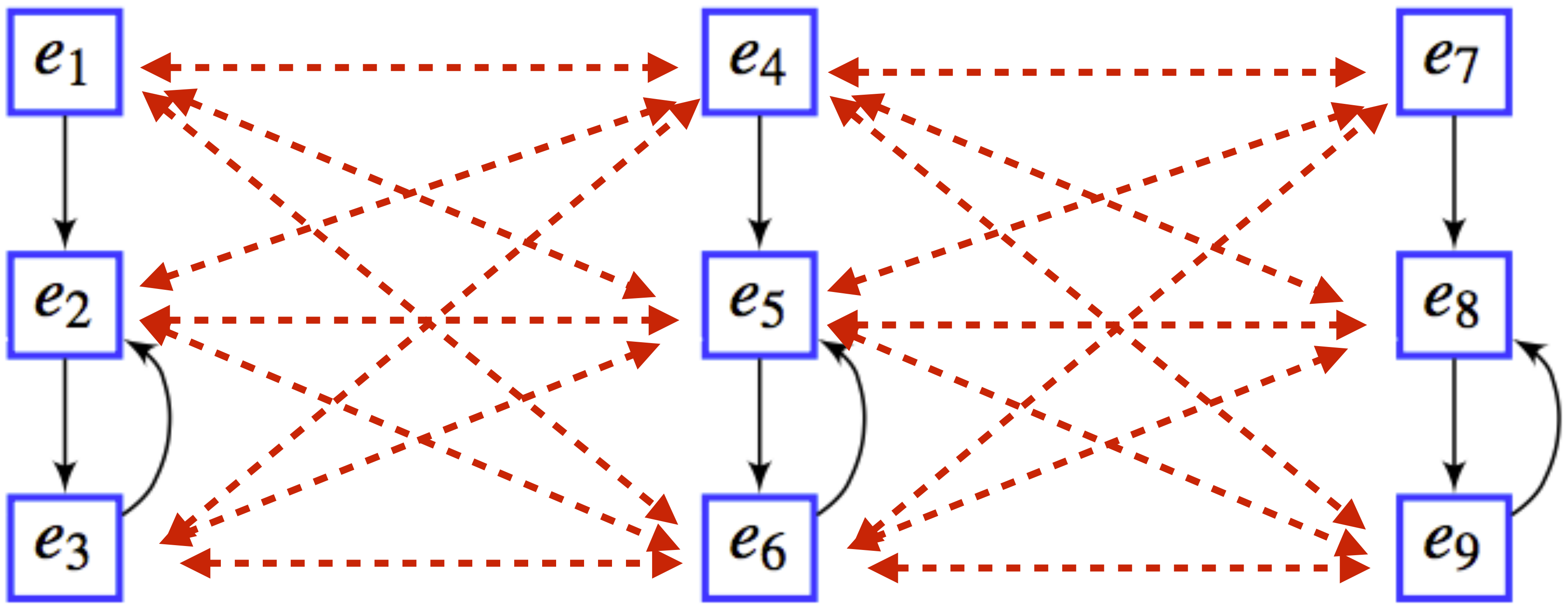
... and operates over a shared, global heap

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

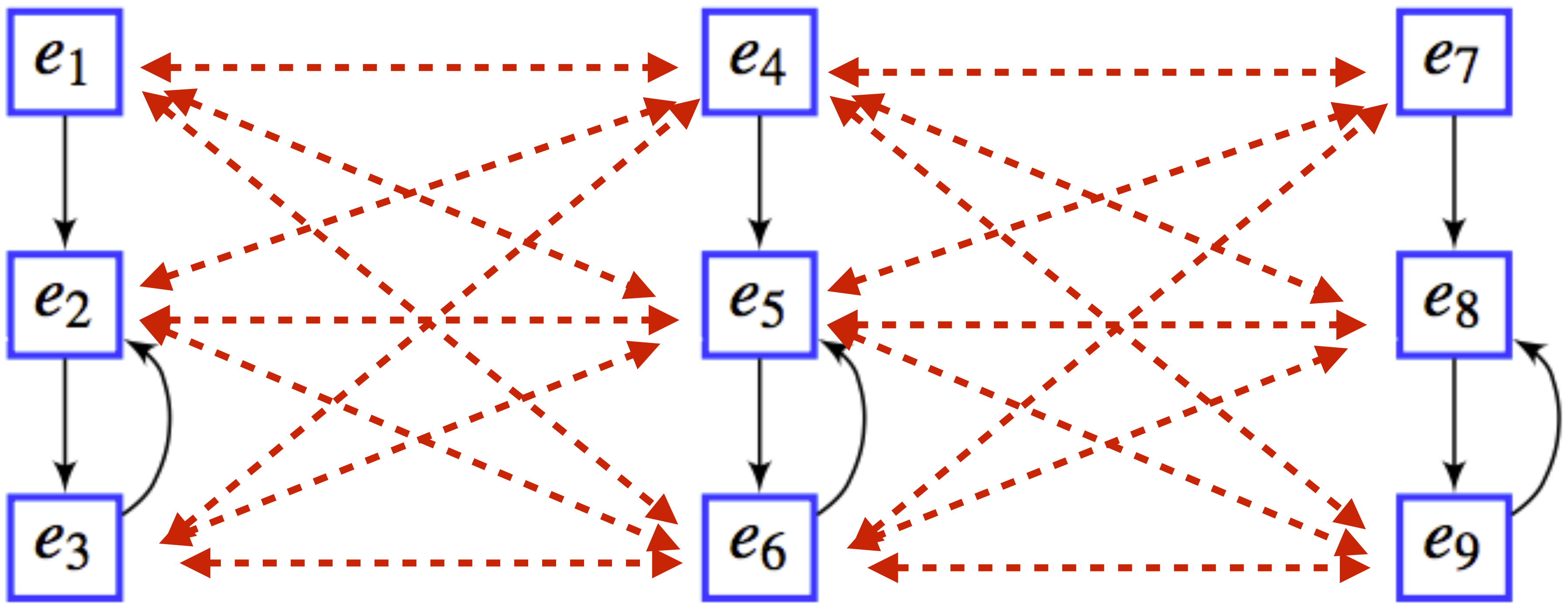
Verification challenge: Interleavings



Verification challenge: Interleavings

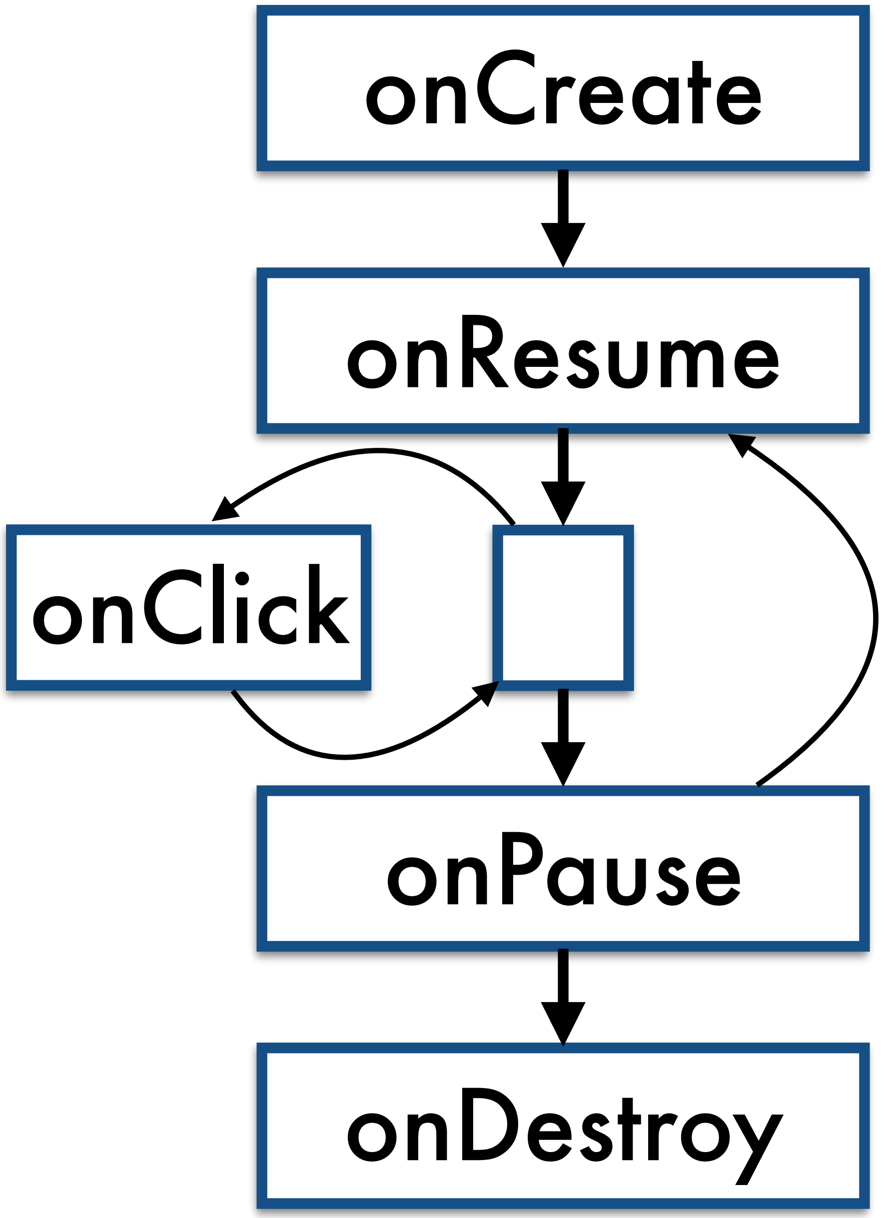


Verification challenge: Interleavings



Previous "lifecycle-sensitive" analyses do not consider inter-component interleavings

But it shouldn’t be so hard ...



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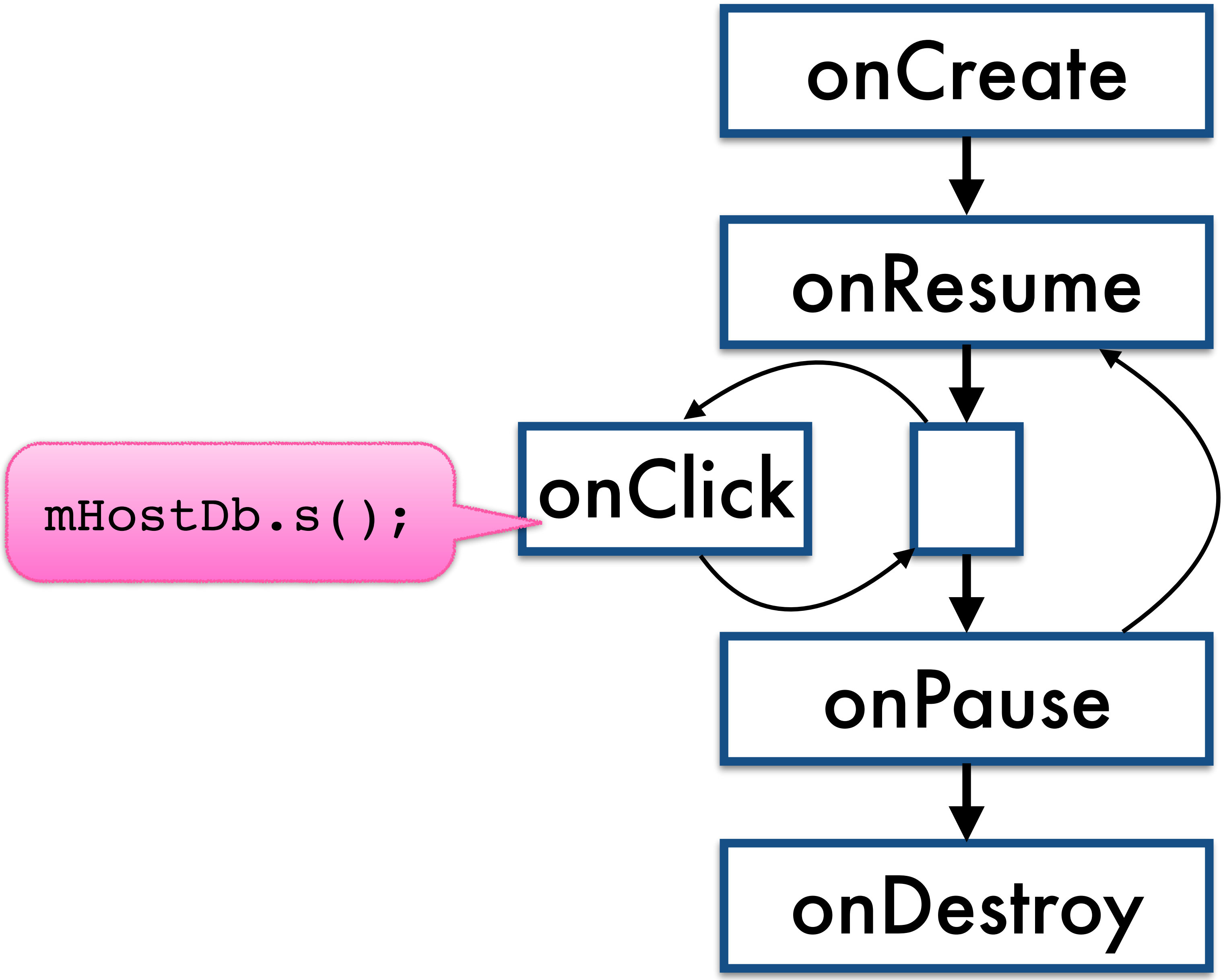

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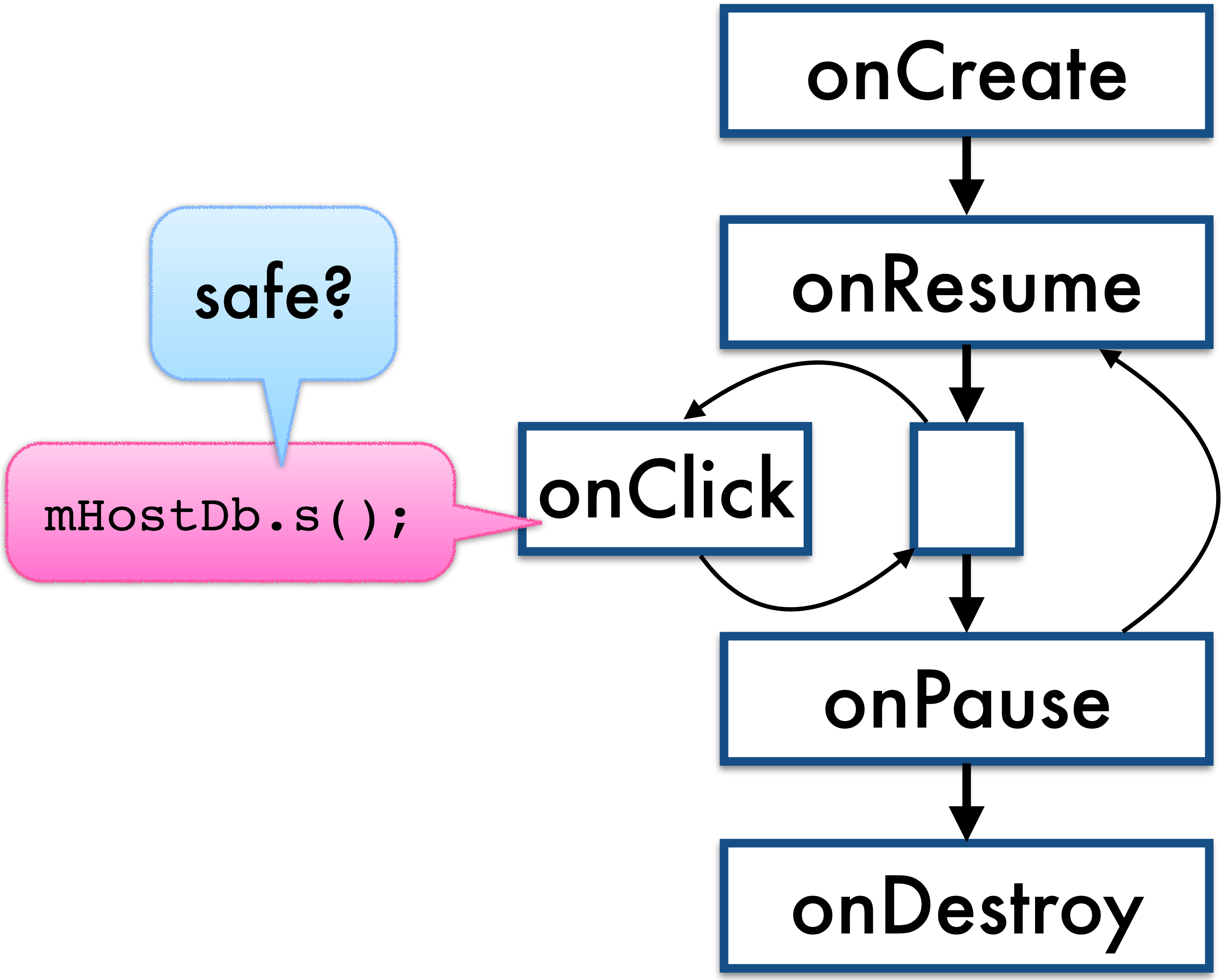

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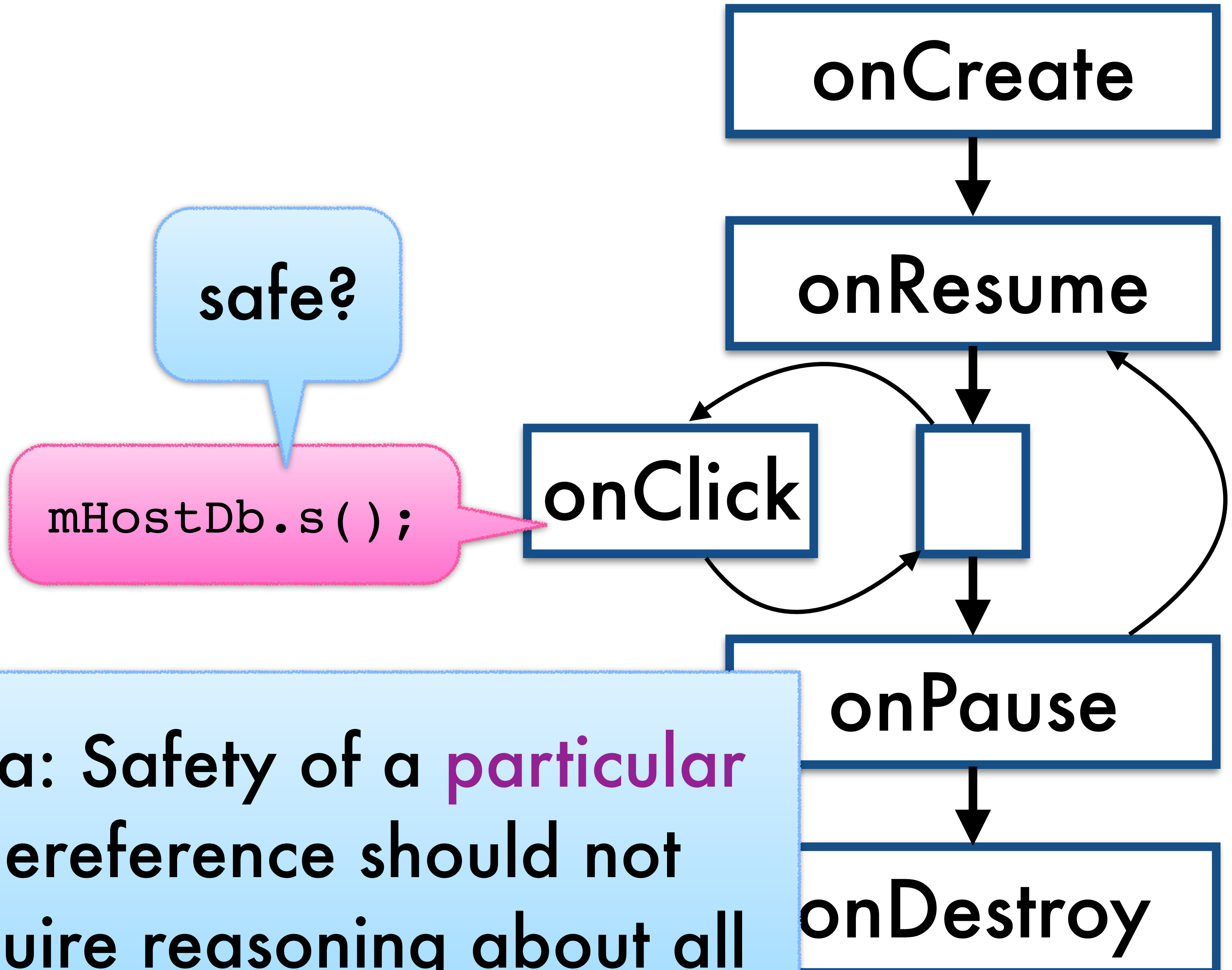
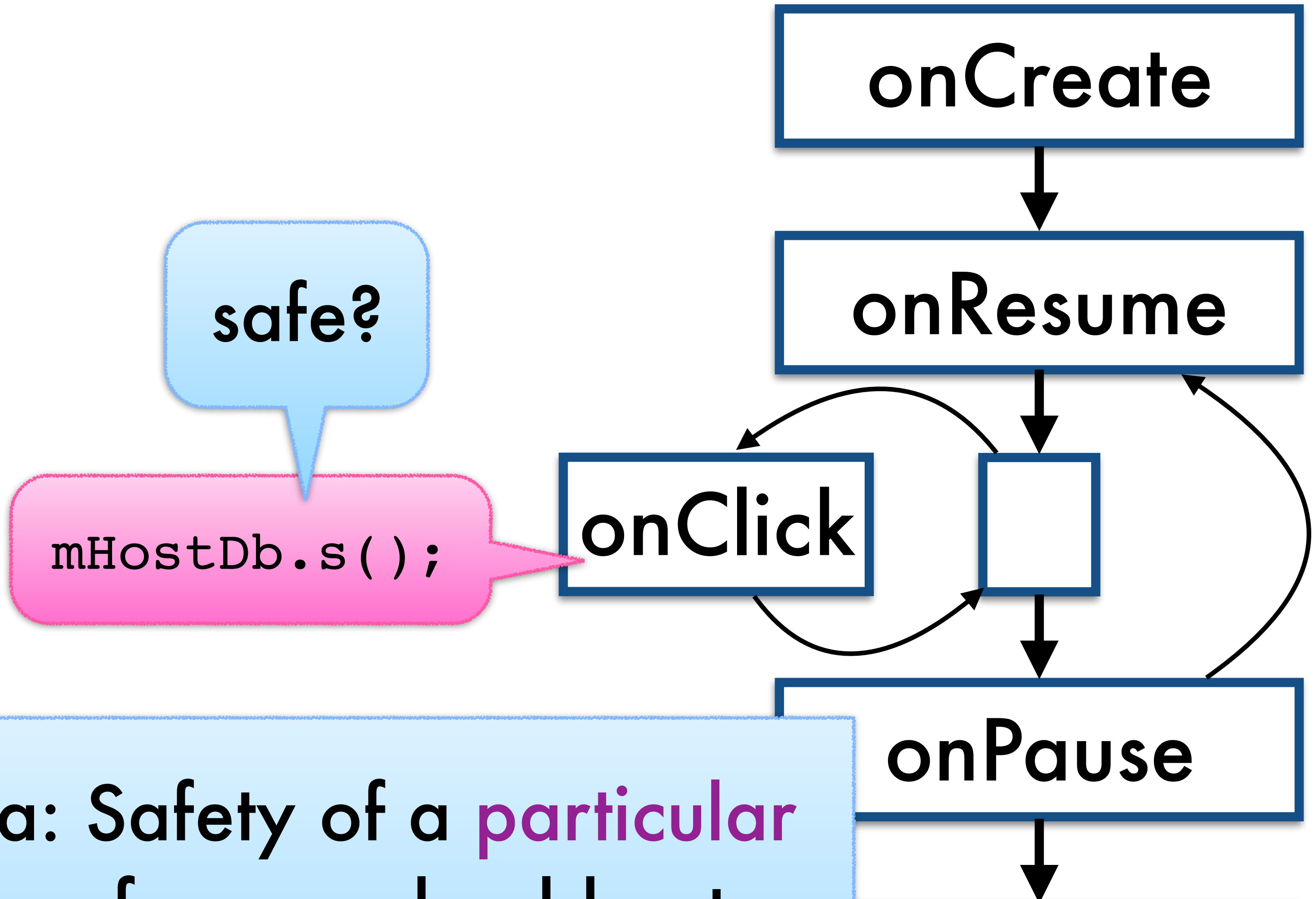


Idea: Safety of a particular dereference should not require reasoning about all callback interleavings

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

safe?

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

Goal-directed program analysis

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

safe?

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Goal-directed program analysis

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`mHostDb.s();`

`mHostDb == null`

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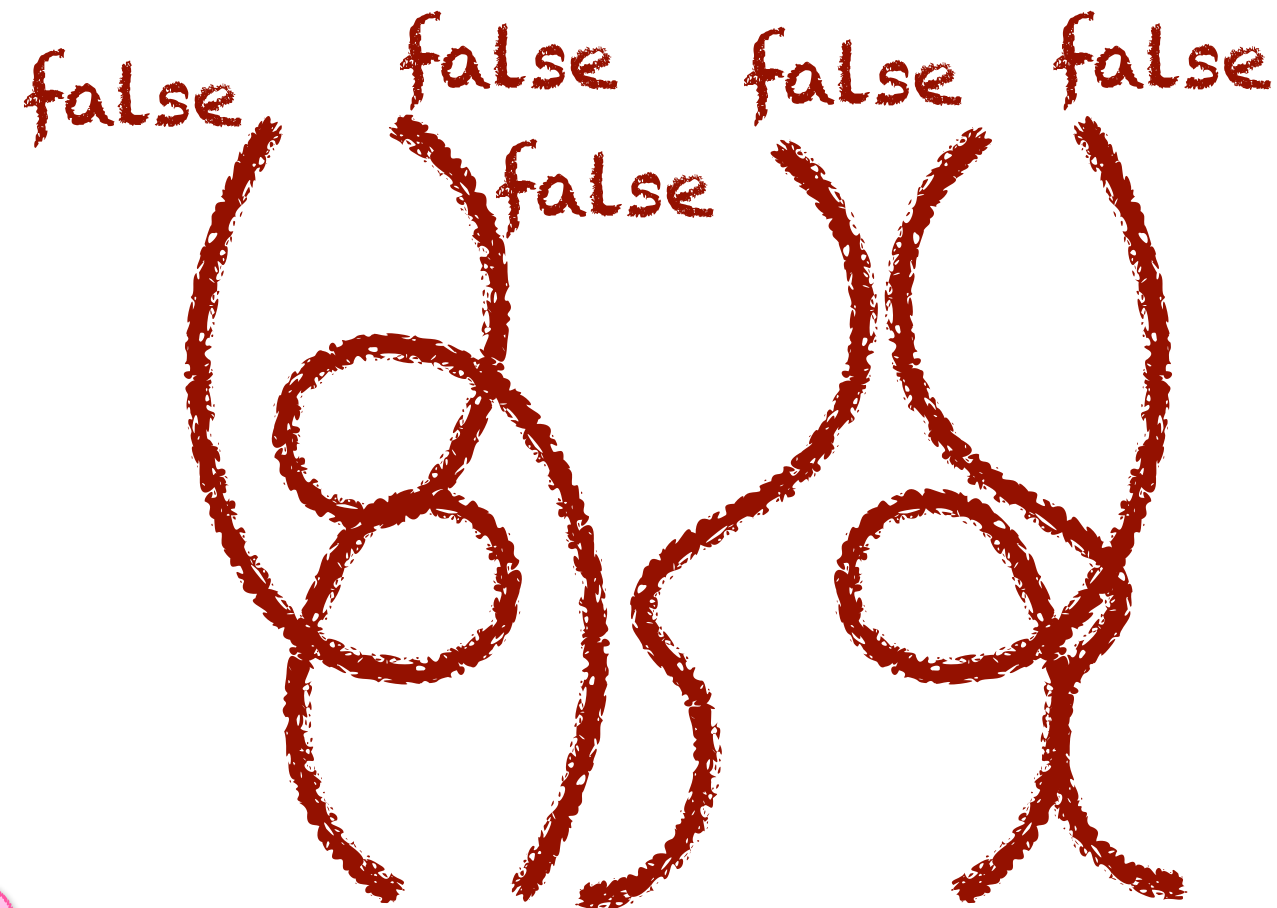

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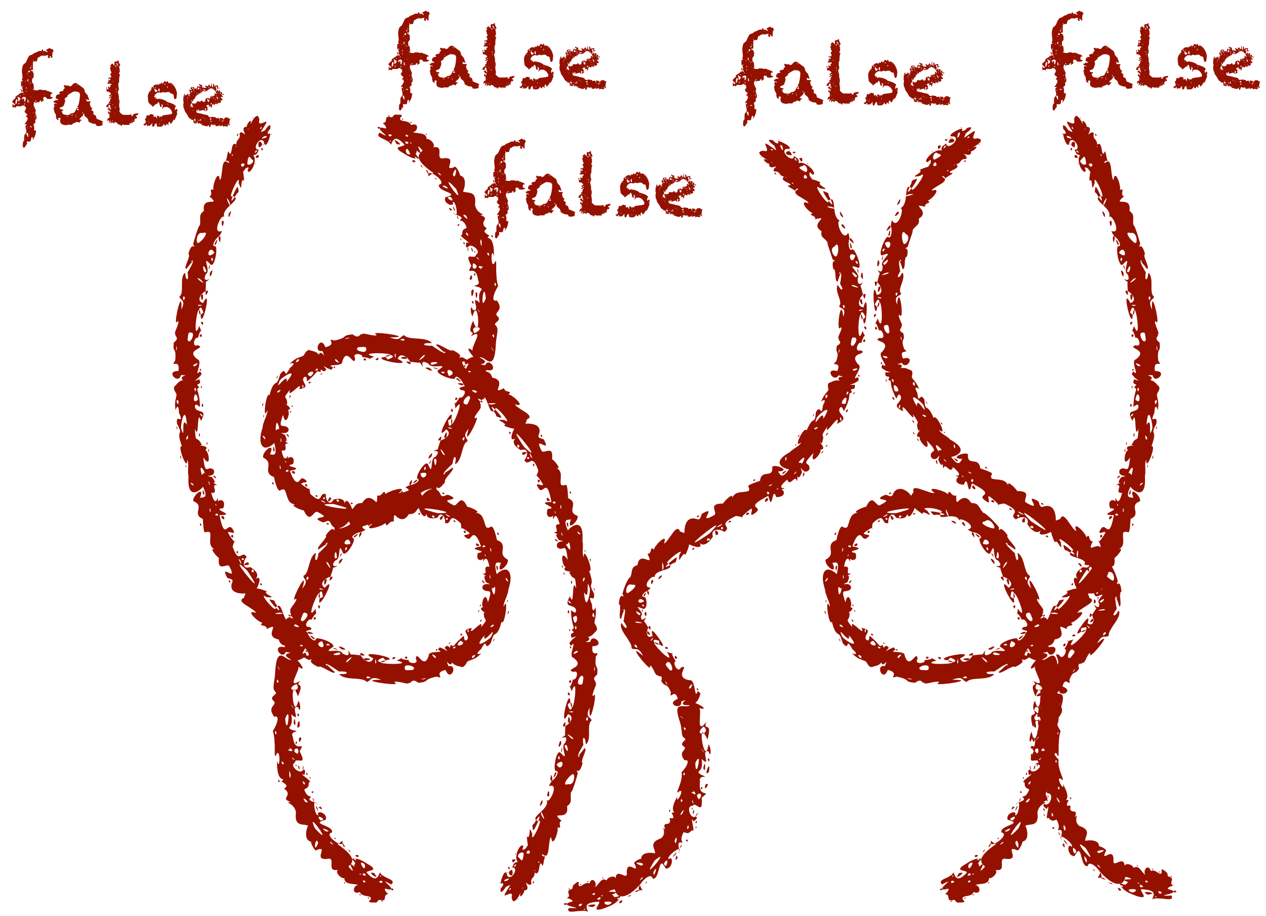

$$(\mathbf{this} \mapsto \widehat{t} * \widehat{t} \cdot \texttt{mHostDb} \mapsto \widehat{a} * \mathsf{true}) \wedge \widehat{a} = \mathsf{null}$$

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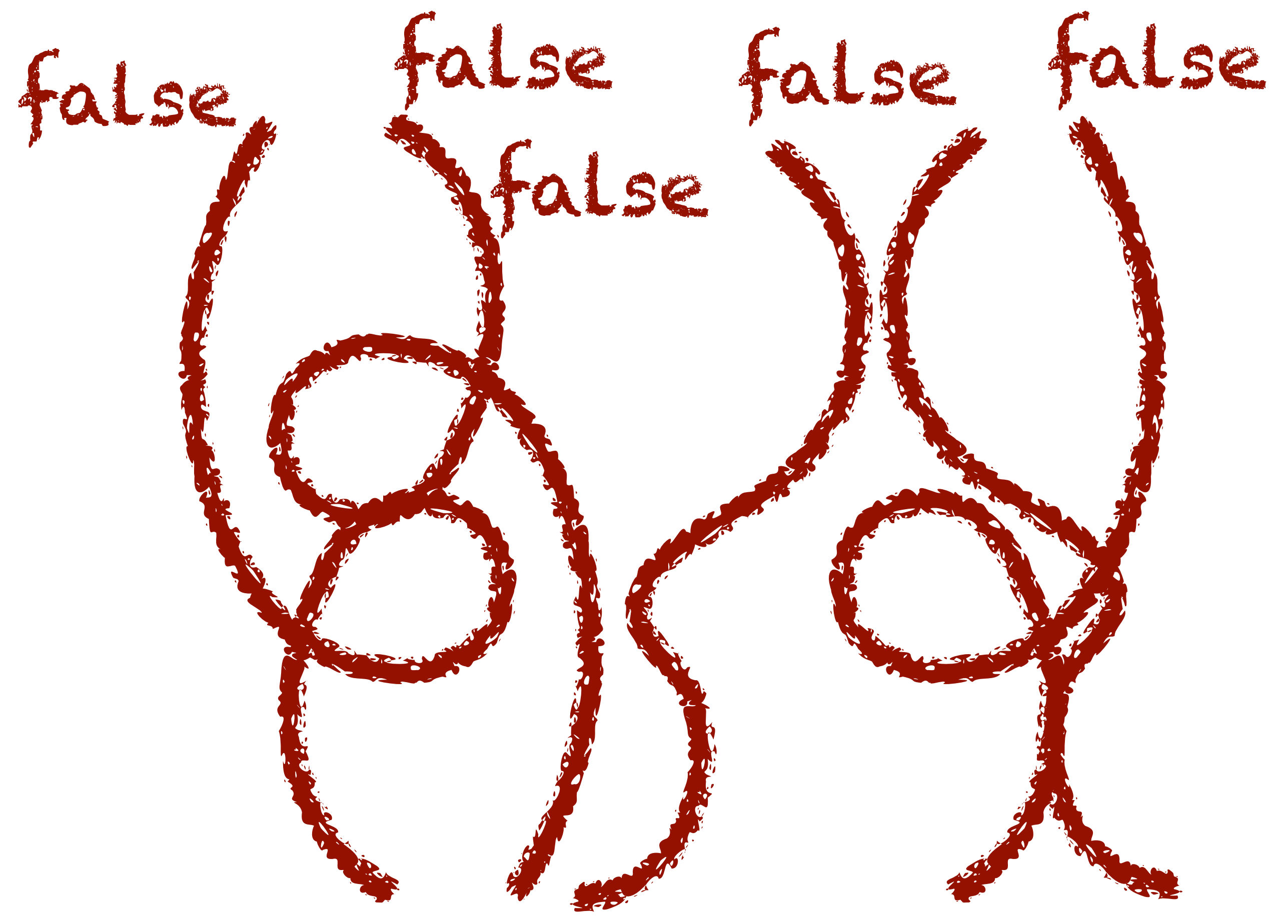

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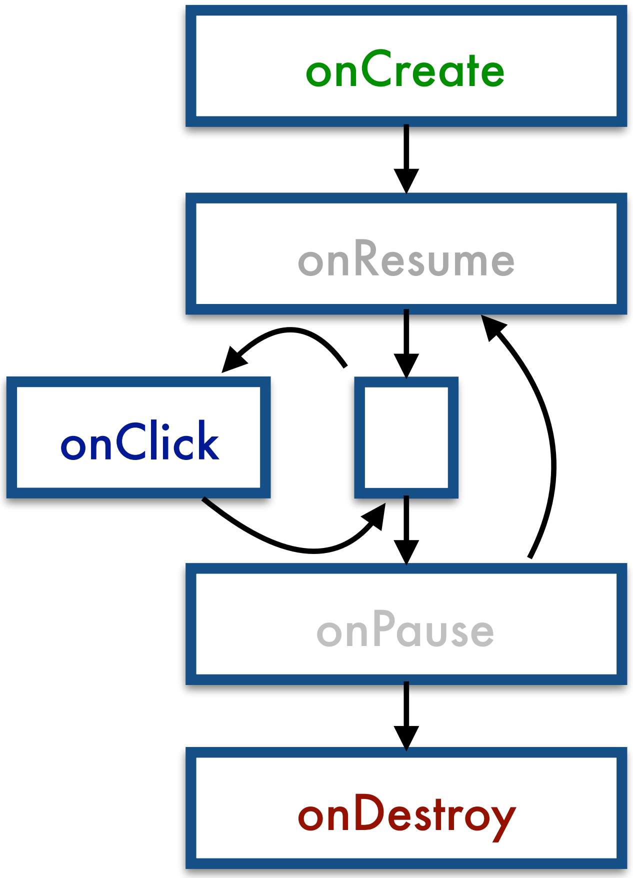
Thresher: A precise backwards abstract interpretation with separation logic constraints to refute error conditions [PLDI'13]

Two dereferences: one safe and one buggy



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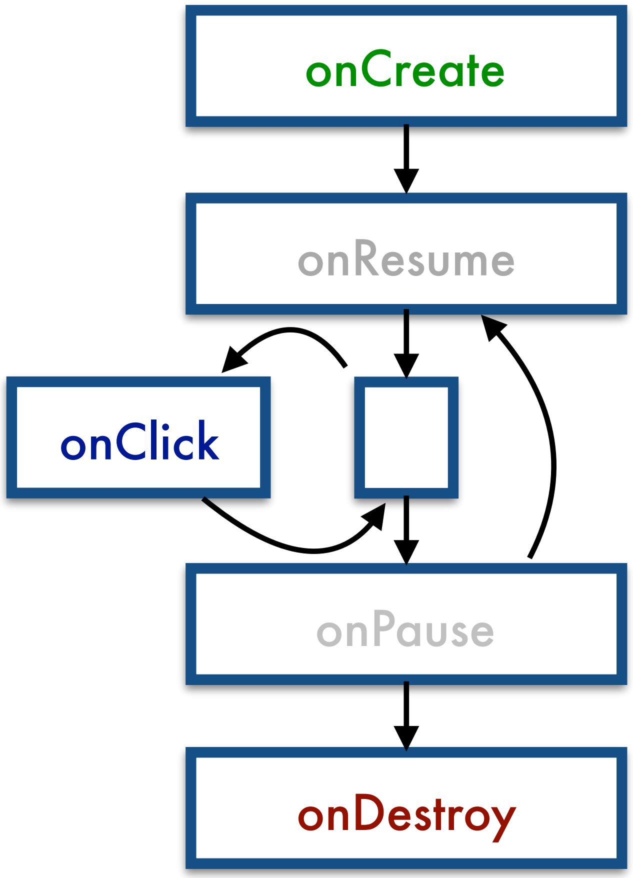


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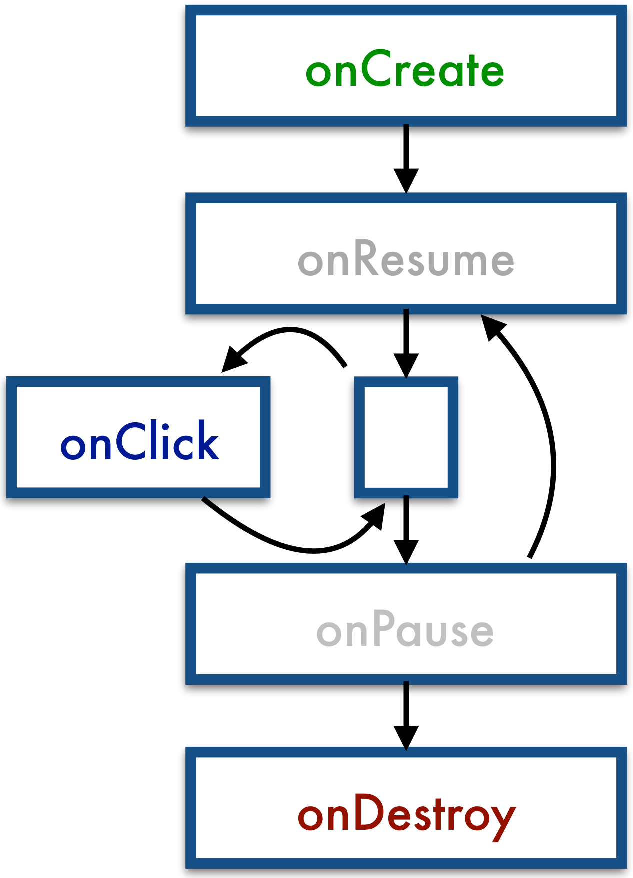


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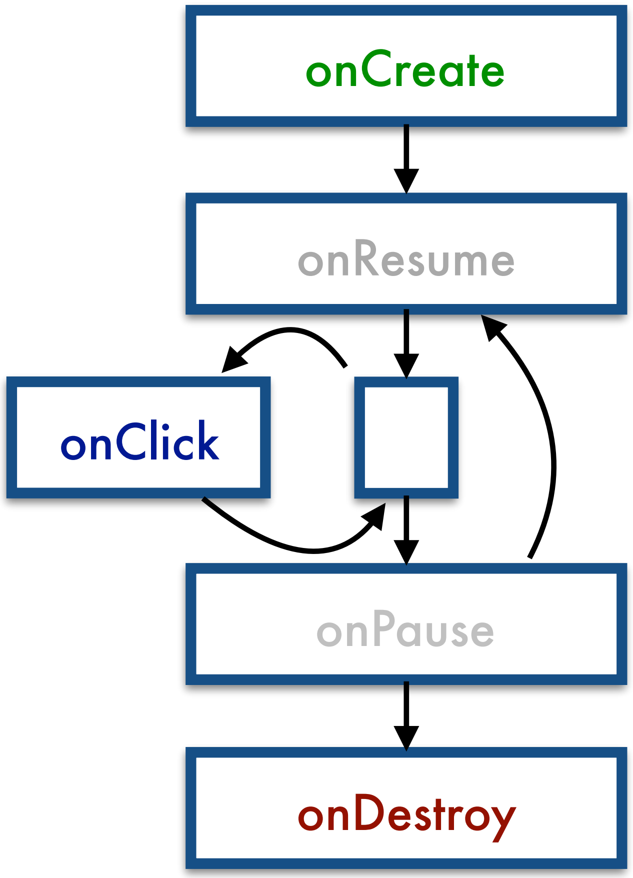


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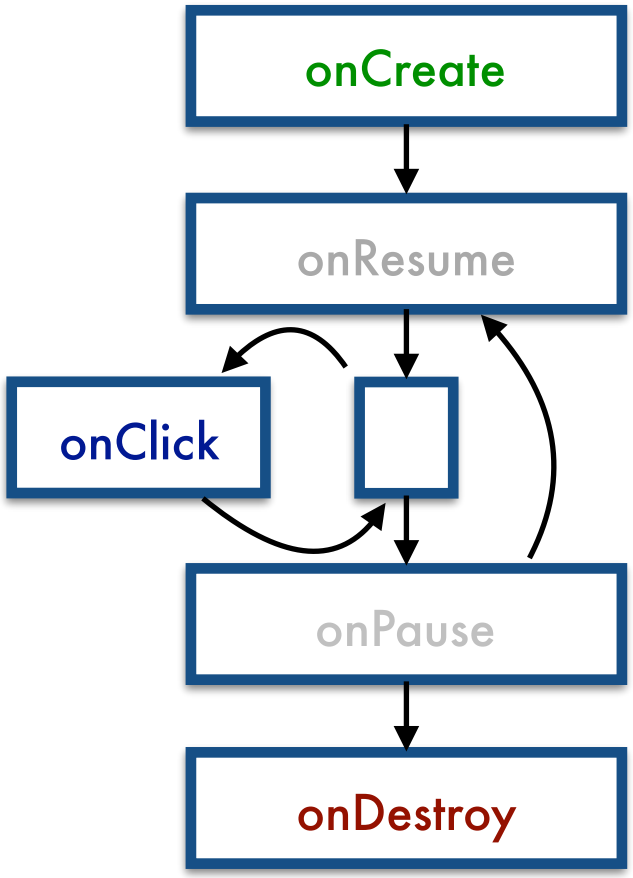

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lifecycle constraints relevant

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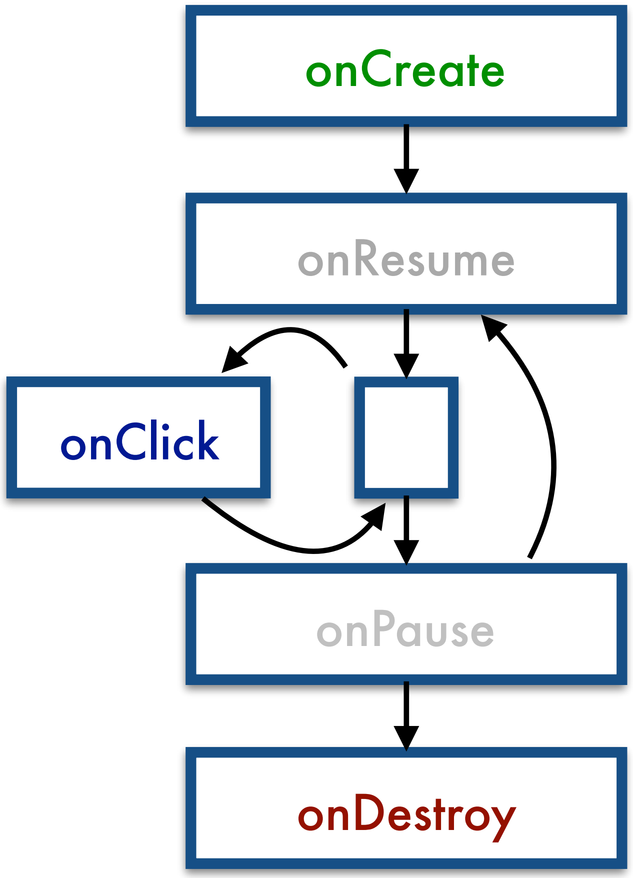


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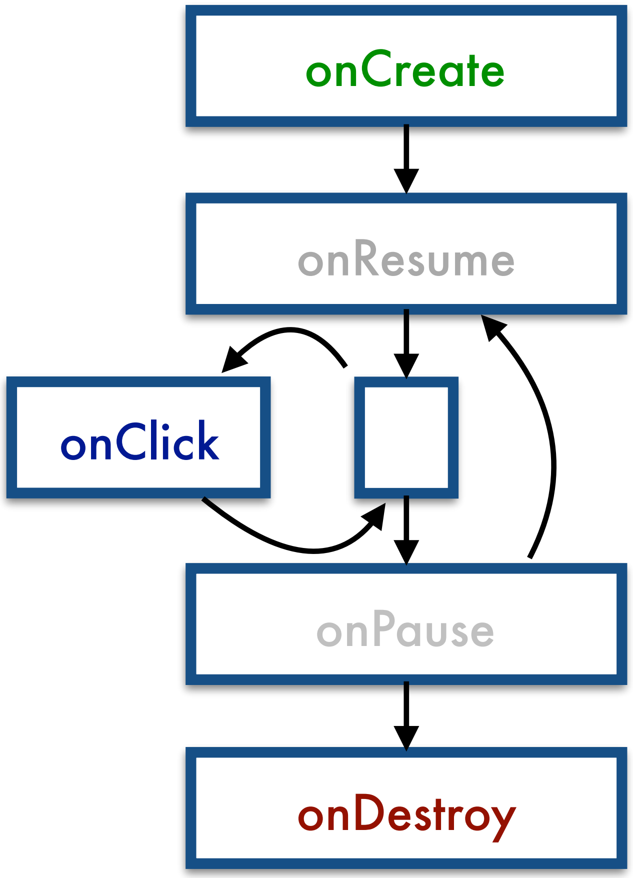


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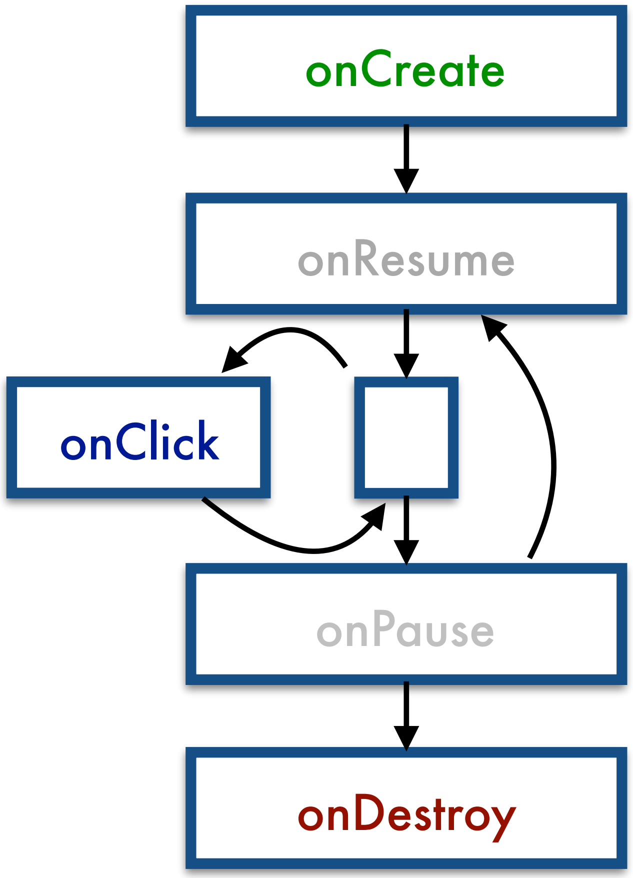


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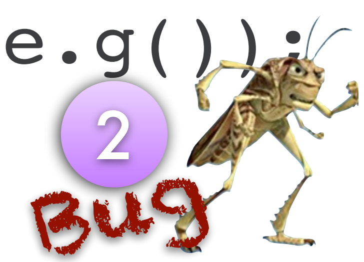

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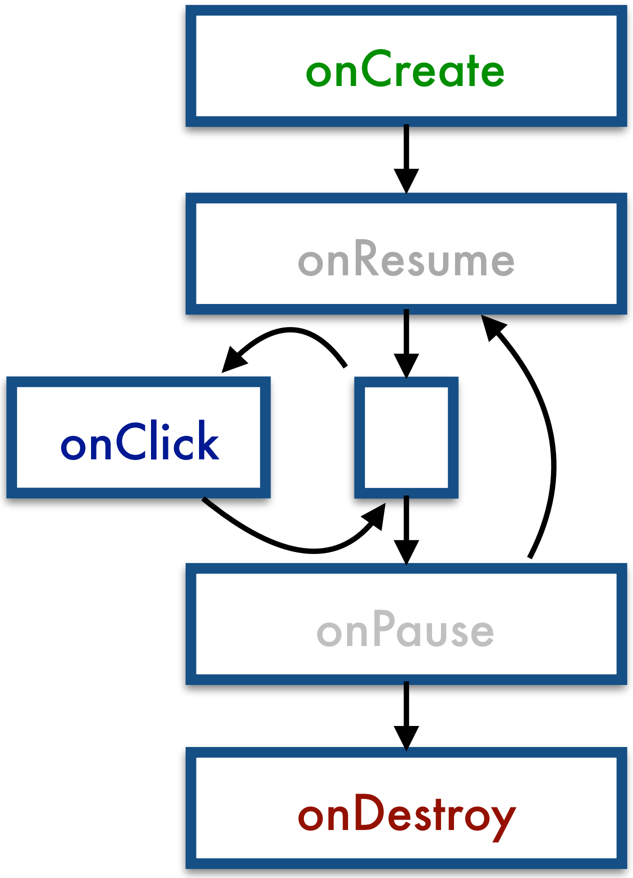


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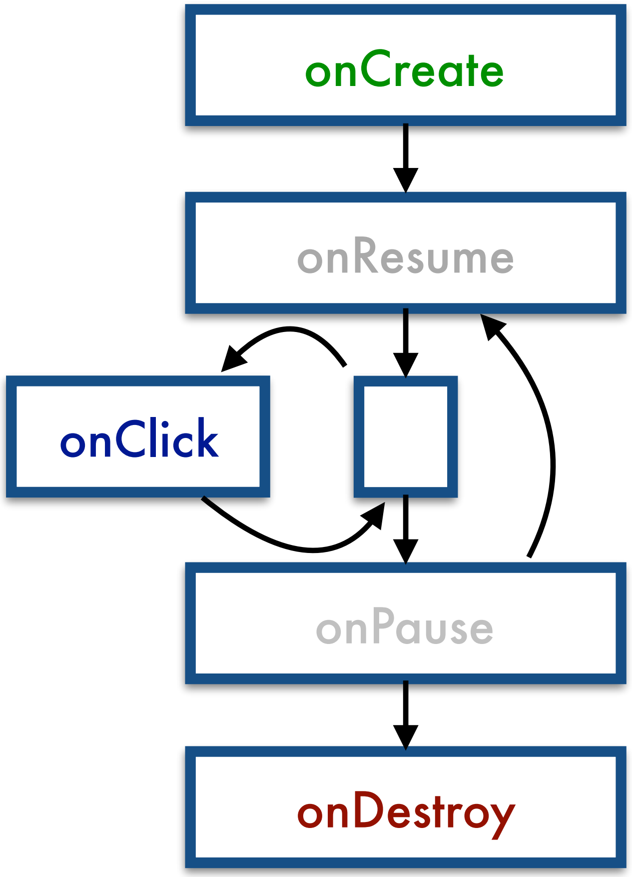
safe?

Need to consider some but not all callback ordering constraints

Idea: Jumping to relevant callbacks



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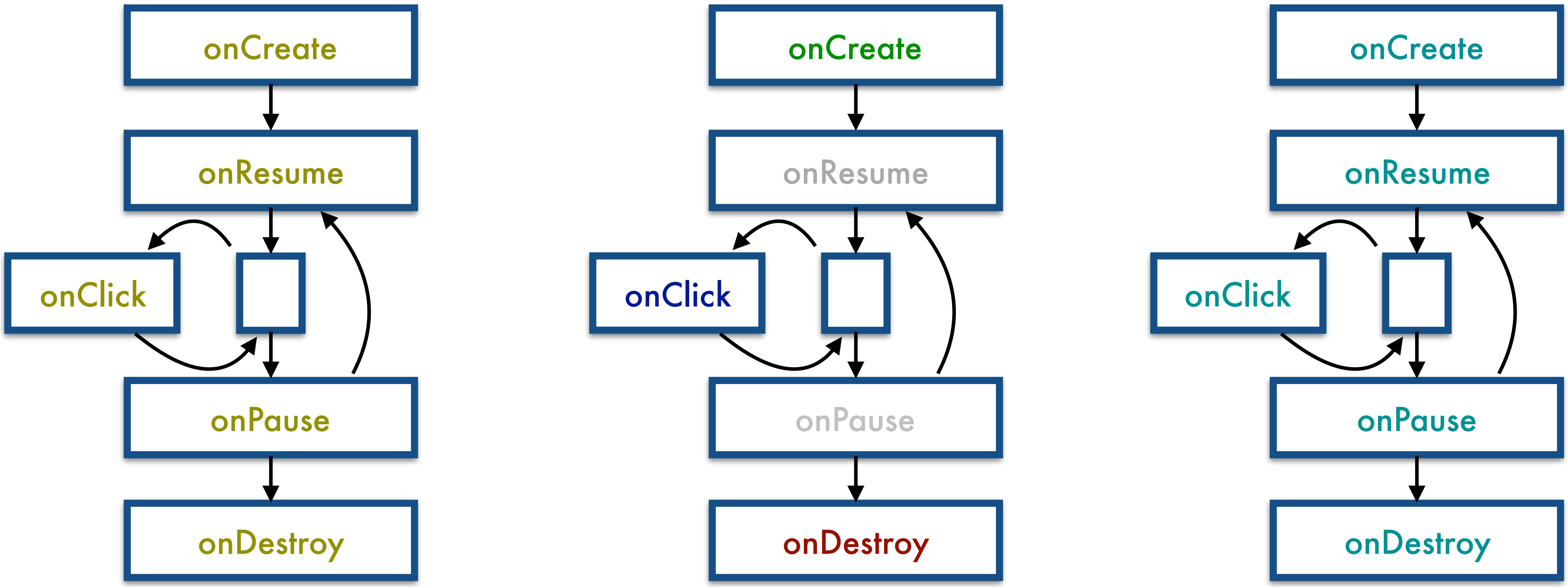

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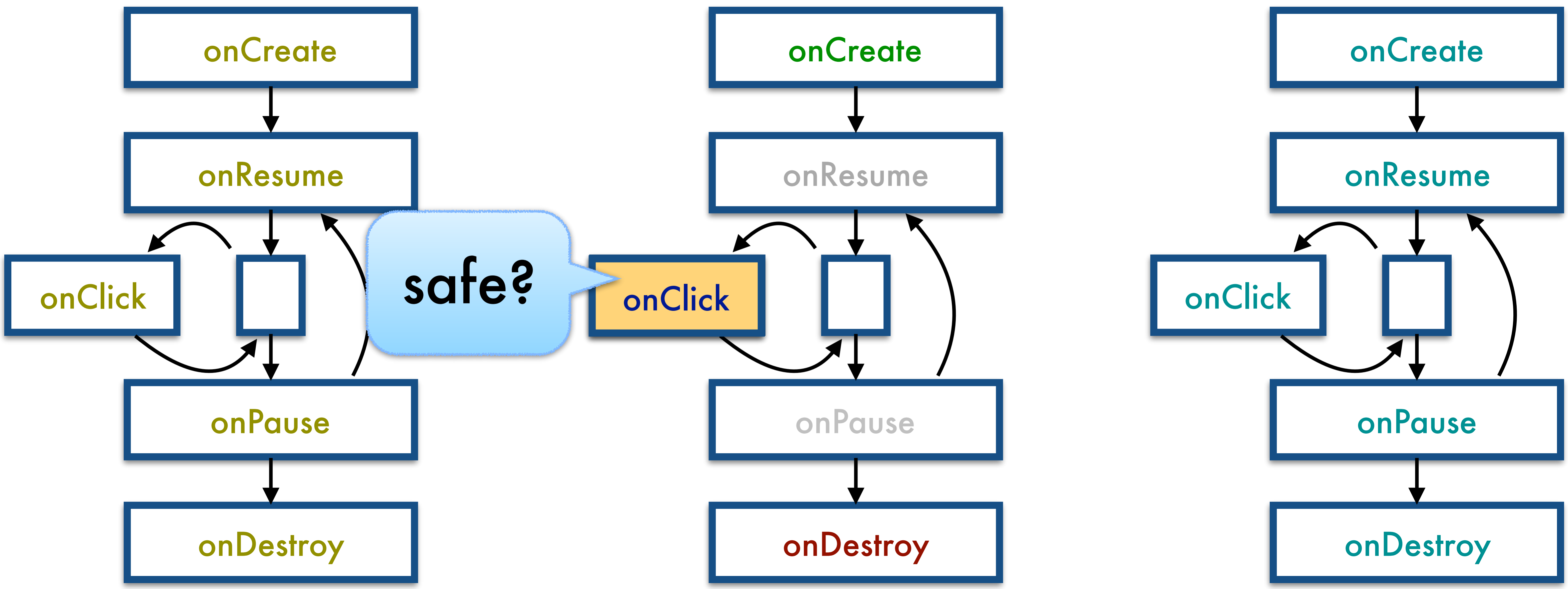

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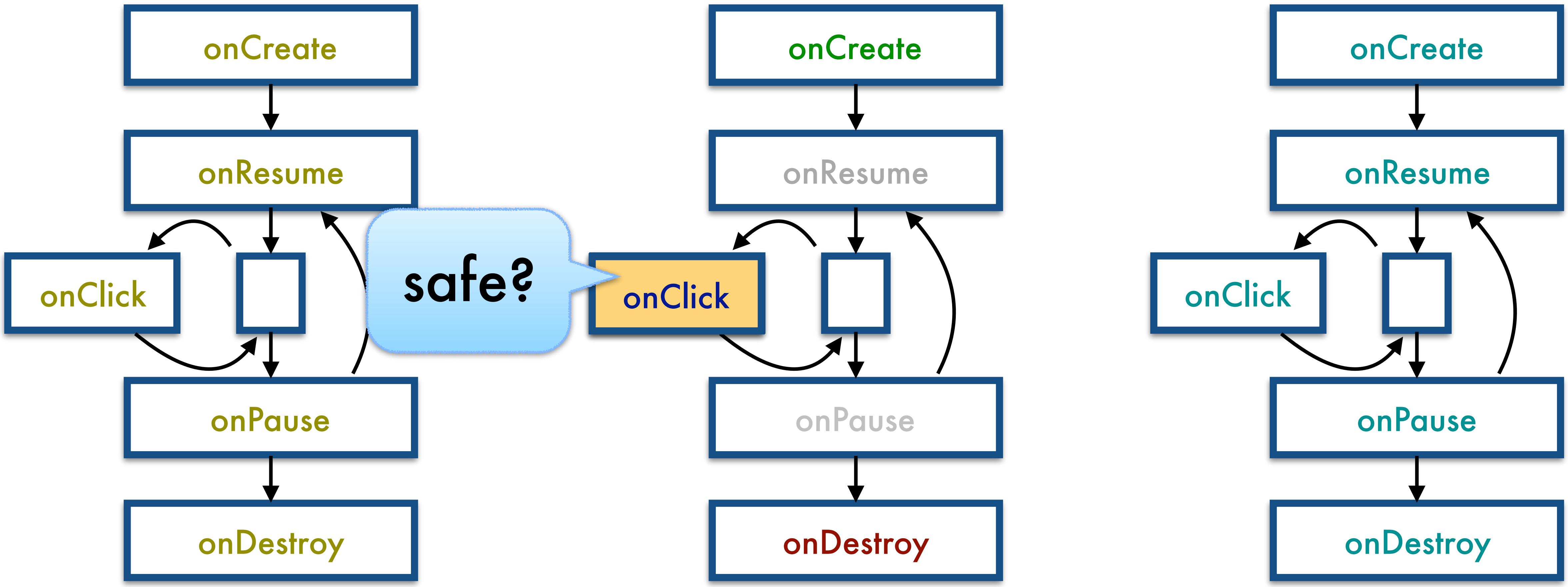
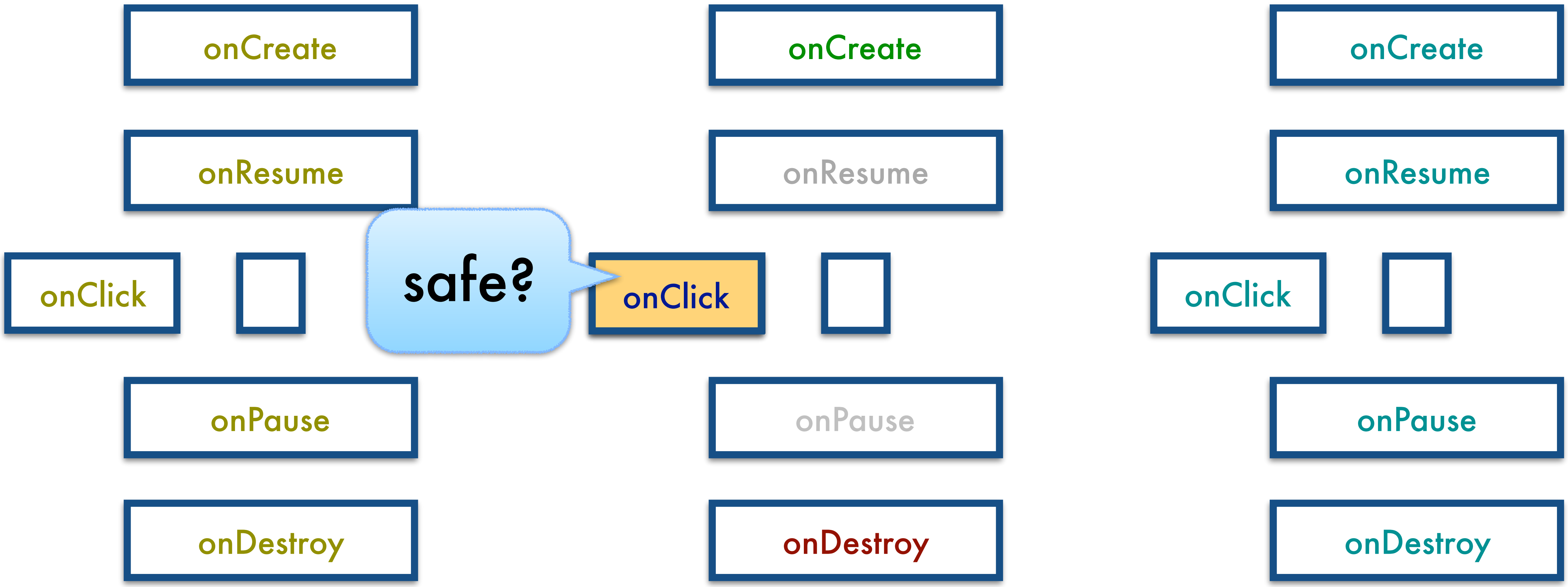


Find data relevant callbacks

Idea: Jumping to relevant callbacks



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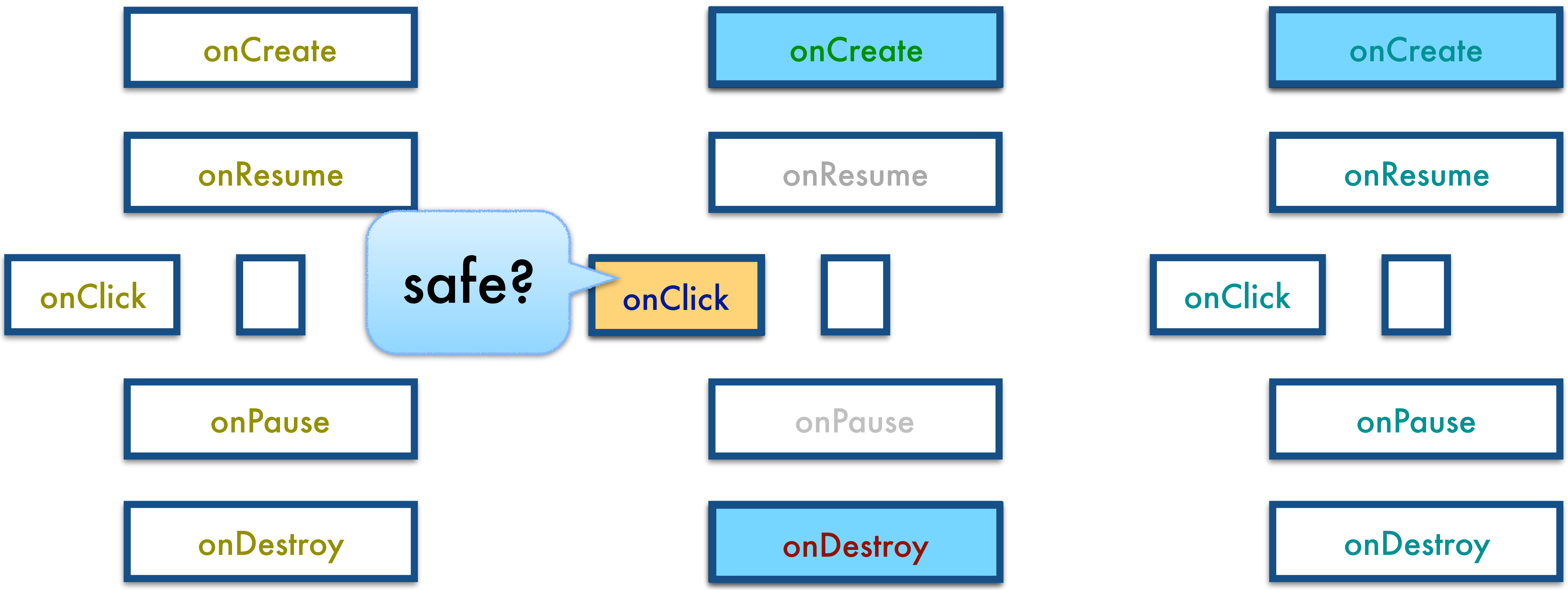

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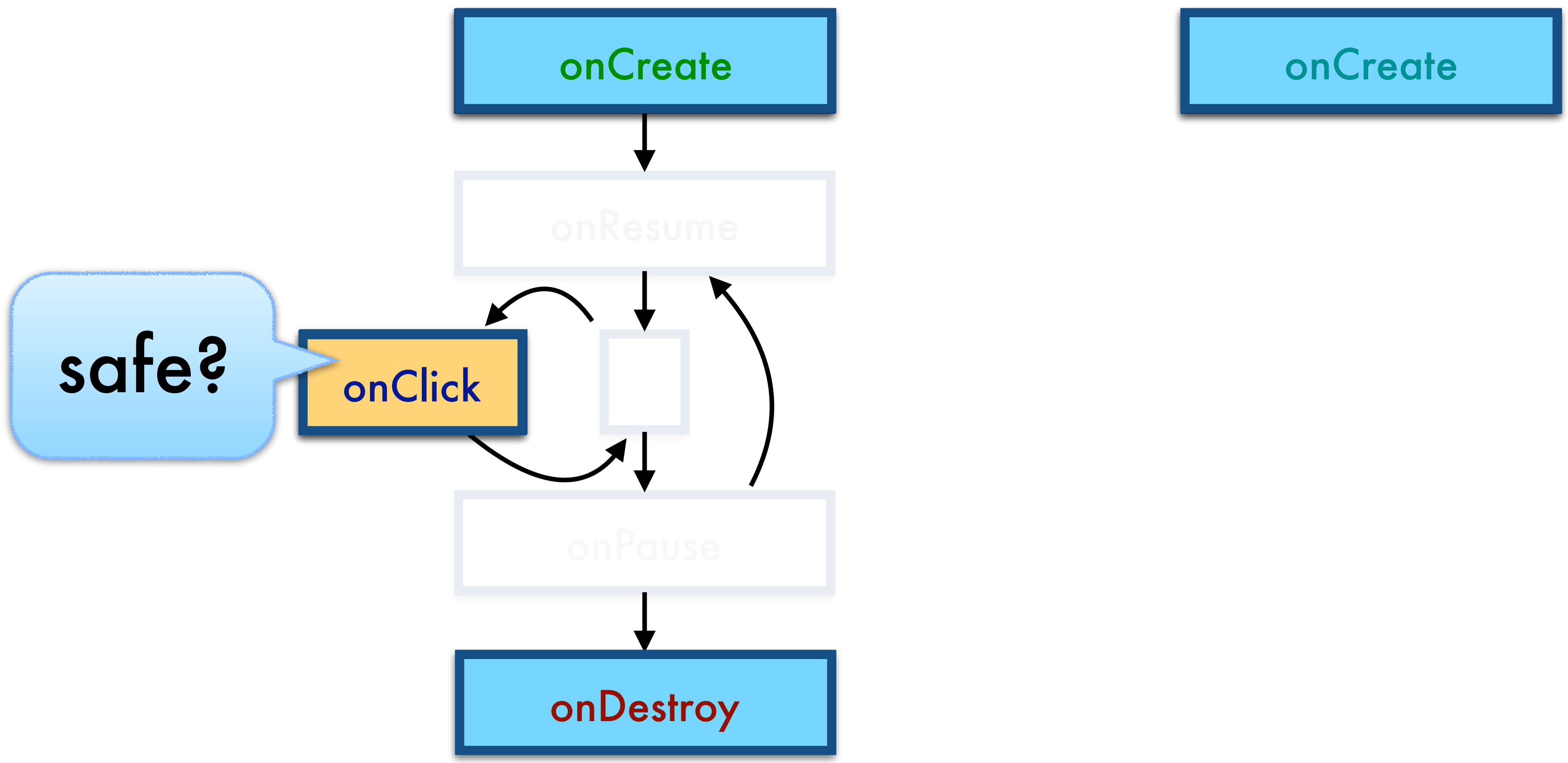

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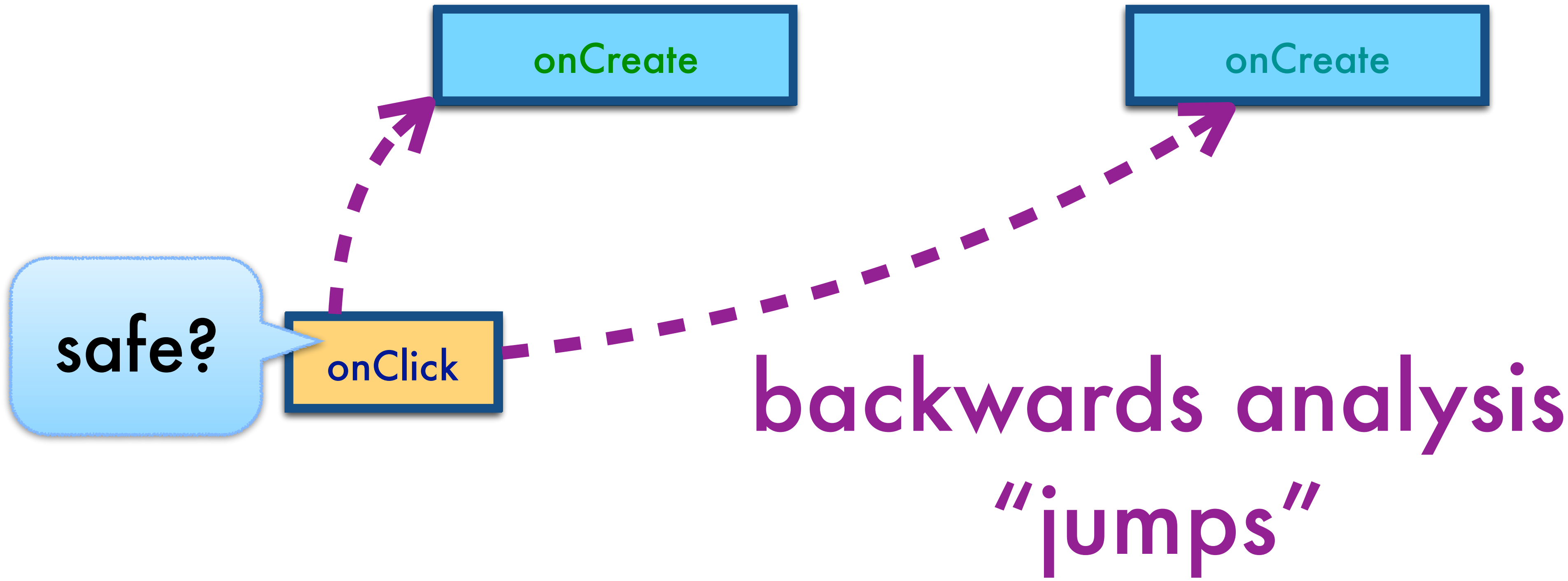

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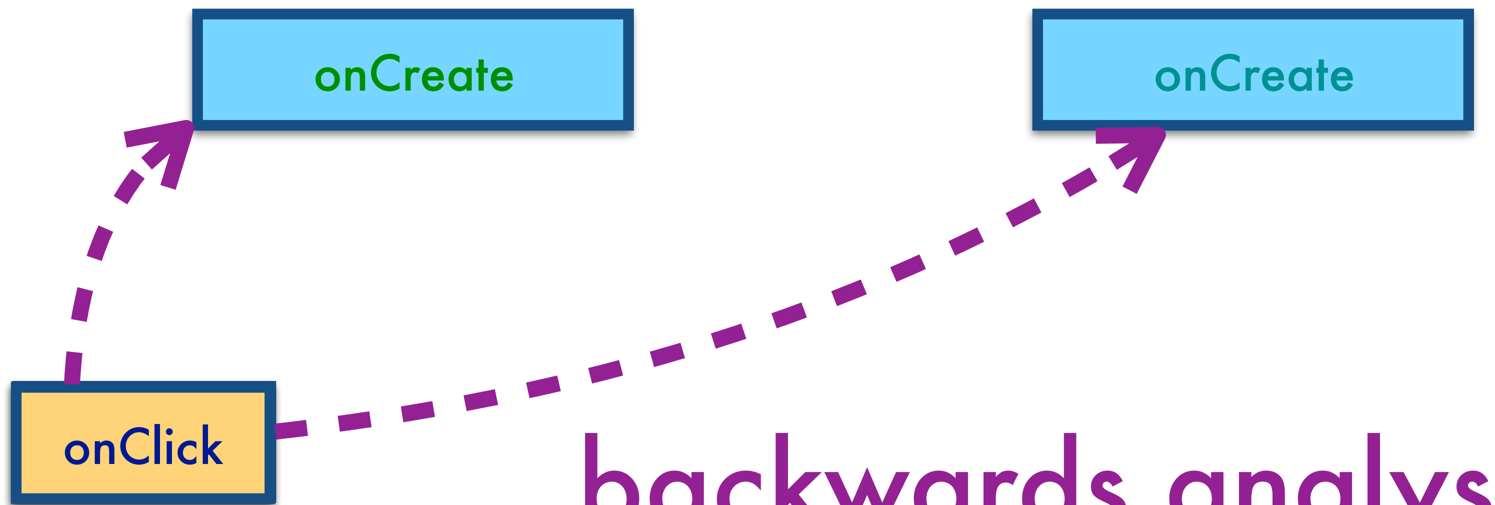
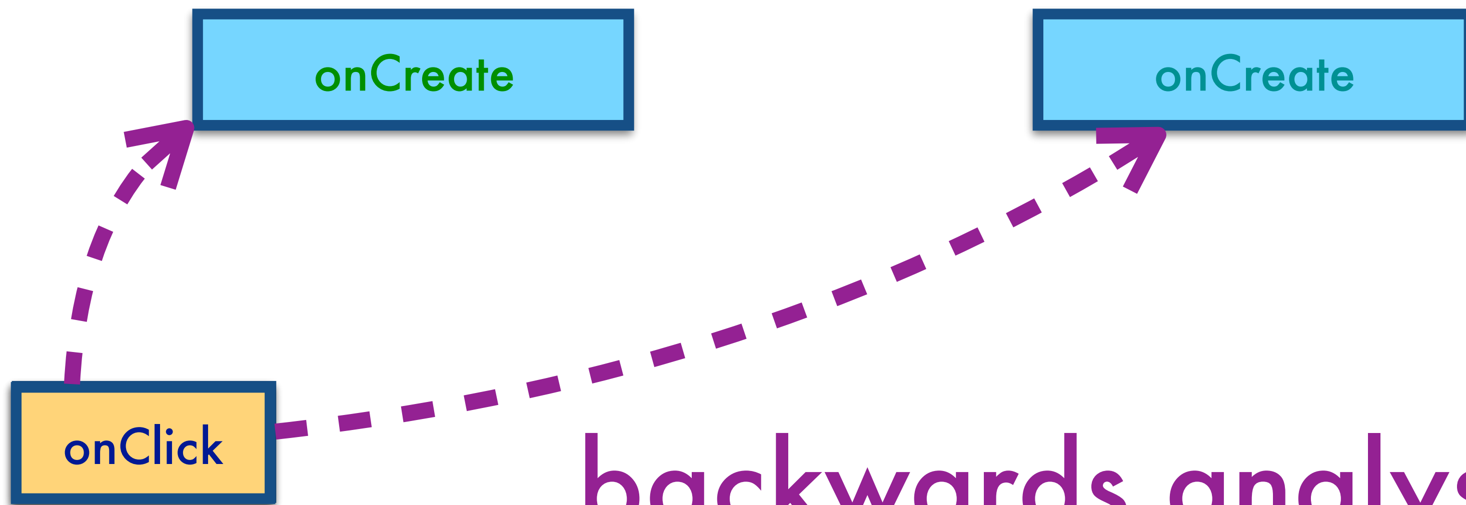
Contributions



backwards analysis
“jumps”

Contributions



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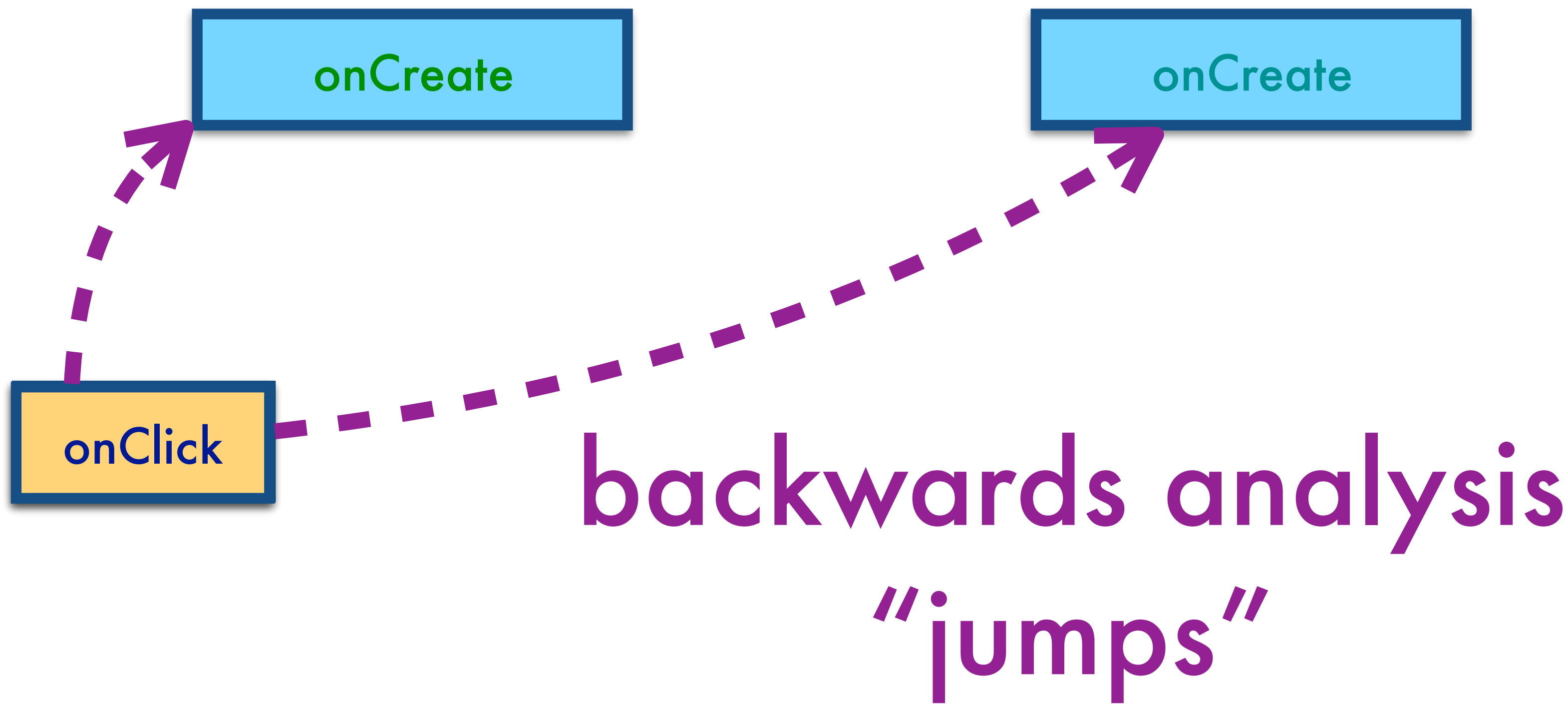
1 $\ell_1 \mathrel{-\!\![c]\!\!\rightarrow} \ell_2$ Framework for jumping analyses

Contributions



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

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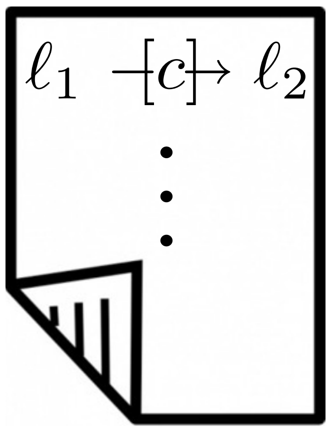

Program

A program model for a jumping analysis

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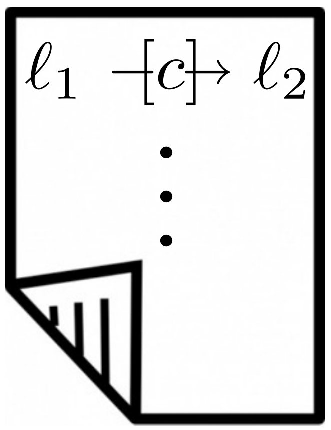

Program

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

A program model for a jumping analysis

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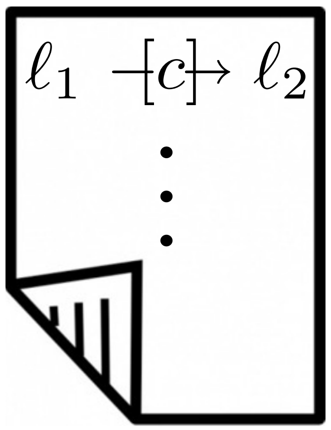

Program

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

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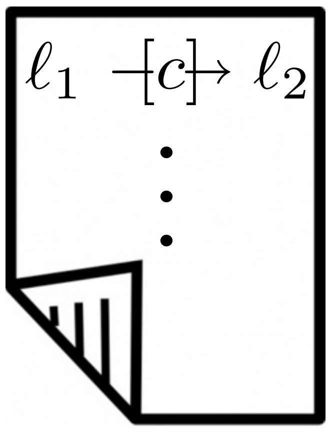

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Analysis parameters

A program model for a jumping analysis

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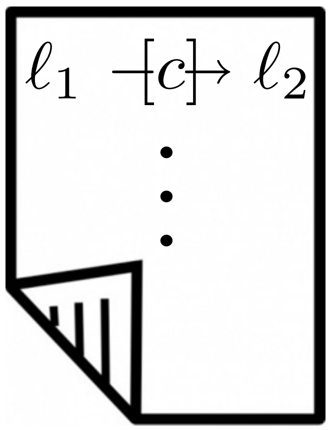

Program

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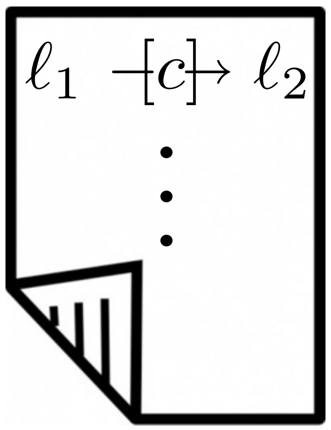
Analysis parameters

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

Backward transfer functions

A program model for a jumping analysis $\ell_1 \dashv\!\![c]\!\!\rightarrow \ell_2$



Program

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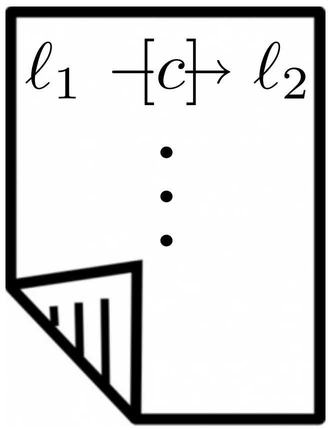
ℓ_{cur}

Current location

A program model for a jumping analysis $\ell_1 \dashv\![c]\!\!\rightarrow \ell_2$



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

ℓ_{cur}

Current location

Q_{cur}

Current query

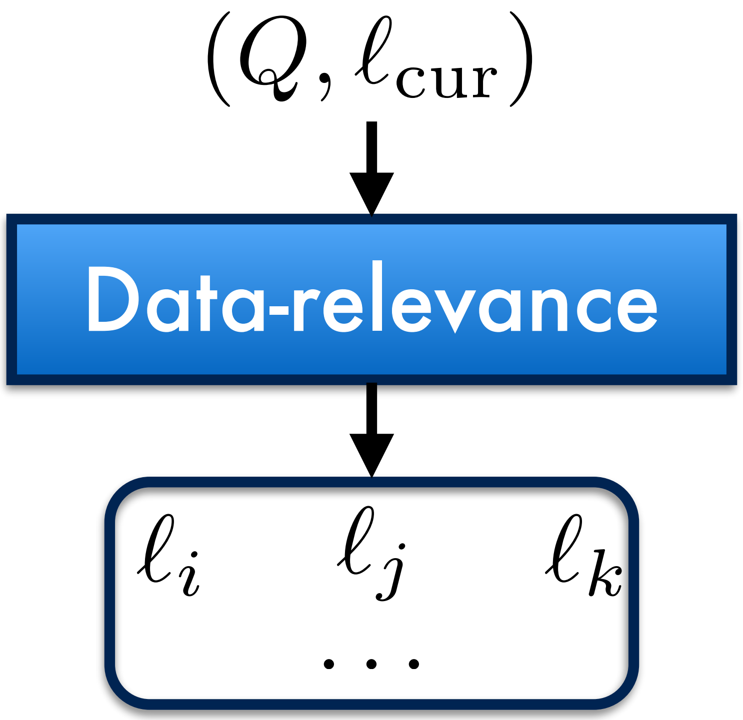
Data-relevance identifies writes

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

(Q, ℓ_{cur})

Data-relevance identifies writes

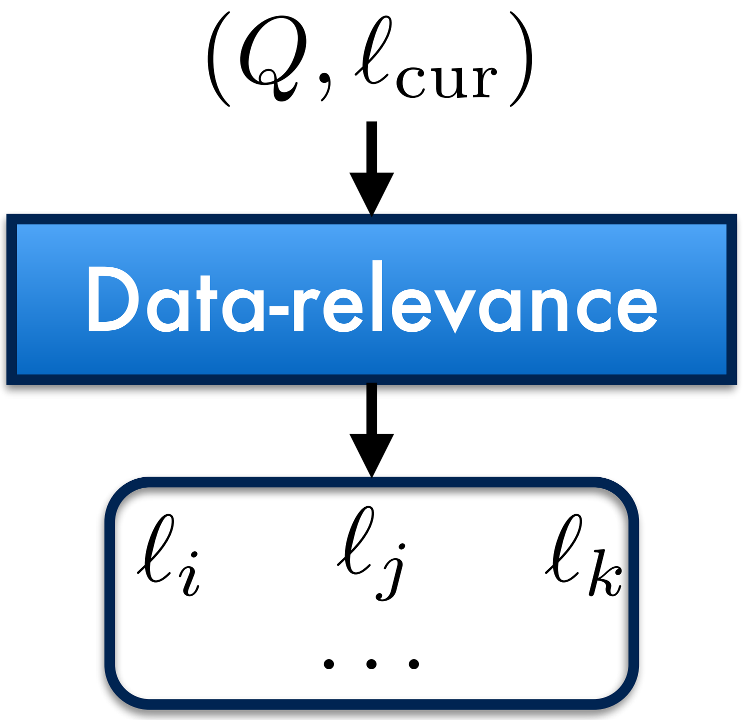
1 $\ell_1 \xrightarrow{[c]} \ell_2$



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

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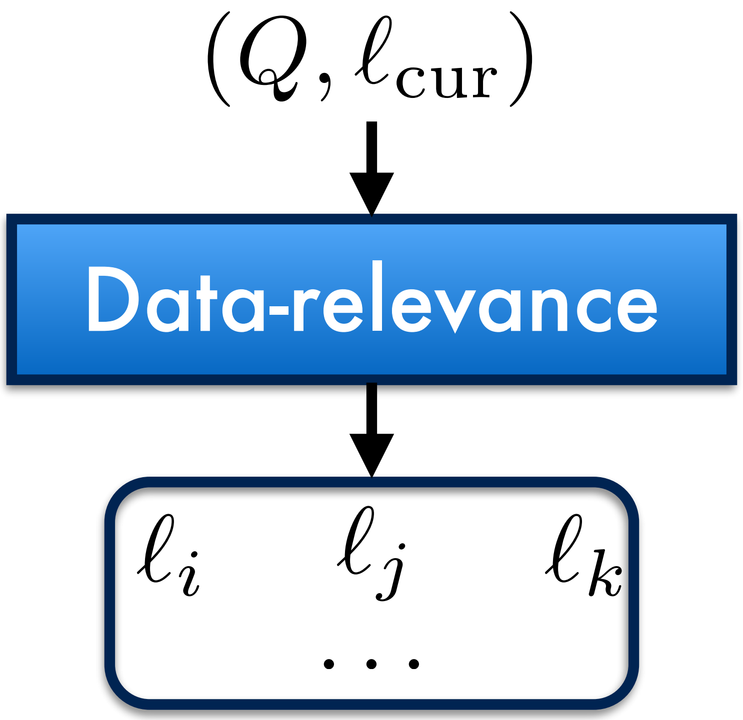


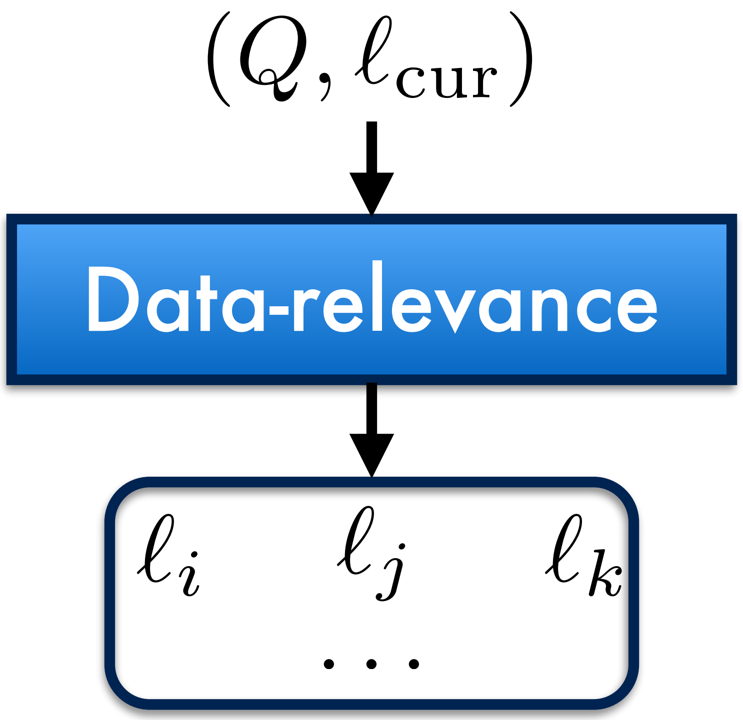
Identify locations that can write to the query Q.

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



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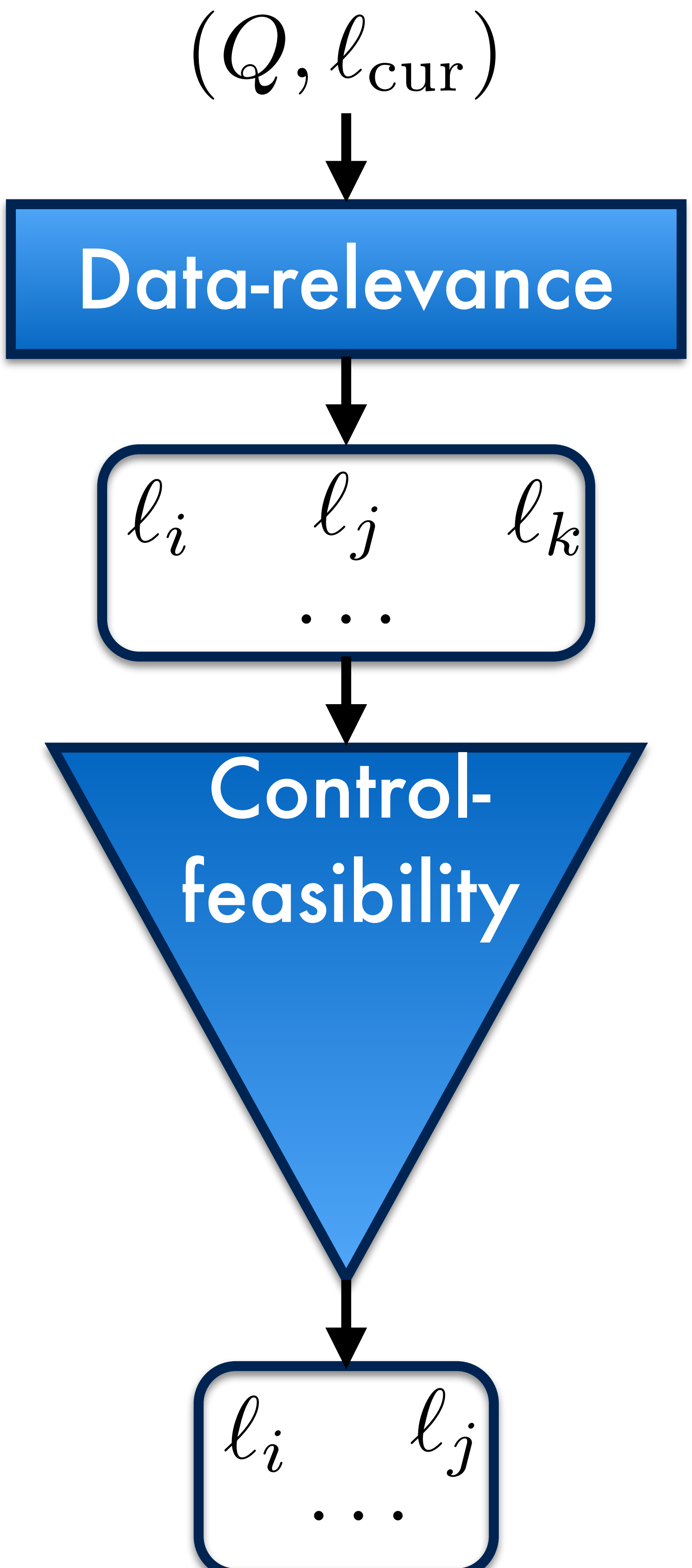

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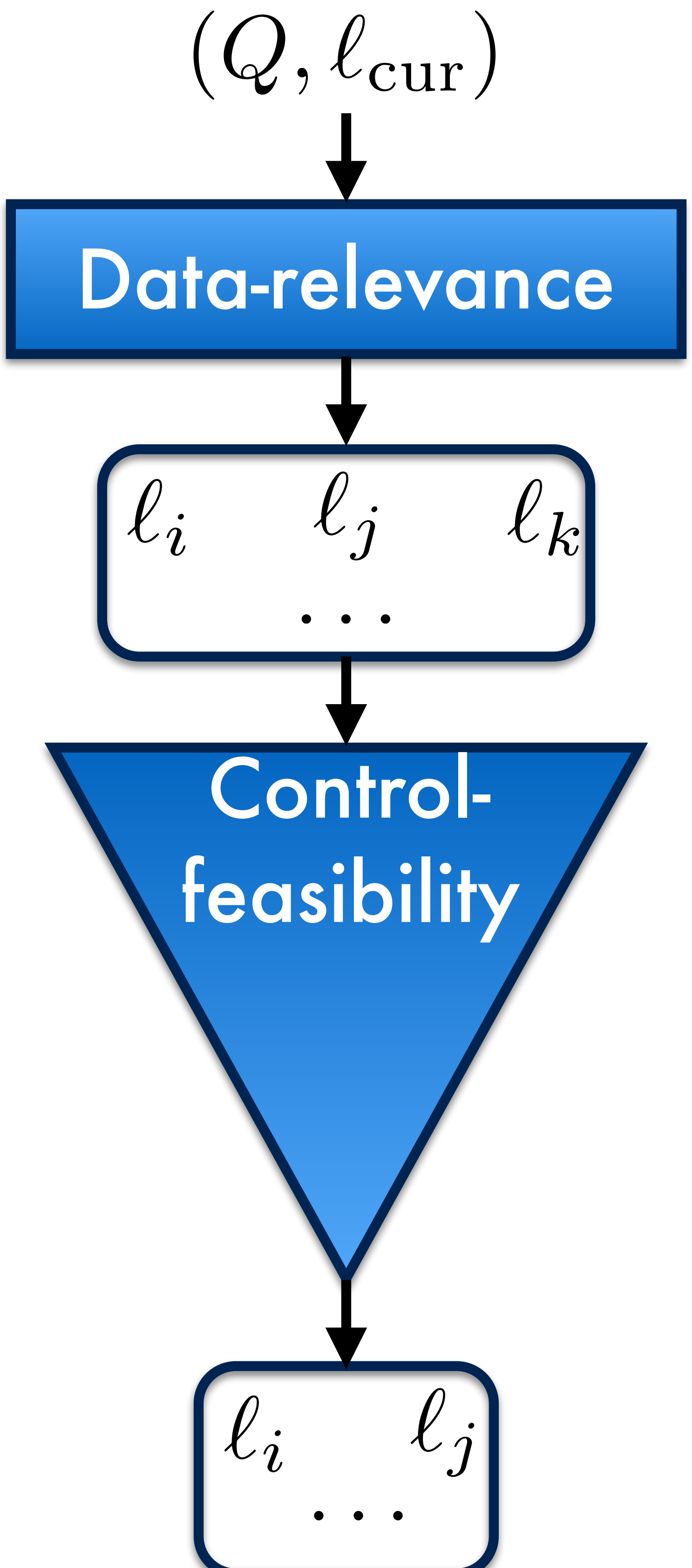

Filter the set of data-relevant locations using control flow and the current program point

Control-feasibility selectively recovers flow-sensitivity

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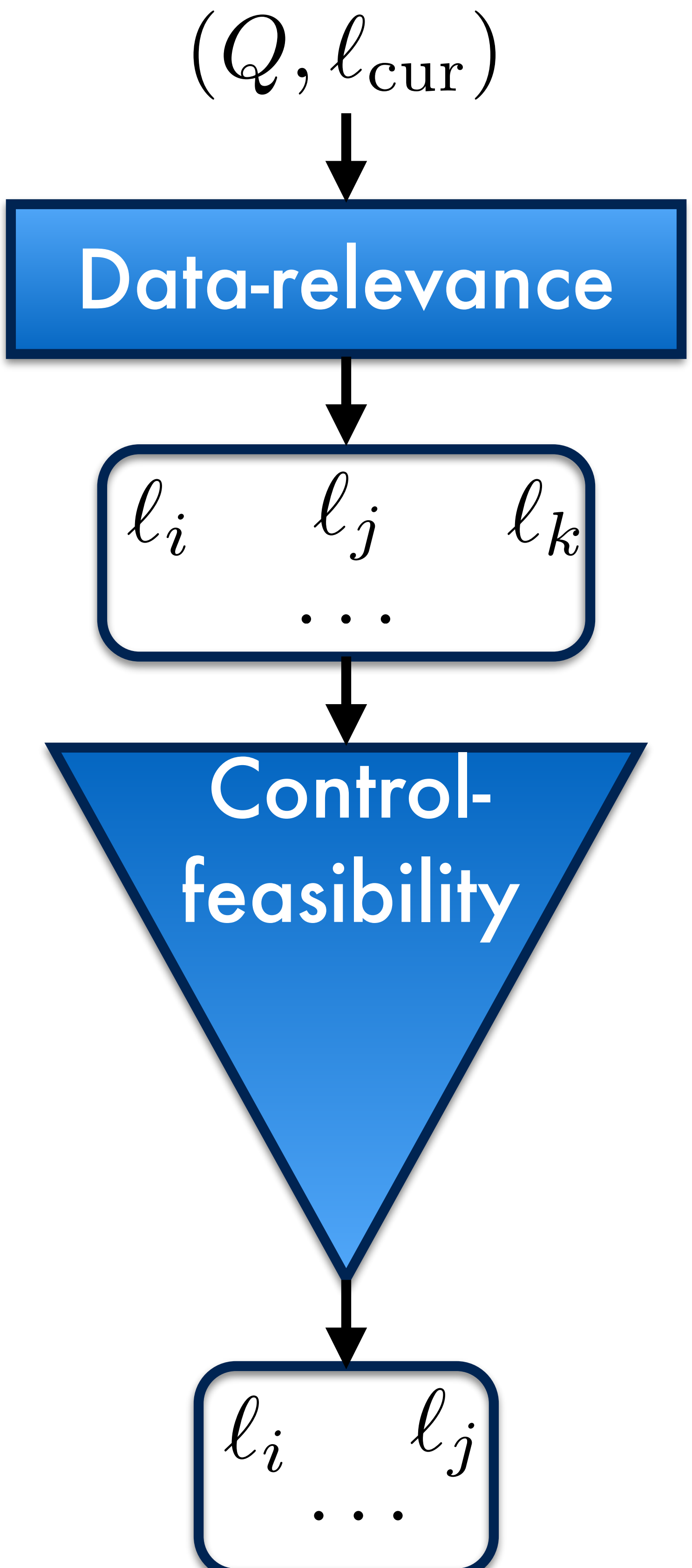

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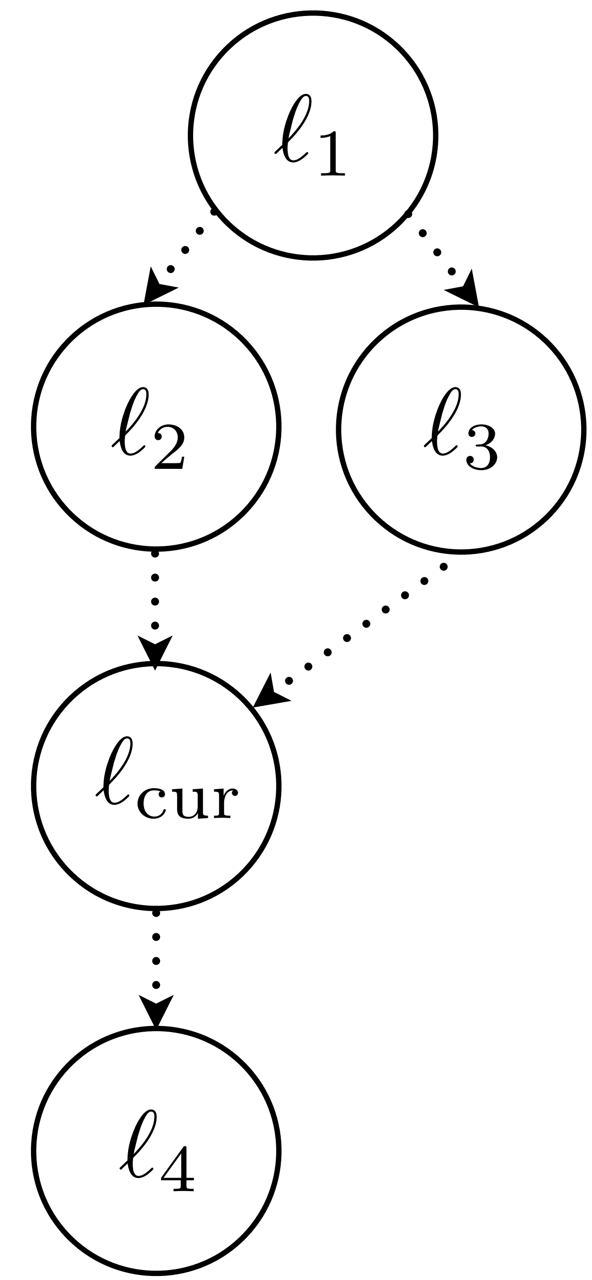

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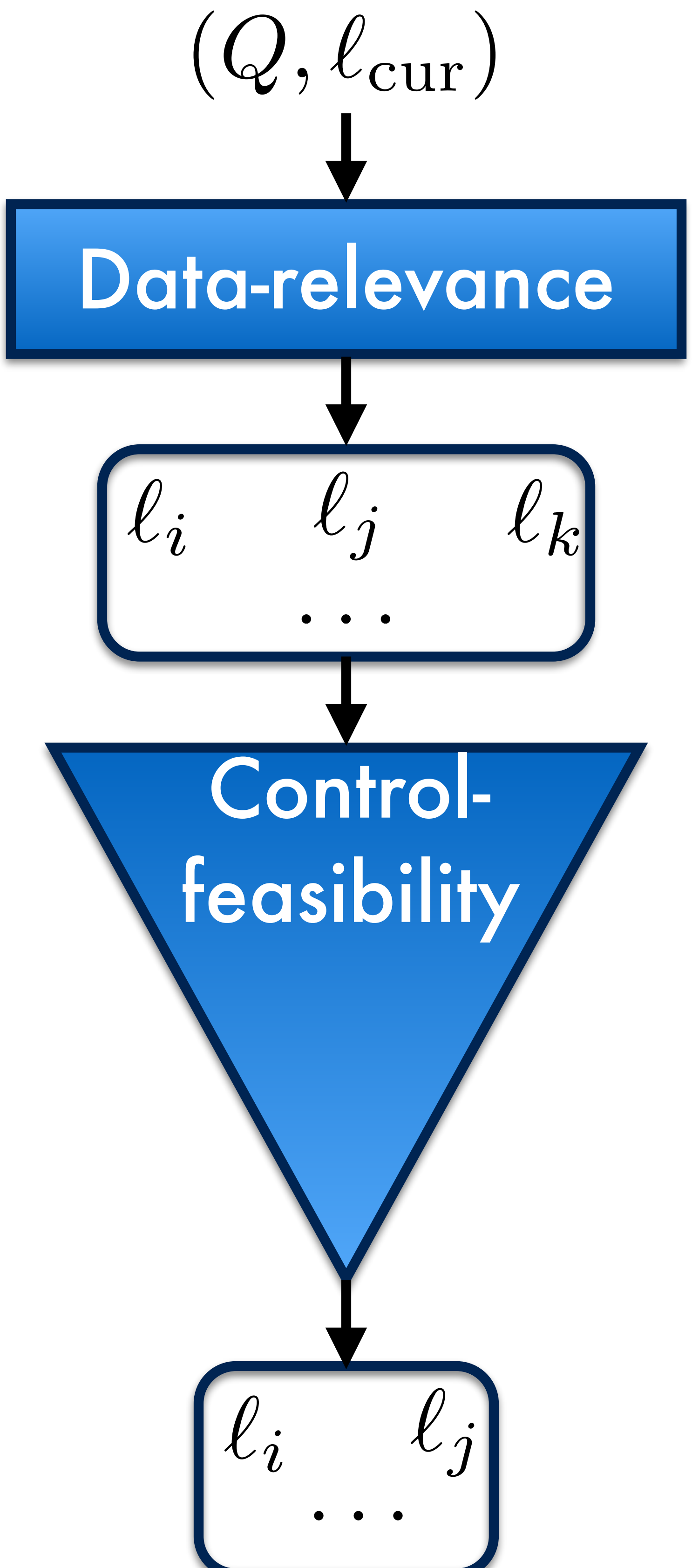
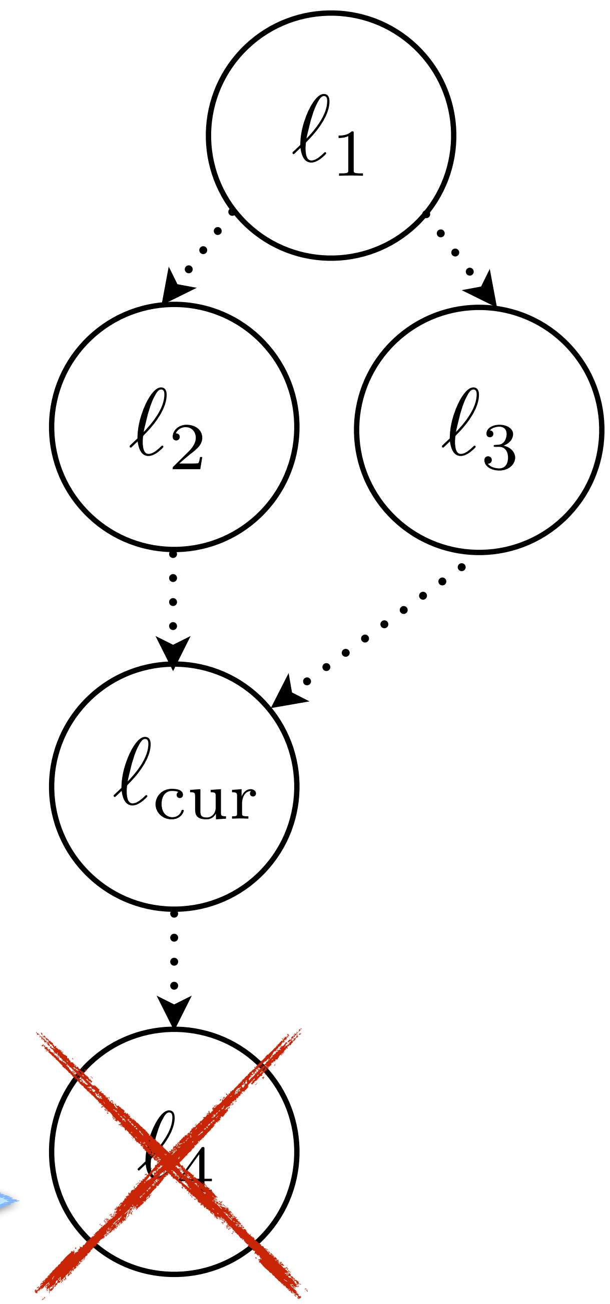


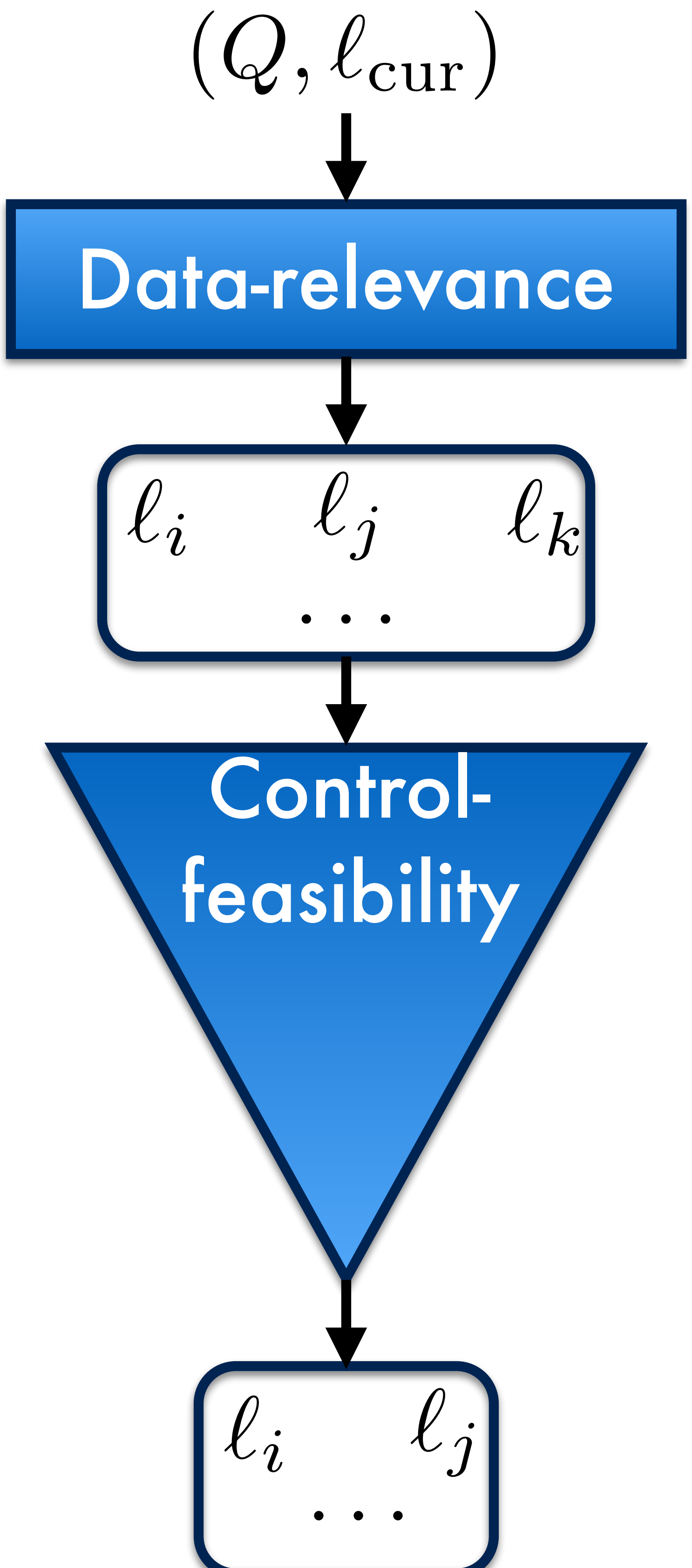
Filter the set of data-relevant locations using control flow and the current program point

Not backward-reachable from current location



Control-feasibility selectively recovers flow-sensitivity

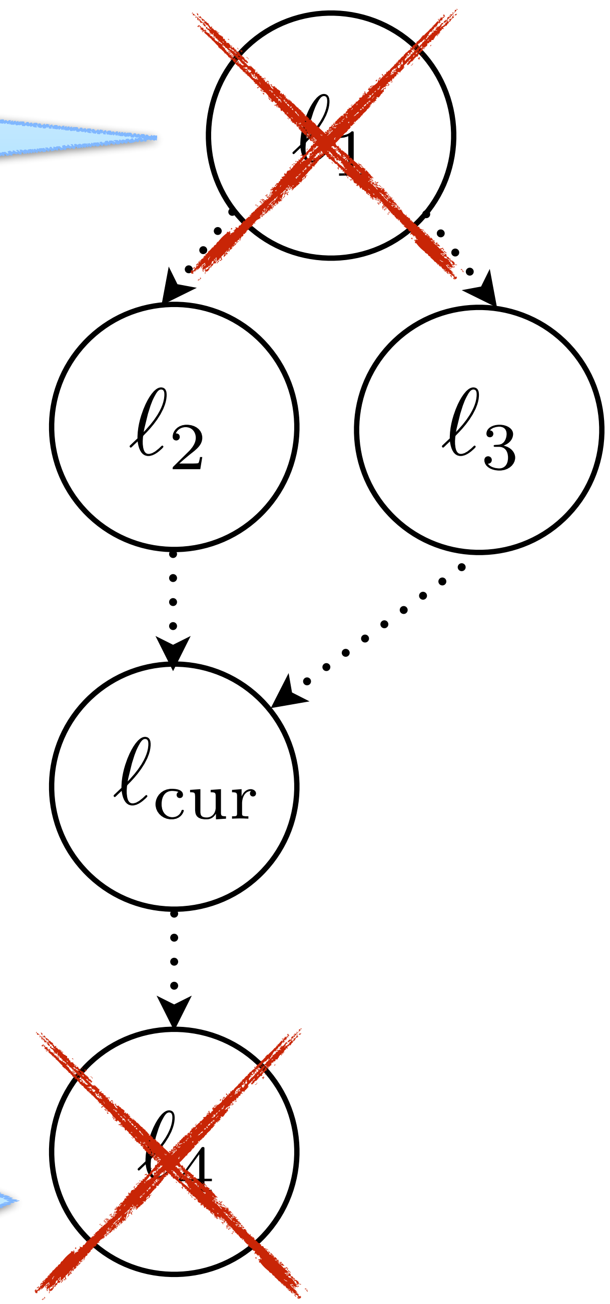
1 $\ell_1 \;\dashv\!\![c]\!\!\to\; \ell_2$



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

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

ℓ_{cur}

Current location

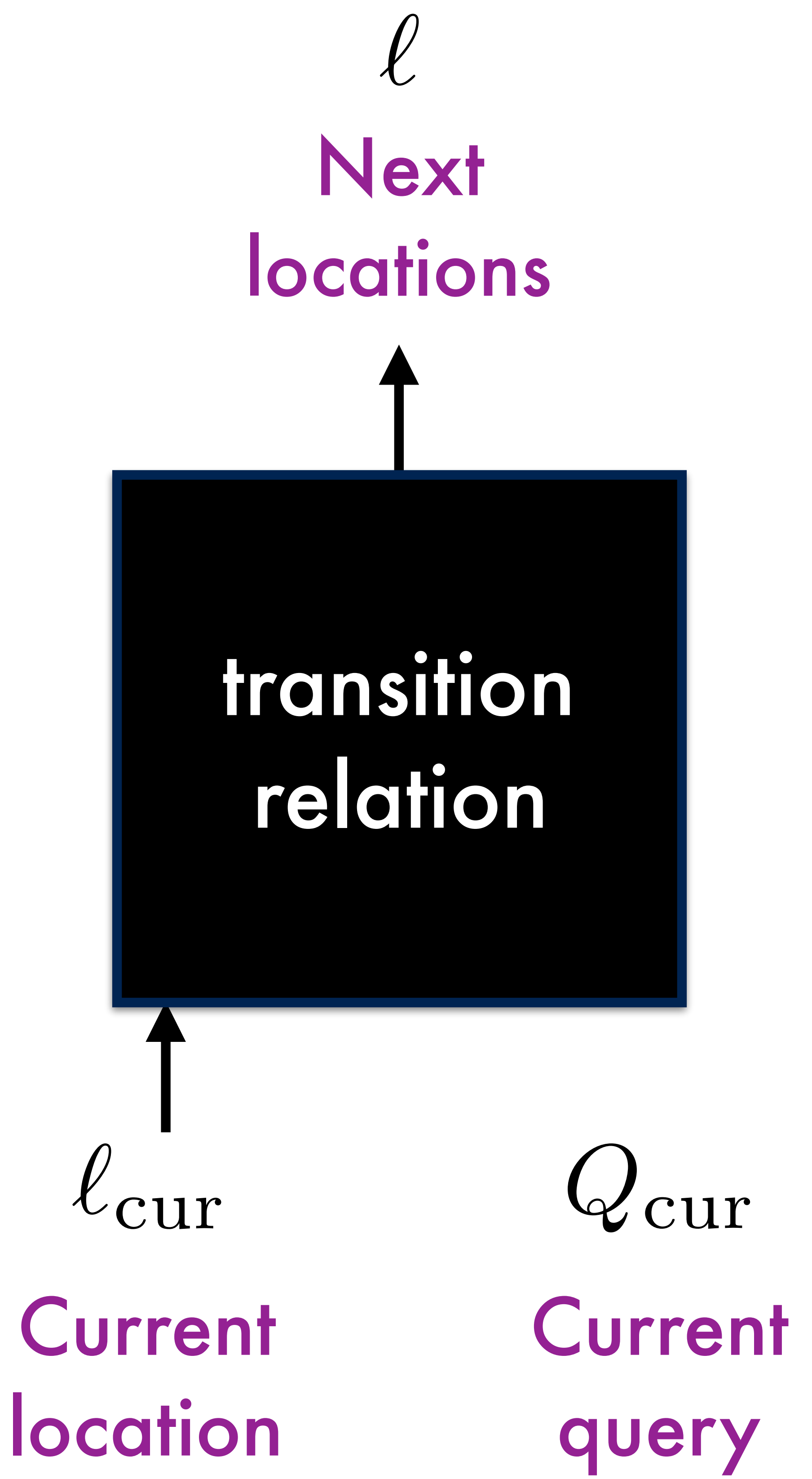
Q_{cur}

Current query

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

1

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



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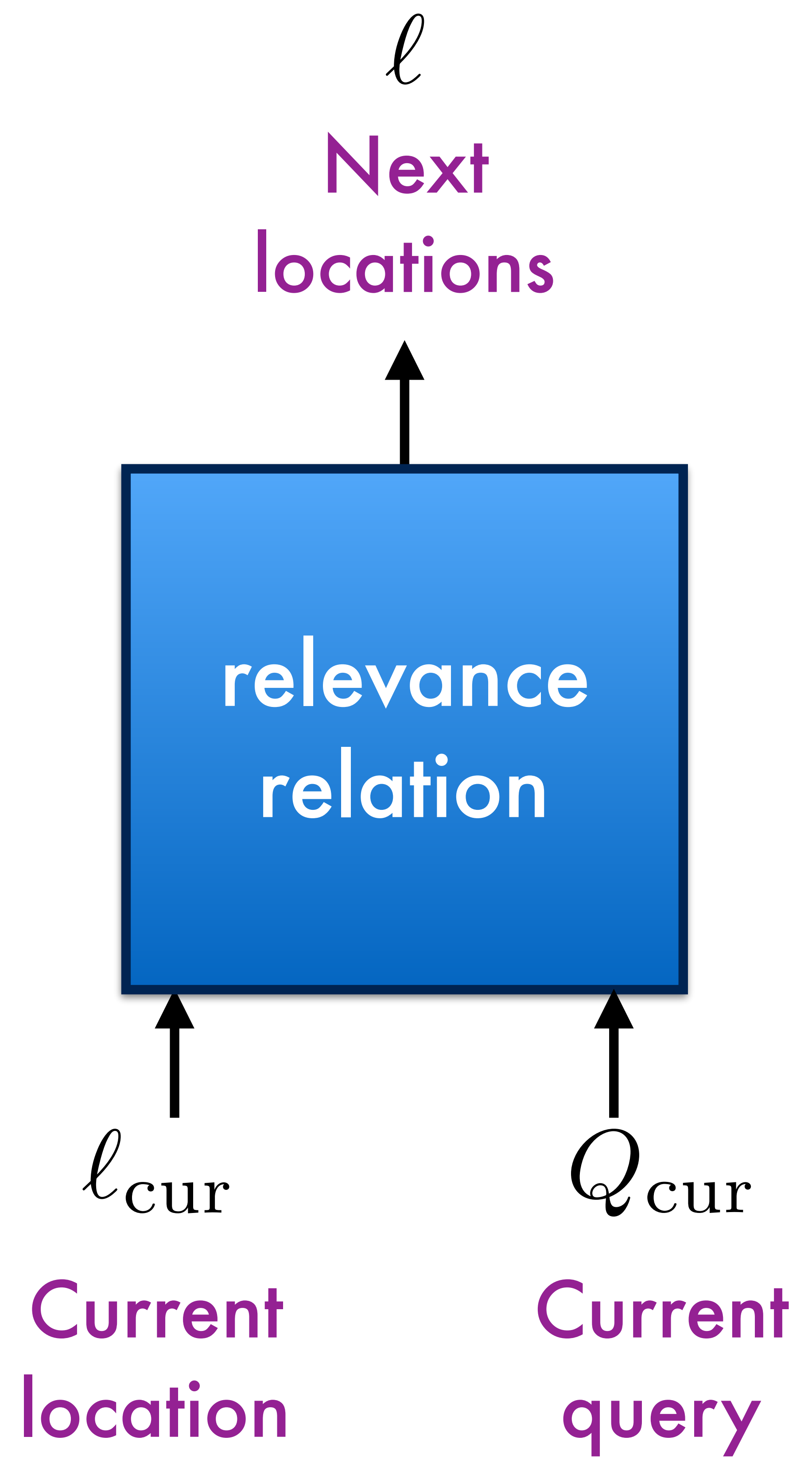
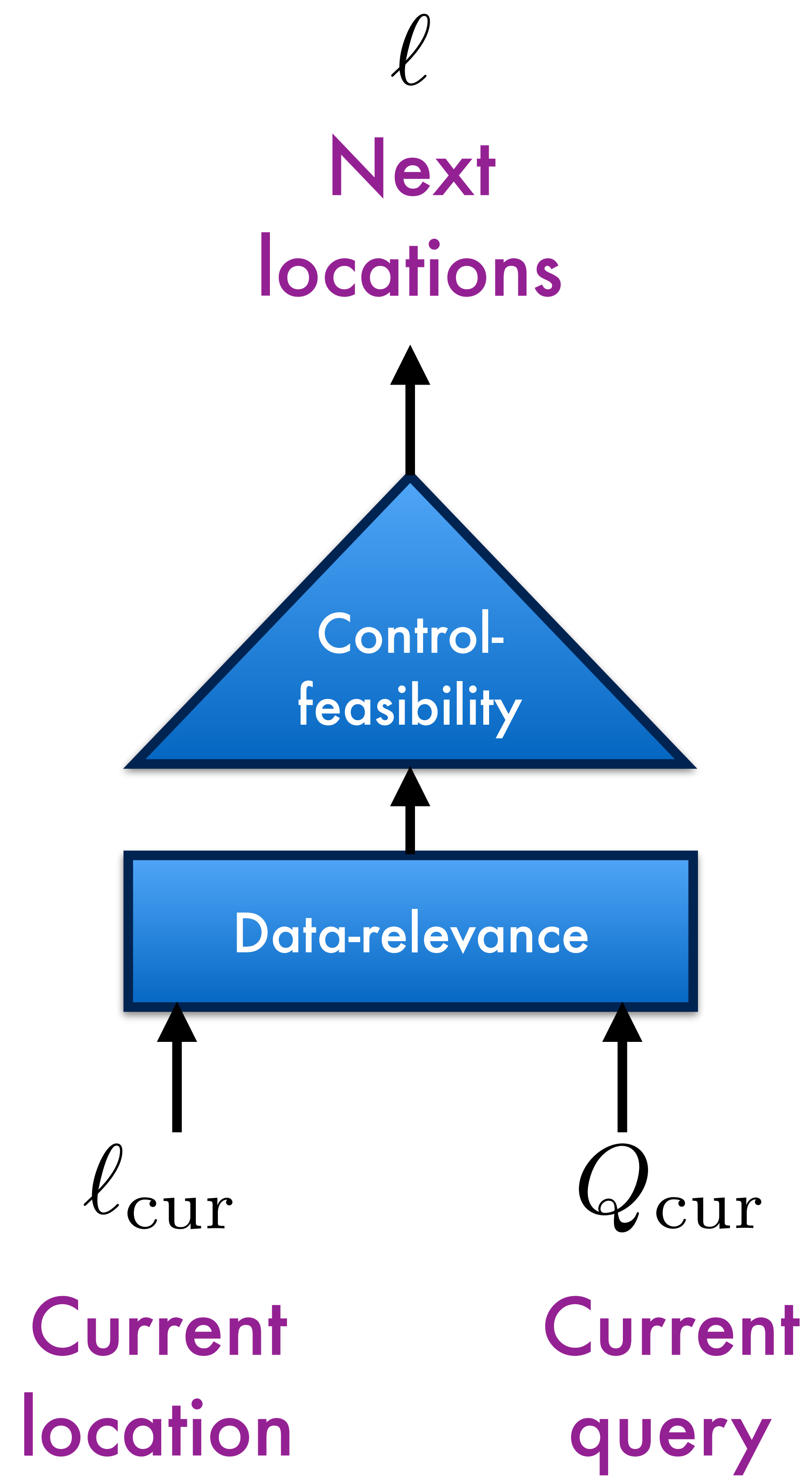


Jumping enables sparse, selective, on-the-fly control-flow abstraction

1

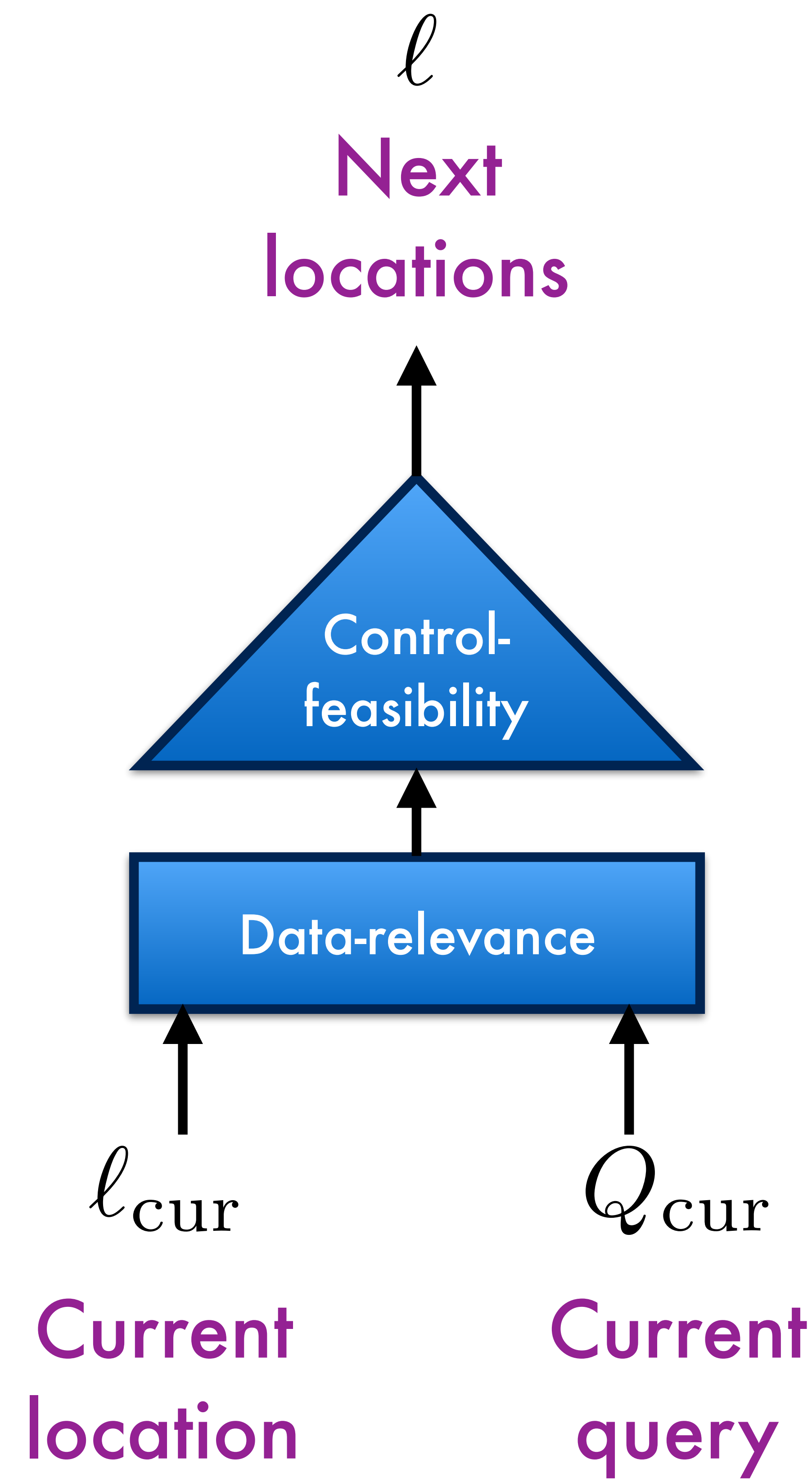
$\ell_1 \xrightarrow{[c]} \ell_2$



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

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

Precision	-insensitive	-sensitive
flow		
path		
context		

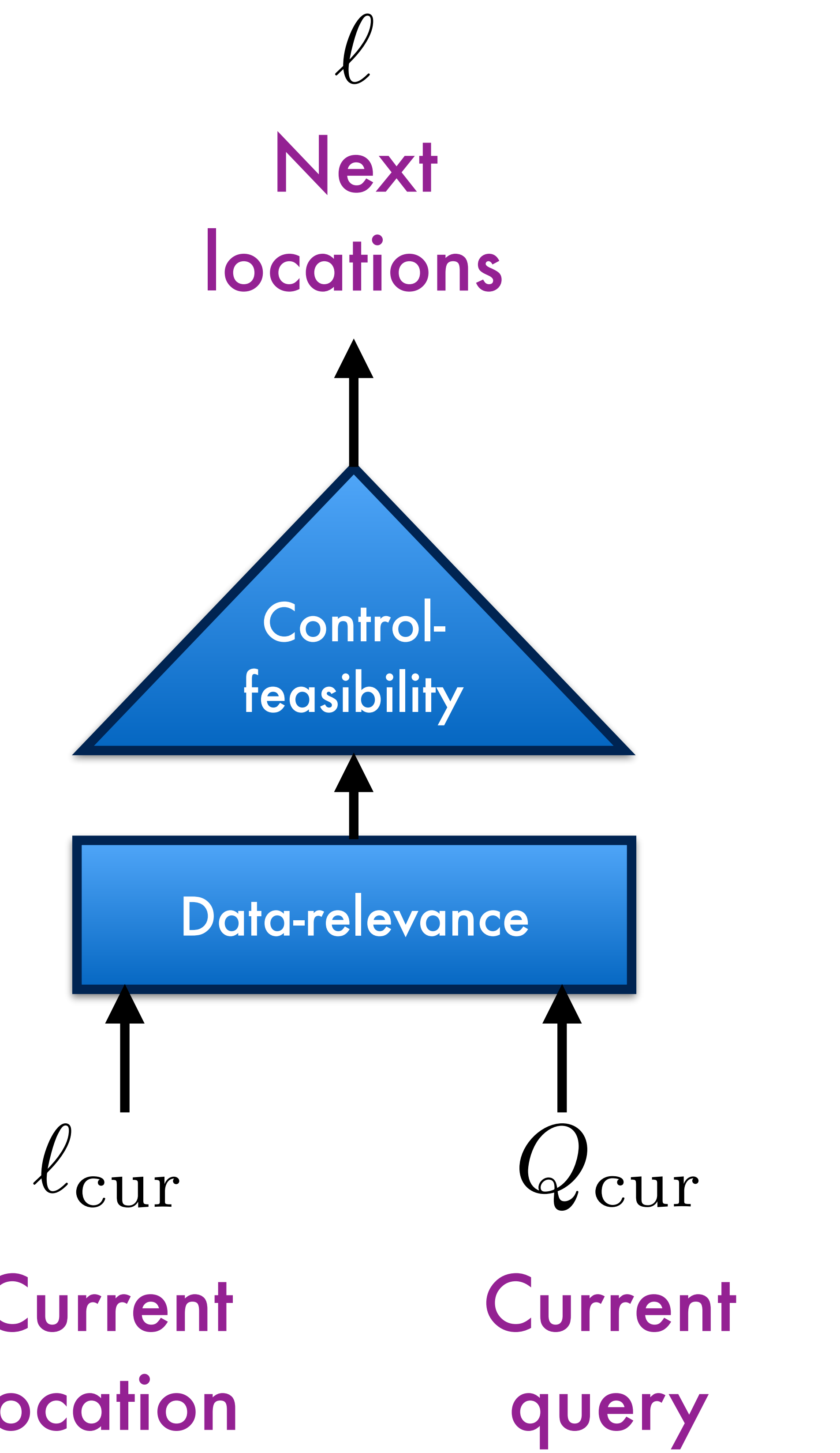


Jumping enables sparse, selective, on-the-fly control-flow abstraction

$\ell_1 \dashrightarrow[c] \ell_2$

Precision	-insensitive	-sensitive
flow		
path		
context		

no filter



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

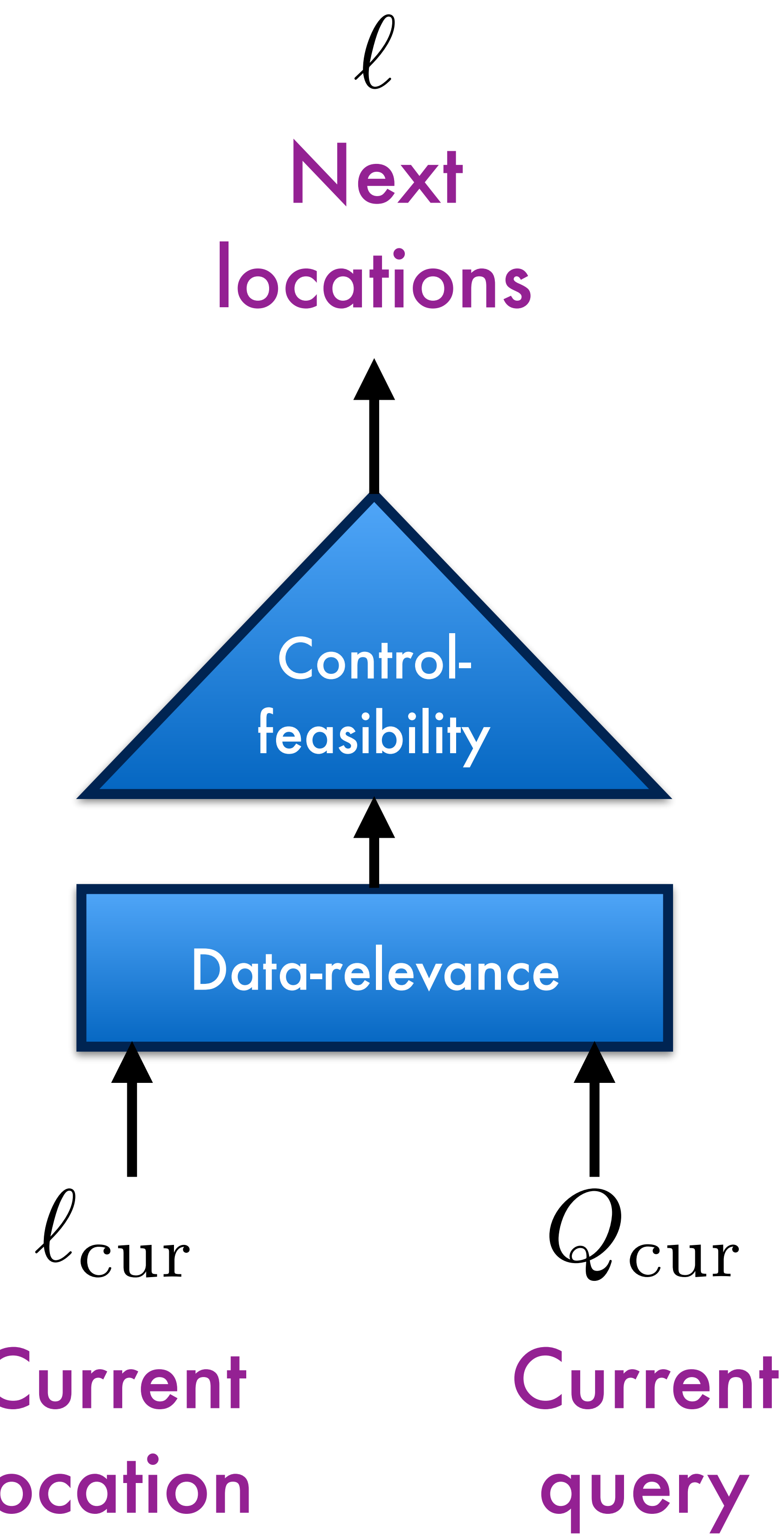
1

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

Precision	-insensitive	-sensitive
flow		
path		
context		

no filter

all locations



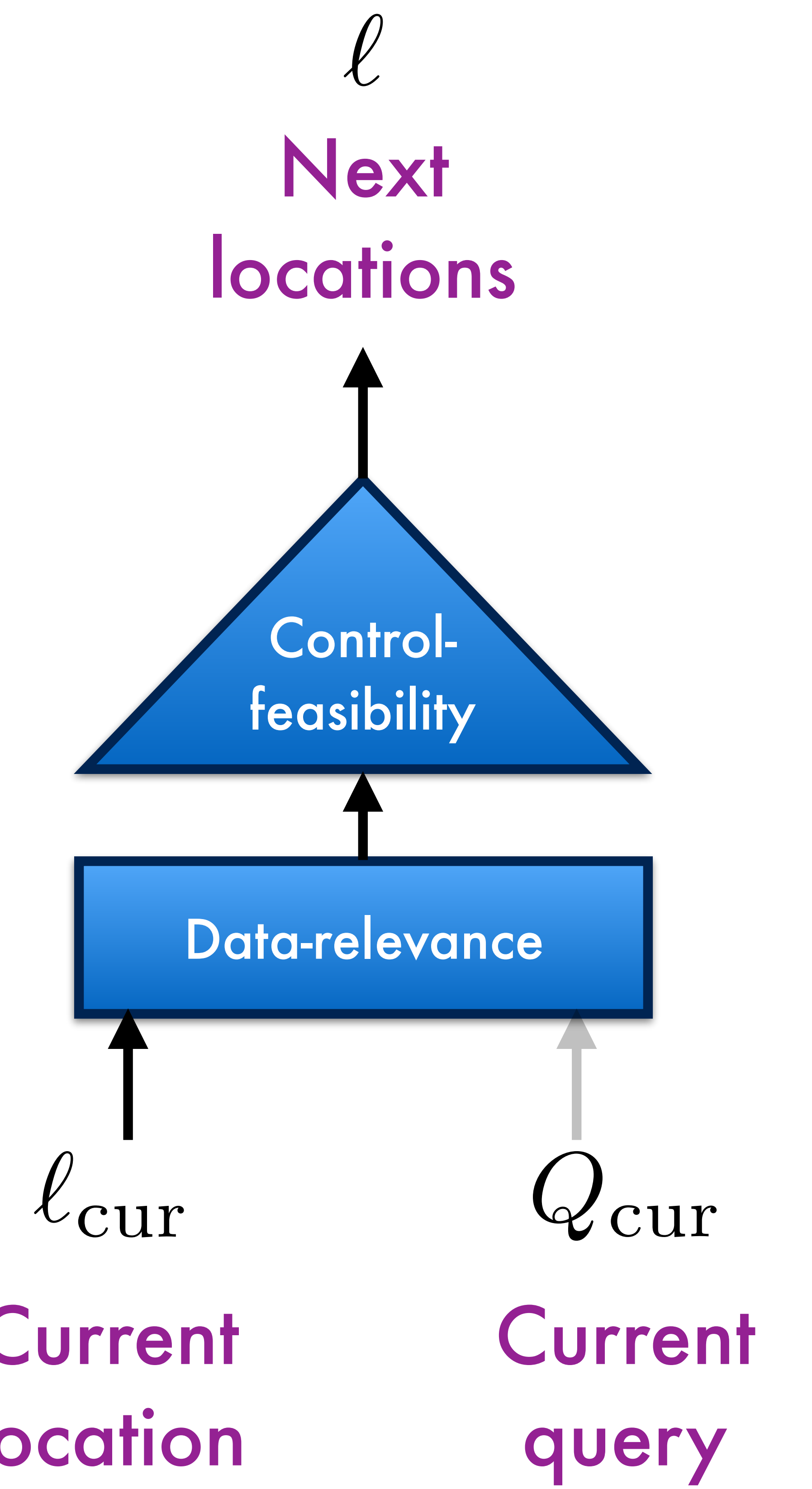
Jumping enables sparse, selective, on-the-fly control-flow abstraction

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

Precision	-insensitive	-sensitive
flow		
path		
context		

no filter

all locations



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

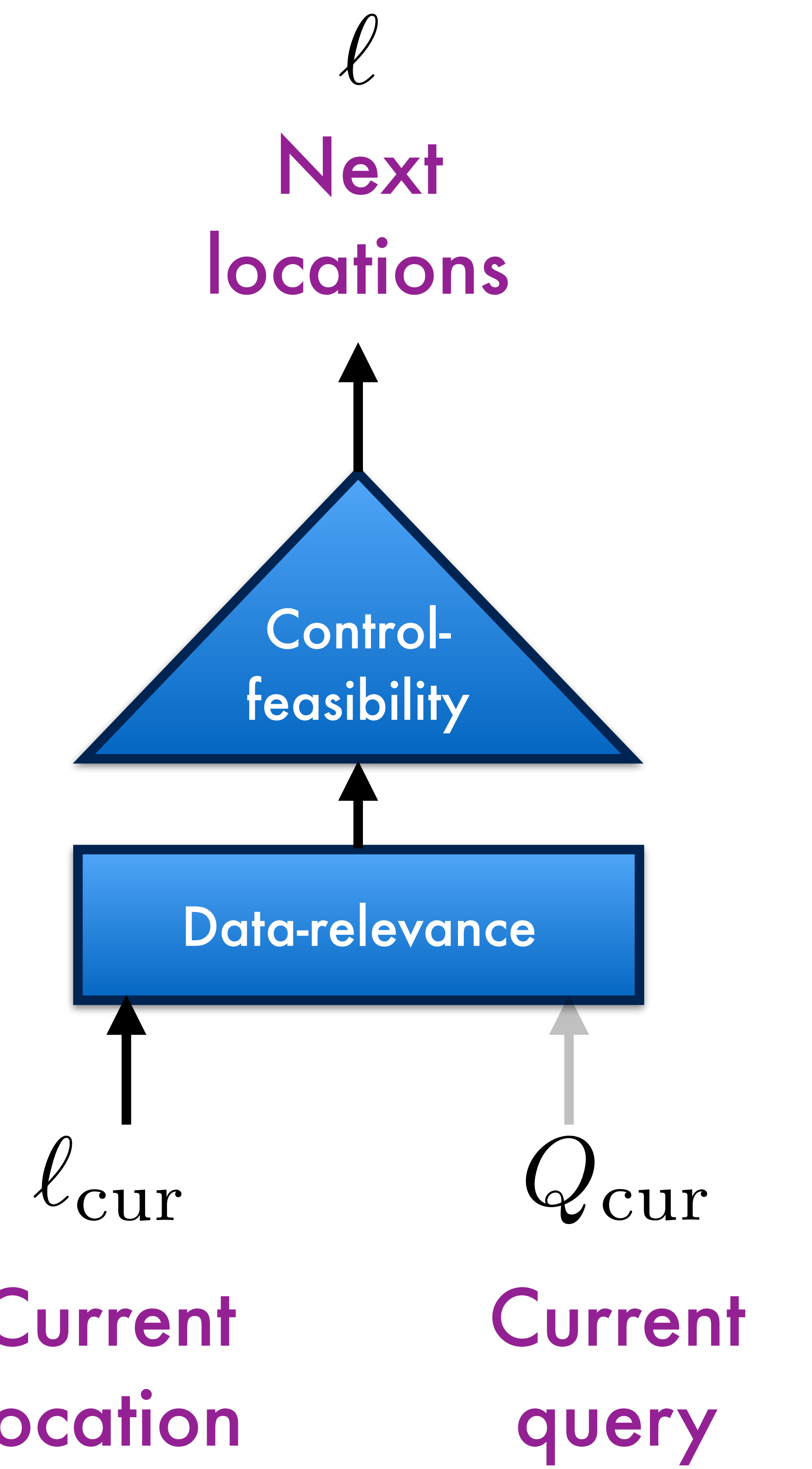
1

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

Precision	-insensitive	-sensitive
flow	✔	
path		
context		

no filter

all locations



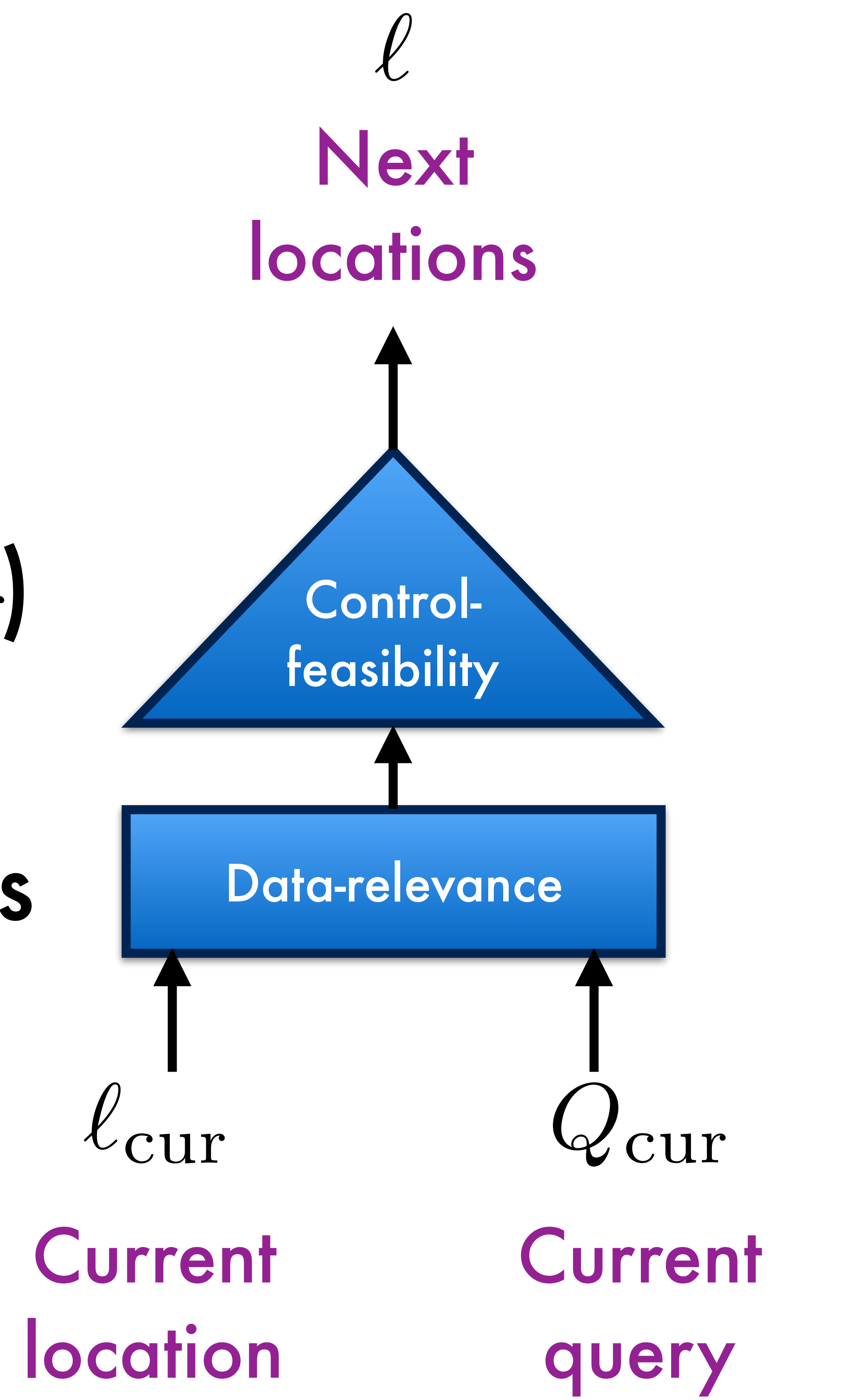
Jumping enables sparse, selective, on-the-fly control-flow abstraction

1

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

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

all locations



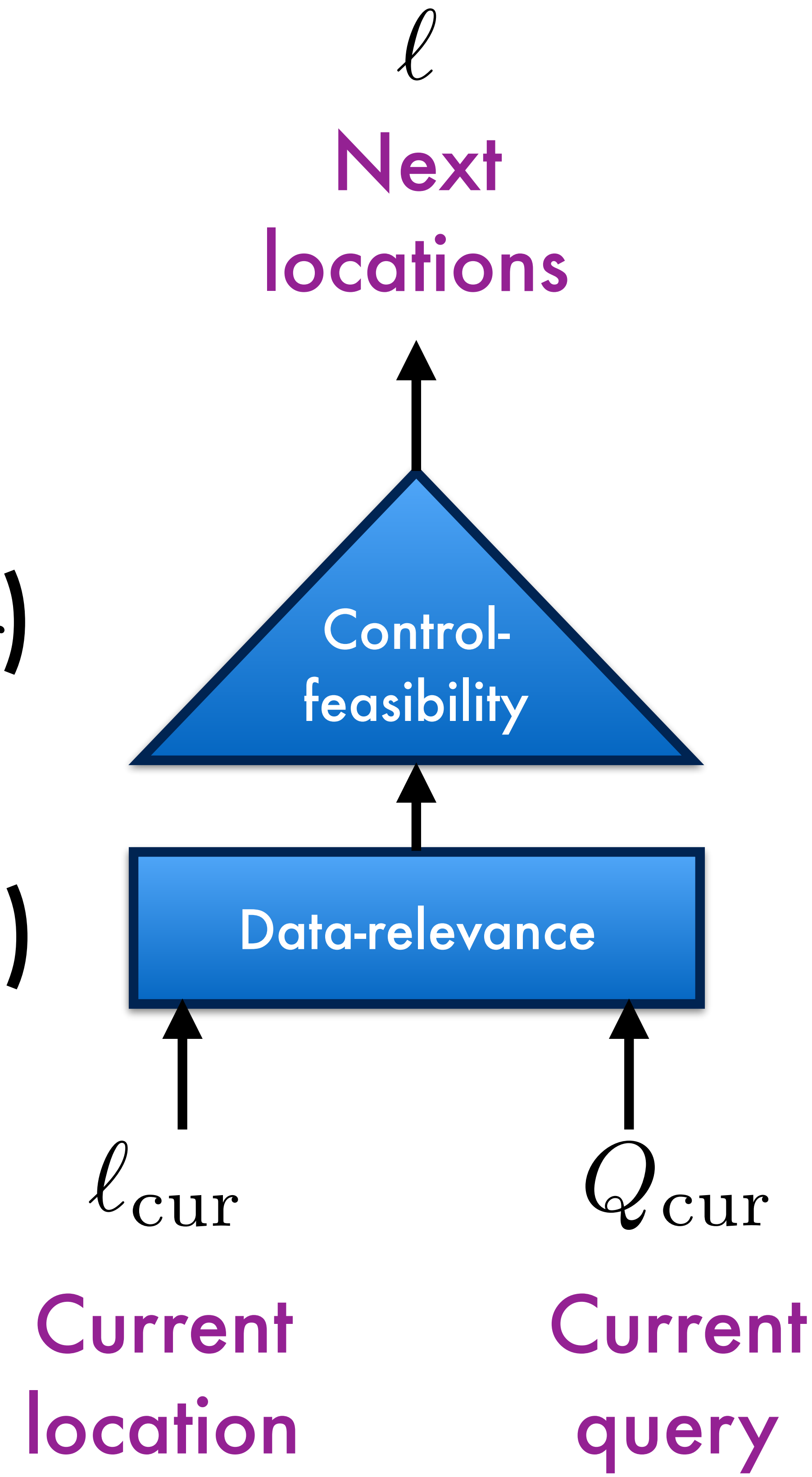
Jumping enables sparse, selective, on-the-fly control-flow abstraction

1

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

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

all mods(Q_{cur})



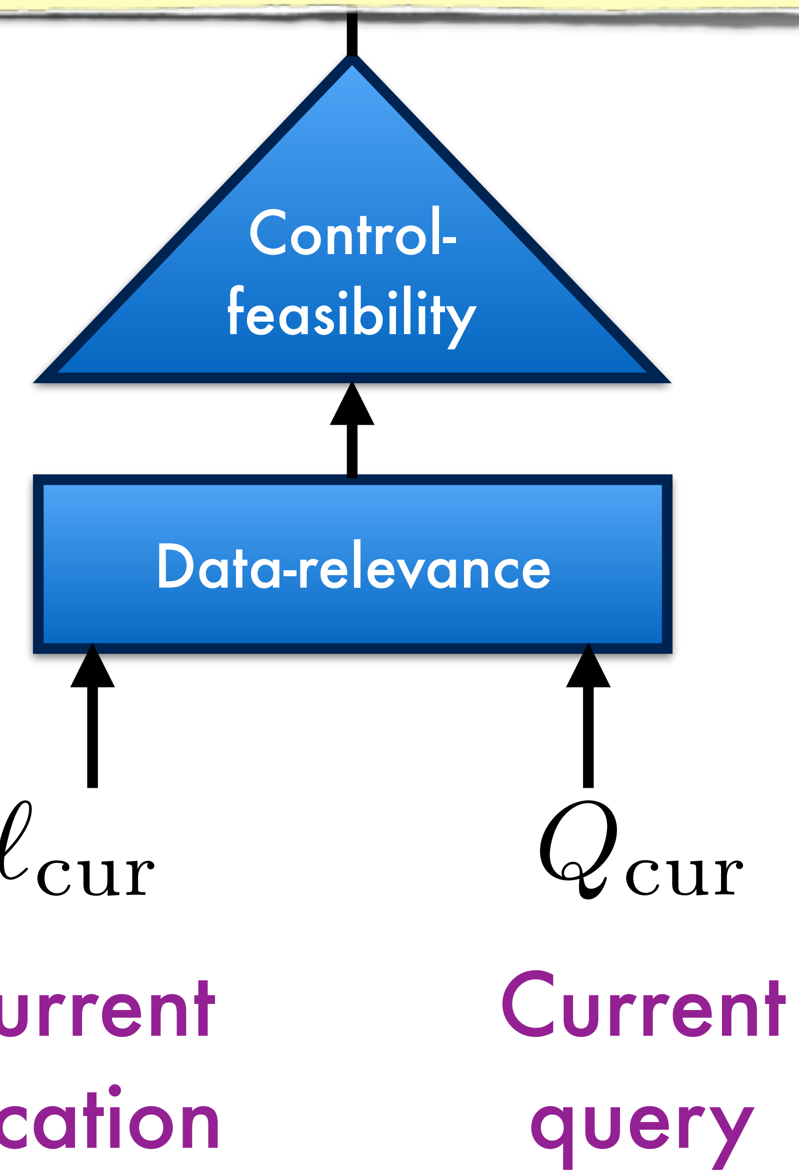
Jumping enables sparse, selective, on-the-fly (1) control-flow abstraction

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

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

only feasible-preds(ℓ_{cur}, Q_{cur})

all mods(Q_{cur})



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

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

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

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

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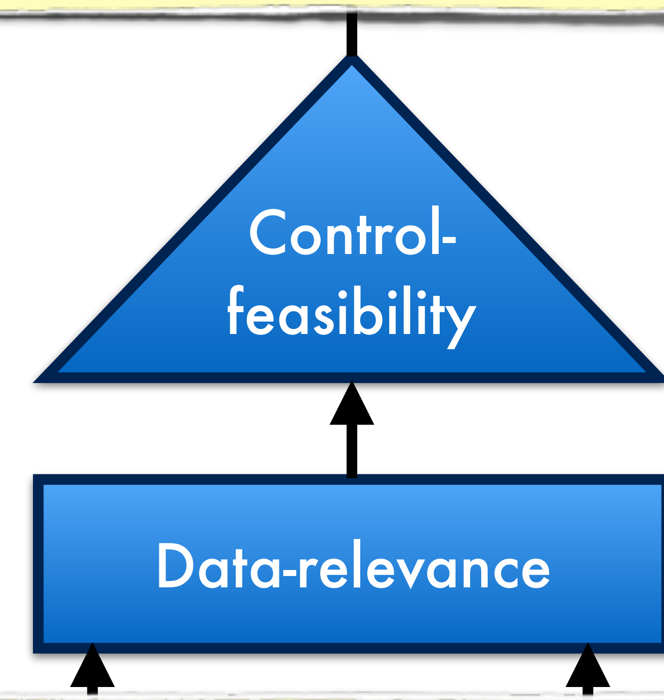
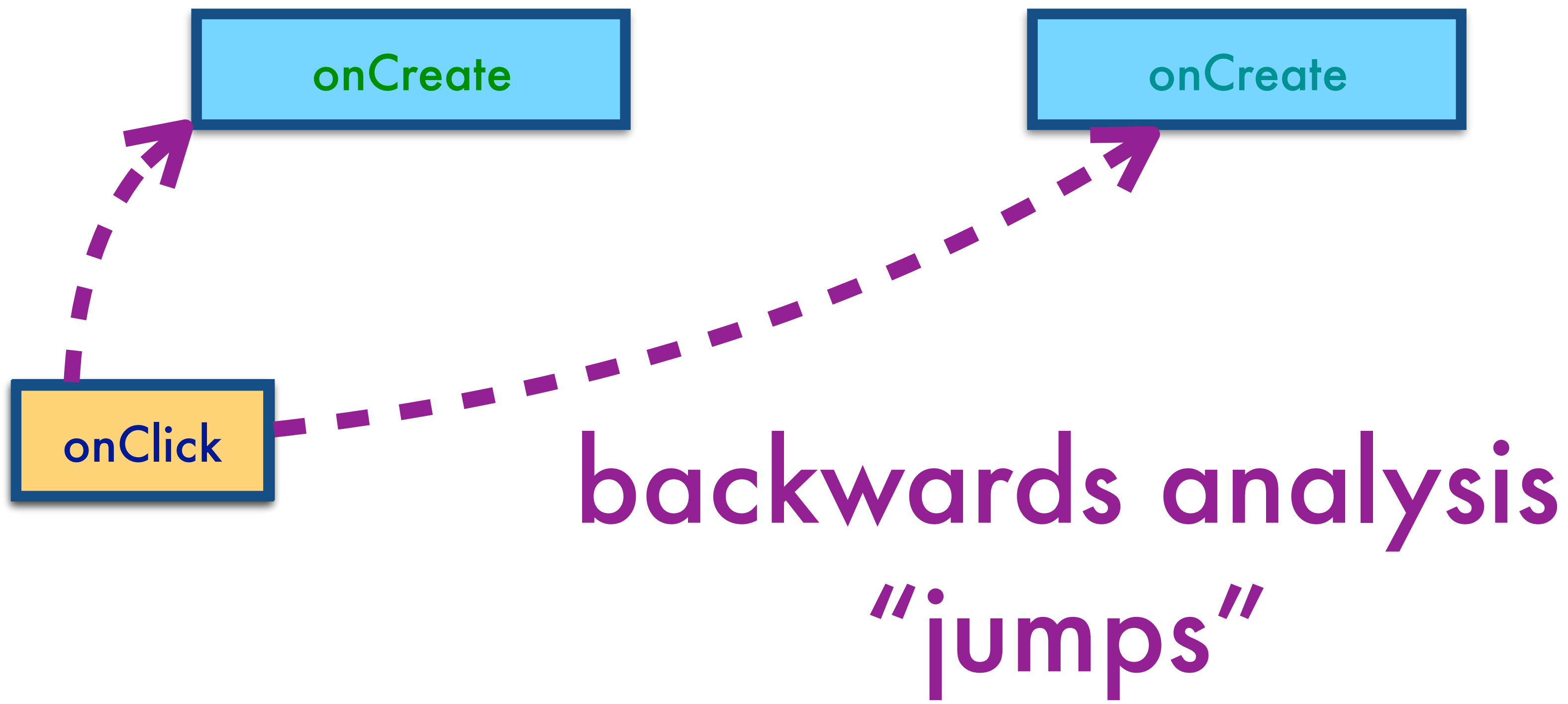


Be selective by varying the relevance relation at each analysis step

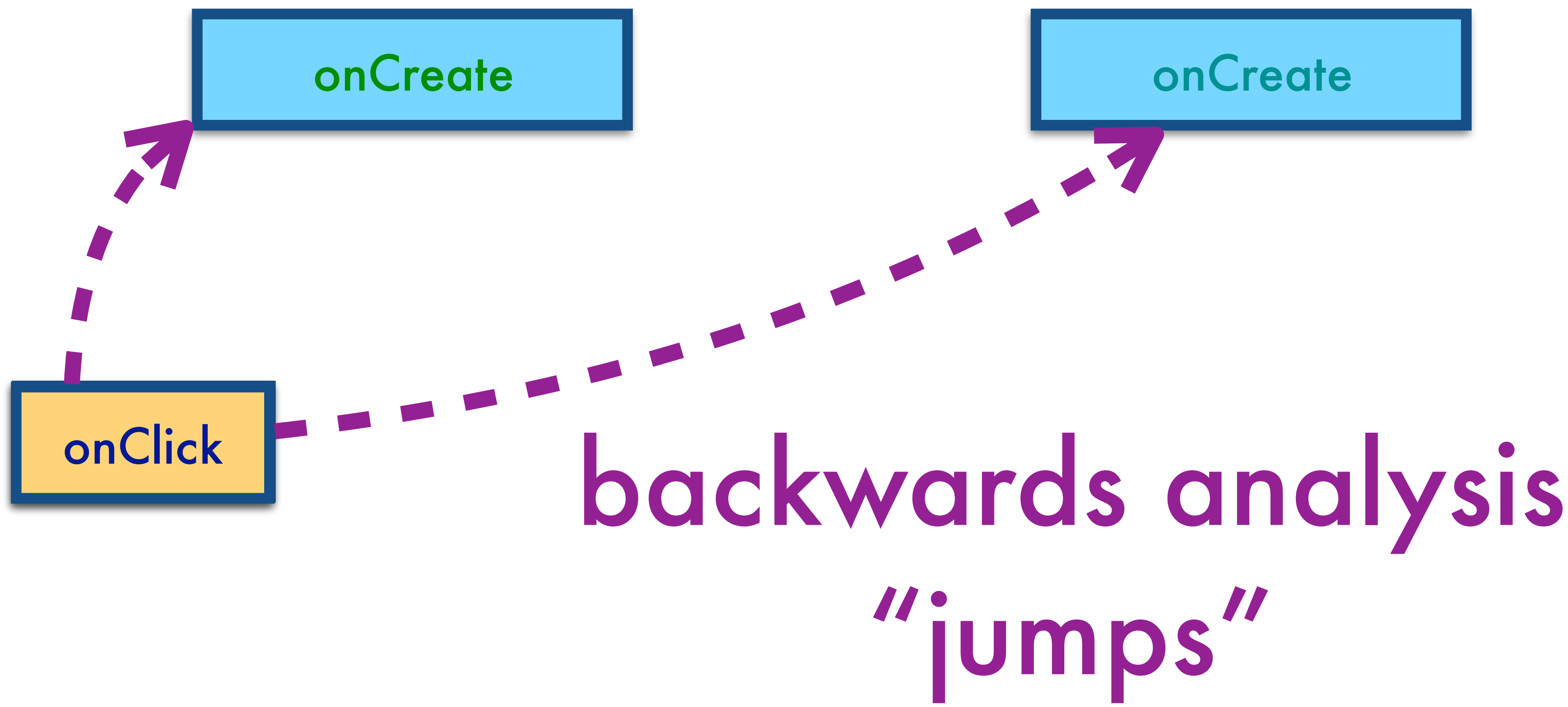
Contributions



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

2  Applied to Android events

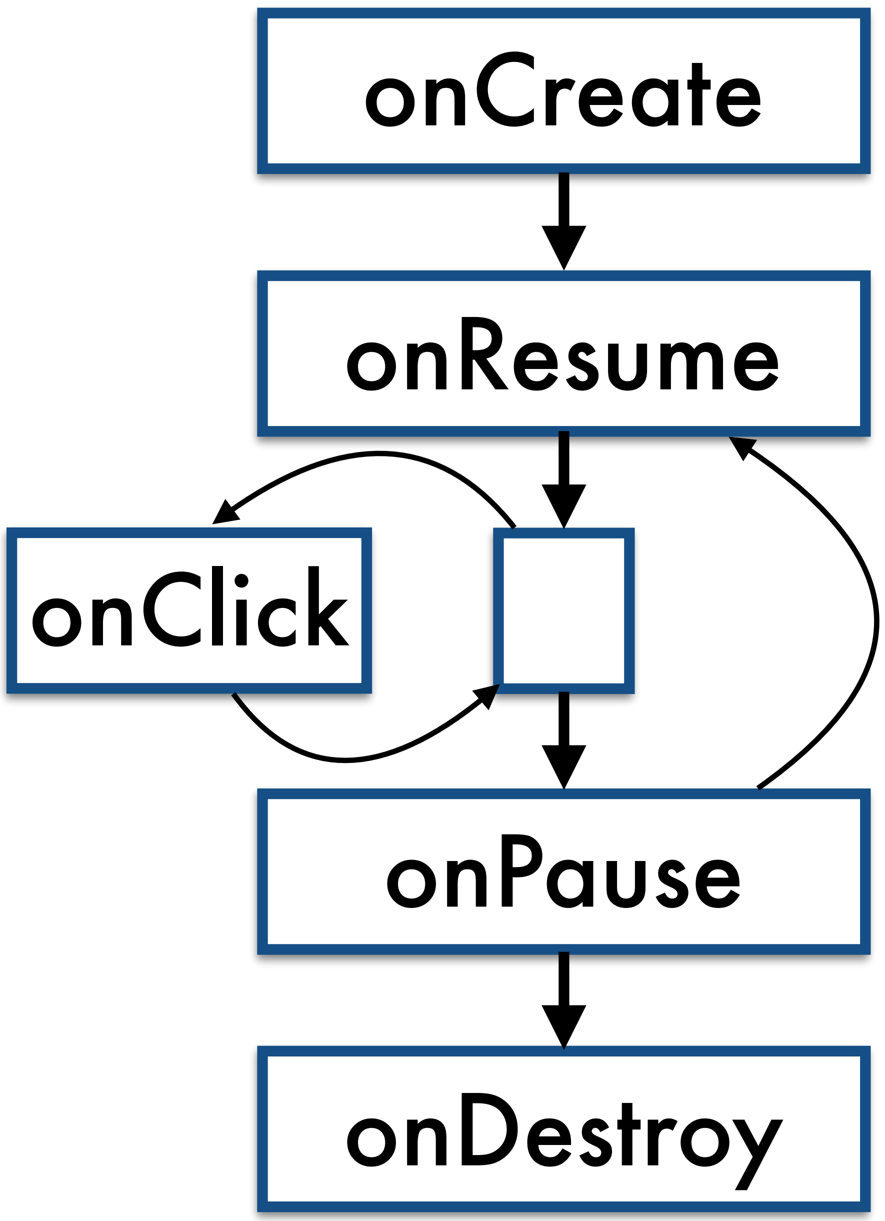
Contributions



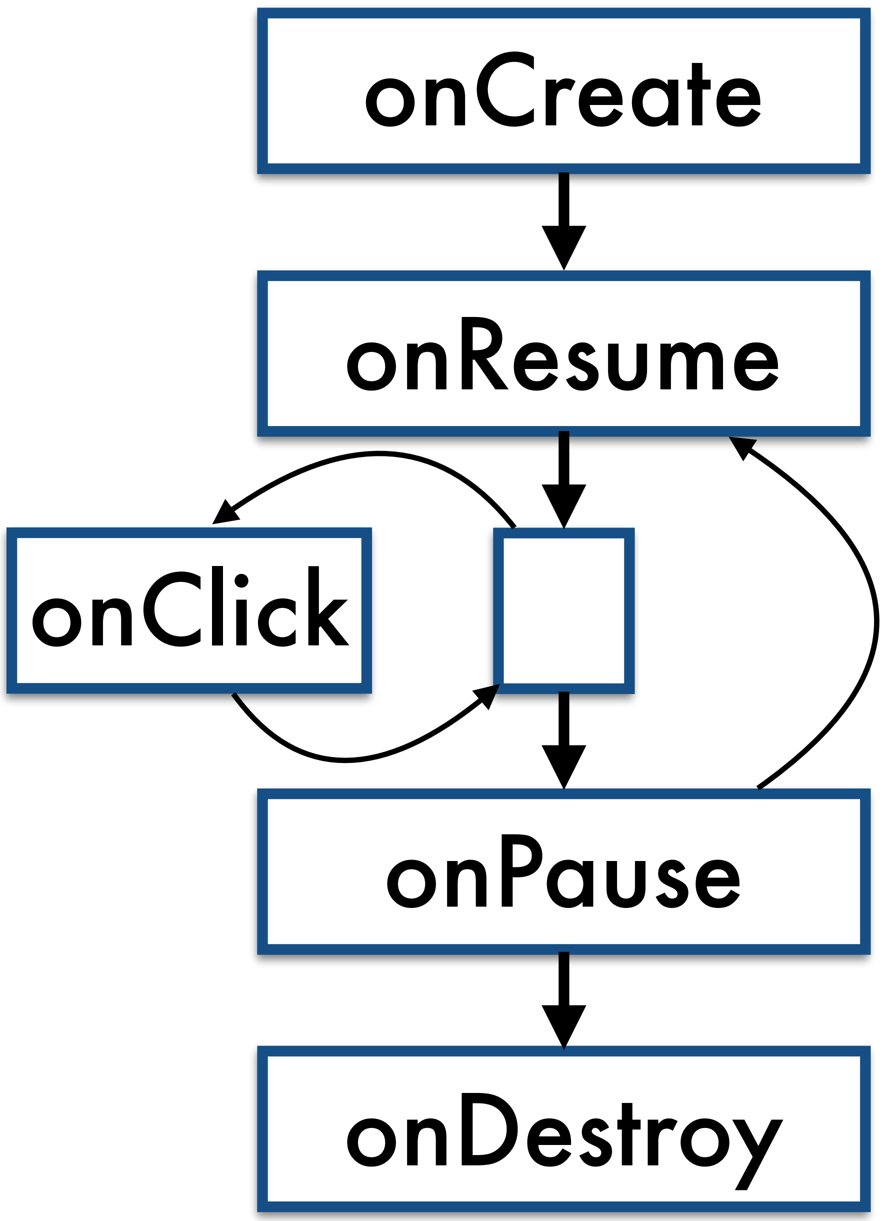
1 $\ell_1 \;-\!\![c]\!\!\rightarrow \ell_2$ Framework for jumping analyses

2 Applied to Android events

Formalizing lifecycle graphs

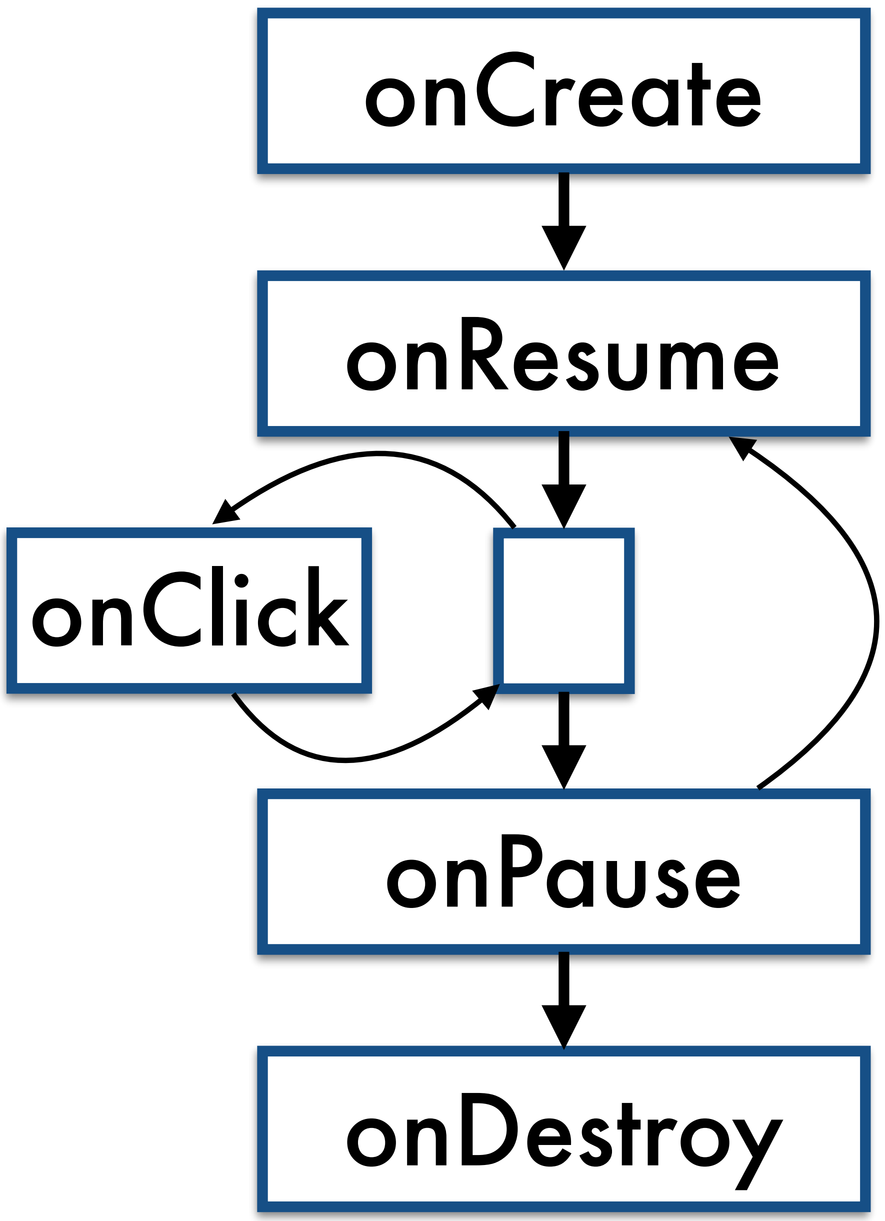


Formalizing lifecycle graphs



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

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

A jumping policy for Android analysis

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

Evaluation 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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120 to 1,320 callbacks

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

10 open source Android apps

3,000 to 55,000 lines of code
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Compared 3 analyses

Nit: flow-insensitive
Thresher: no jumping
Hopper: 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)
textsecure	38	5921	3643	698	330 (53)
k-9	55	19032	11968	3104	1988 (36)
wordpress	57	15066	9775	2431	1362 (44)
Total	**266**	**62562**	**41071**	**9968**	**5412 (54)**

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[illegible]	[illegible]8	5921	3643	698	330 (53)
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Many derefs

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Is jumping effective?

Flow-insensitive

No jumping

Jumping

unproven derefs

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Thr and Hop: 10 second budget per deref

Is jumping effective?

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Thresher has 74% fewer than Nit

Is jumping effective?

unproven derefs

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drupaleditor	3	928	679	179	72 (60)
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Total	**266**	**62562**	**41071**	**9968**	**5412 (54)**

Hopper has 54% fewer than Thresher

Is jumping effective?

	KLOC	Deref	Nit	Thr	Hop (Impr %)	% Proven
		unproven derefs				
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
github	19	3603	2520	601	290 (52)	92
seriesguide	32	8184	5438	986	625 (37)	92
connectbot	33	2190	1562	316	74 (77)	97
textsecure	38	5921	3643	698	330 (53)	94
k-9	55	19032	11968	3104	1988 (36)	90
wordpress	57	15066	9775	2431	1362 (44)	91
Total	**266**	**62562**	**41071**	**9968**	**5412 (54)**	$\boxed{\textbf{92}}$

Is jumping effective?

		unproven derefs				
	KLOC	**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
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github	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92
seriesguide	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92
connectbot	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	97
textsecure	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	94
k-9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	90
wordpress	57	15066	9775	2431	1362 (44)	91
Total	**266**	**62562**	**41071**	**9968**	**5412 (54)**	$\boxed{\textbf{92}}$

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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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

Tria ... se

Re ... e

containe ...

Only 17 false ...

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

Found 11 bugs in 4 apps
(lastfm, seriesguide, connectbot, wordpress)

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10/11 patches accepted

Summary

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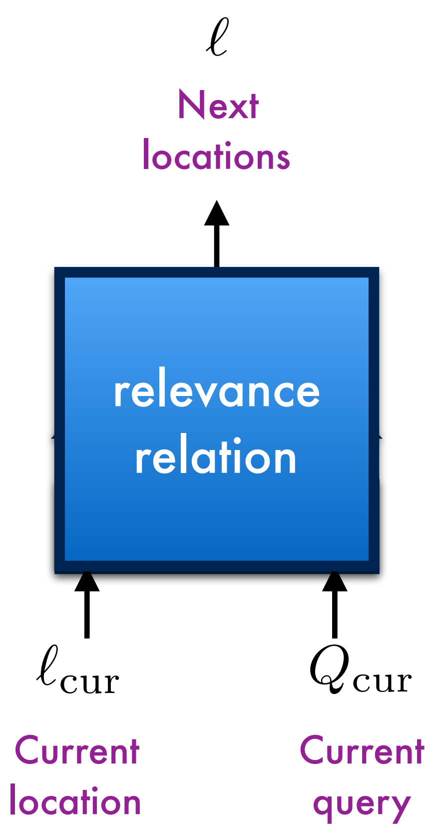
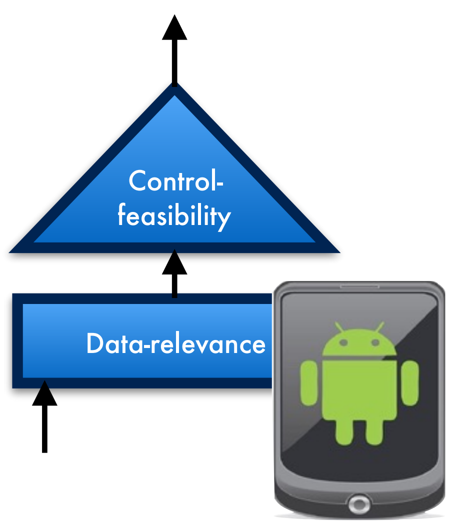


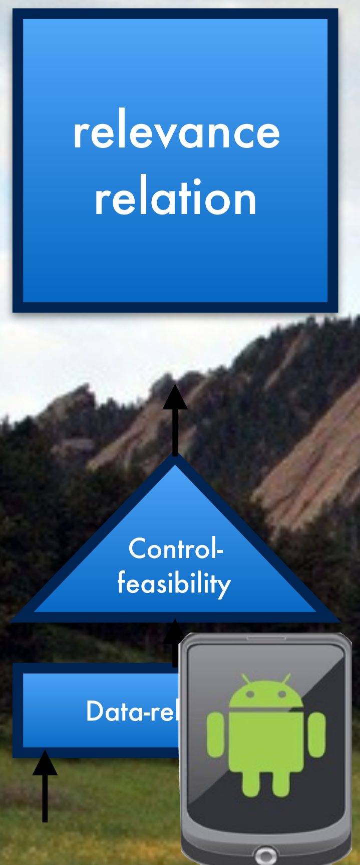
Selective control-flow abstraction via a sound relevance relation

Summary

Selective control-flow abstraction via a sound relevance relation



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



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
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PLV


Cerny


Chang


Hammer


Sankaranaryananan


Somenzi

Goal-directed:
abstraction-refinement versus abstraction-coarsening

staged abstraction refinement
(e.g., CEGAR)

on-the-fly abstraction
coarsening

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abstraction-refinement versus abstraction-coarsening

staged abstraction refinement
(e.g., CEGAR)

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.

Goal-directed: abstraction-refinement versus abstraction-coarsening

staged abstraction refinement
(e.g., CEGAR)

Staged

Run analysis multiple times, abstraction changes only between runs.

Refinement

Start with imprecise abstraction,
become more precise.

on-the-fly abstraction
coarsening

On-the-fly

Run analysis once, abstraction changes during analysis.

Coarsening

Start with precise abstraction,
become less precise.