Scaling Automatic Modular Verification

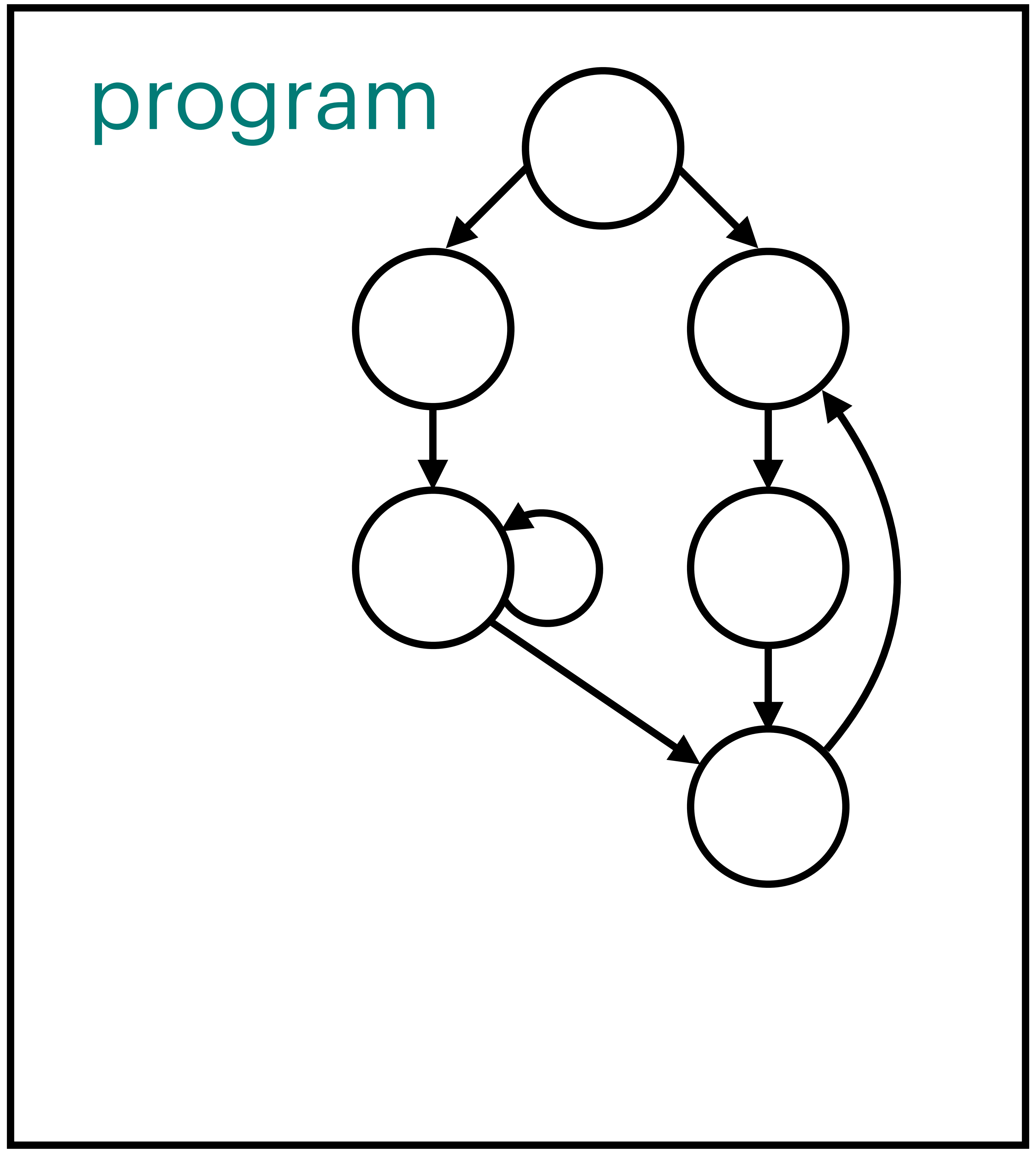
Lauren Pick

Automated Software Verification

verification problem

Automated Software Verification

verification problem



Automated Software Verification

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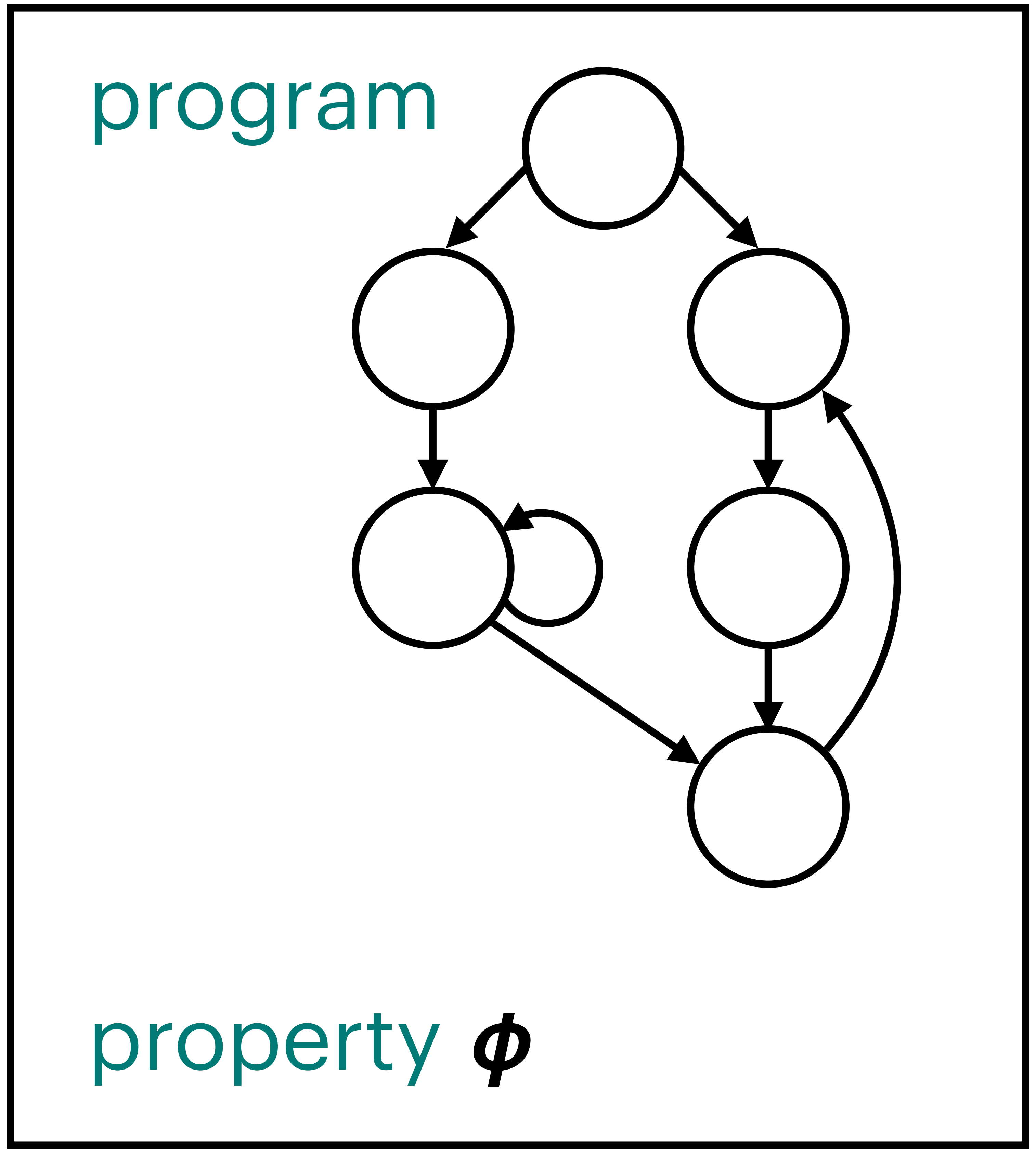

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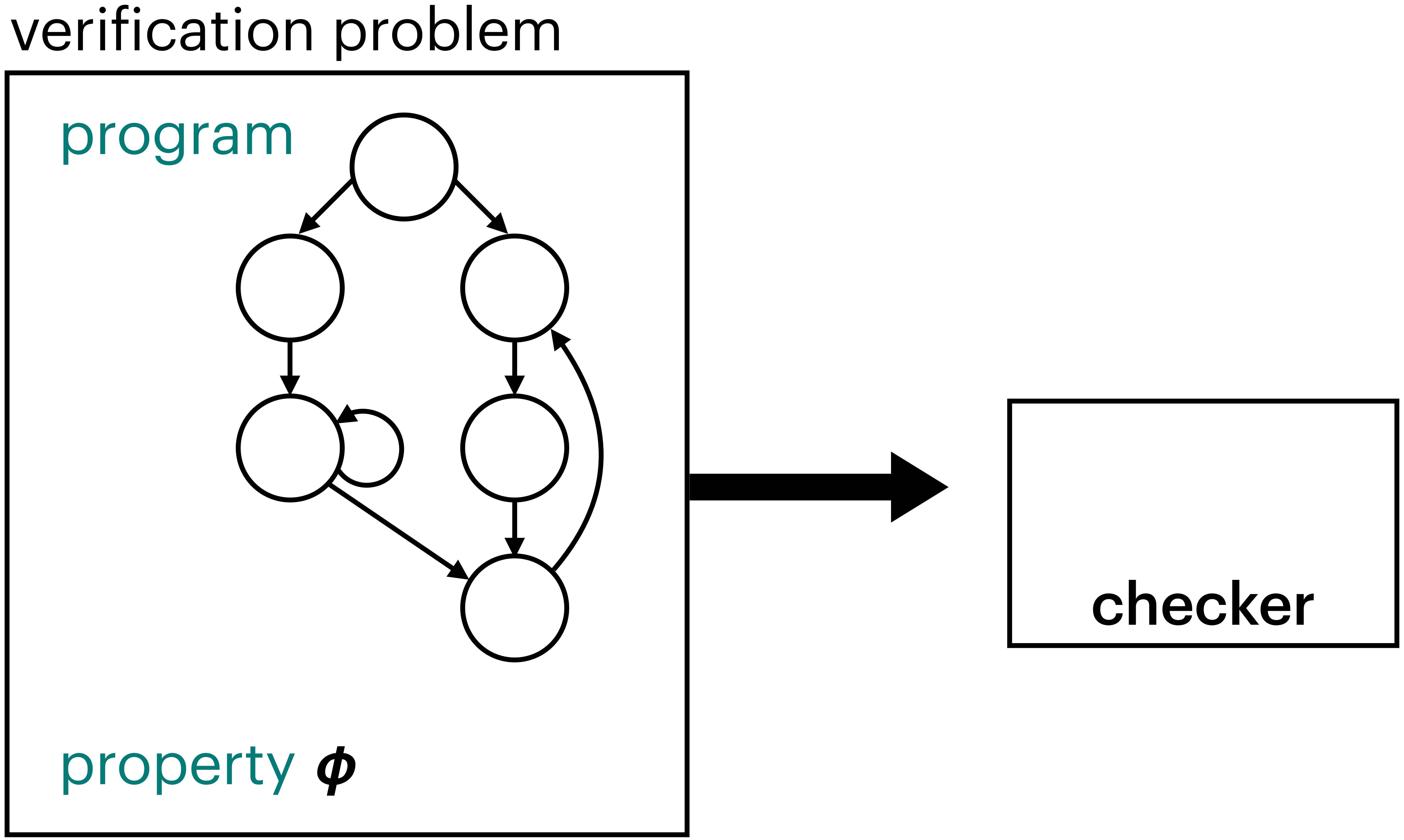

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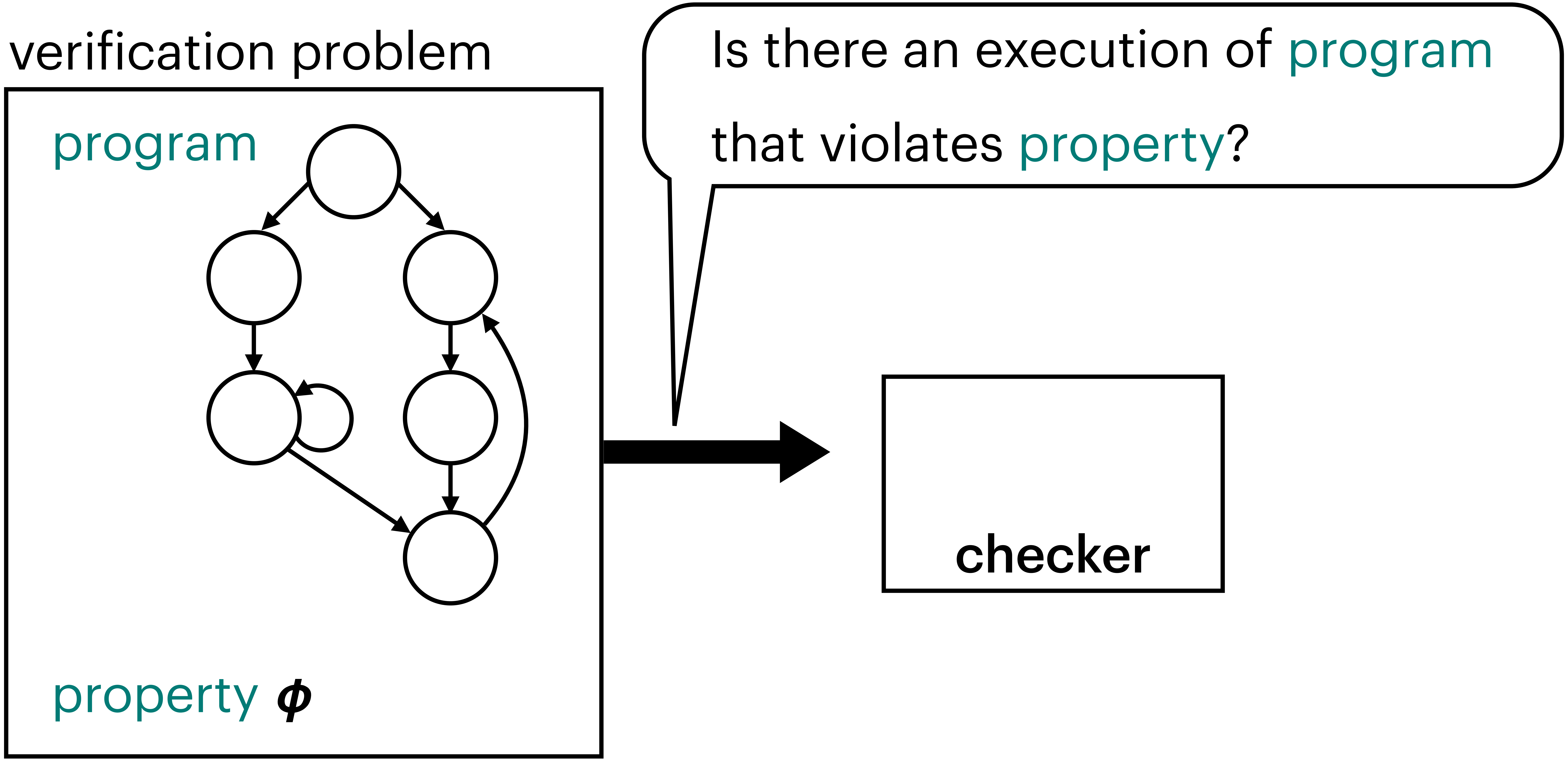

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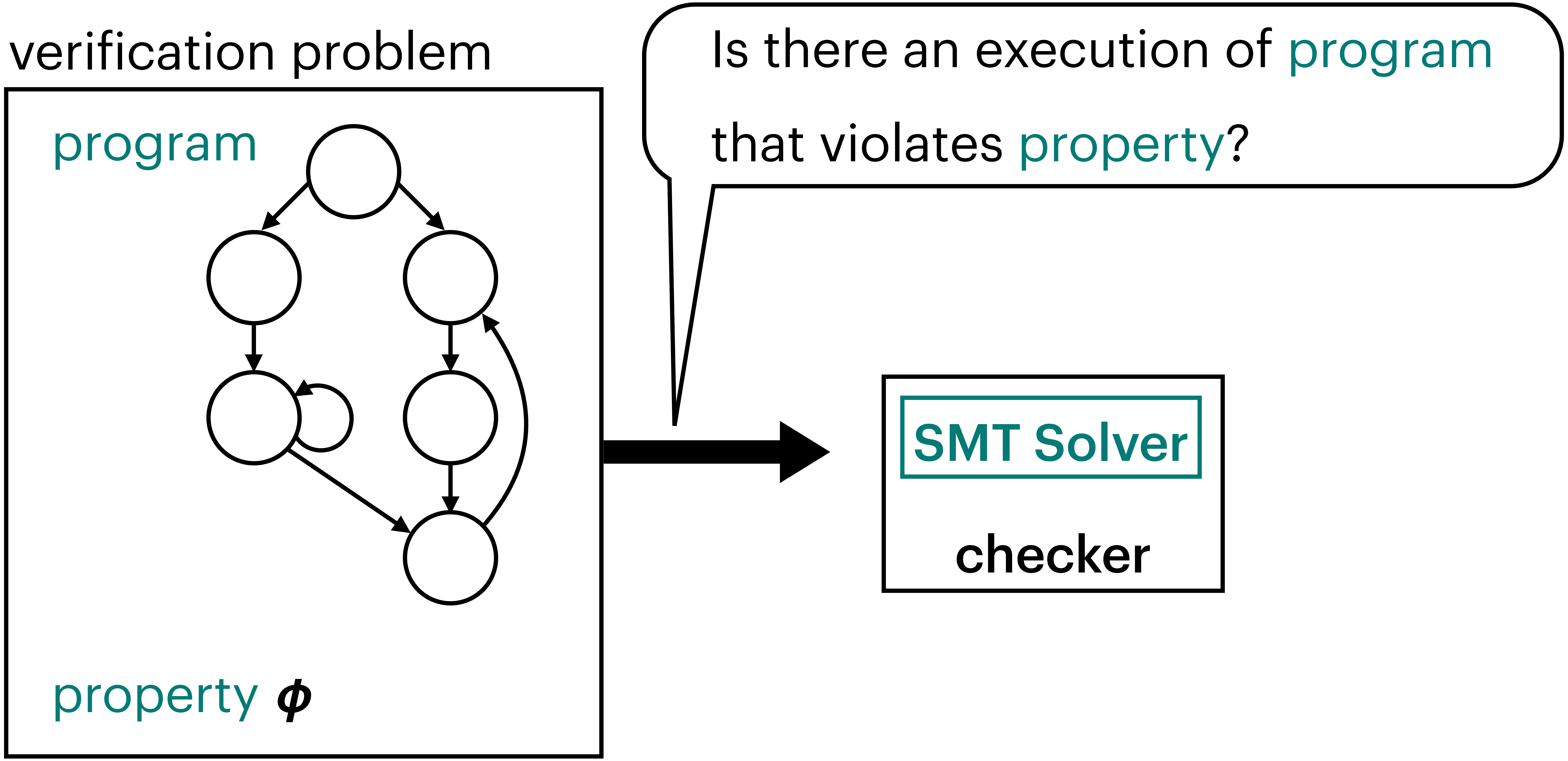

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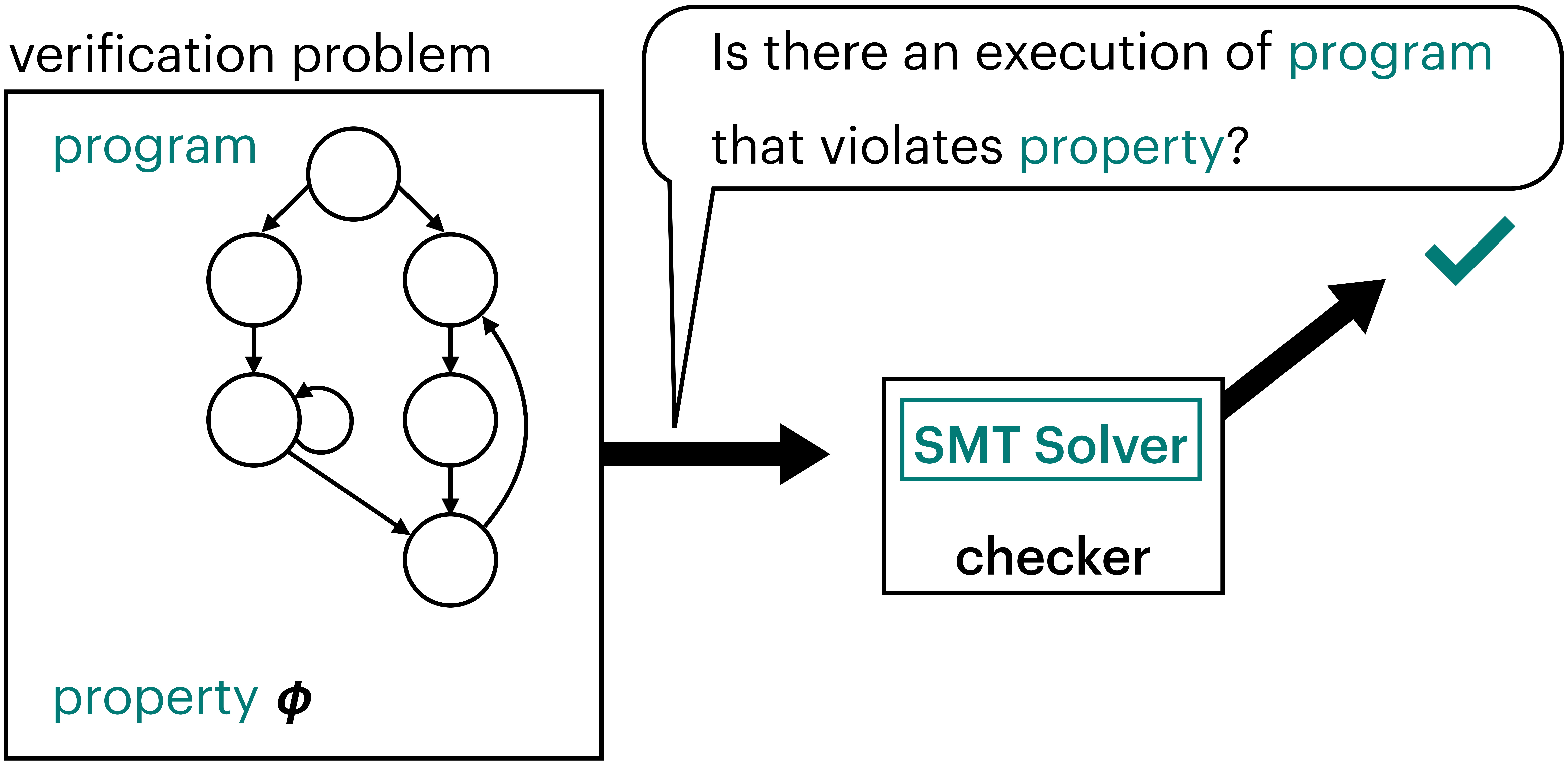

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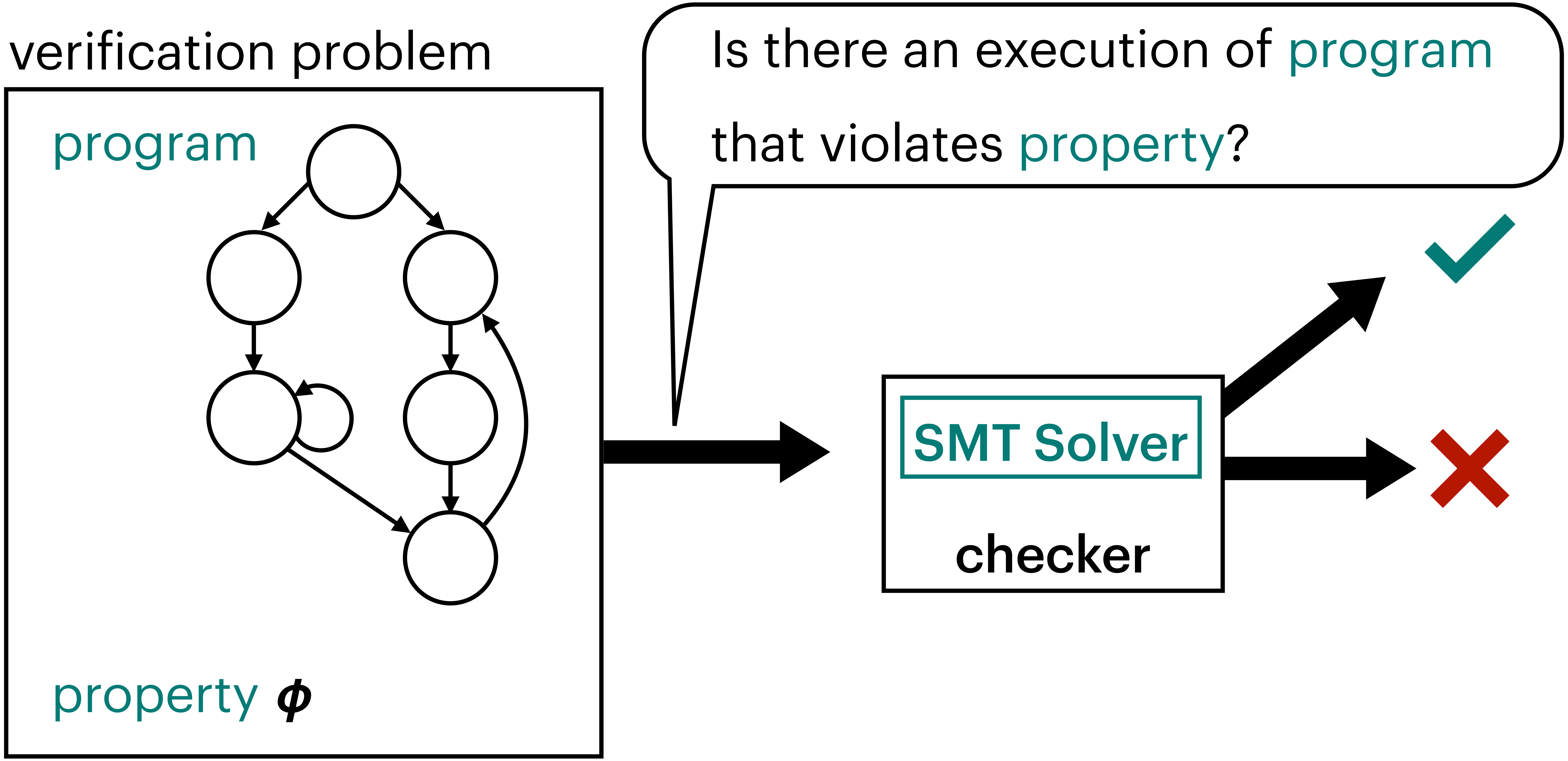

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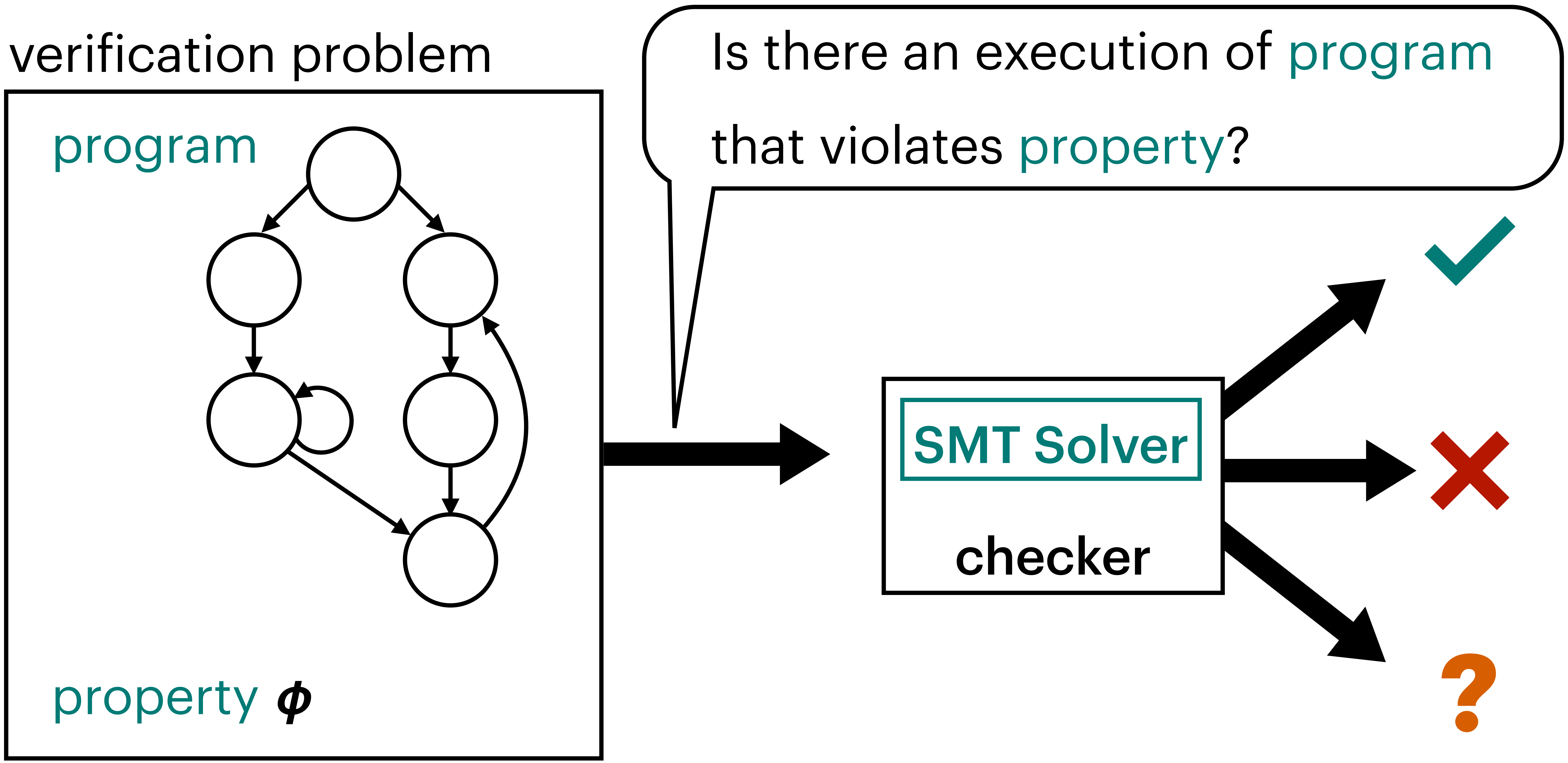

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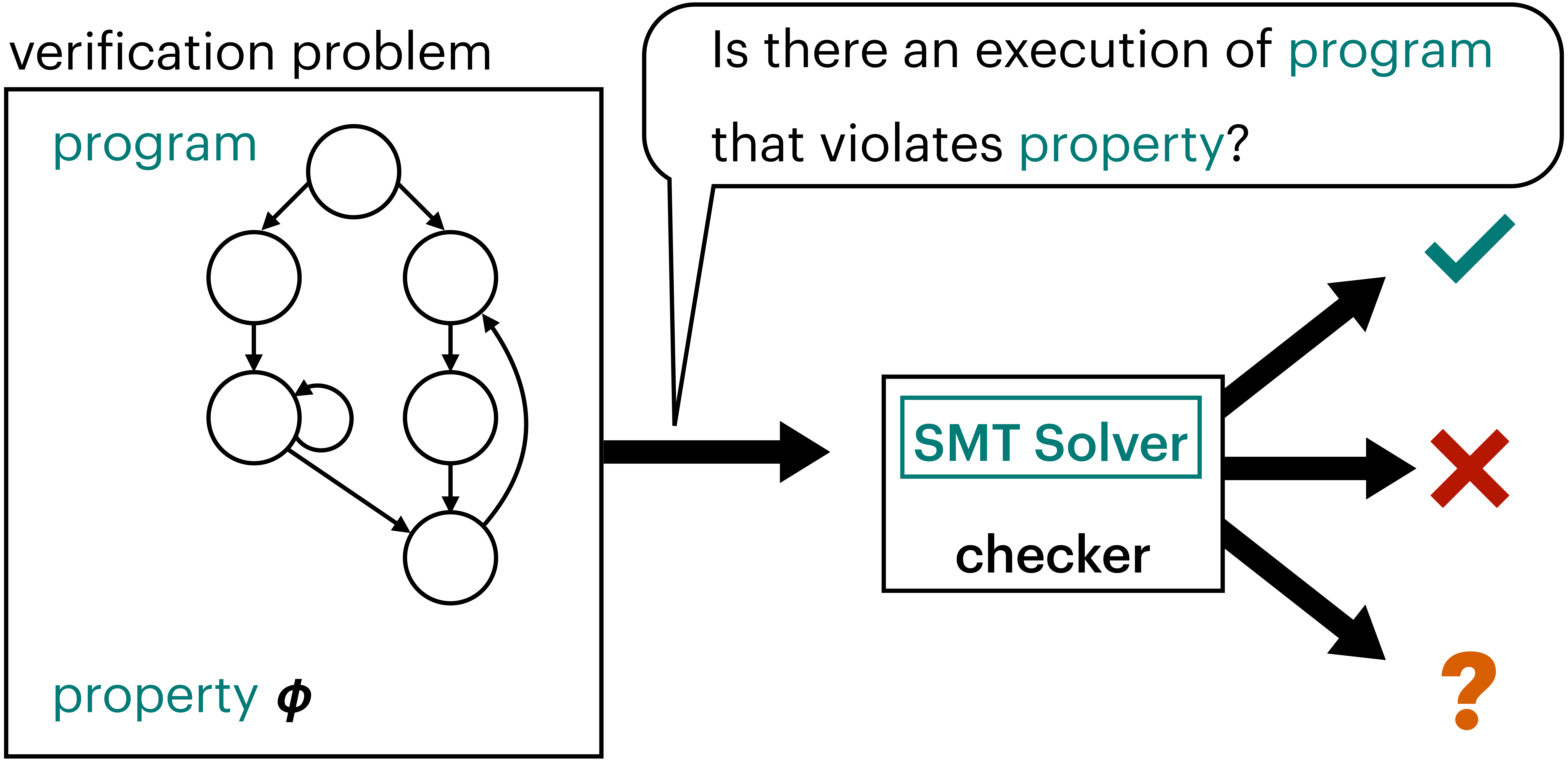

Undecidable in general.

Satisfiability Modulo Theories (SMT) Solvers

SMT Solver

Satisfiability Modulo Theories (SMT) Solvers

formula $\boldsymbol{\phi}$ → **SMT Solver**

Satisfiability Modulo Theories (SMT) Solvers

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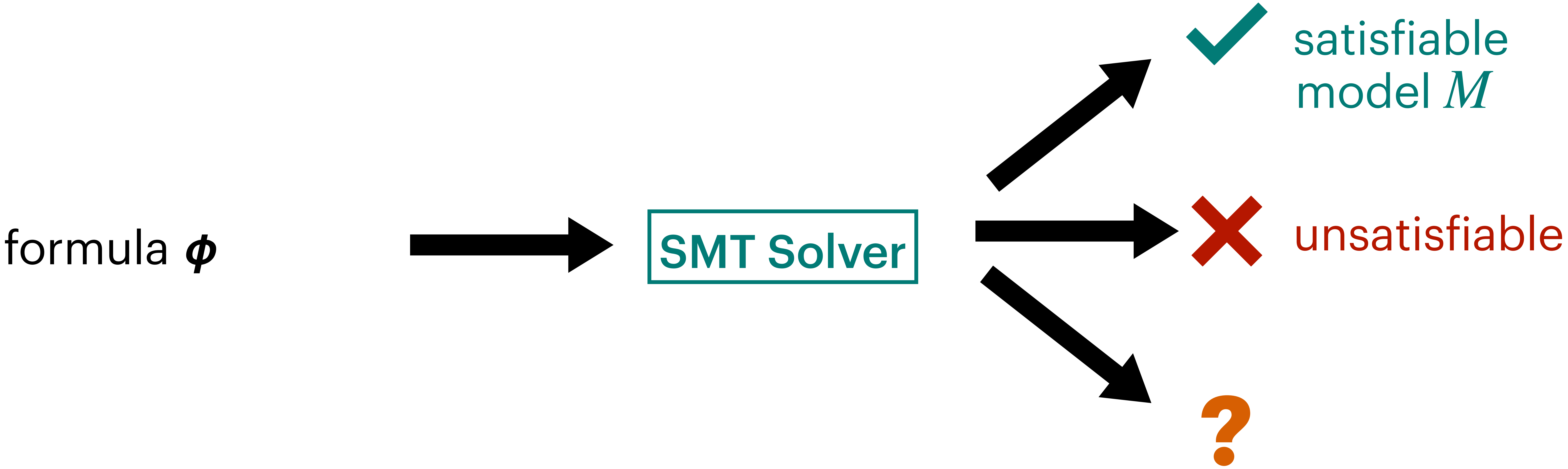

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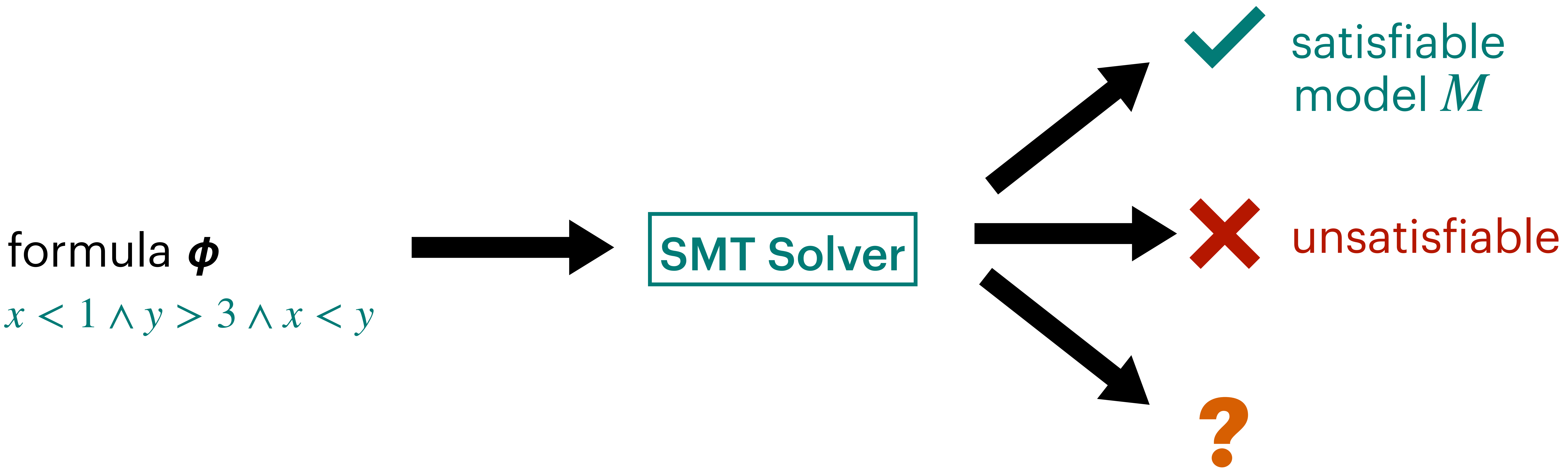

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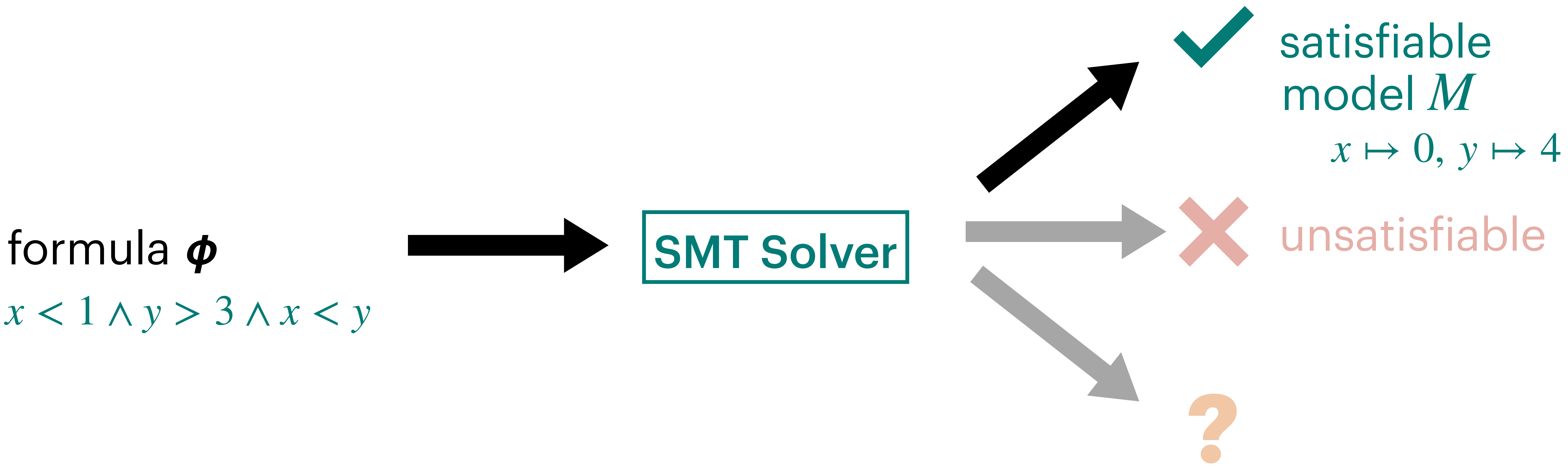

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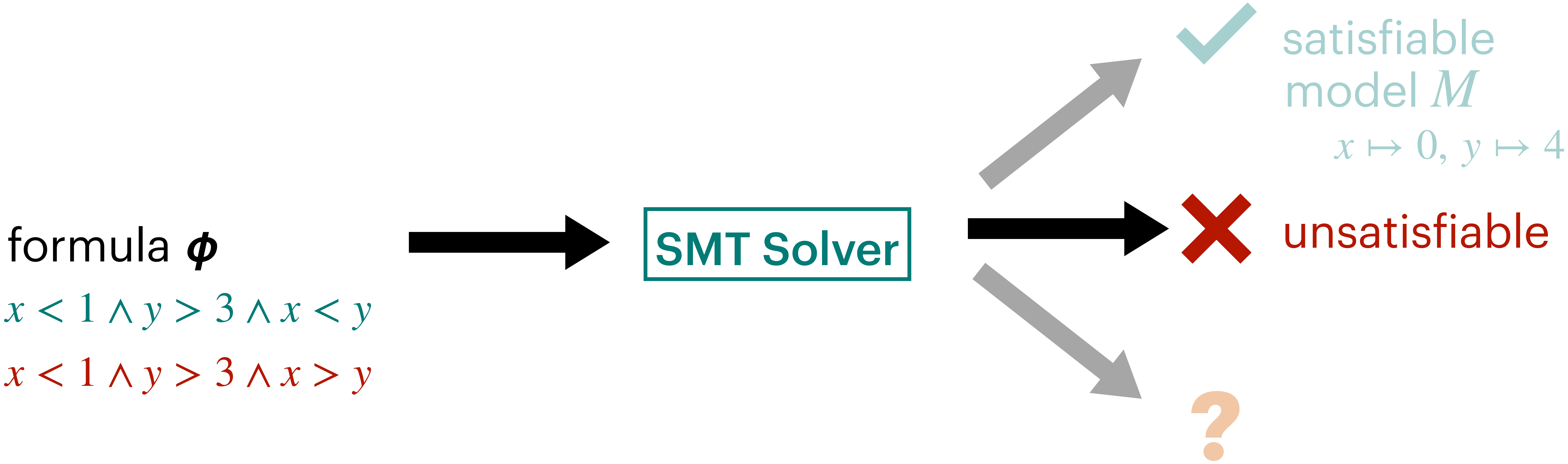

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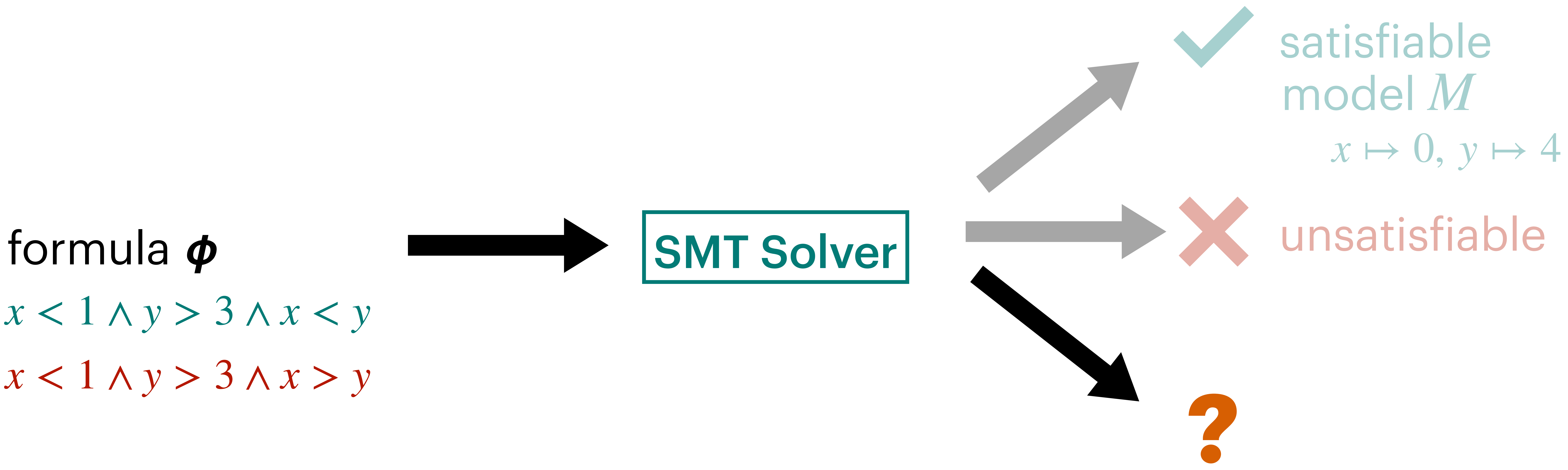

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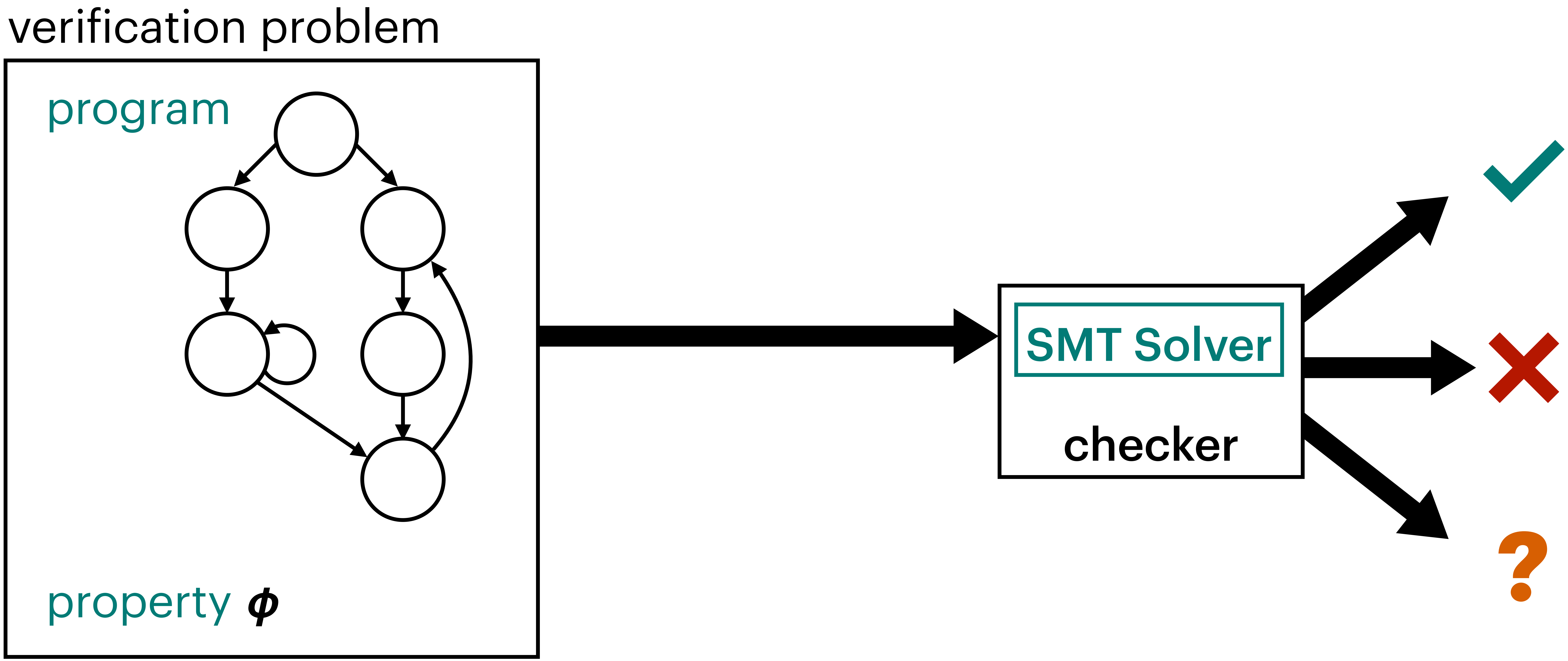

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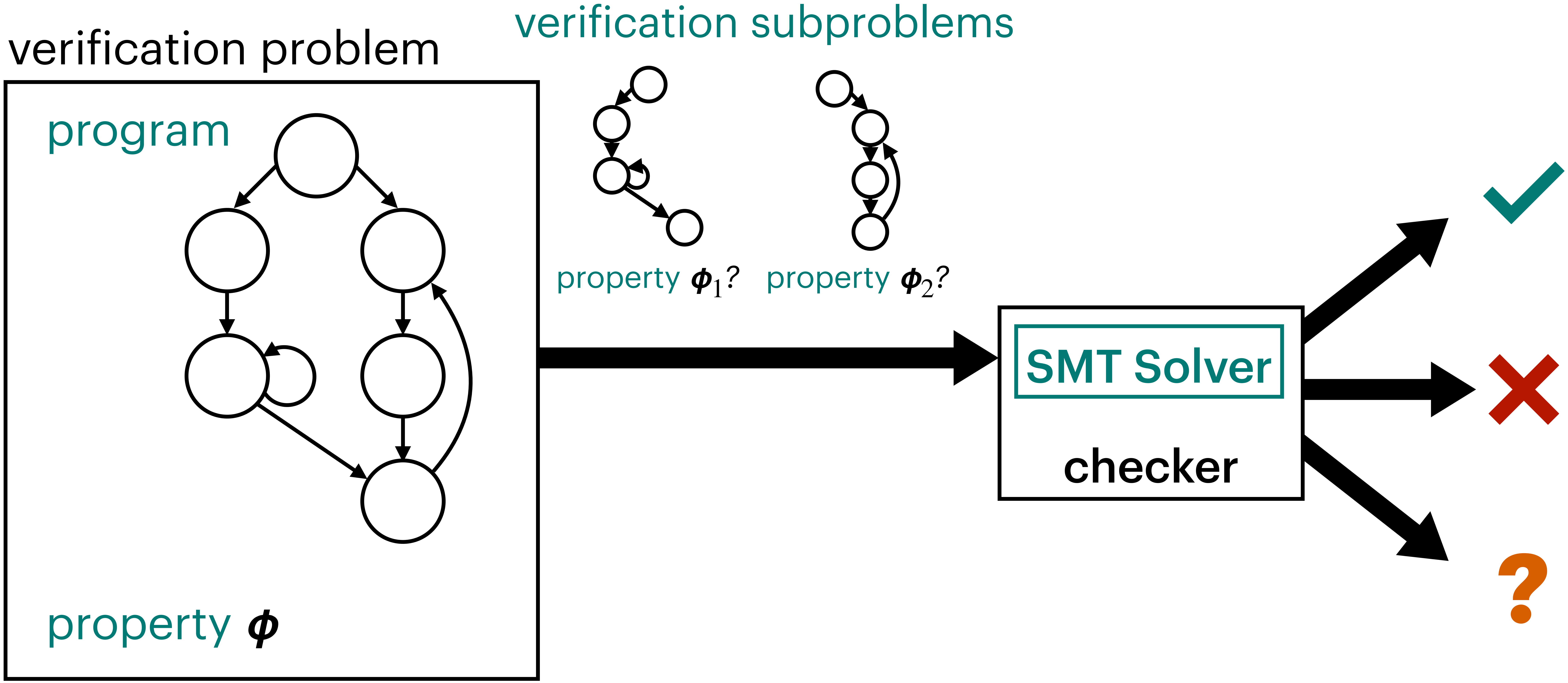

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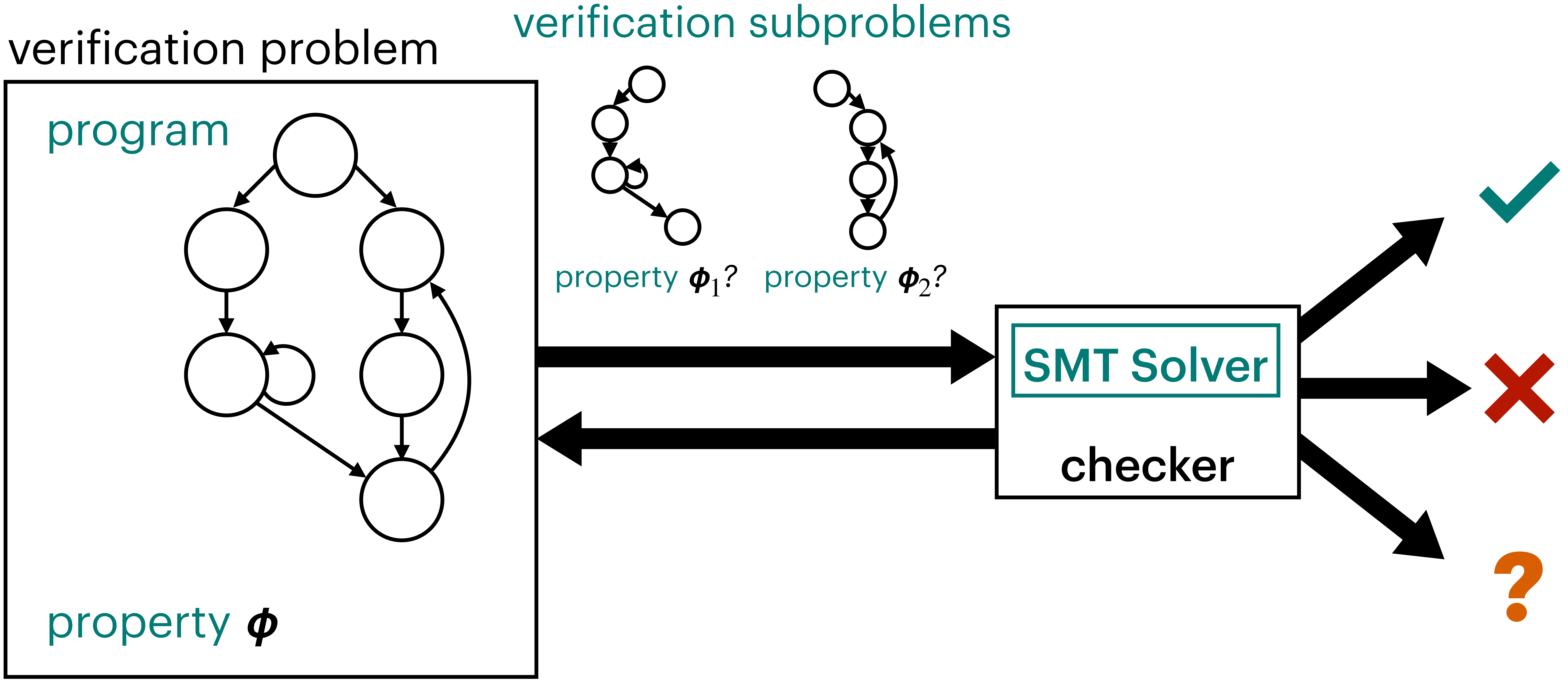

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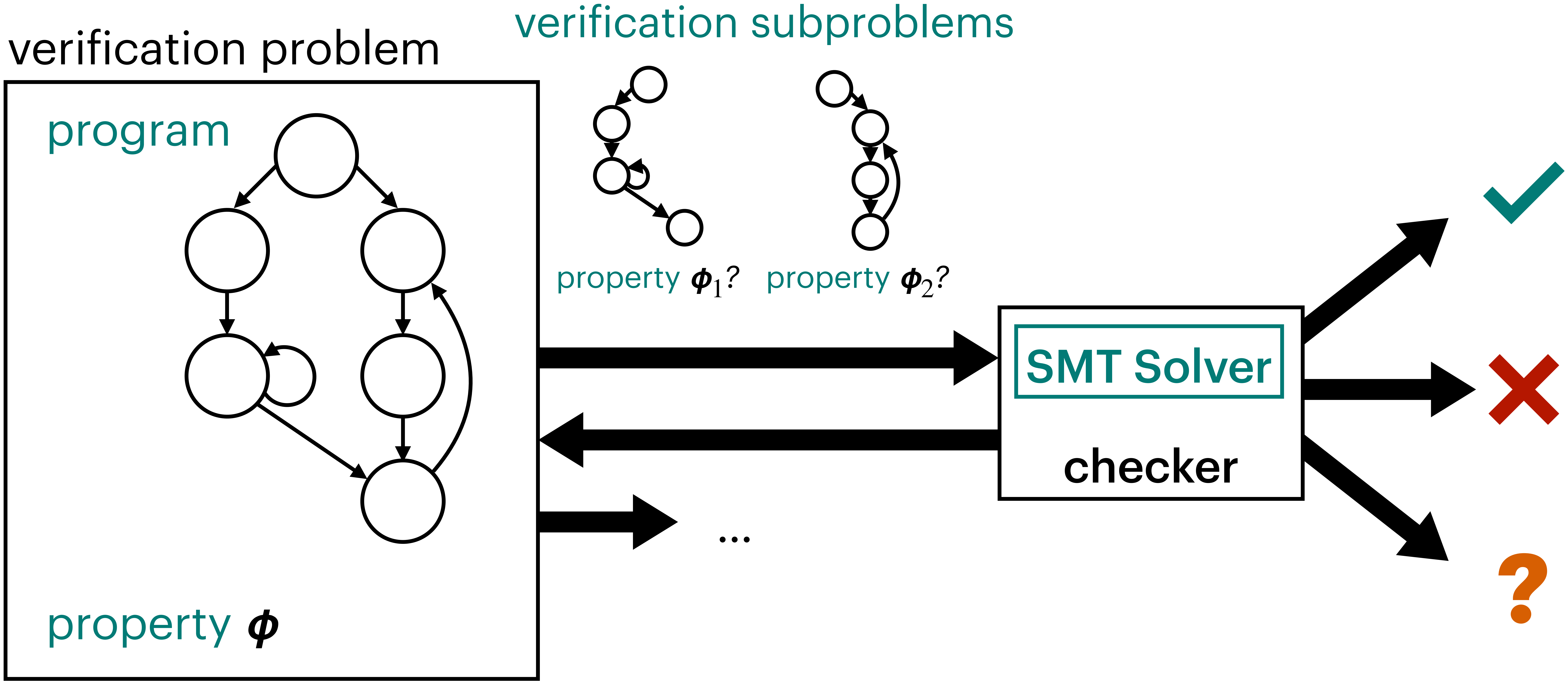

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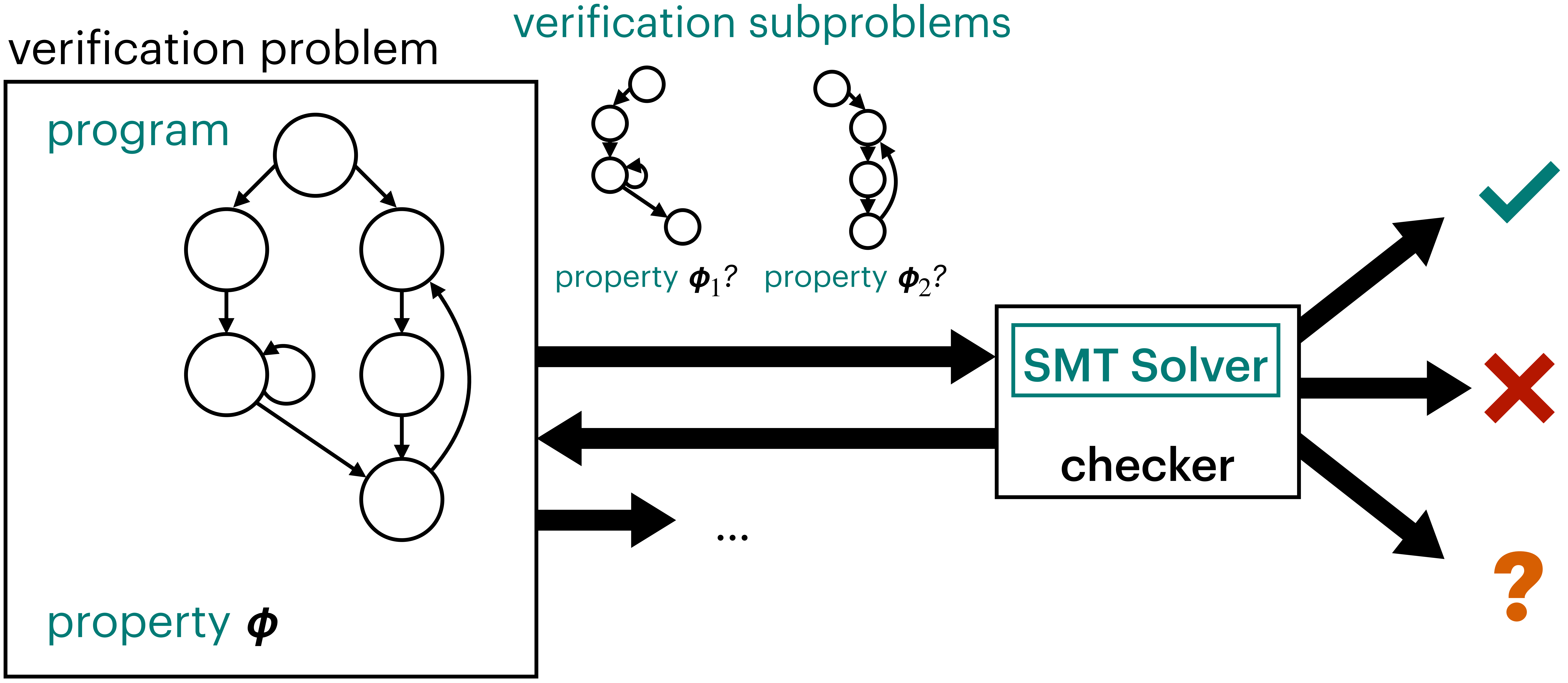

Verification subproblems can involve discovery of inductive invariants

Verification of Transition Systems

For a transition system $(S, T, Init)$:

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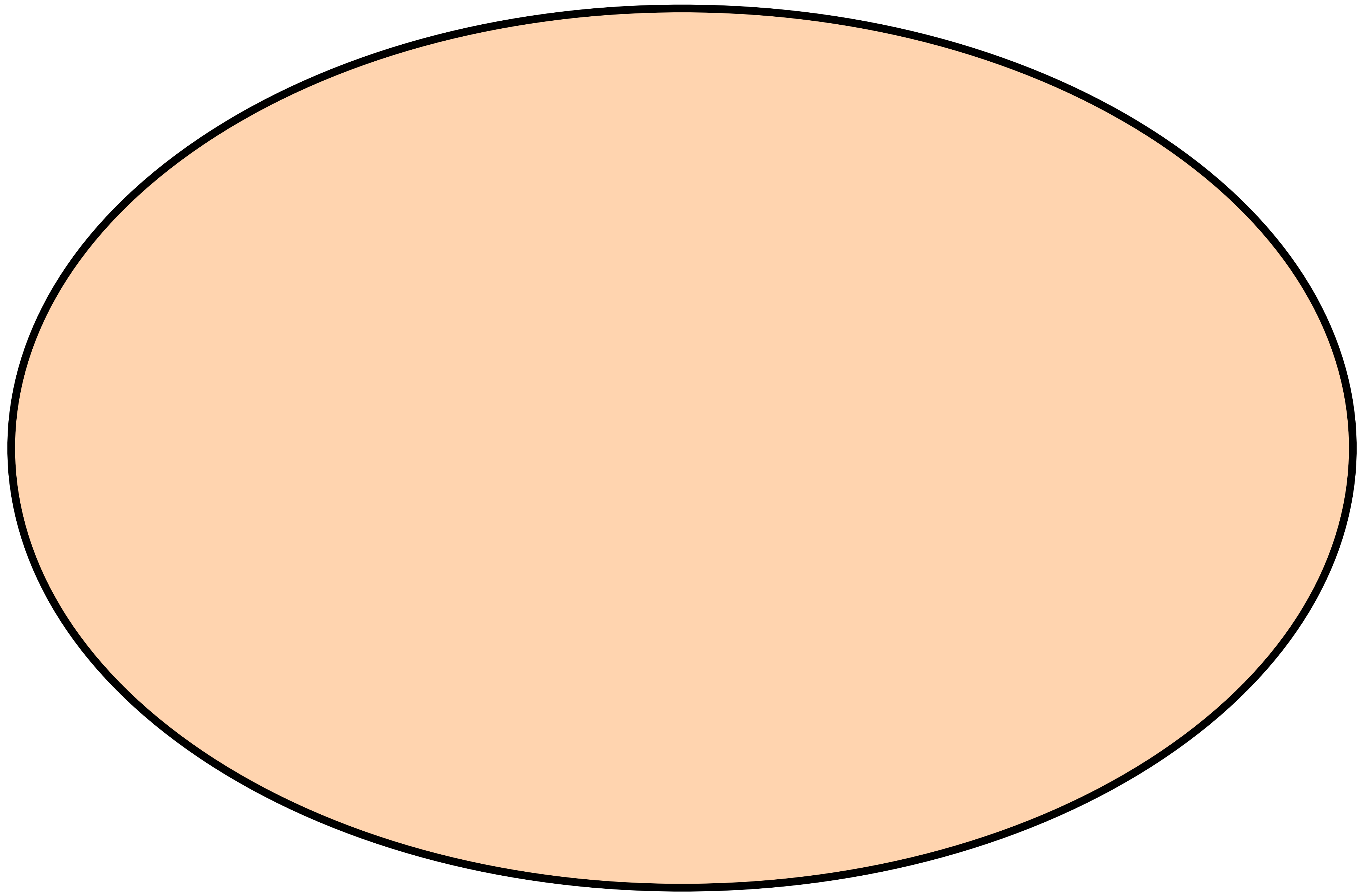

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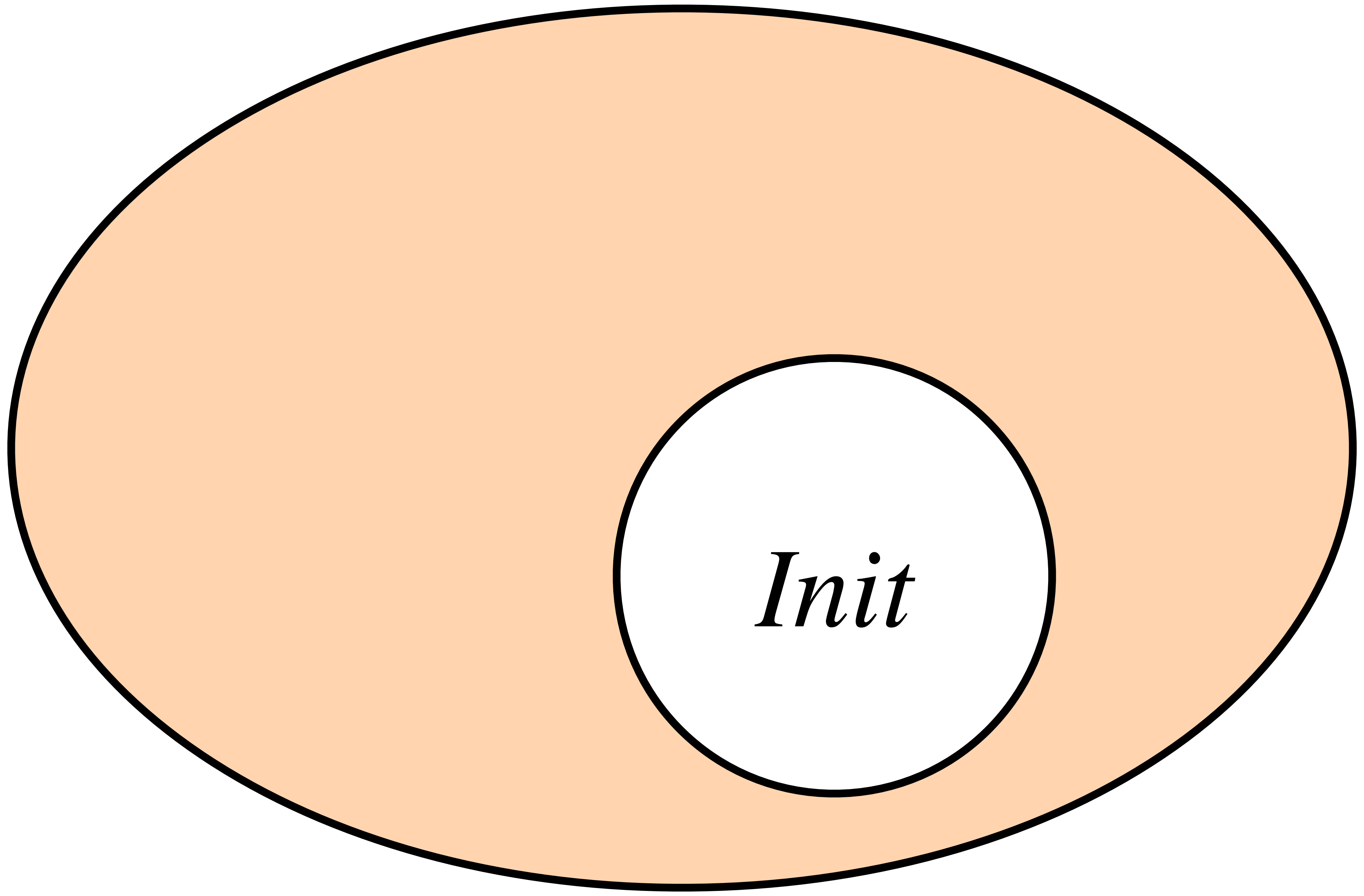

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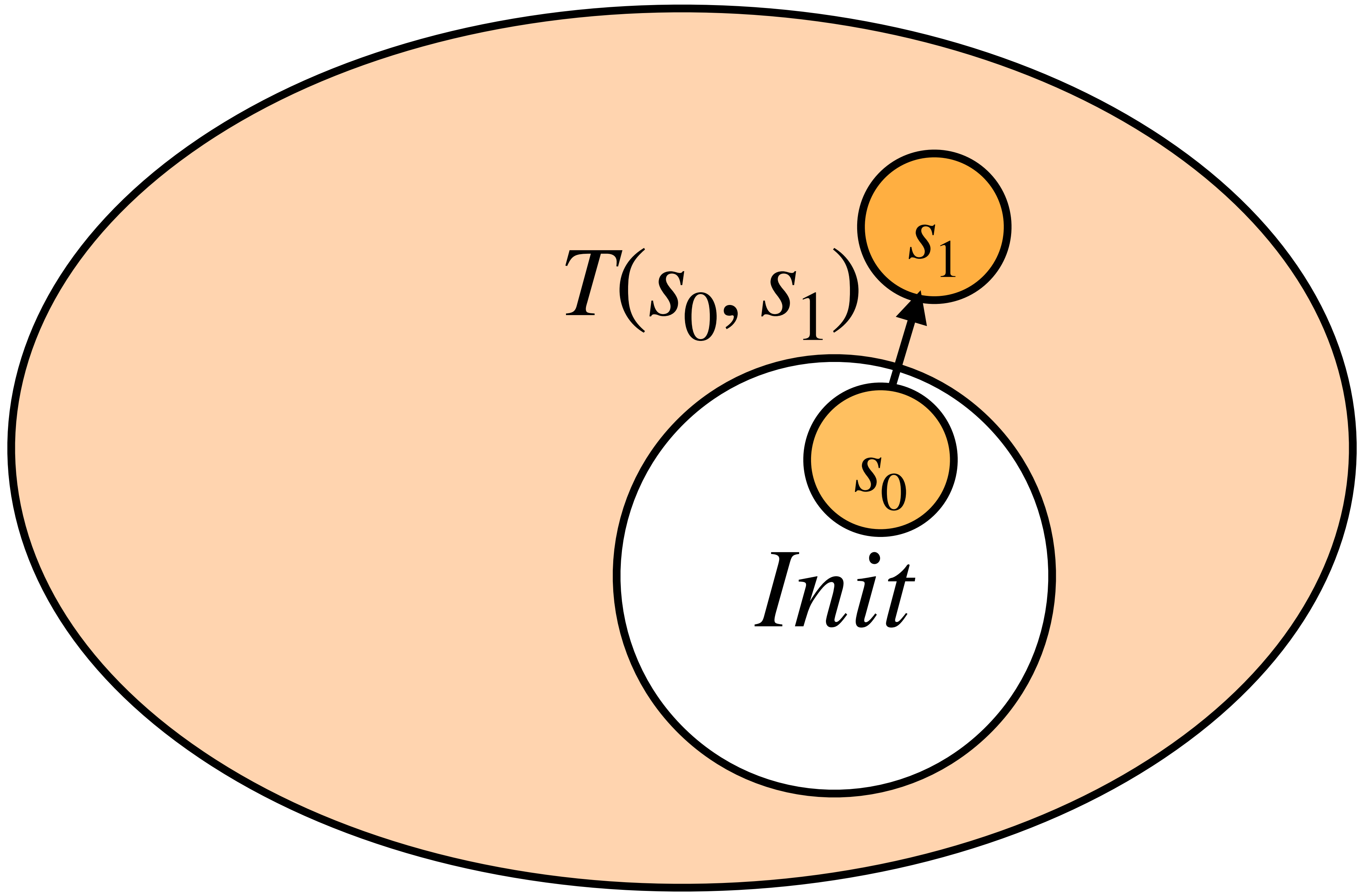

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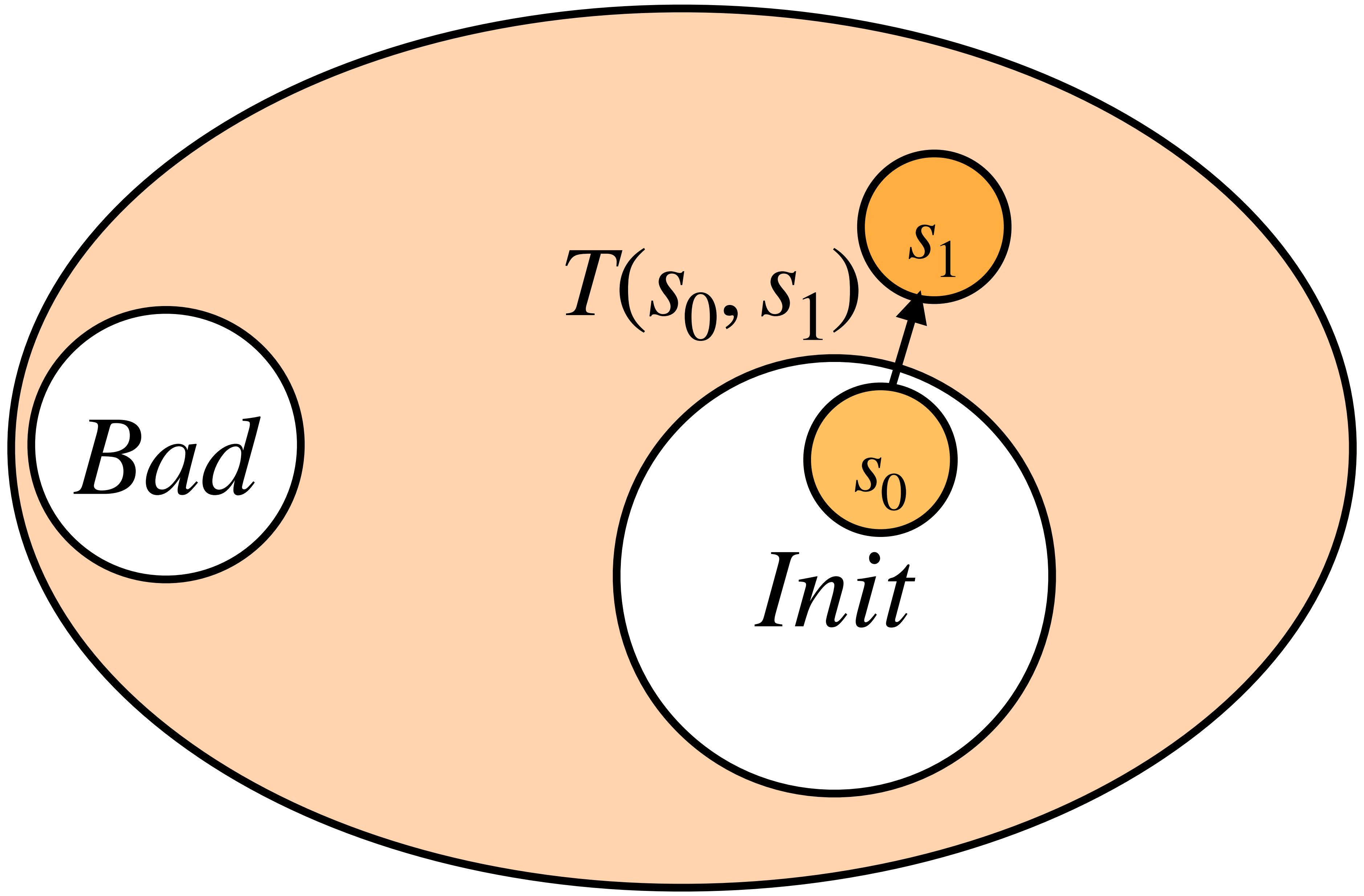

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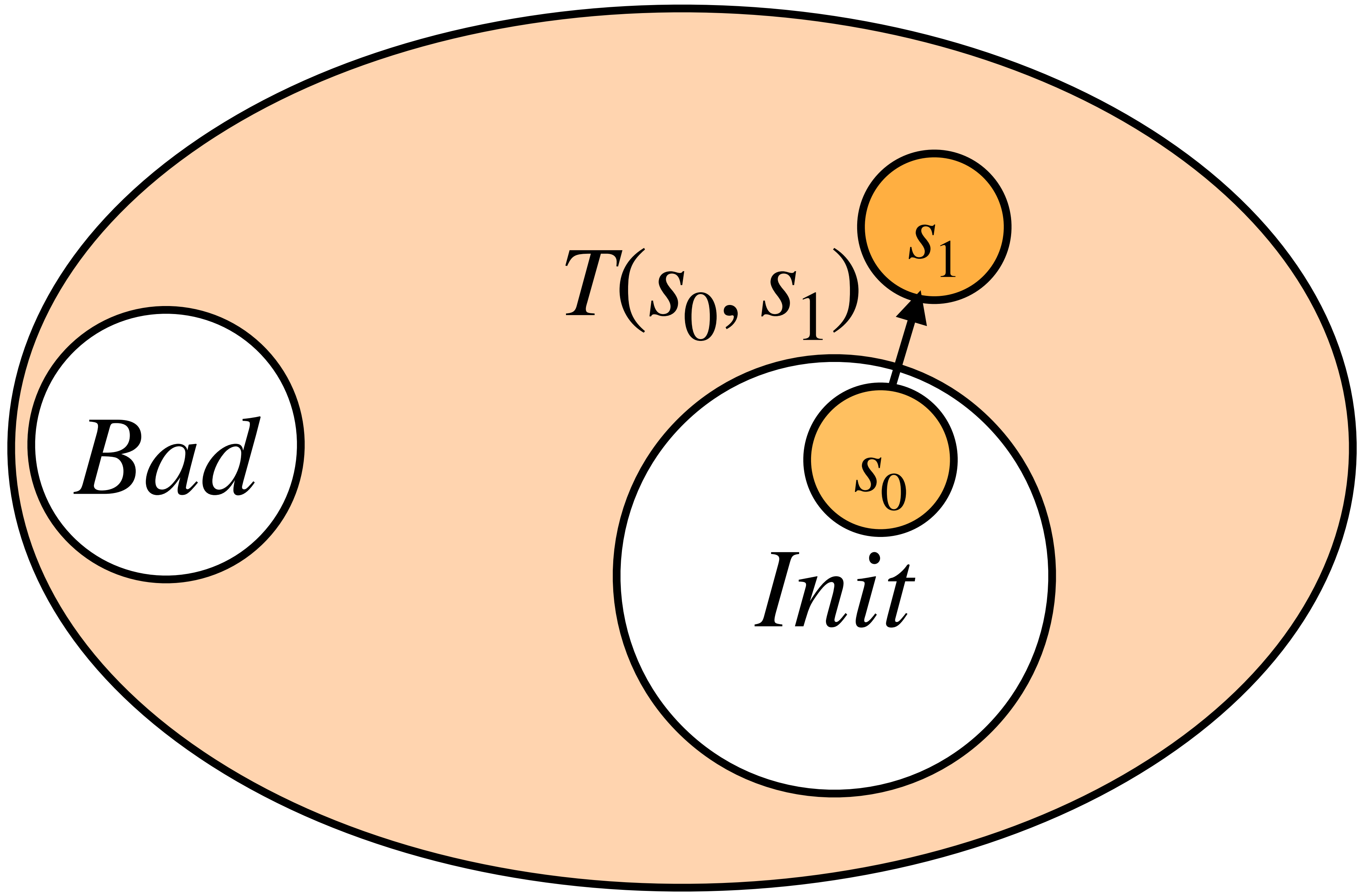

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Want to prove *safety property* that no Bad states are reachable from $Init$ states

Inductive Invariants for Transition Systems

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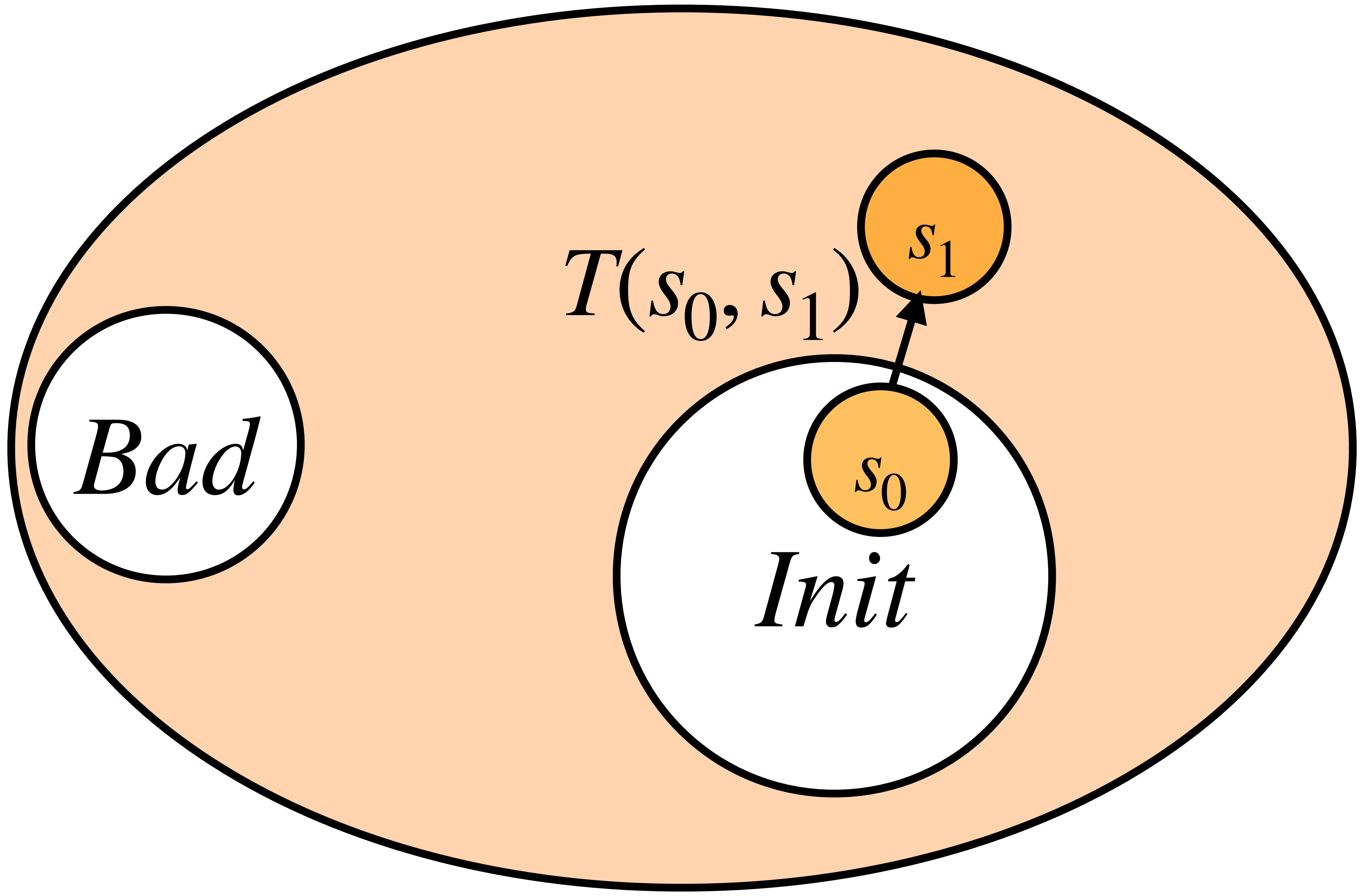

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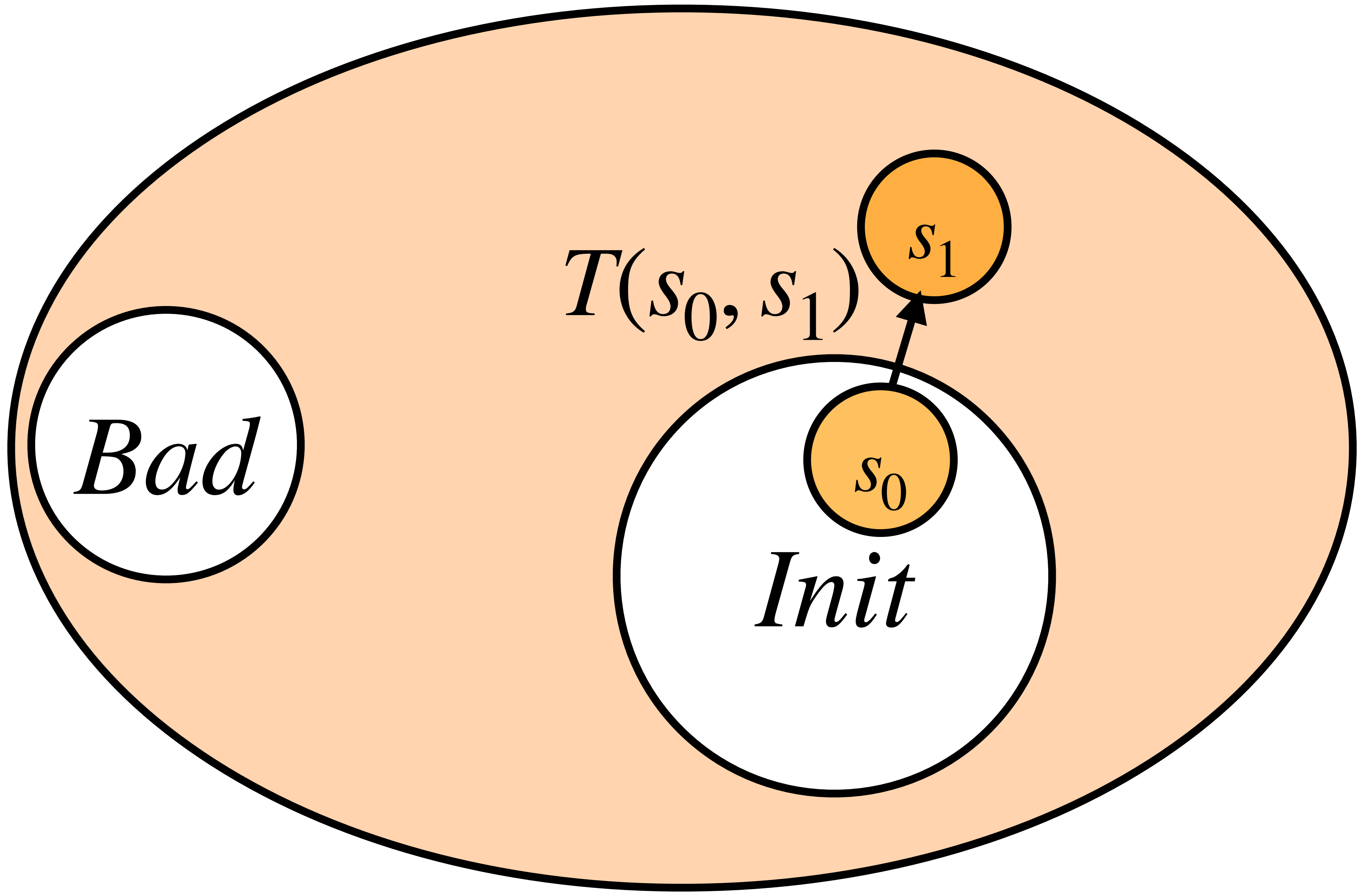

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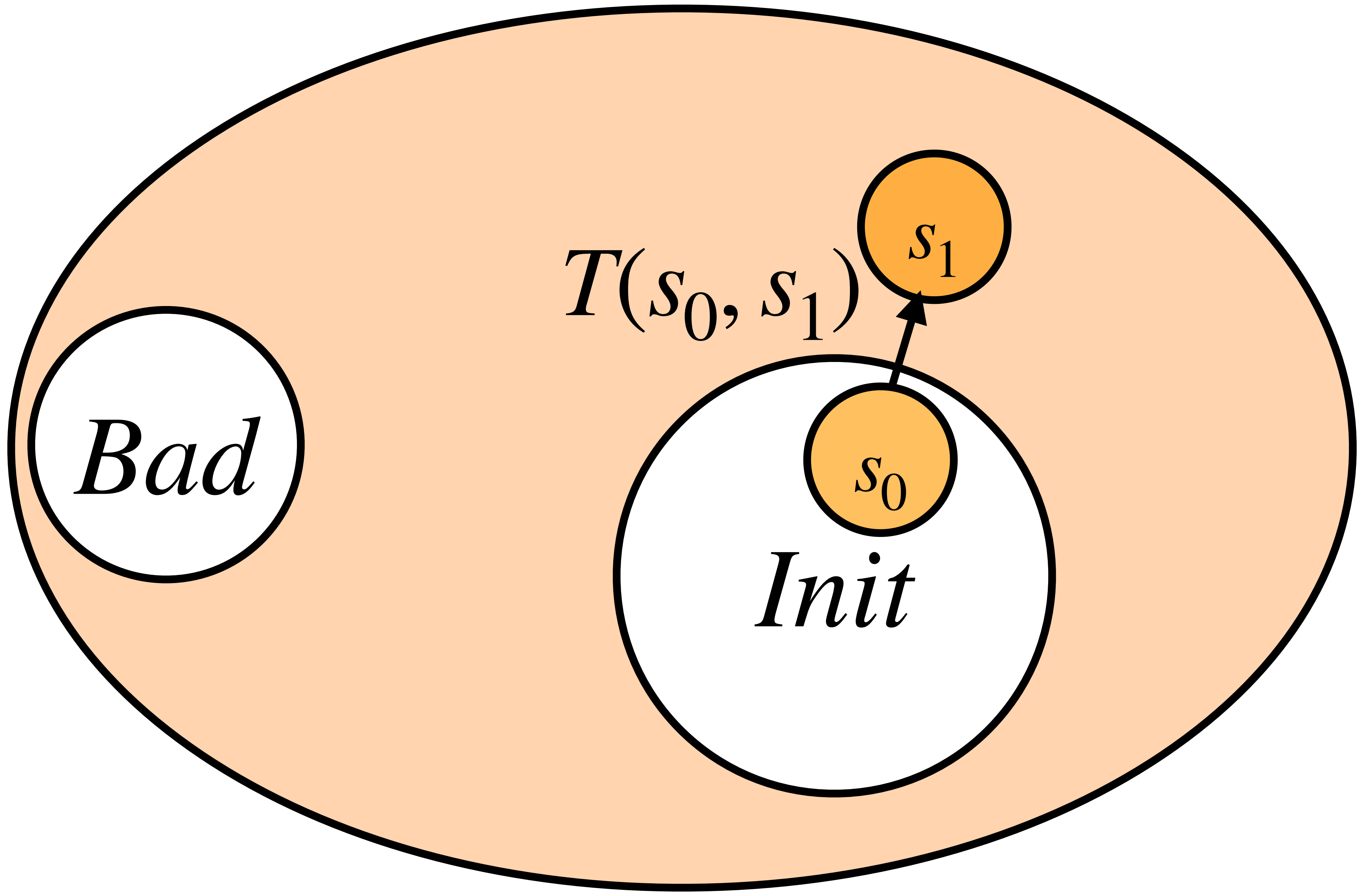

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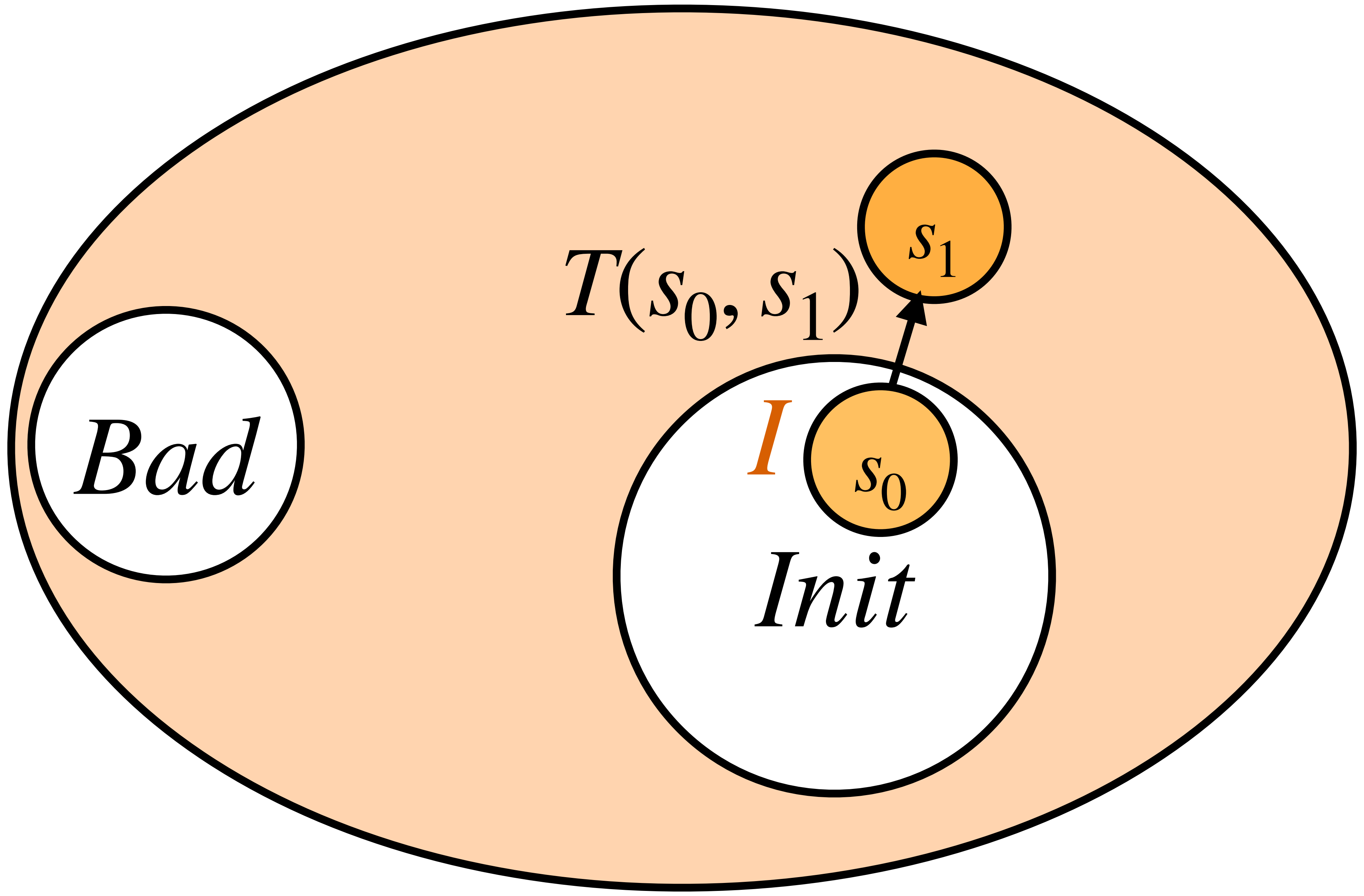

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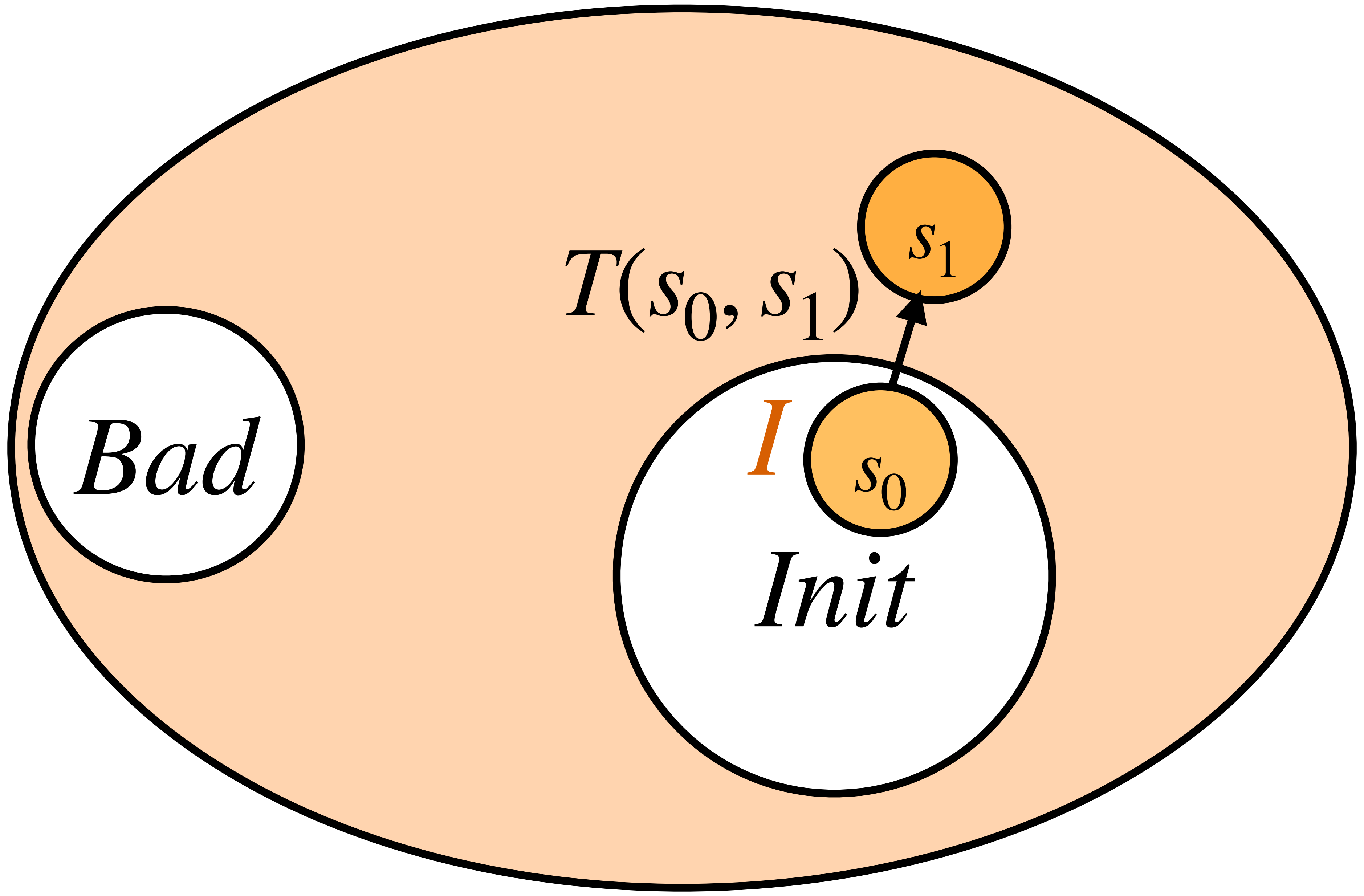

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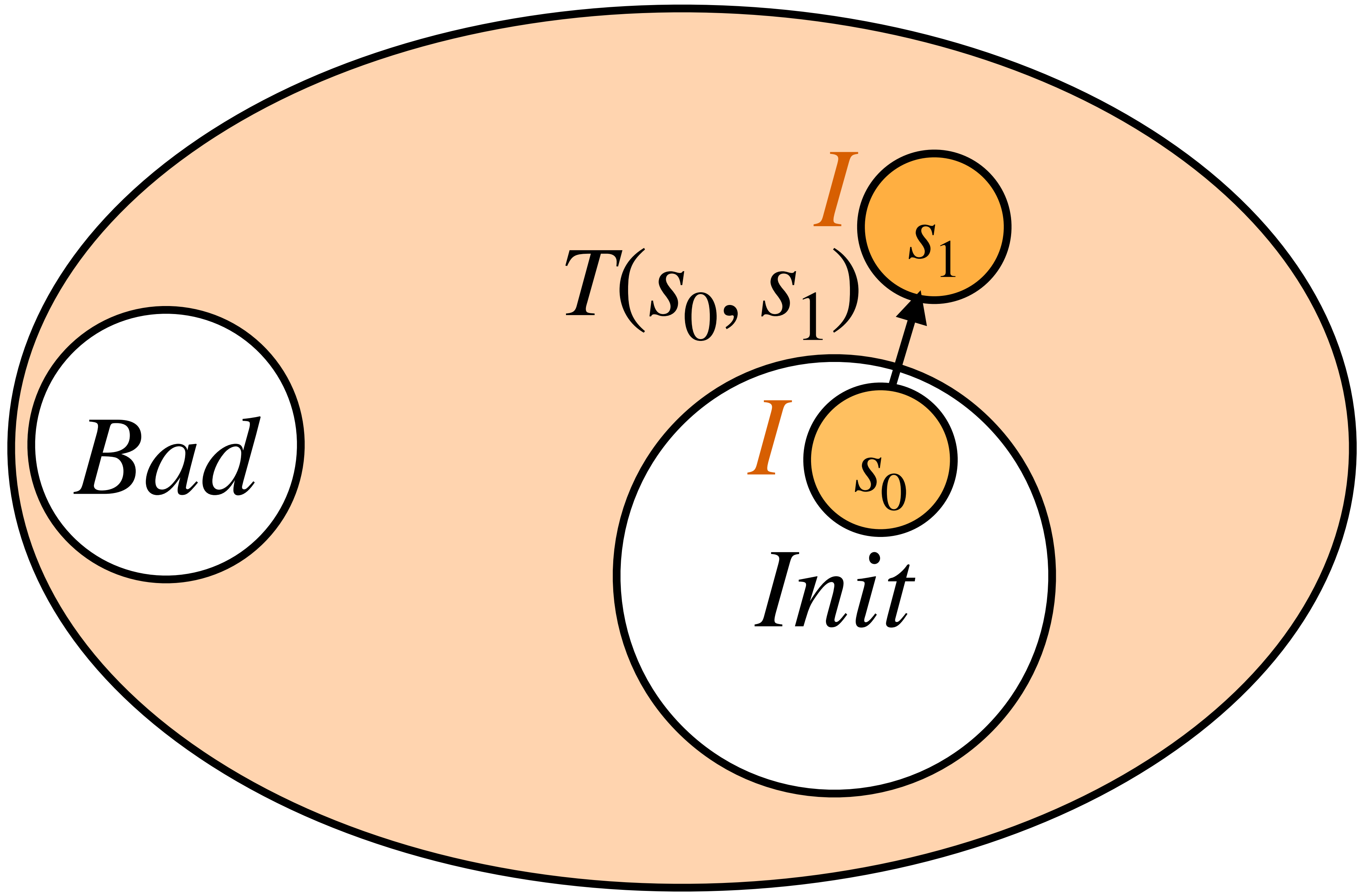

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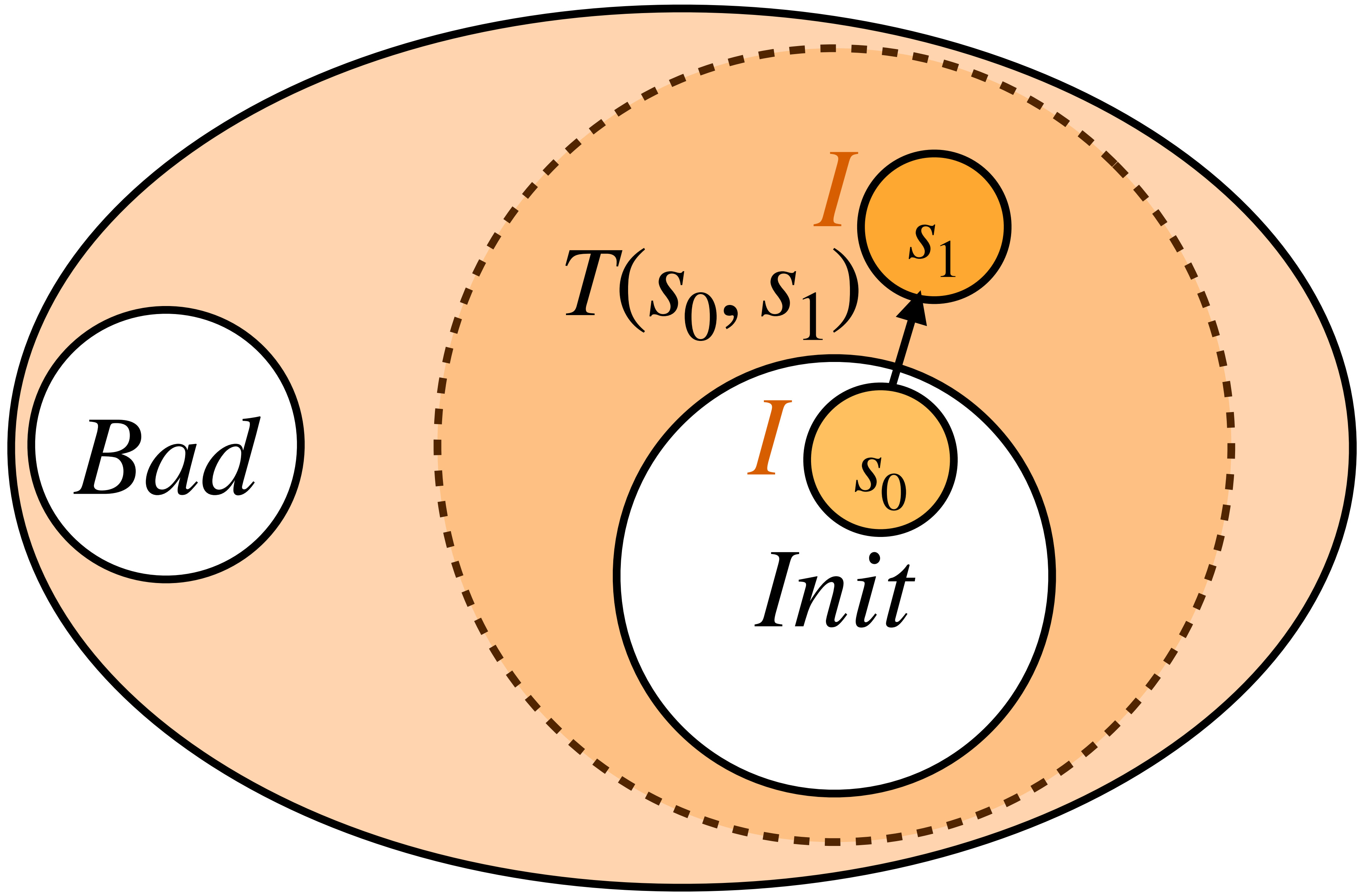

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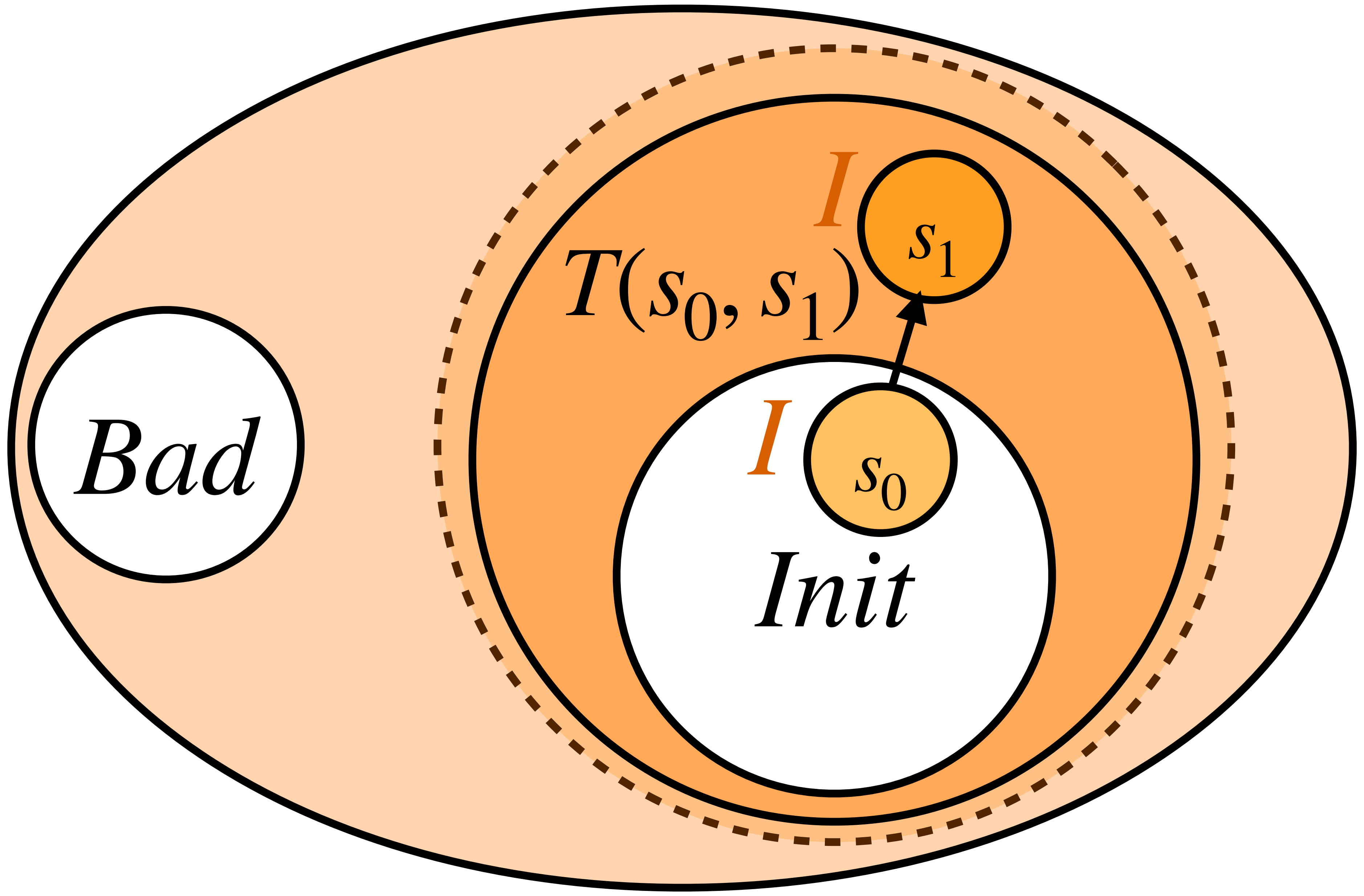

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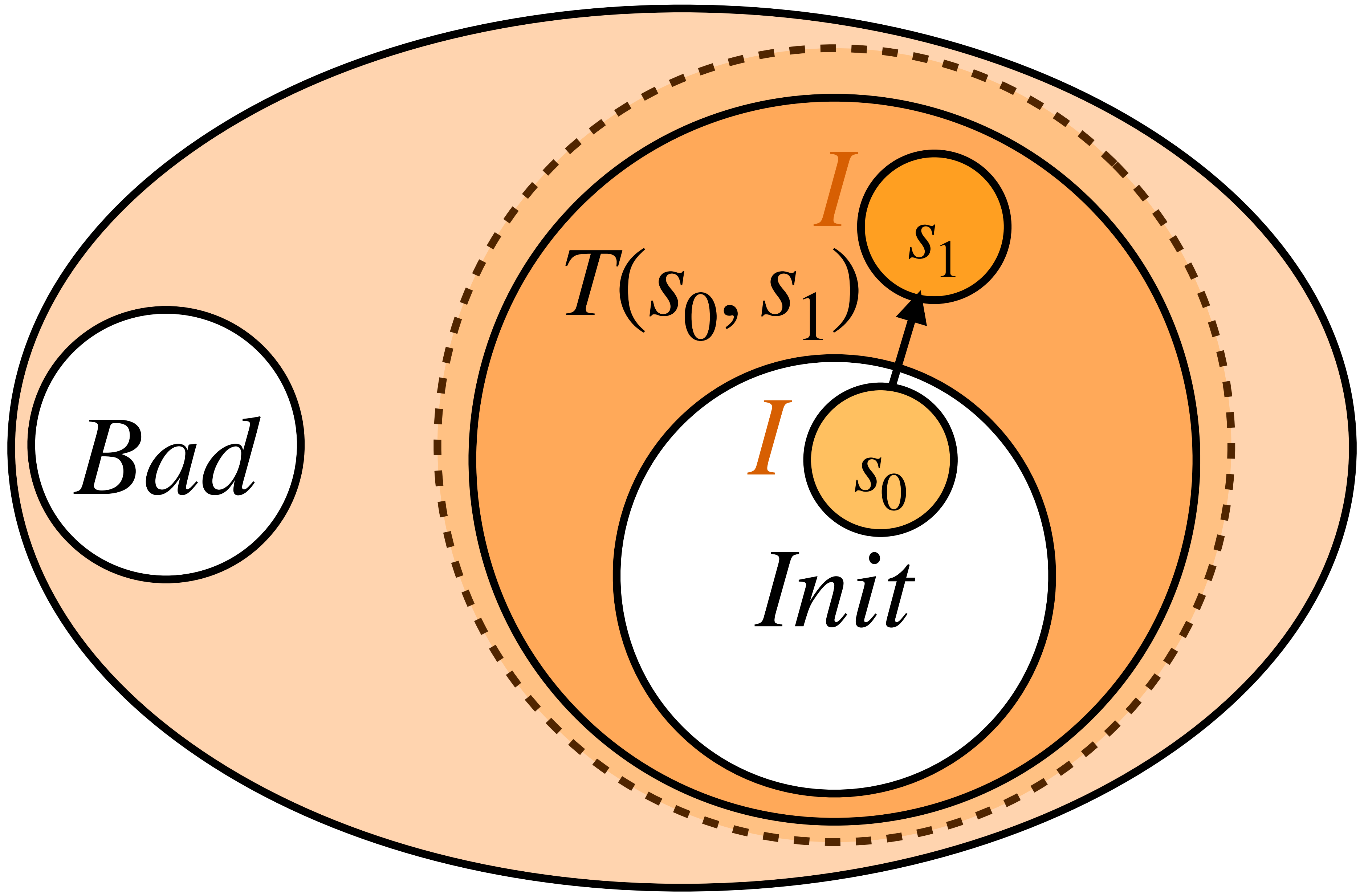

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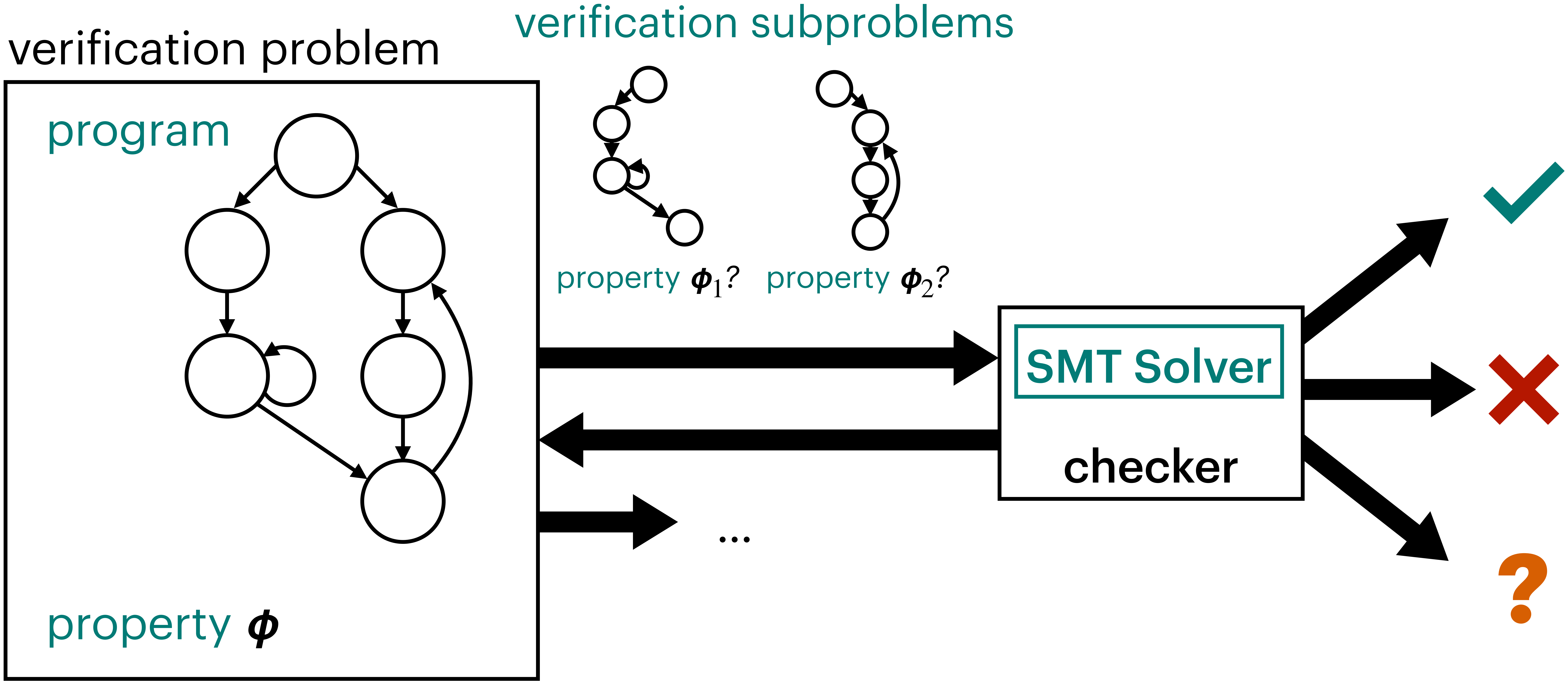
Can use invariants to help prove safety properties: $\forall s \in S \,.\, I(s) \Rightarrow \neg Bad(s)$

Automated Modular Verification



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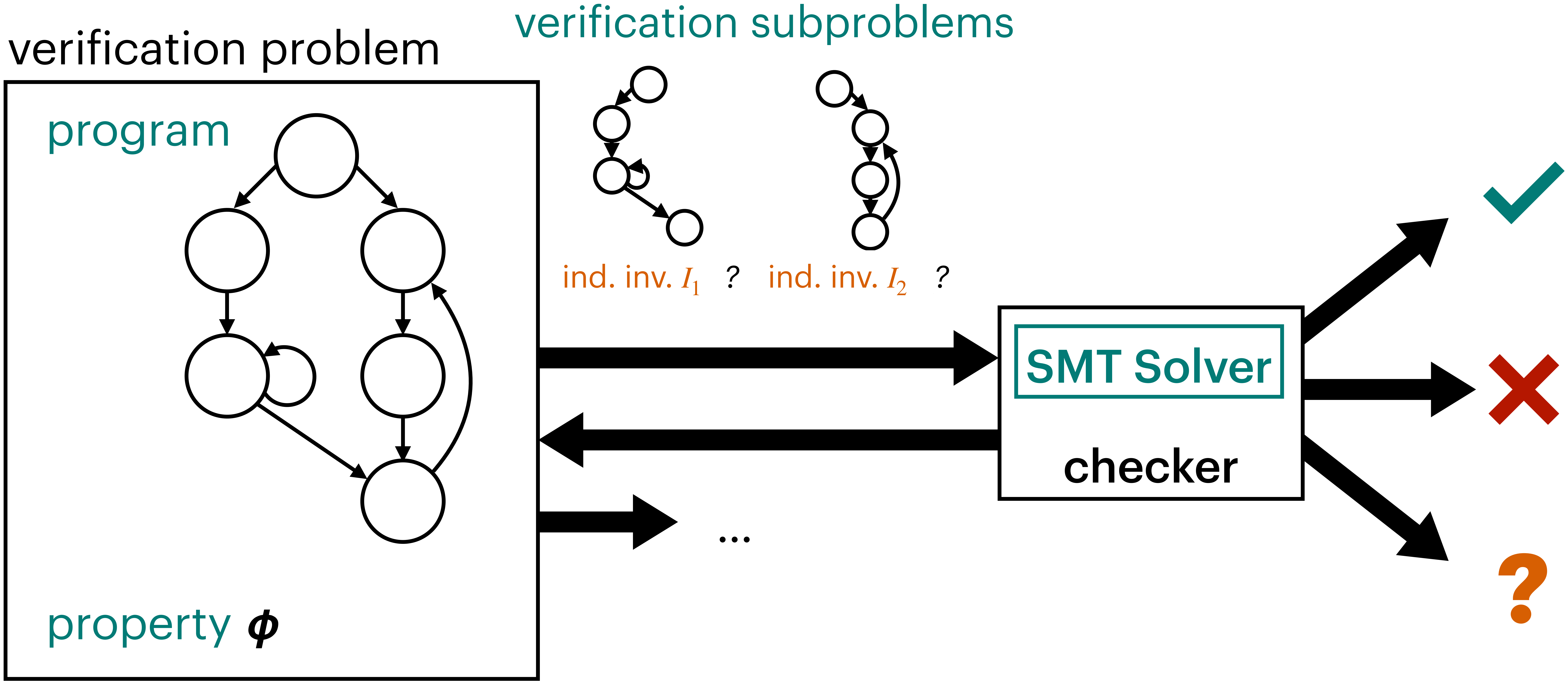

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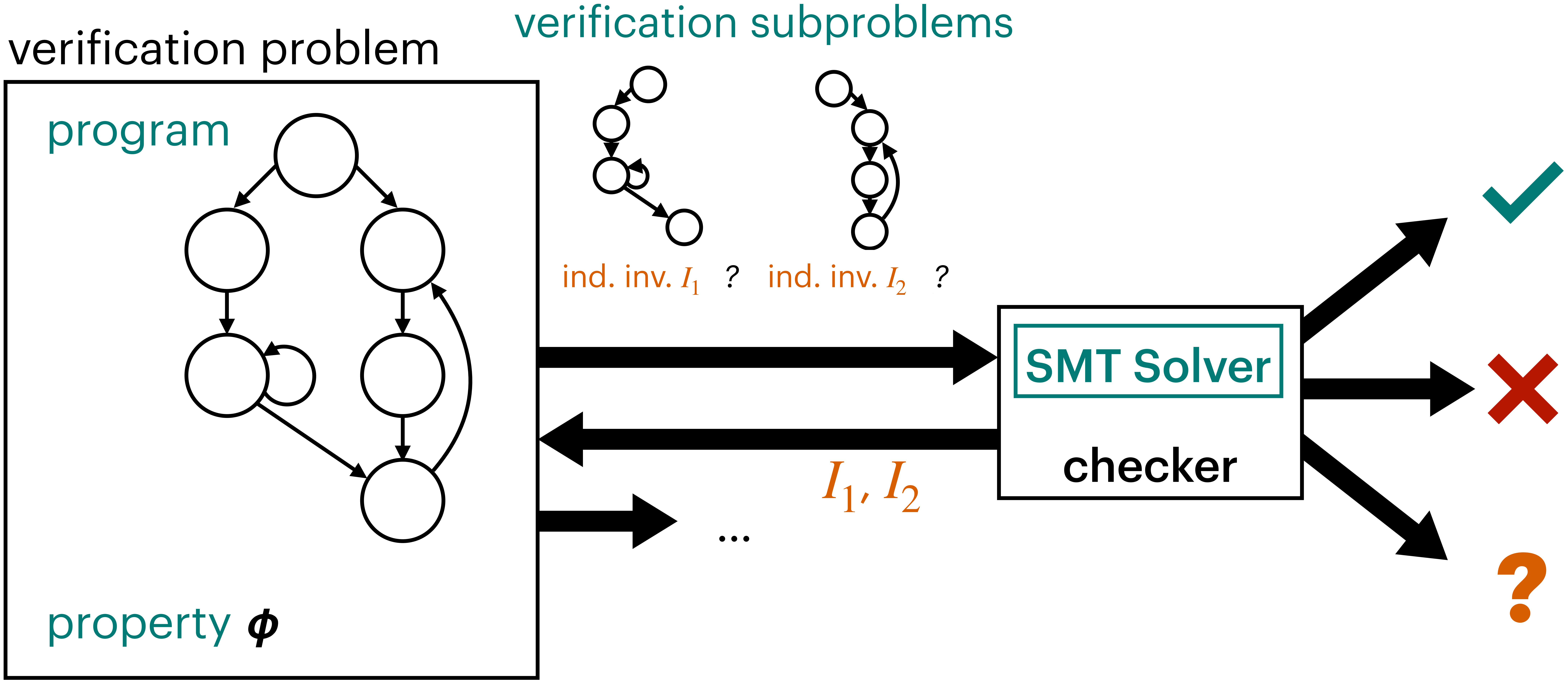

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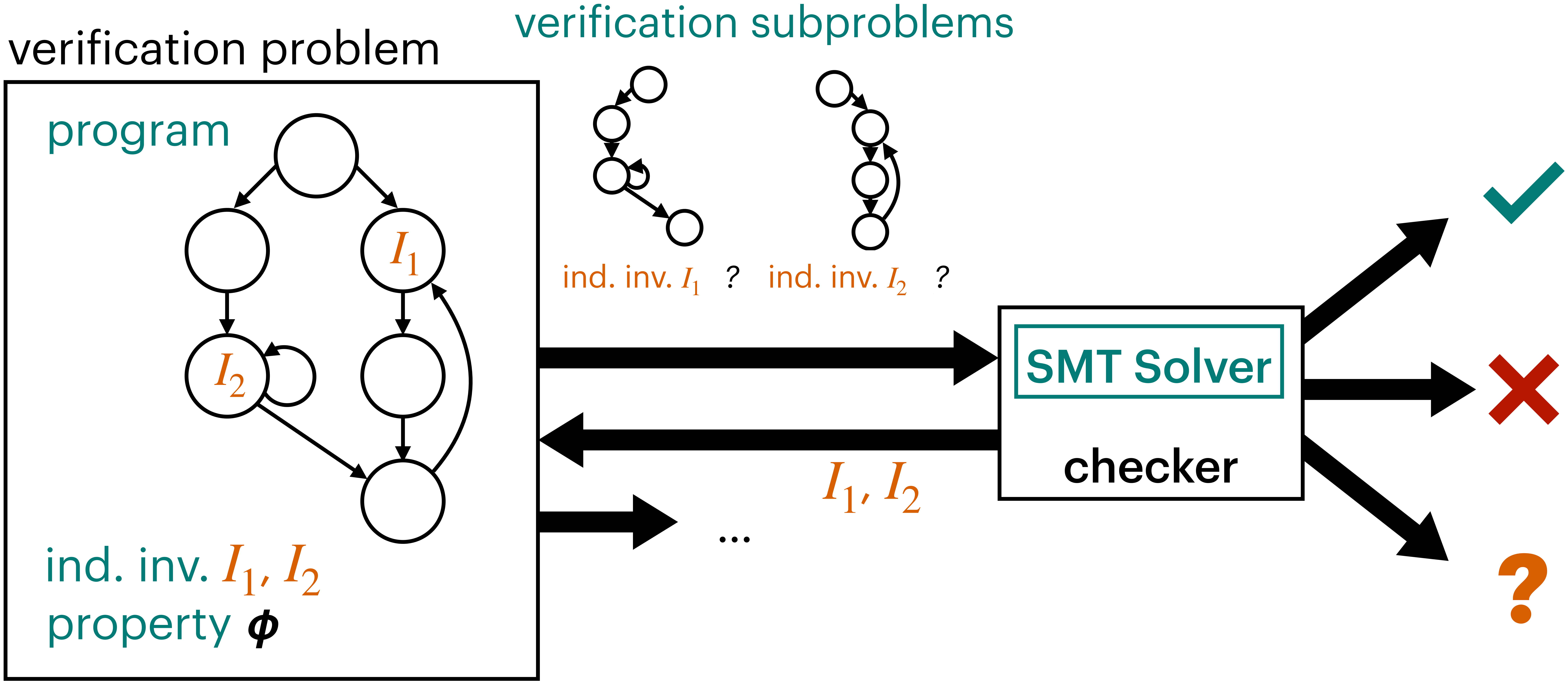
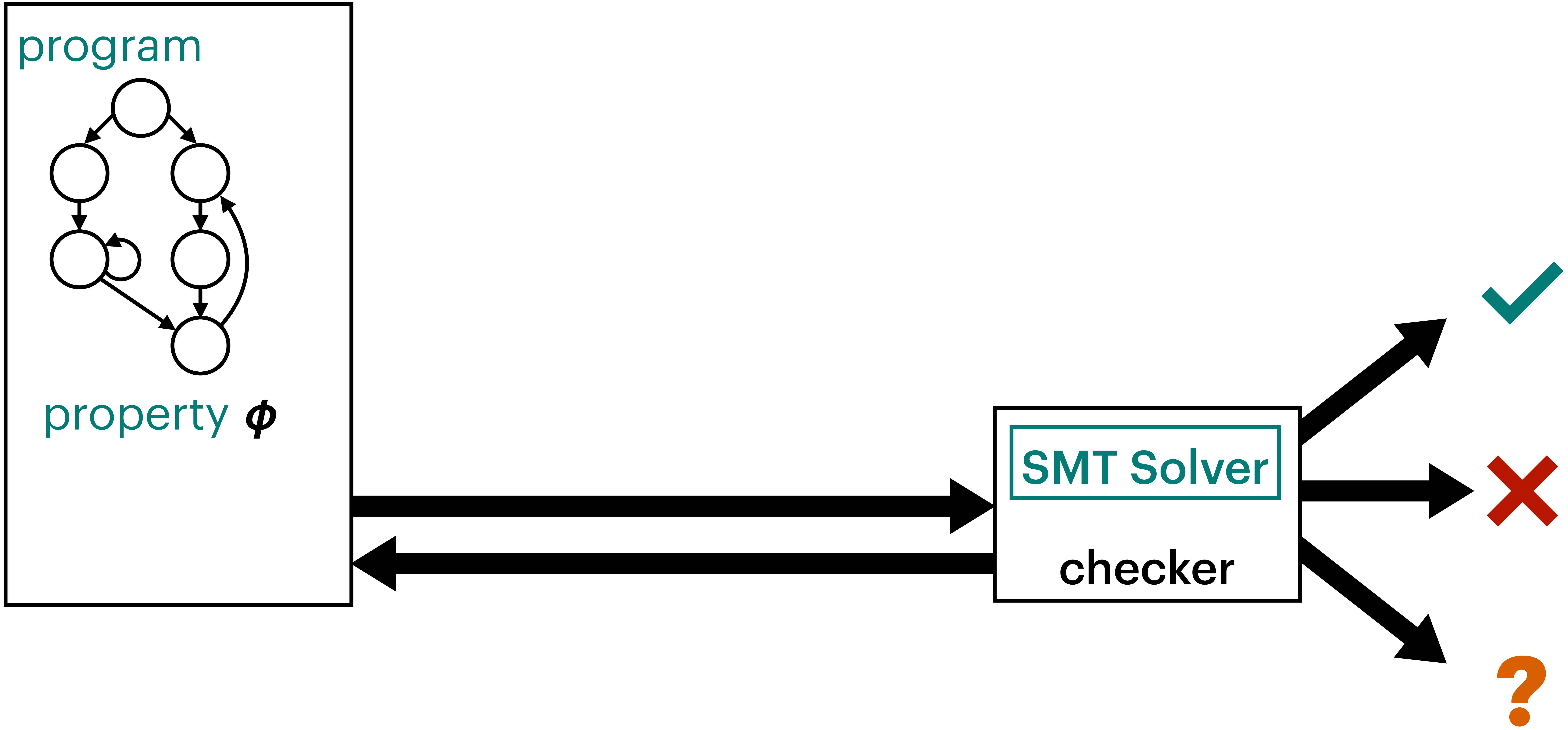


Invariant Discovery

Consider how to discover invariants



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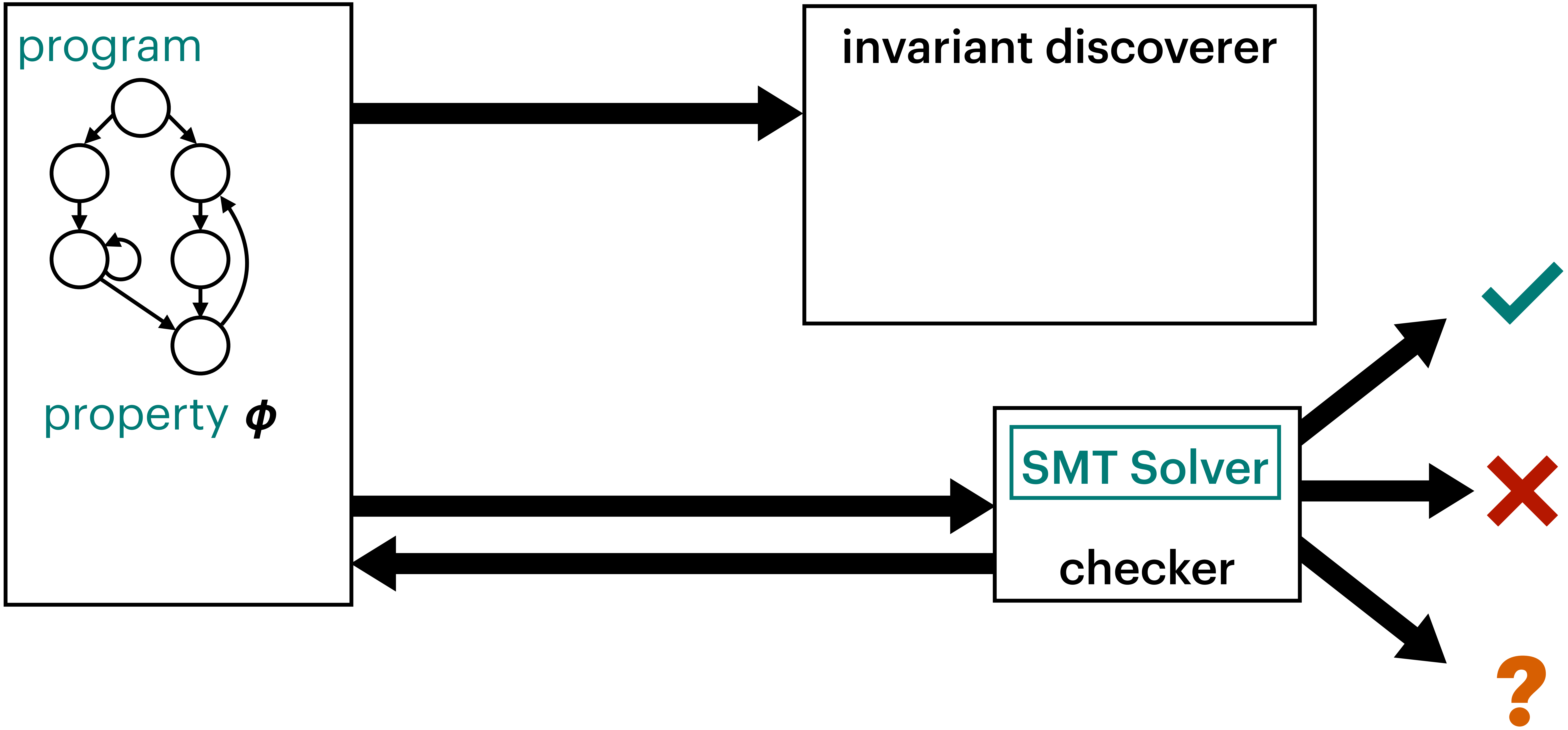

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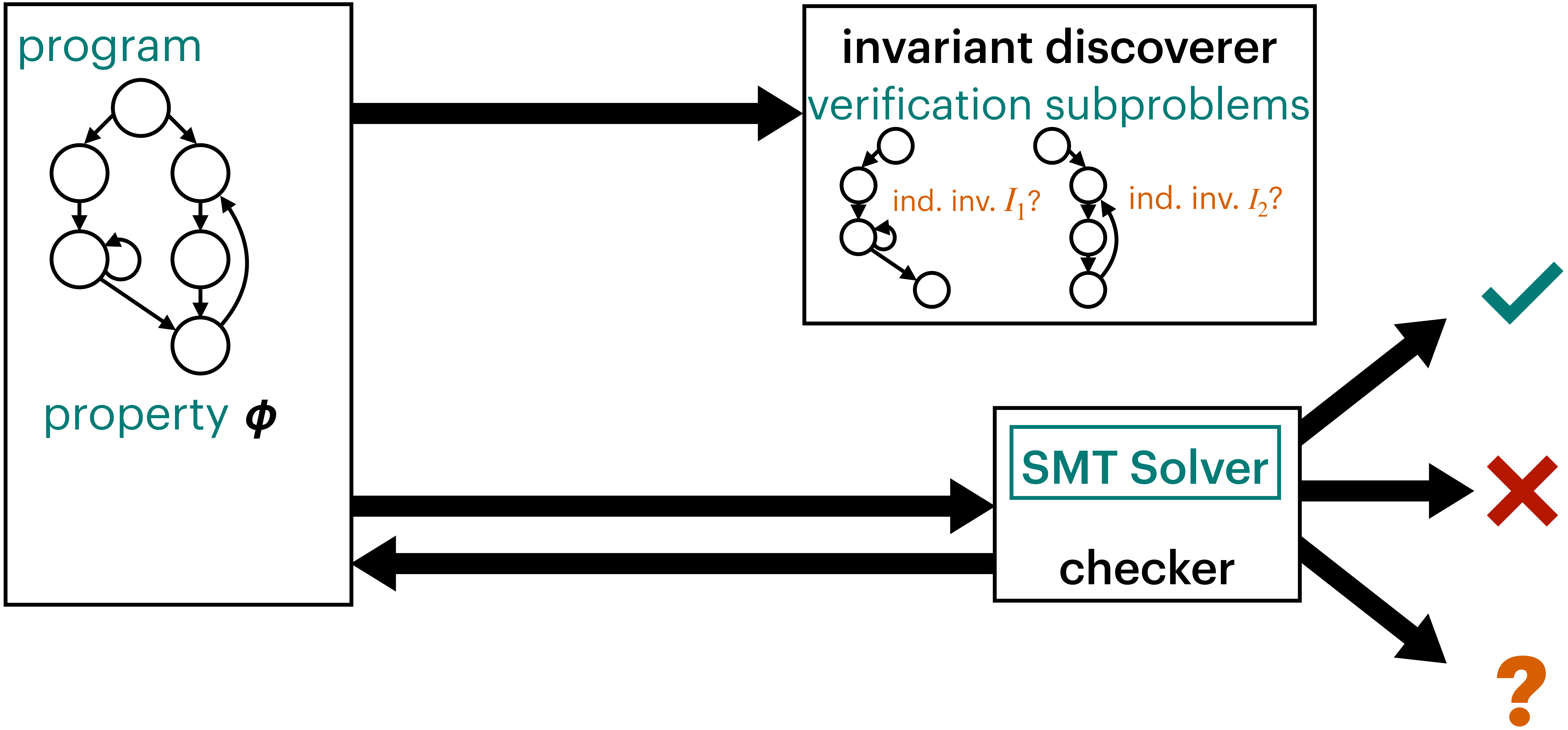

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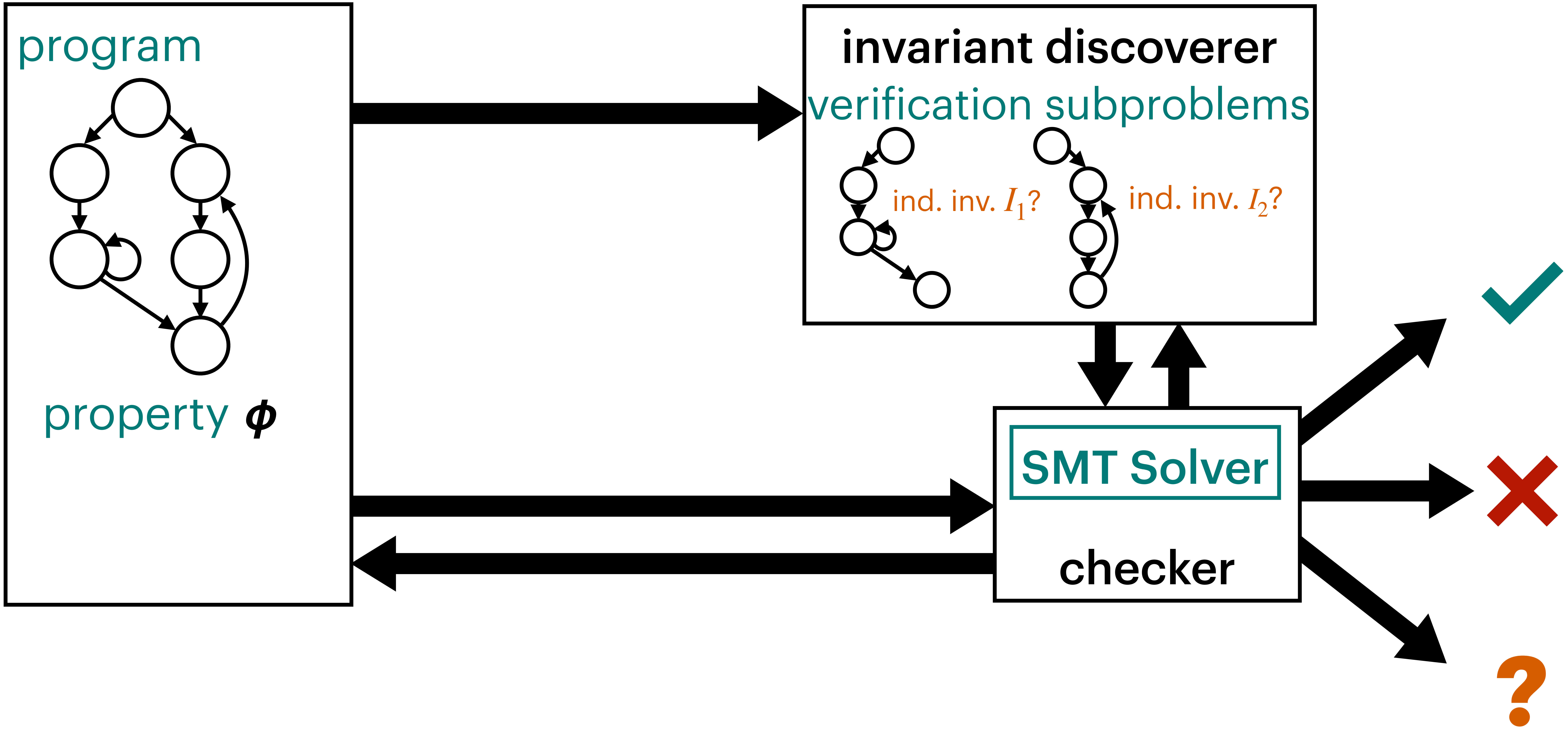

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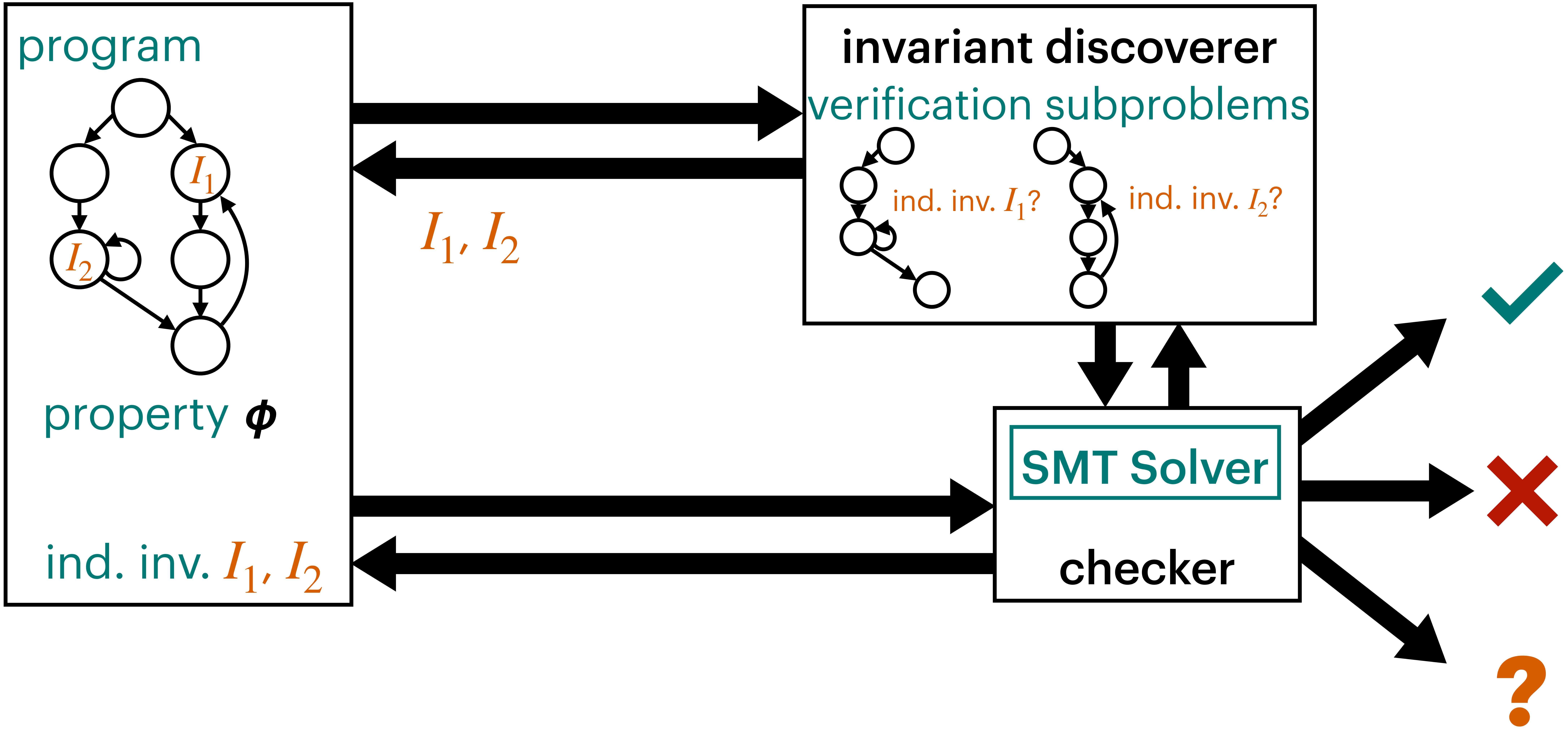

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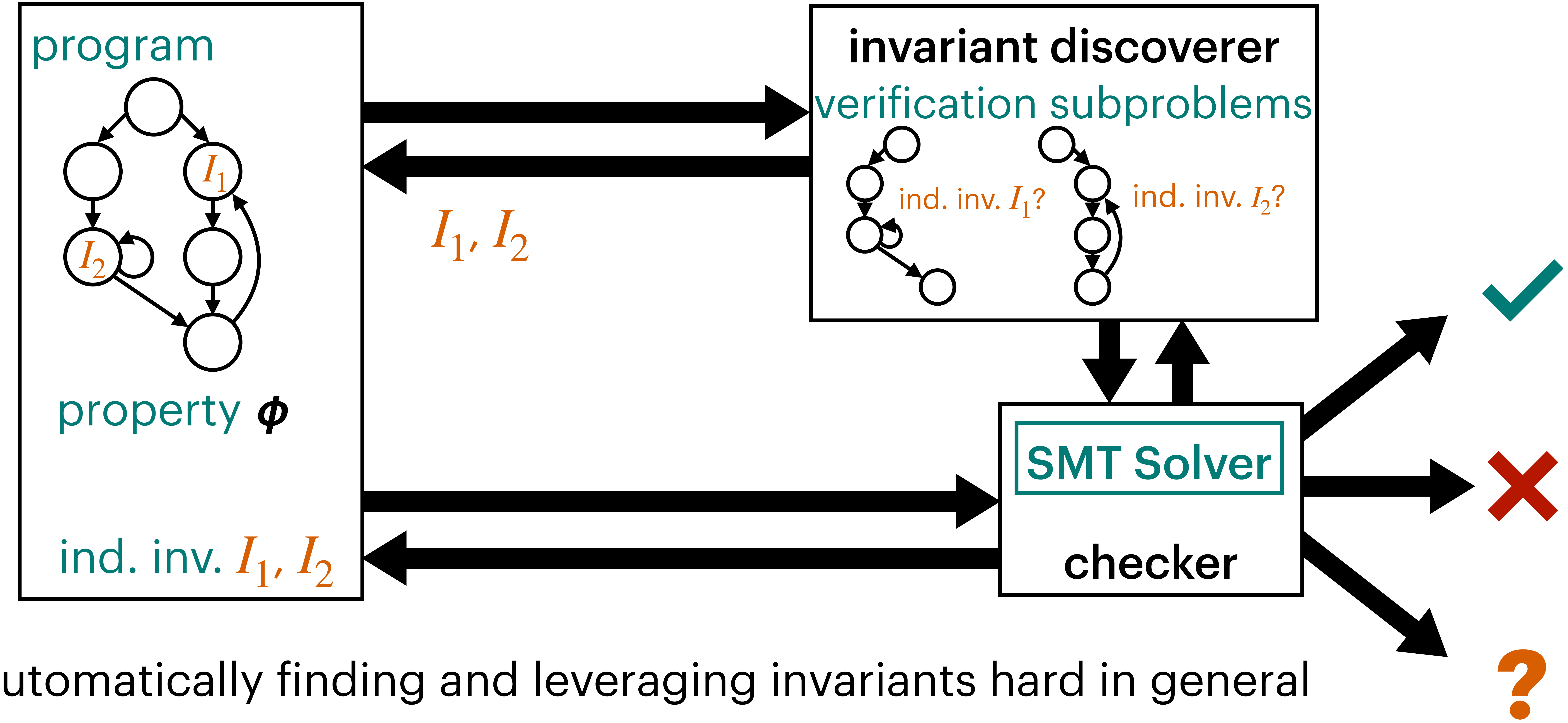
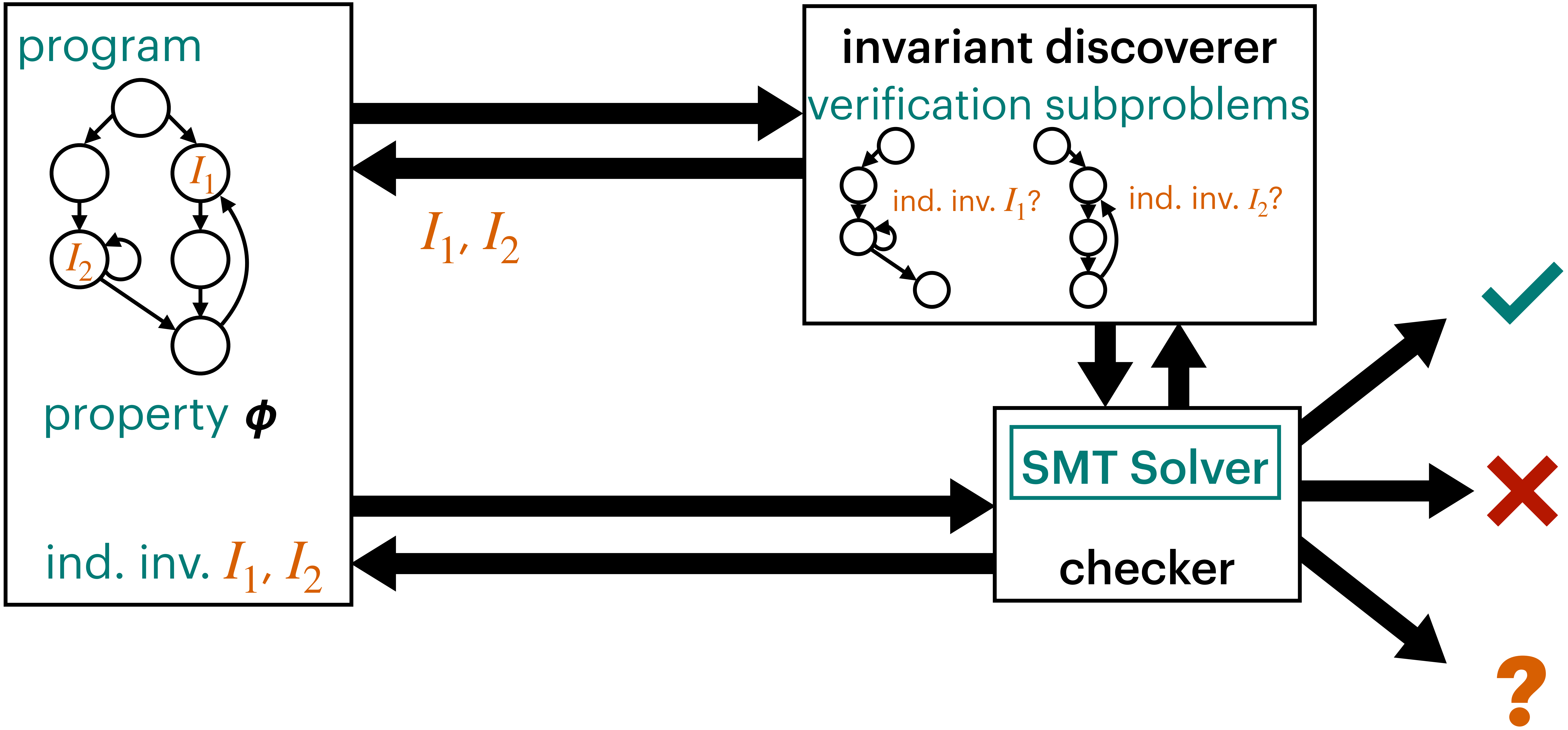


Automatically finding and leveraging invariants hard in general

Structure and Syntax

Structural info about programs and properties can help with:

- **performance**
- **scalability**
- **relevance**



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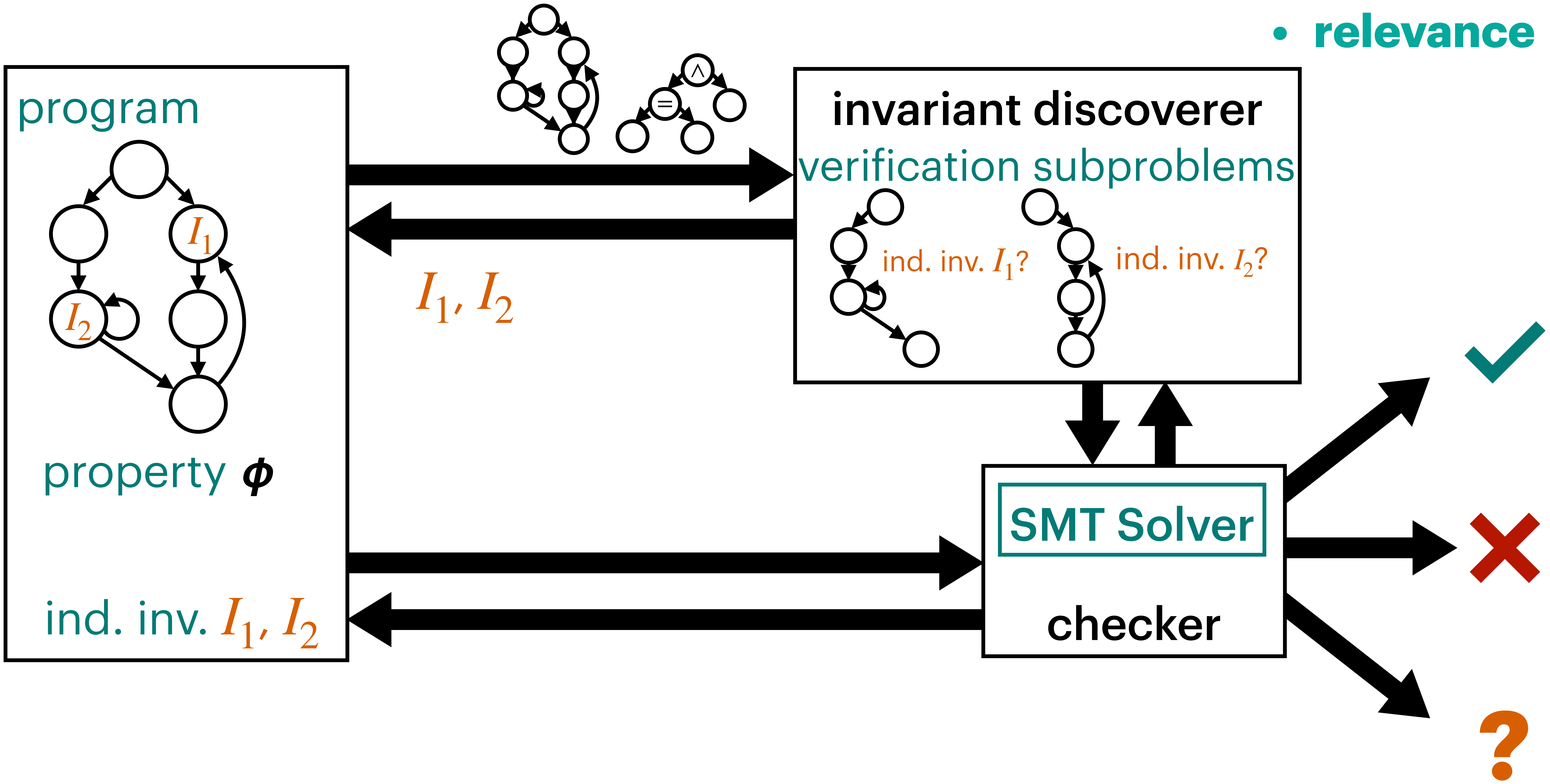

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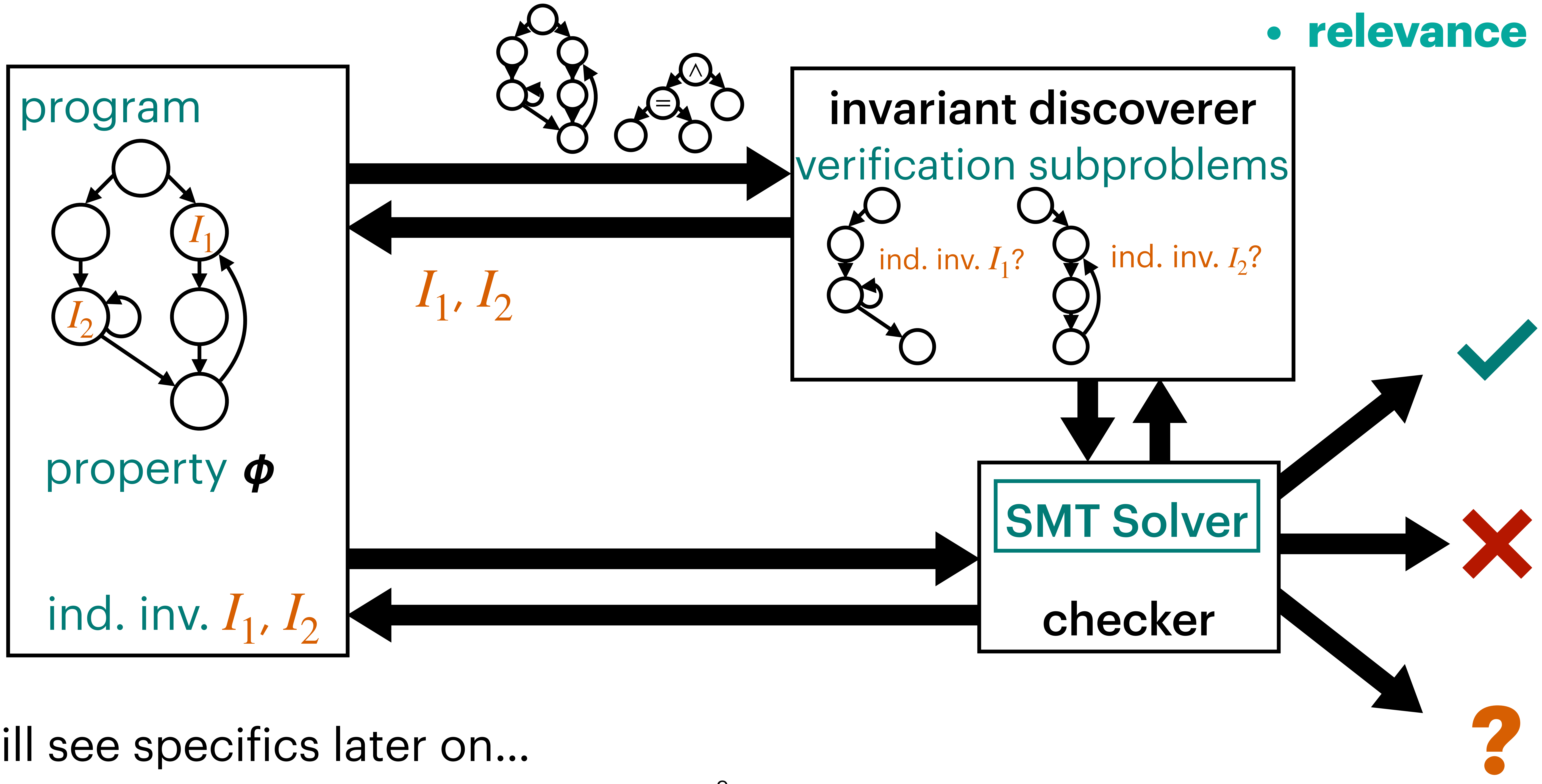

Will see specifics later on...

Contributions

How to exploit **structure** of both **programs** and **properties**
to infer and leverage **invariants** that improve **scalability** and **performance**
in SMT-based automated verification.

Programs and Properties

Consider **certain kinds** of programs + properties rather than **general** ones

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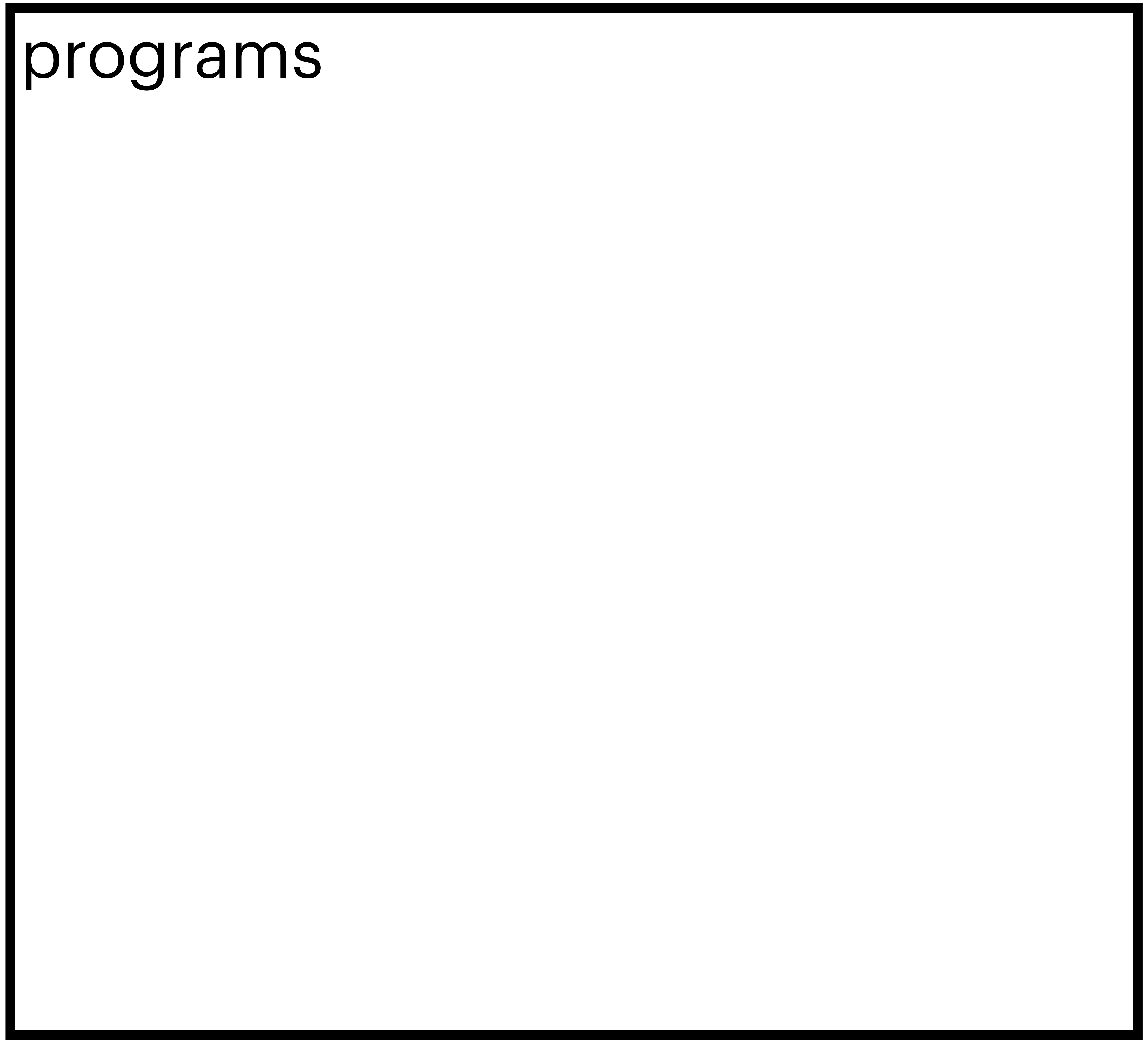

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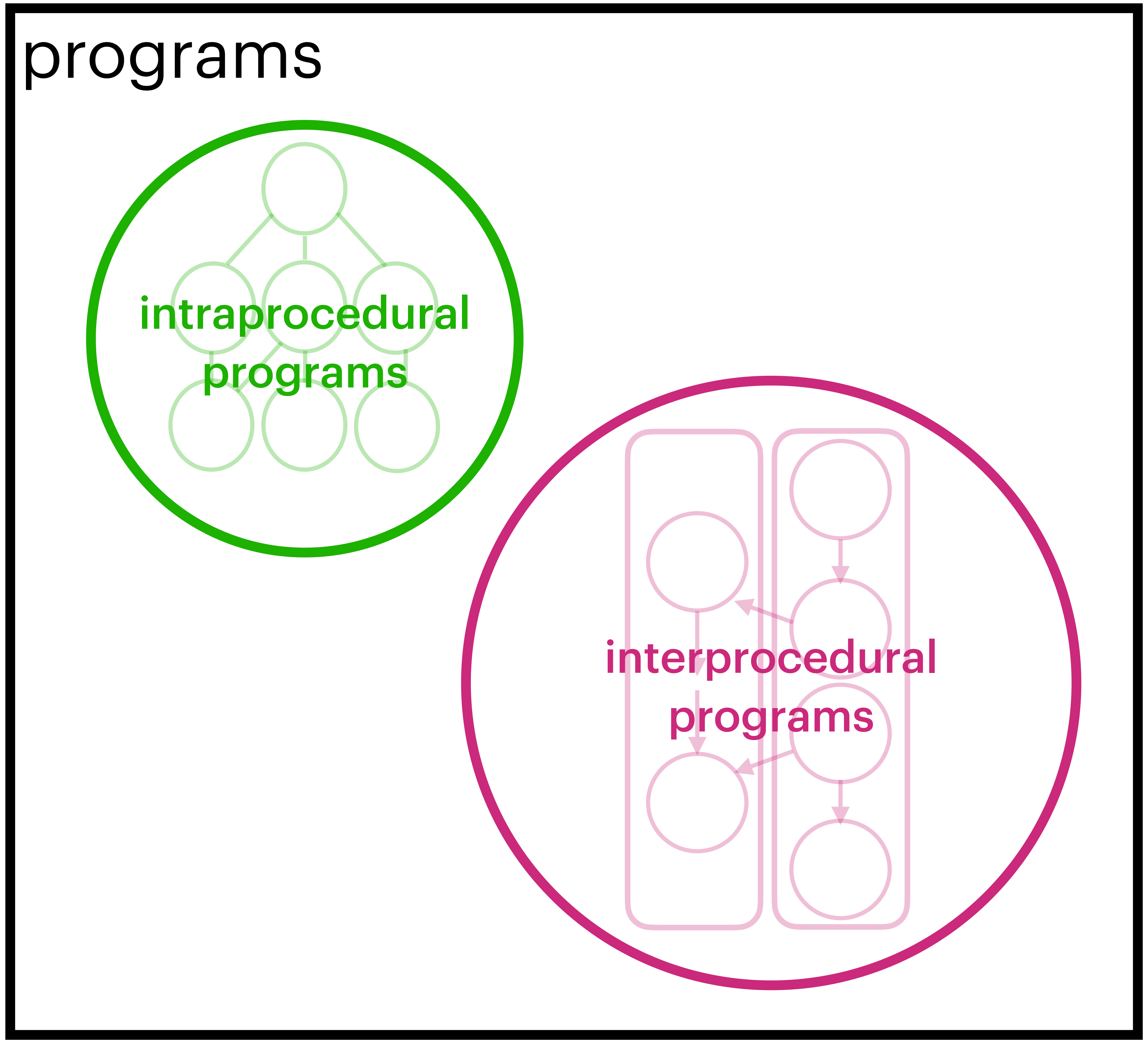

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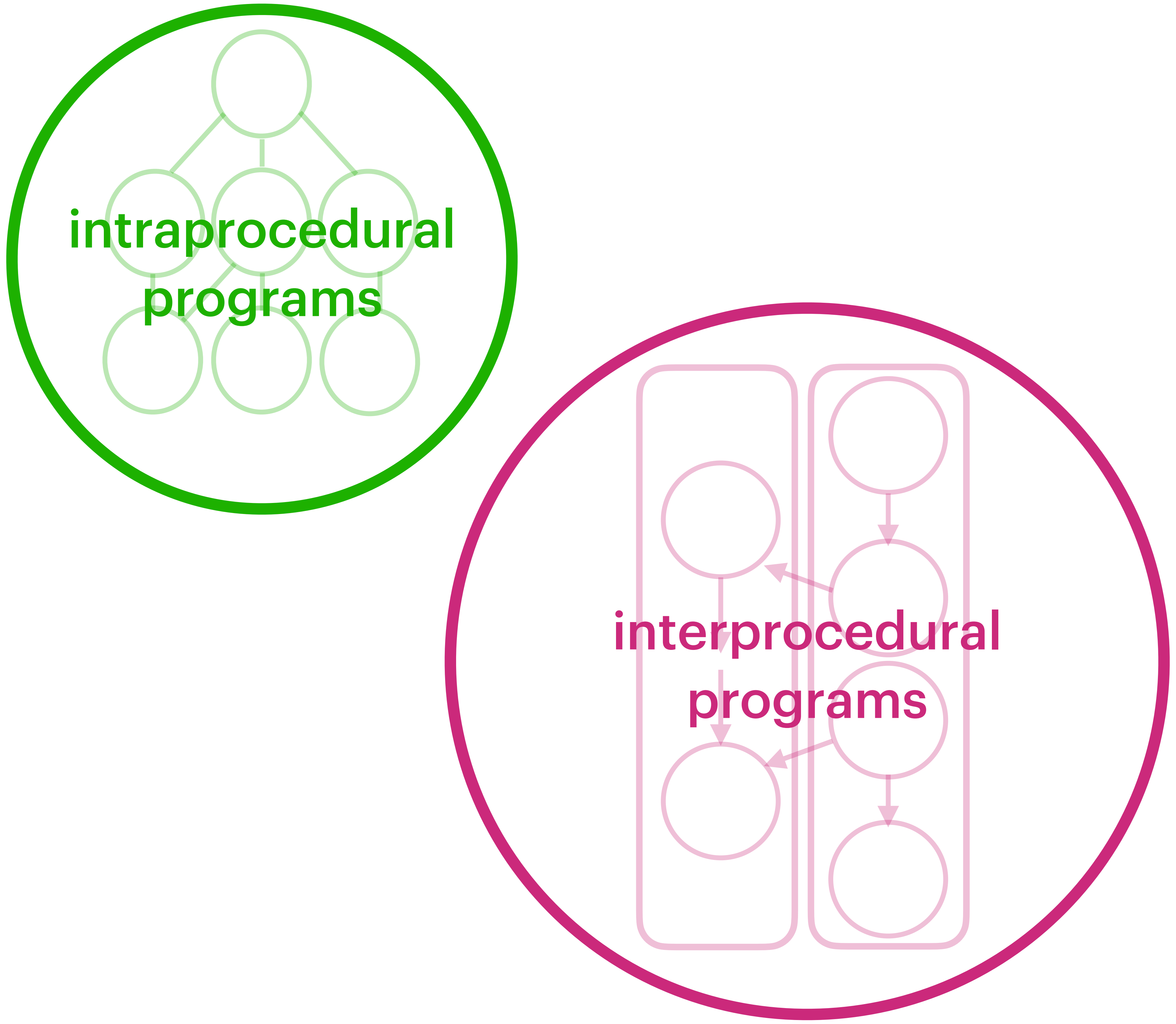
programs



properties

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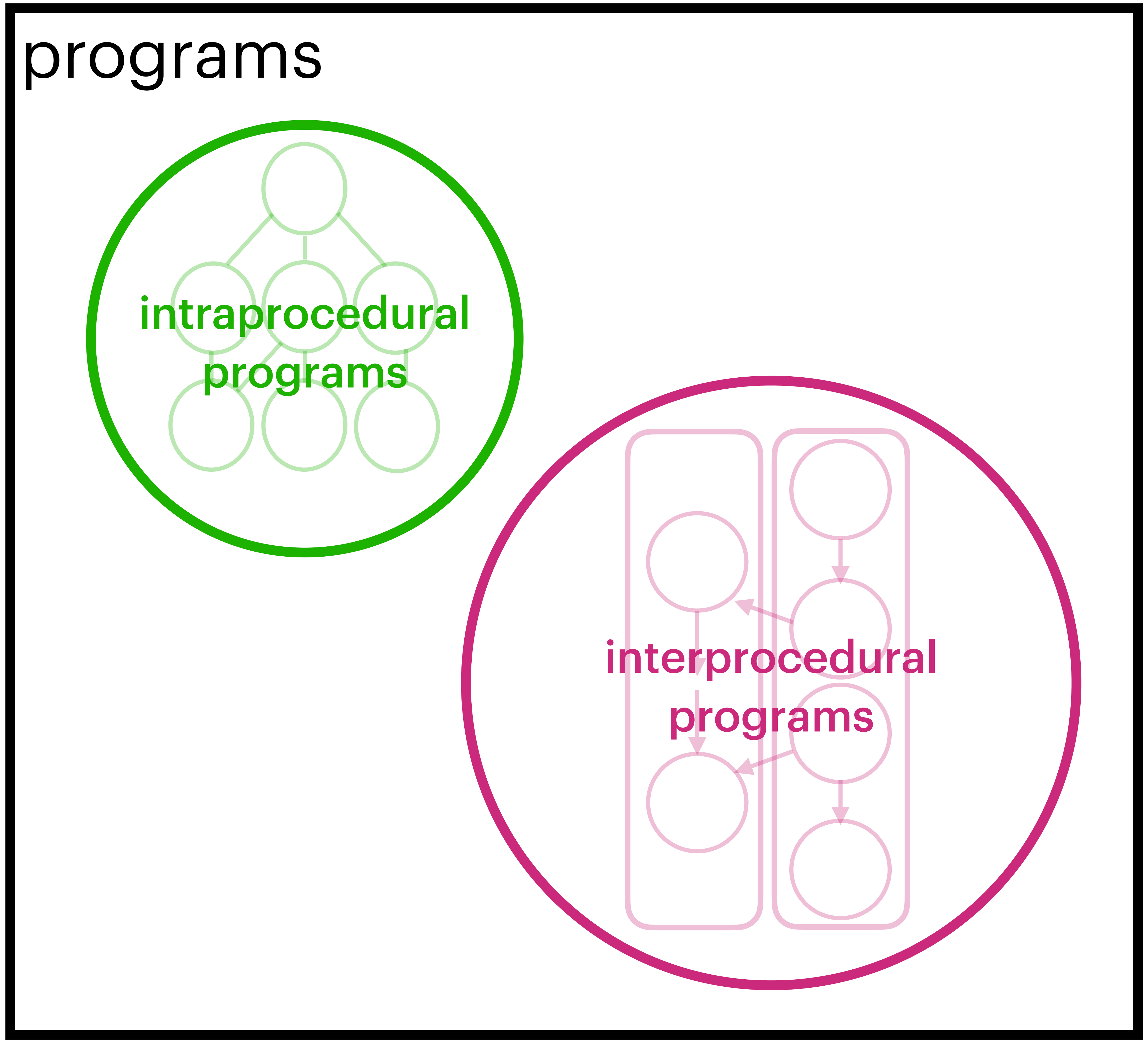

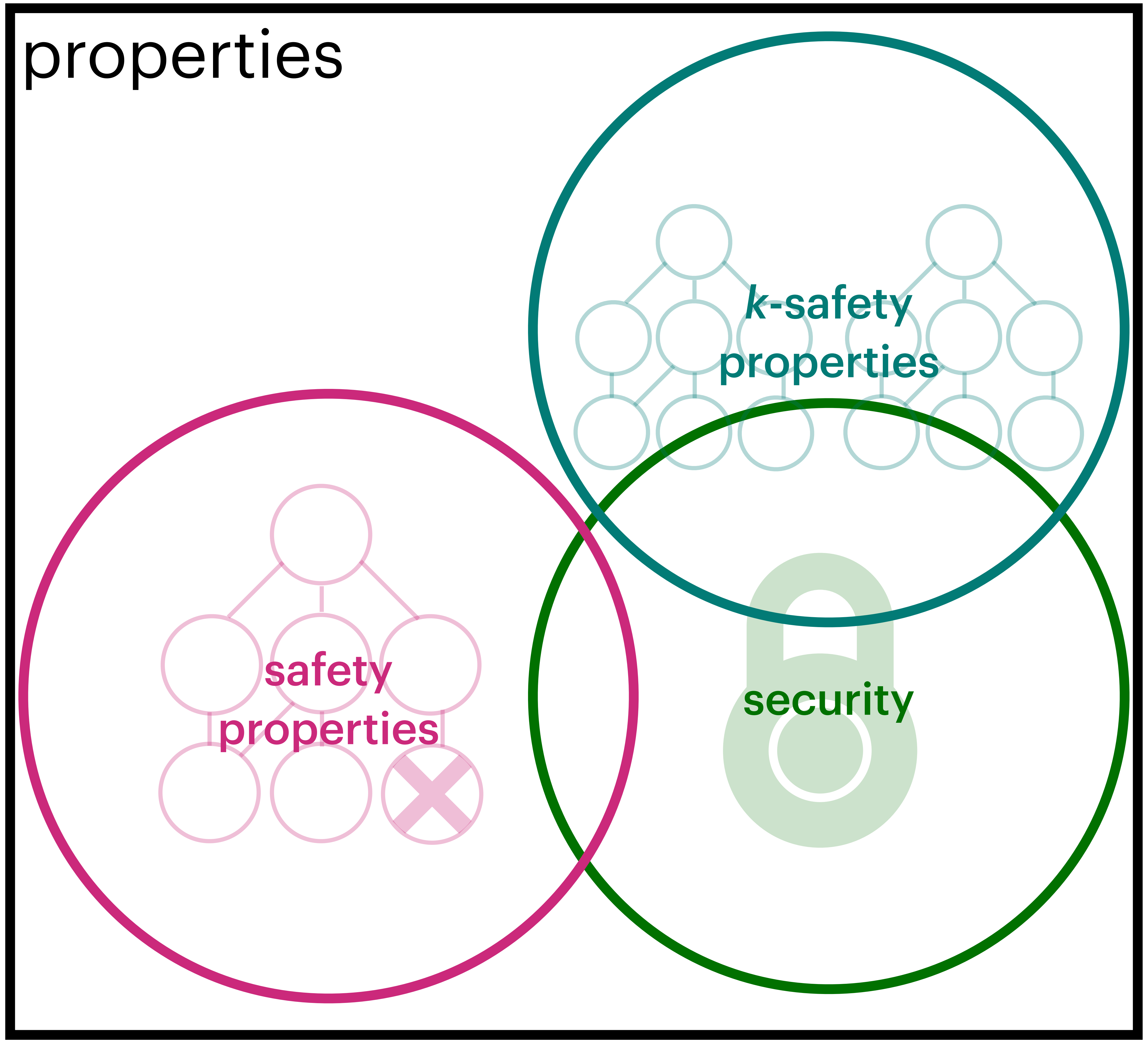

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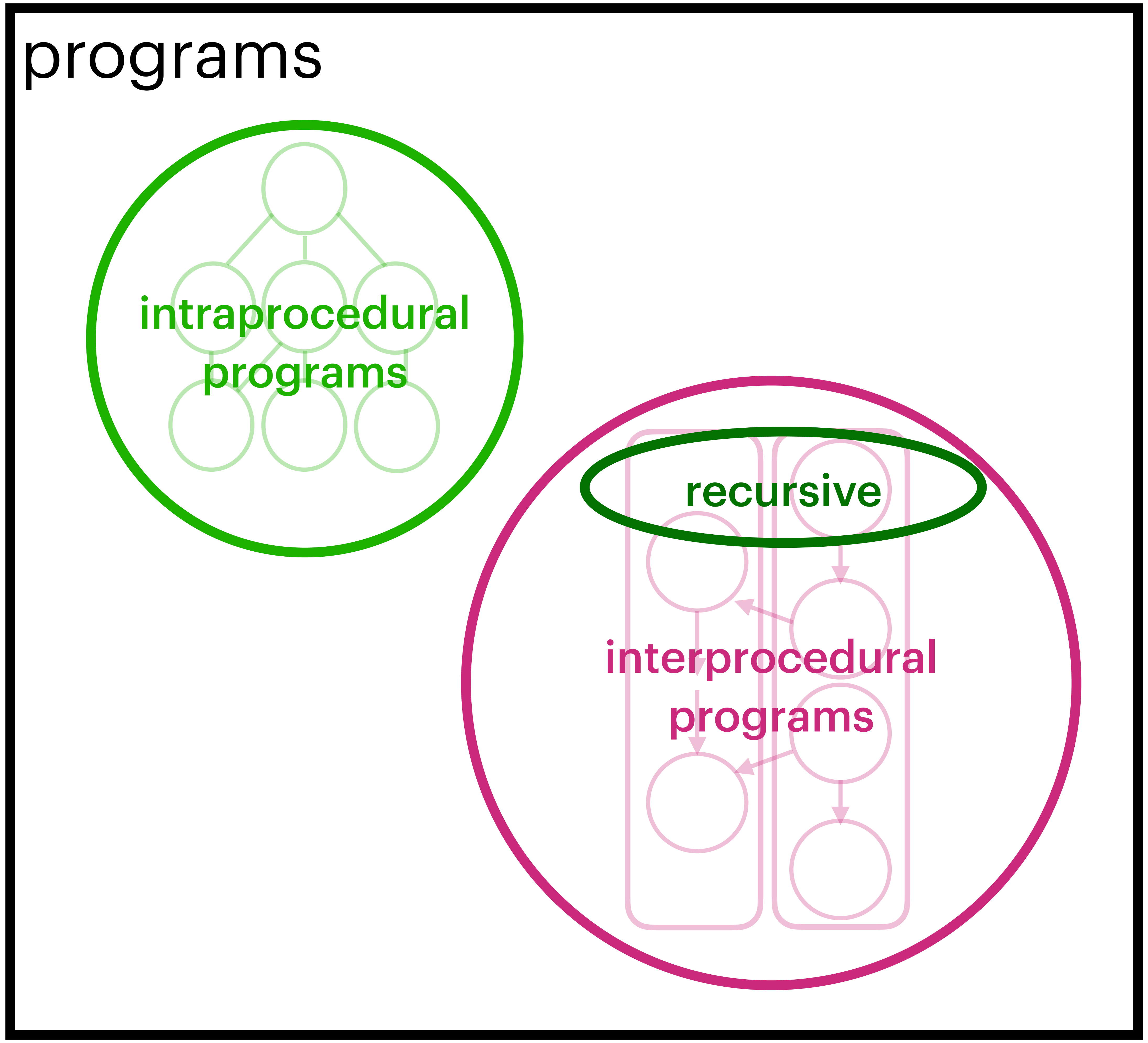

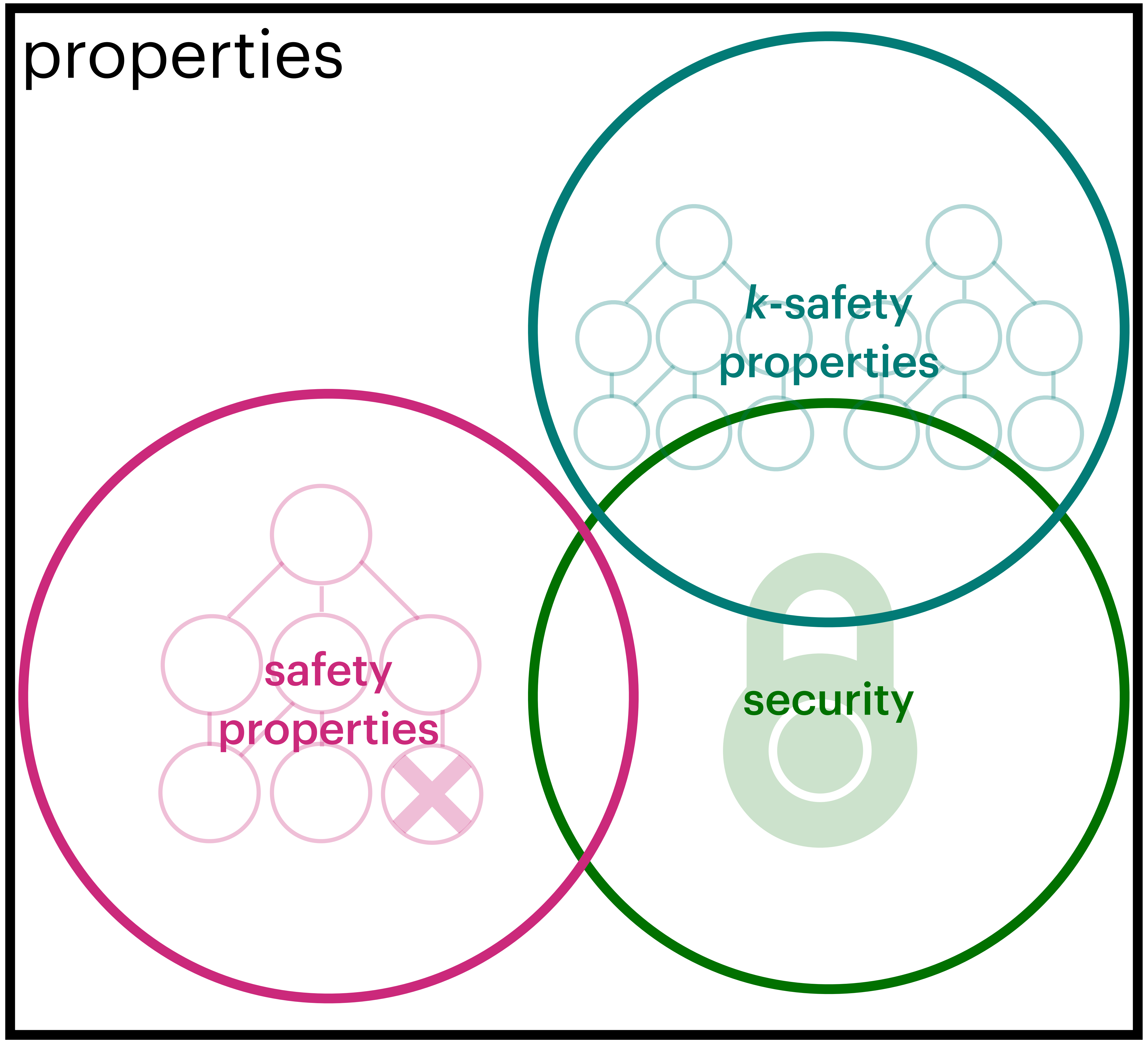

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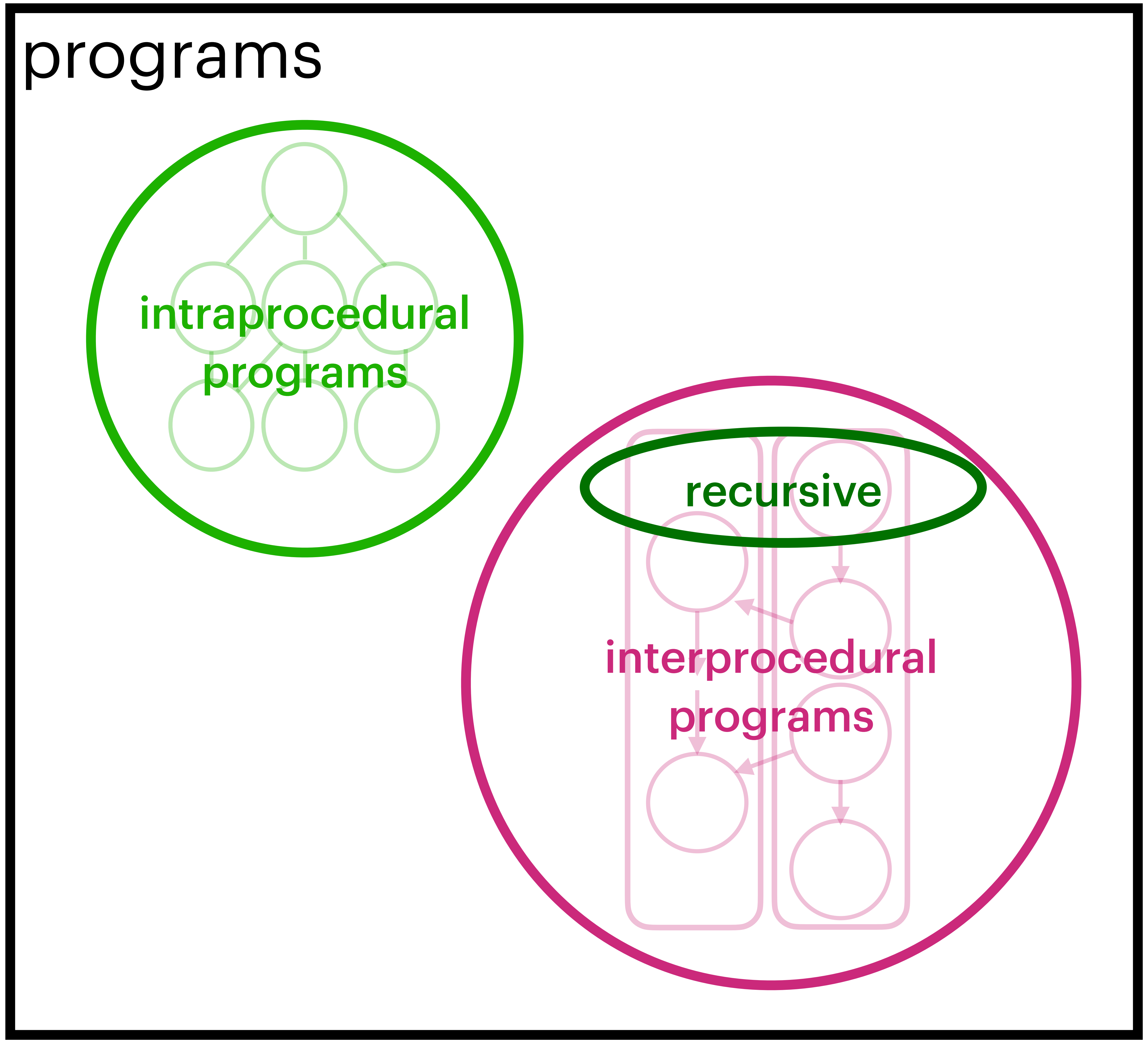

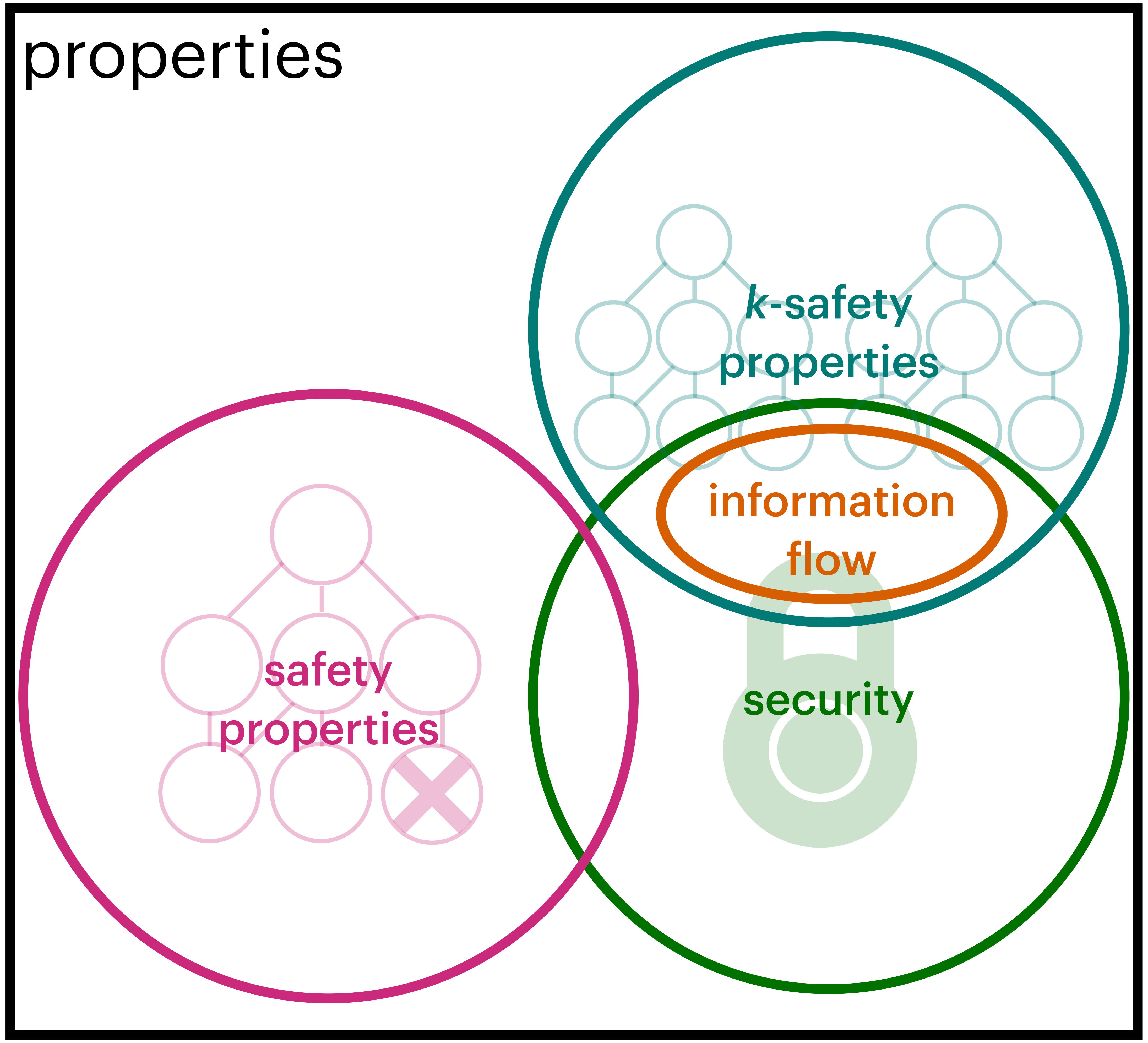

Classes of Verification Problems

I. *k*-safety Verification

II. Interprocedural Program Verification

III. Information-Flow Verification

Classes of Verification Problems

Will talk about each of these in turn

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Will talk about the third most detail
(Extra slides on the second)

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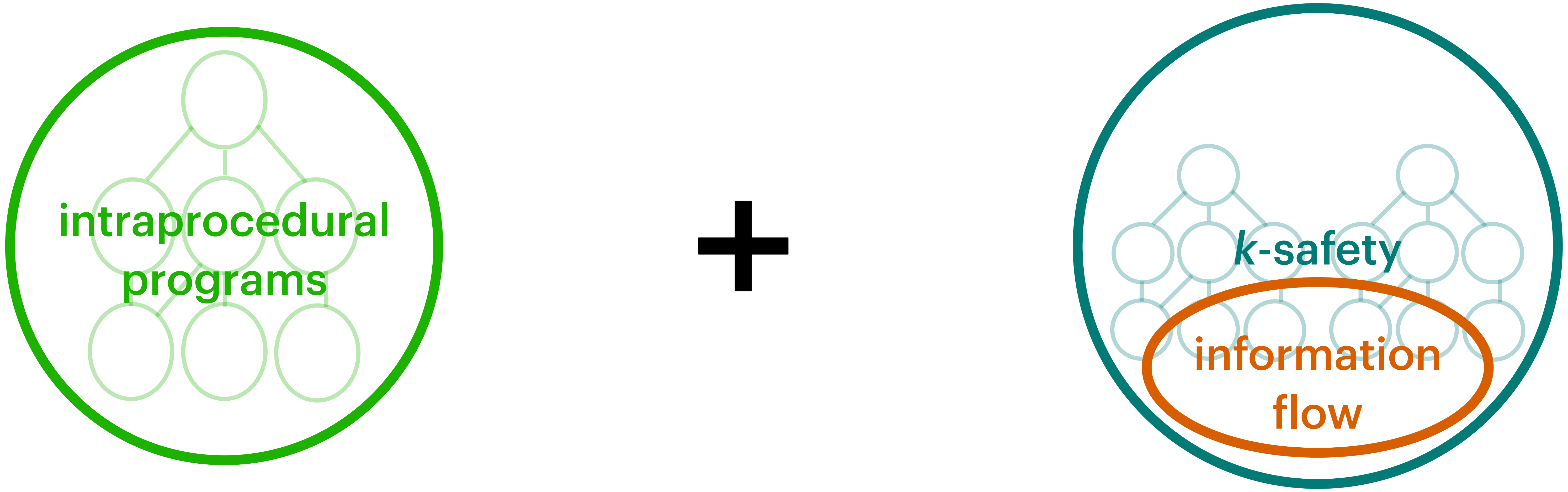
Constrained Horn Clauses

III. Information-Flow Verification
Constrained Horn Clauses

- No (specialized) heap modeling
- No higher-order functions
- Static call graph

Cartesian Hoare Logic, Sousa and Dillig, PLDI'16

I. *k*-safety Verification

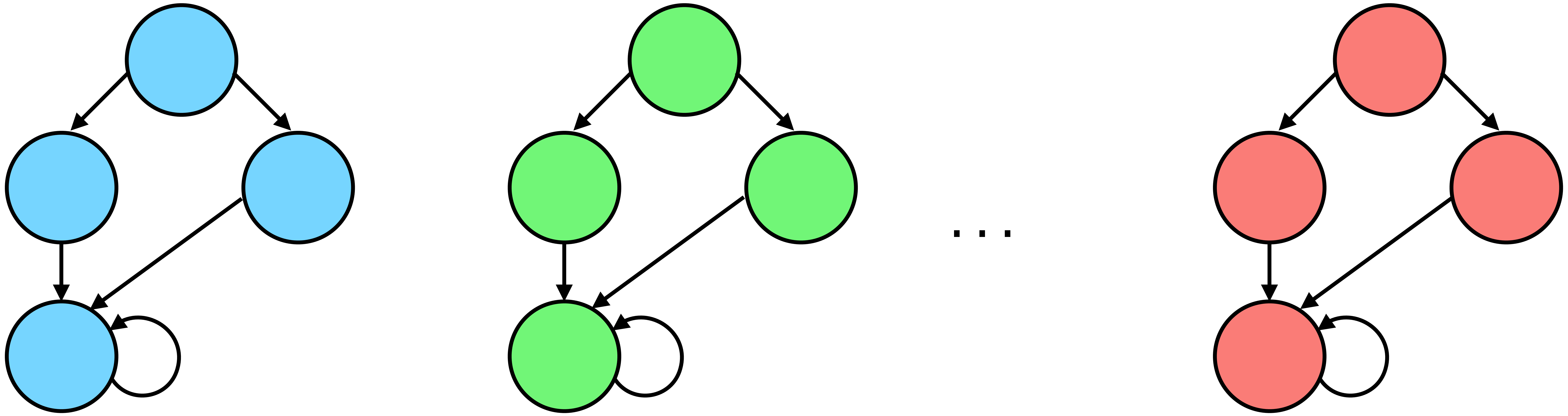


Single-procedure programs (may contain loops)

Properties over k copies of the same program

Relational Invariants

Relate the *k* program copies at intermediate points



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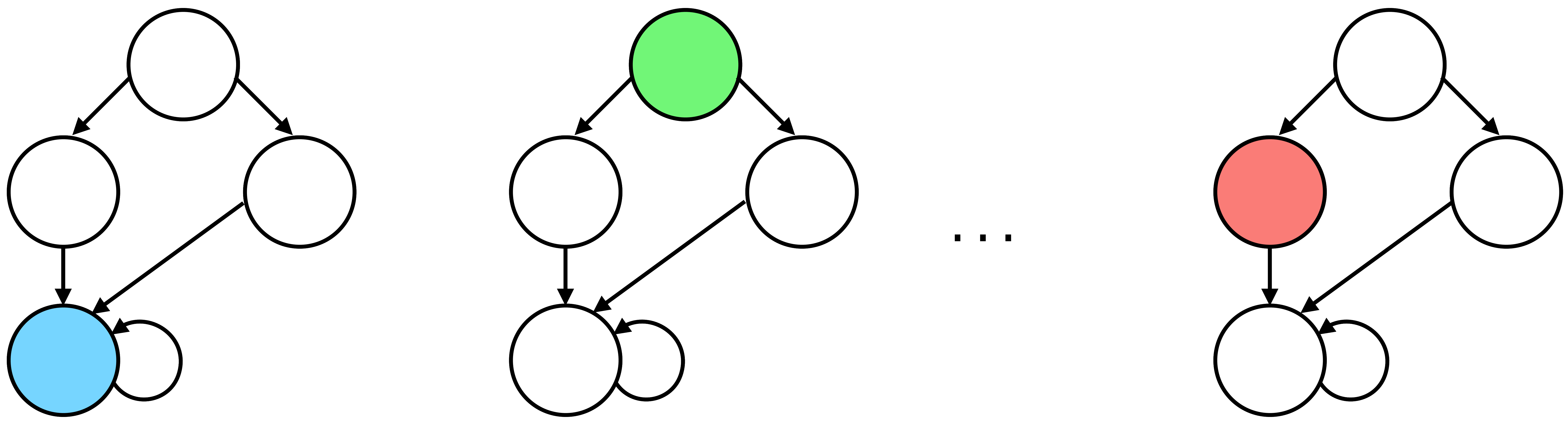

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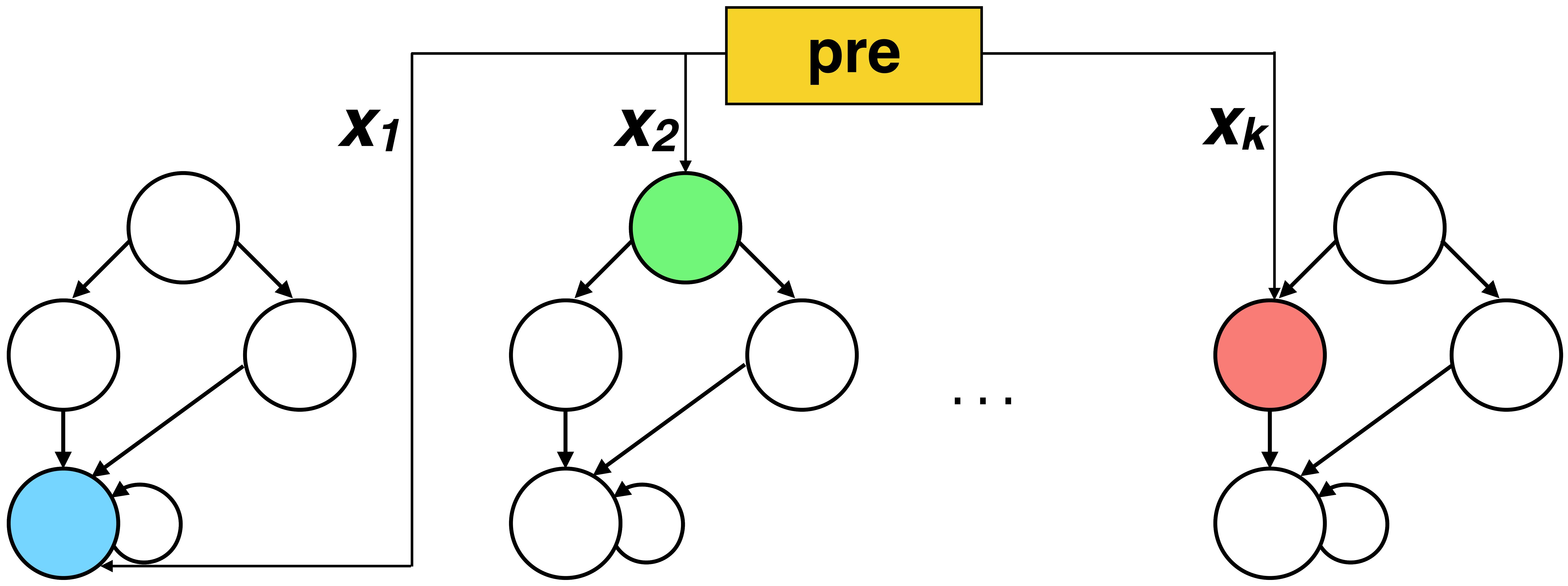

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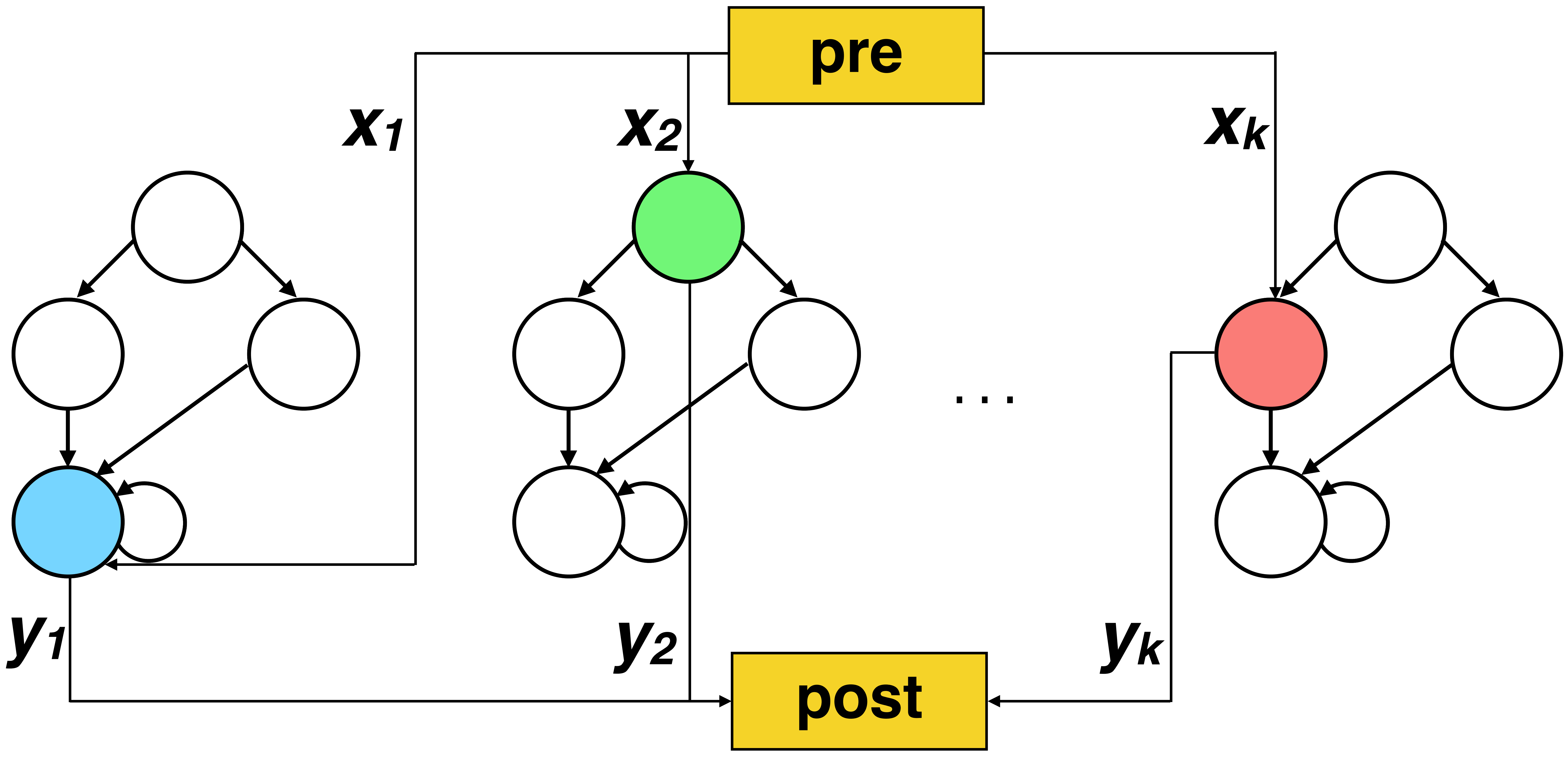

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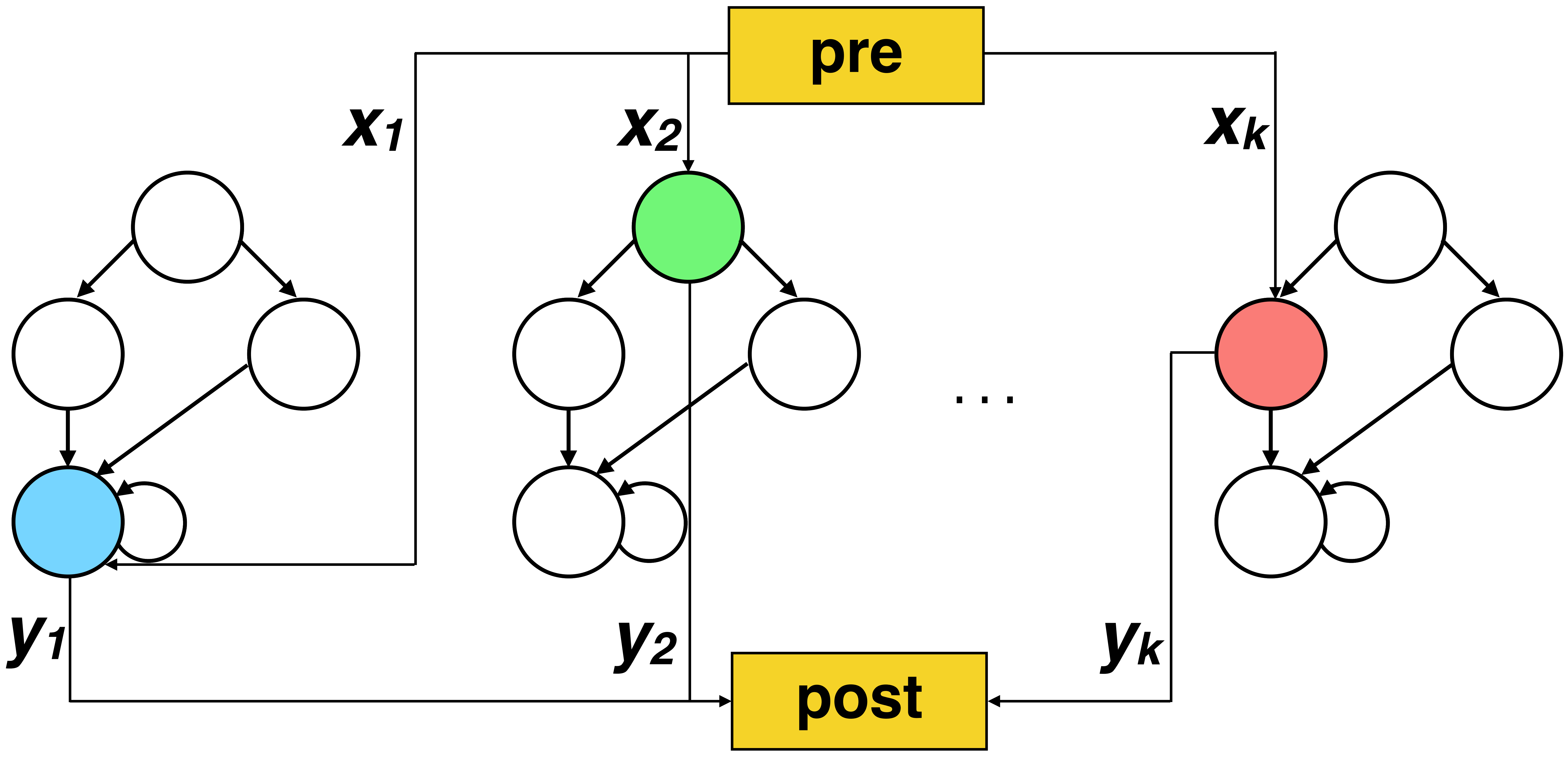

How to **leverage** and how (where) to **infer** them for scalable verification?

Symmetry and Synchrony

L. Pick, G. Fedyukovich, A. Gupta. Exploiting Synchrony and Symmetry in Relational Verification, CAV'18

Symmetry and Synchrony

How to **leverage** relational properties?

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How to **leverage** relational properties?

Symmetries in properties lead to redundant subtasks, so **prune** them

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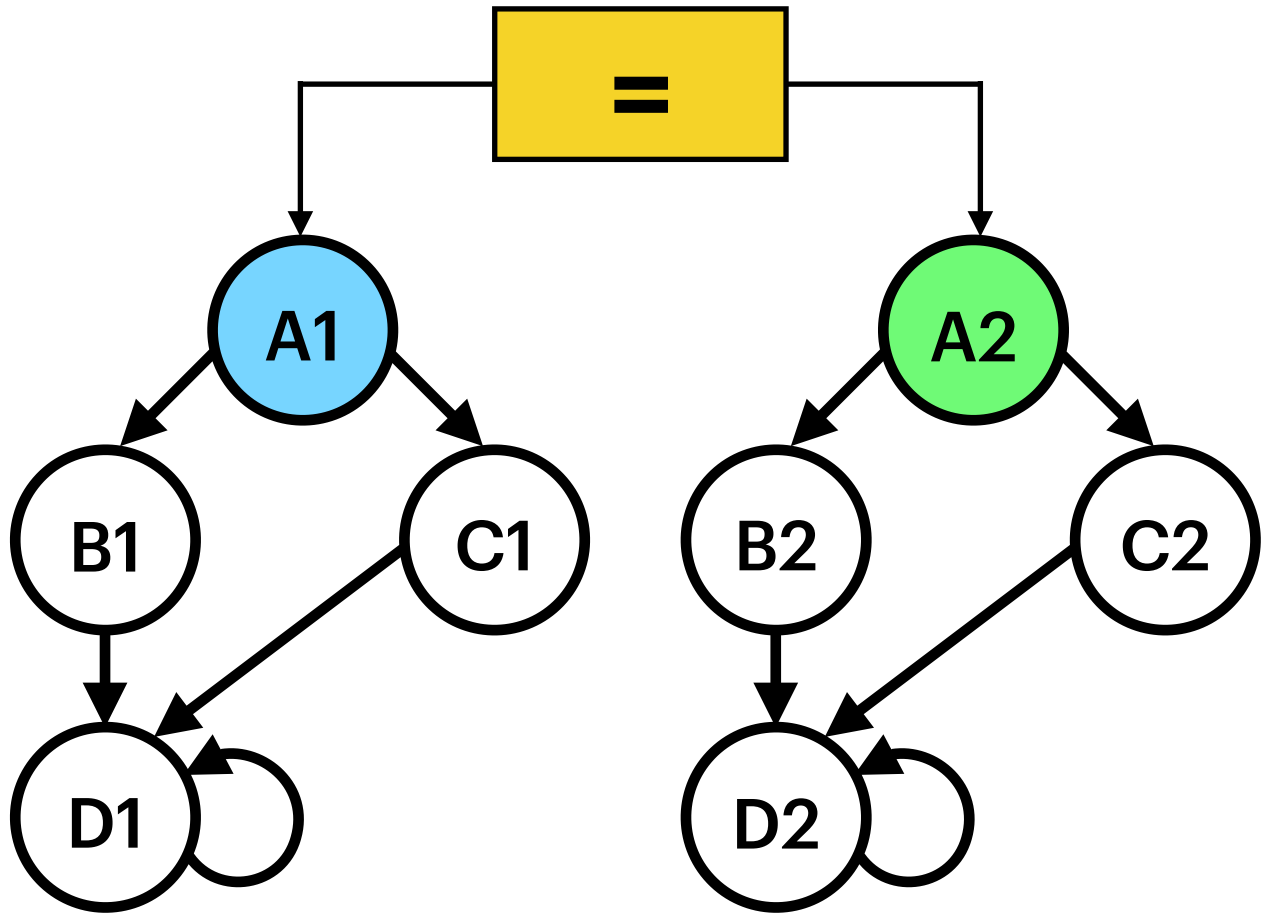

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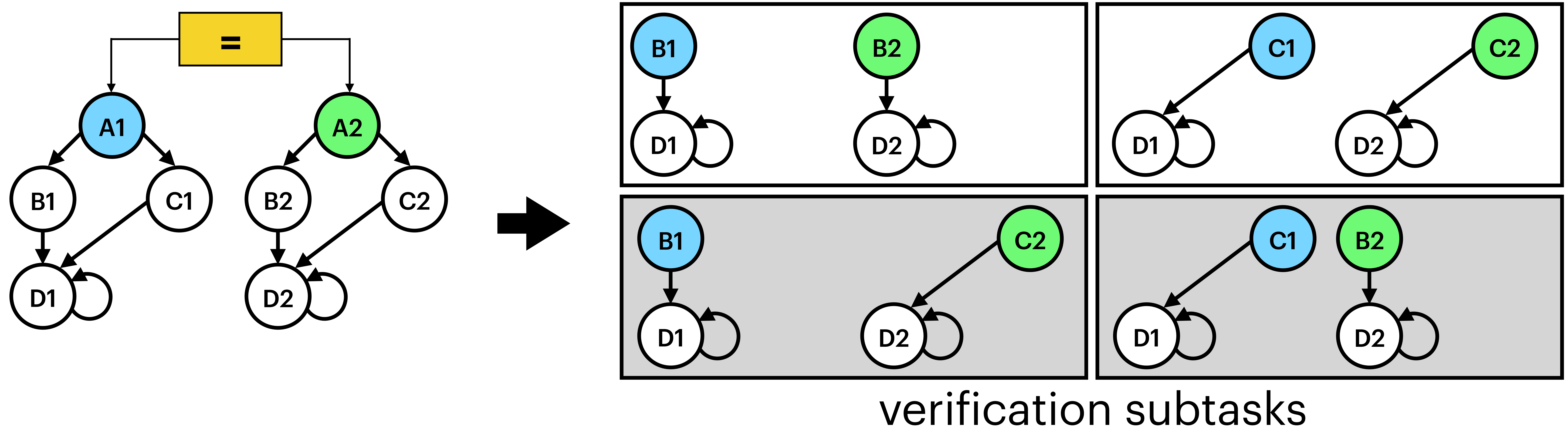

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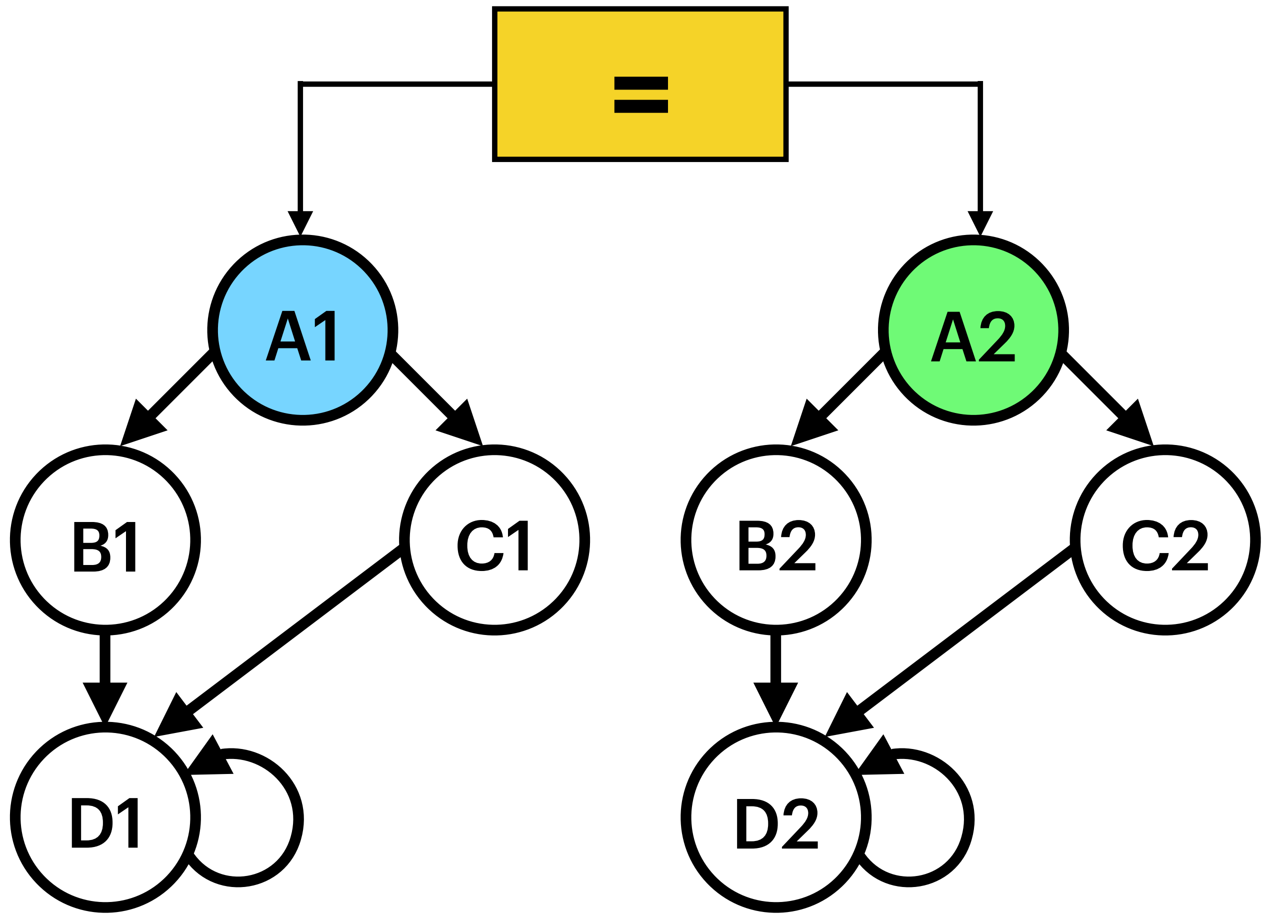
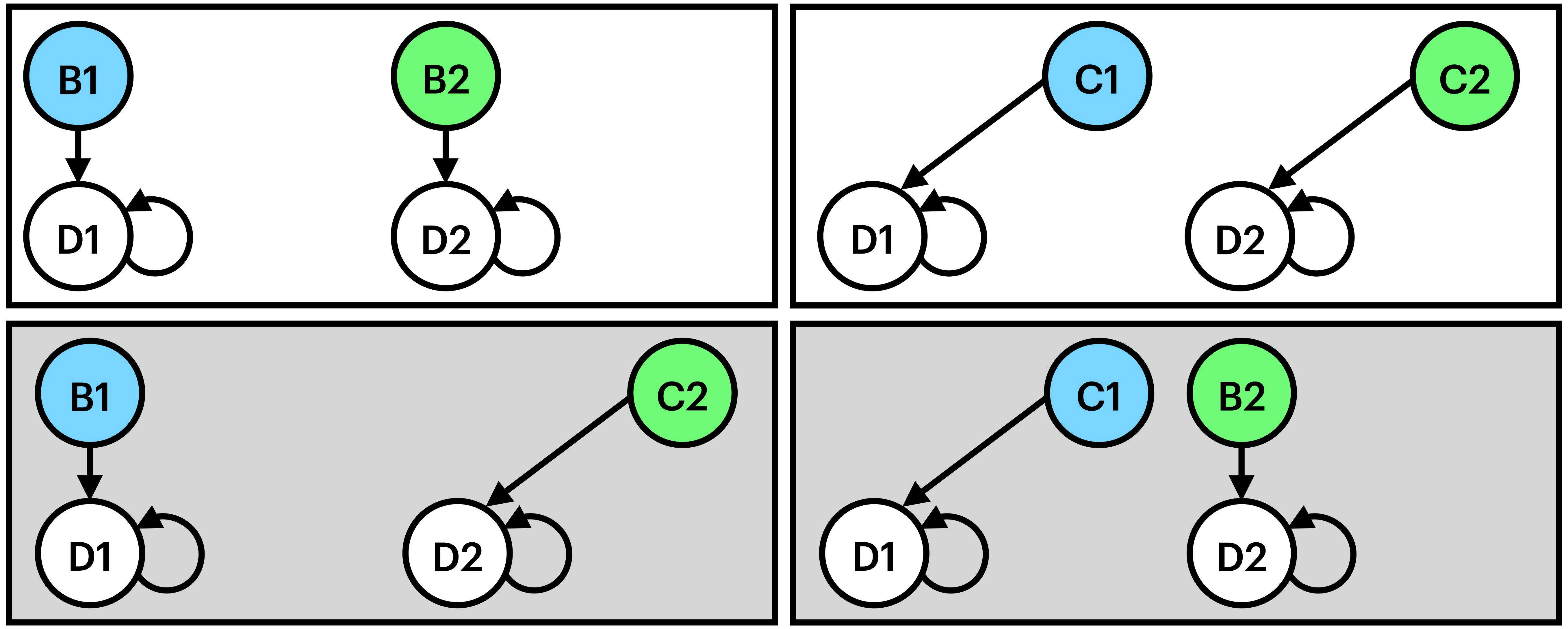


Property symmetry 1↔2



verification subtasks

L. Pick, G. Fedyukovich, A. Gupta. Exploiting Synchrony and Symmetry in Relational Verification, CAV'18

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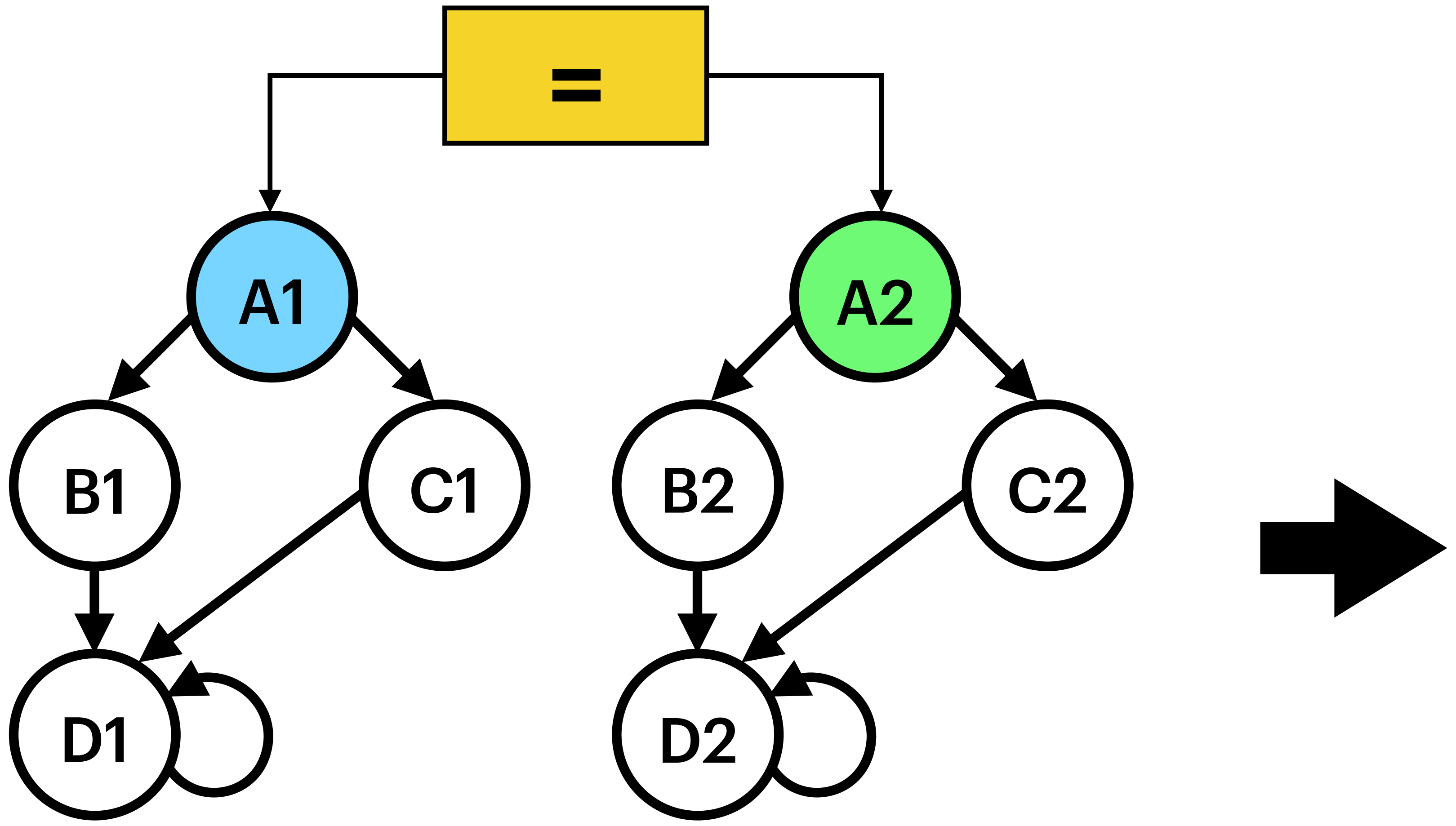

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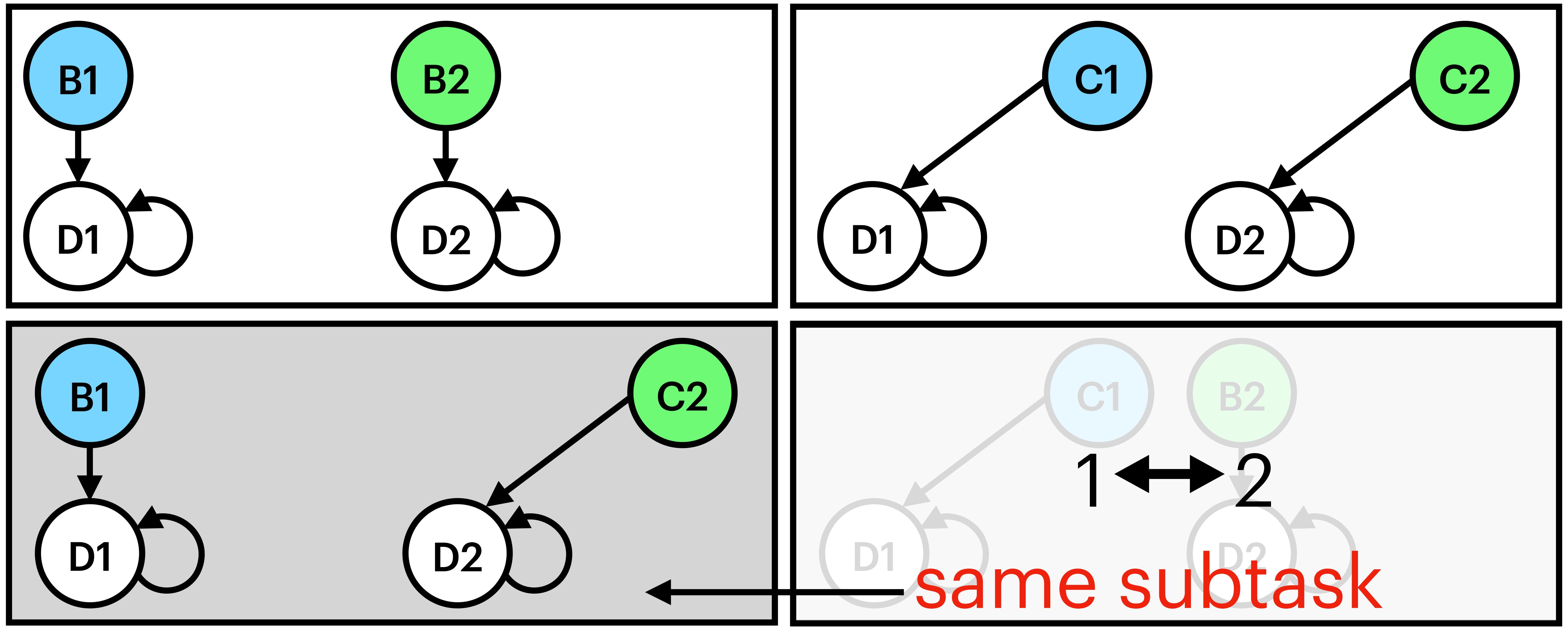

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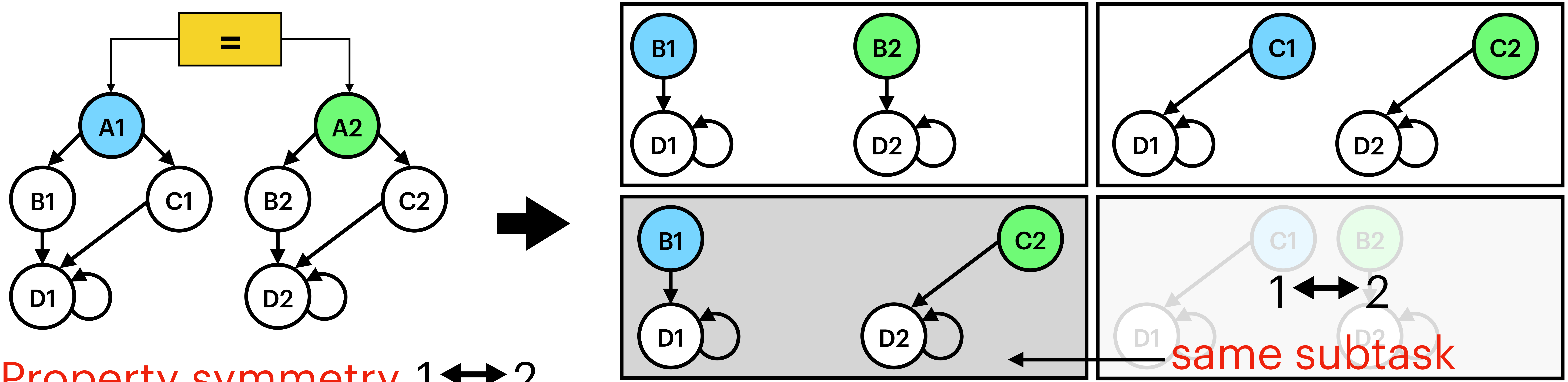

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verification subtasks

How to **infer** relational properties?

L. Pick, G. Fedyukovich, A. Gupta. Exploiting Synchrony and Symmetry in Relational Verification, CAV'18

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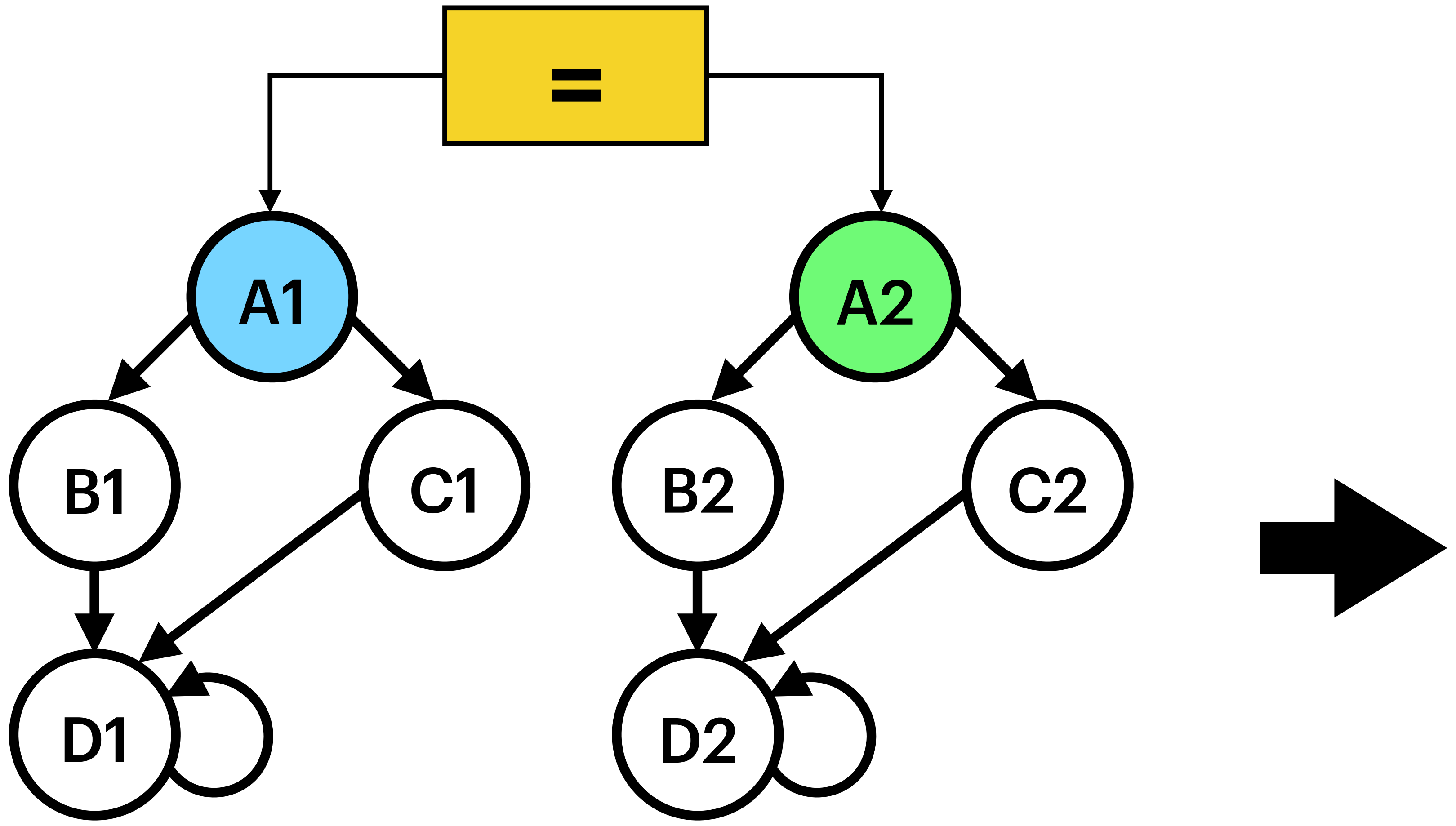

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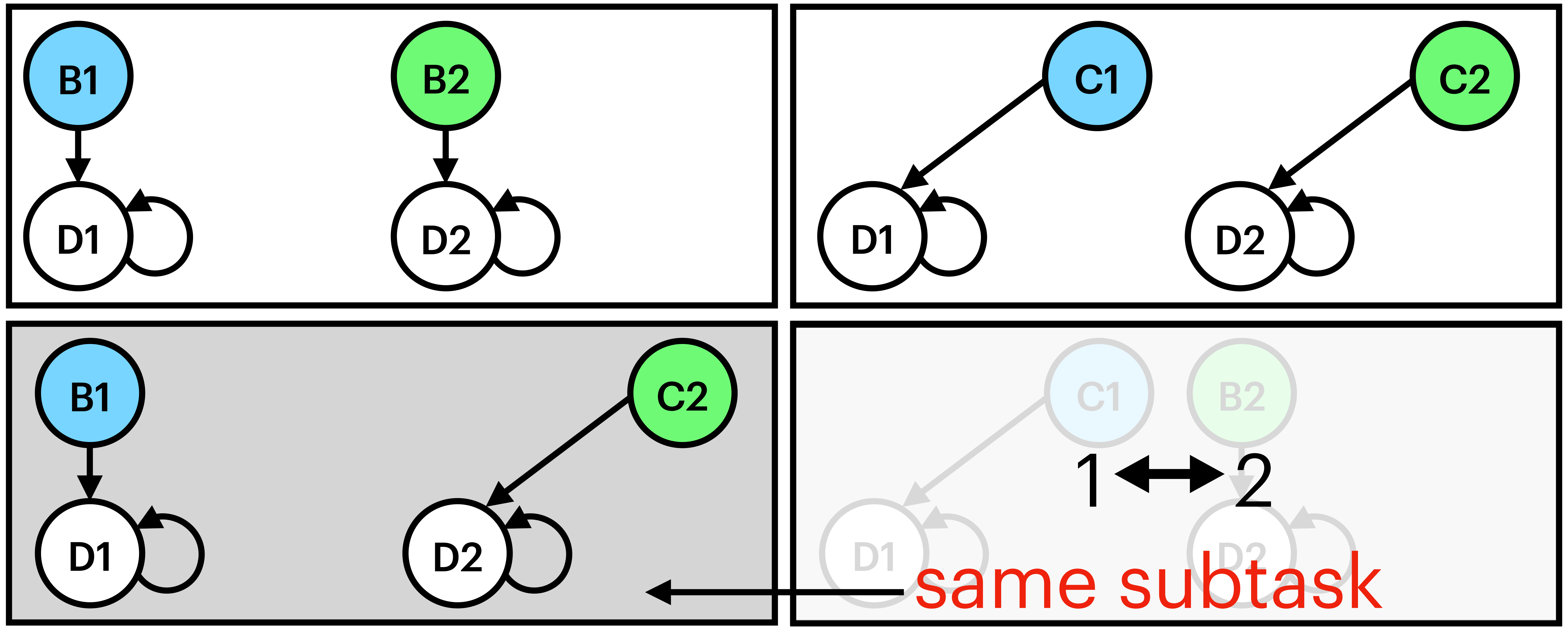
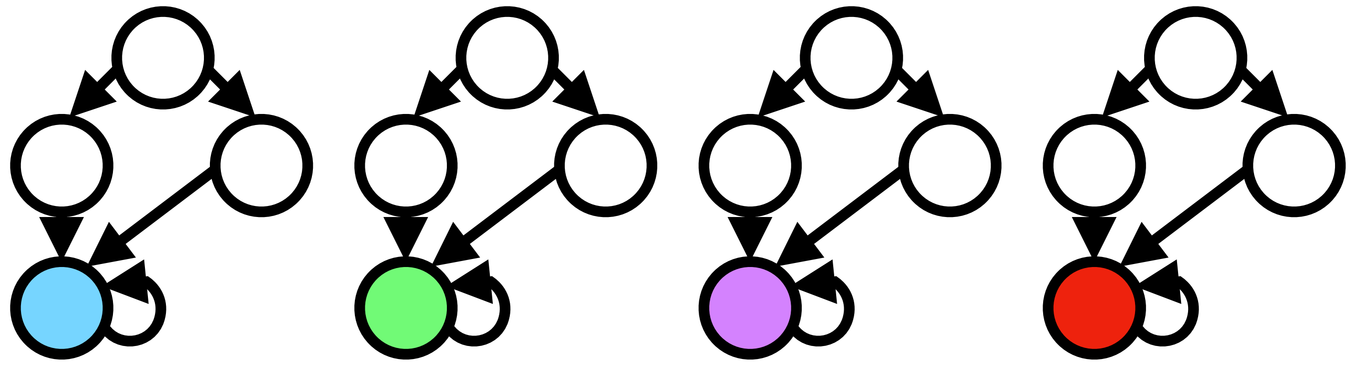


verification subtasks

How to **infer** relational properties?

Use **synchrony** technique for loops for fewer and simpler invariants



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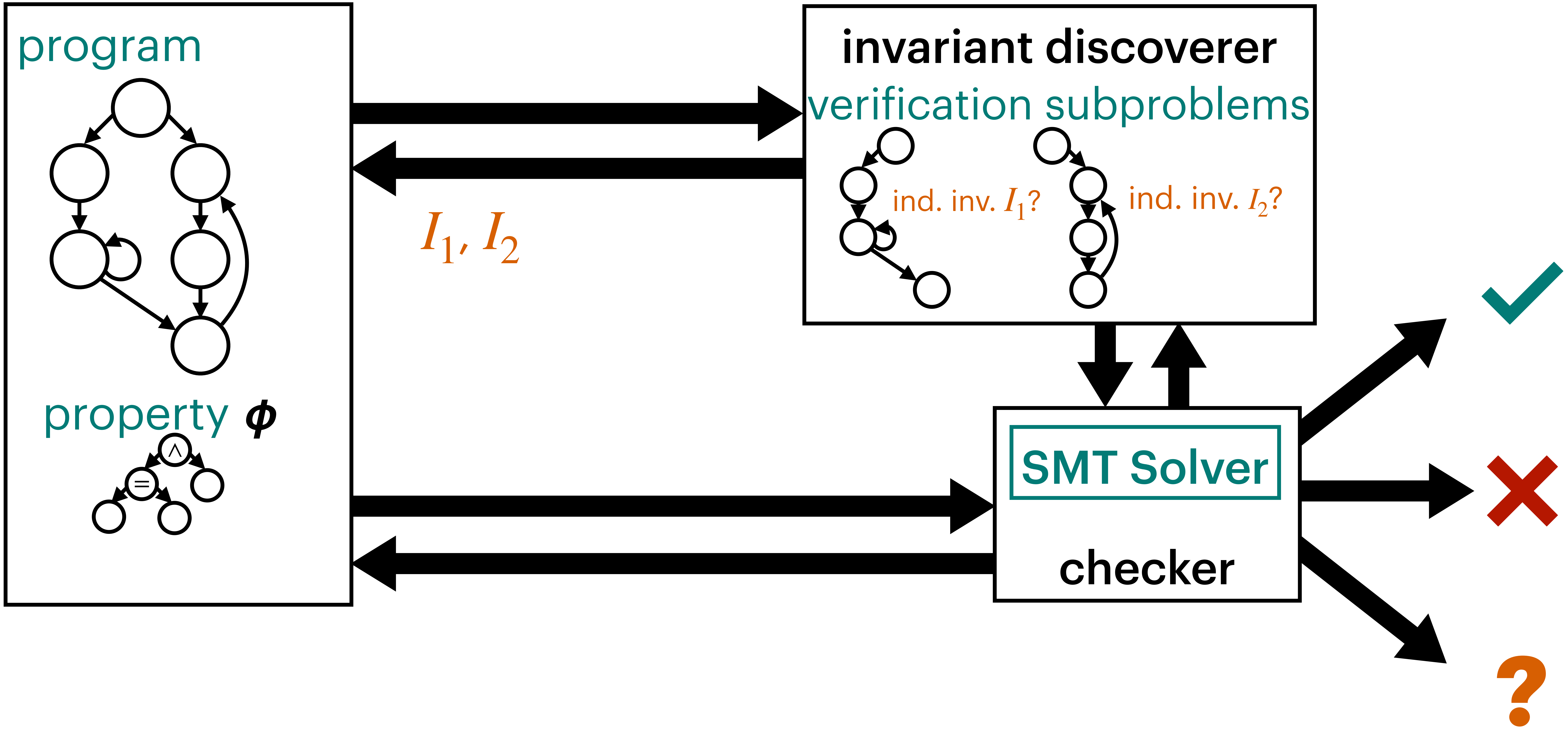
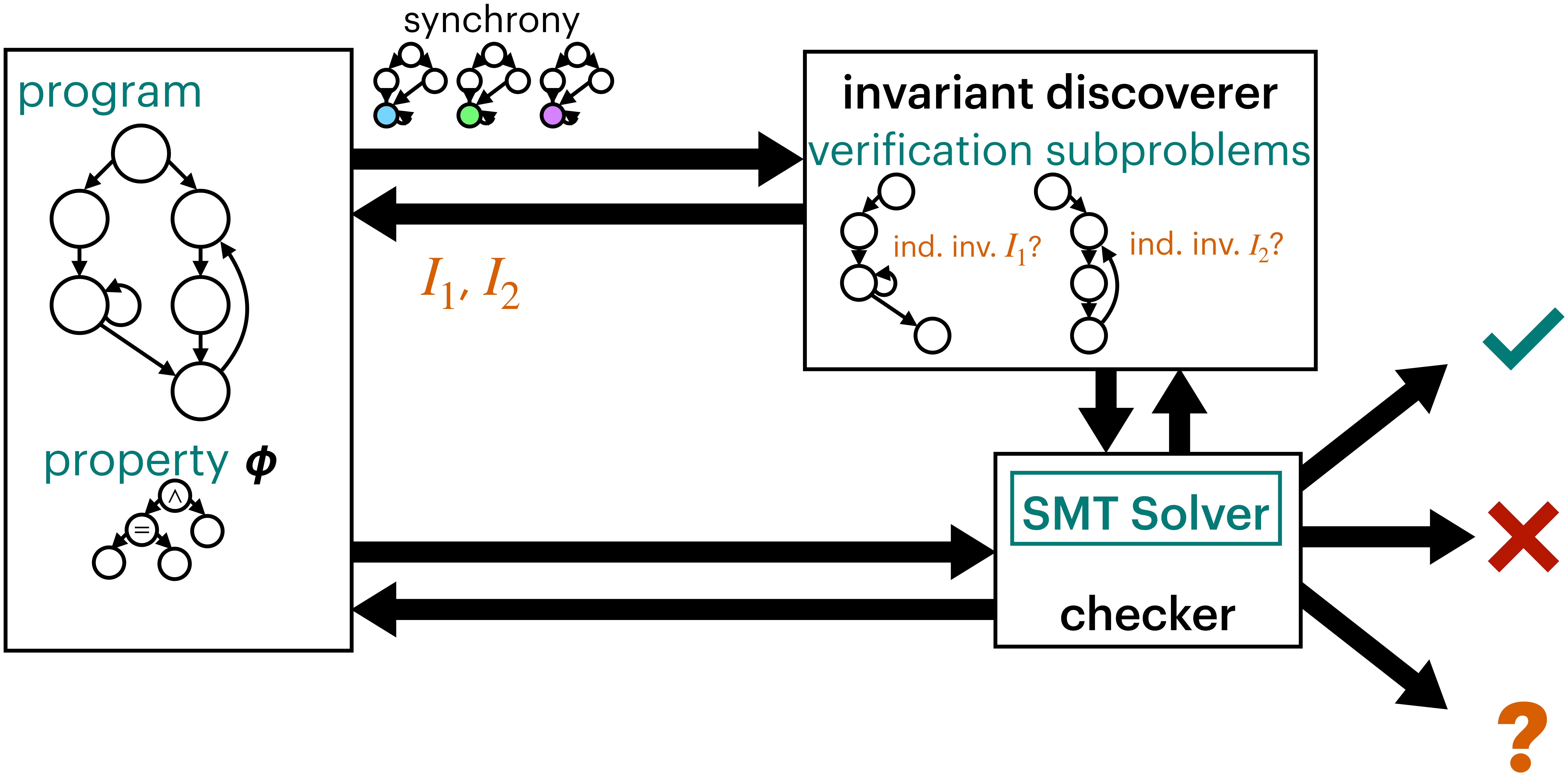
k-safety Verification



k-safety Verification



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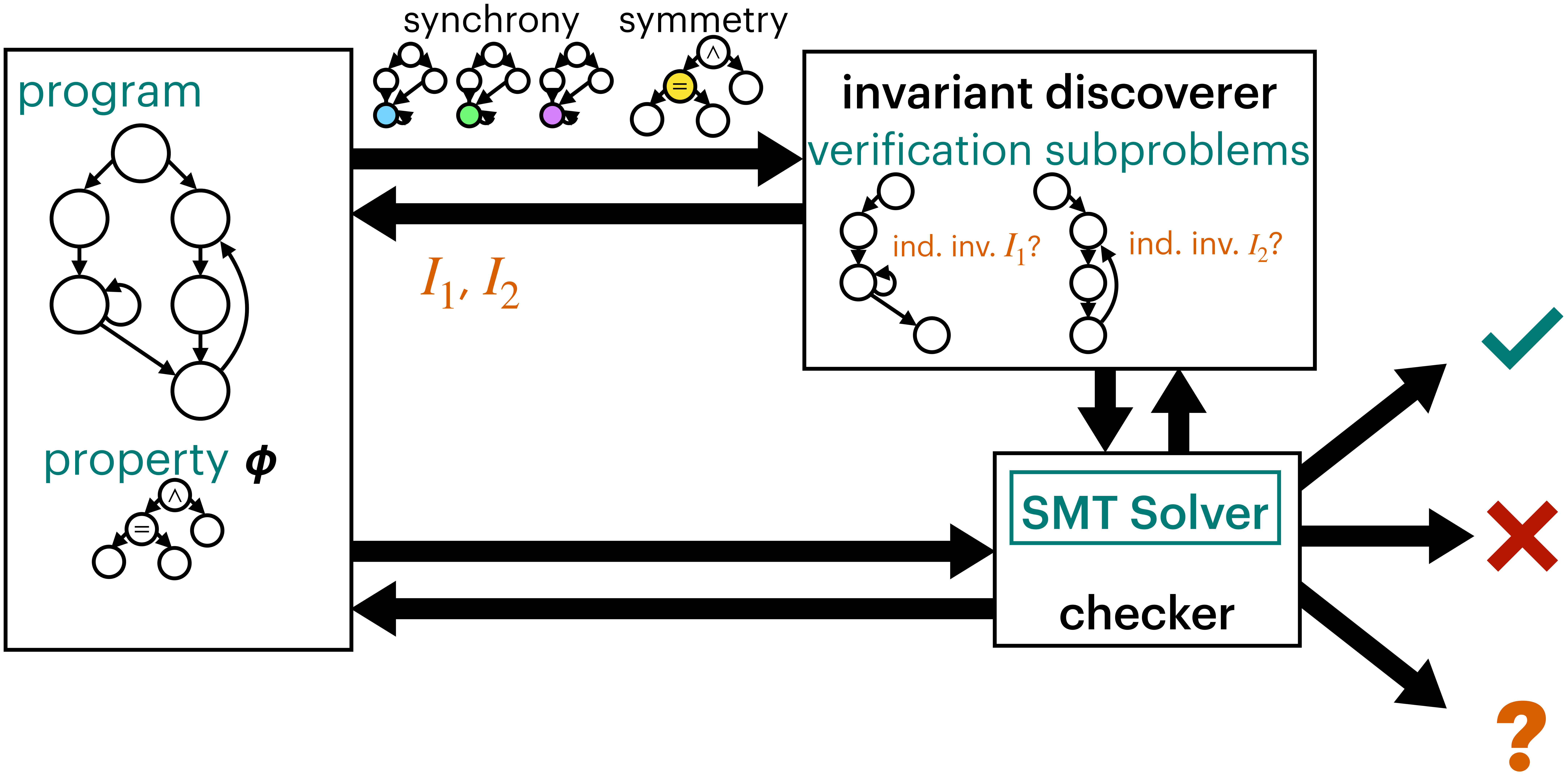
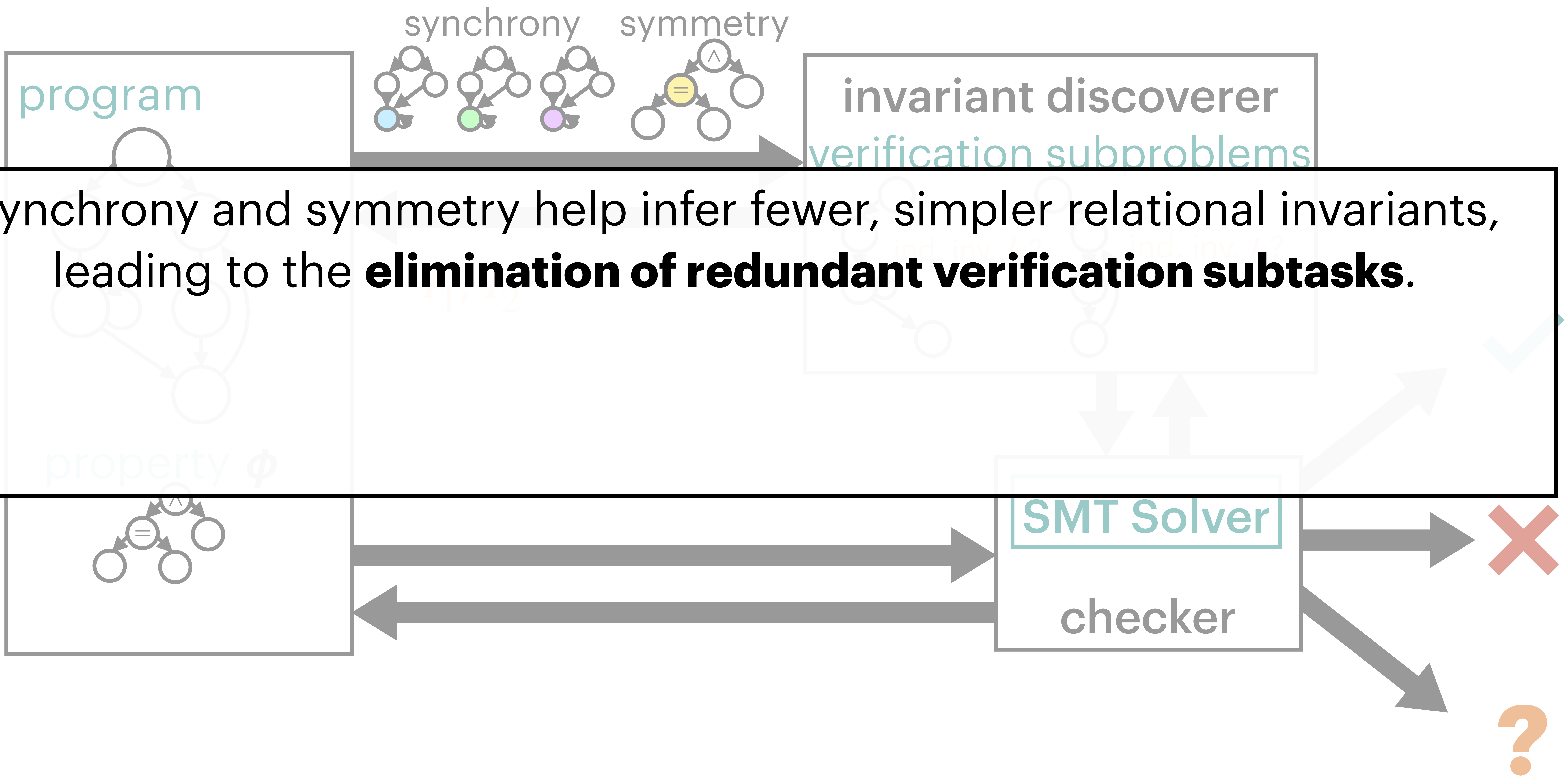
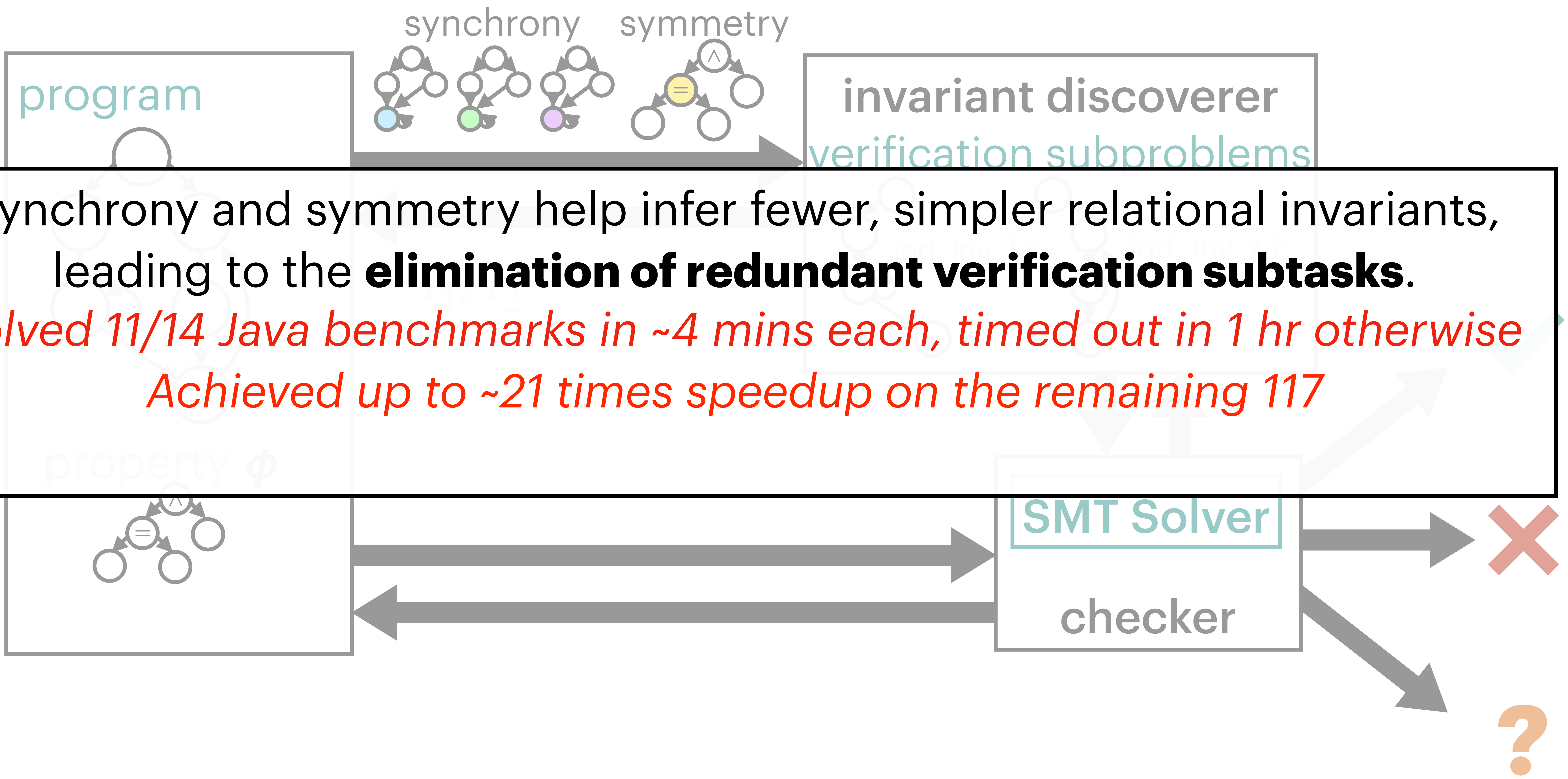


k-safety Verification



Synchrony and symmetry help infer fewer, simpler relational invariants, leading to the **elimination of redundant verification subtasks**.

k-safety Verification



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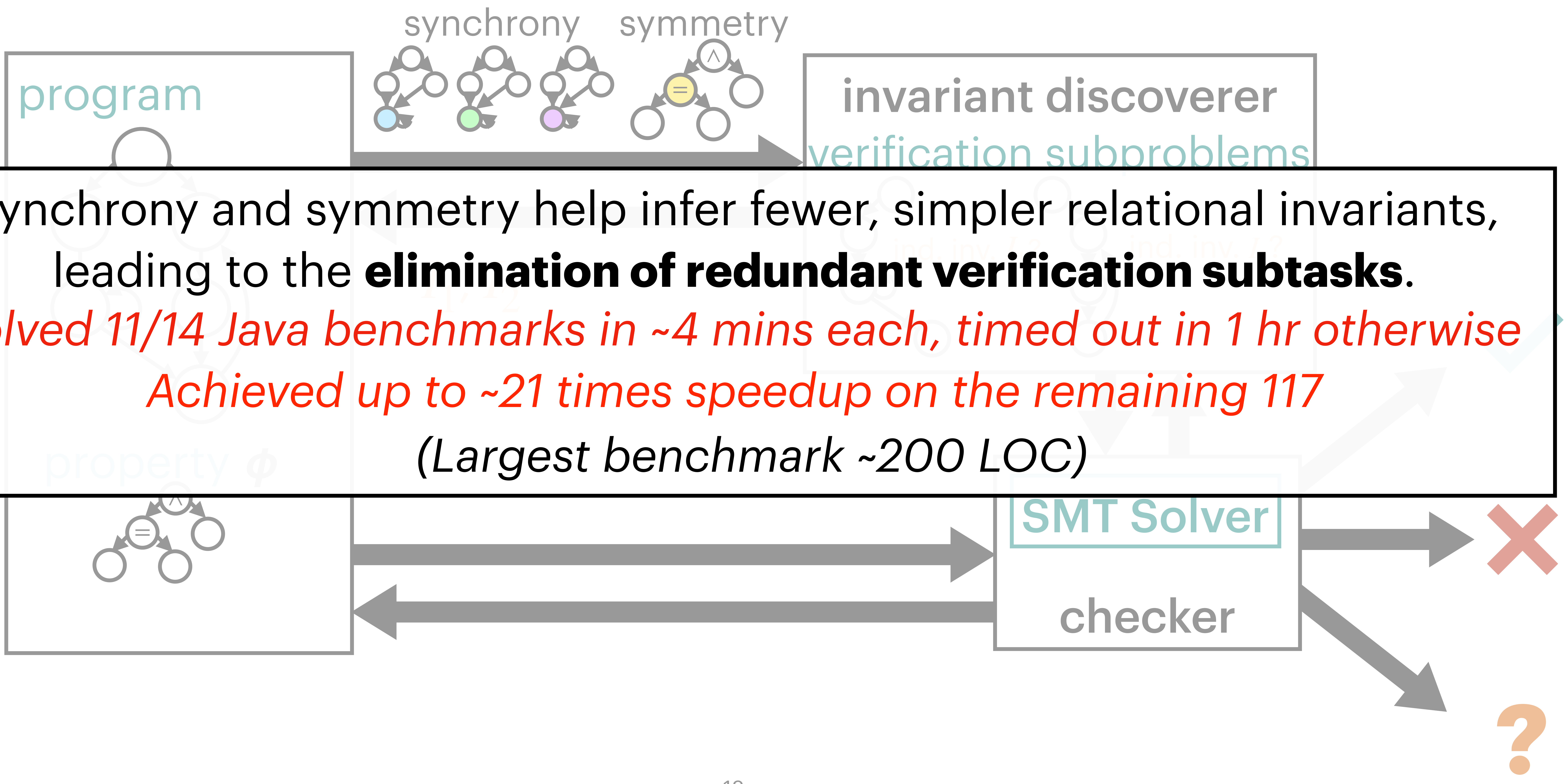
Solved 11/14 Java benchmarks in ~4 mins each, timed out in 1 hr otherwise

Achieved up to ~21 times speedup on the remaining 117

k-safety Verification



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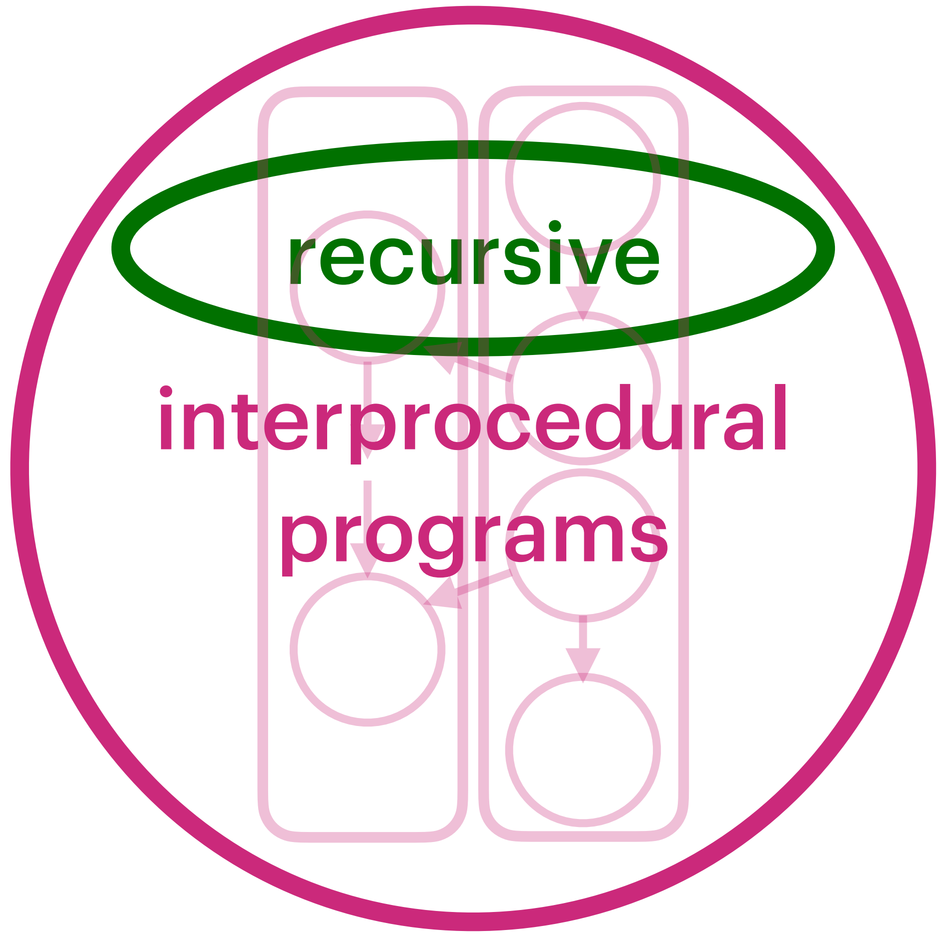
(Largest benchmark ~200 LOC)

II. Interprocedural Program Verification

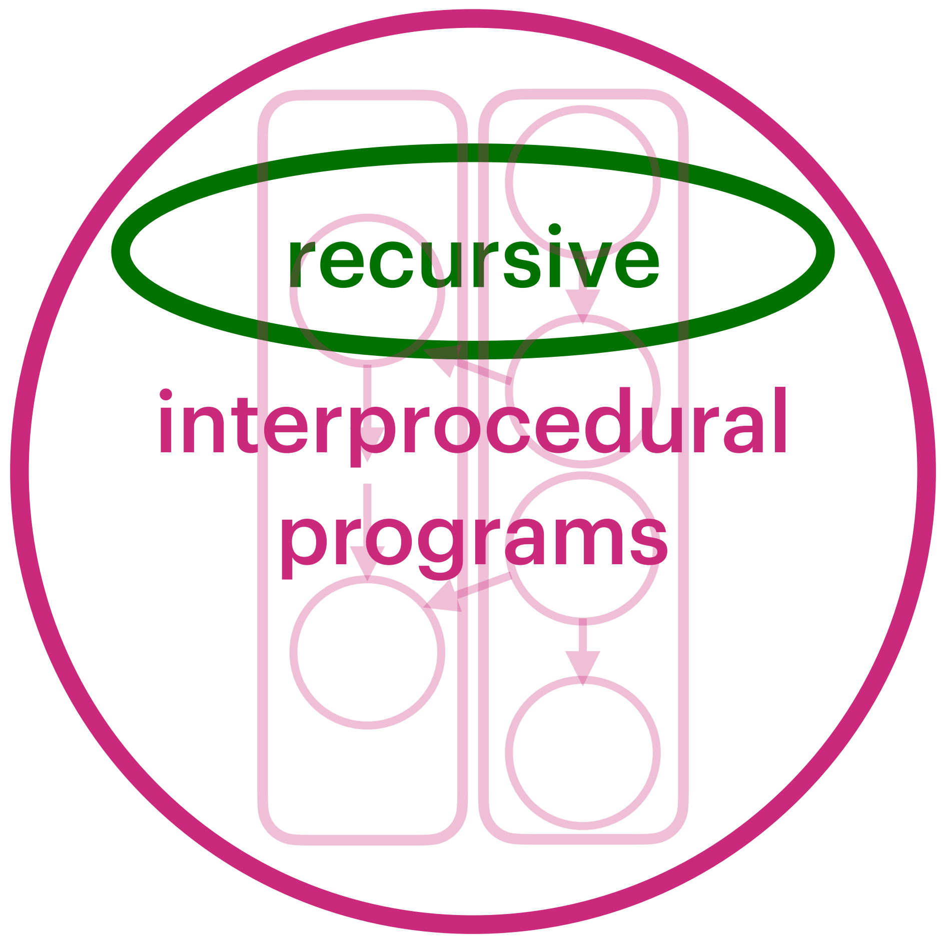


+

Multiple-procedure programs
(may contain recursion)

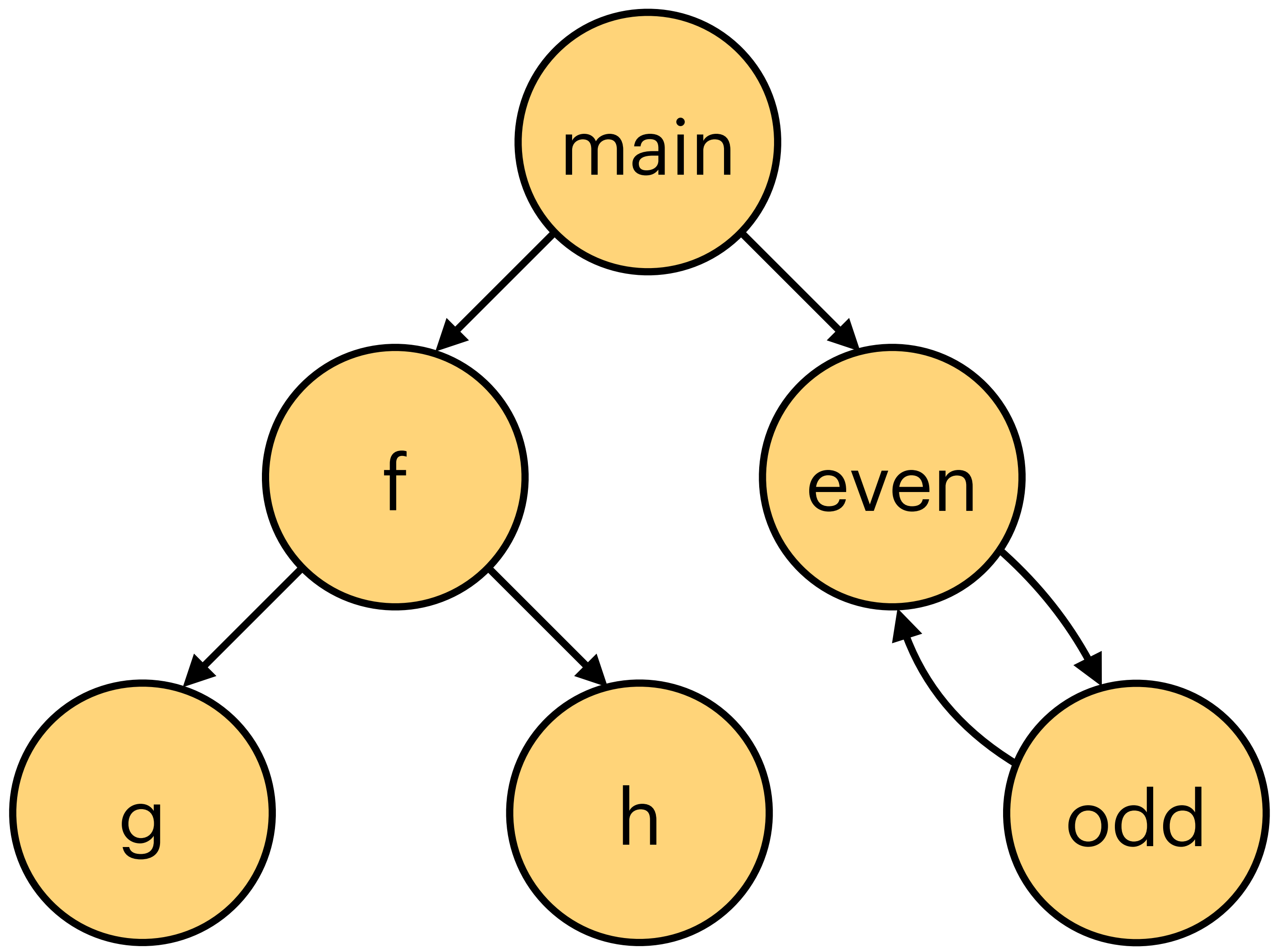
General safety properties
(hoisted to entry procedure)

Interprocedural Programs

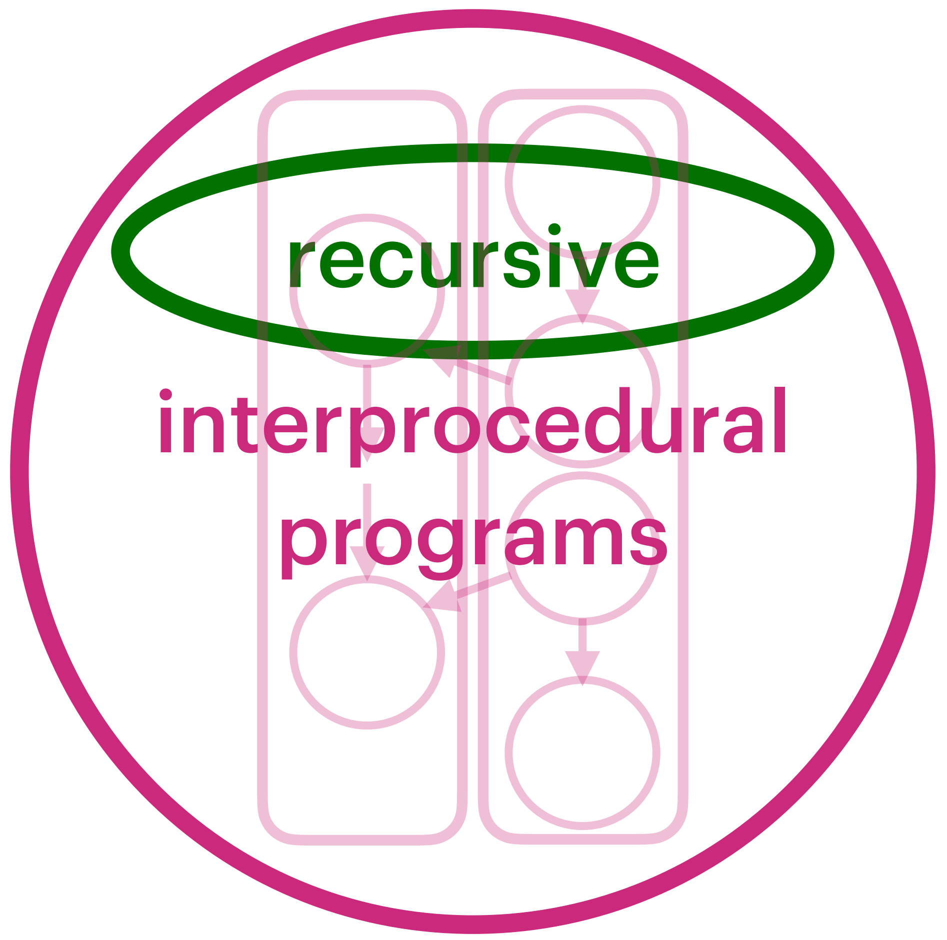


Have call graphs

Example call graph



Interprocedural Programs



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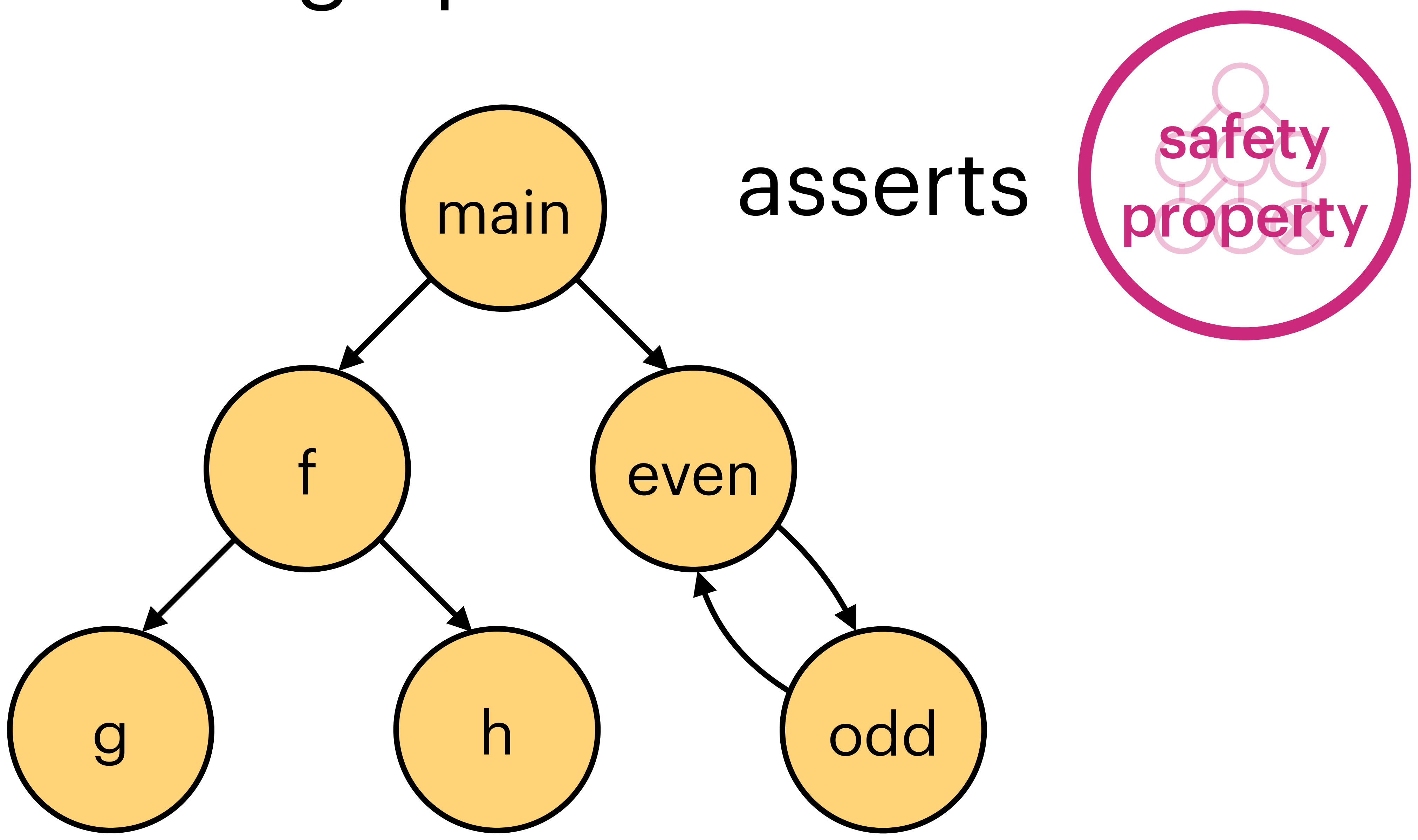
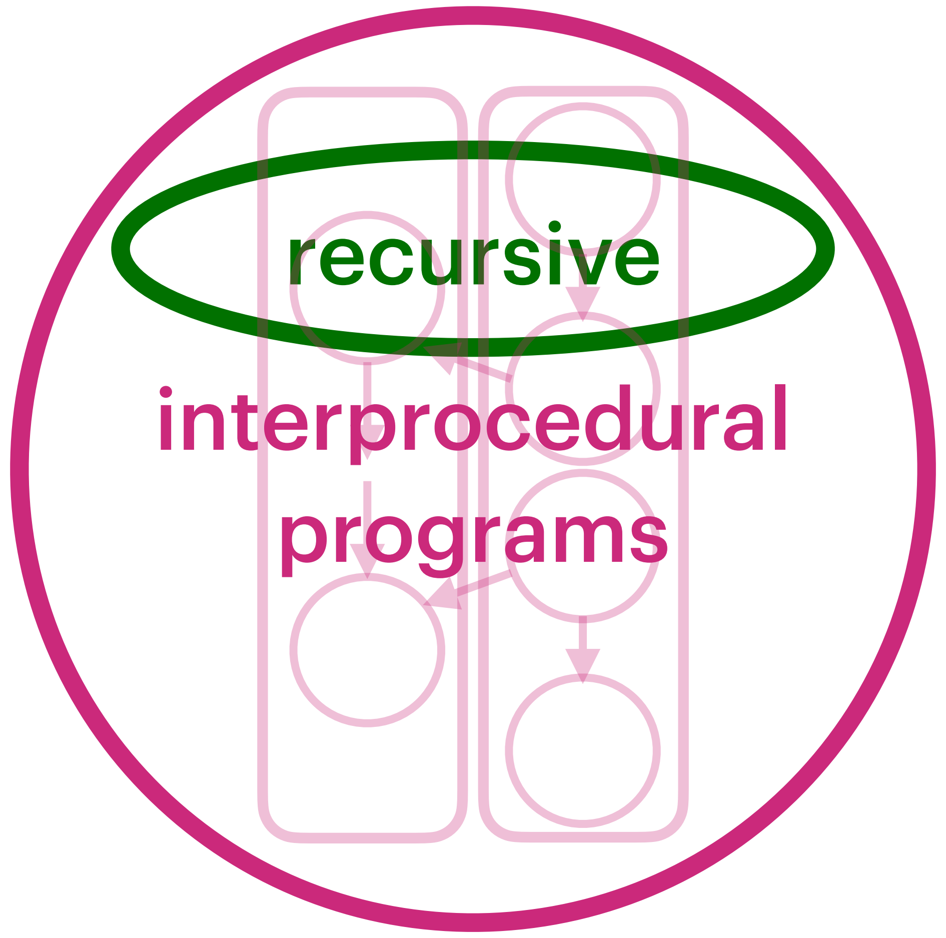


Interprocedural Programs



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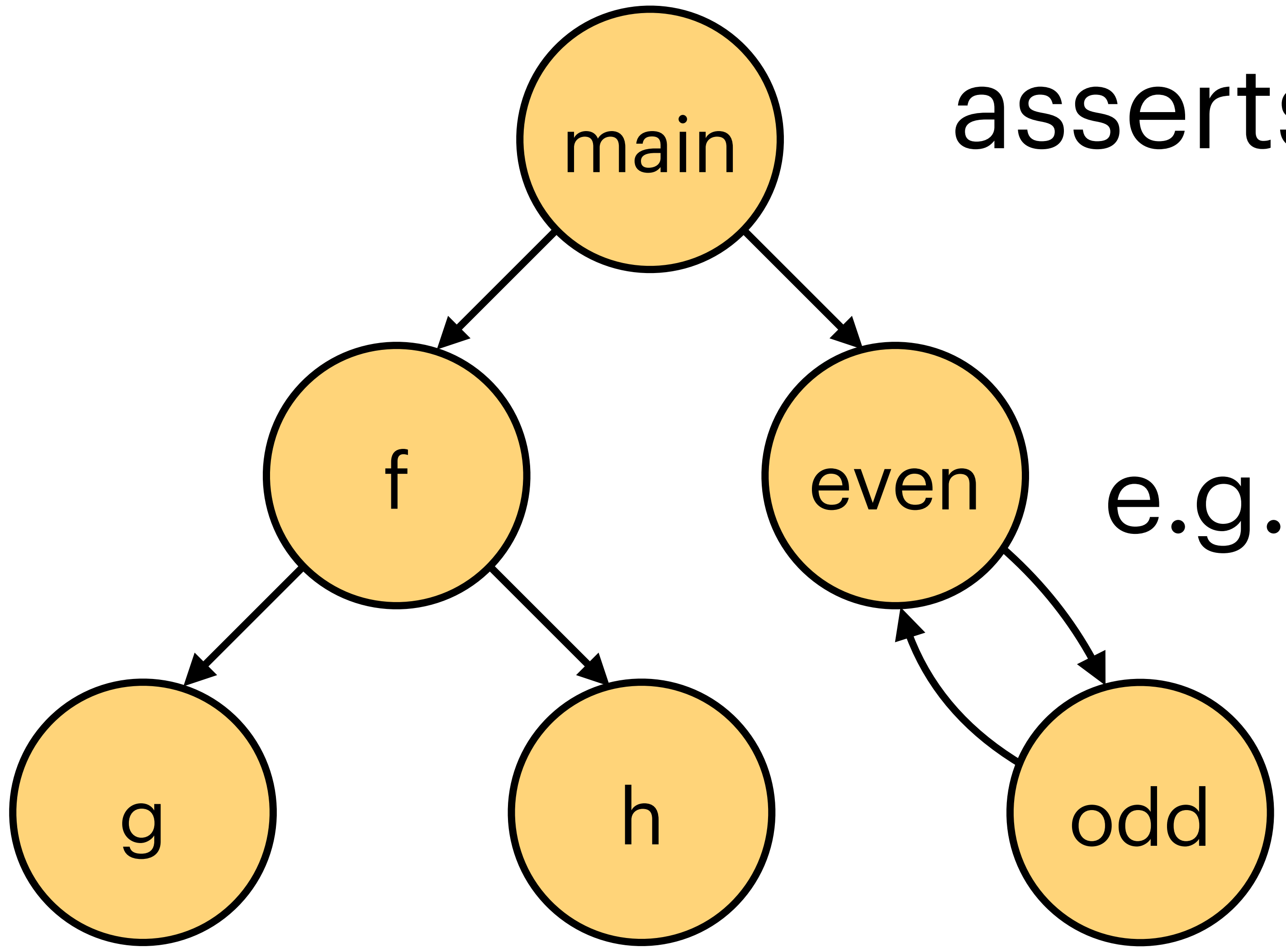

asserts

e.g., $even(f(x)) \bmod 2 \equiv 0$

Interprocedural Programs

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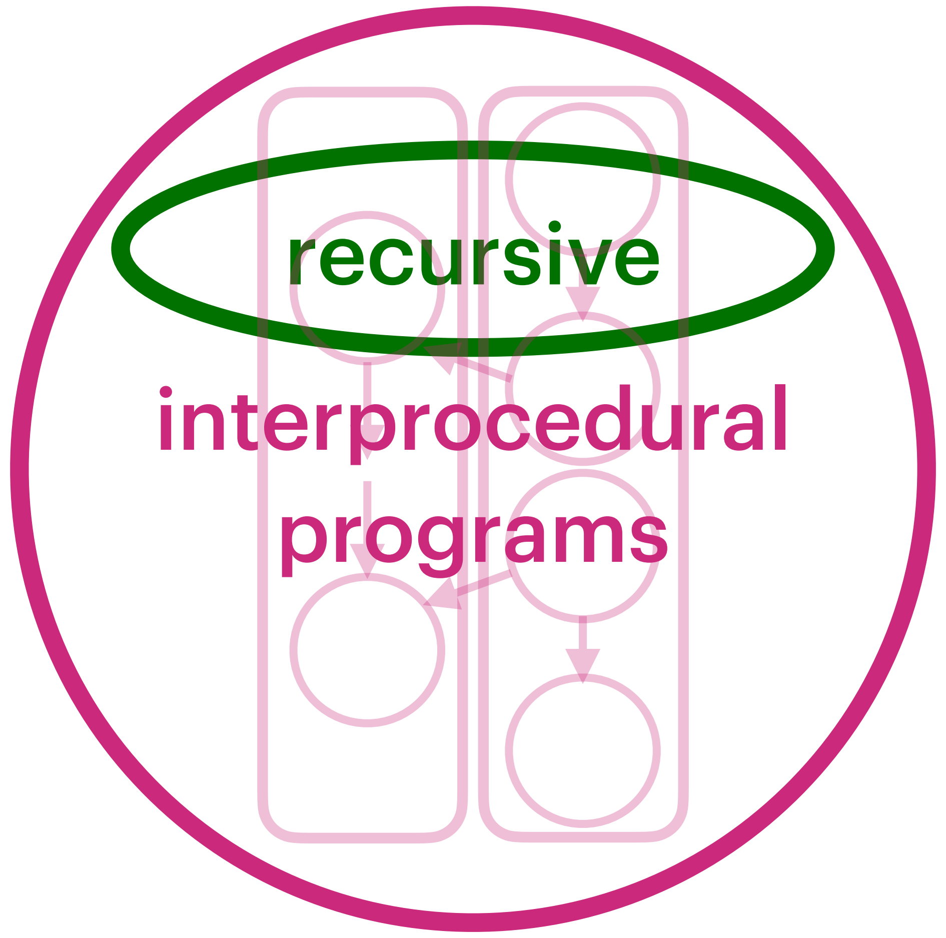

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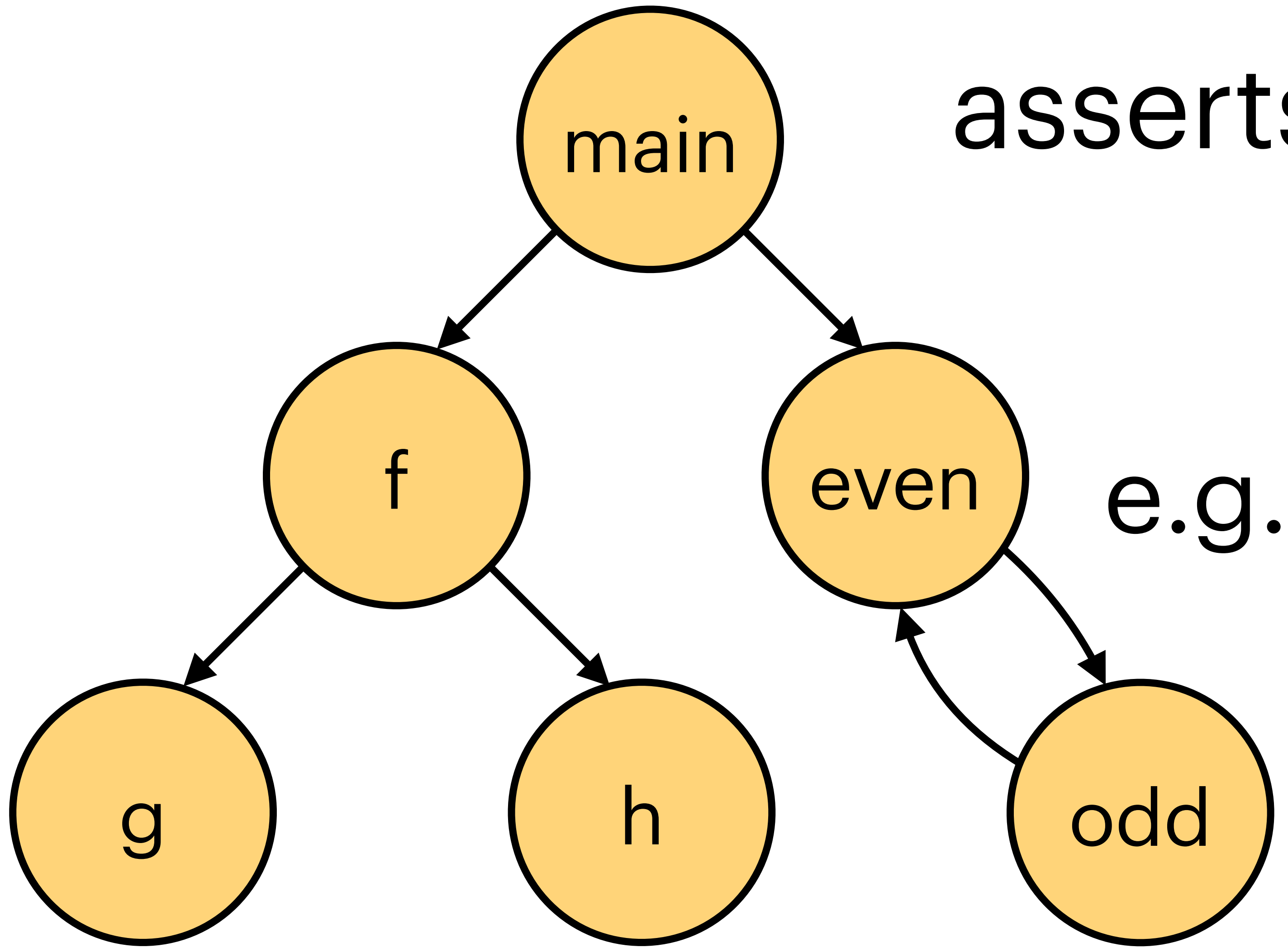


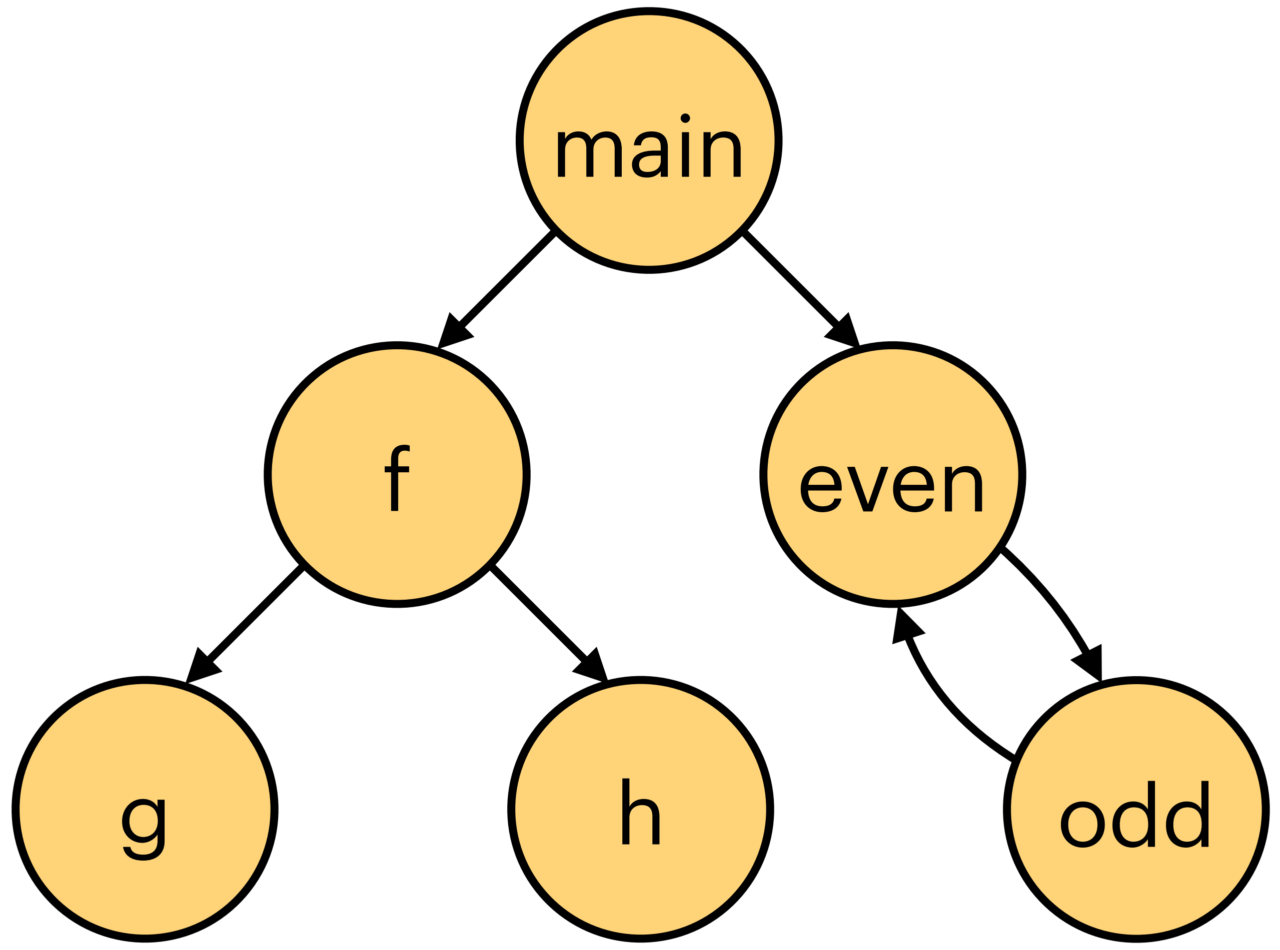
asserts

e.g., $even(f(x)) \bmod 2 \equiv 0$

Will derive and use over- and under-approximate procedure summaries

Modular Verification of Interprocedural Programs

Infer and use procedure summaries (invariants)



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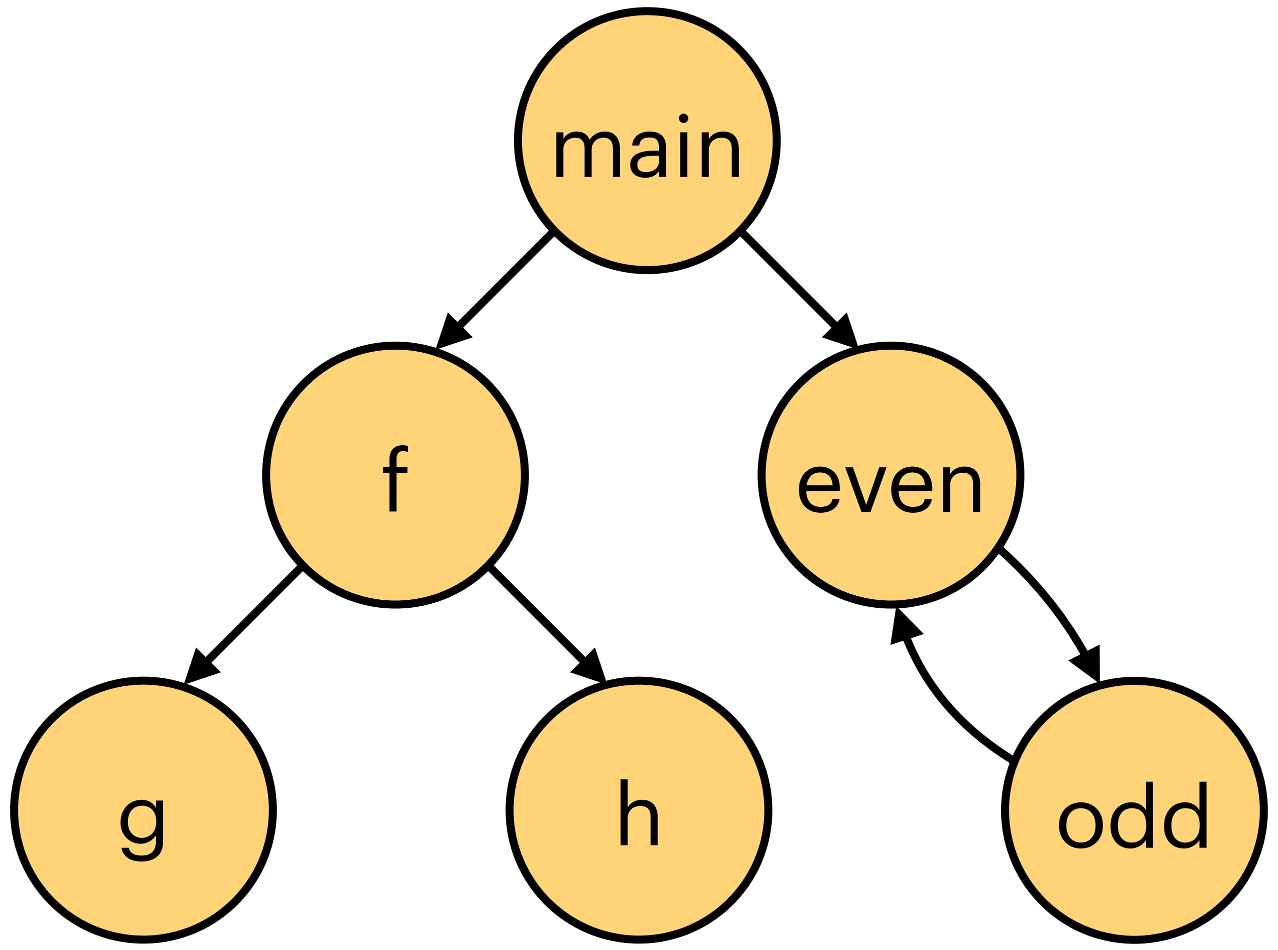

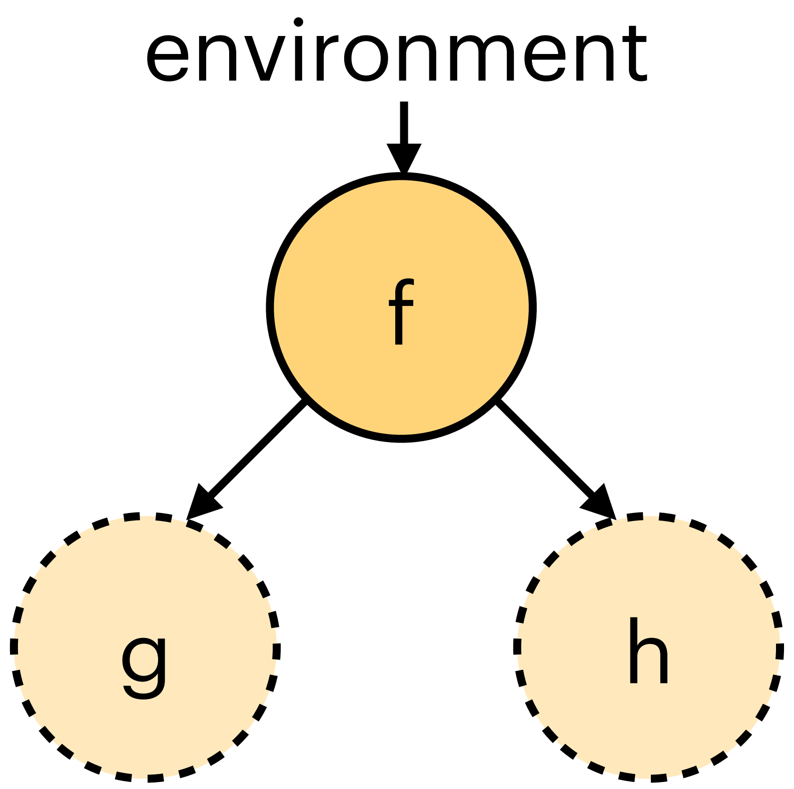

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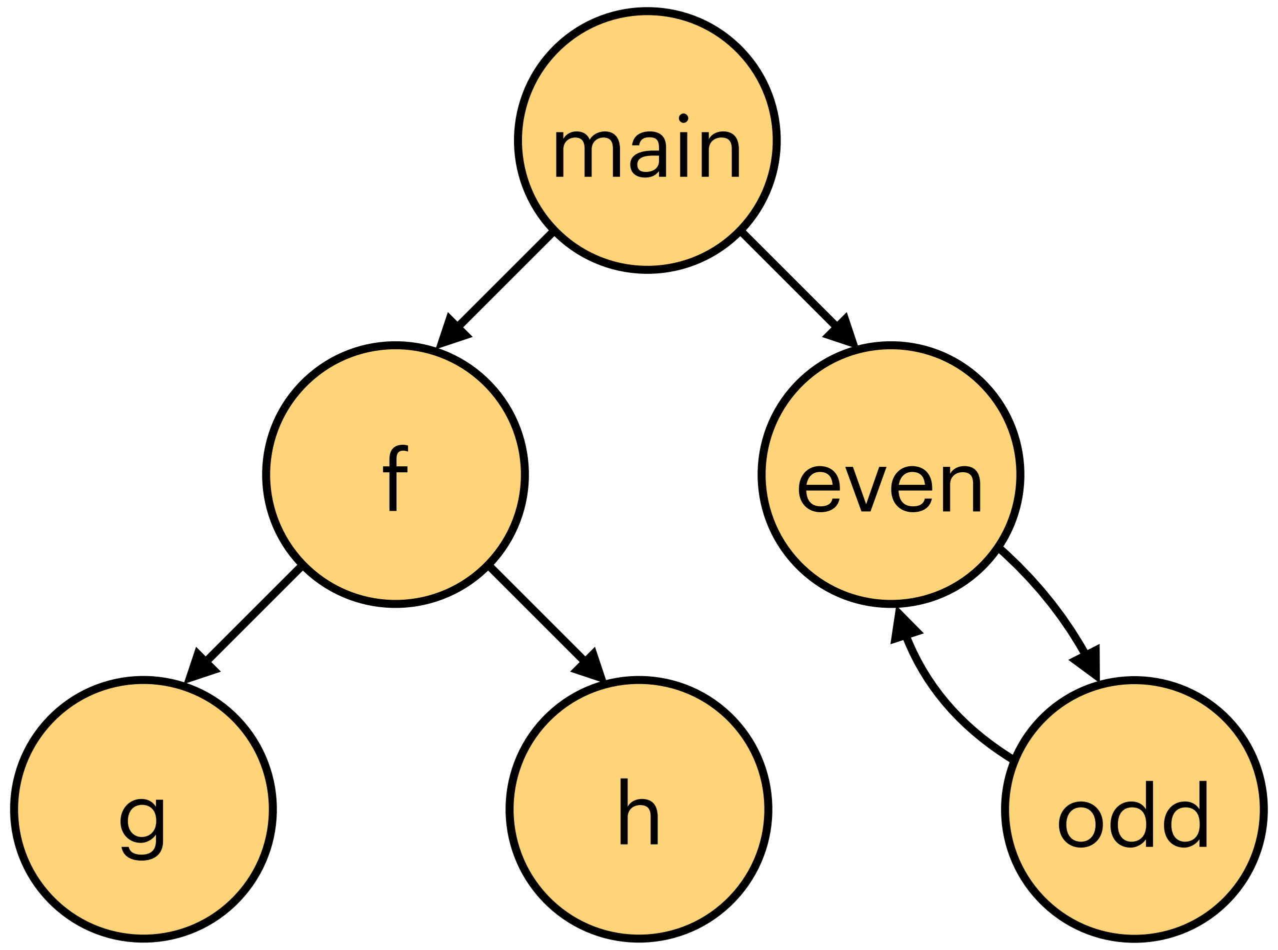

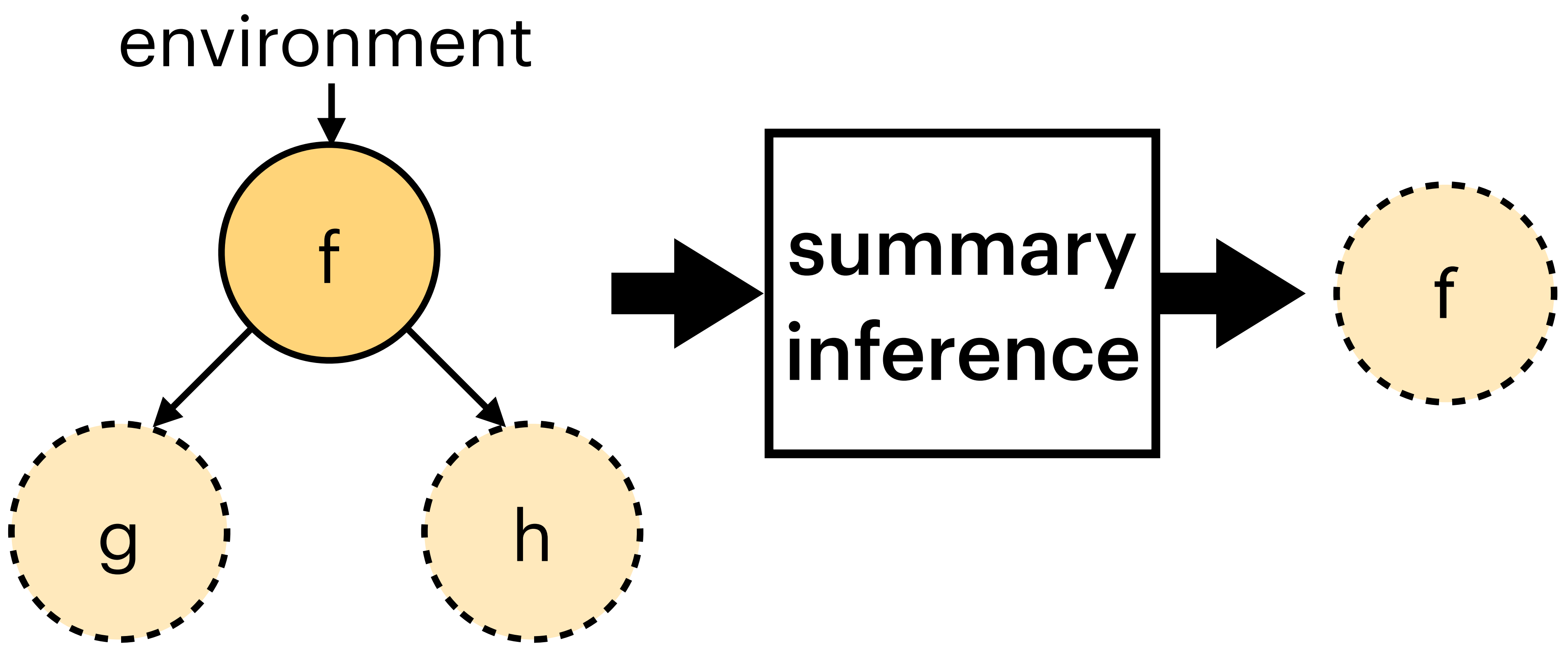

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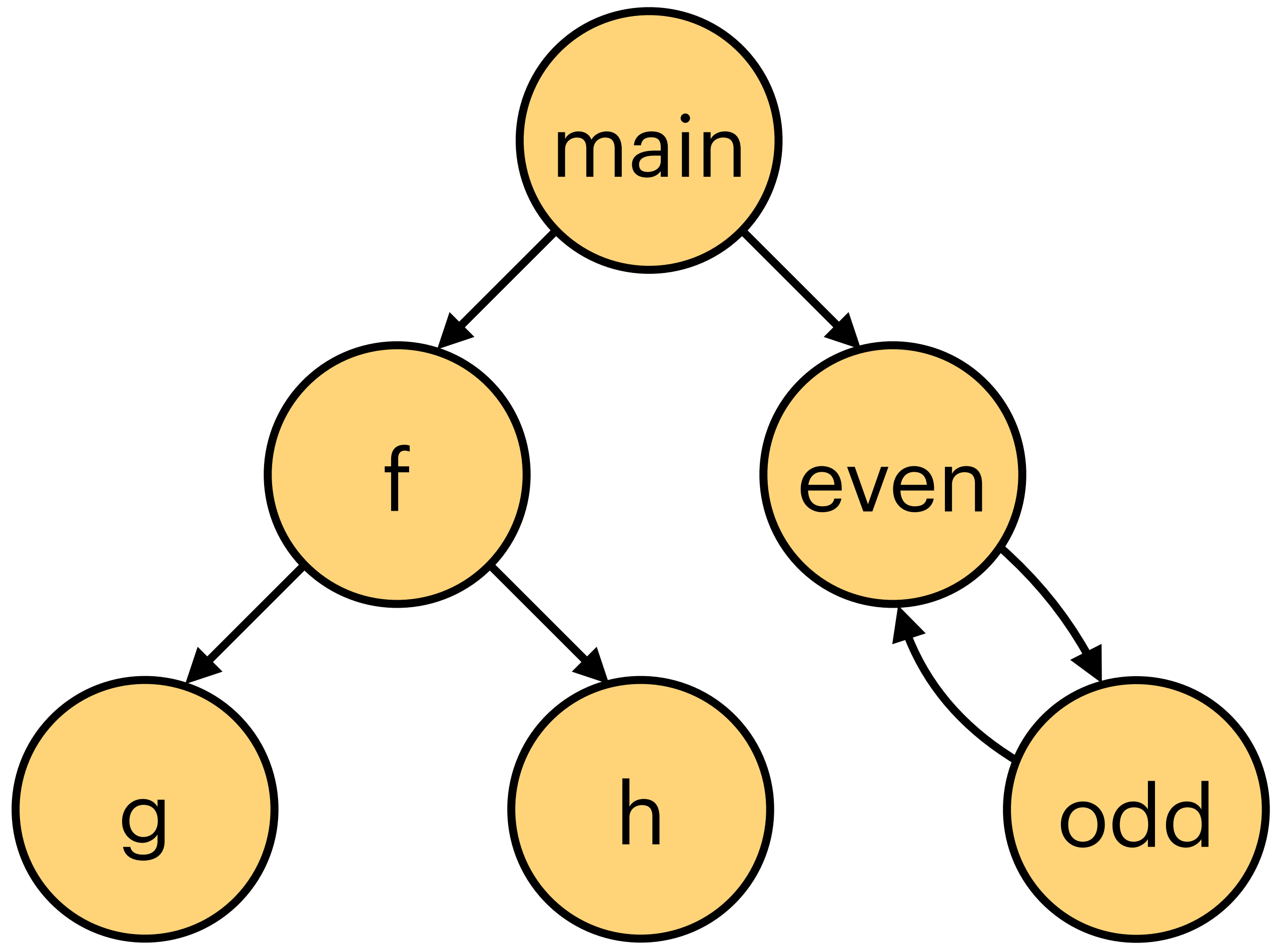

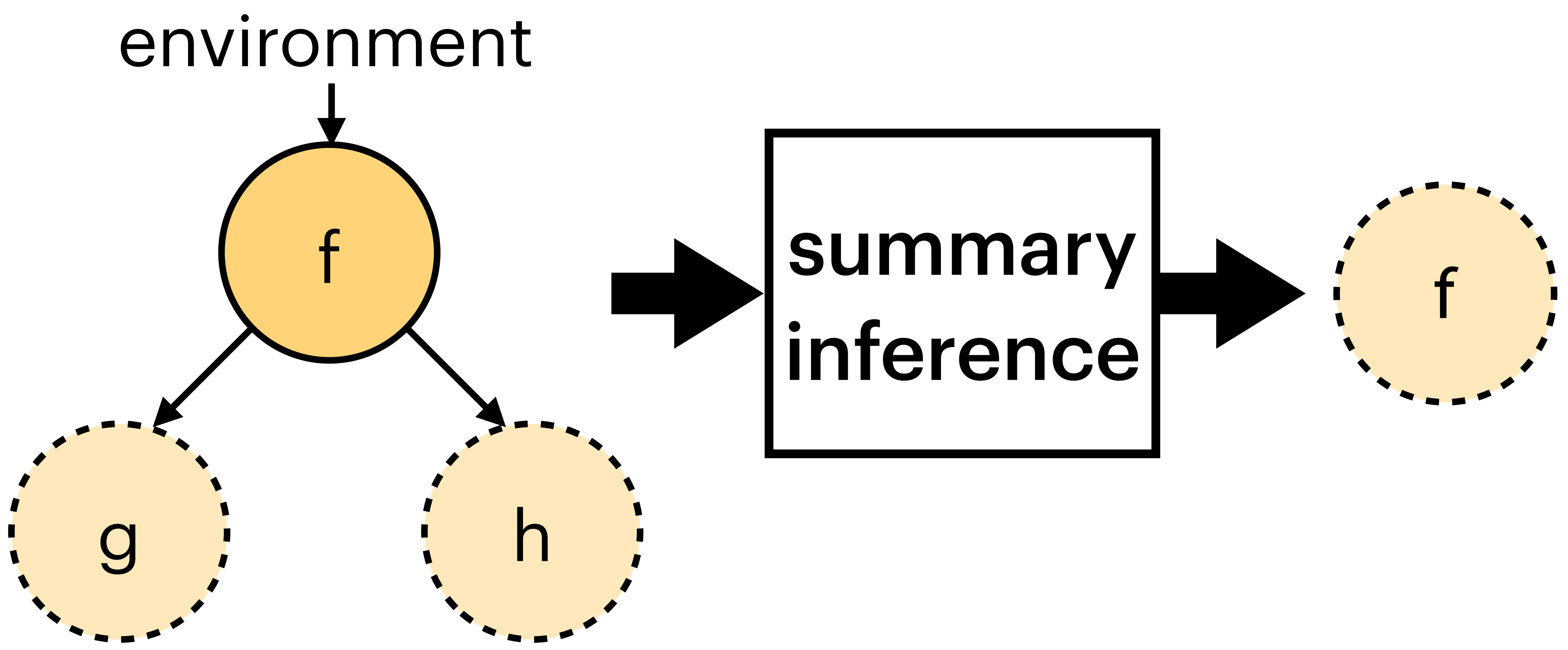

to handle mutual recursion

Modular Verification of Interprocedural Programs

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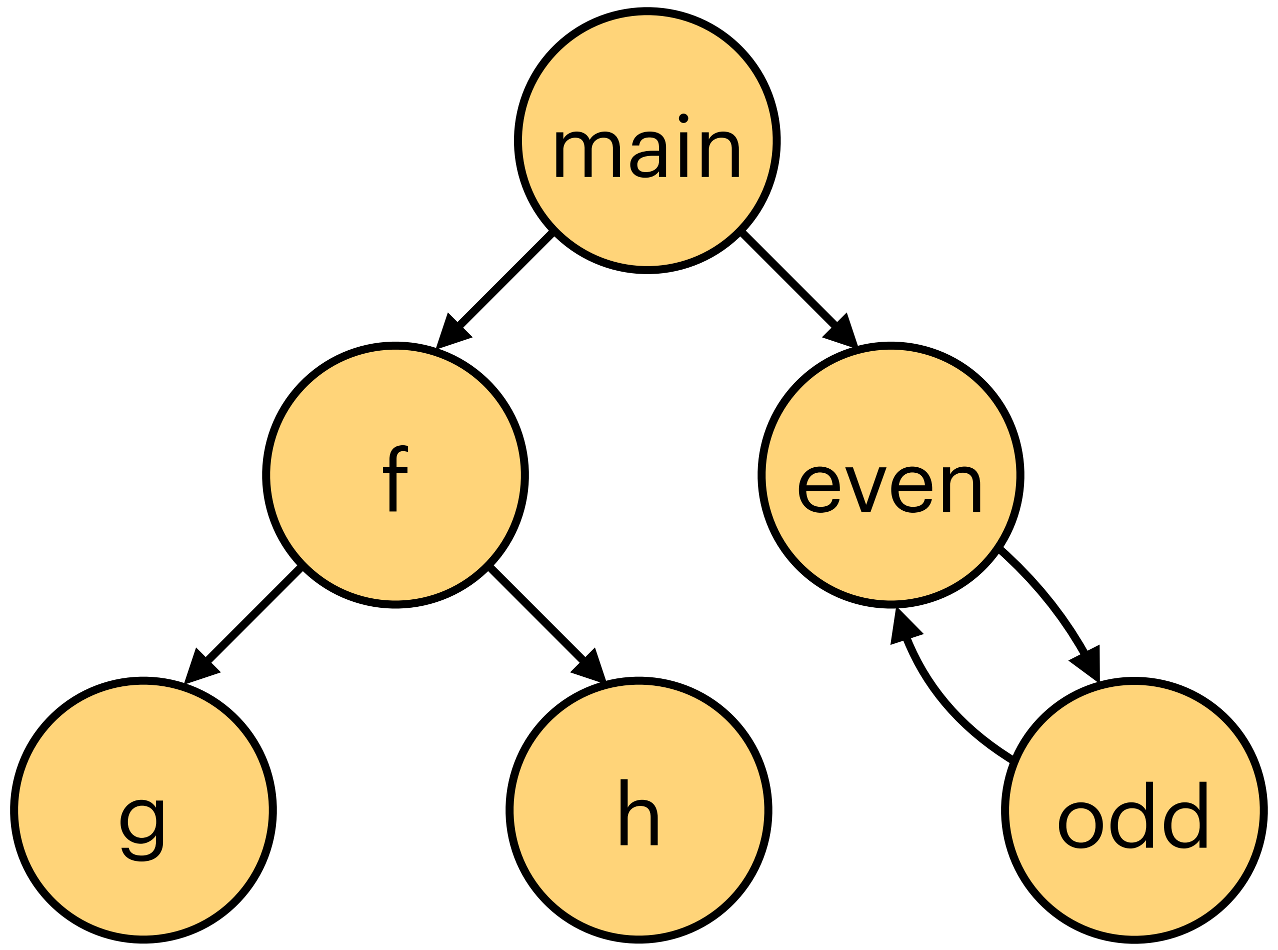

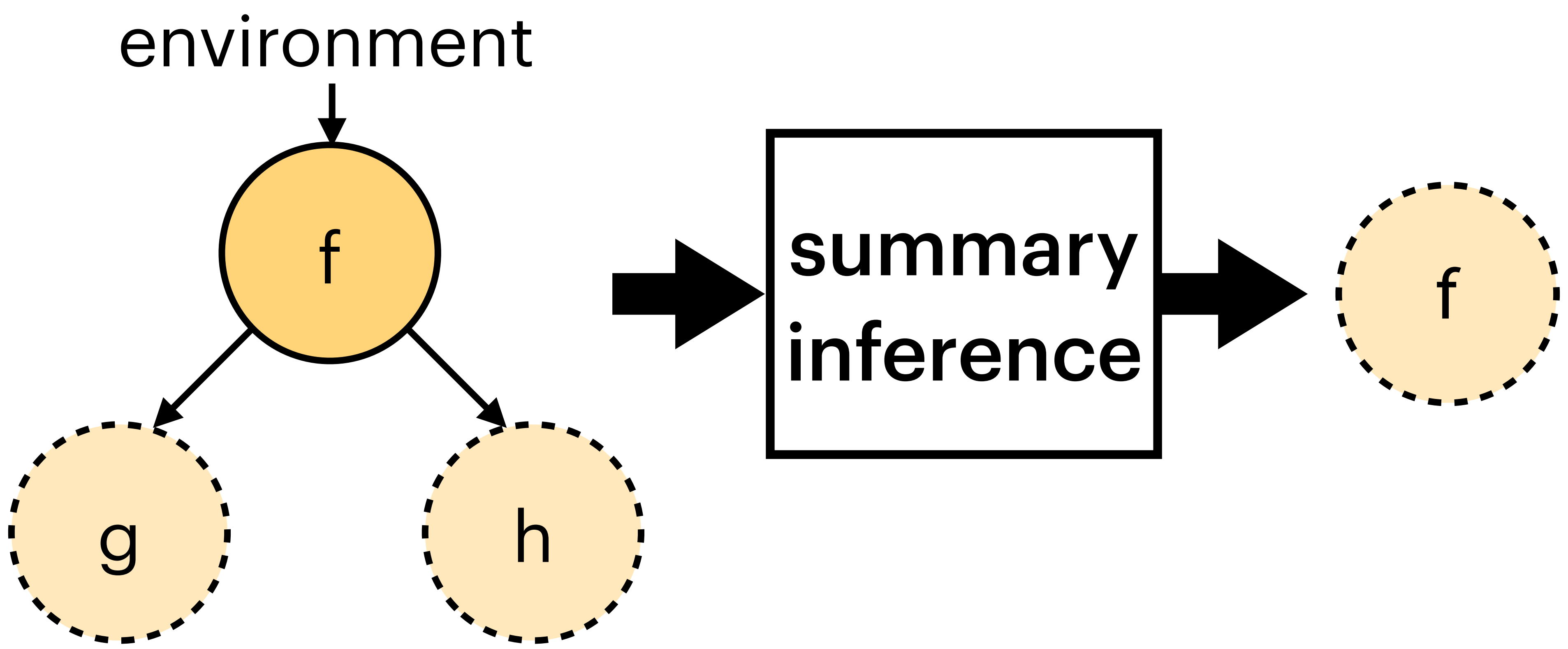

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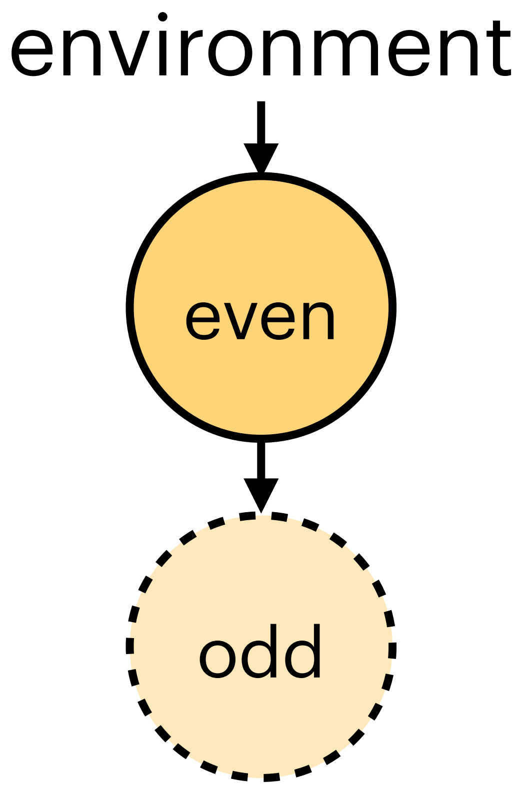

Modular Verification of Interprocedural Programs

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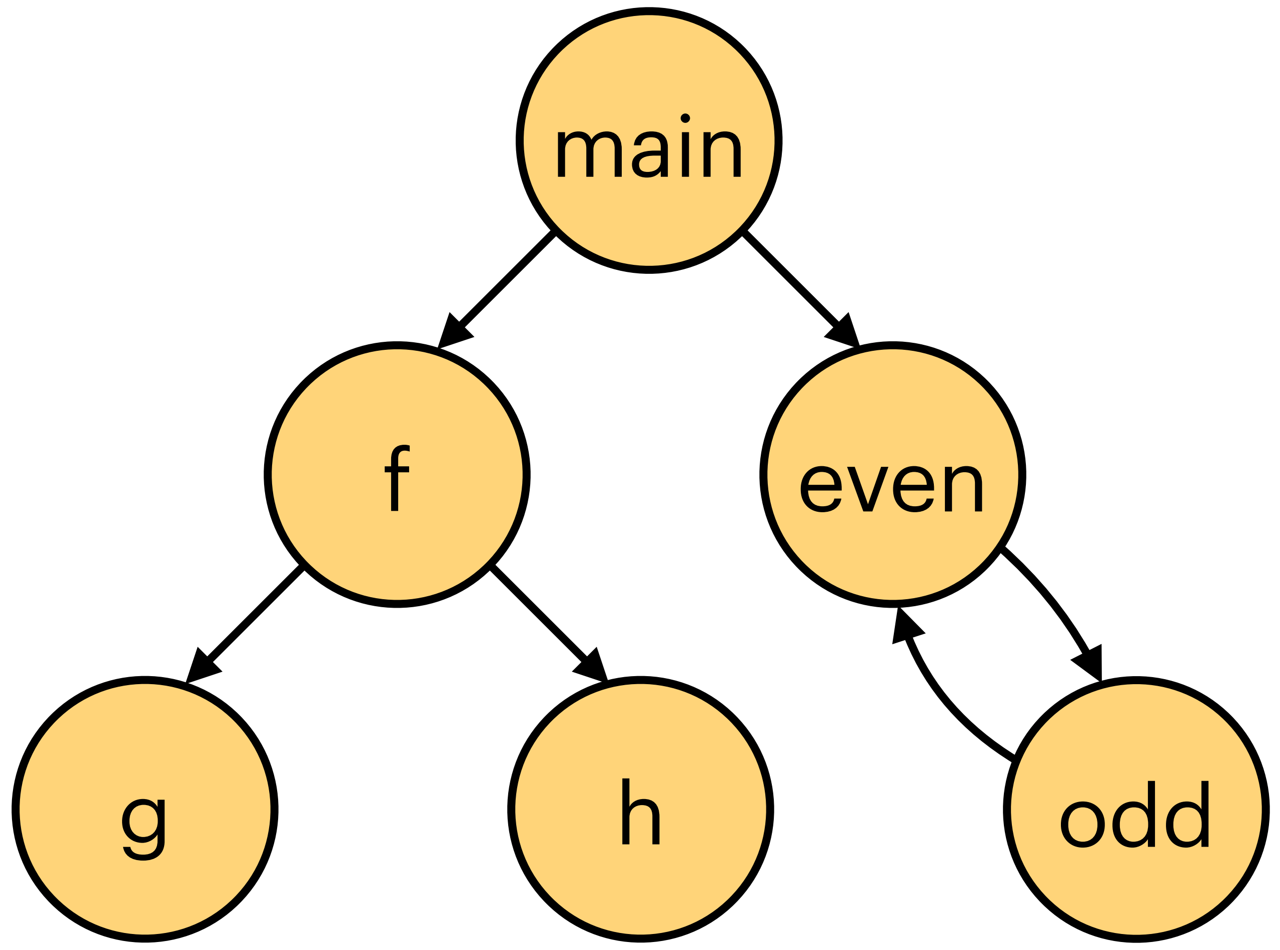

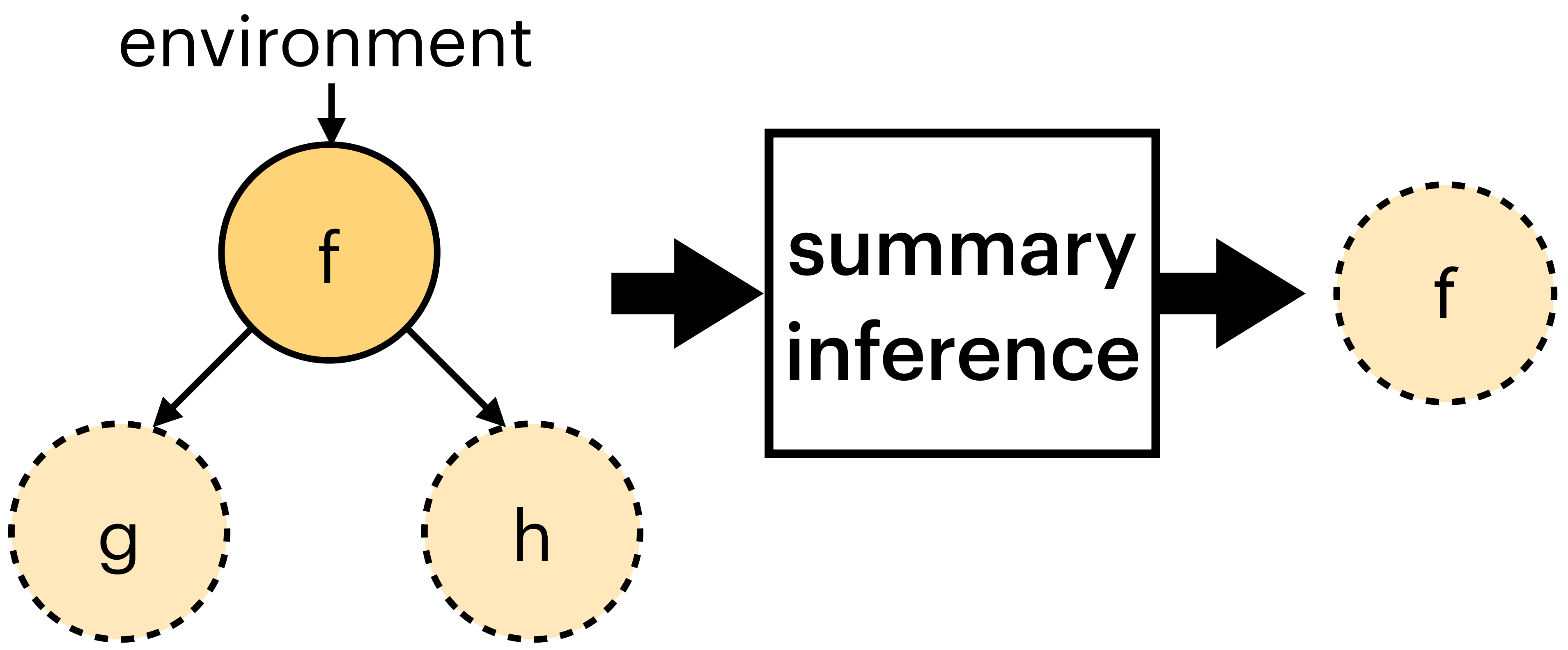

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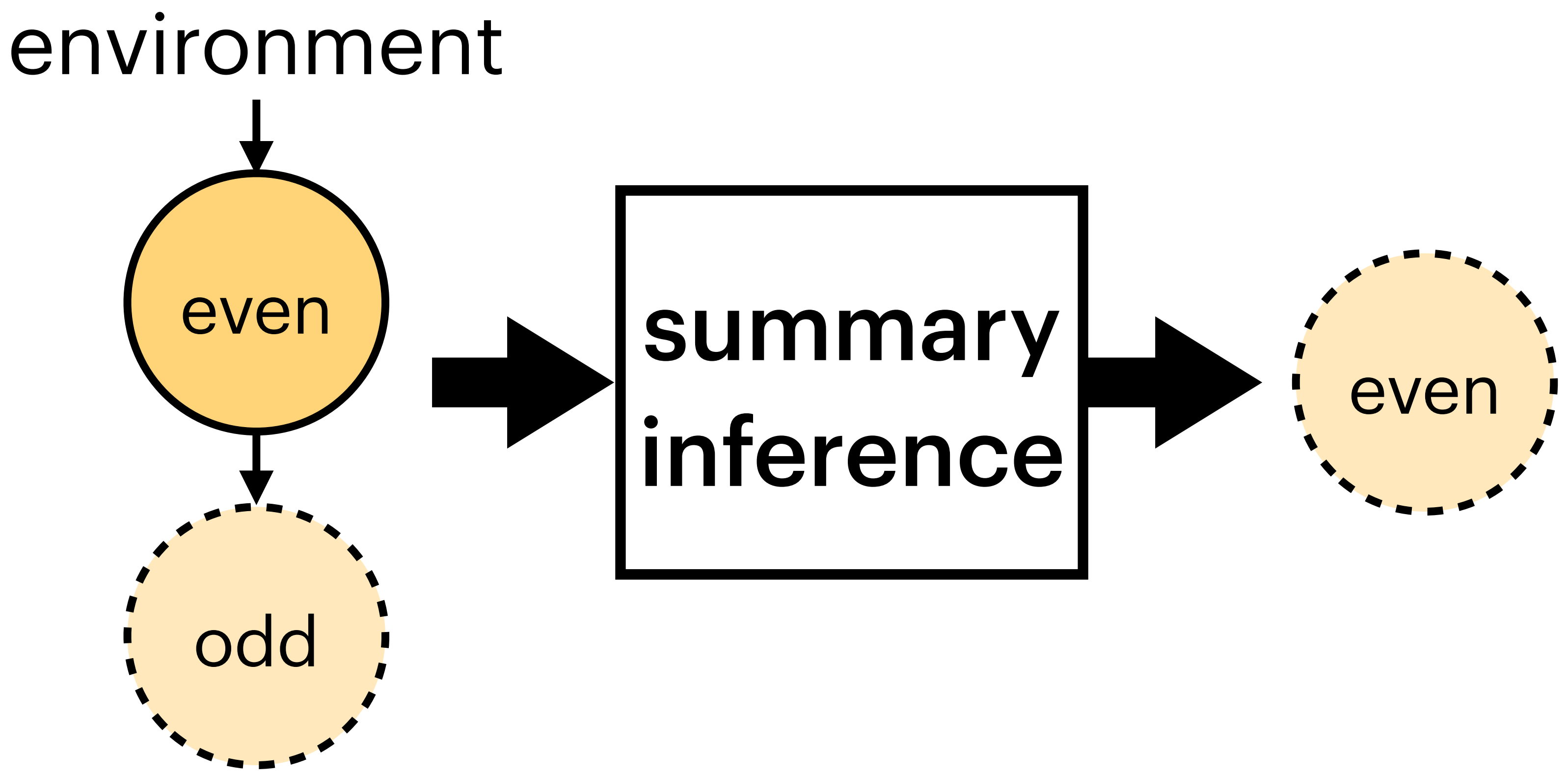

Modular Verification of Interprocedural Programs

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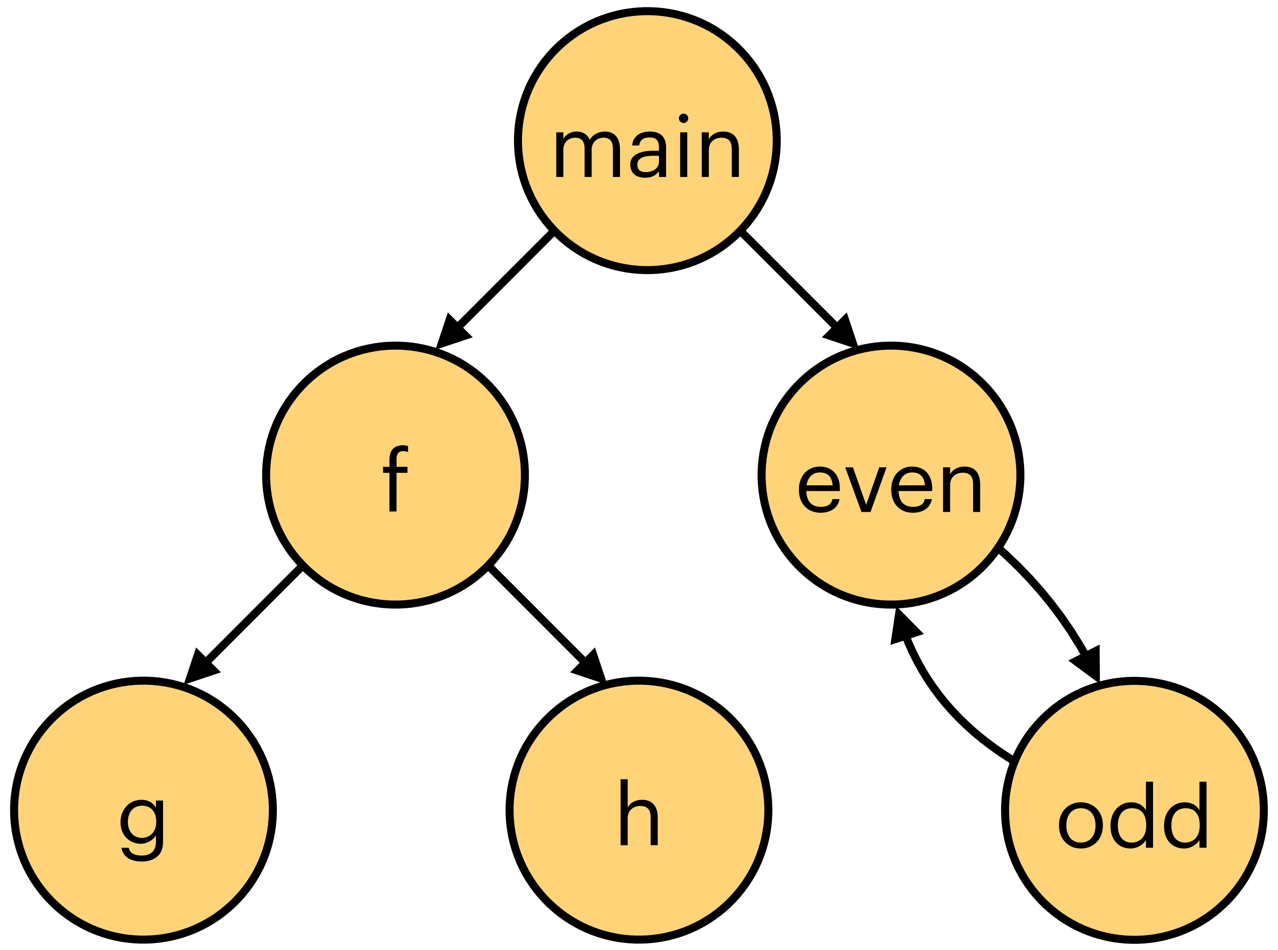
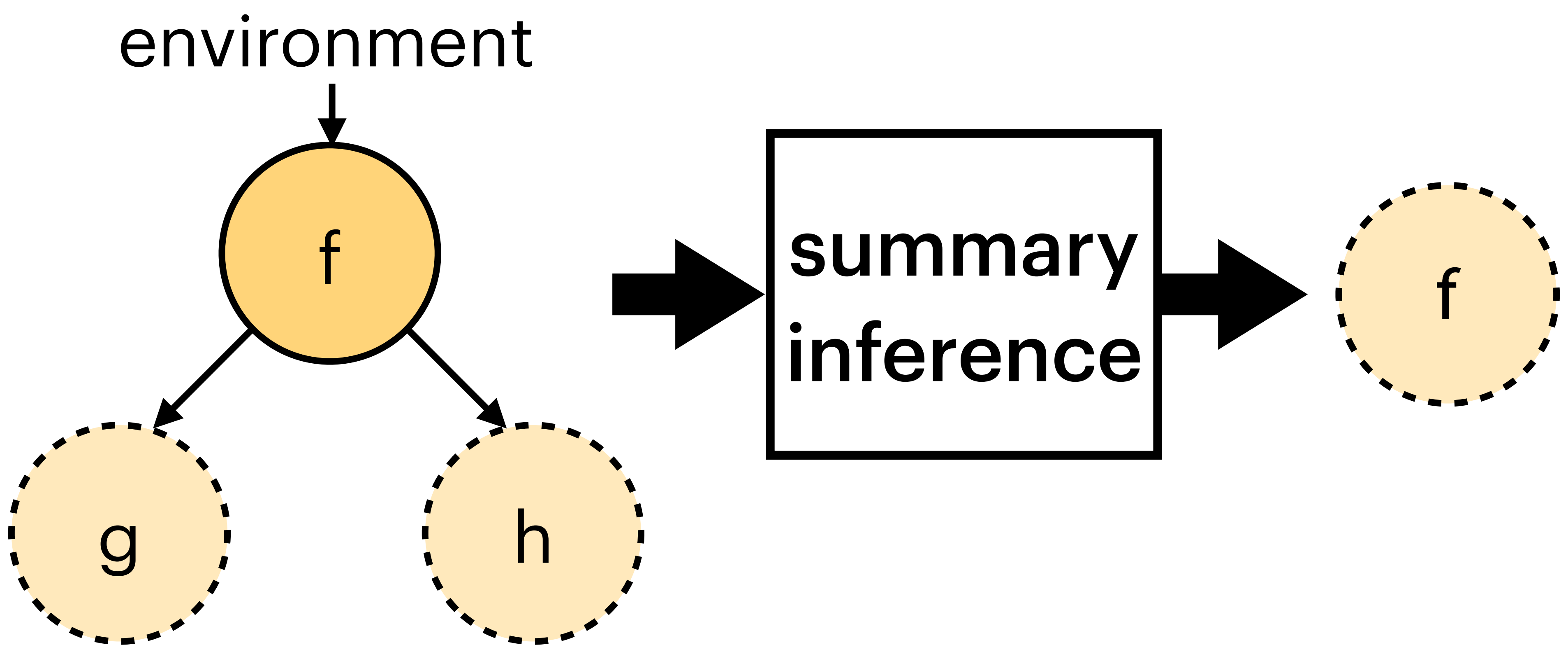
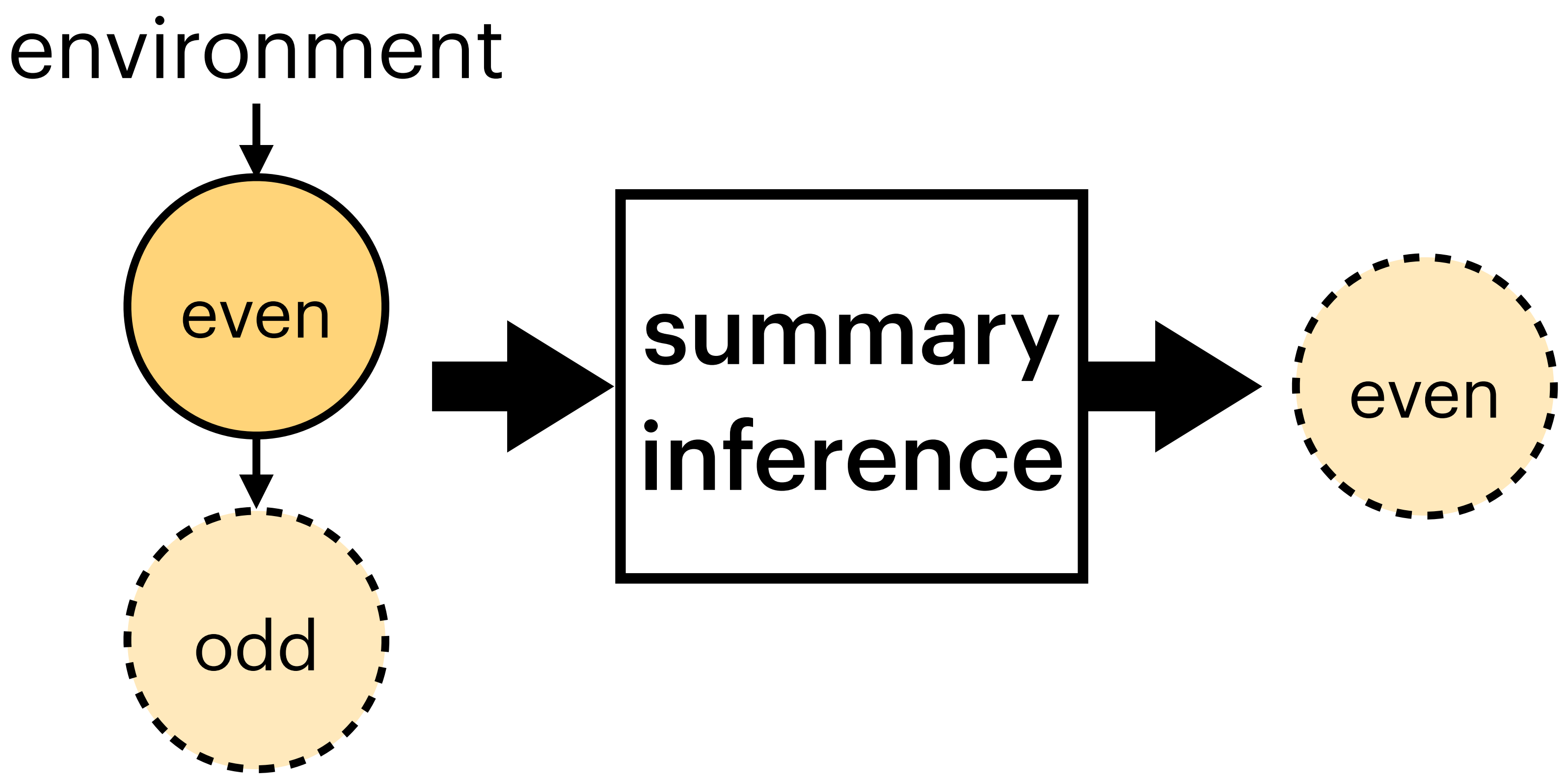


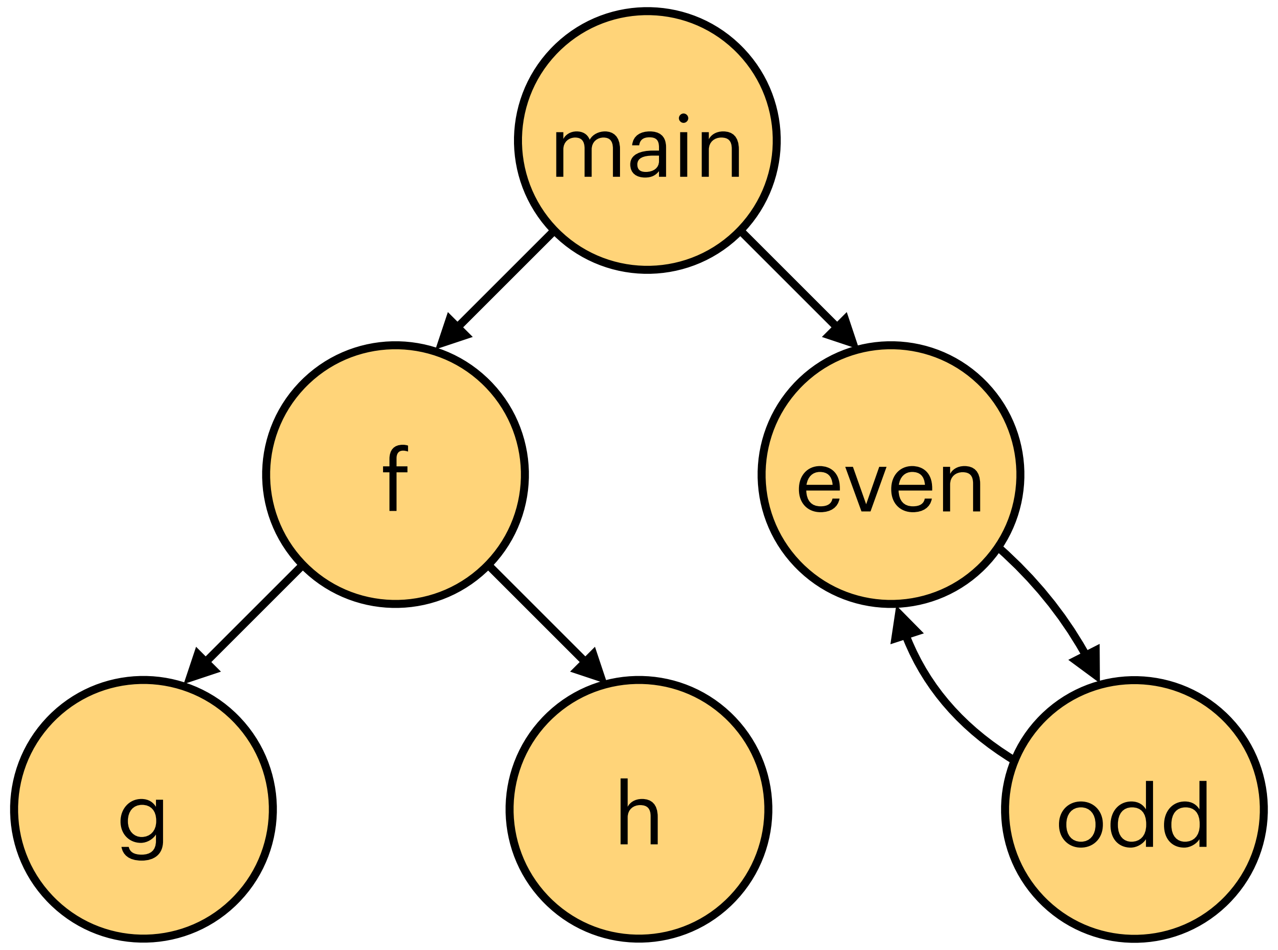


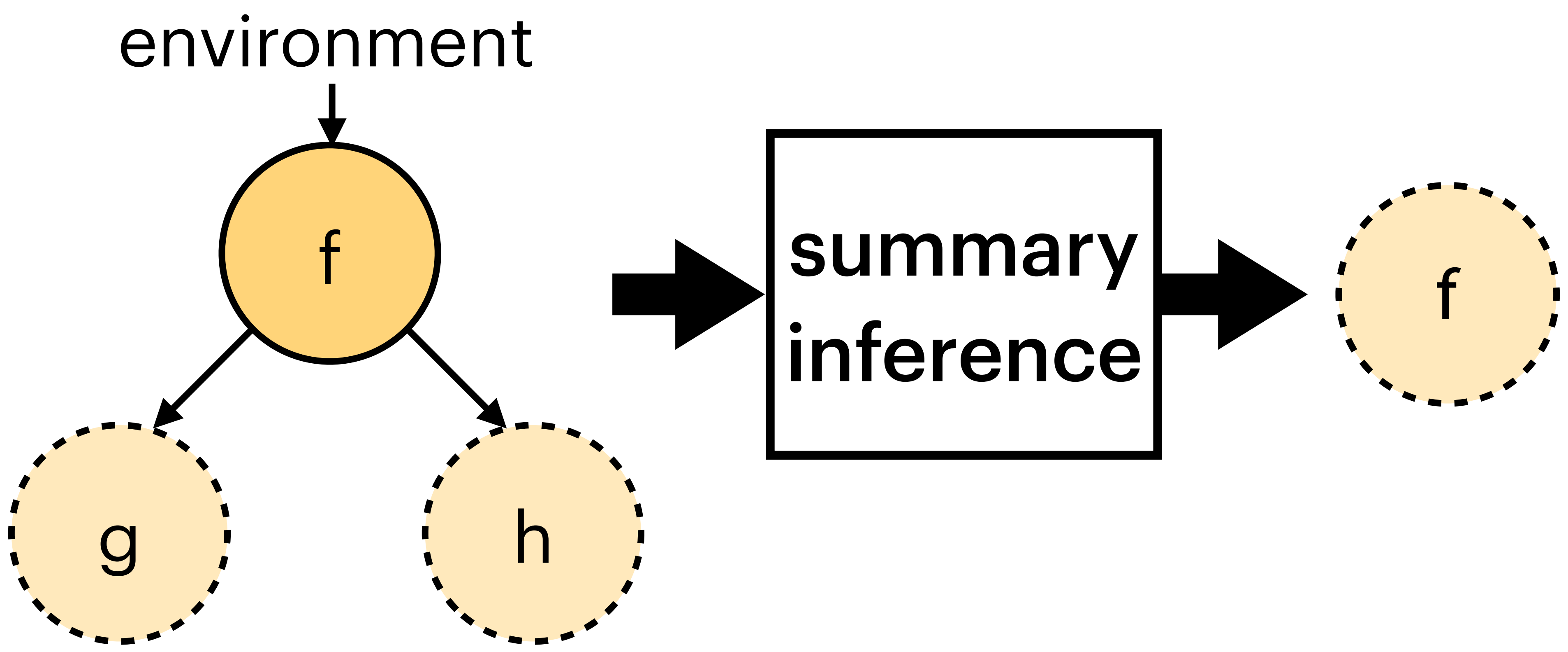
to handle mutual recursion and scale verification



Modular Verification of Interprocedural Programs

Infer and use procedure summaries (invariants)





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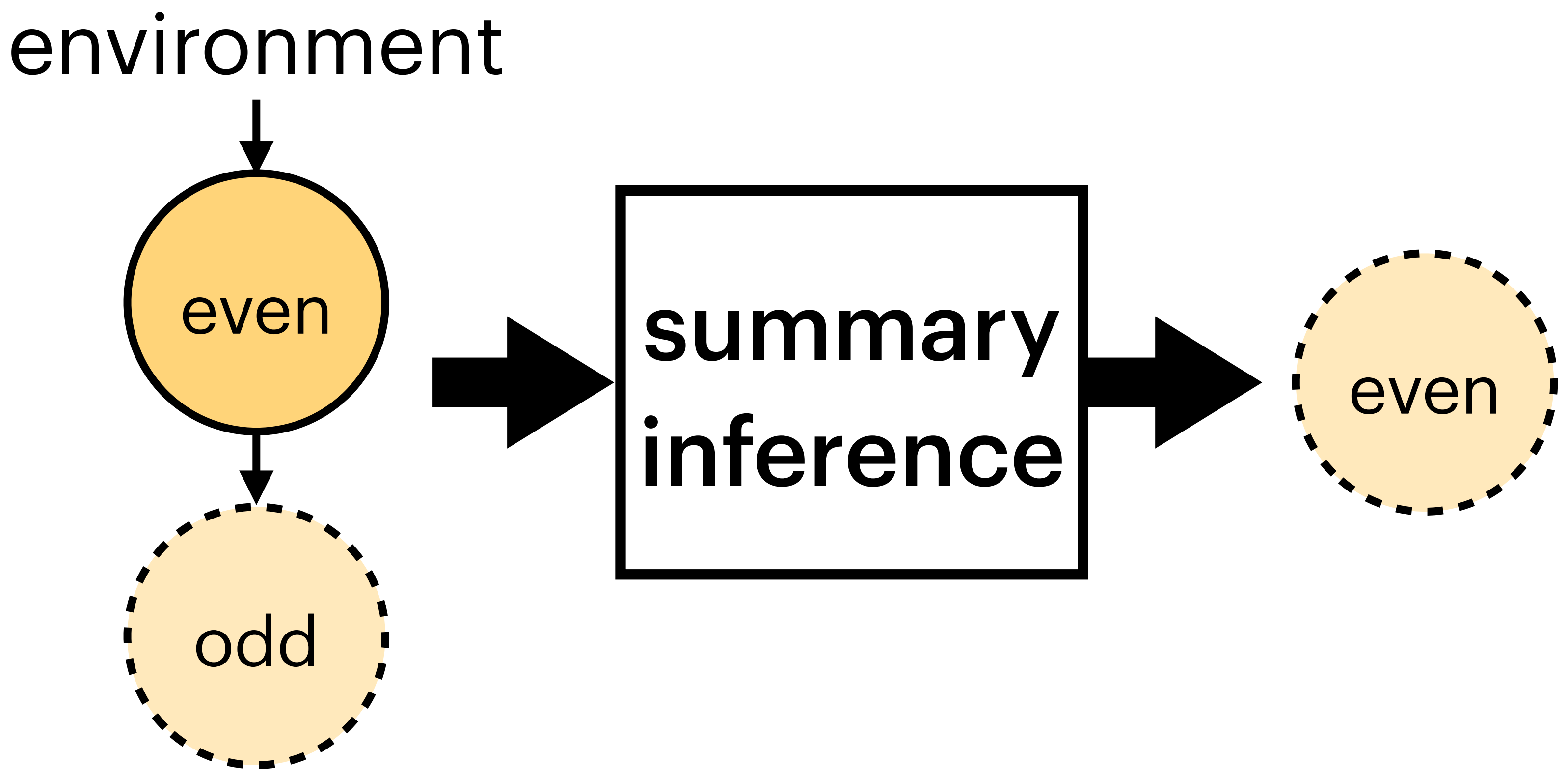
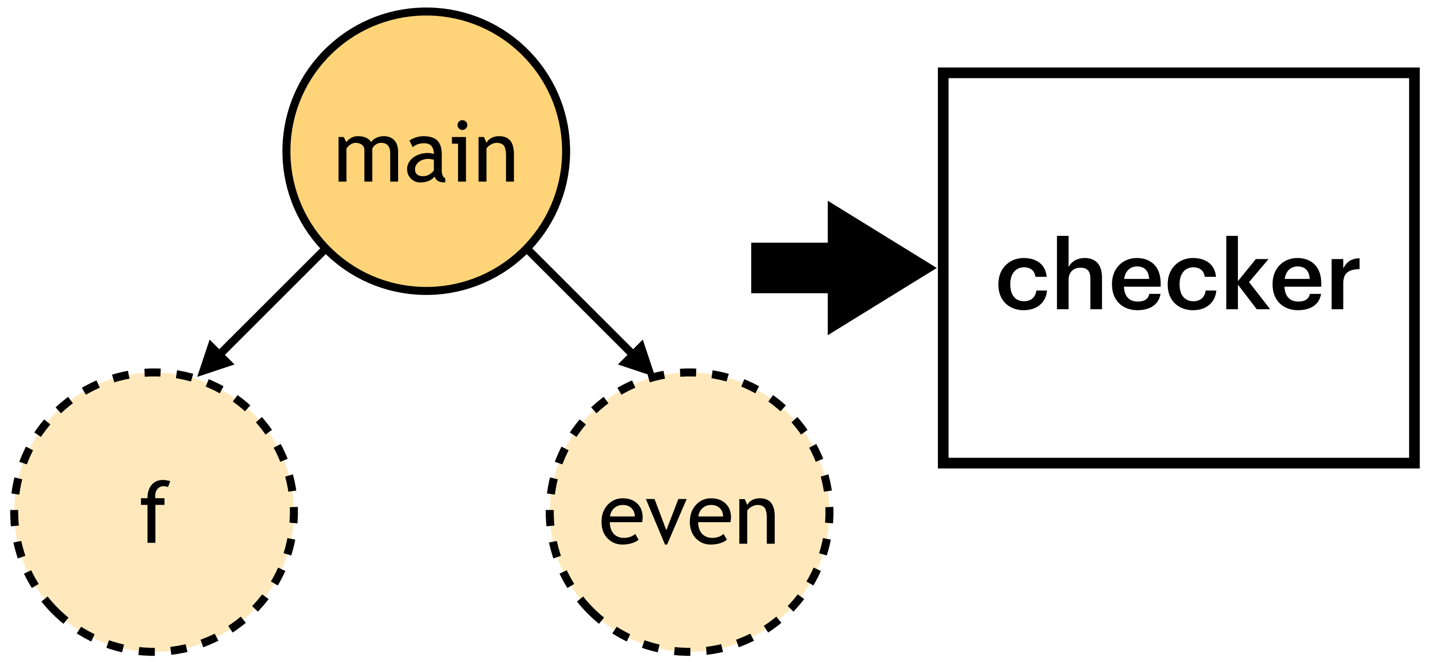
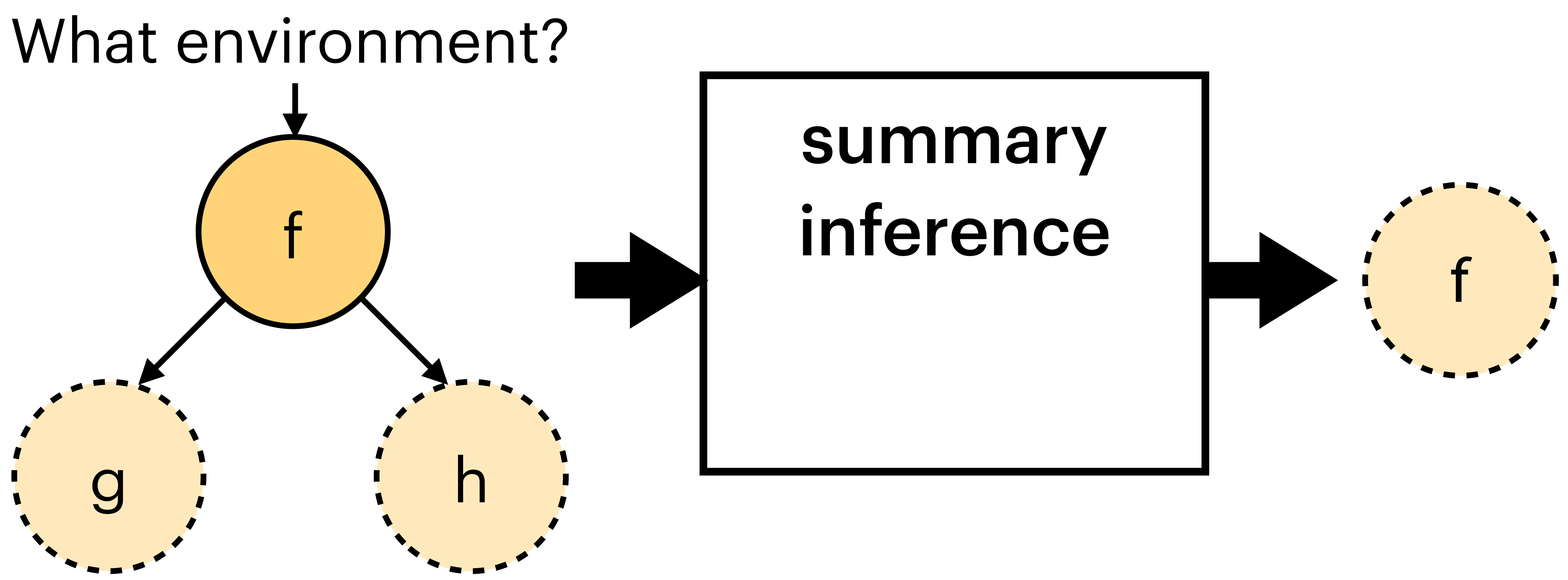




Scalable Inference vs. Relevance of Invariants



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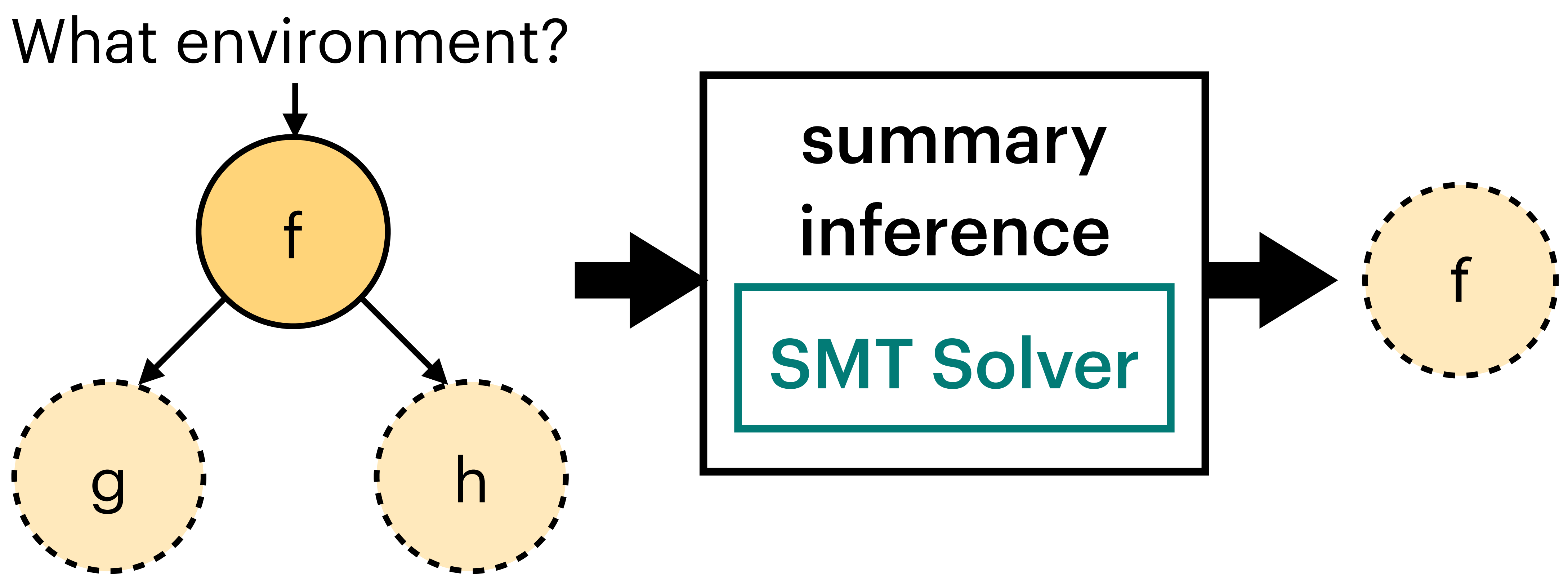

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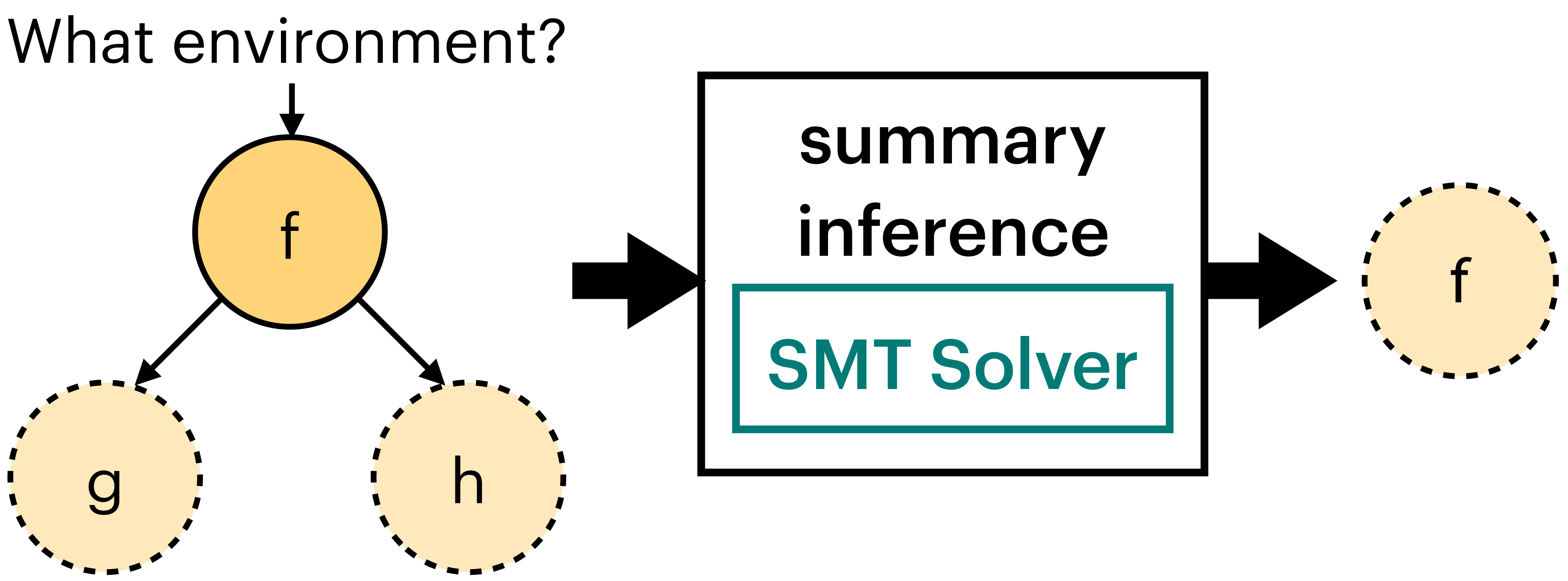

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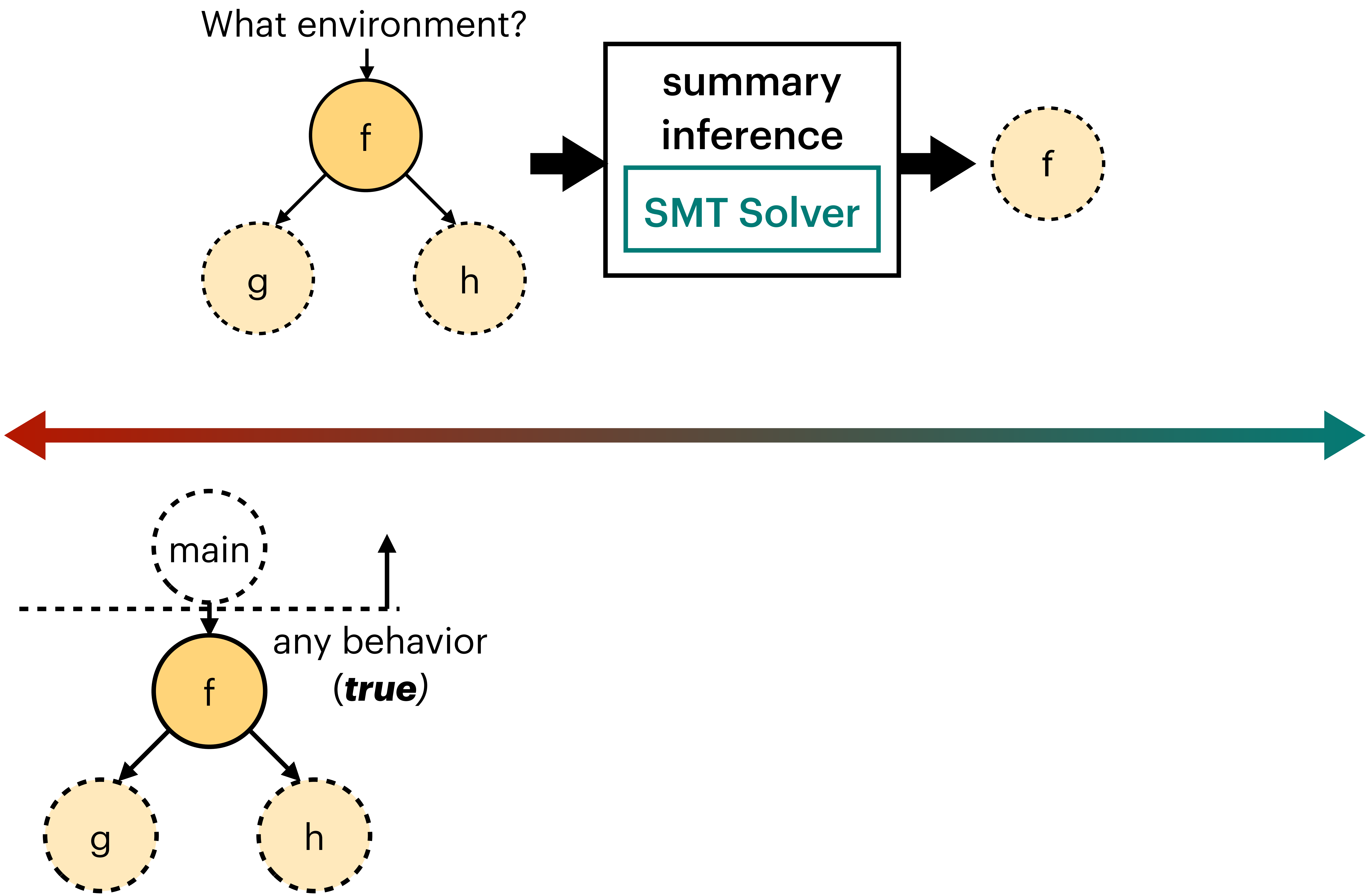
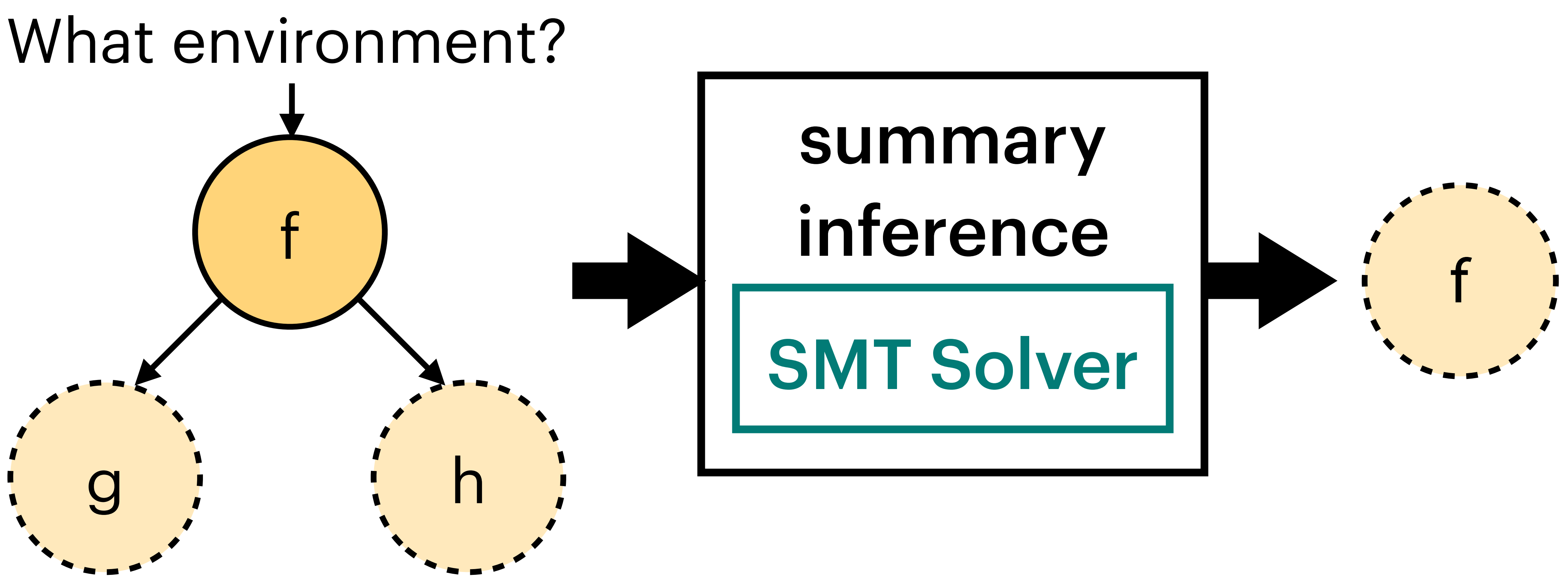
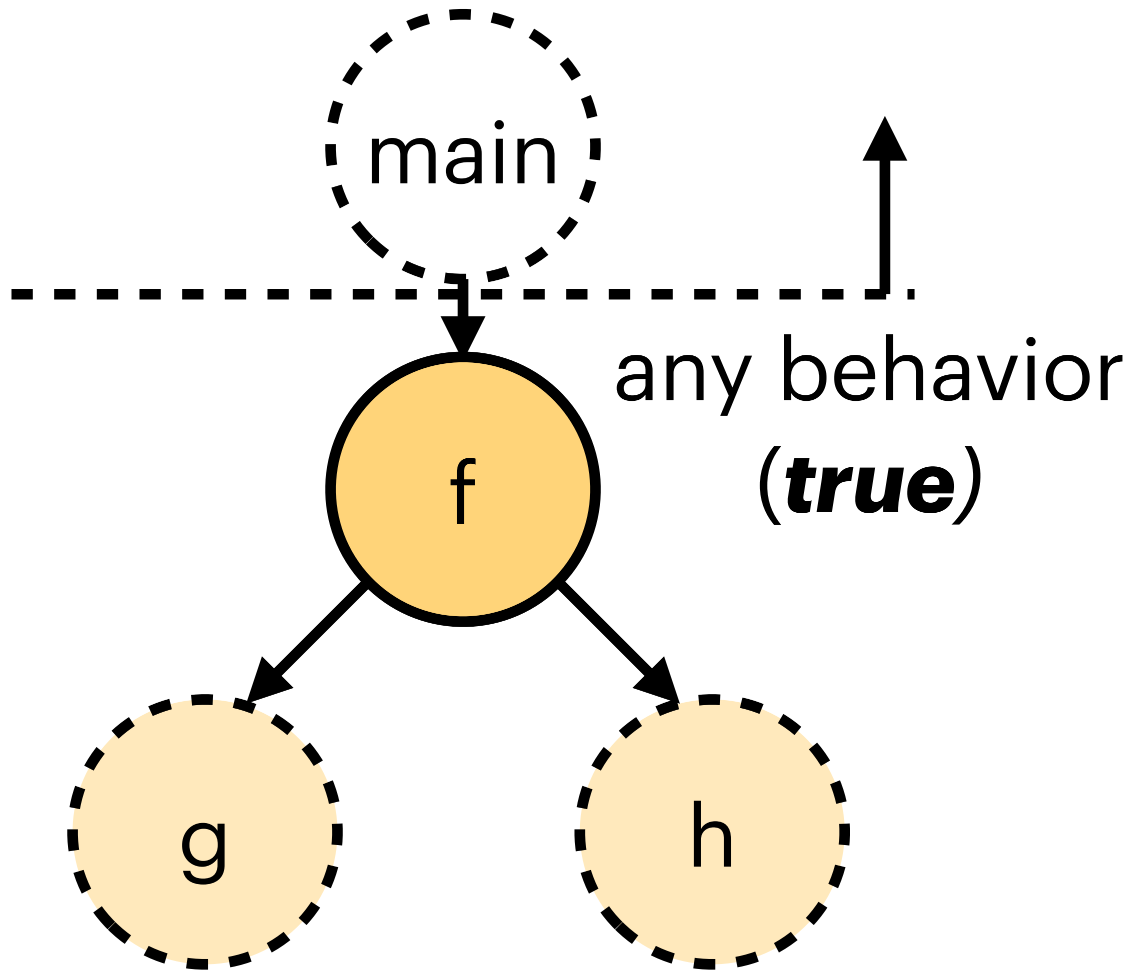


Scalable Inference vs. Relevance of Invariants

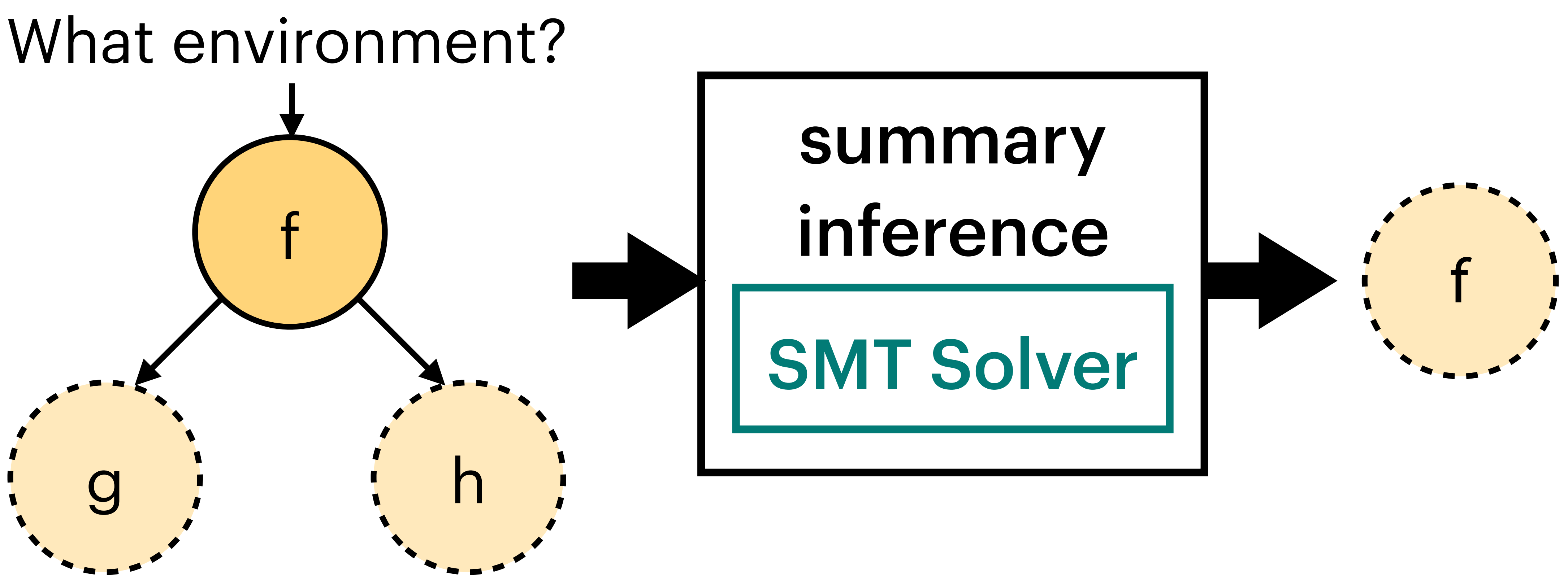


most scalable

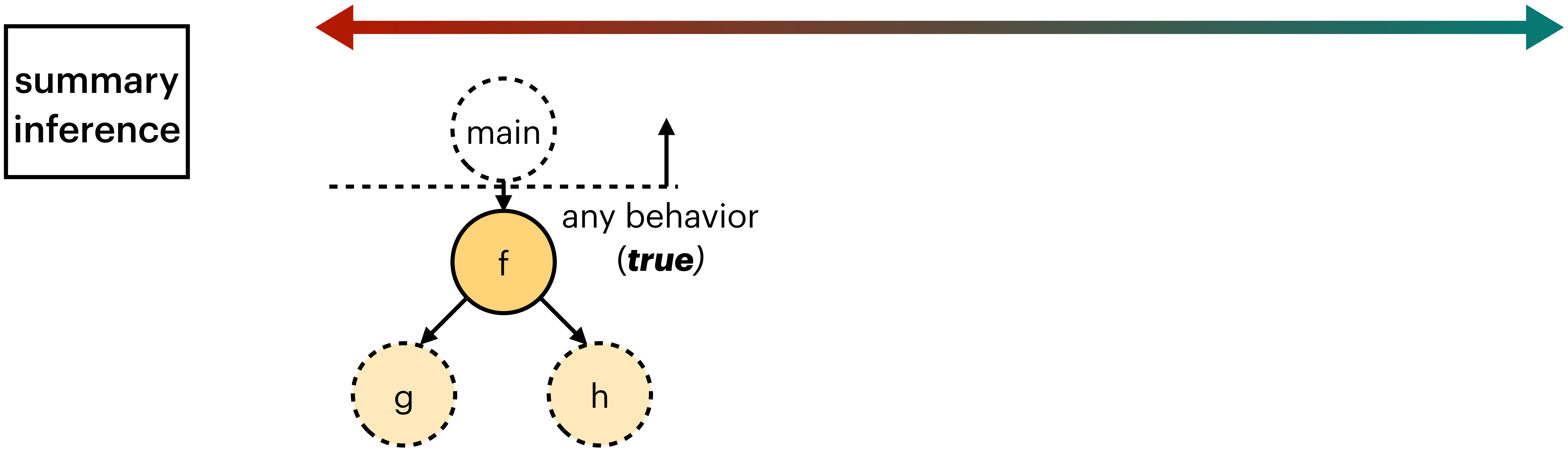
summary inference



Scalable Inference vs. Relevance of Invariants

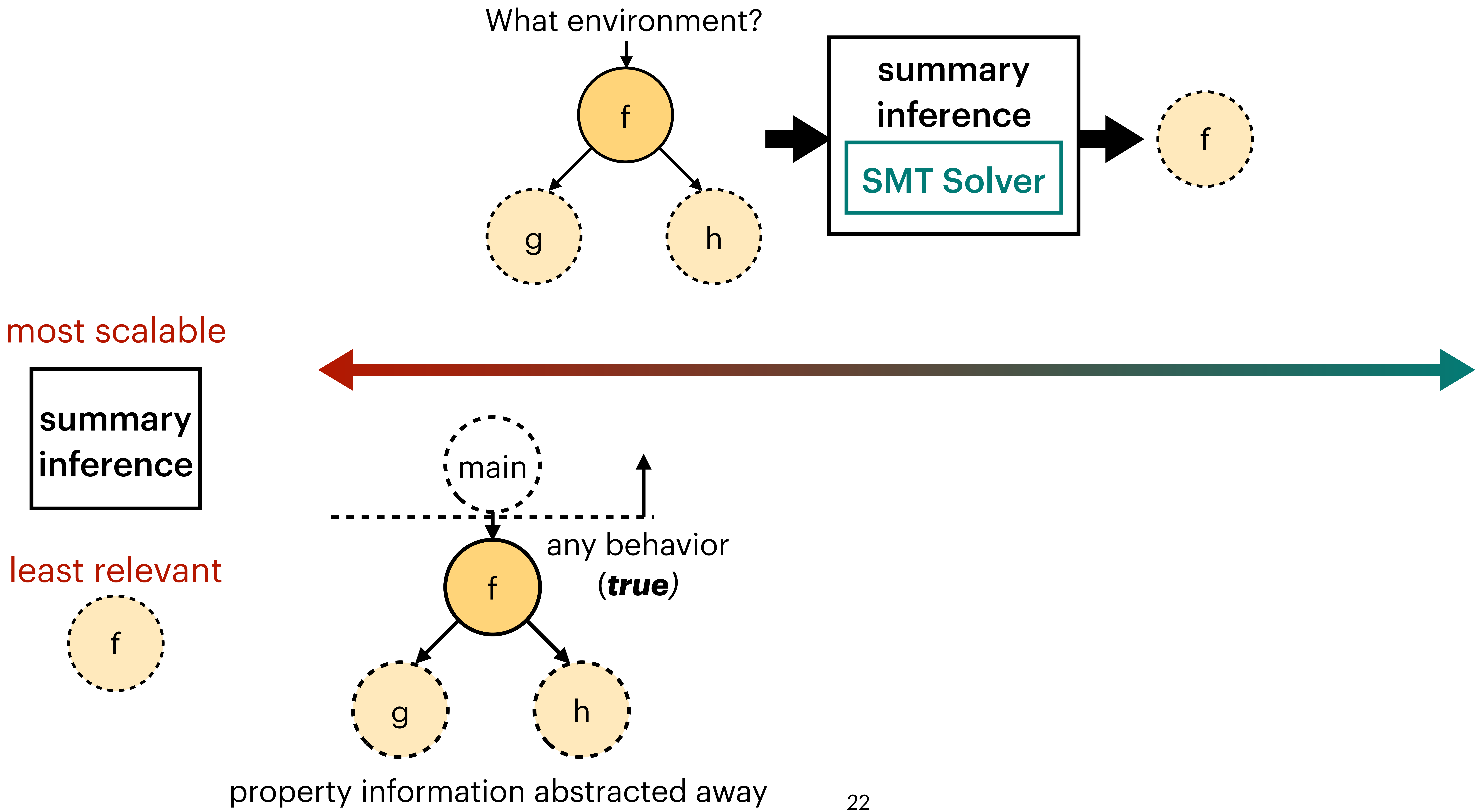


most scalable

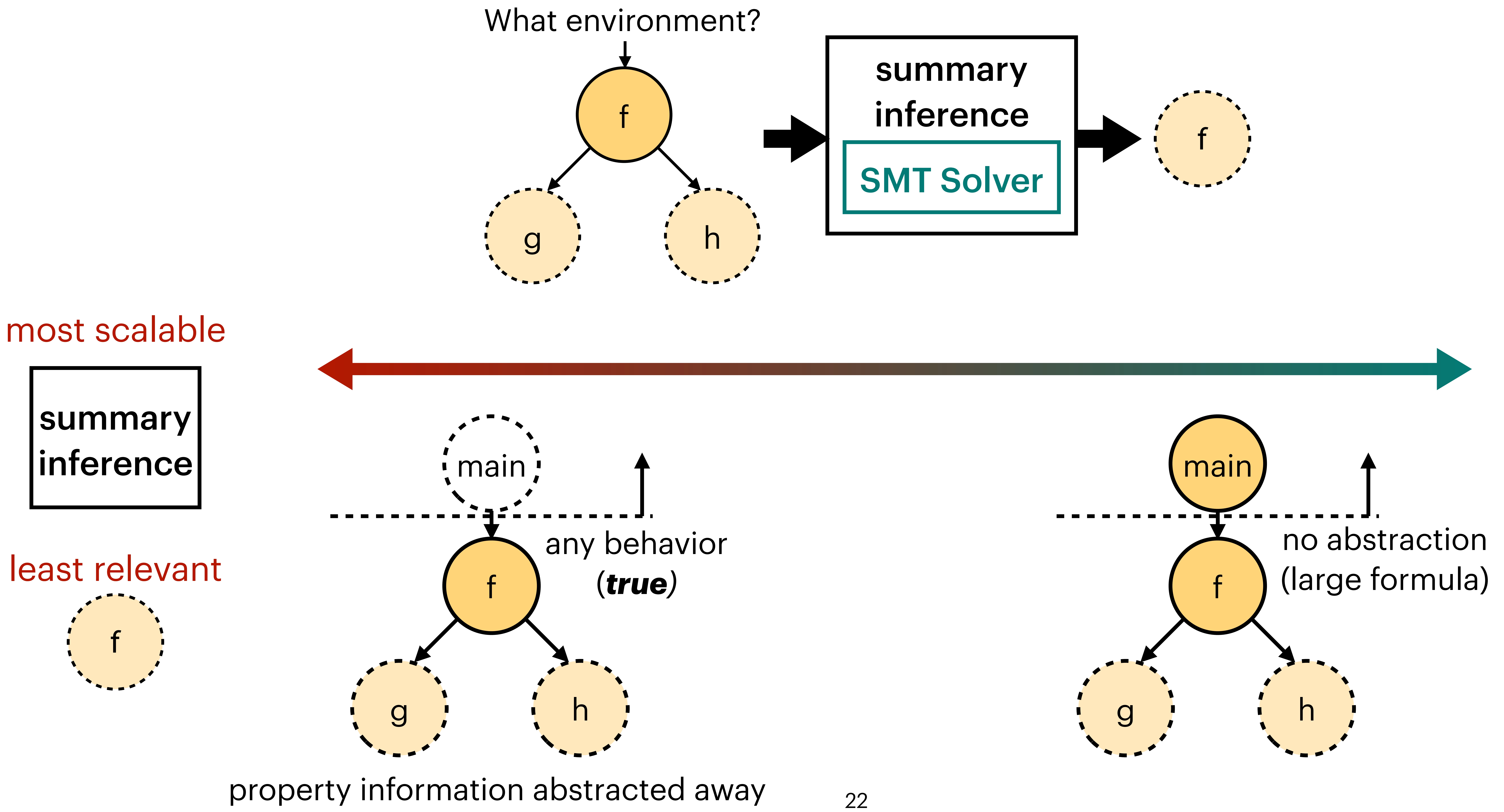


property information abstracted away

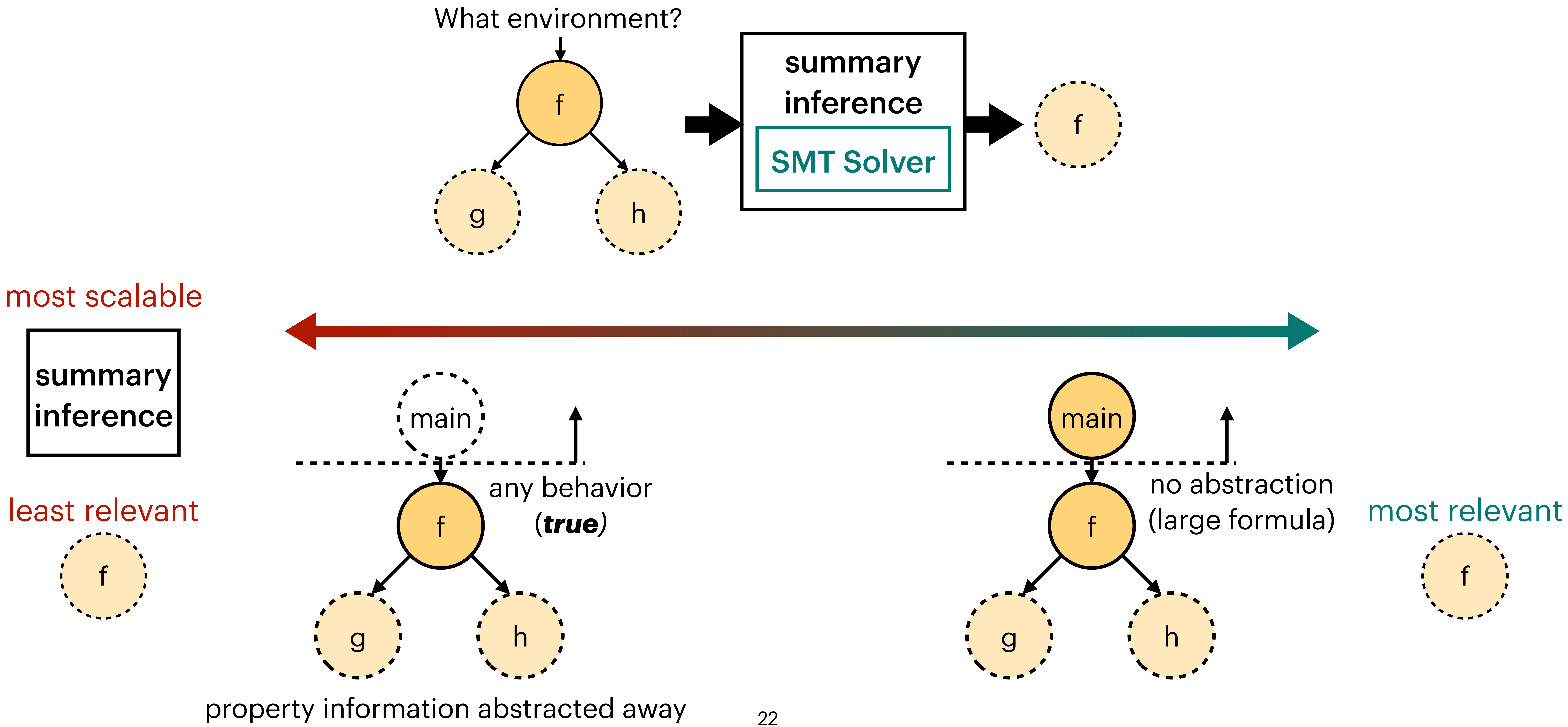
Scalable Inference vs. Relevance of Invariants



Scalable Inference vs. Relevance of Invariants



Scalable Inference vs. Relevance of Invariants



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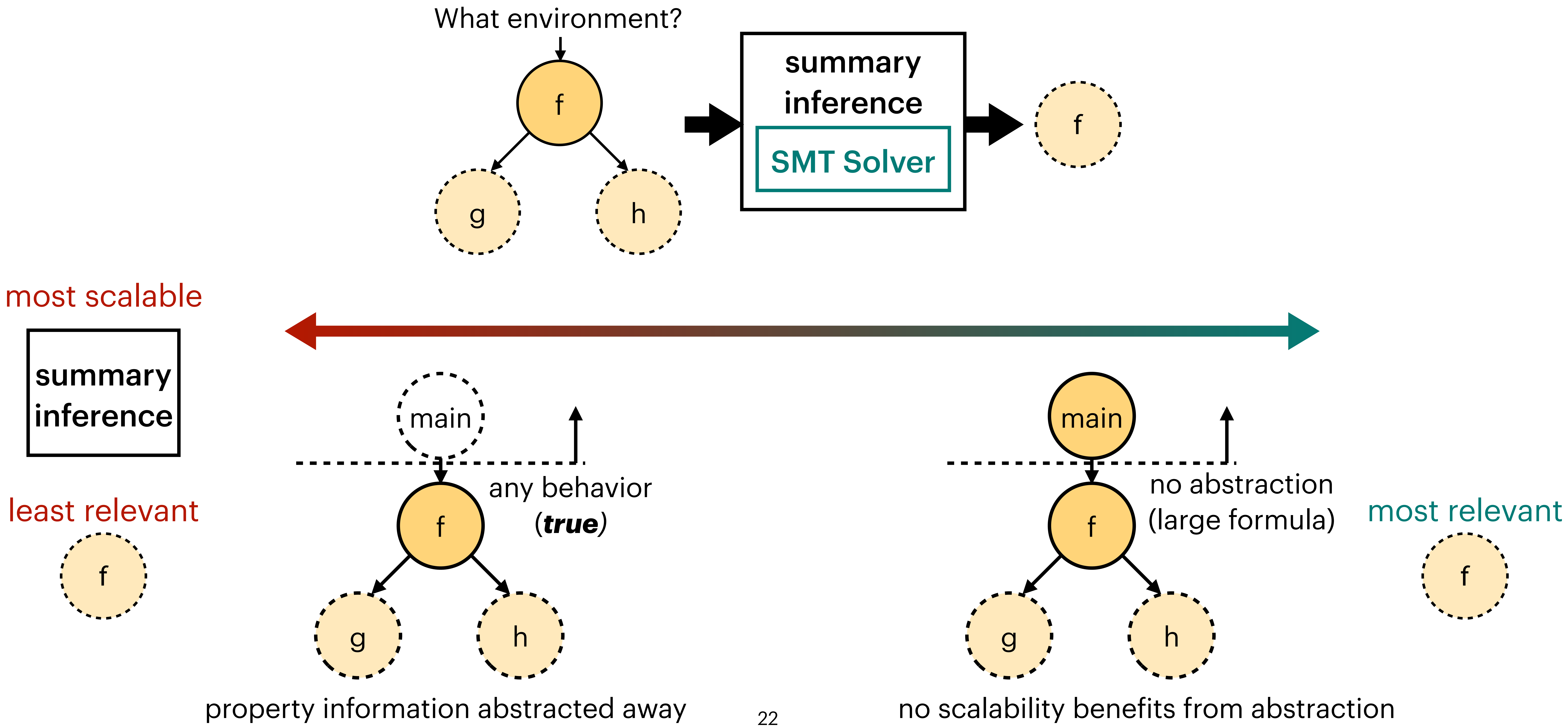

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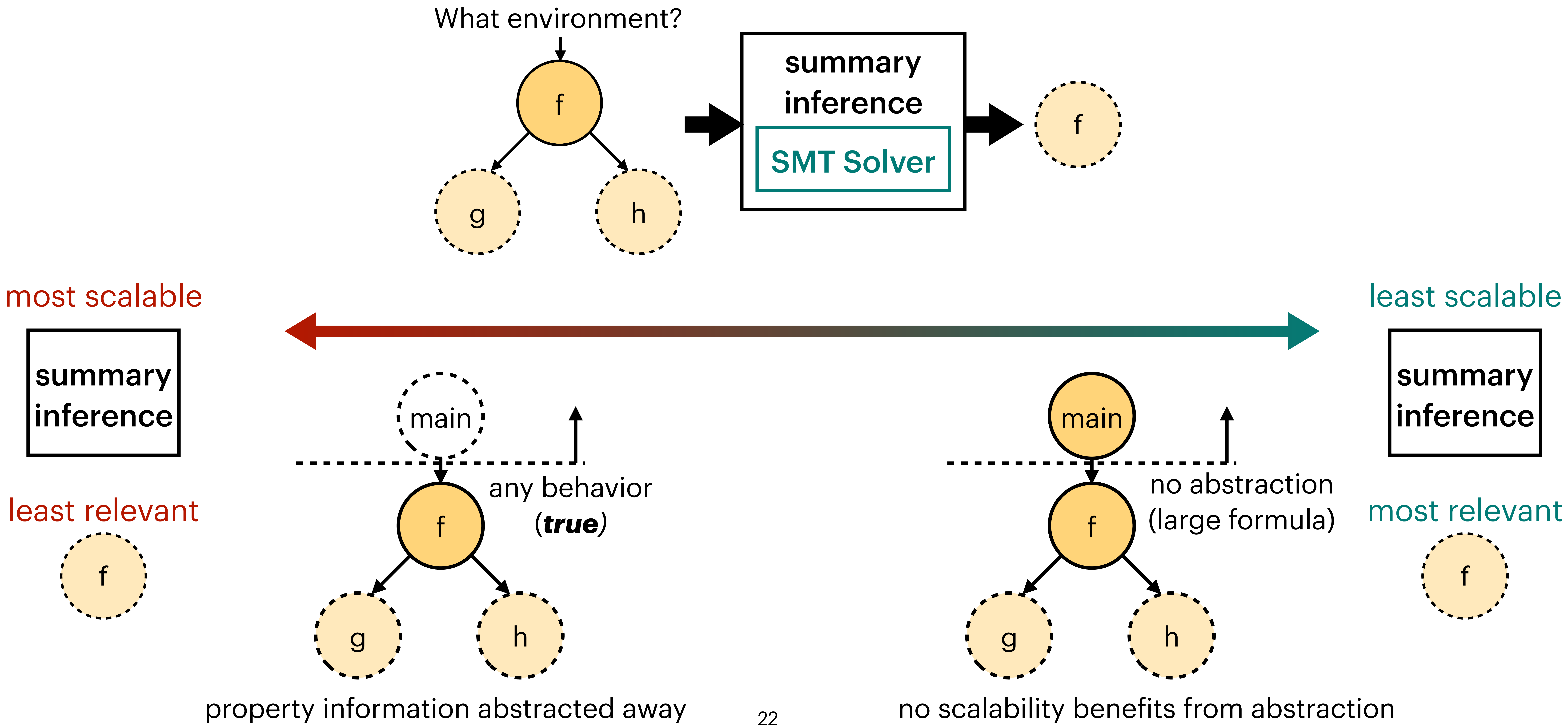

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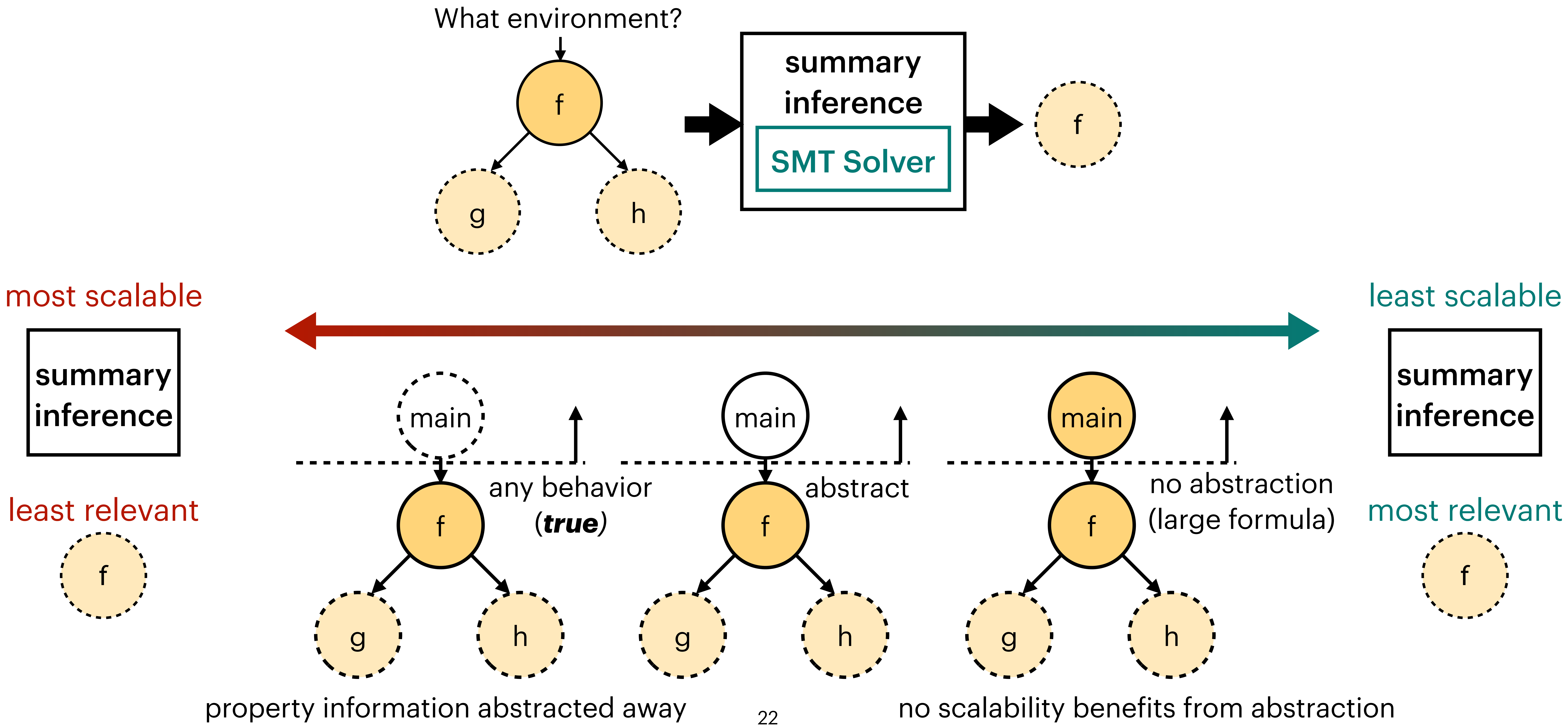
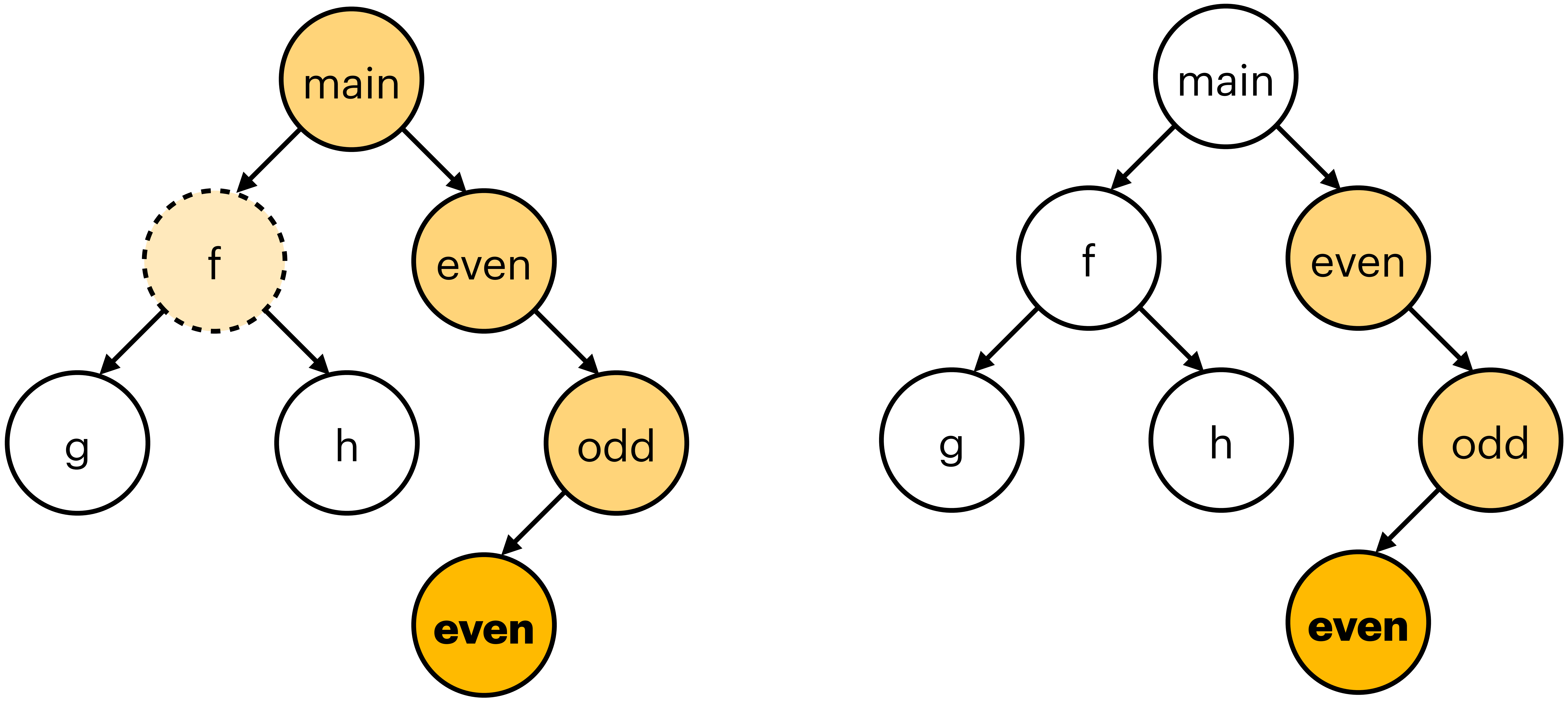


Bounded Environments



Unbounded Procedure Summaries from Bounded Environments, Pick et al., VMCAI'21

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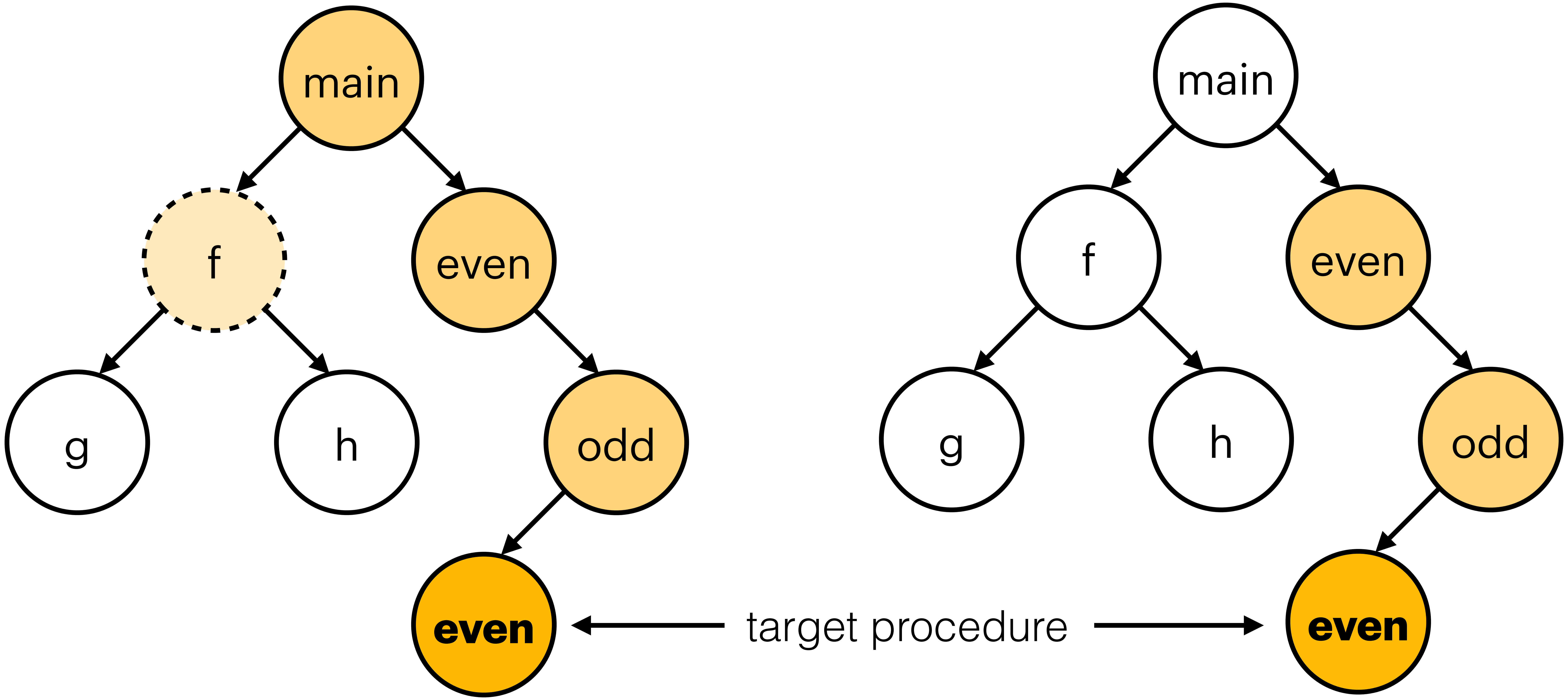

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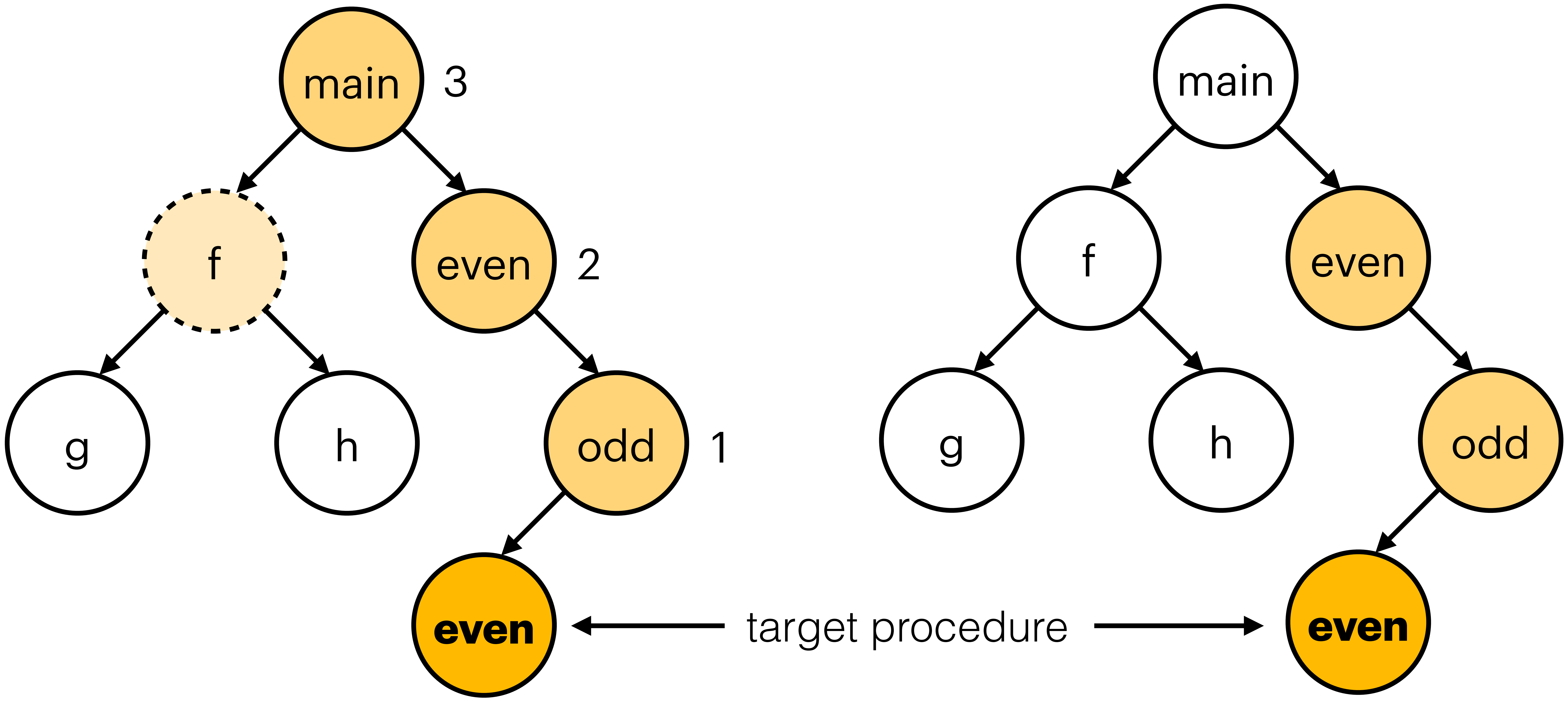

Unbounded Procedure Summaries from
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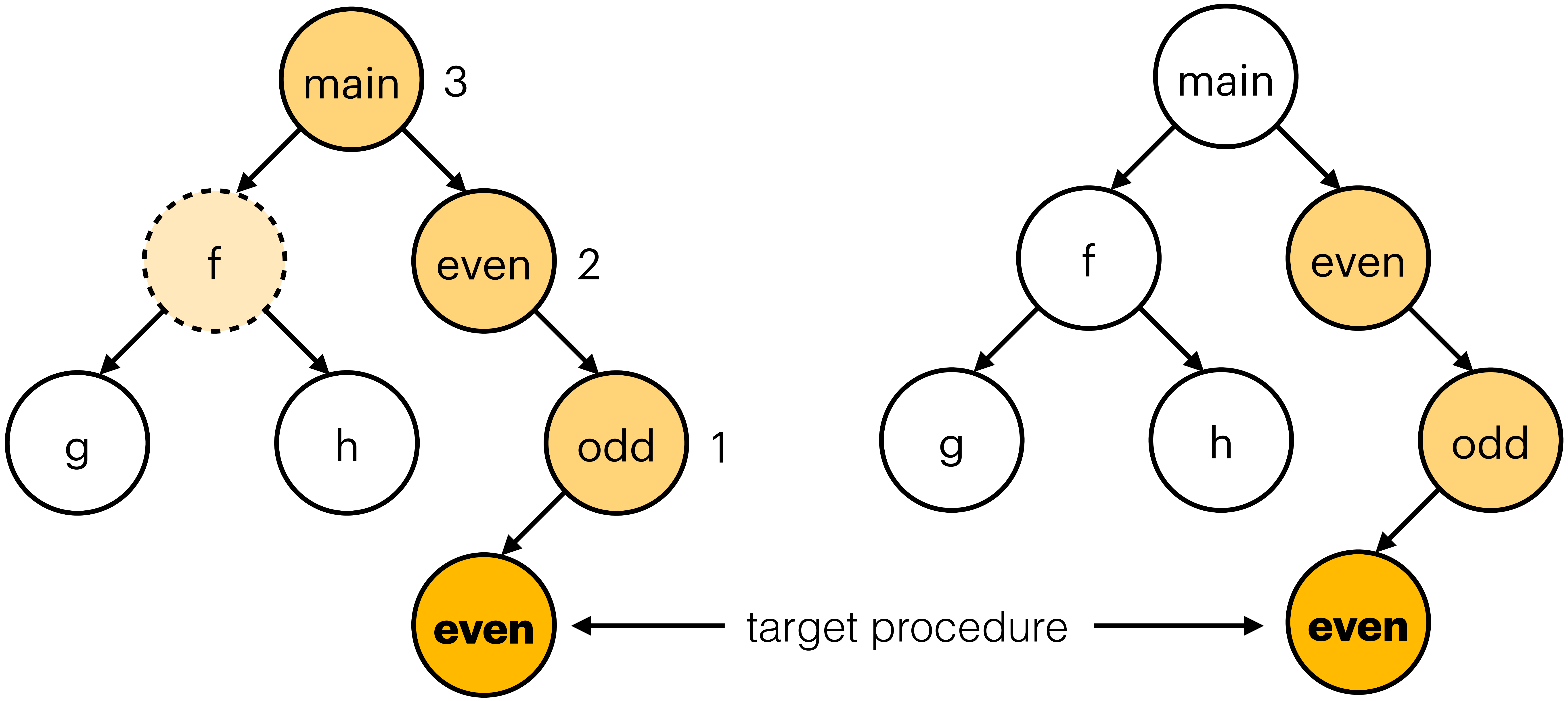
Bounded Environments

3-bounded environment



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Bounded Environments

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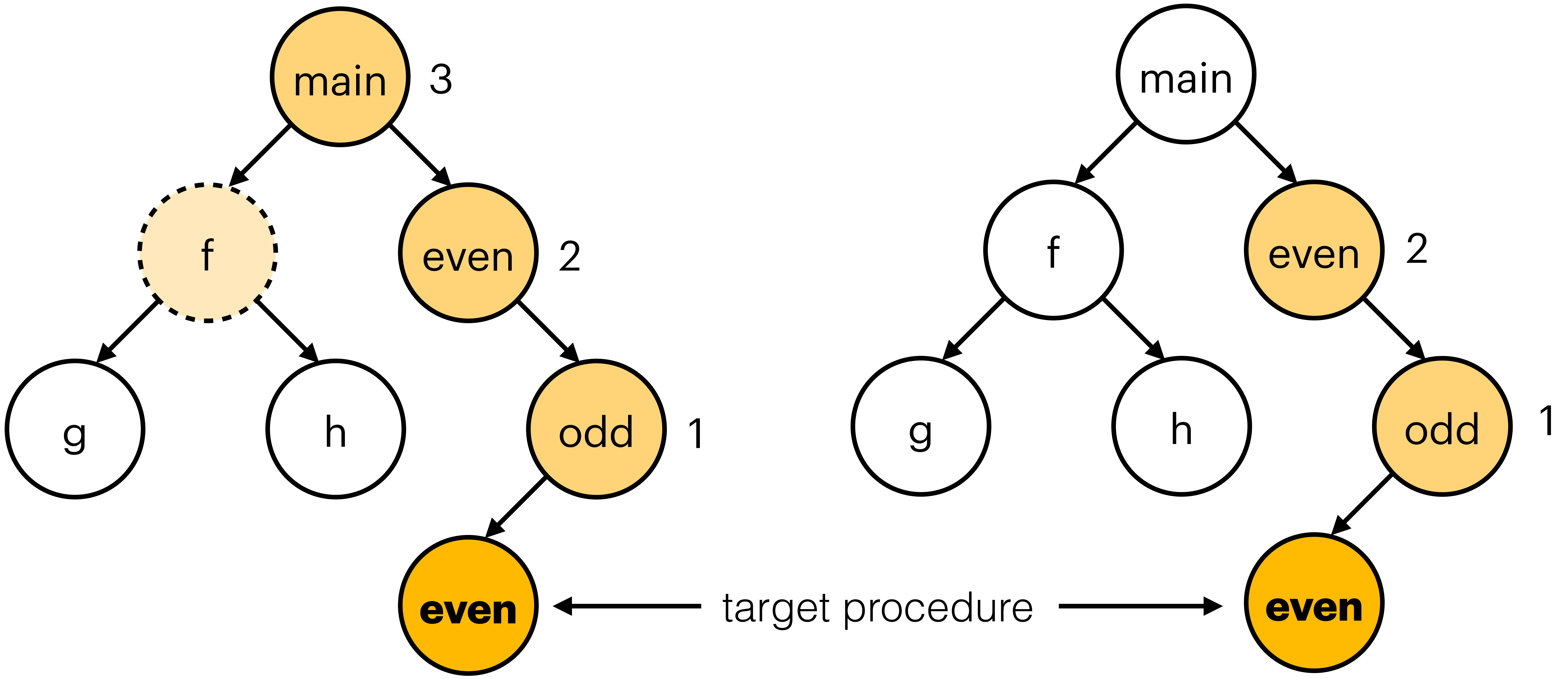

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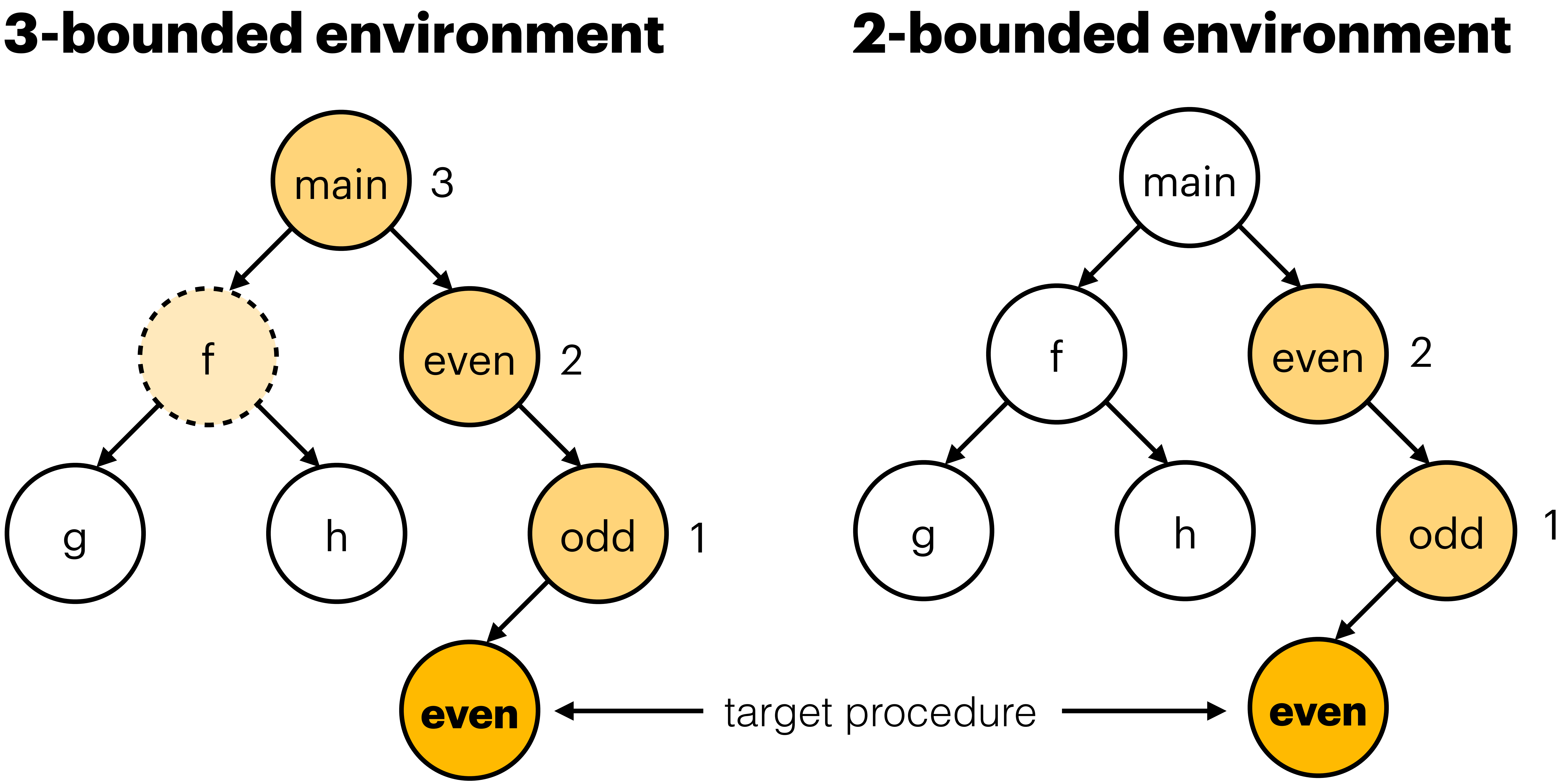

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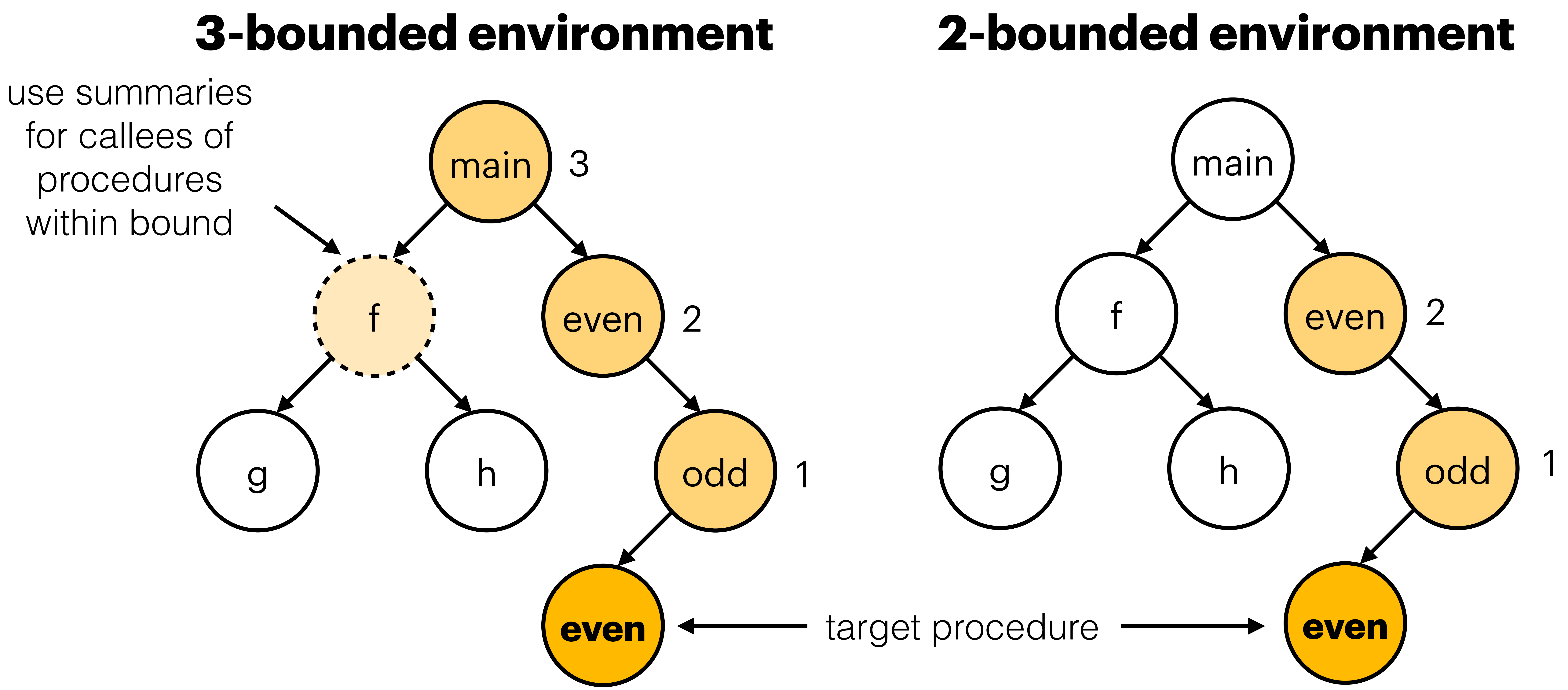

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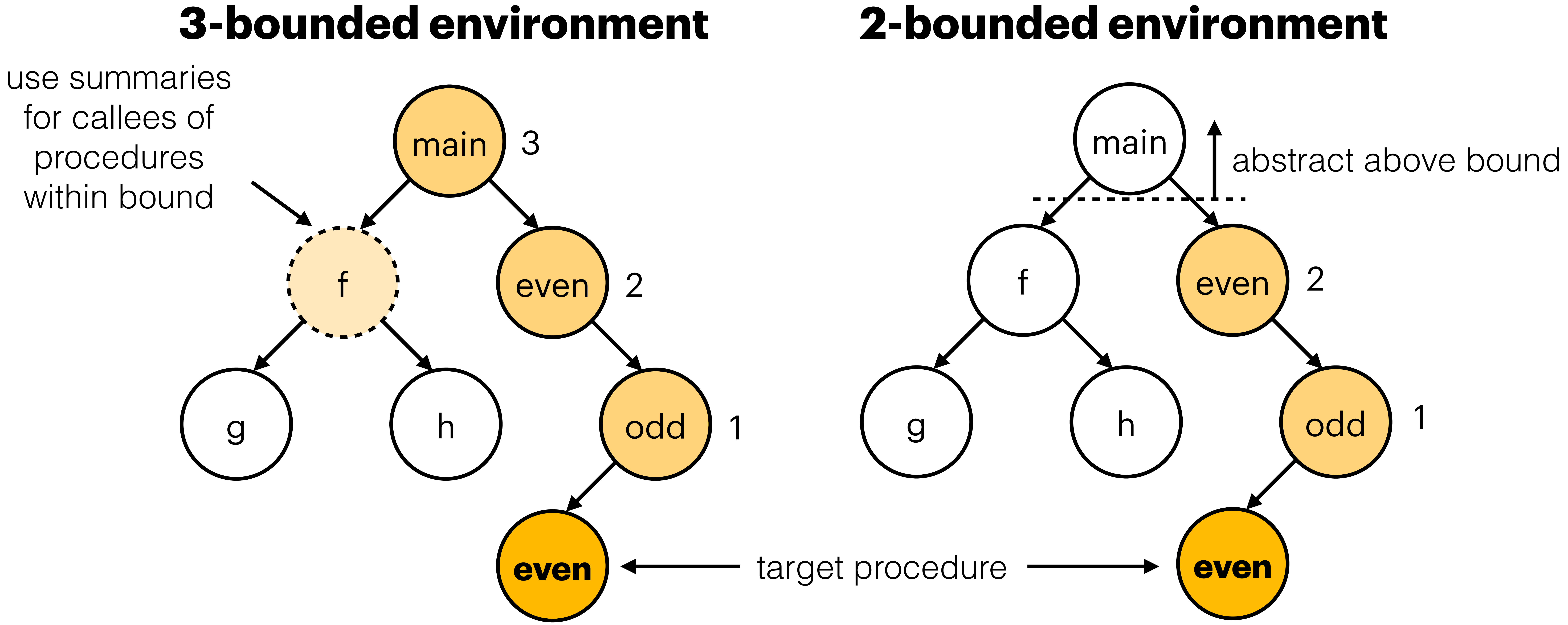

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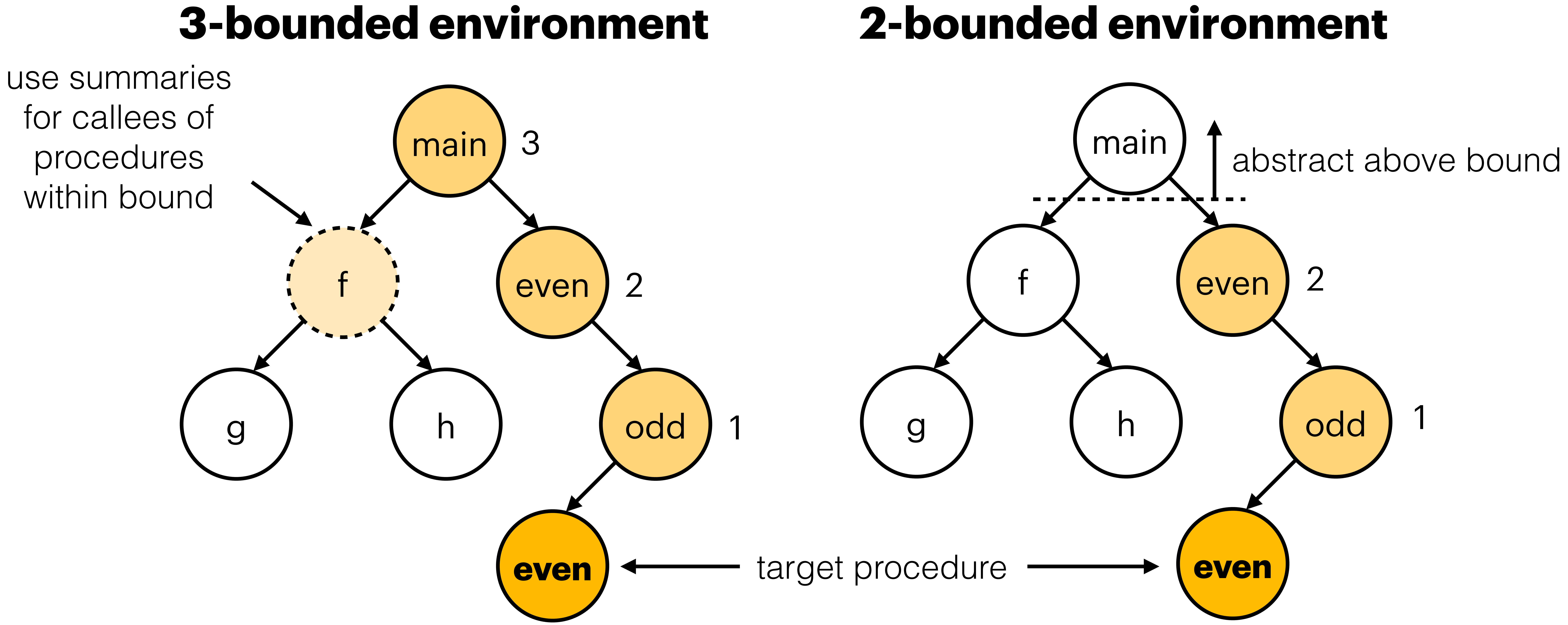
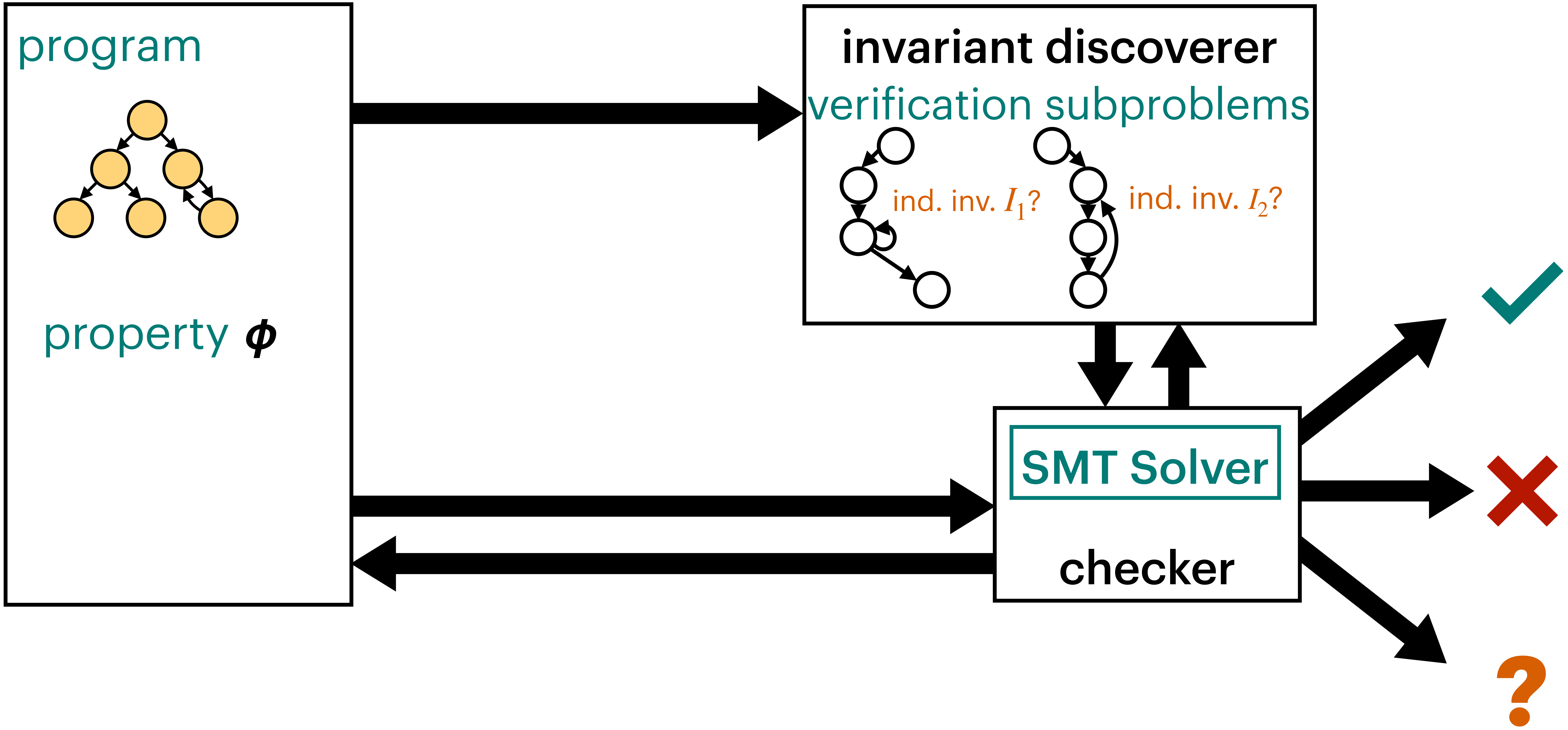


Larger bound, more relevant/less scalable

Unbounded Procedure Summaries from Bounded Environments, Pick et al., VMCAI'21

Interprocedural Program Verification



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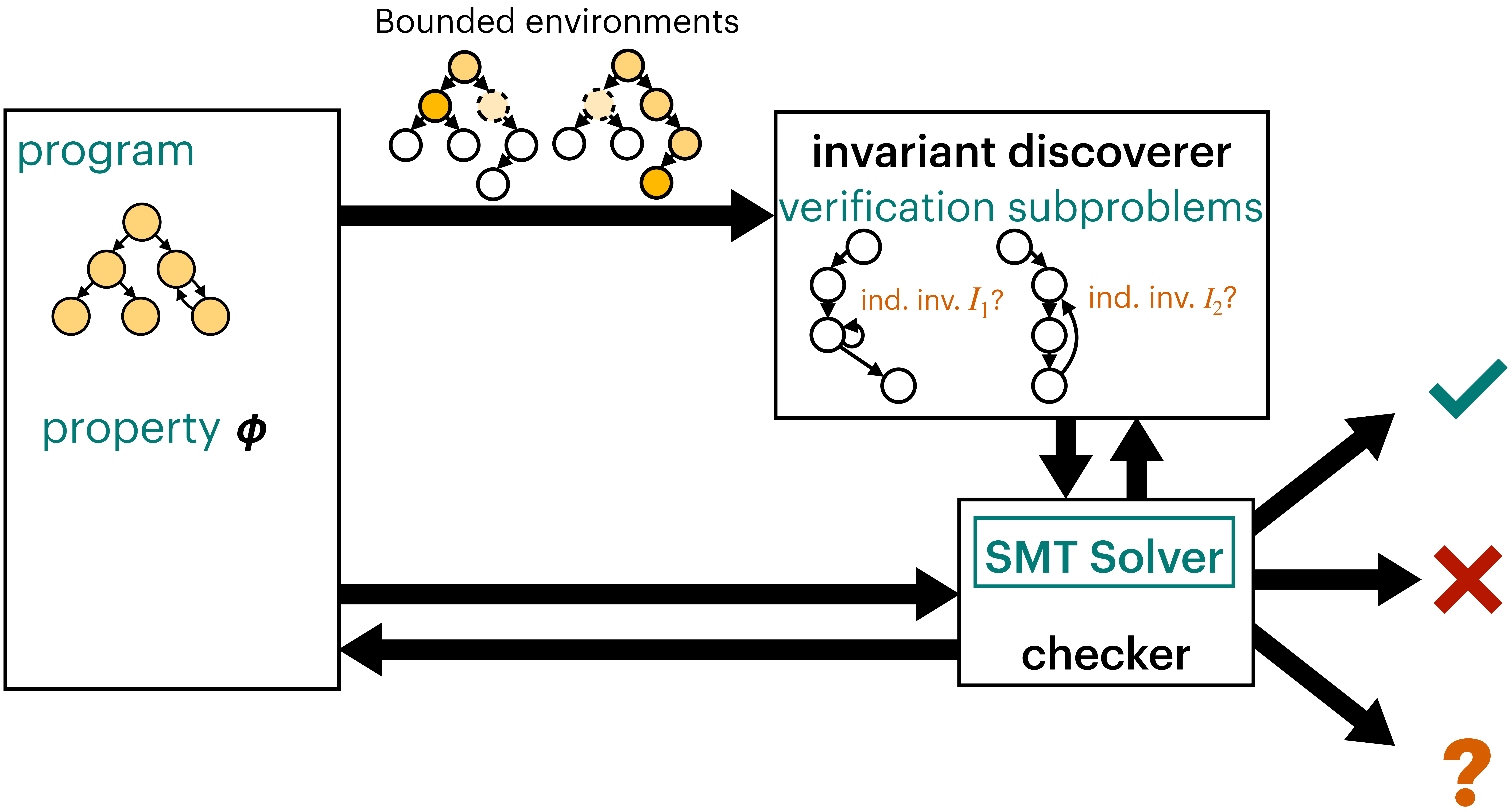

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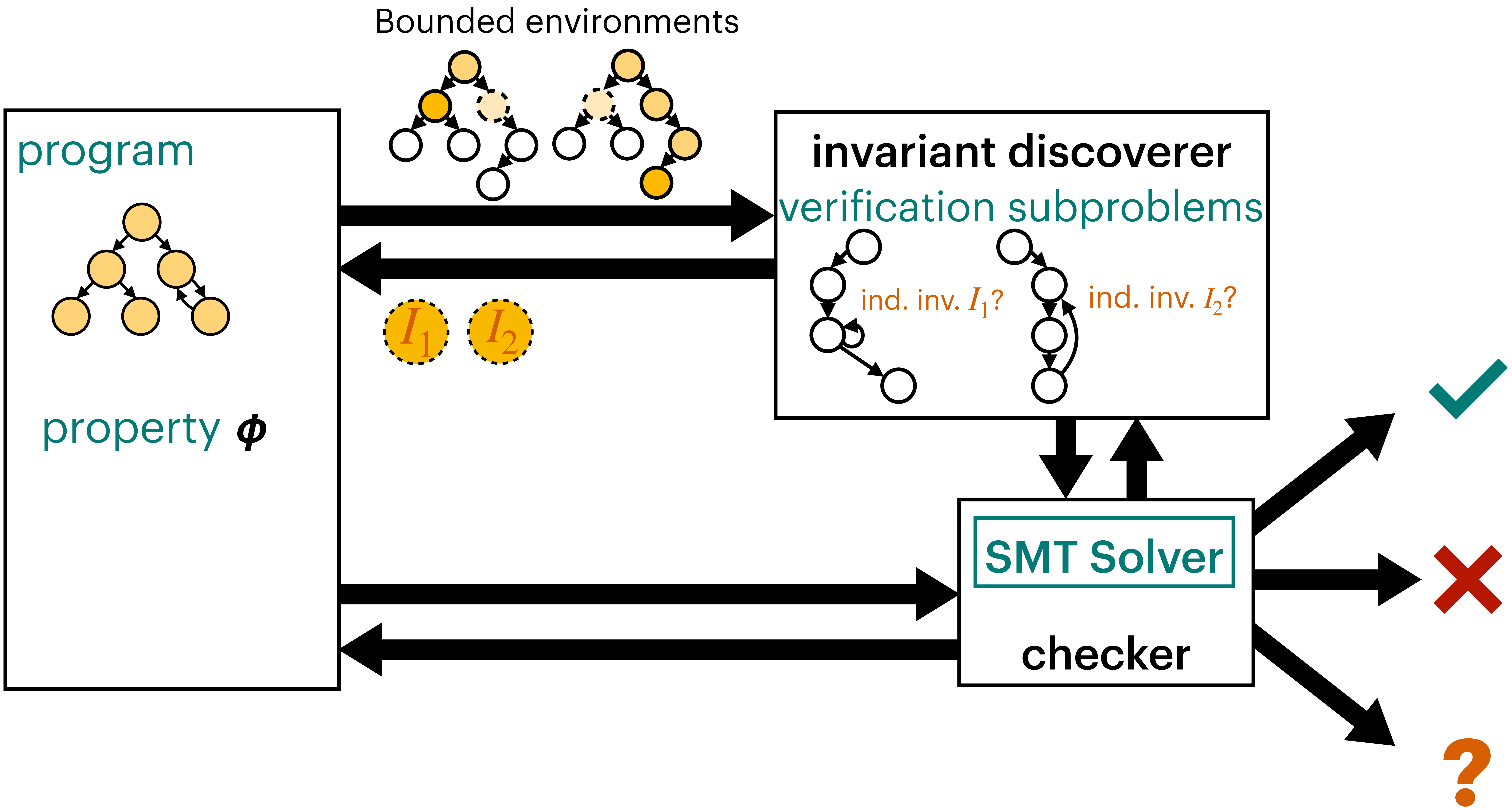

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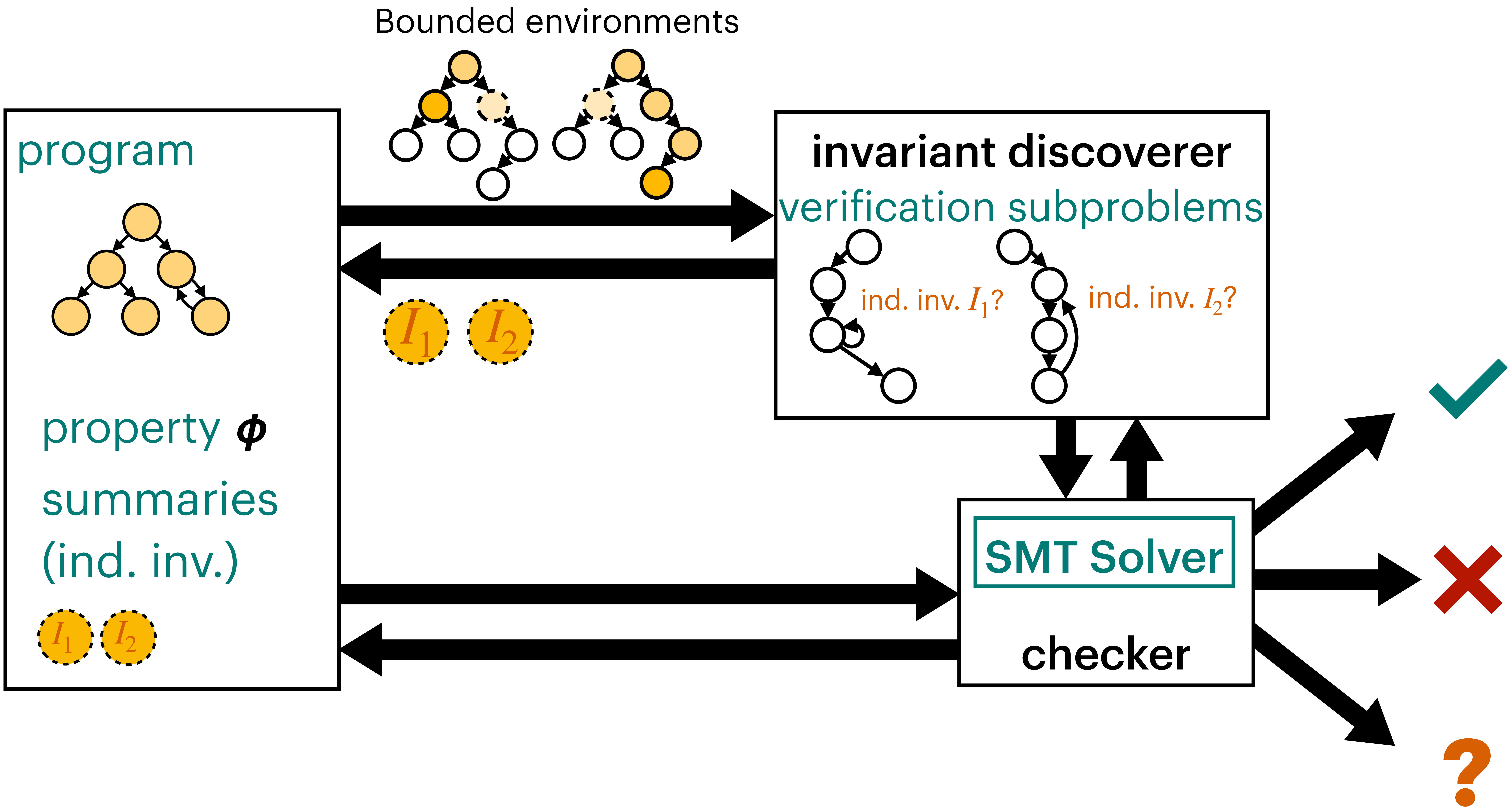
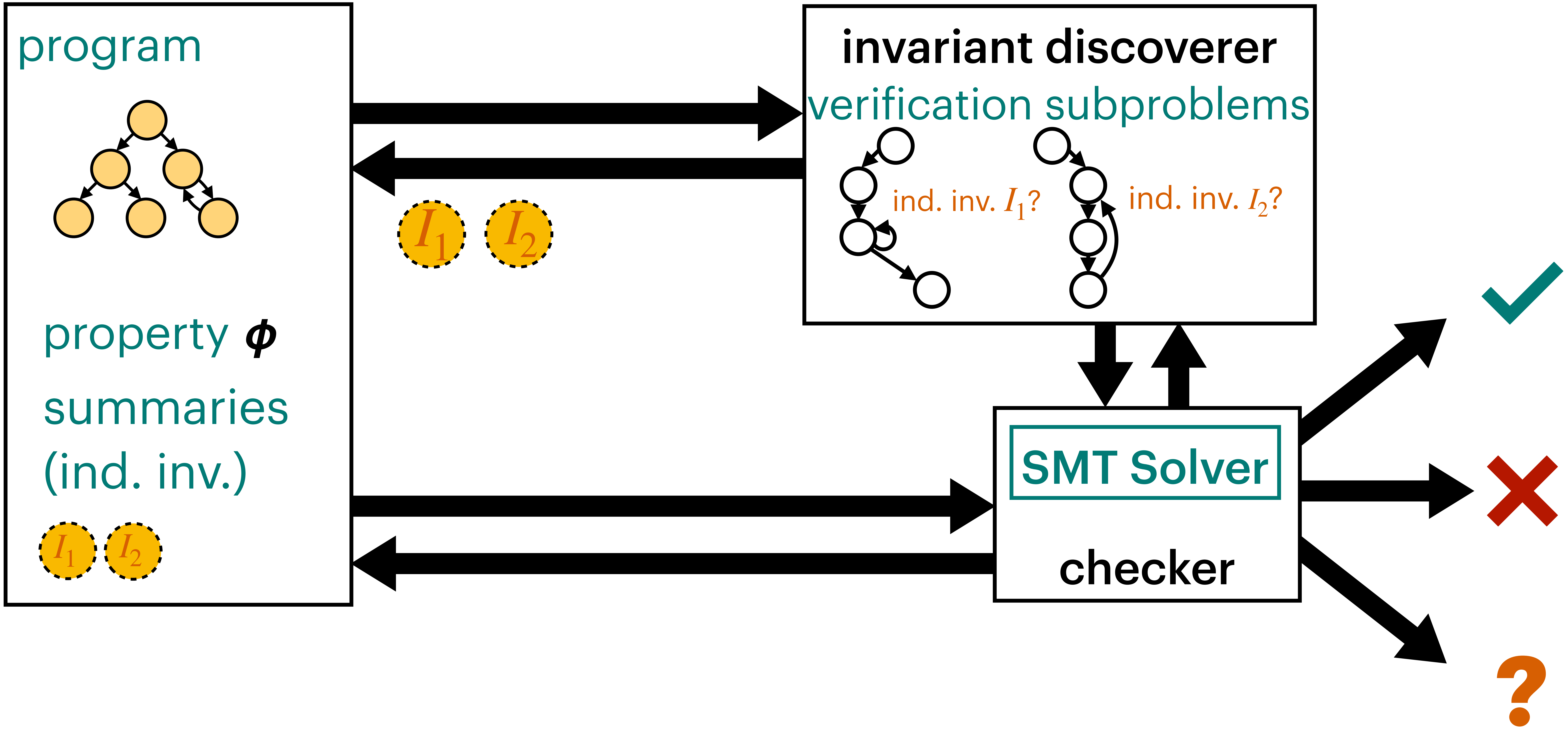


Interprocedural Program Verification

To deal with mutual recursion, use environment-callee EC lemmas

Bounded environments



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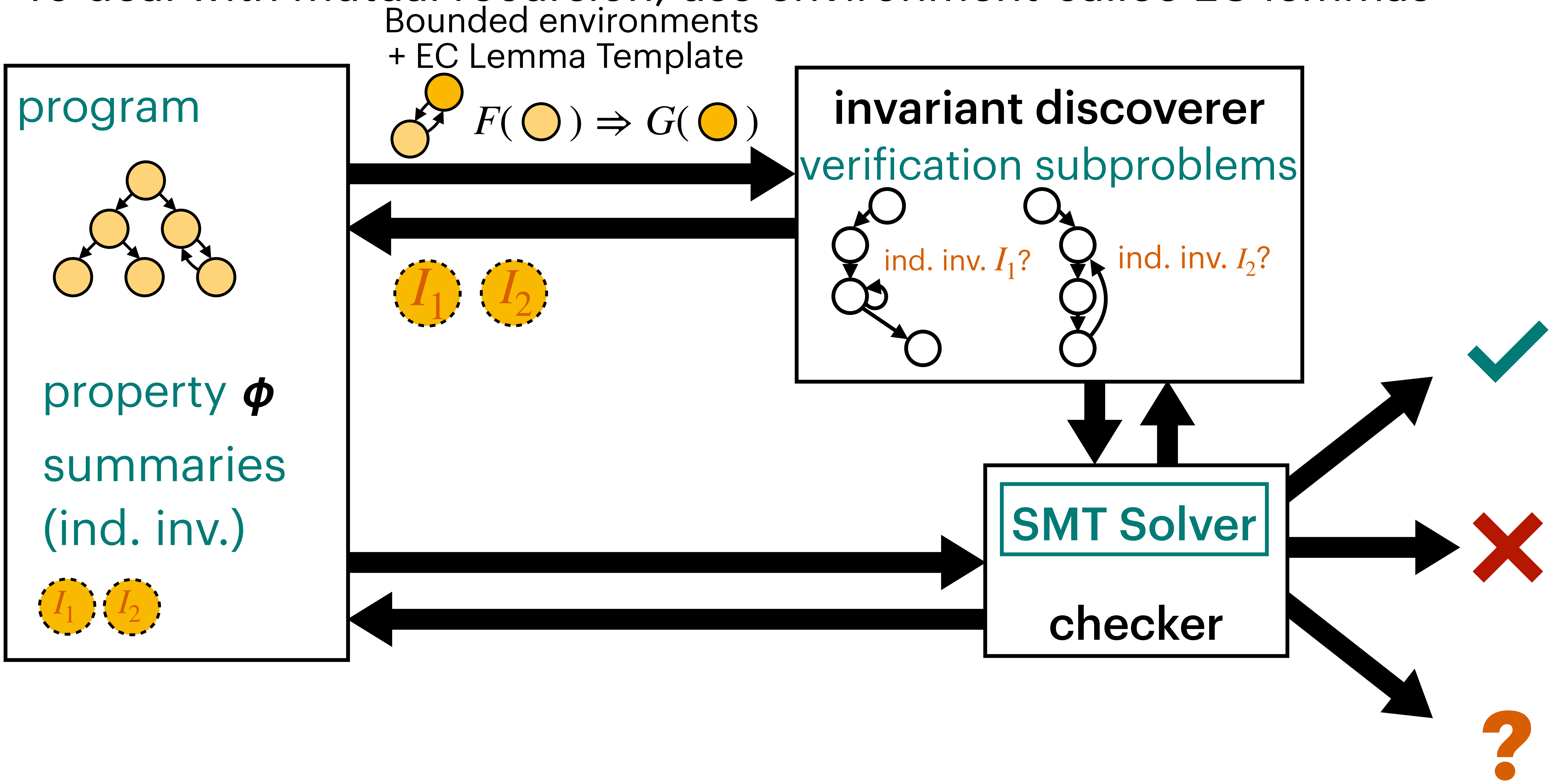

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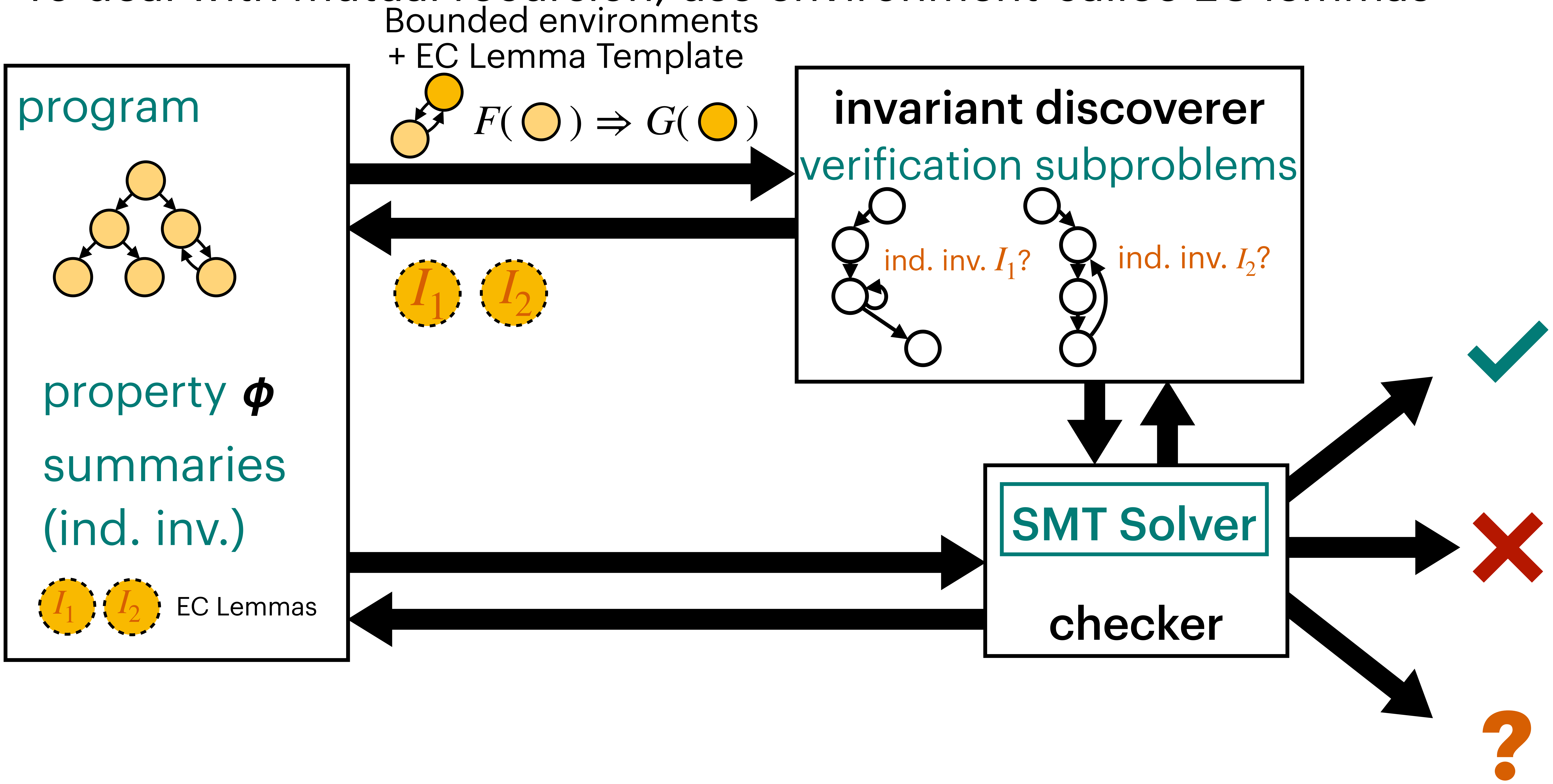

Experimental Results

Implemented in tool called Clover built on top of FreqHorn constrained Horn clause solver [Fedyukovich et al., 2017]

[1] Komuravelli et al., Formal Methods in Sys. Des.'16
[2] Hojjat and Rümer, FMCAD'18
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	Clover (b=10)	**Spacer** [1]	**Eldarica** [2]	**HoIce** [3]	**PCSat** [4]	**Ultimate** [5]
CHC-Comp (101)	77	93	**94**	92	81	76
Real World (16)	**16**	8	12	14	3	15
Mutual Recursion (46)	**45**	13	4	14	5	0
Total (163)	**138**	114	110	120	89	91

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Comparable to other tools in general (timeout 10 min), excels at mutual recursion

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Experimental Results

Experimental Results

EC Lemmas are useful!

	Clover (b=10)	Clover (b=10), no EC lemmas
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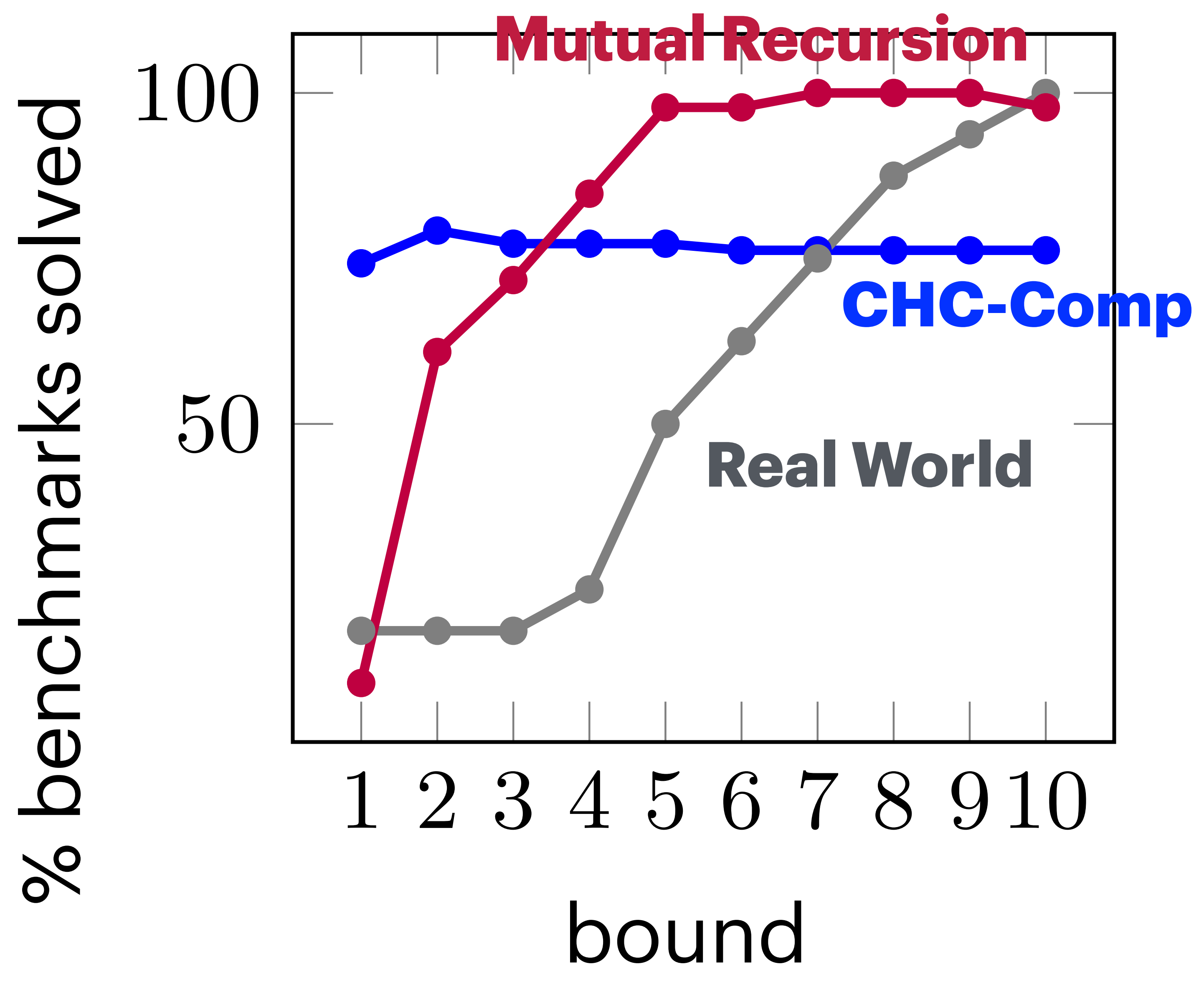
Different bounds help for different benchmark sets



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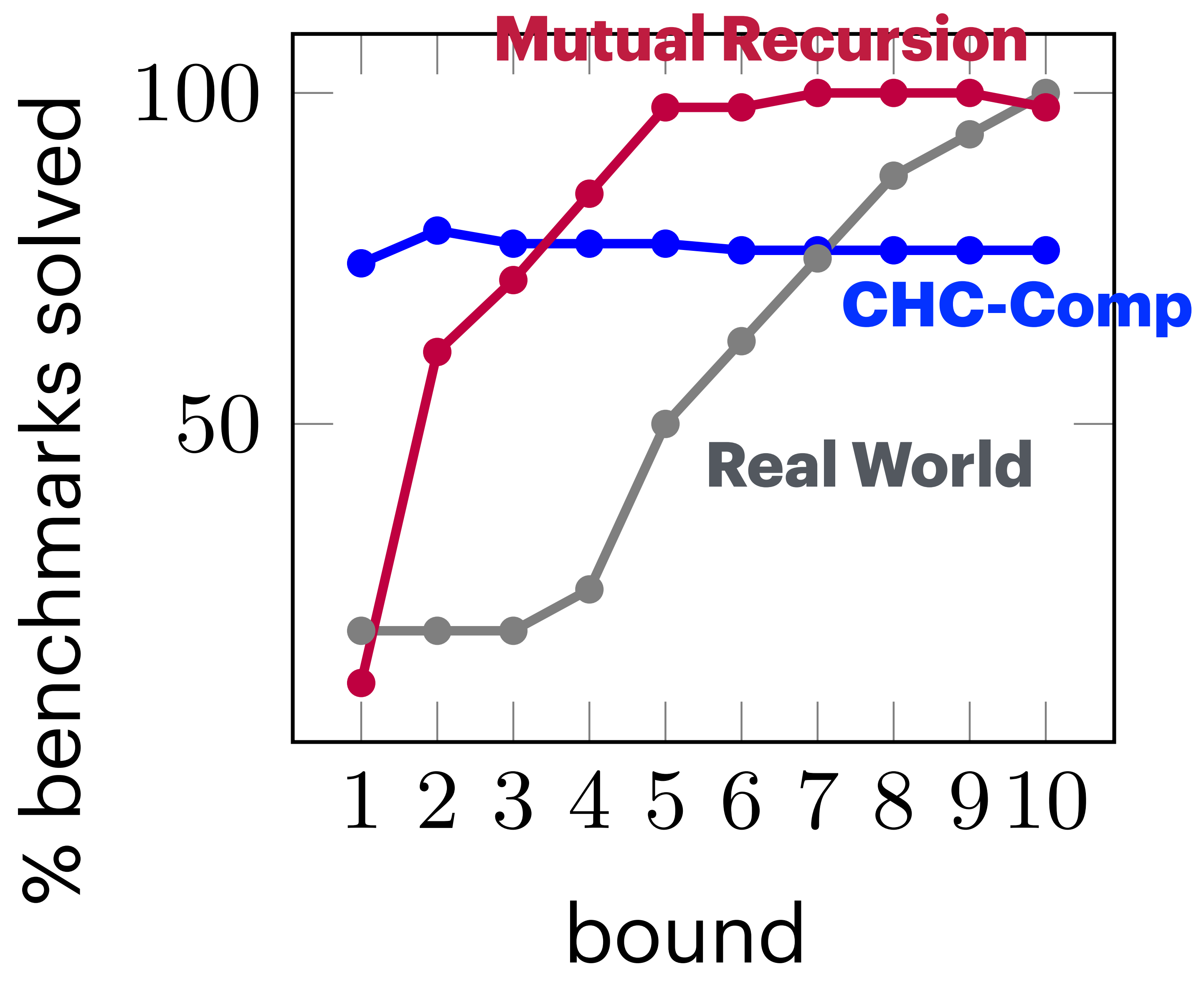

e.g., bounds 7-9 were best for Mutual Recursion

Related Work

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Constrained-Horn-Clause-Based Program Verification

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Program Analysis and Verification

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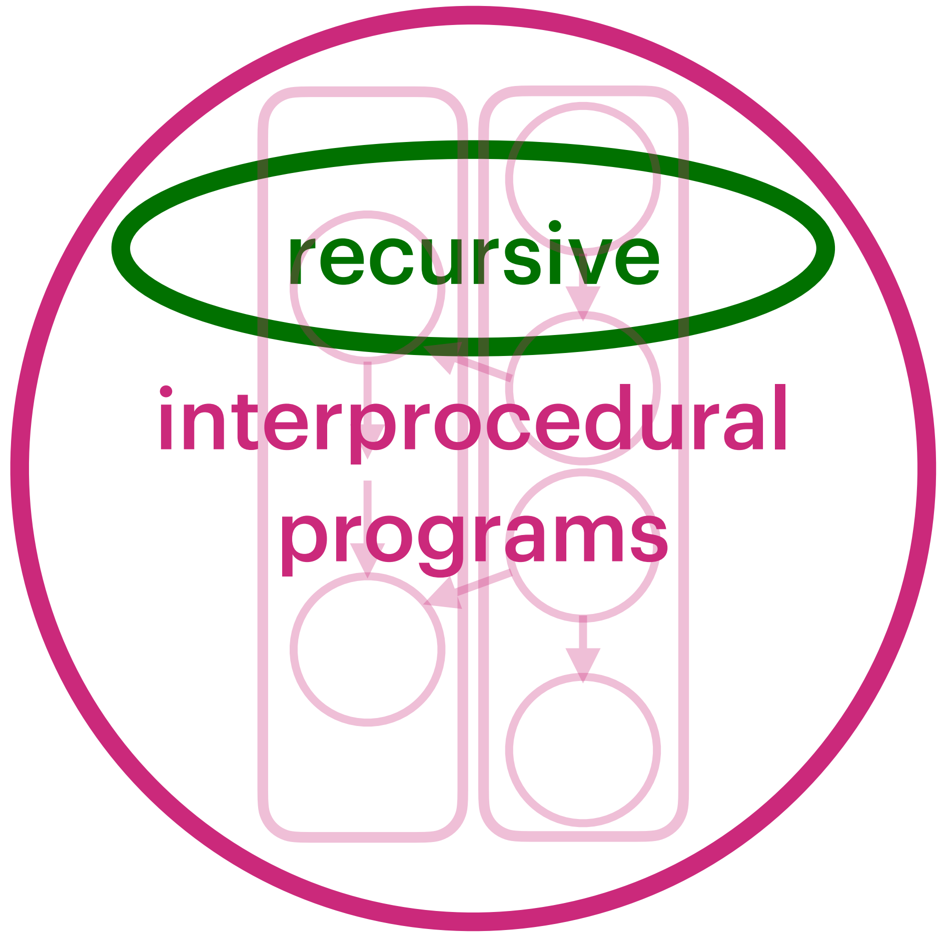
No bounded environments or EC lemmas

III. Information Flow Checking for Interprocedural Programs



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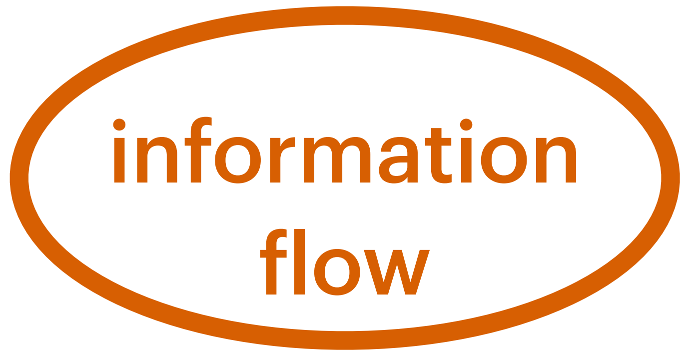


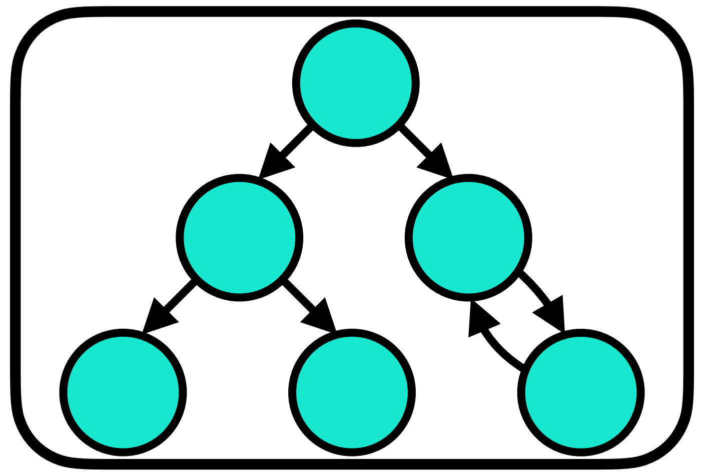
Multiple-procedure programs (may contain recursion)

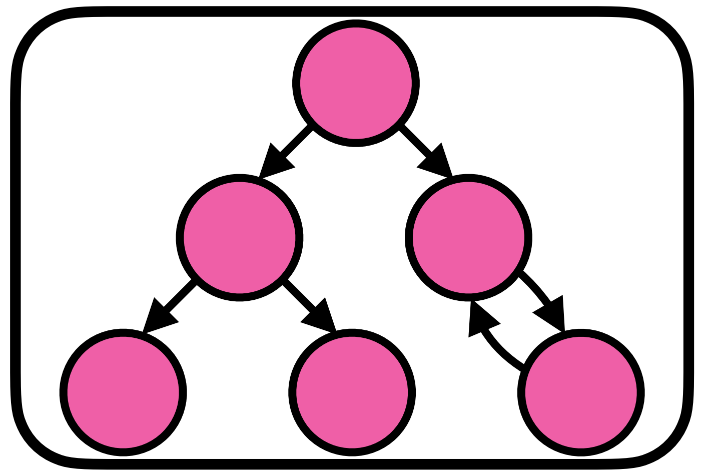
Information-flow security properties

Information-flow properties

Information-flow properties

2-safety property ***relating*** 2 copies of the same program with **equalities** on subsets of corresponding components, e.g., noninterference:





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High-security inputs shown in red

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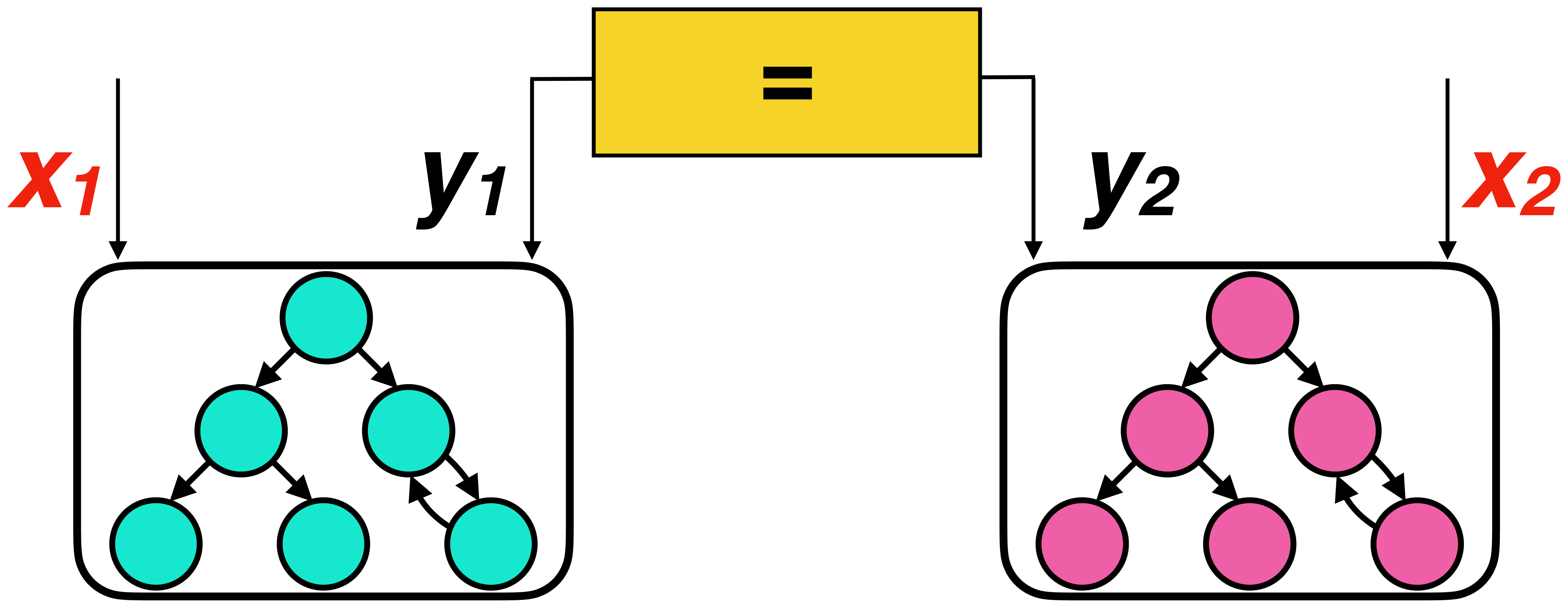

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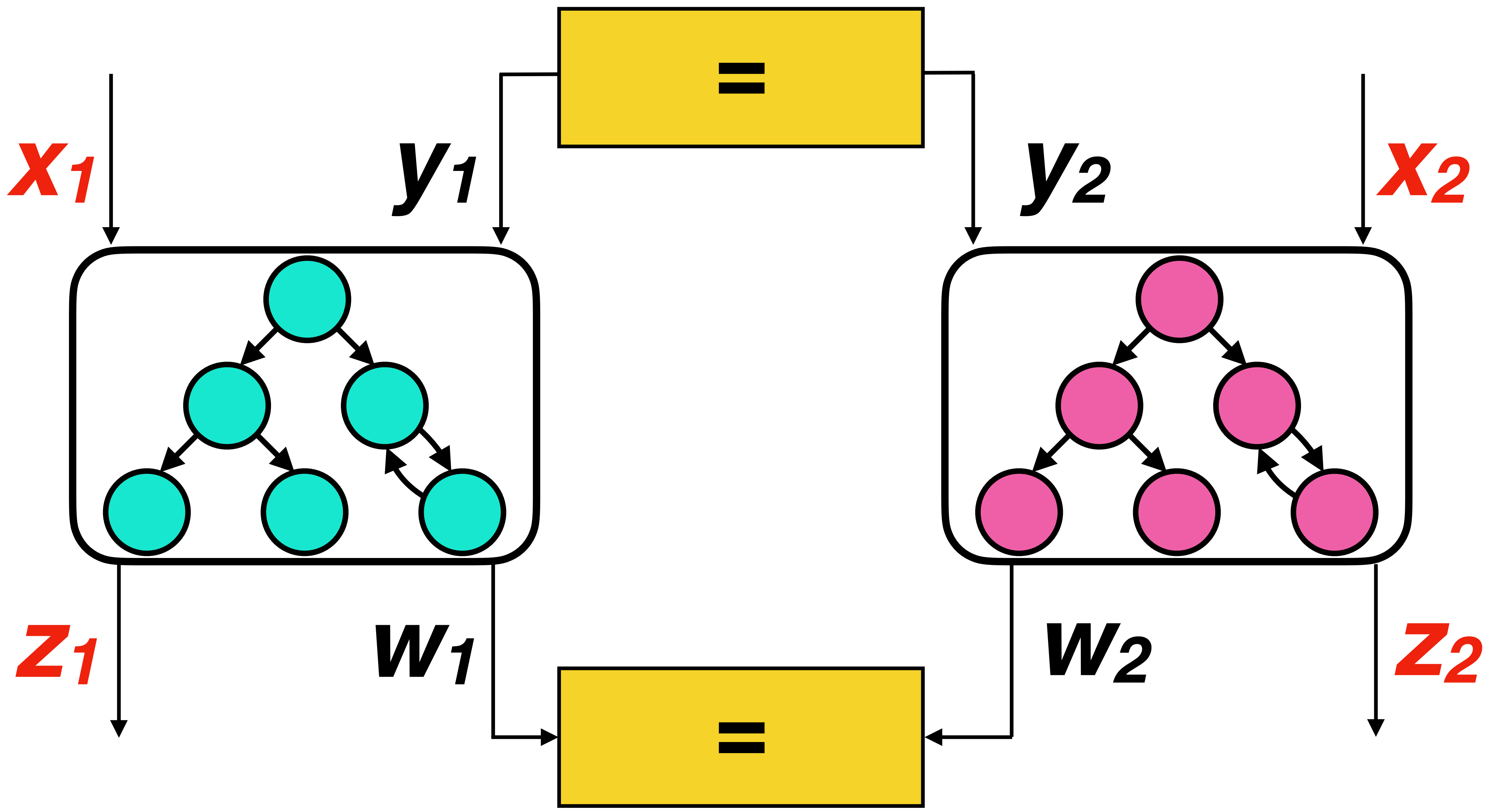
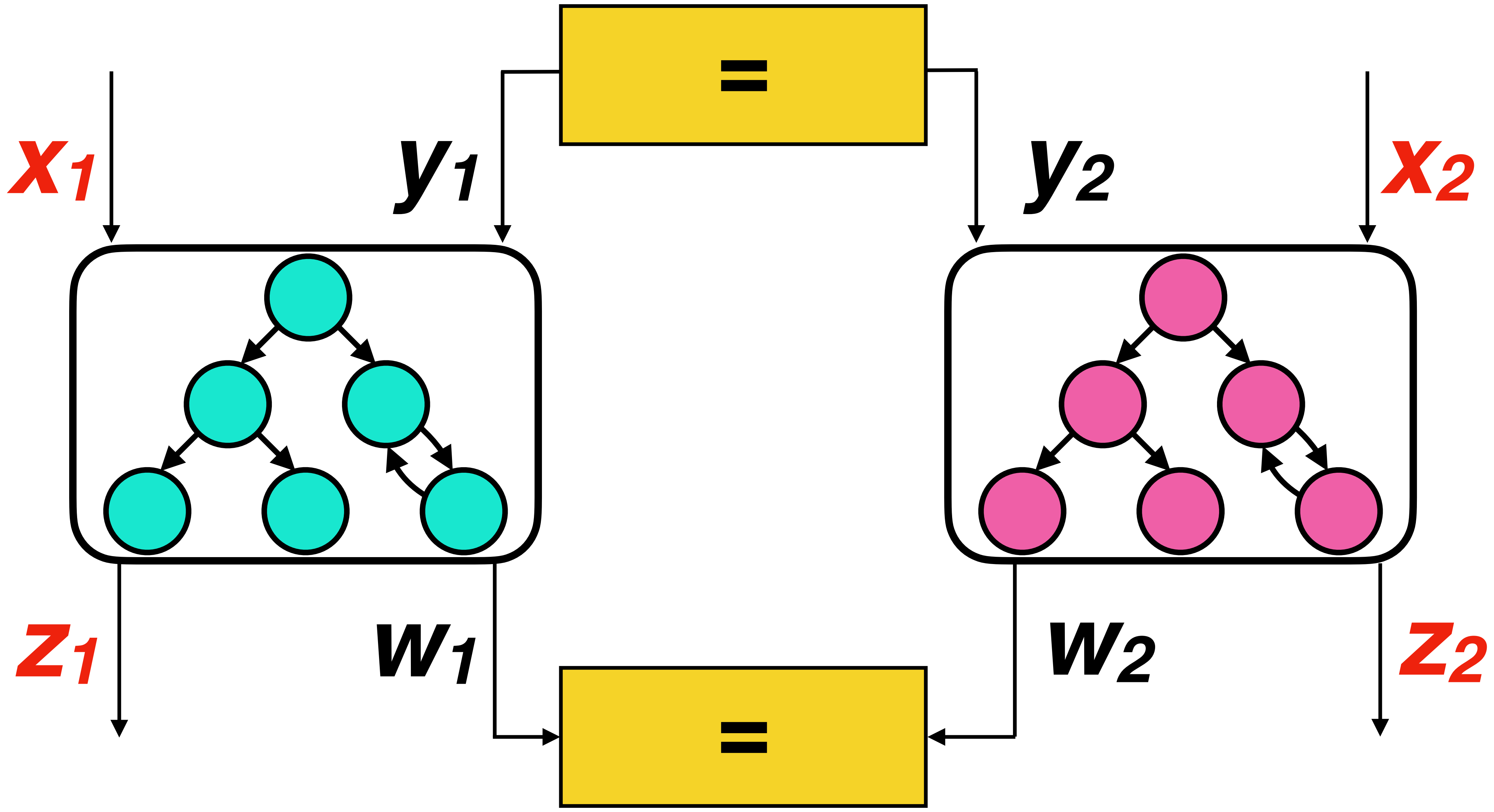


Product Programs

Can turn 

into 

by constructing a product program



Secure information flow by self-composition, Barthe et al., CSFW'04
Relational verification using product programs, Barthe et al., FM'11

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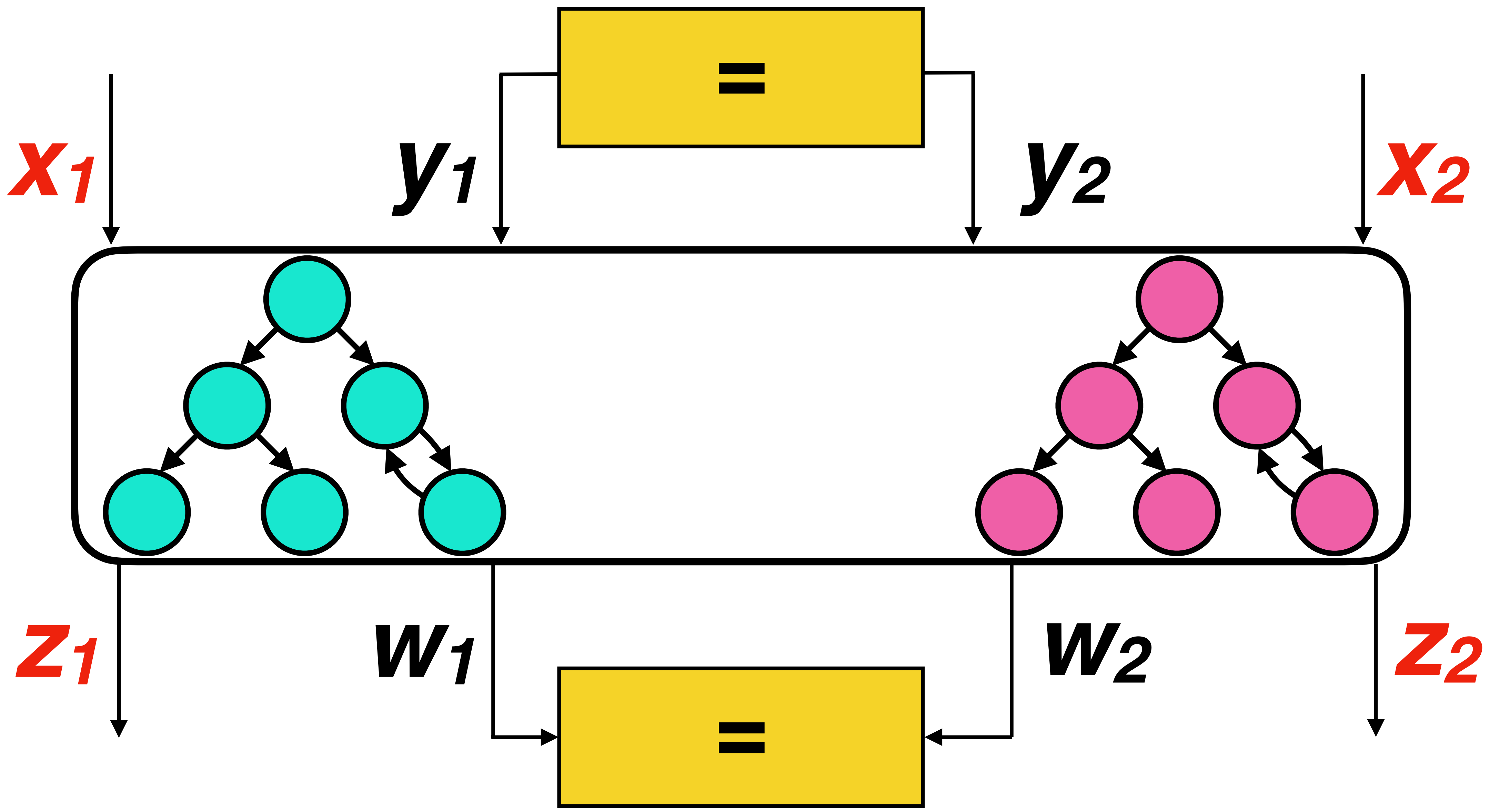

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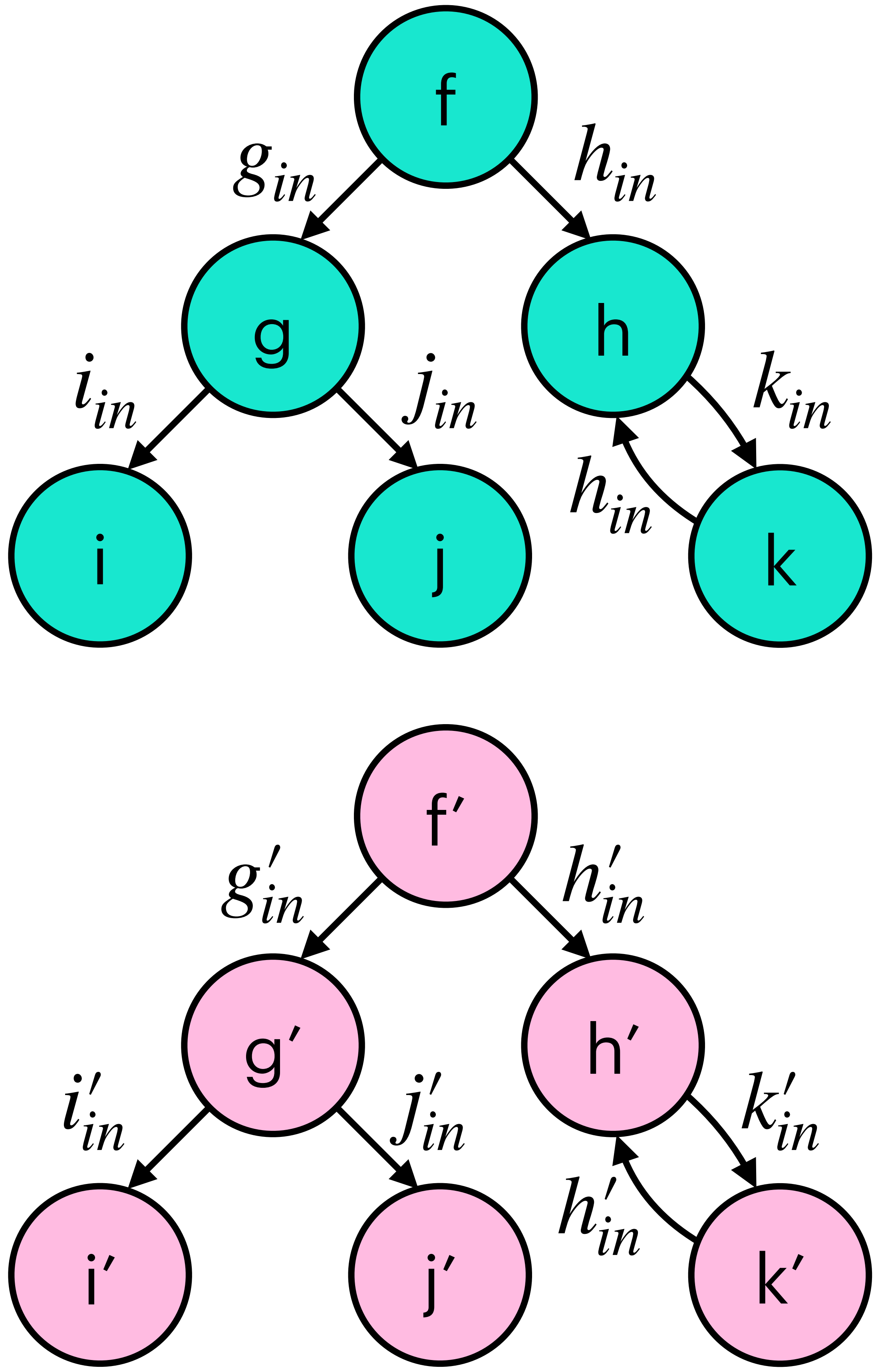
Modular Product Programs



Modular product programs, Eilers et al., ESOP'18

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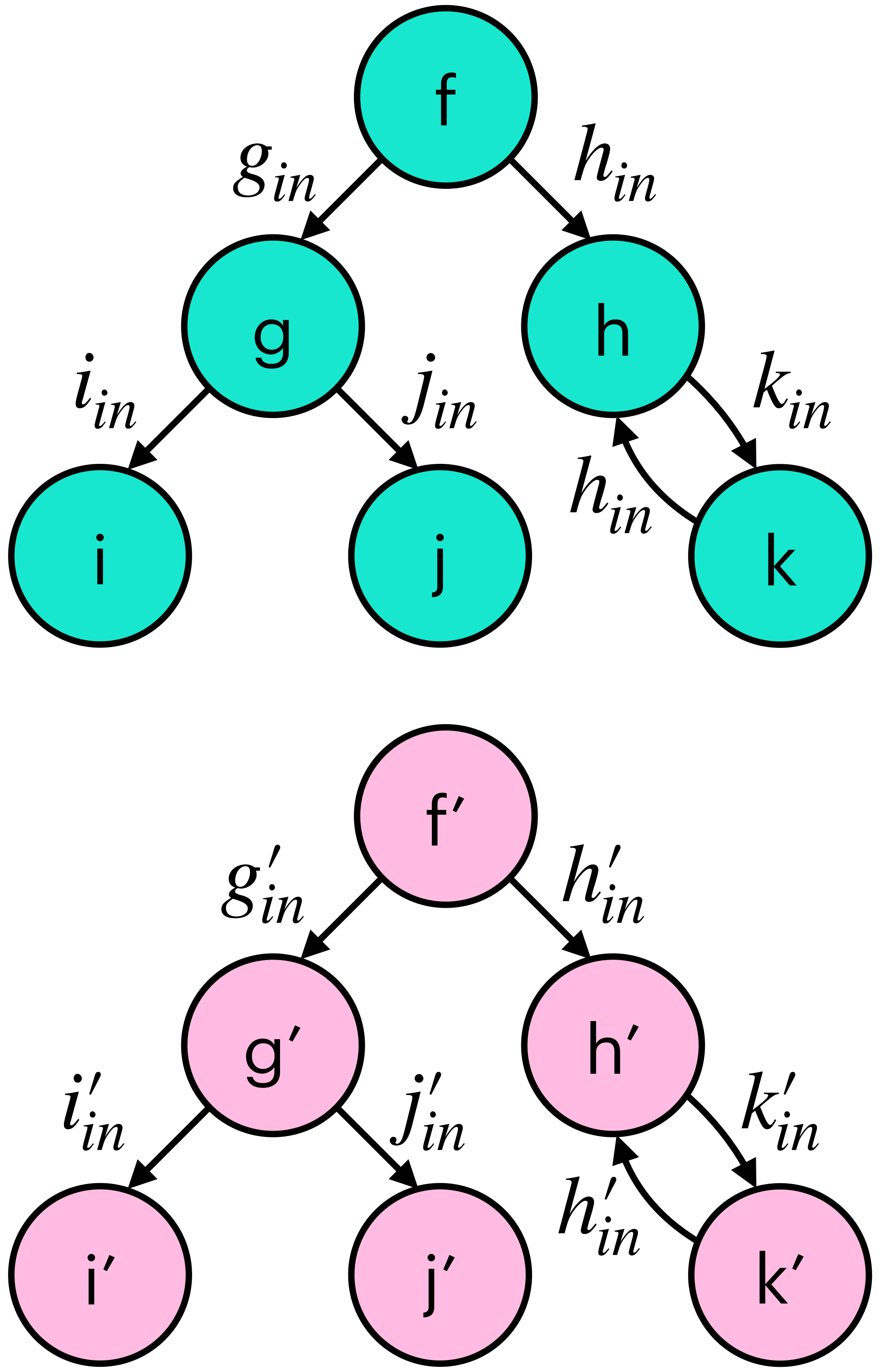

Labels denote input variables

Modular product programs, Eilers et al., ESOP'18

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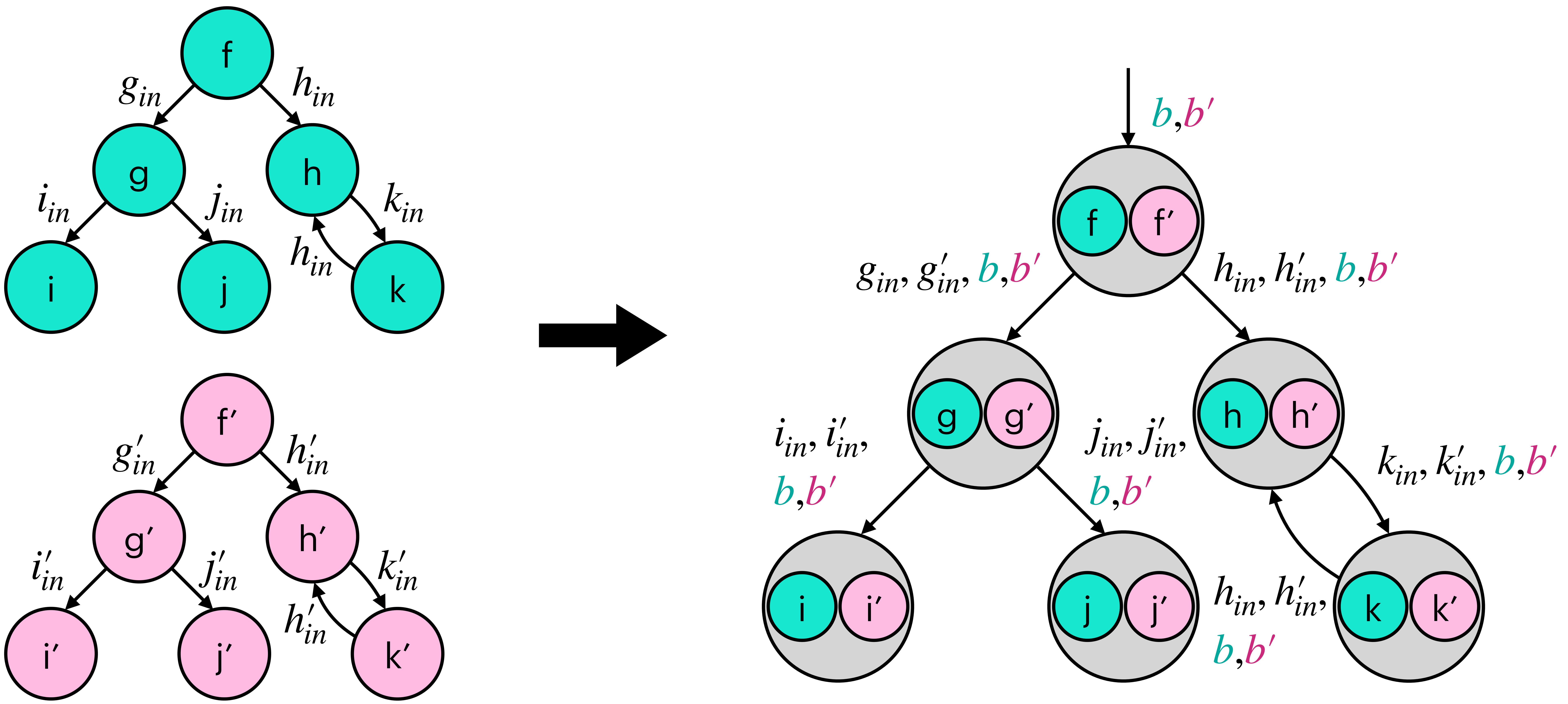

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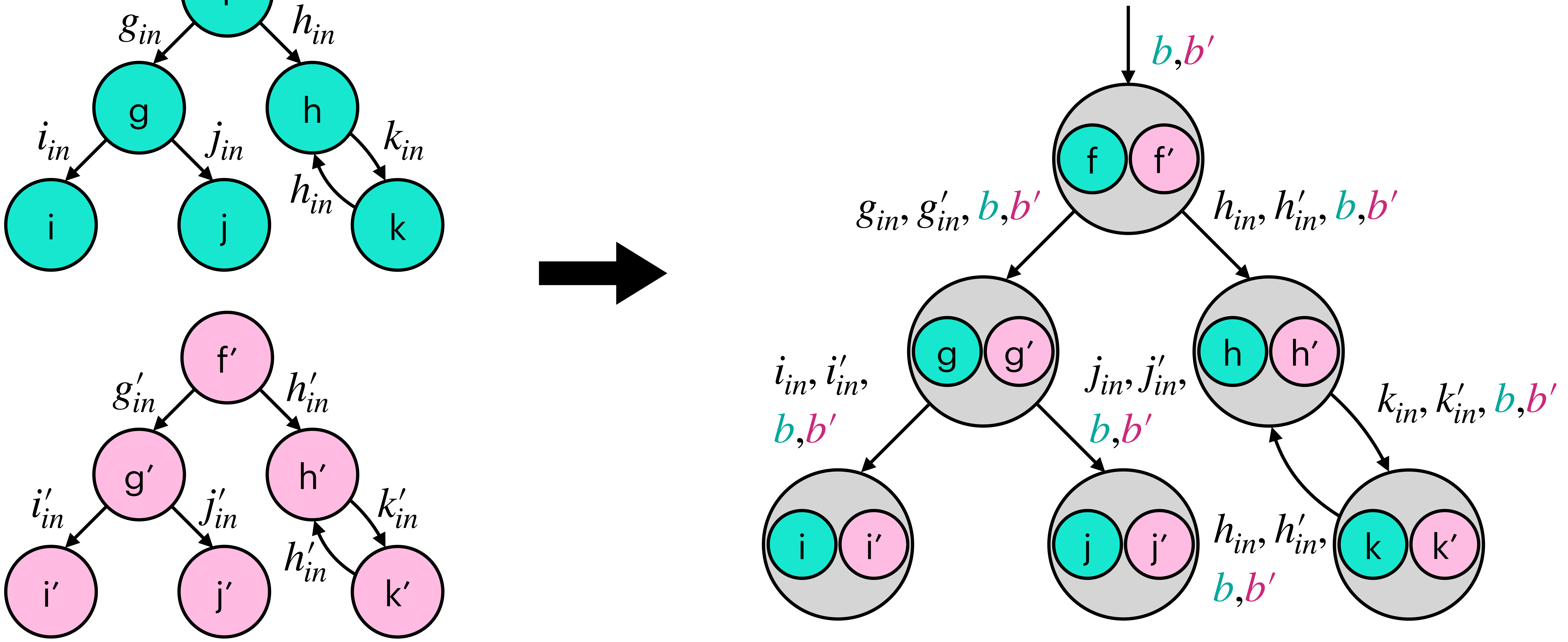
Modular product programs, Eilers et al., ESOP'18

Modular Product Programs

Activation variables b, b' specify if copy is active



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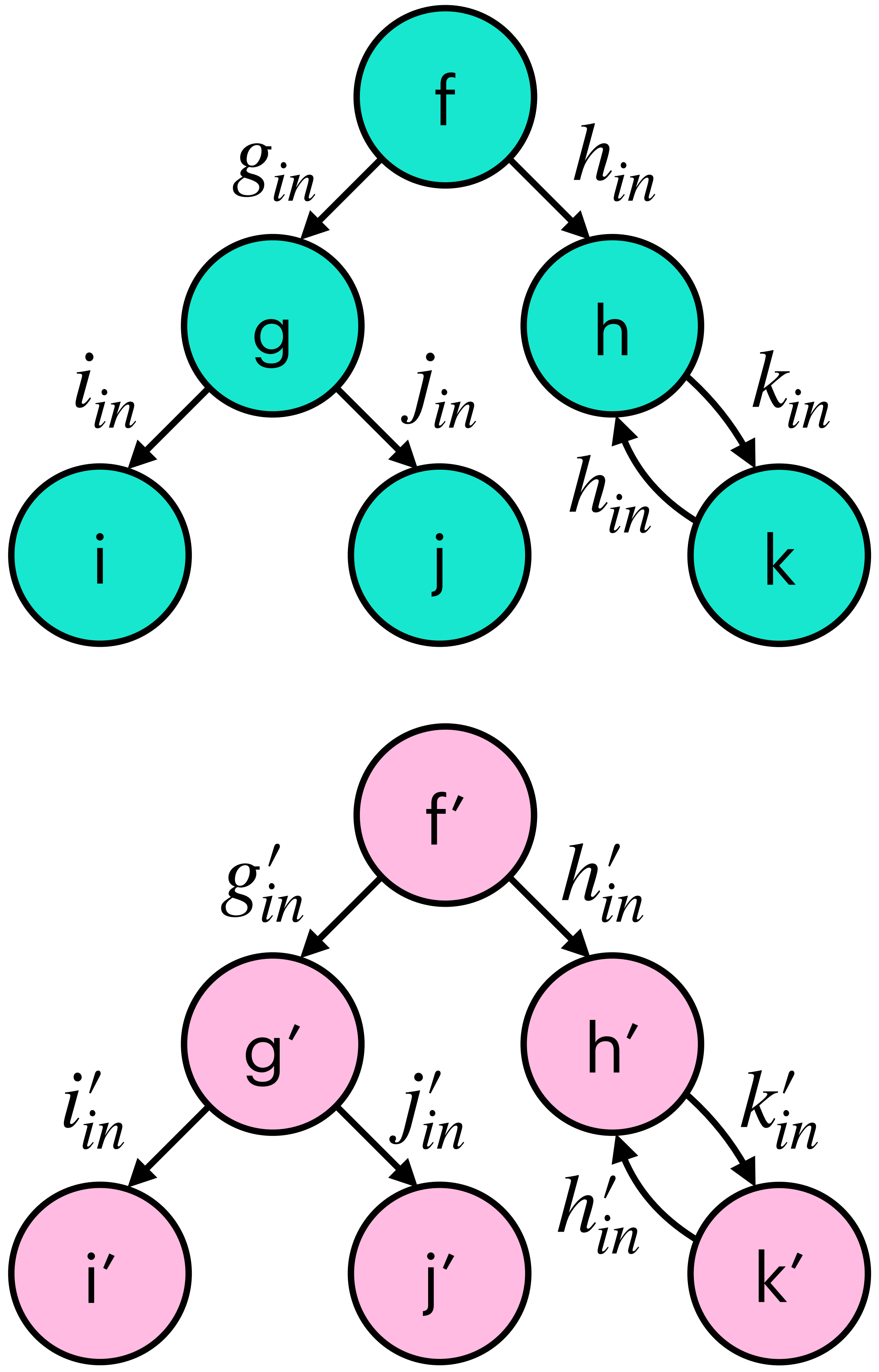

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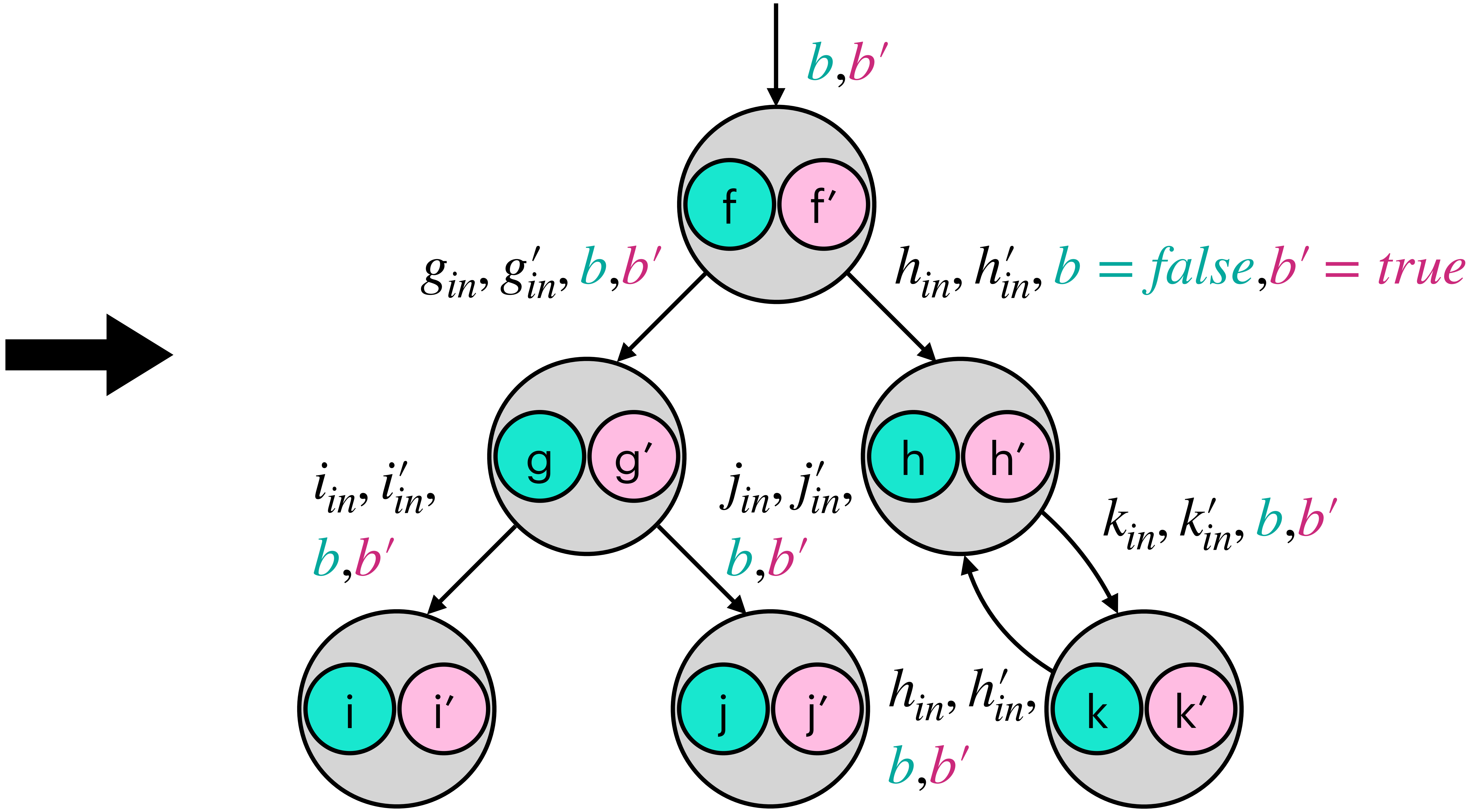

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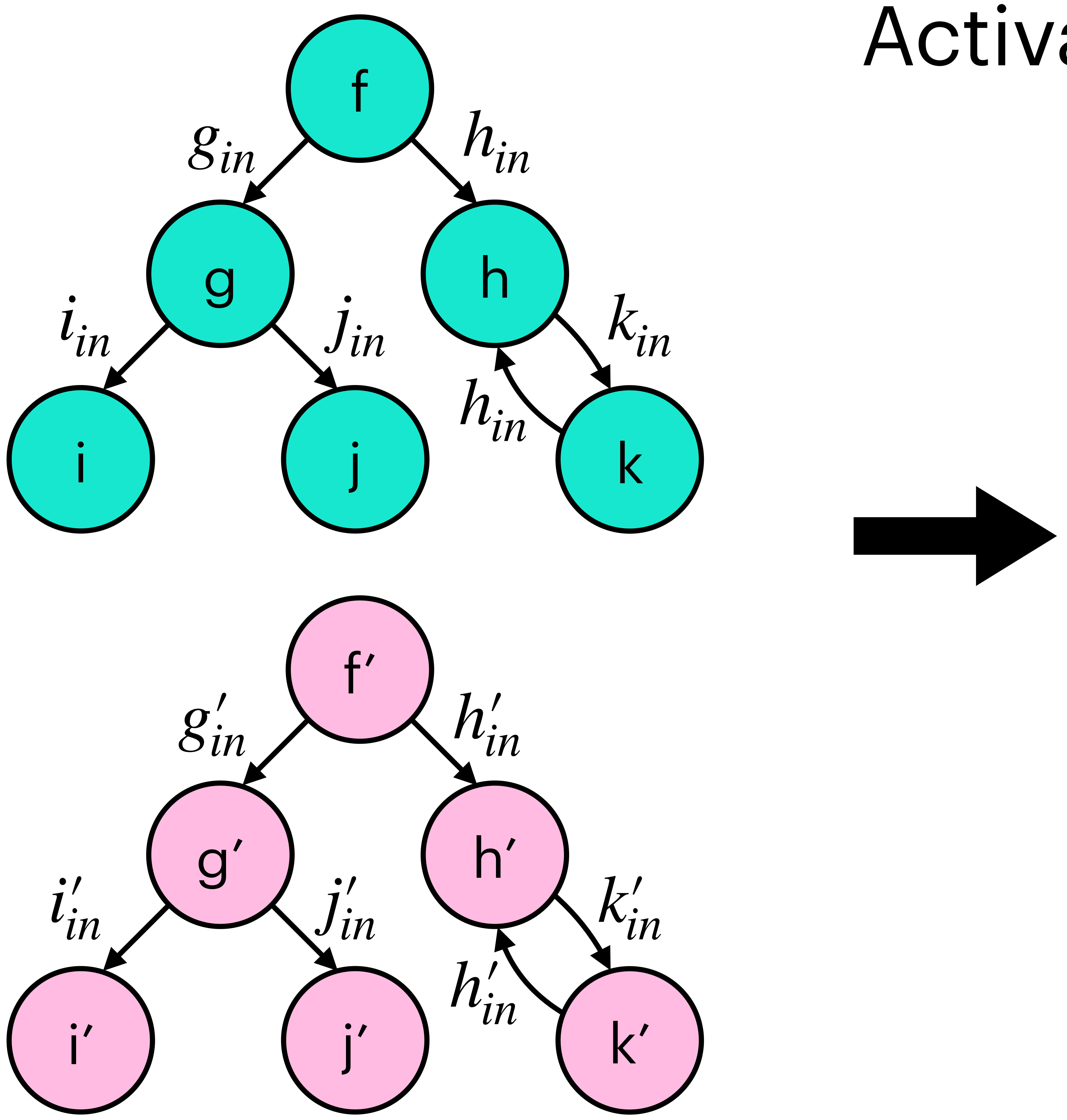

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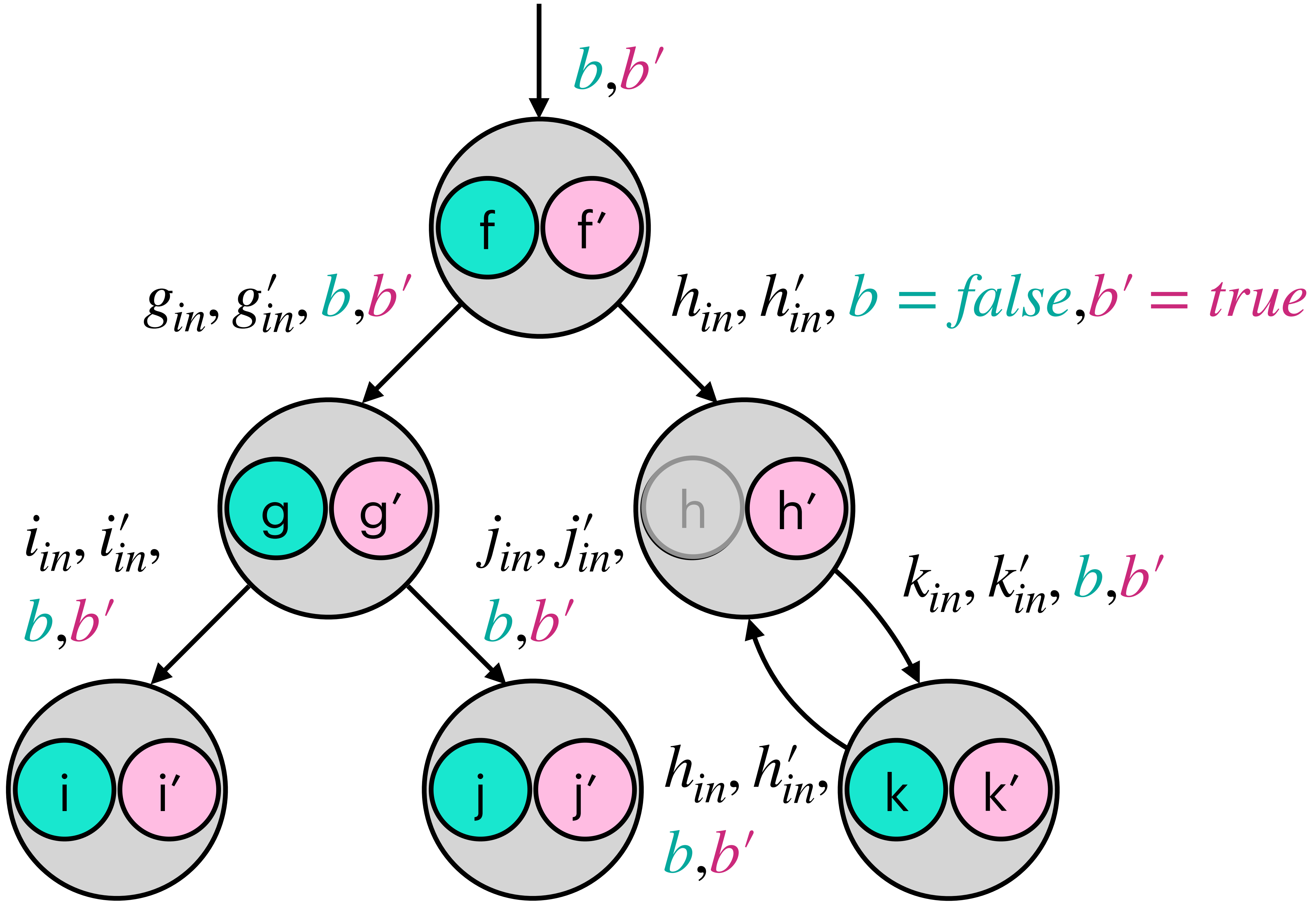

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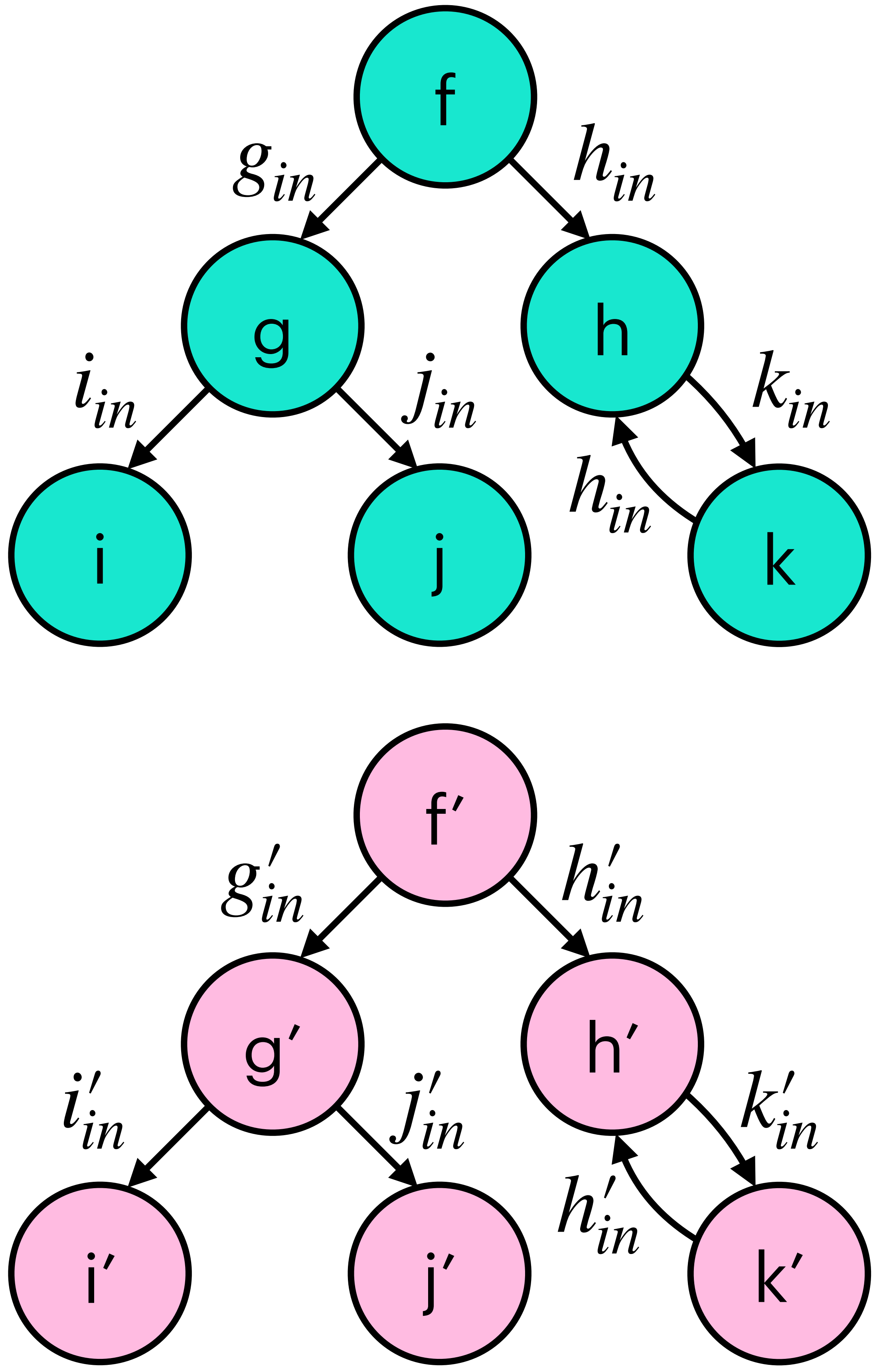

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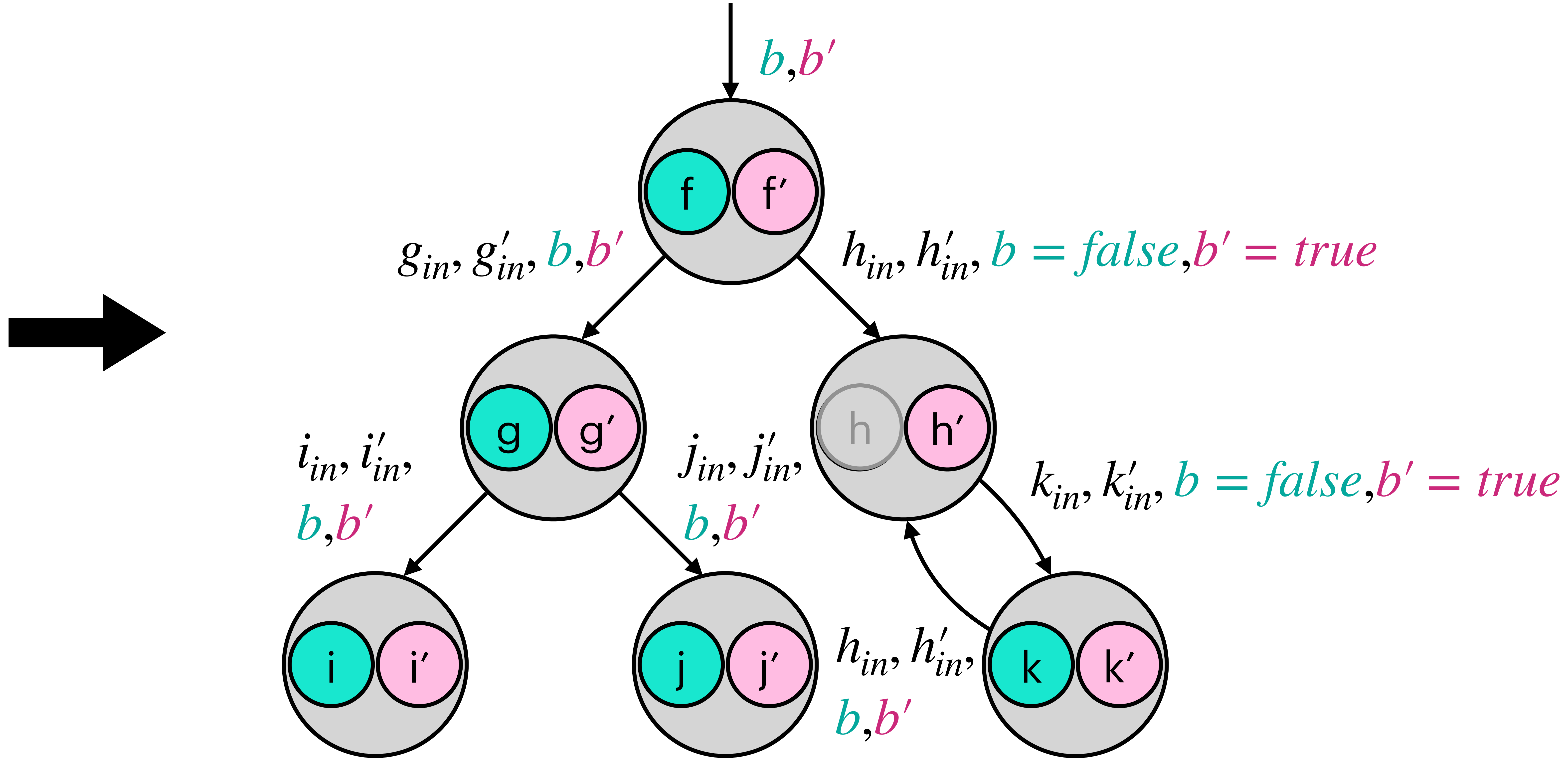
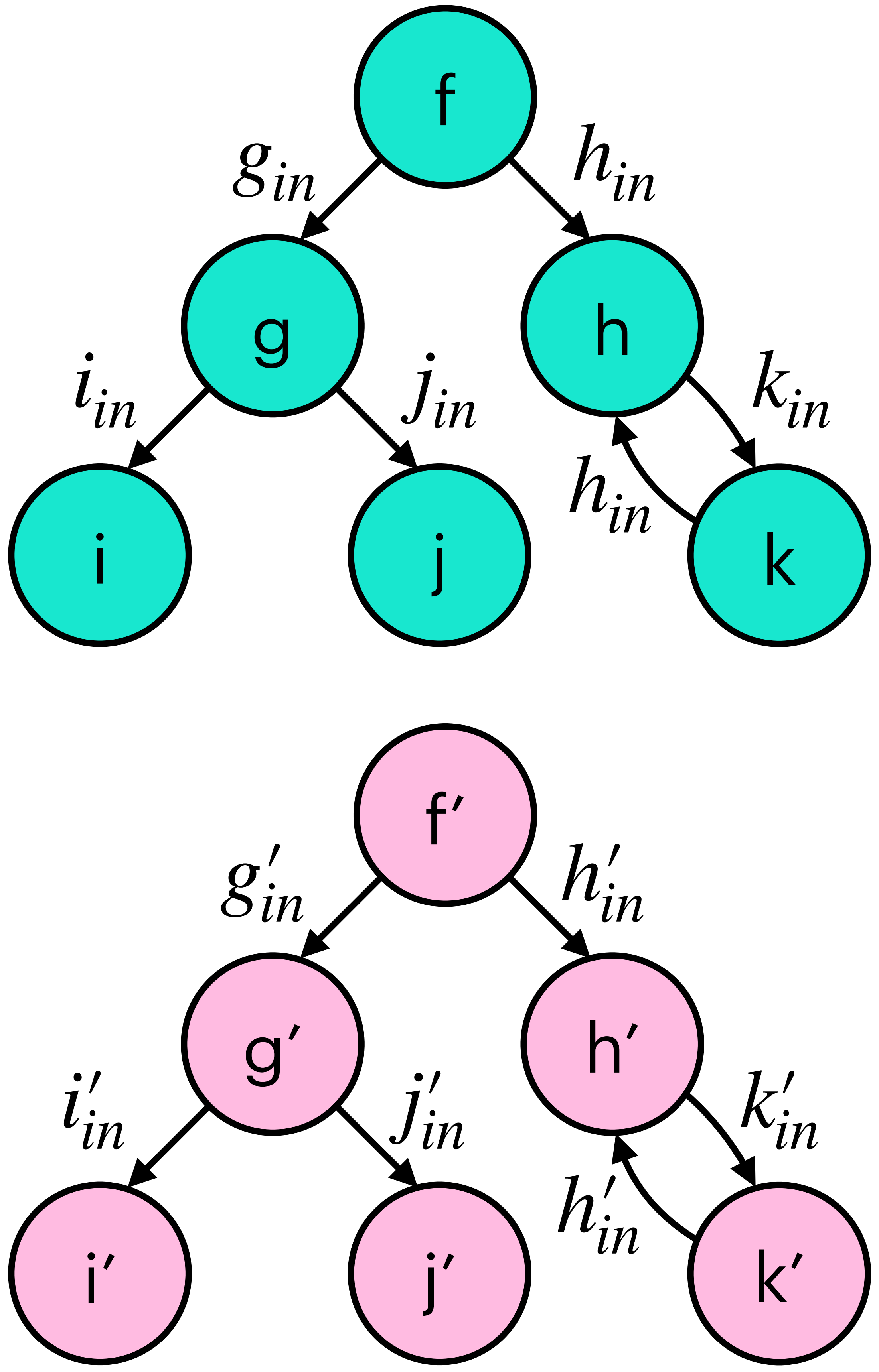
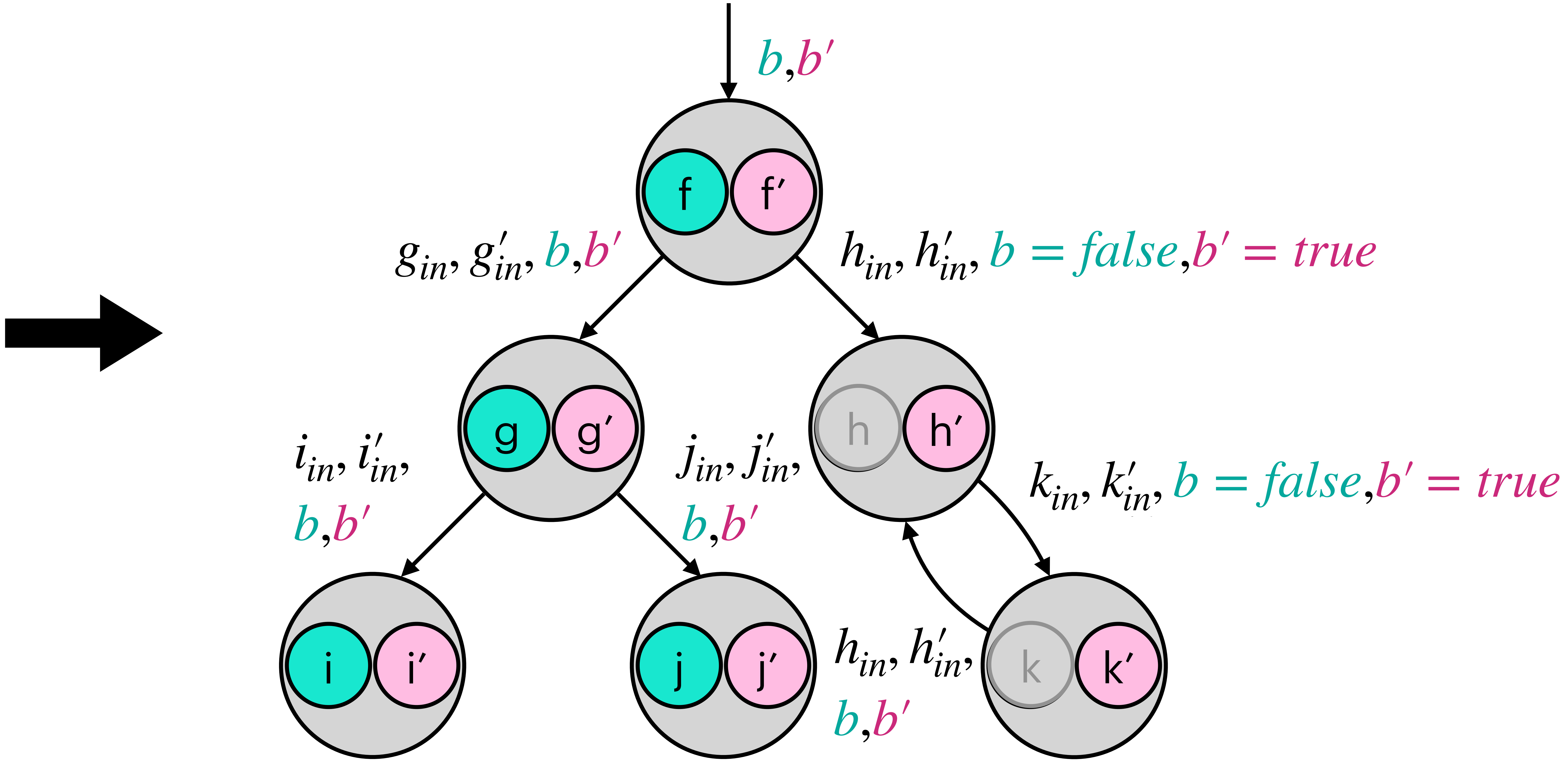


Modular product programs, Eilers et al., ESOP’18

Modular Product Programs

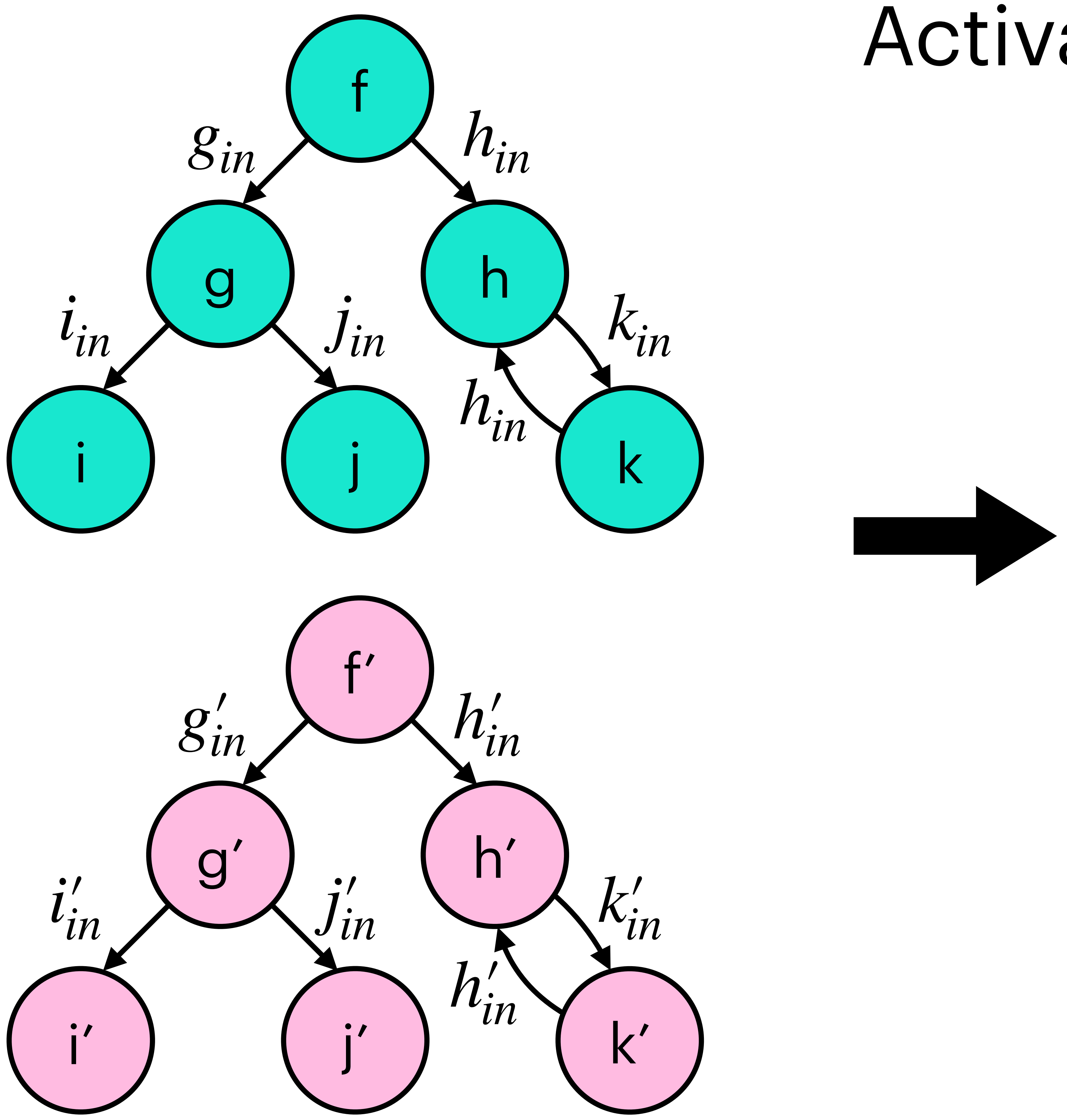


Activation variables b, b' specify if copy is active

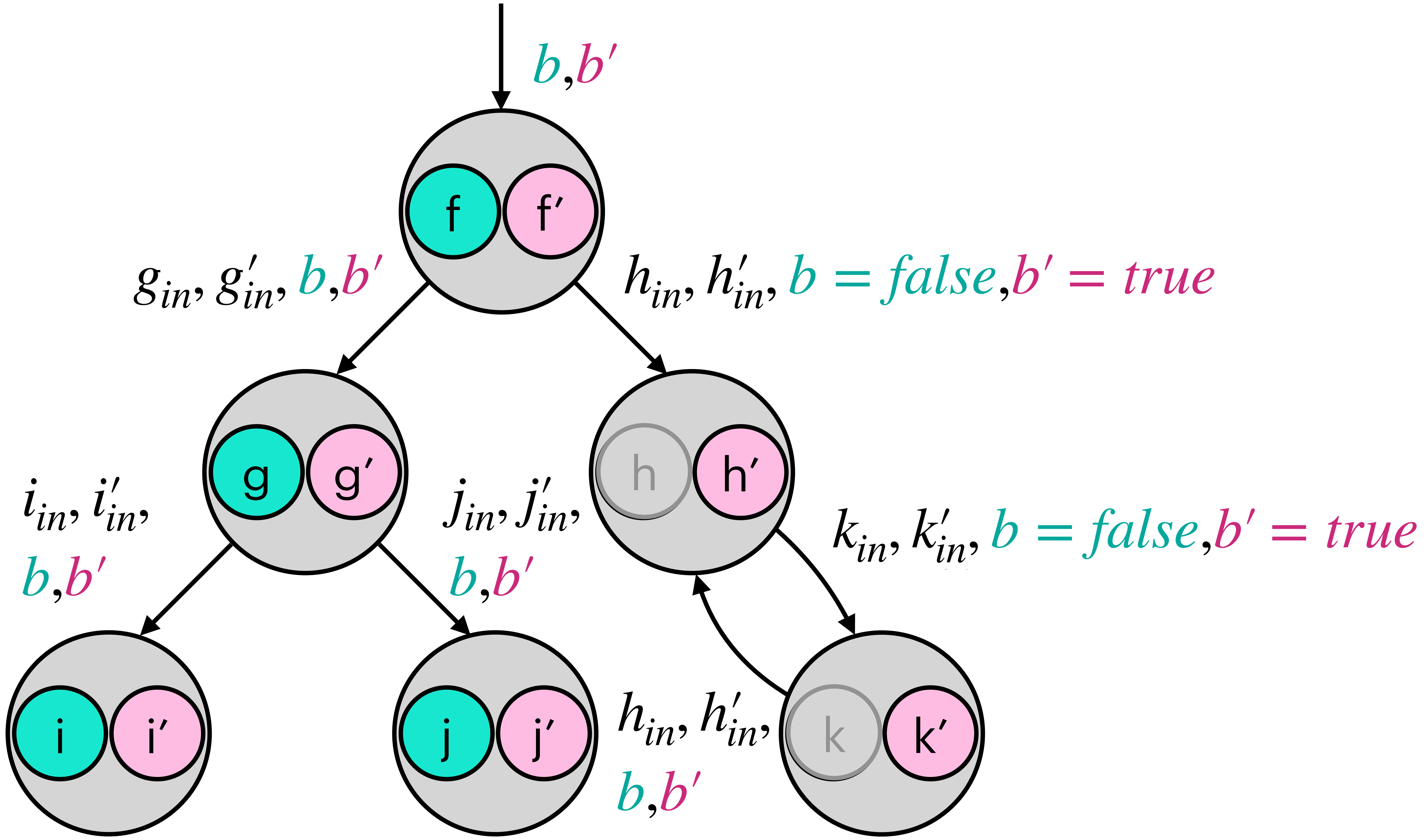


Modular product programs, Eilers et al., ESOP’18

Modular Product Programs



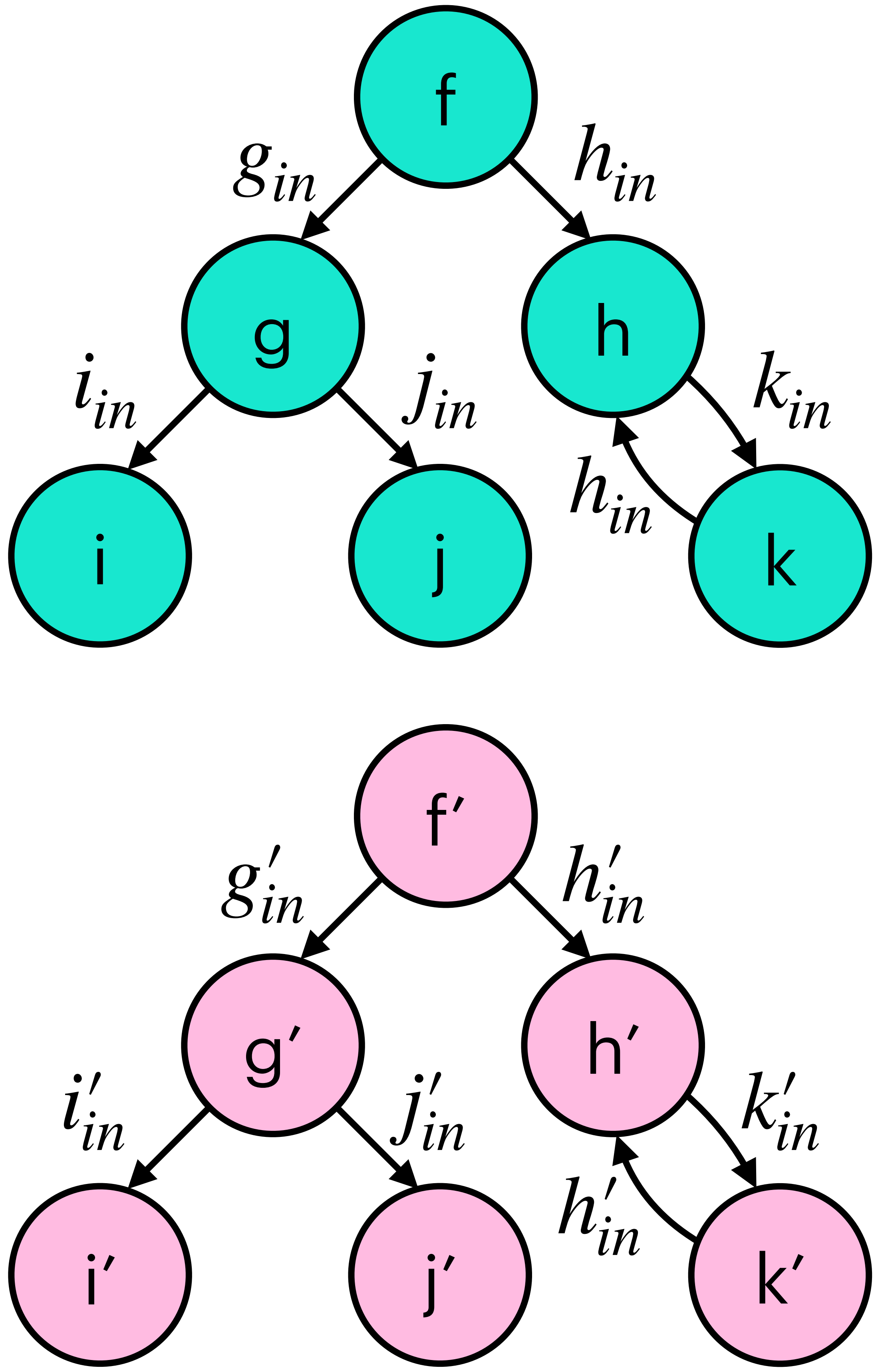
Activation variables b, b' specify if copy is active



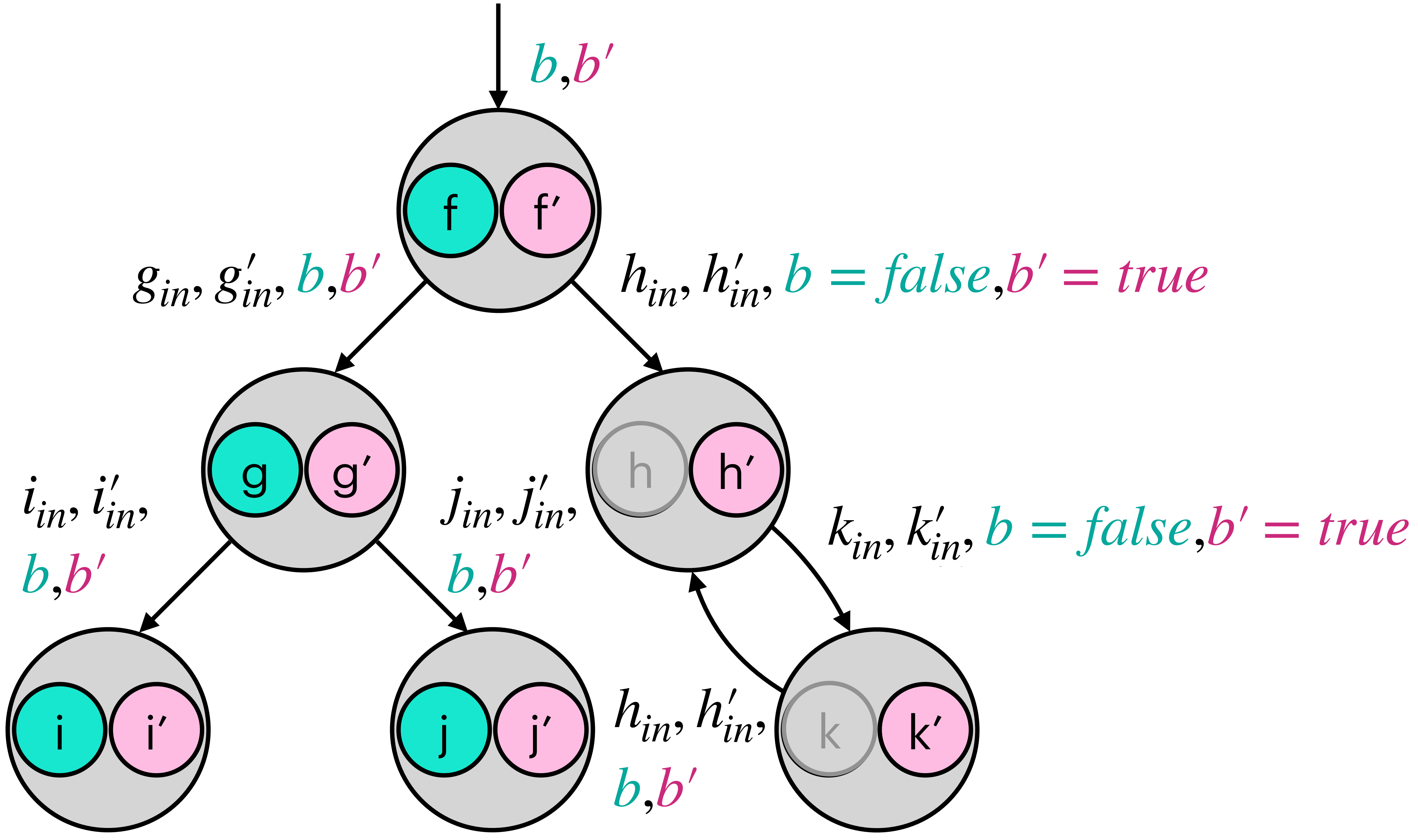
Required user-provided annotations (which variables are high-/low-security?)

Modular product programs, Eilers et al., ESOP'18

Modular Product Programs



Activation variables b, b' specify if copy is active

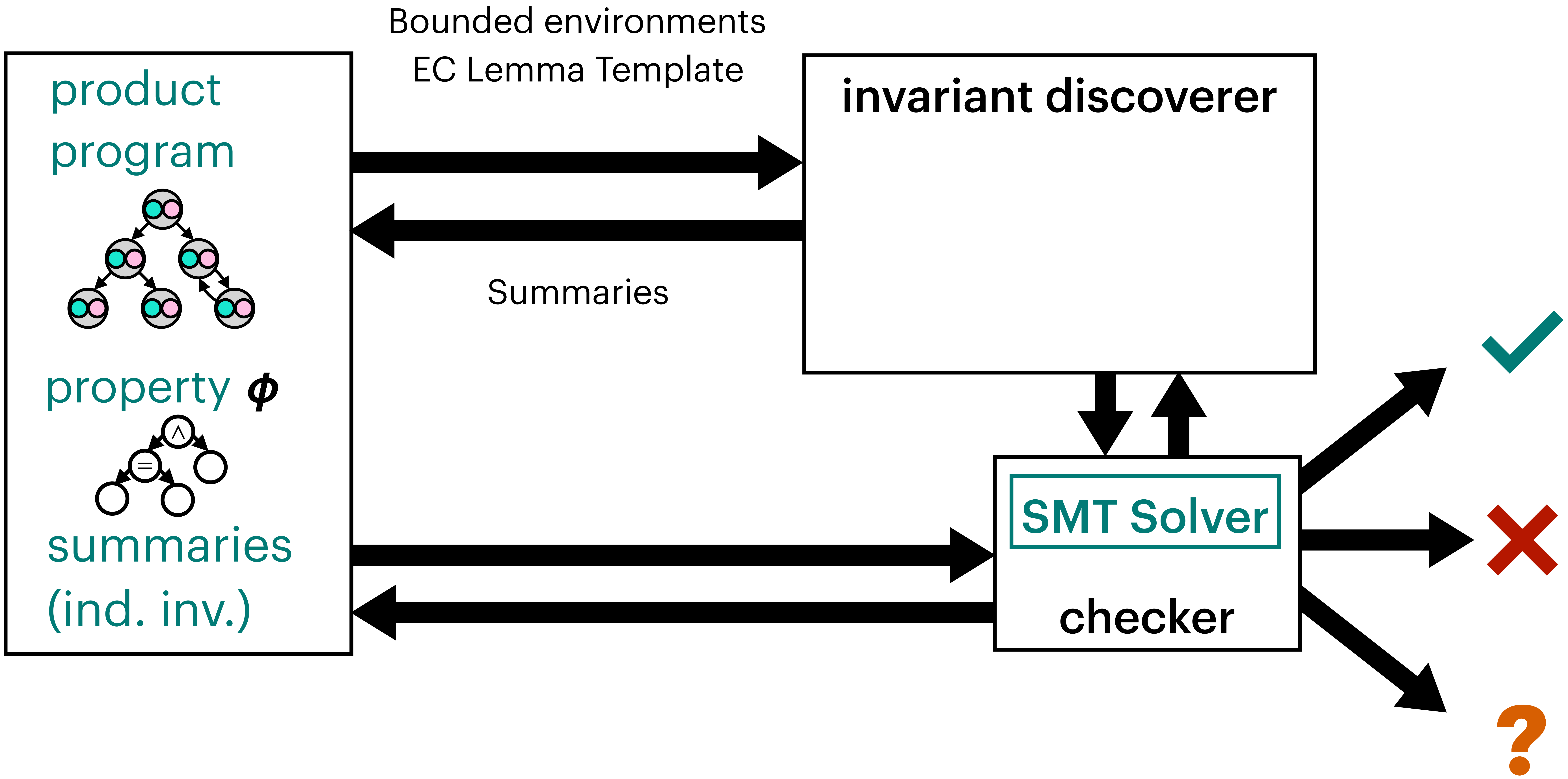


Required user-provided annotations (which variables are high-/low-security?)

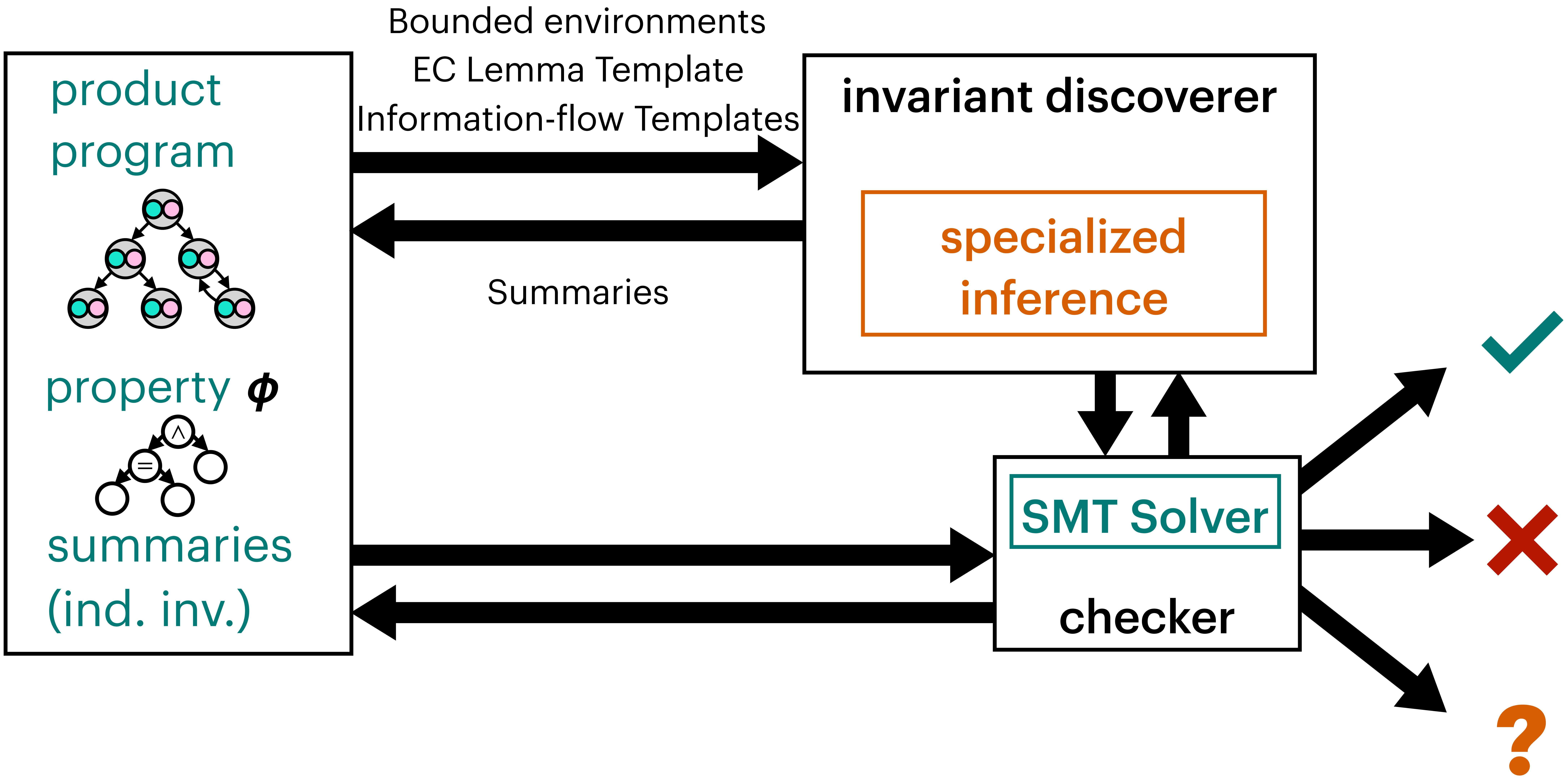
Can we infer these invariants?

Modular product programs, Eilers et al., ESOP’18

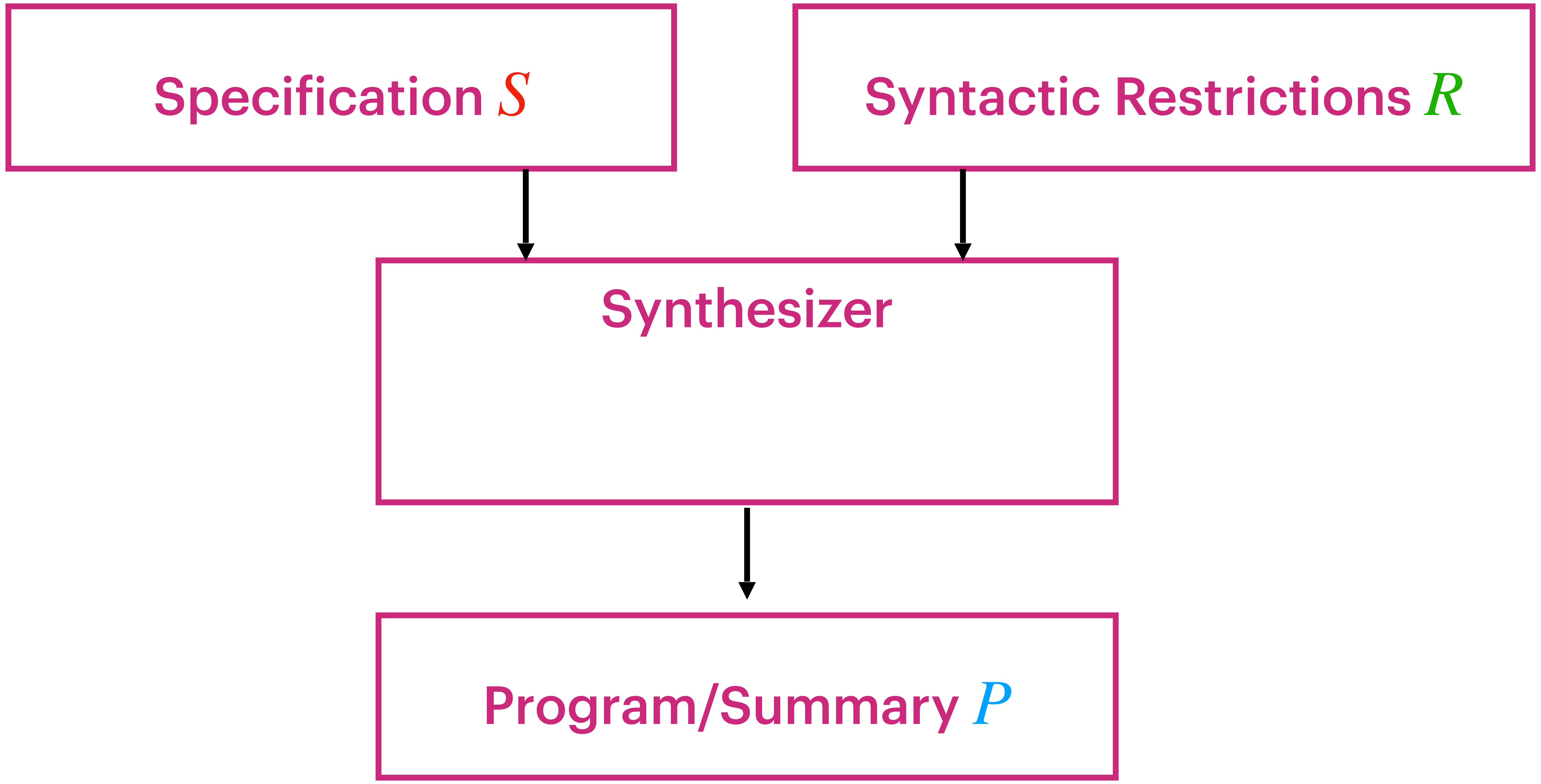
Adapting Interprocedural Program Verification



Adapting Interprocedural Program Verification



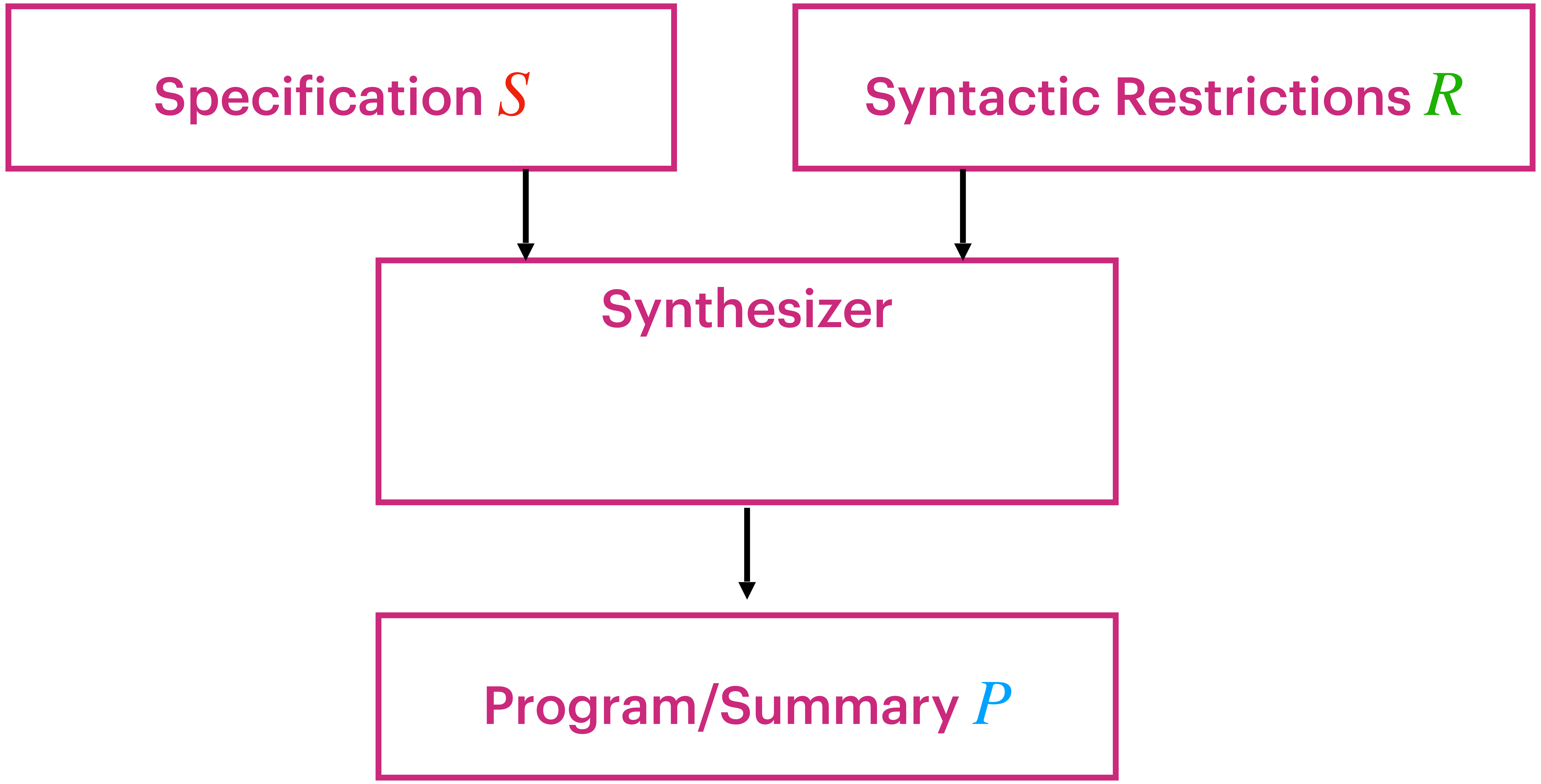
Syntax-Guided Synthesis (SyGuS)



Syntax-Guided Synthesis, Alur et al., FMCAD'13

Syntax-Guided Synthesis (SyGuS)

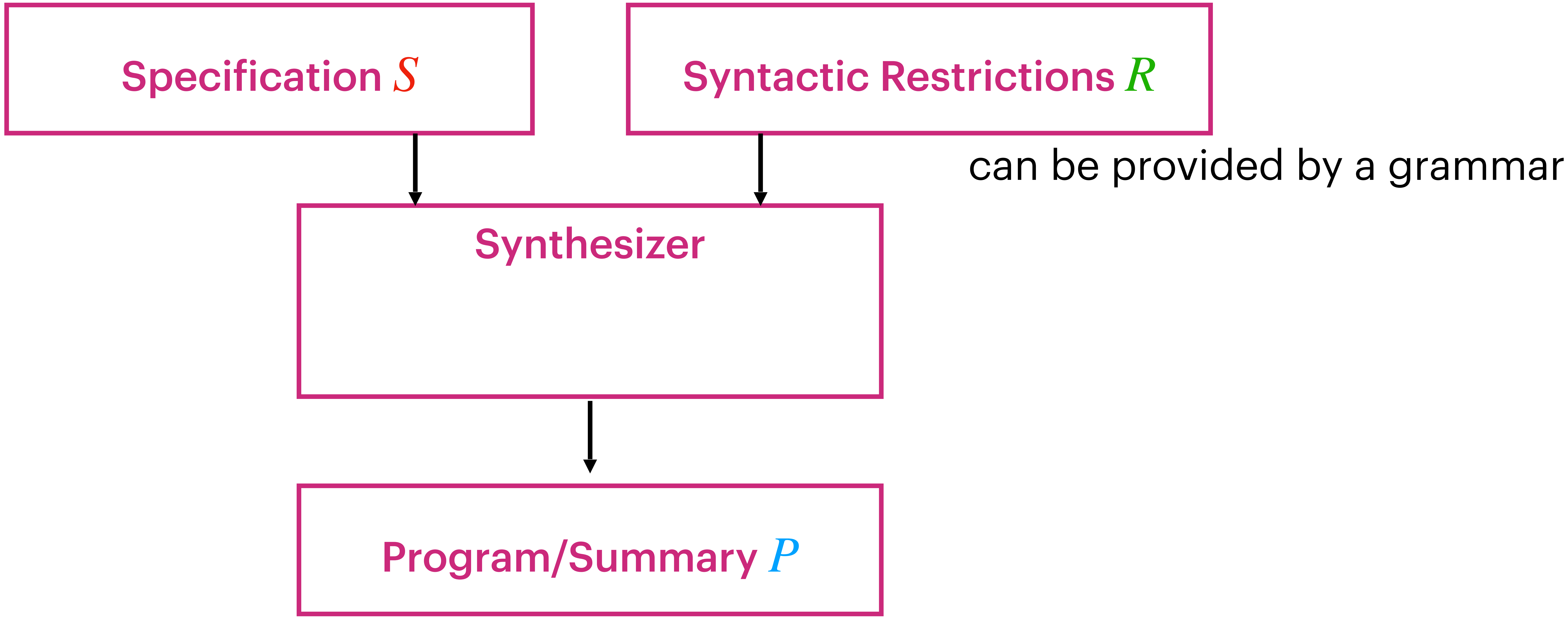
$$\exists P \in [\![R]\!] . \forall i . P(i) \vDash S(i)$$



Syntax-Guided Synthesis, Alur et al., FMCAD'13

Syntax-Guided Synthesis (SyGuS)

$$\exists\, P \in [\![R]\!] \,.\, \forall i \,.\, P(i) \vDash S(i)$$



Syntax-Guided Synthesis, Alur et al., FMCAD'13

Syntax-Guided Synthesis (SyGuS)

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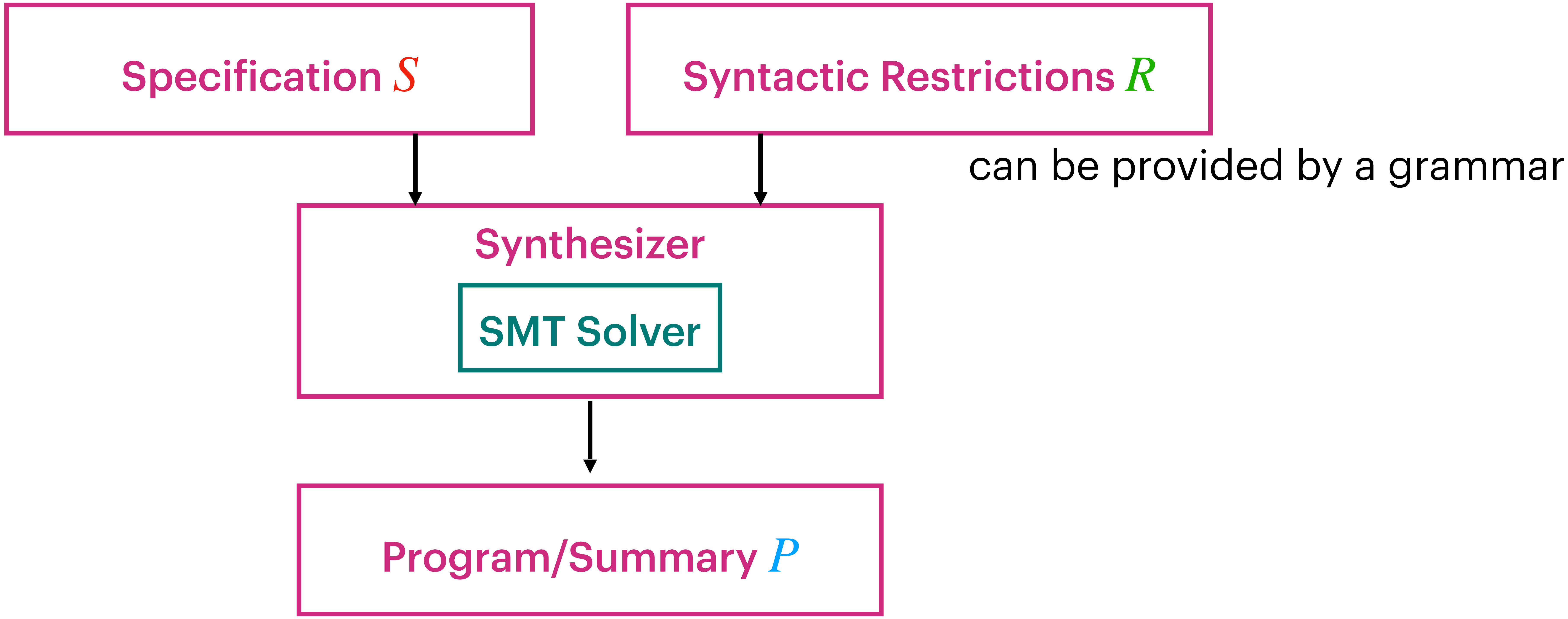
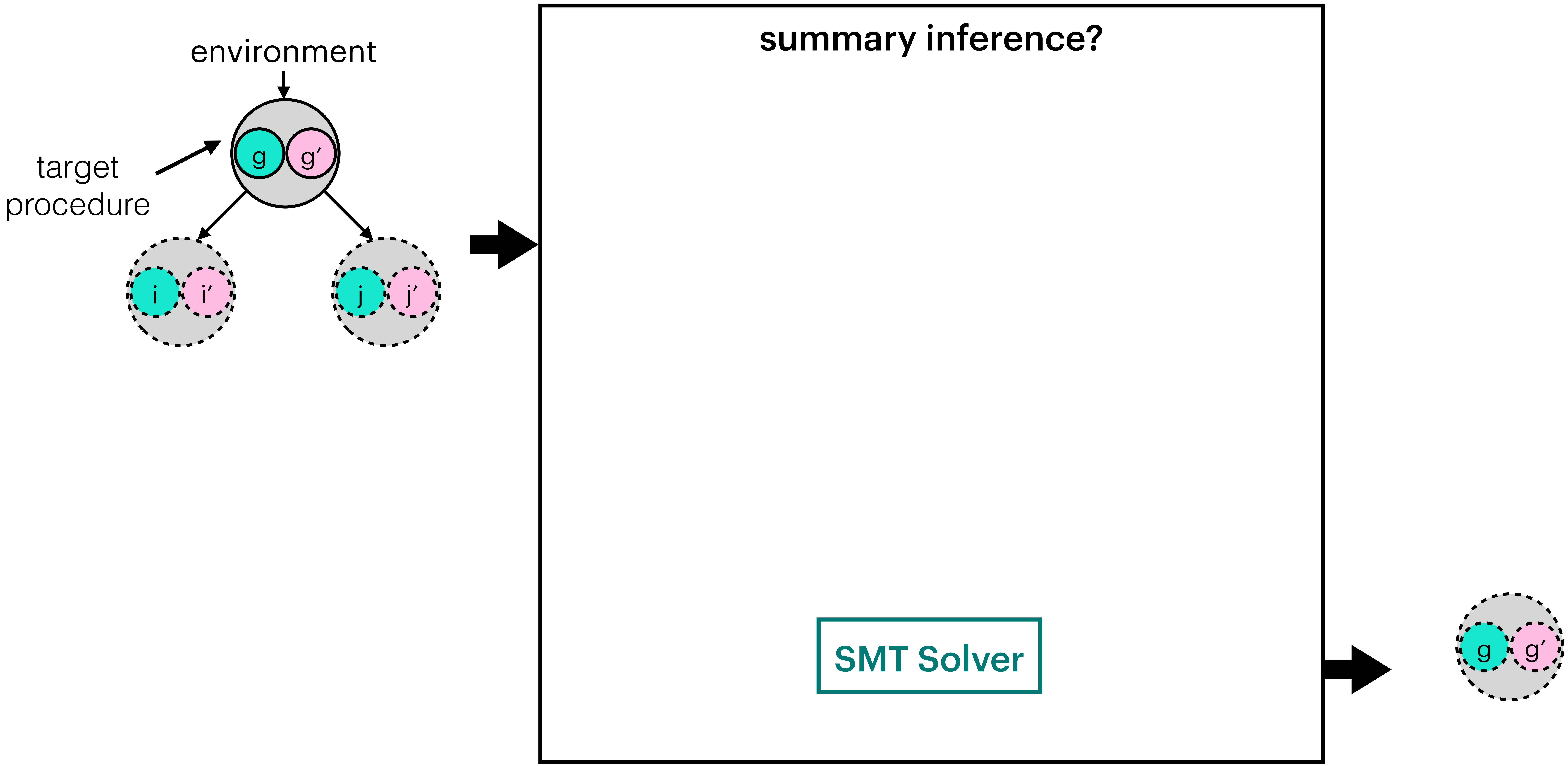
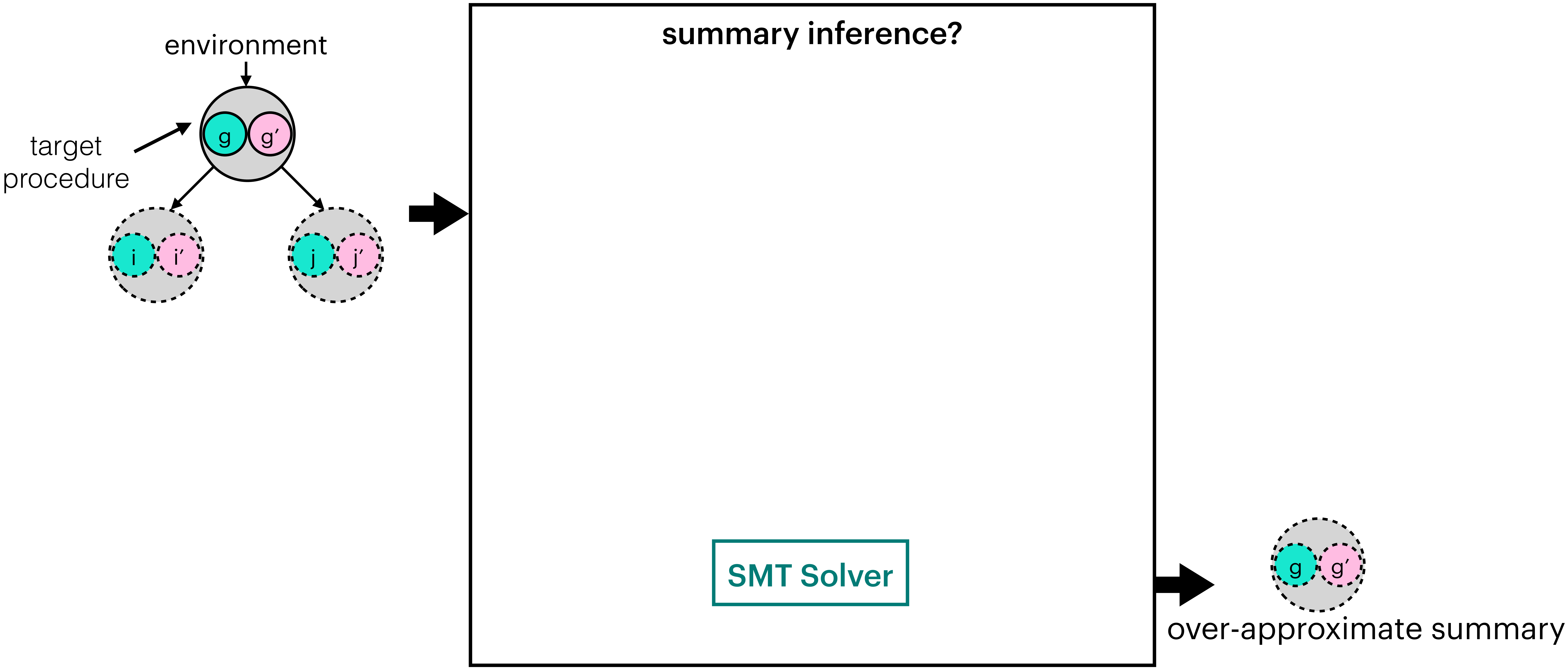


Syntax-Guided Synthesis, Alur et al., FMCAD'13

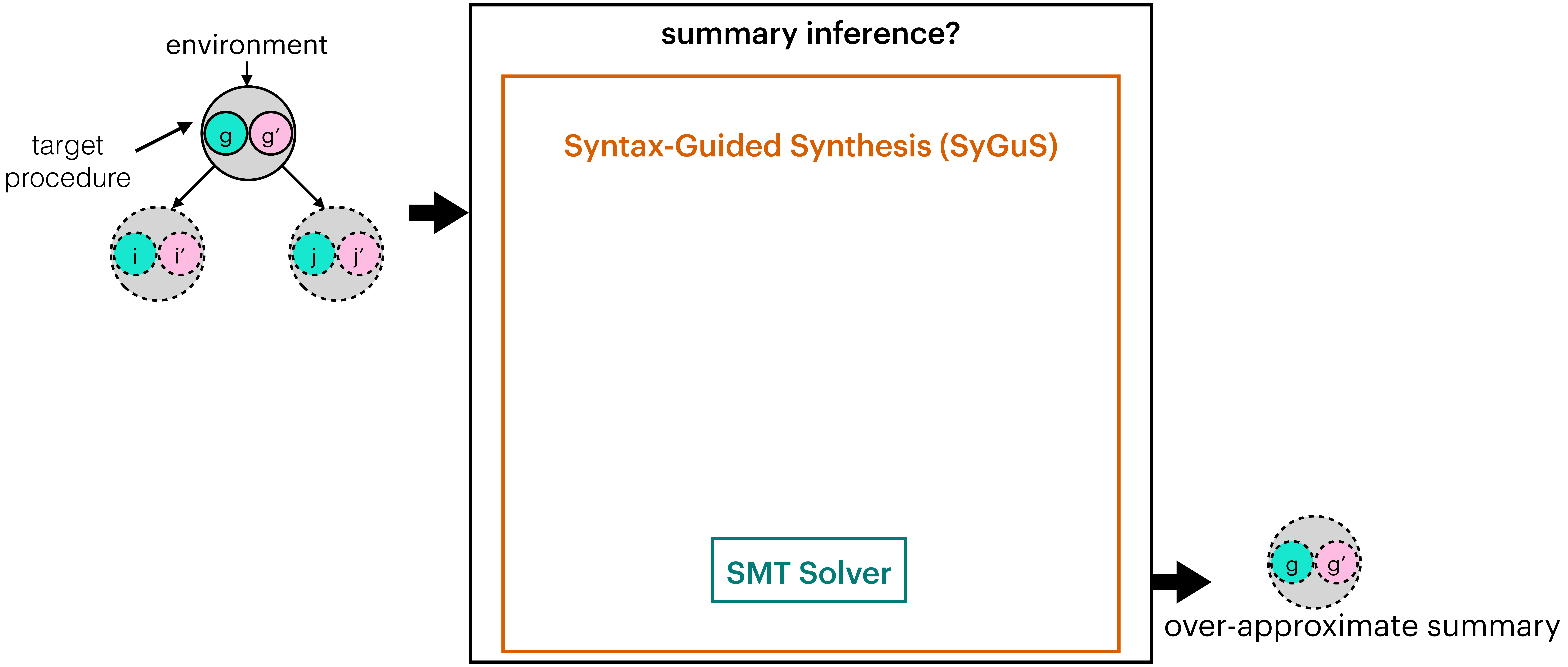
Information-Flow Summary Inference



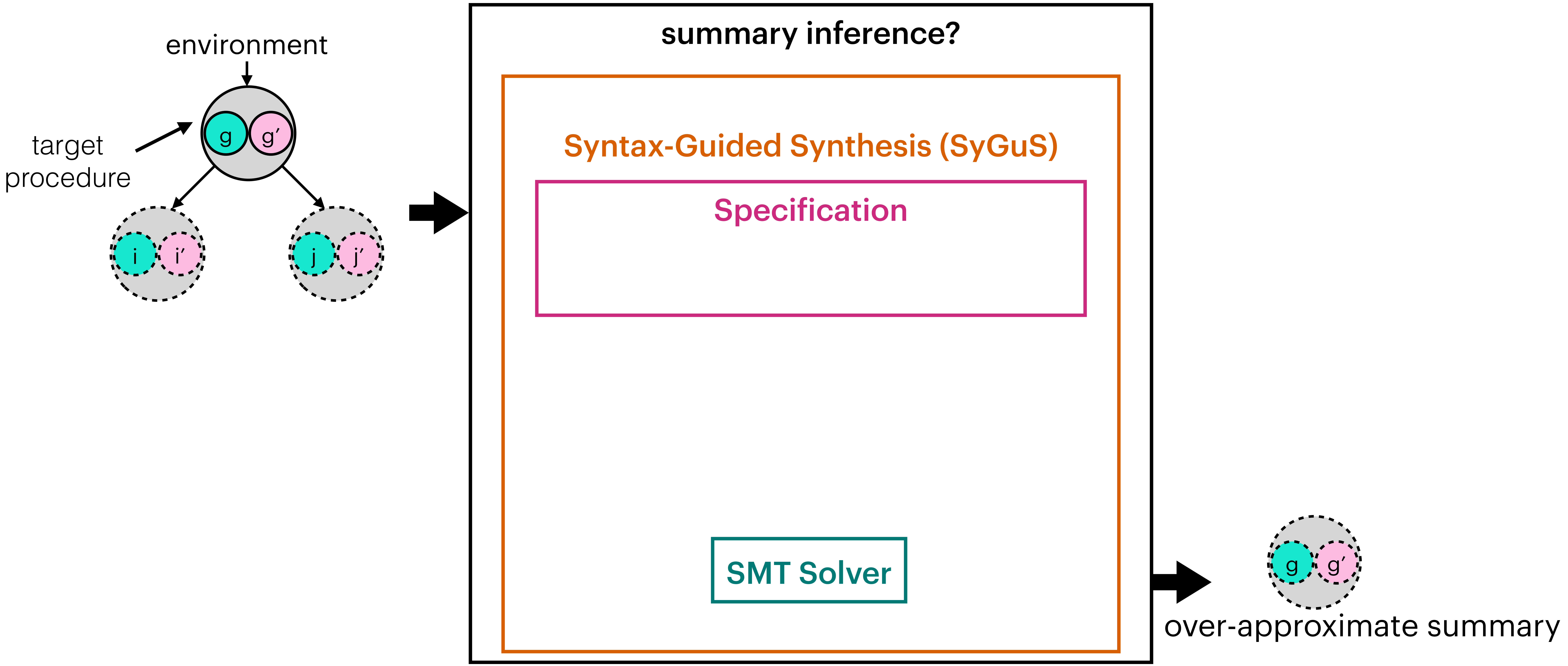
Information-Flow Summary Inference



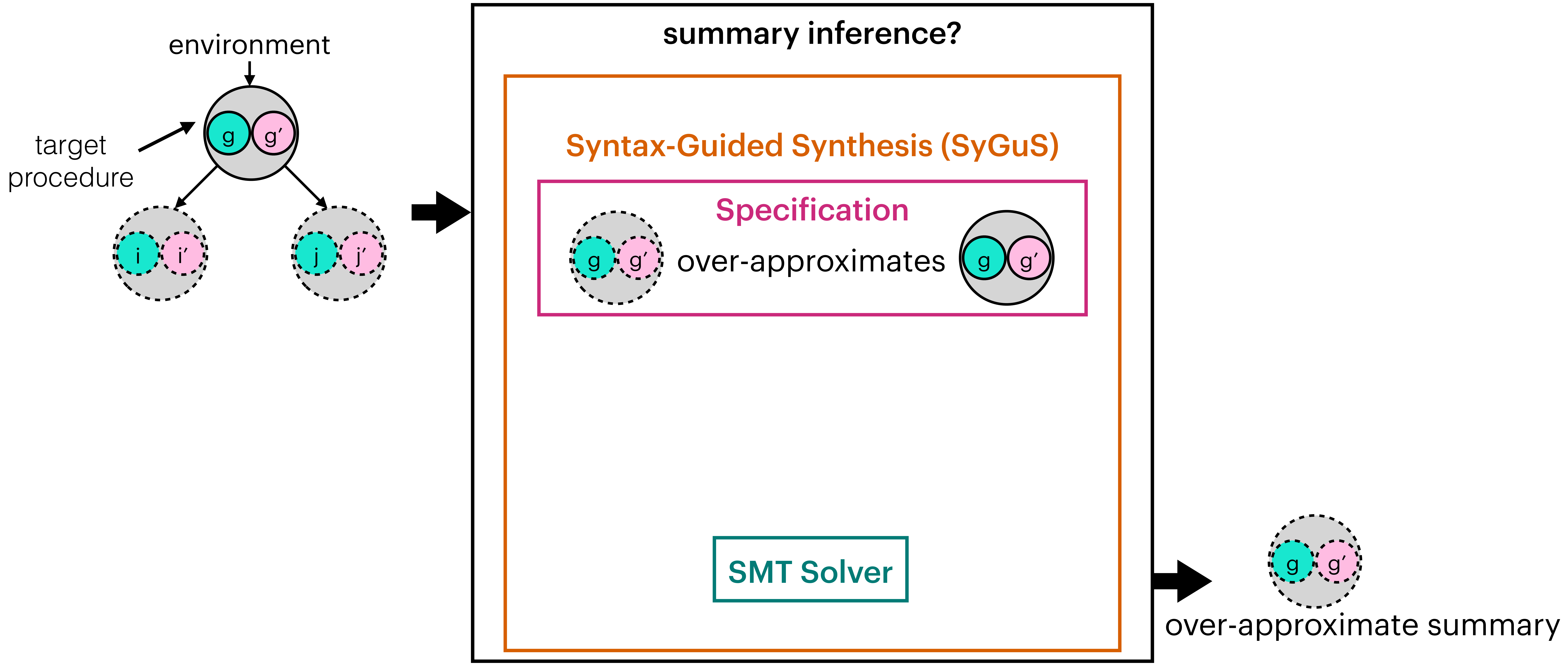
Information-Flow Summary Inference



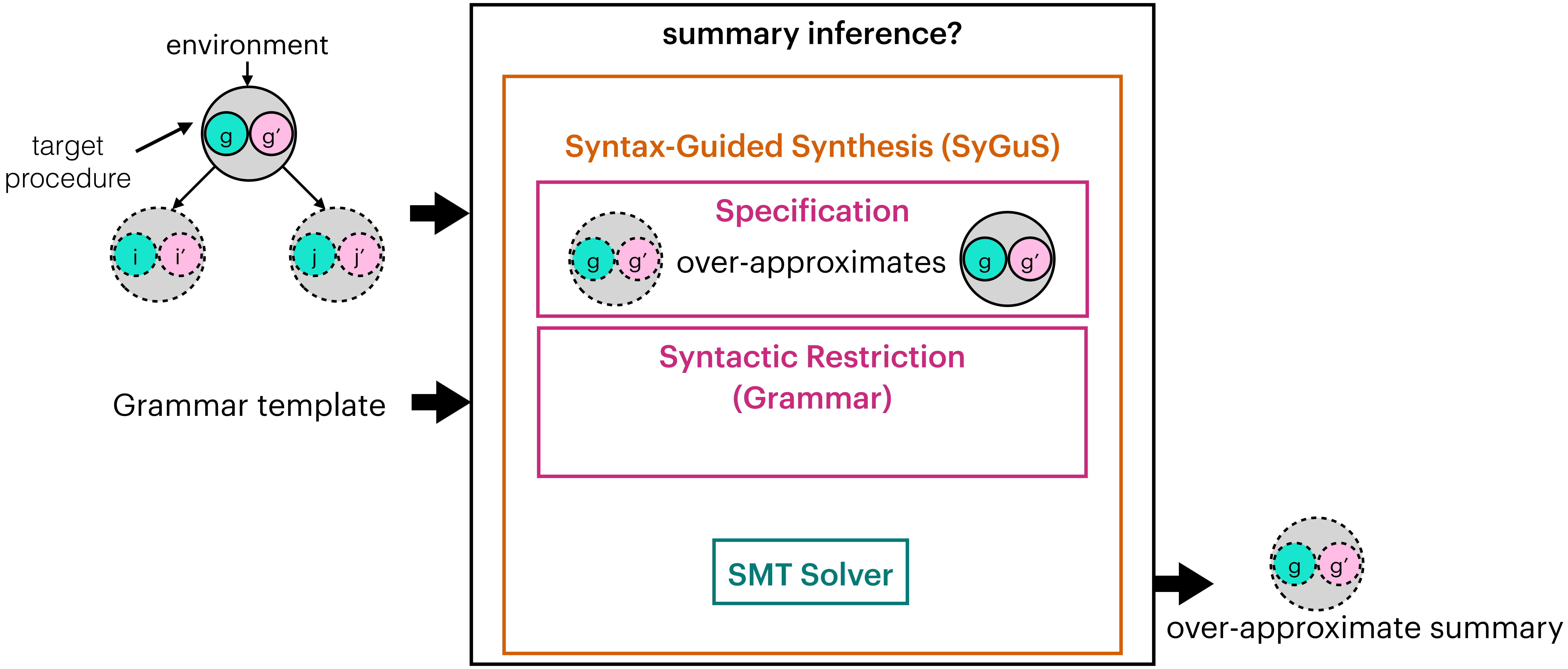
Information-Flow Summary Inference



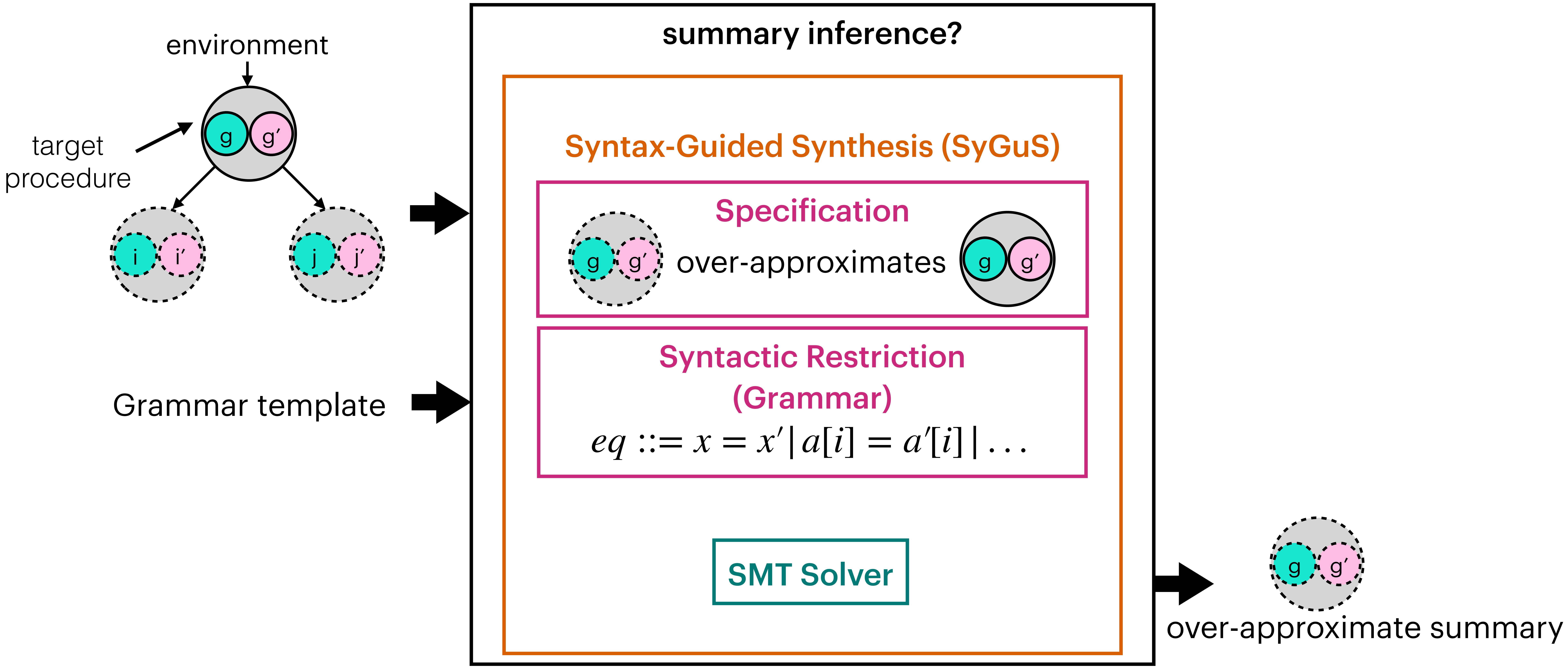
Information-Flow Summary Inference



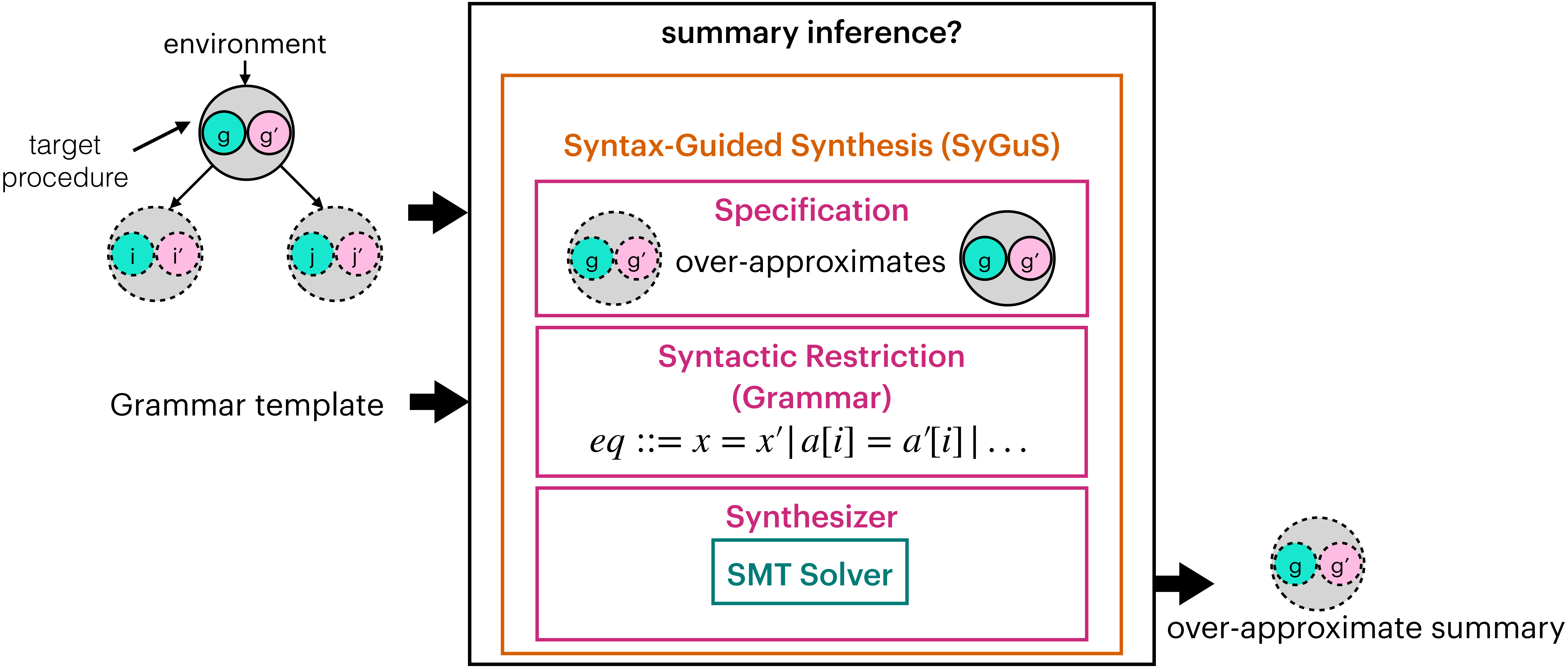
Information-Flow Summary Inference



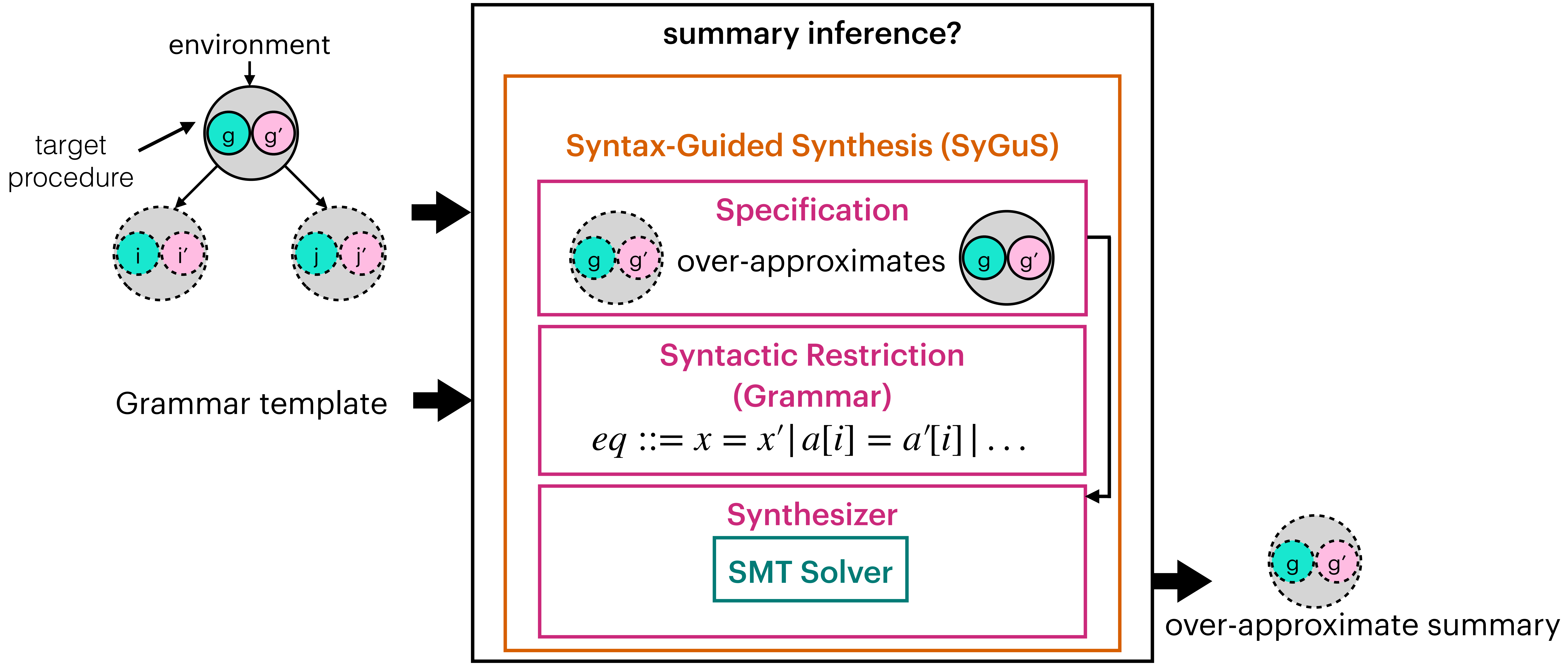
Information-Flow Summary Inference



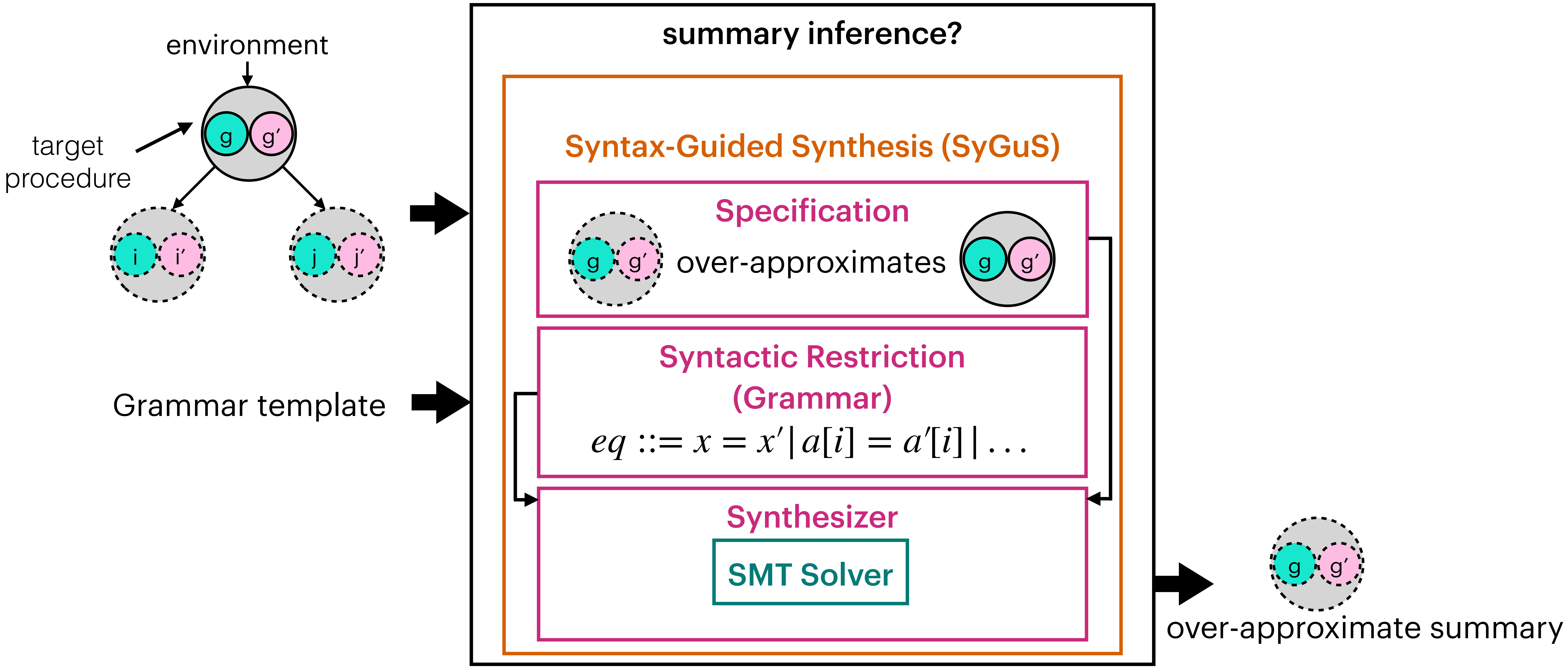
Information-Flow Summary Inference



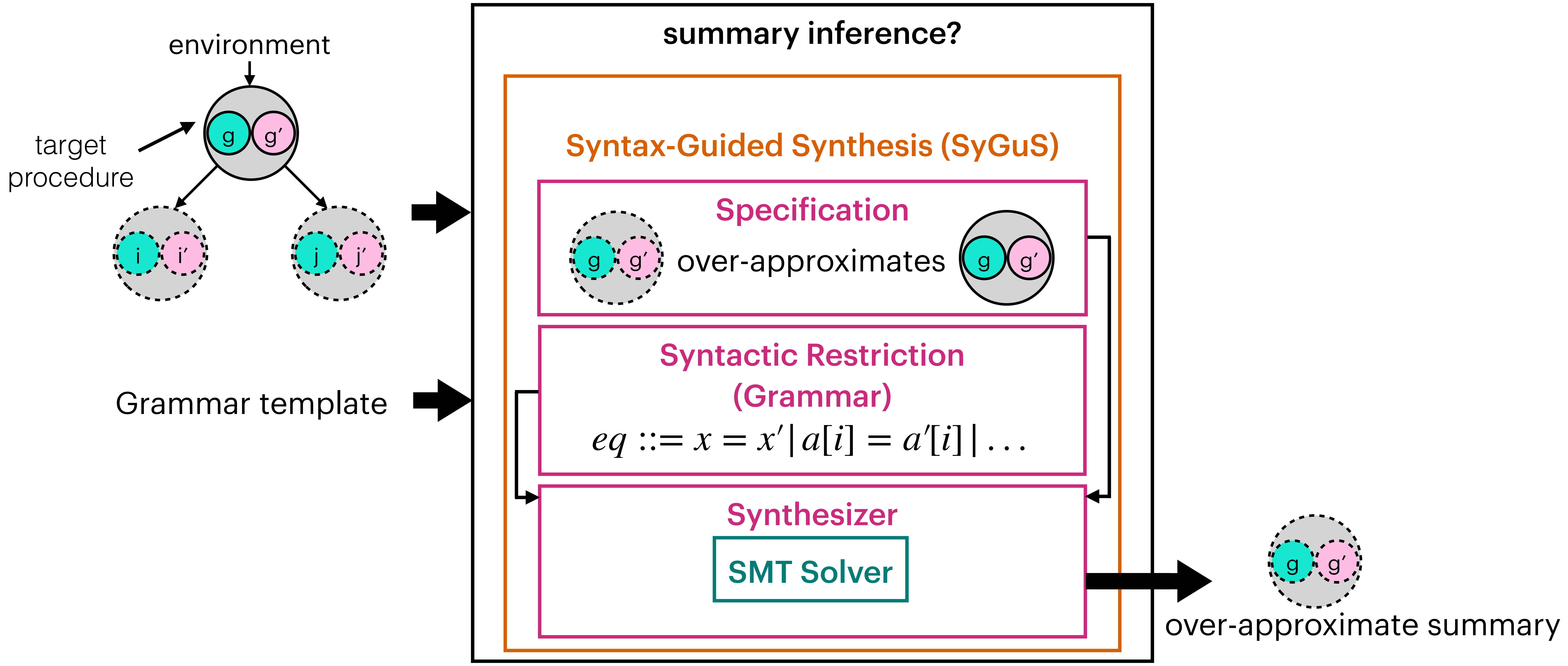
Information-Flow Summary Inference



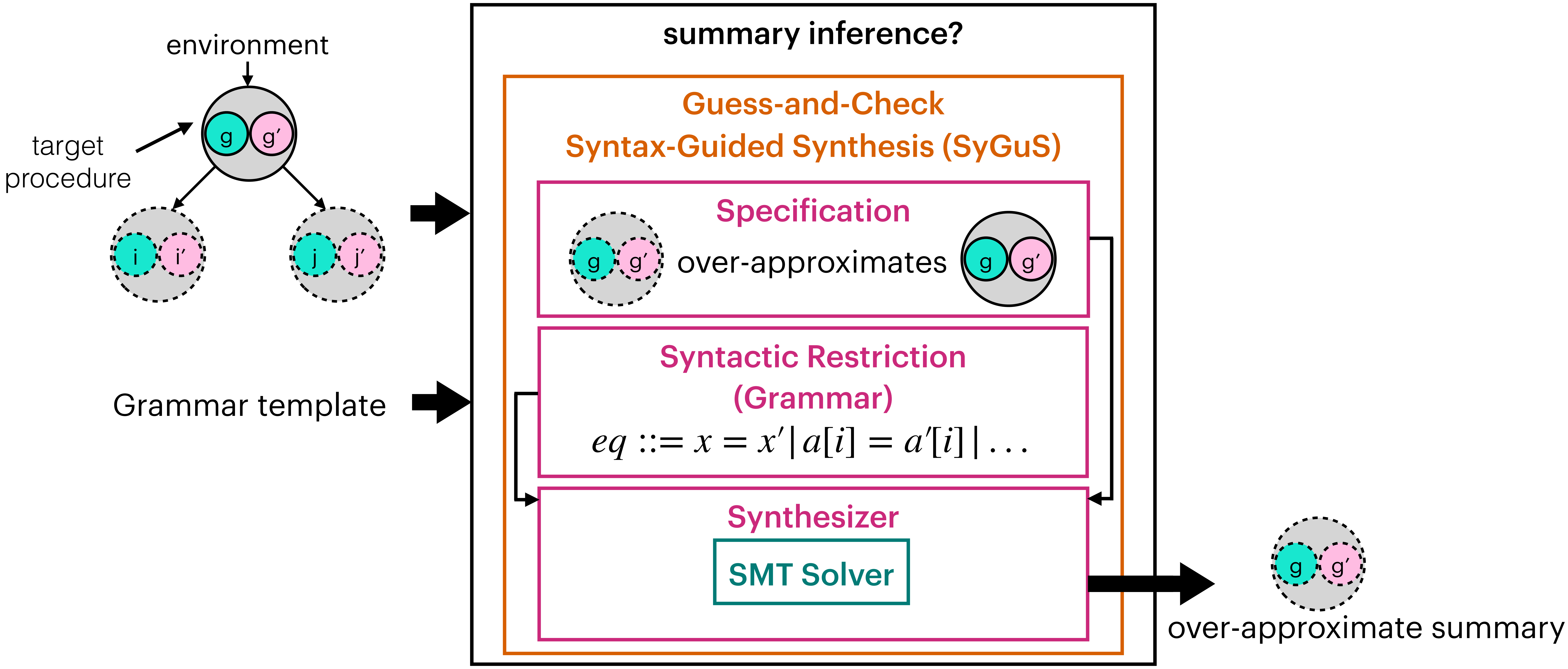
Information-Flow Summary Inference



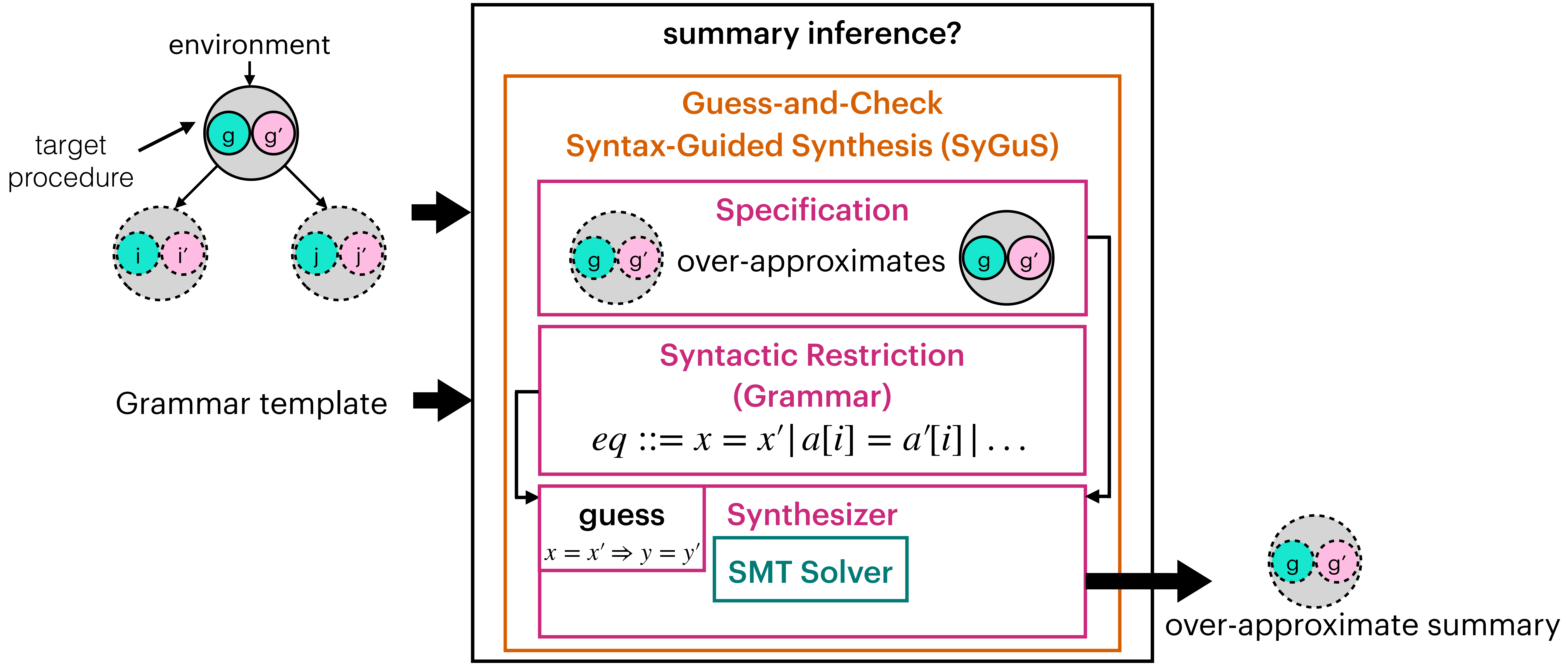
Information-Flow Summary Inference



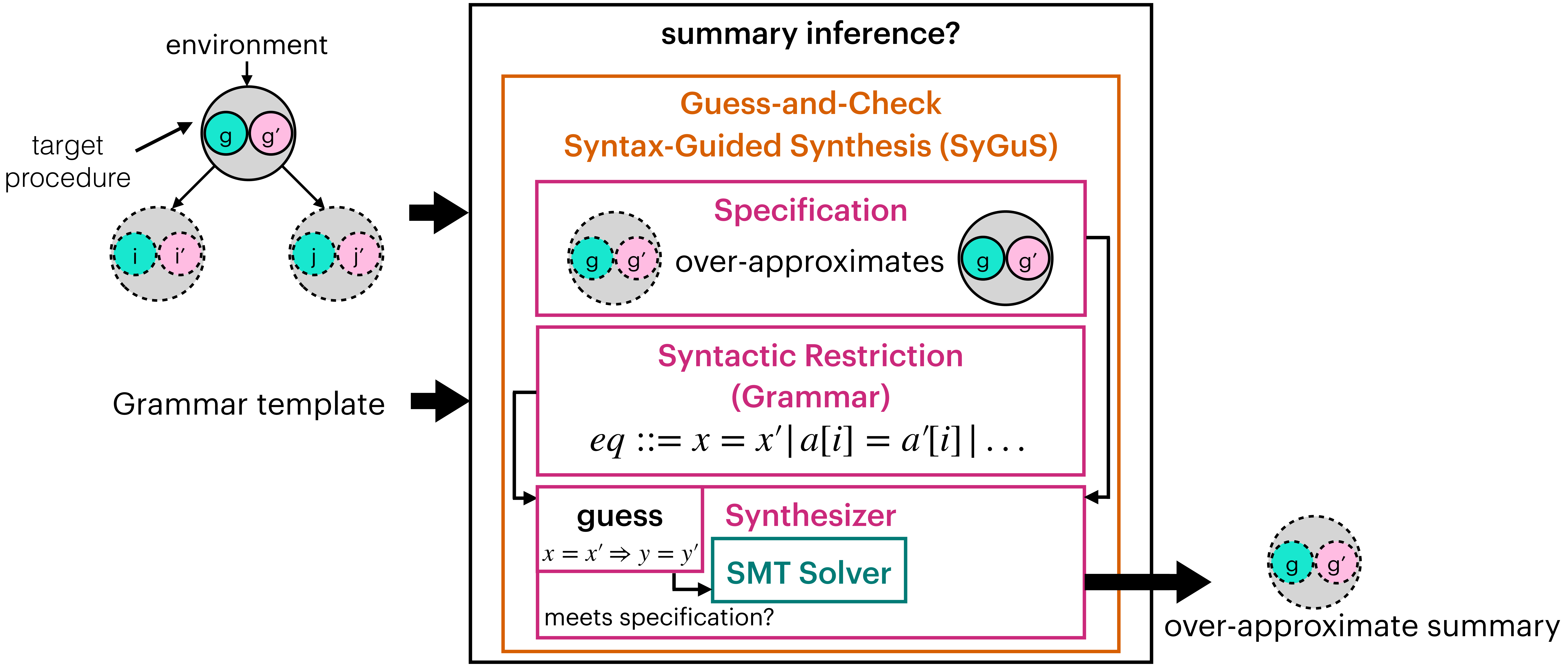
Information-Flow Summary Inference



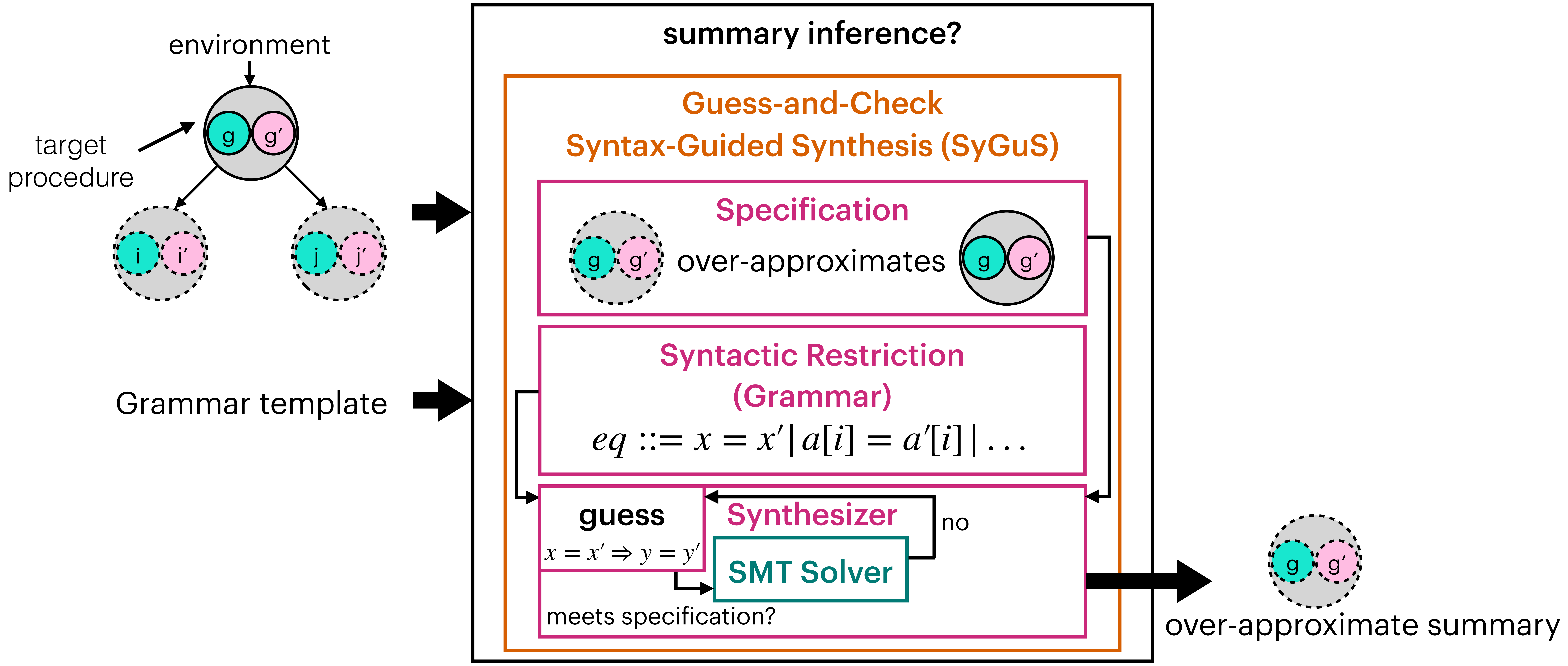
Information-Flow Summary Inference



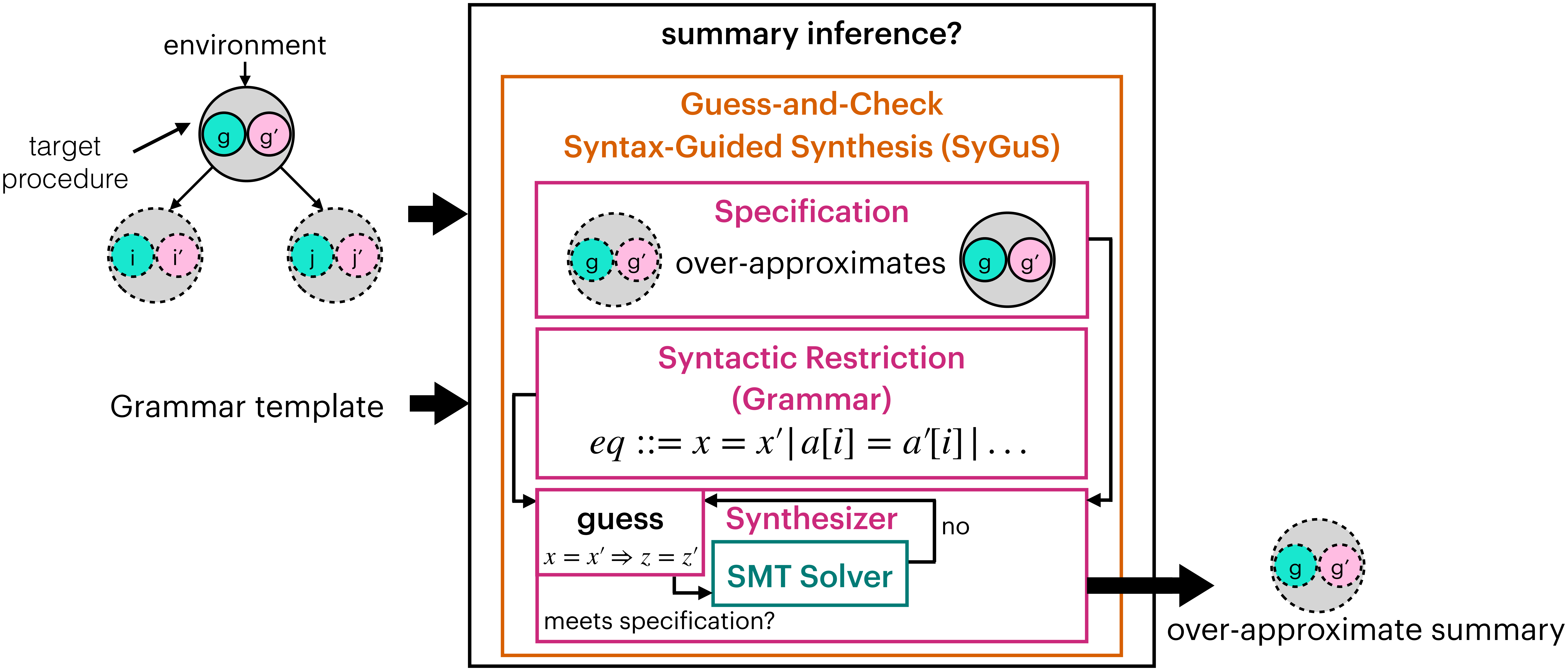
Information-Flow Summary Inference



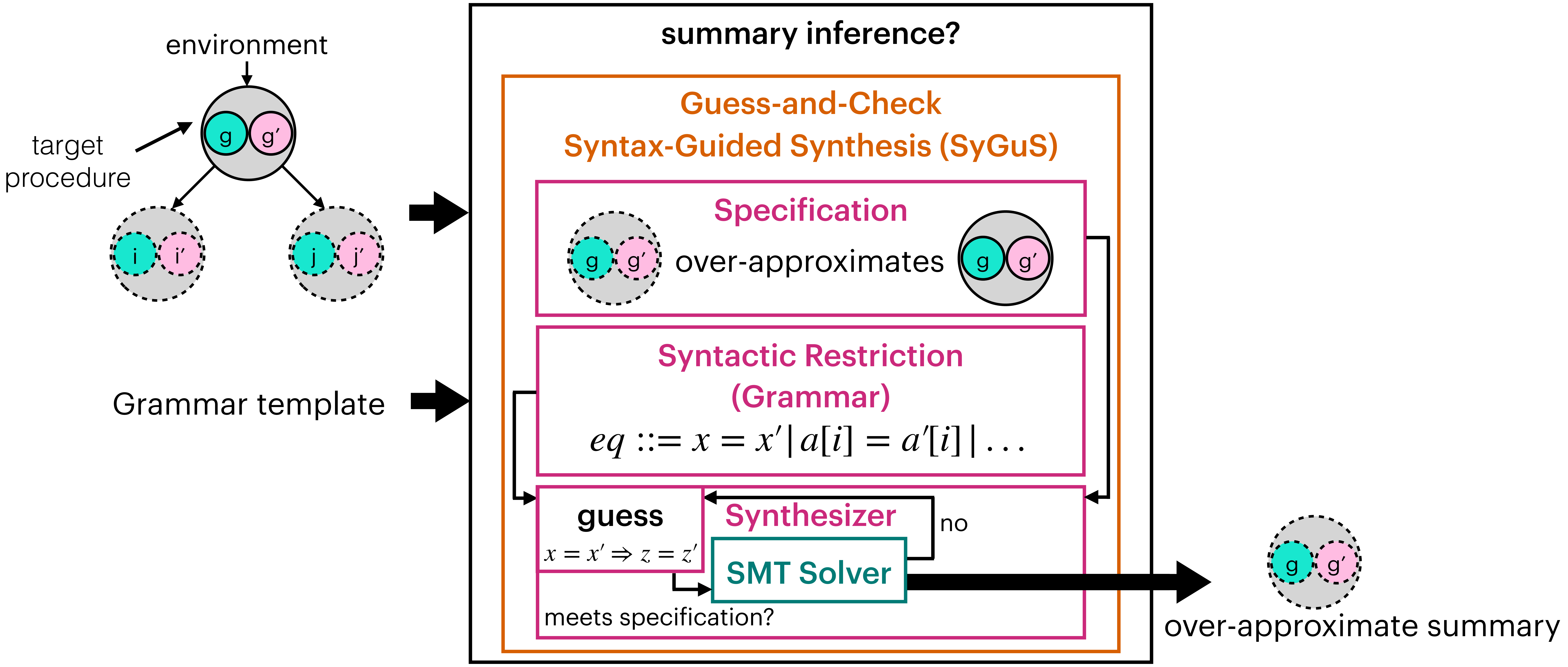
Information-Flow Summary Inference



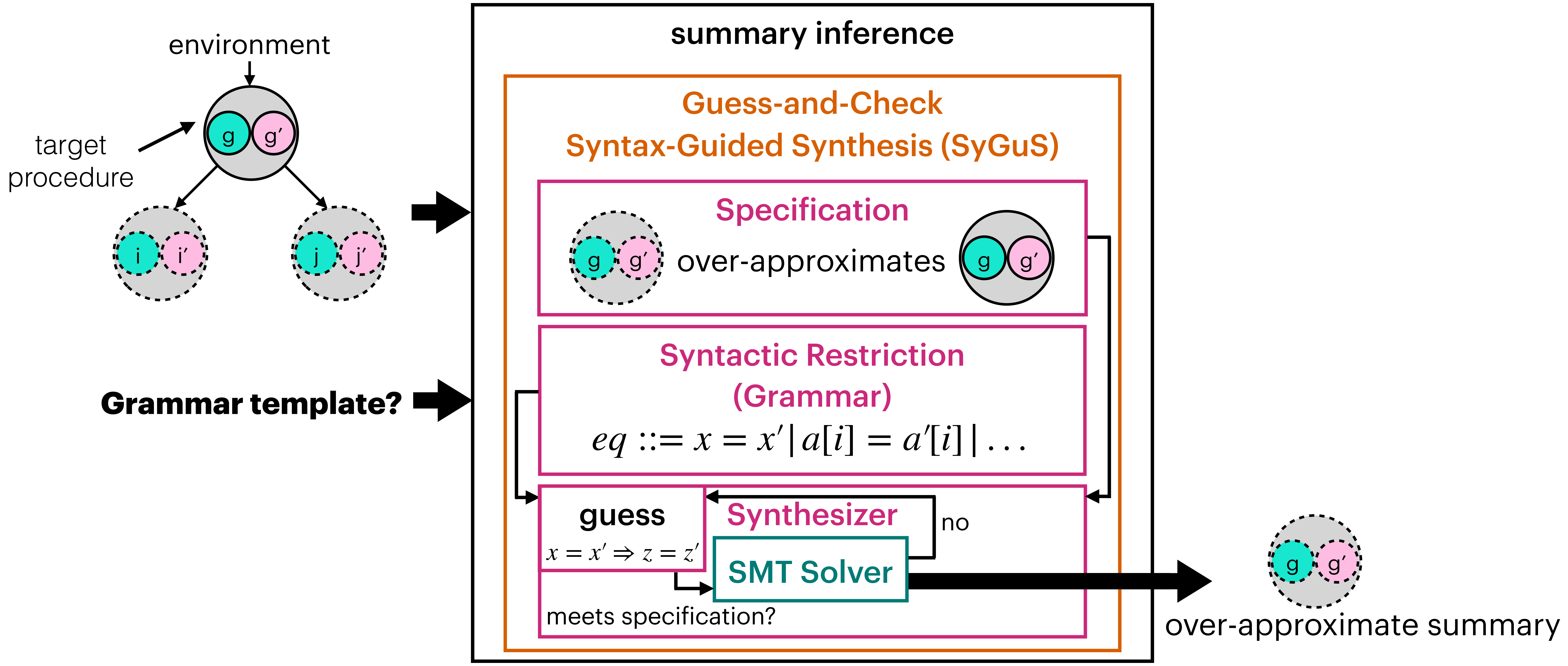
Information-Flow Summary Inference



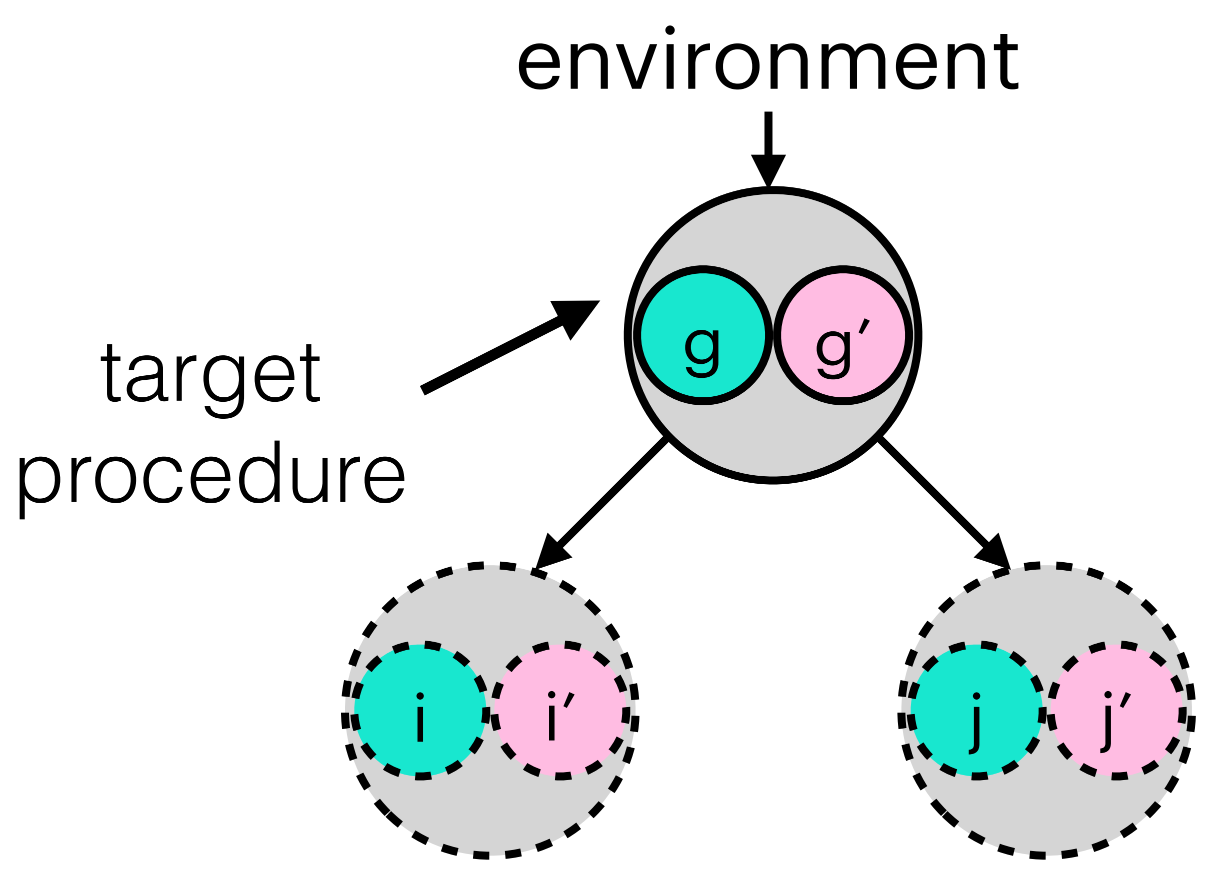
Information-Flow Summary Inference



Inferring Summaries with SyGuS

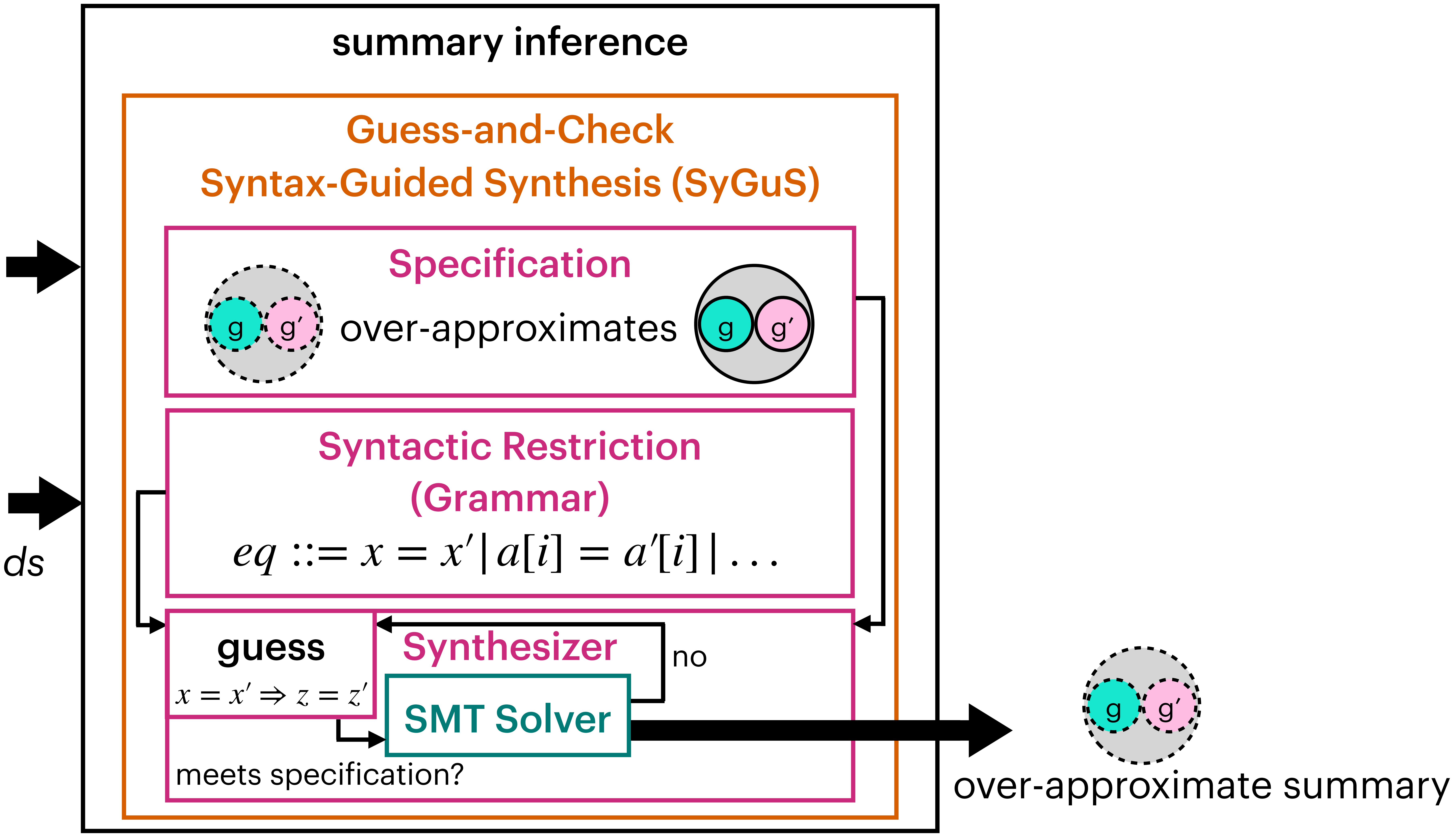


Inferring Summaries with SyGuS

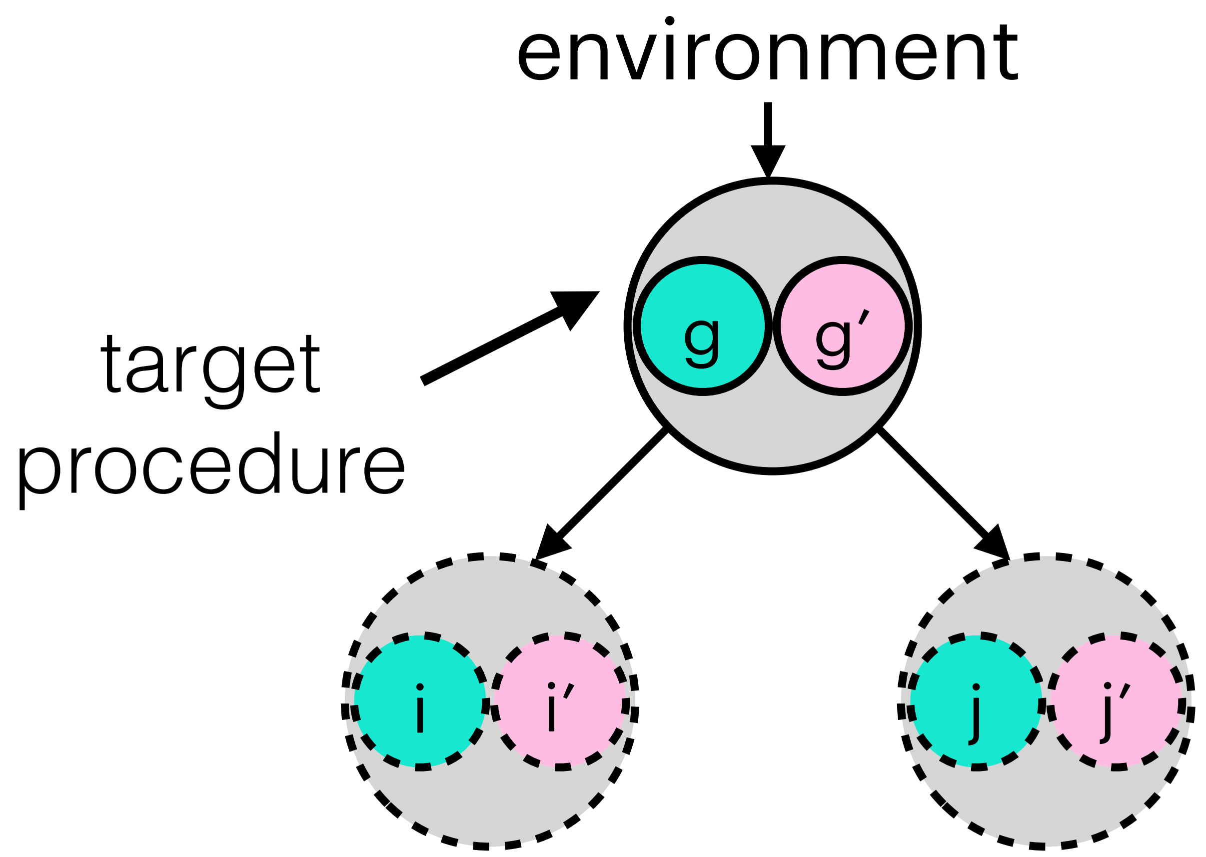


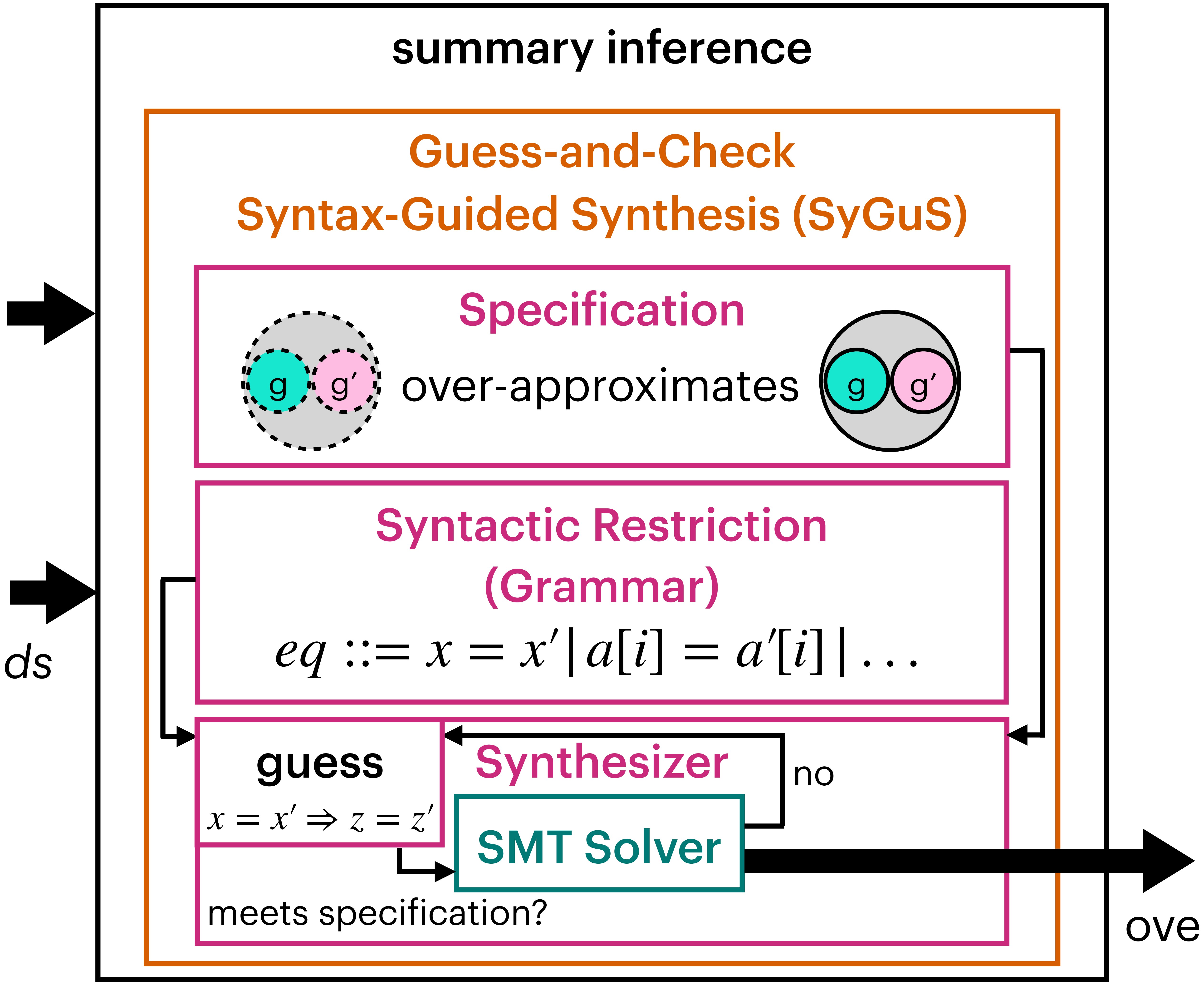
Grammar template?

Will talk about *three kinds*



Inferring Summaries with SyGuS





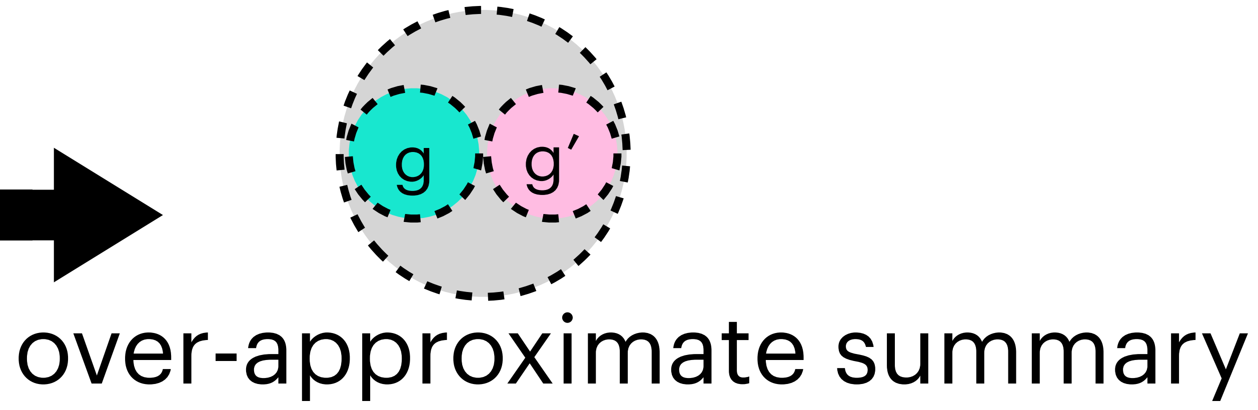
Grammar template?

Will talk about *three kinds*

Quantifier-Free

Quantified Array

Property-Directed



Grammar Templates

Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

Grammar Templates

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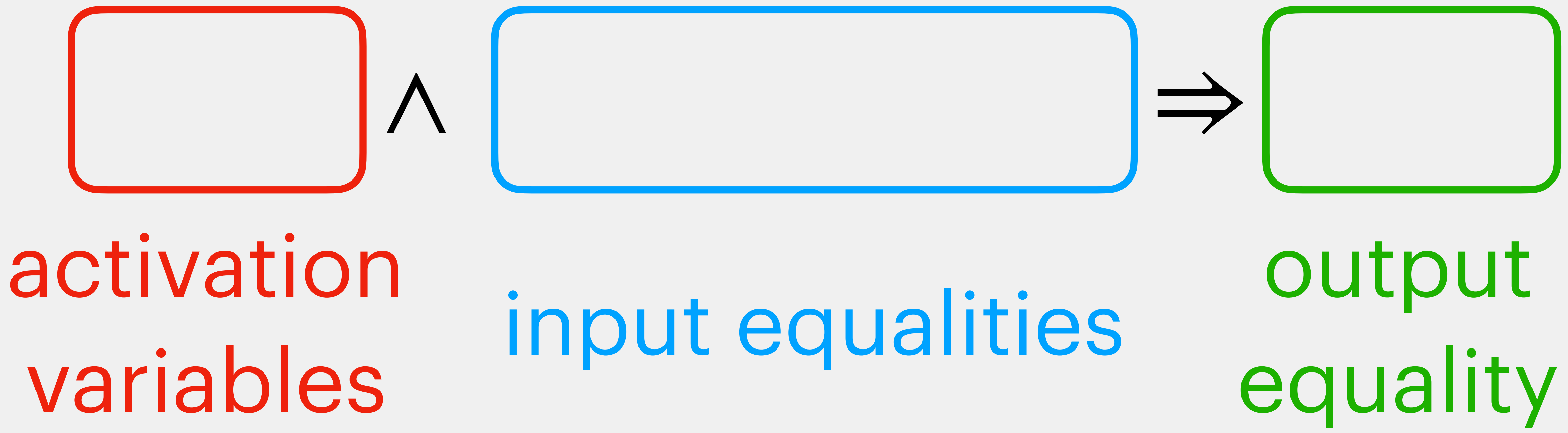
Quantifier-free

Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

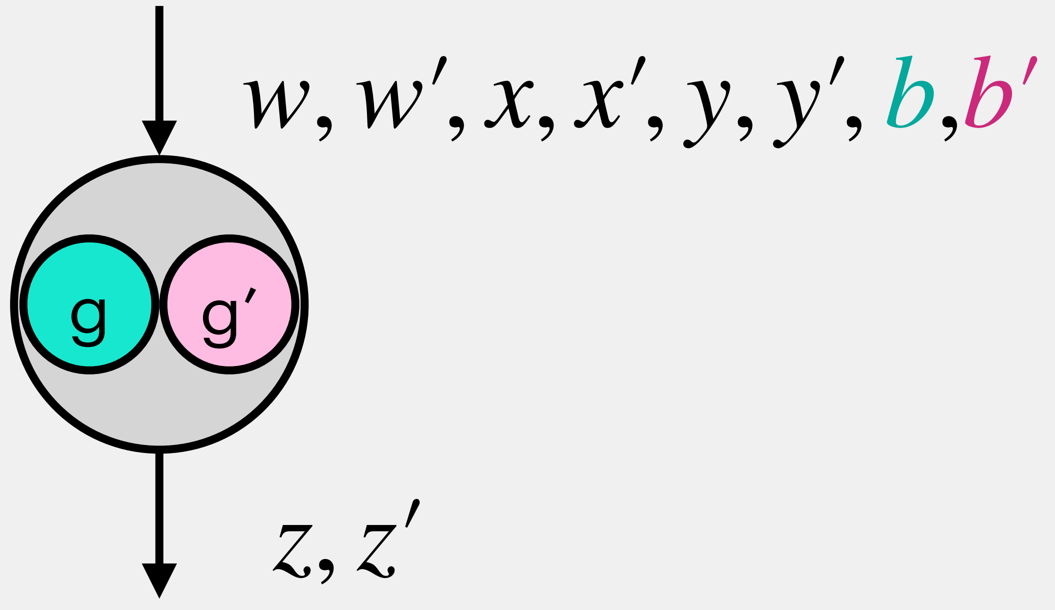
Quantifier-free

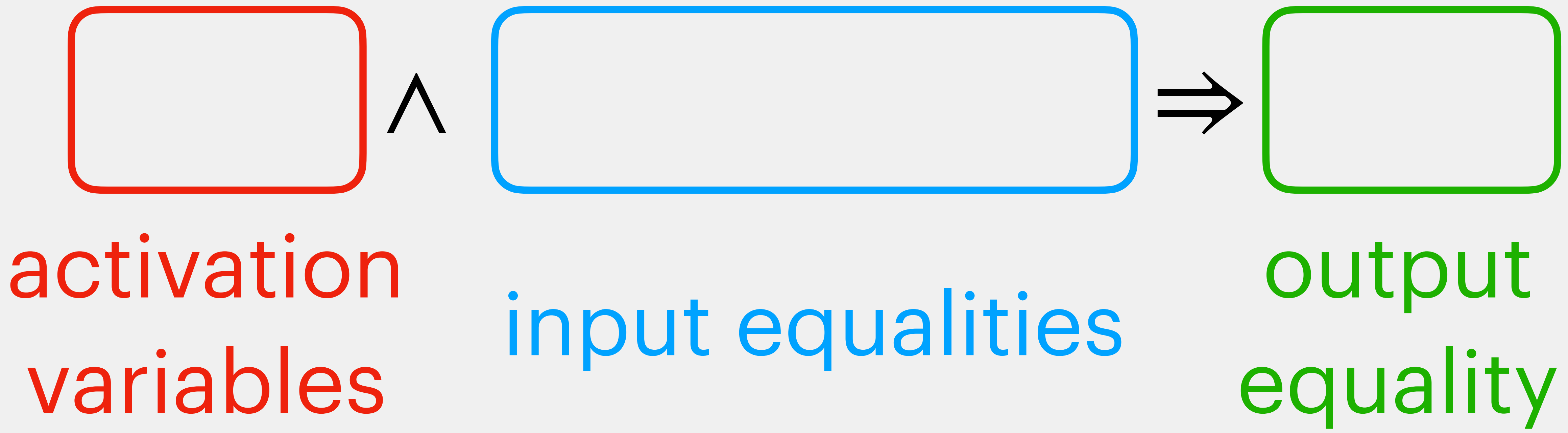


Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

Quantifier-free



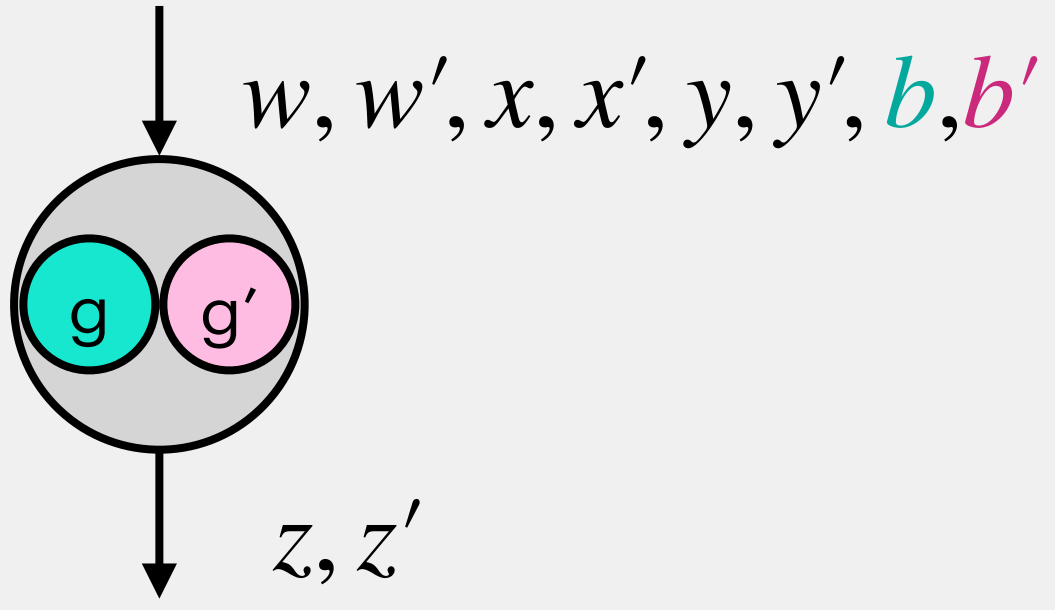


Grammar Templates

Insight:

information flow involves **equalities** on subsets of corresponding components

Quantifier-free



$b \wedge b' \wedge \square \Rightarrow \square$

activation variables

input equalities

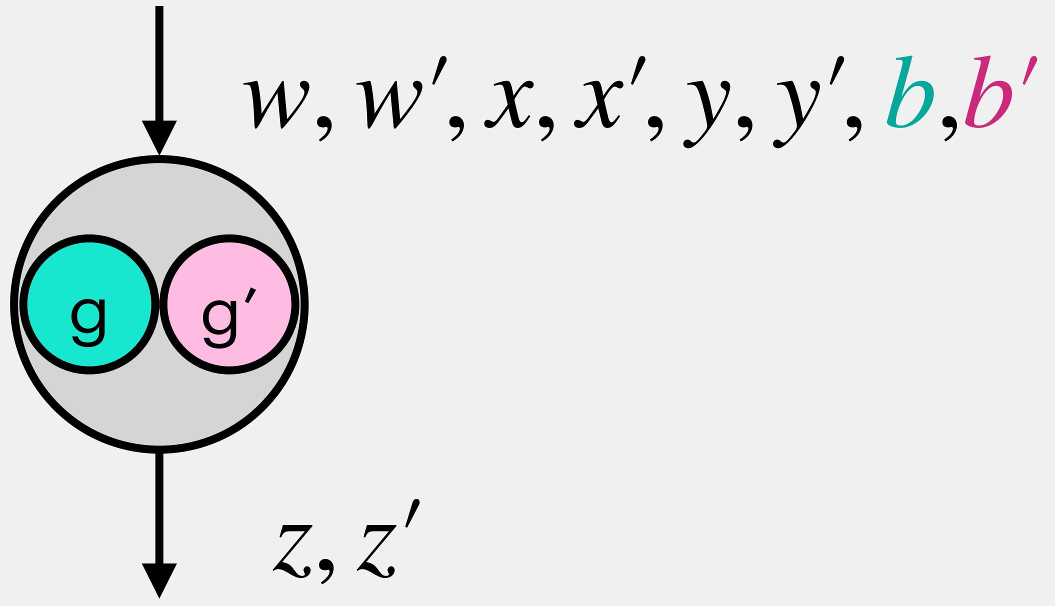
output equality

Grammar Templates

Insight:

information flow involves **equalities** on subsets of corresponding components

Quantifier-free



$$b \wedge b' \wedge x = x' \wedge y = y' \Rightarrow \square$$

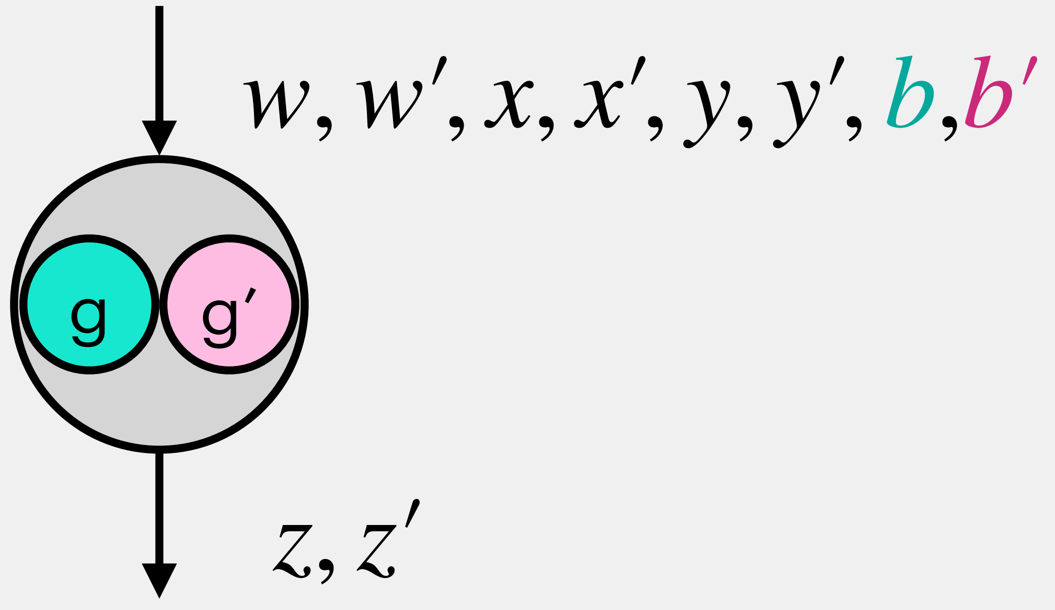
activation variables | input equalities | output equality

Grammar Templates

Insight:

information flow involves **equalities** on subsets of corresponding components

Quantifier-free



$$\boxed{b \land b'} \land \boxed{x = x' \land y = y'} \Rightarrow \boxed{z = z'}$$

activation variables

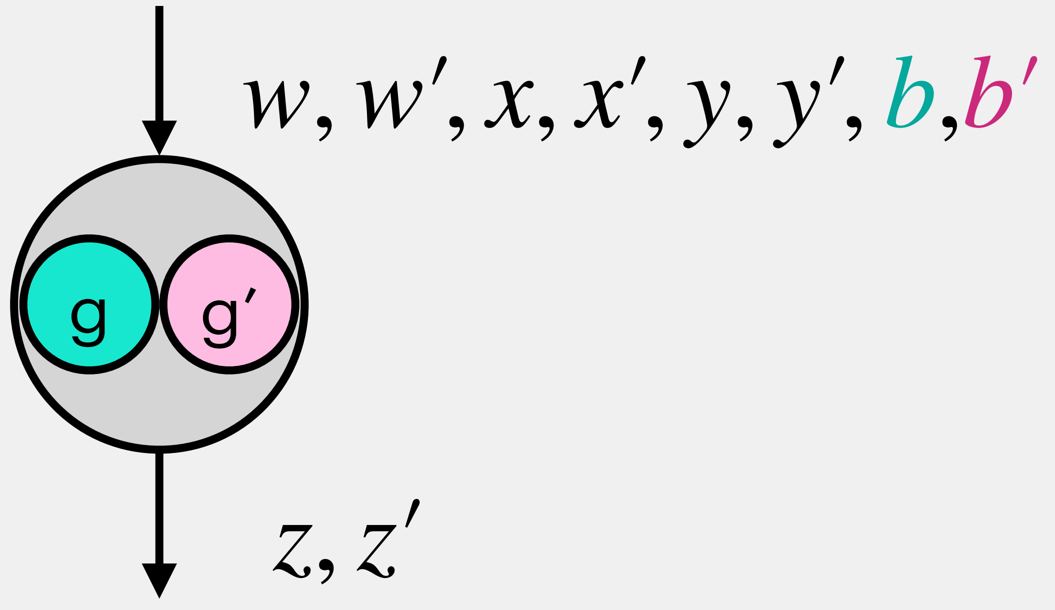
input equalities

output equality

Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

Quantifier-free



$$b \wedge b' \wedge x = x' \wedge y = y' \Rightarrow z = z'$$

activation variables ($b \wedge b'$)

input equalities ($x = x' \wedge y = y'$)

output equality ($z = z'$)

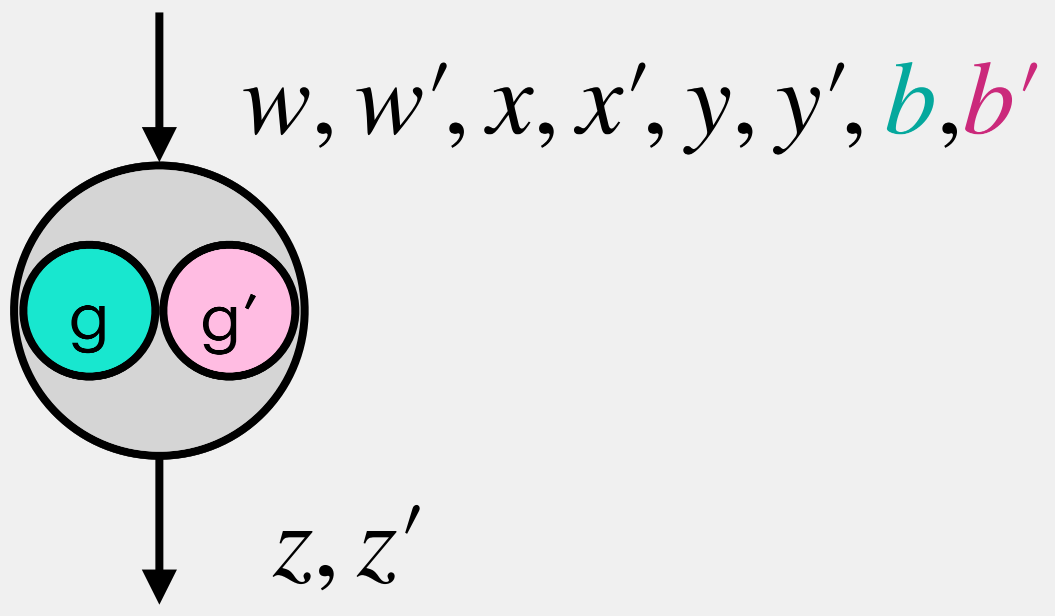
Quantified Array

Grammar Templates

Insight:

information flow involves **equalities** on subsets of corresponding components

Quantifier-free



$$\boxed{b \wedge b'} \wedge \boxed{x = x' \wedge y = y'} \Rightarrow \boxed{z = z'}$$

activation variables | input equalities | output equality

Quantified Array

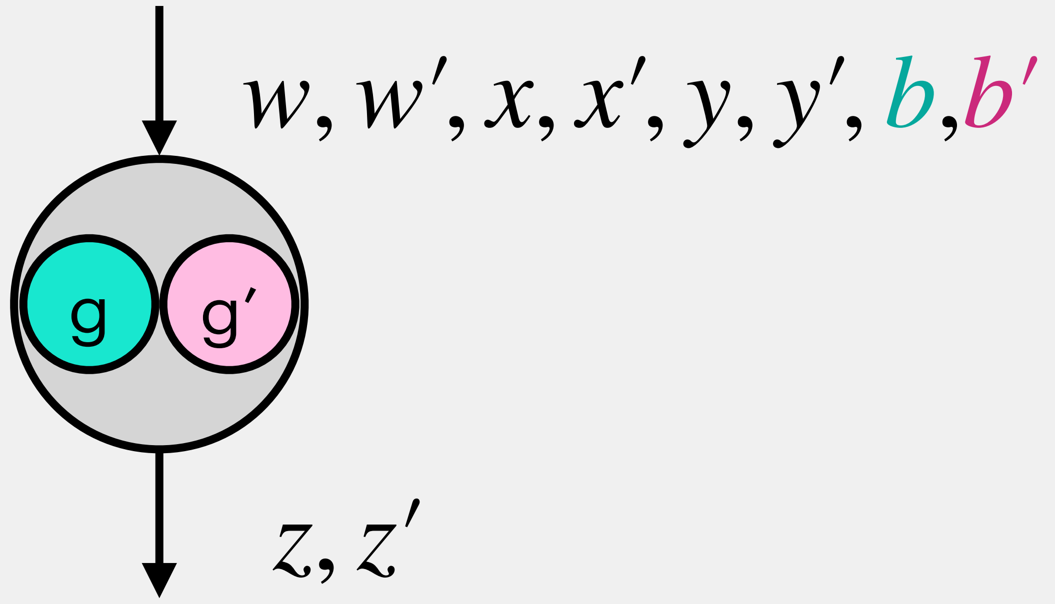
$$\forall \boxed{} . \boxed{} \wedge \boxed{} \wedge \boxed{} \Rightarrow \boxed{}$$

quantified indices | range | activation variables | equalities | cell property

Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

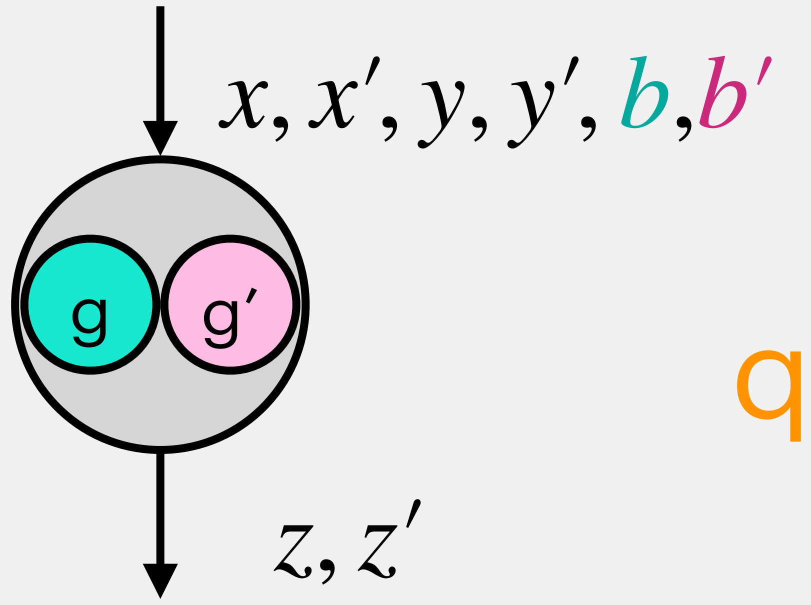
Quantifier-free



$$\boxed{b \wedge b'} \wedge \boxed{x = x' \wedge y = y'} \Rightarrow \boxed{z = z'}$$

activation variables | input equalities | output equality

Quantified Array



$$\forall \boxed{} . \boxed{} \wedge \boxed{} \wedge \boxed{} \Rightarrow \boxed{}$$

quantified indices | range | activation variables | equalities | cell property

Grammar Templates

Insight:
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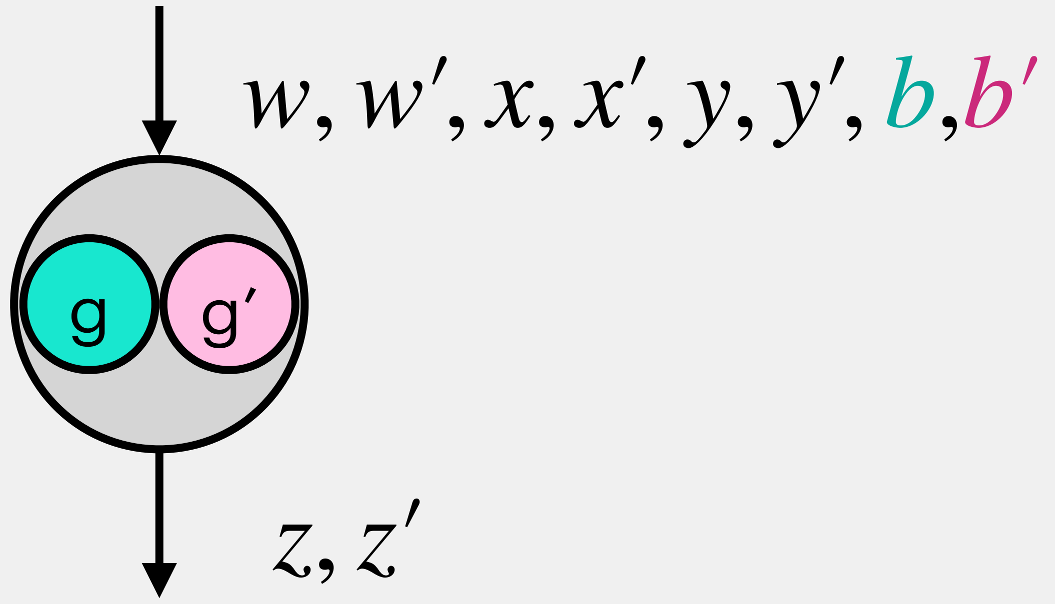
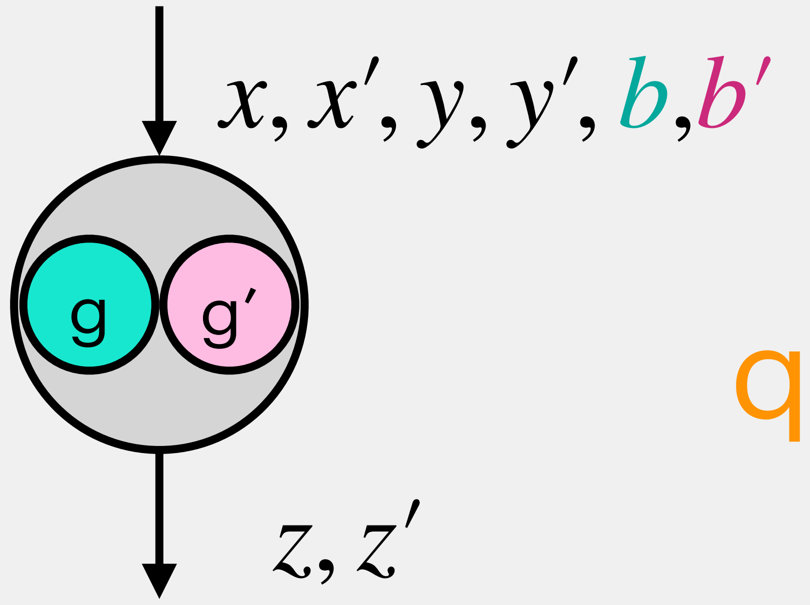


$$b \wedge b' \wedge x = x' \wedge y = y' \Rightarrow z = z'$$

activation variables ($b \wedge b'$) — input equalities ($x = x' \wedge y = y'$) — output equality ($z = z'$)

Quantified Array



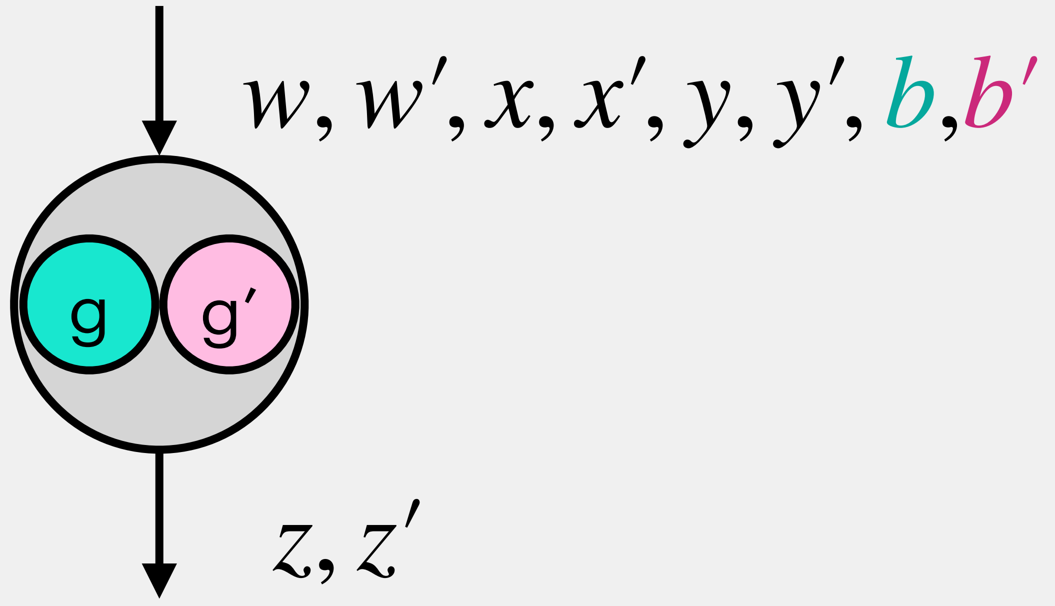
$$\forall\ i, i'.\ [\ \ ] \wedge [\ \ ] \wedge [\ \ ] \Rightarrow [\ \ ]$$

quantified indices (i, i') — range — activation variables — equalities — cell property

Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

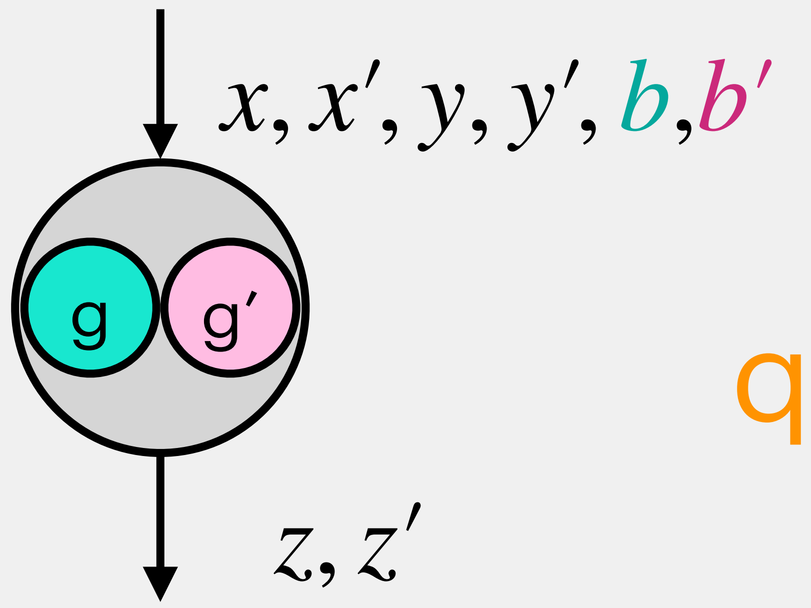
Quantifier-free



$$b \wedge b' \;\wedge\; x = x' \wedge y = y' \Rightarrow z = z'$$

activation variables | input equalities | output equality

Quantified Array



$$\forall\; i, i'.\; 0 \leq i < y \;\wedge\; \square \;\wedge\; \square \Rightarrow \square$$

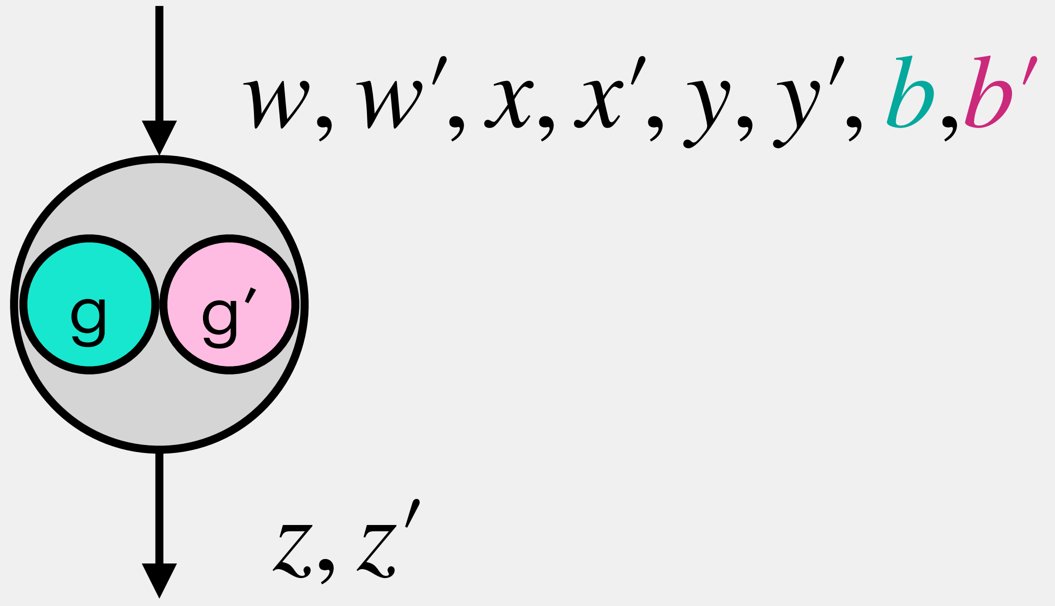
quantified indices | range | activation variables | equalities | cell property

Grammar Templates

Insight:

information flow involves **equalities** on subsets of corresponding components

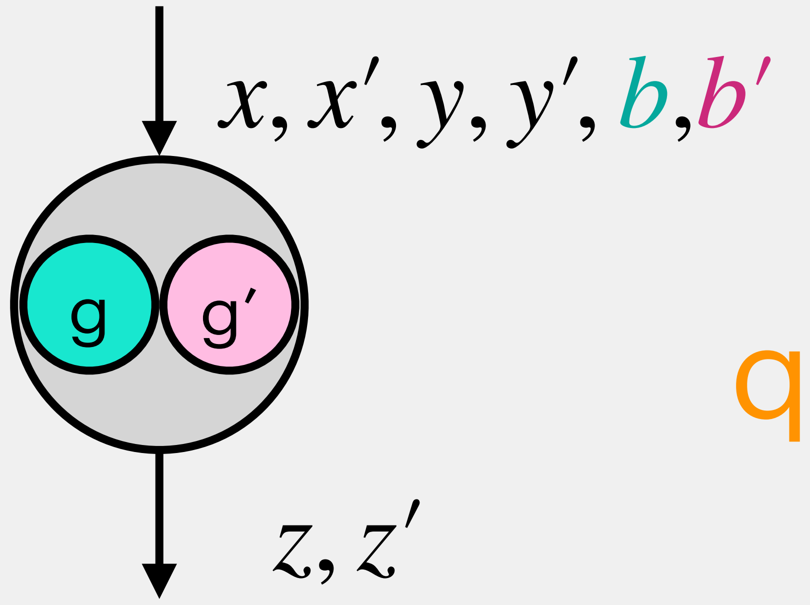
Quantifier-free



$$\boxed{b \wedge b'} \wedge \boxed{x = x' \wedge y = y'} \Rightarrow \boxed{z = z'}$$

activation variables — input equalities — output equality

Quantified Array



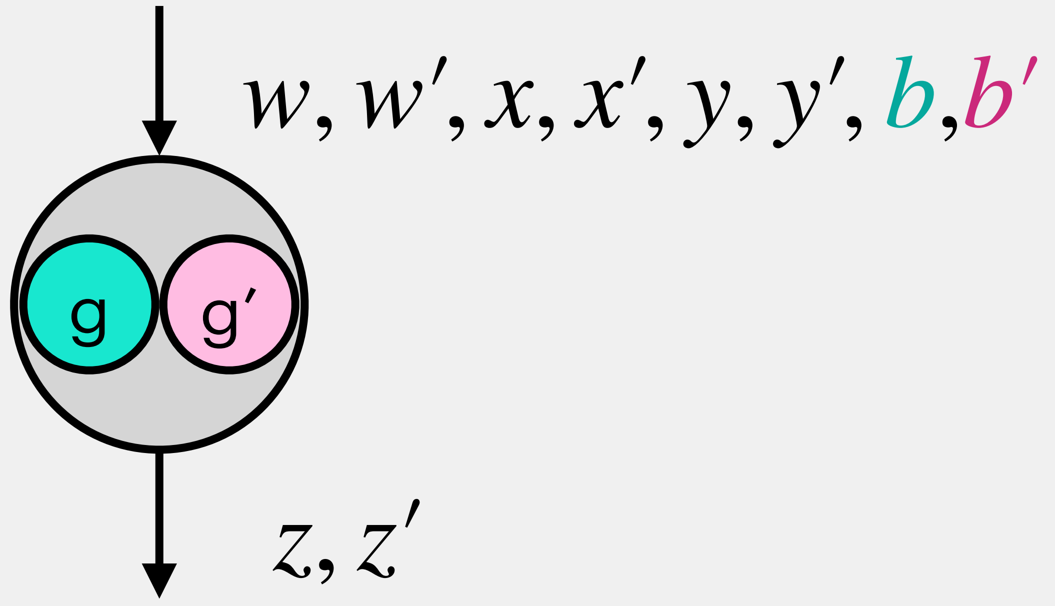
$$\forall\ \boxed{i, i'}\ .\ \boxed{0 \leq i < y} \wedge \boxed{b \wedge b'} \wedge \boxed{} \Rightarrow \boxed{}$$

quantified indices — range — activation variables — equalities — cell property

Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

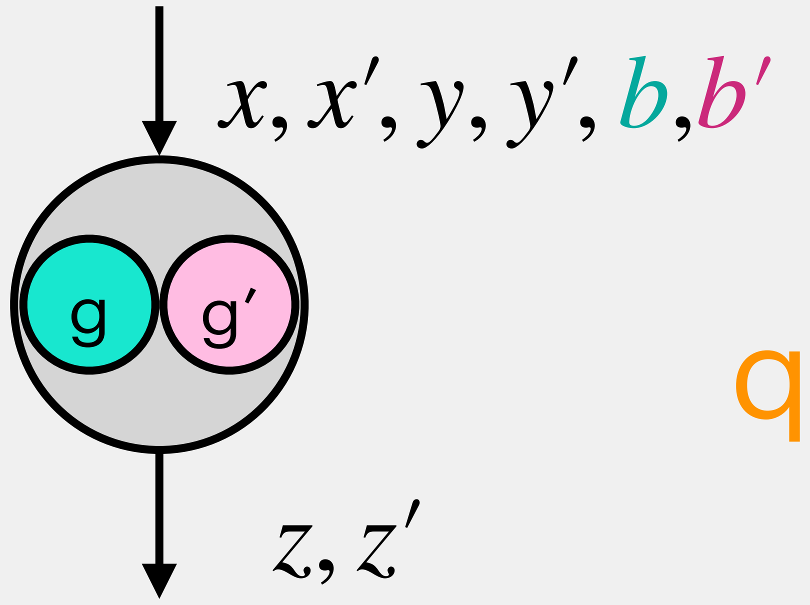
Quantifier-free



$$b \wedge b' \wedge x = x' \wedge y = y' \Rightarrow z = z'$$

activation variables ($b \wedge b'$) · input equalities ($x = x' \wedge y = y'$) · output equality ($z = z'$)

Quantified Array



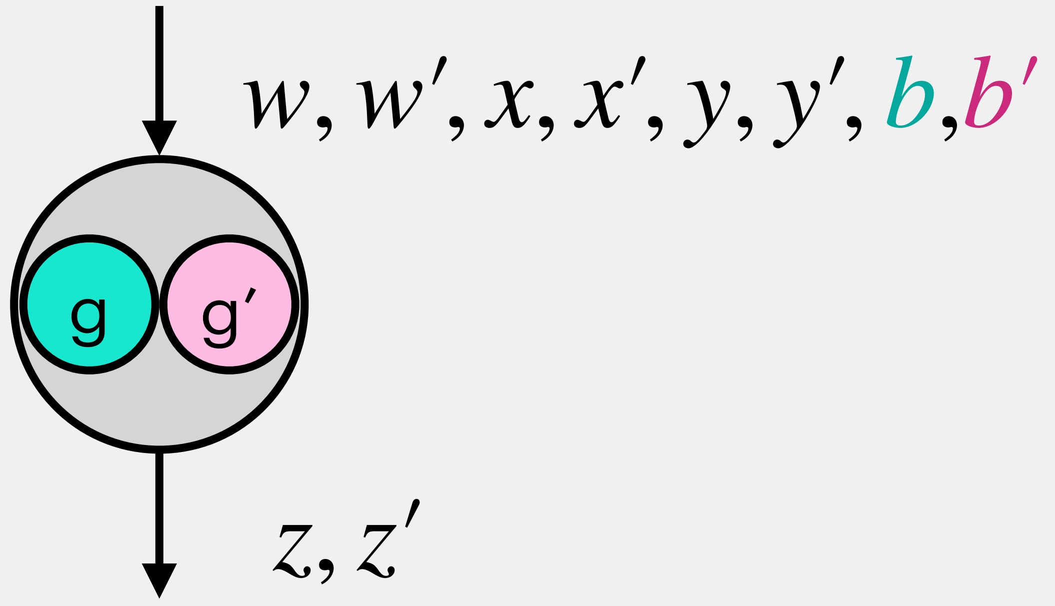
$$\forall\, i, i'.\; 0 \leq i < y \wedge b \wedge b' \wedge i = i' \wedge y = y' \Rightarrow \square$$

quantified indices (i, i') · range ($0 \leq i < y$) · activation variables ($b \wedge b'$) · equalities ($i = i' \wedge y = y'$) · cell property (empty box)

Grammar Templates

Insight:
information flow involves **equalities** on subsets of corresponding components

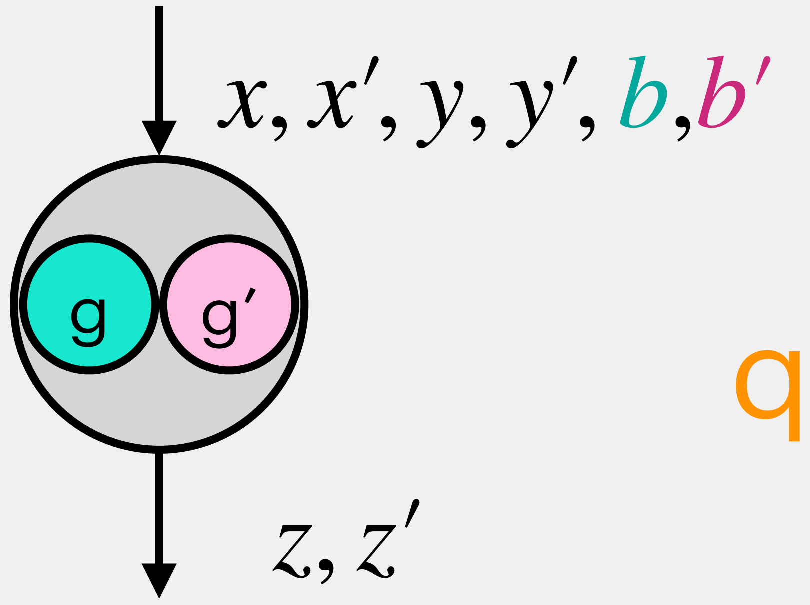
Quantifier-free



$$b \wedge b' \wedge x = x' \wedge y = y' \Rightarrow z = z'$$

activation variables ($b \wedge b'$) — input equalities ($x = x' \wedge y = y'$) — output equality ($z = z'$)

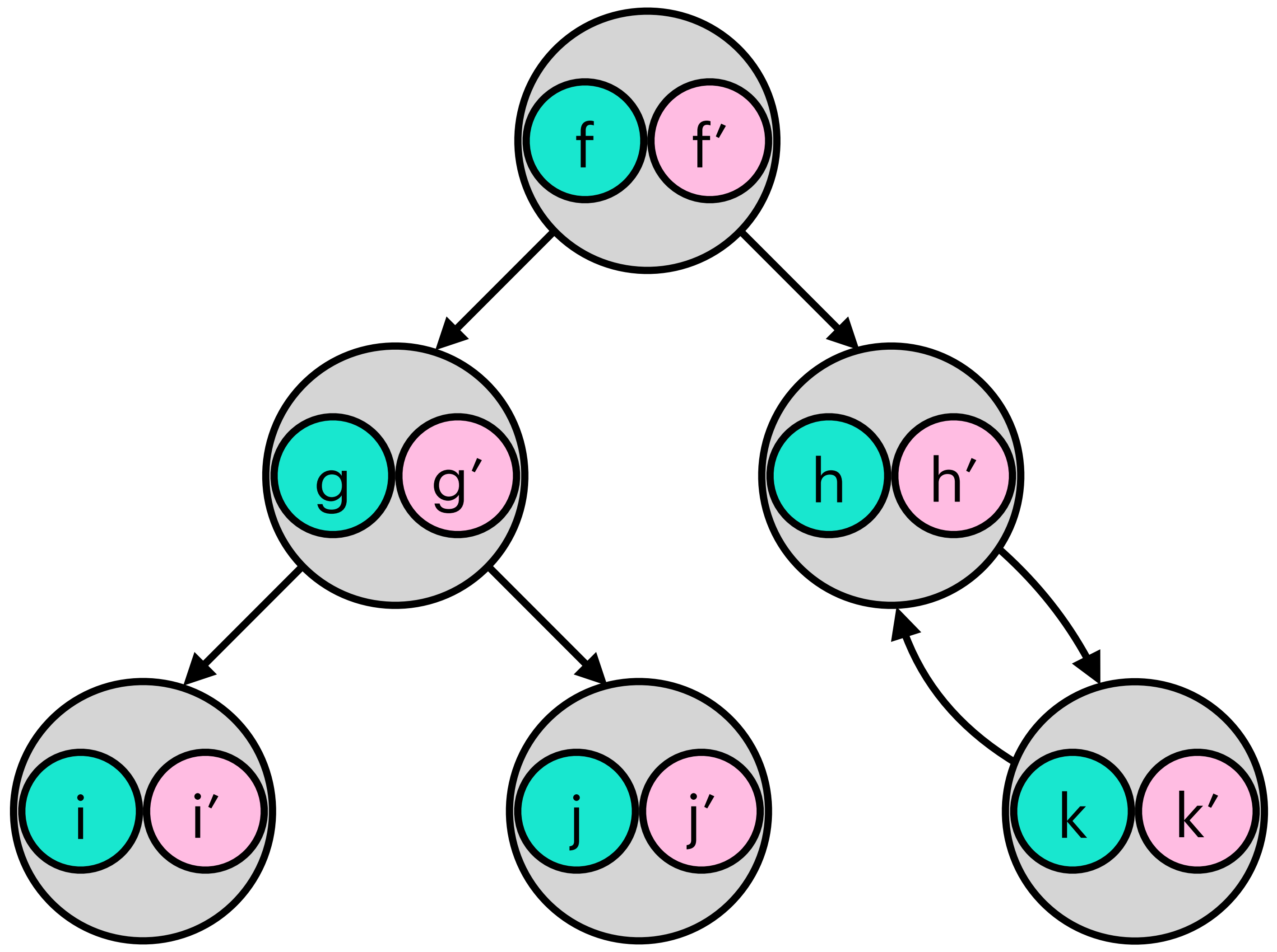
Quantified Array



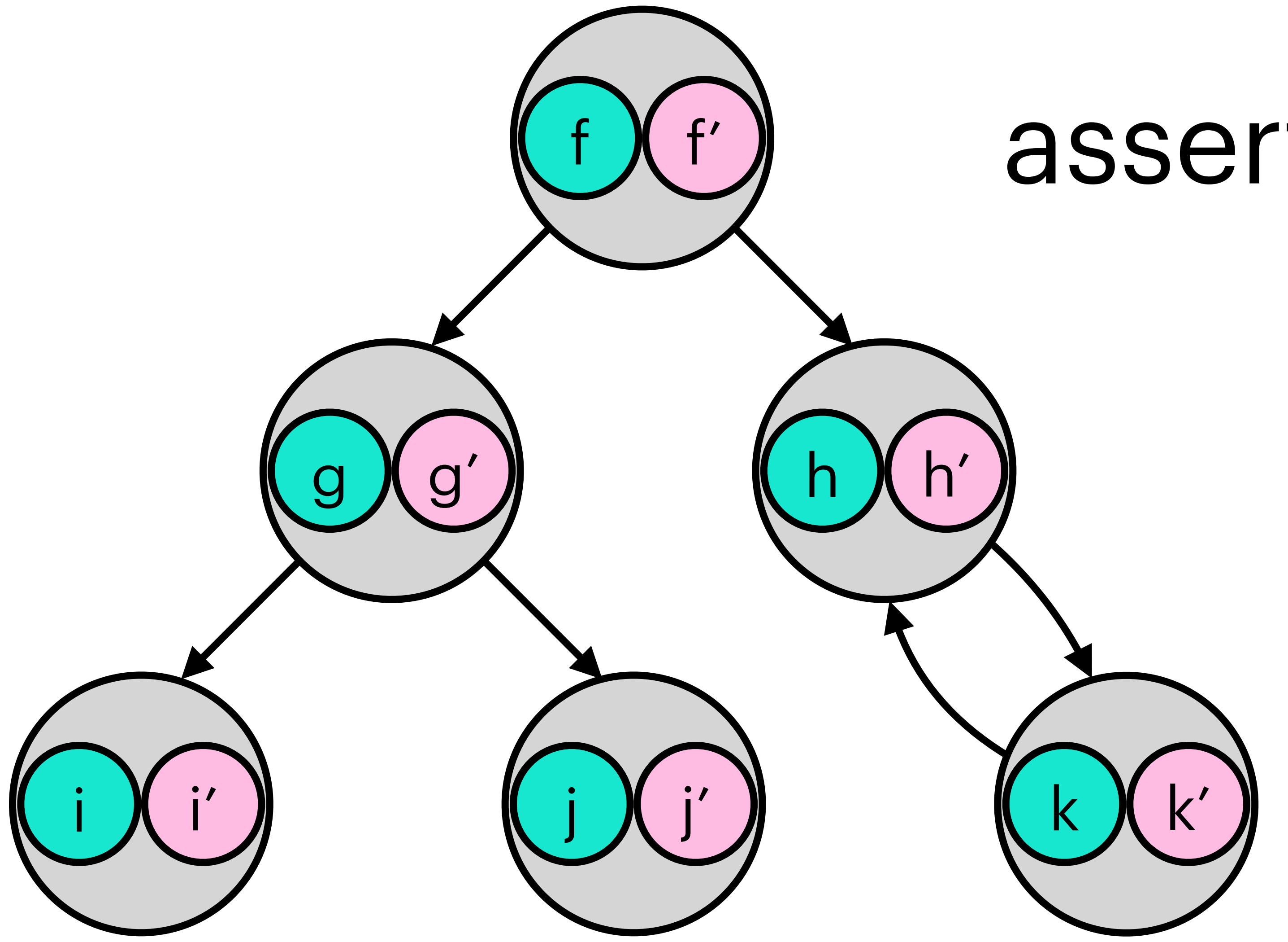
$$\forall\, i, i'.\ 0 \leq i < y \wedge b \wedge b' \wedge i = i' \wedge y = y' \Rightarrow z[i] = z'[i']$$

quantified indices (i, i') — range ($0 \leq i < y$) — activation variables ($b \wedge b'$) — equalities ($i = i' \wedge y = y'$) — cell property ($z[i] = z'[i']$)

Property-Directed Summaries



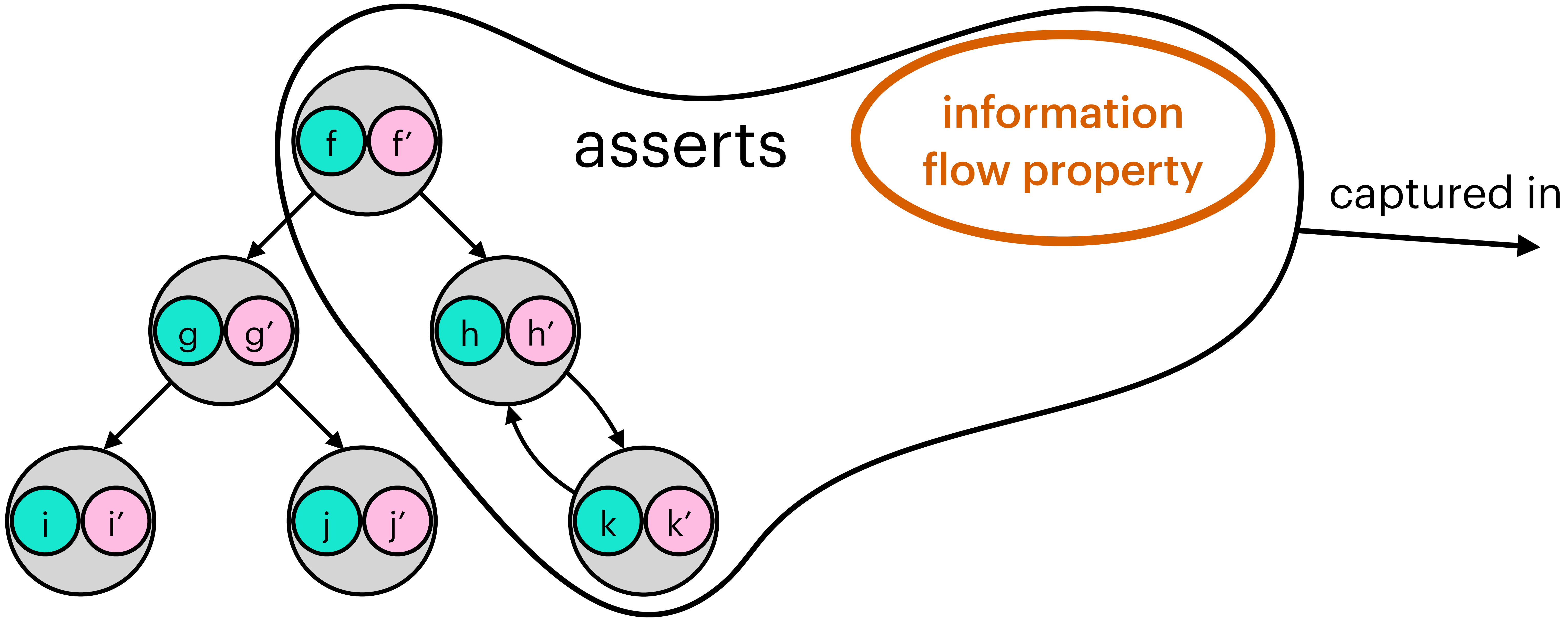
Property-Directed Summaries



asserts

information
flow property

Property-Directed Summaries



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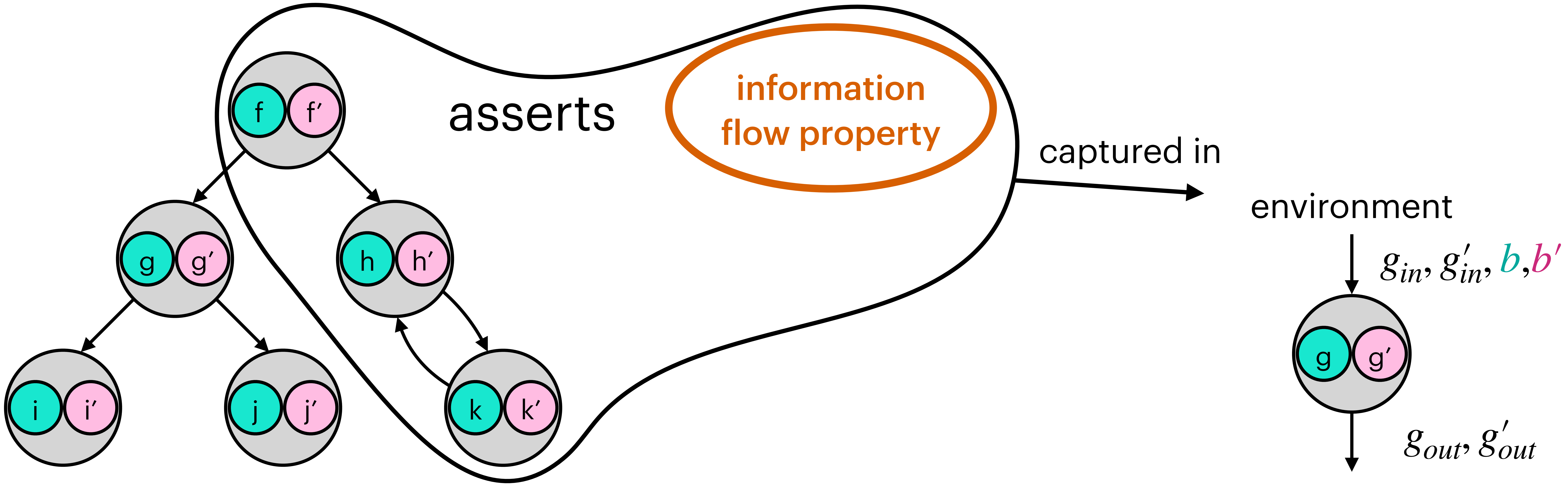

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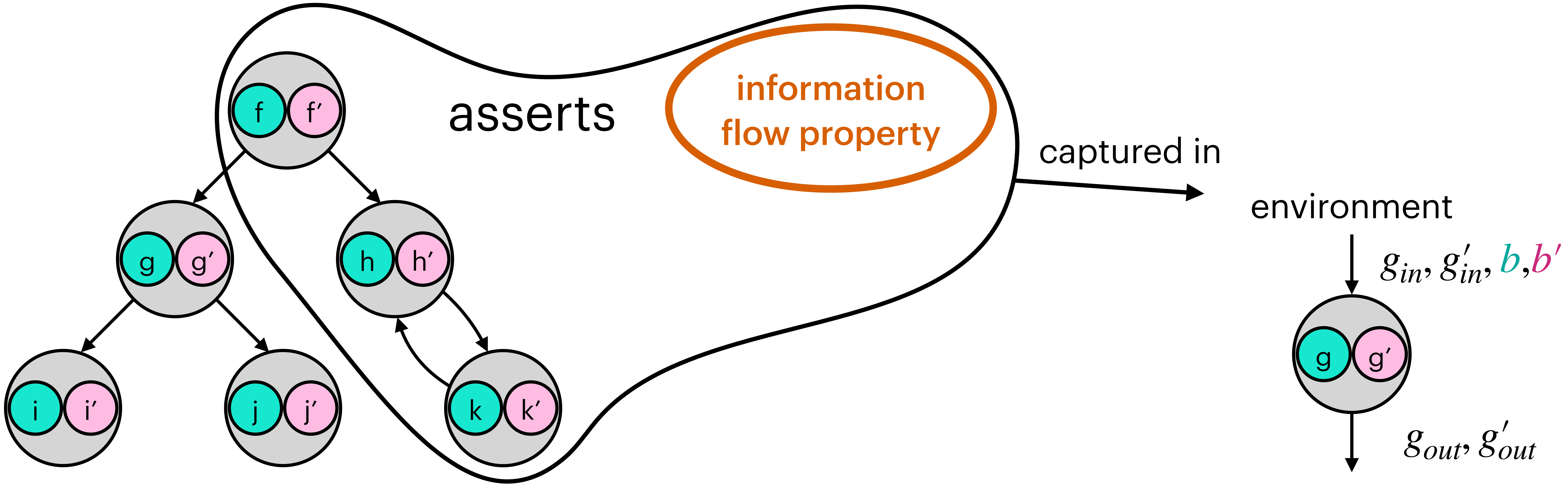

$$\boxed{b \wedge b'} \wedge \boxed{x = x' \wedge y = y'} \Rightarrow \boxed{z = z'}$$

activation variables

input equalities

output equalities

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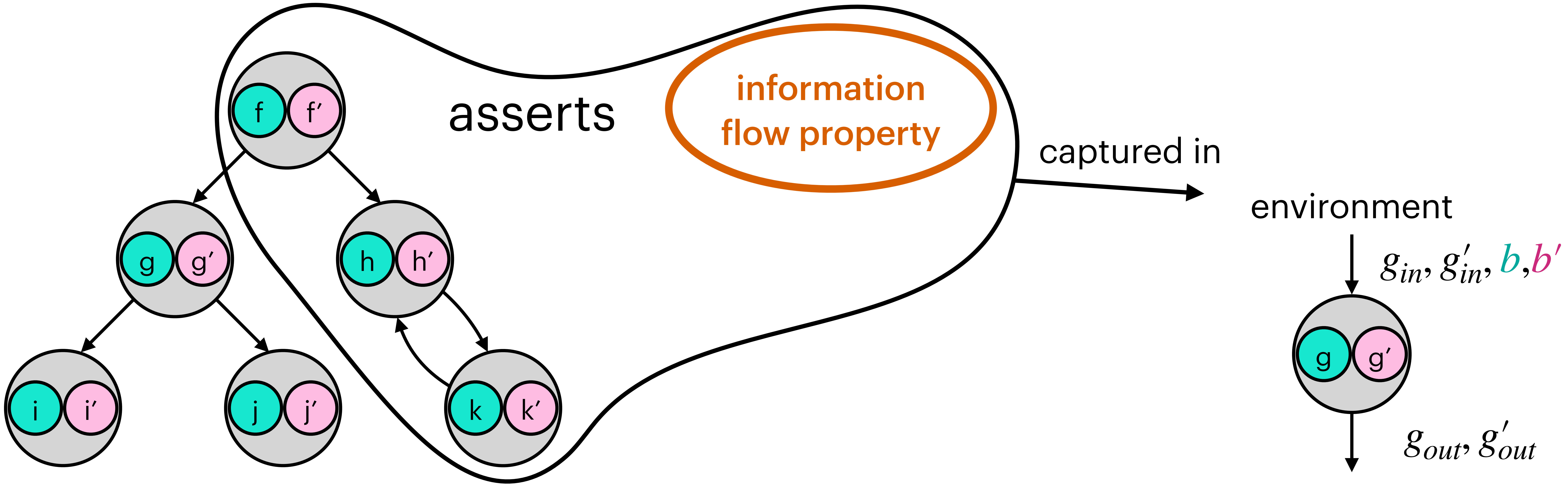

Conjuncts in environment $\wedge$ $\boxed{b \wedge b'}$ $\wedge$ $\boxed{x = x' \wedge y = y'}$ $\Rightarrow$ $\boxed{z = z'}$

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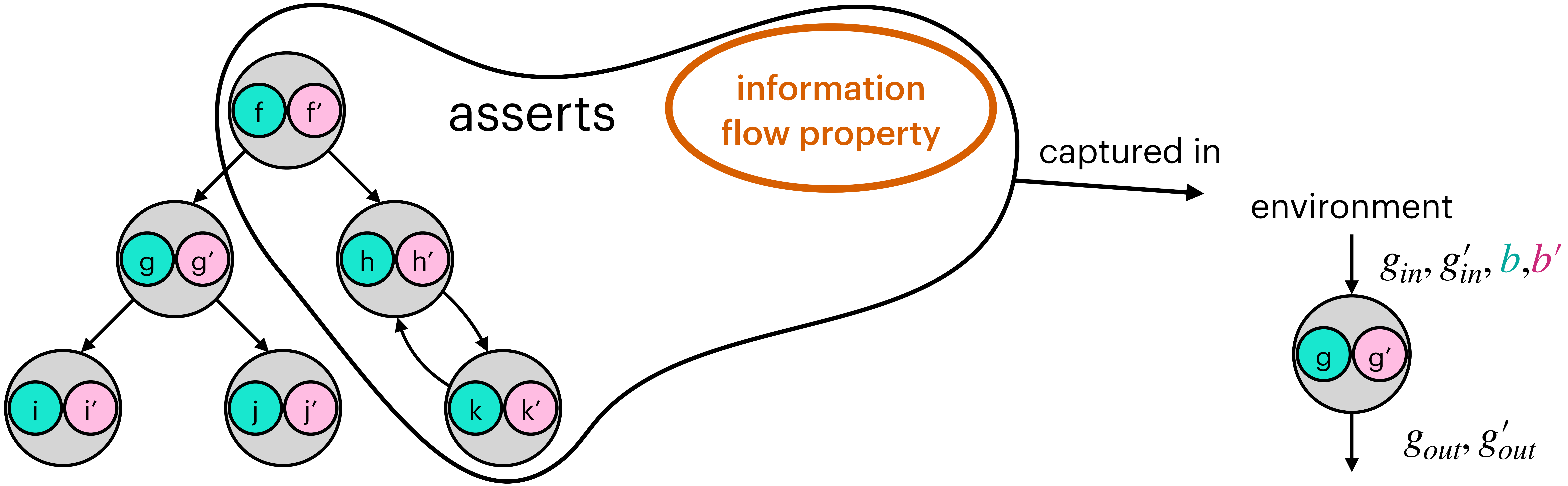

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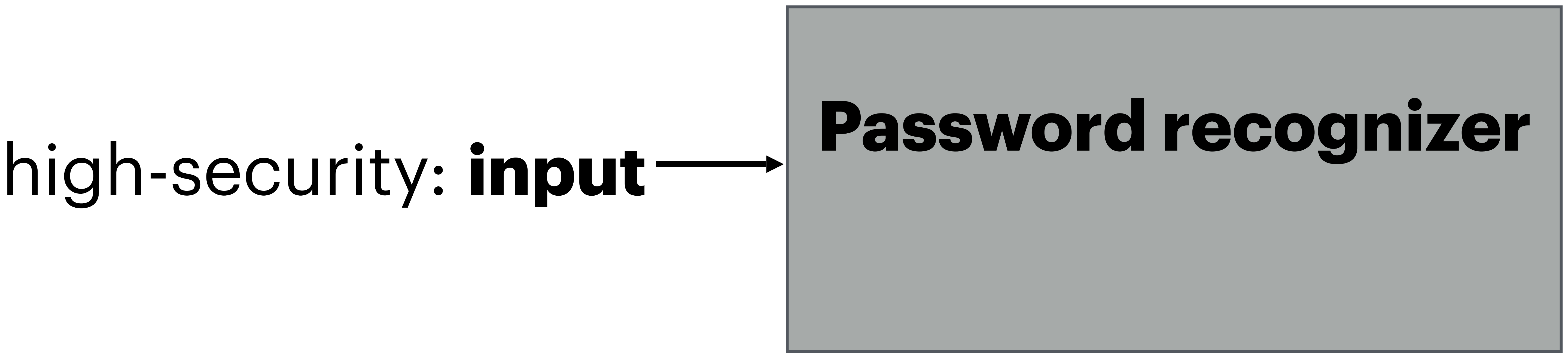
Useful for handling declassification

Declassification

Non-interference alone can be too restrictive

Declassification

Non-interference alone can be too restrictive



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Can *declassify* to allow *some* leakage

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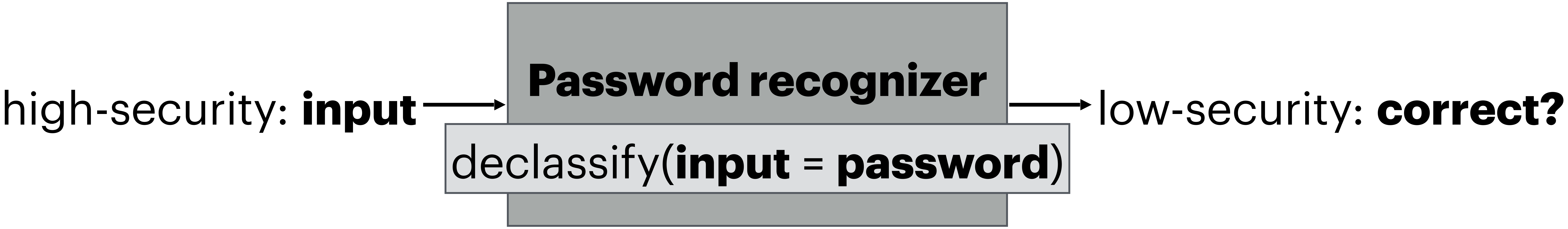

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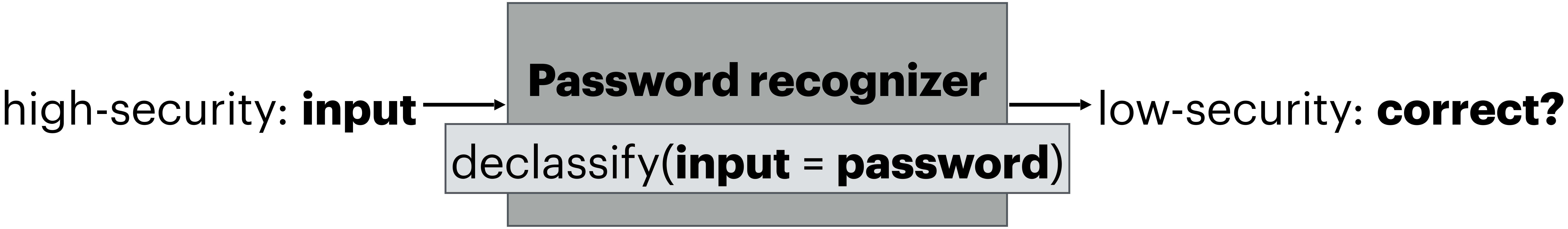

Declassification can be captured in the environment

Experimental Results

Implemented in tool called Flower built on top of Clover

[1] SMT-based model-checking for recursive programs, Komuravelli et al. FMSD.'16
[2] Cartesian Hoare Logic, Sousa and Dillig, PLDI'16

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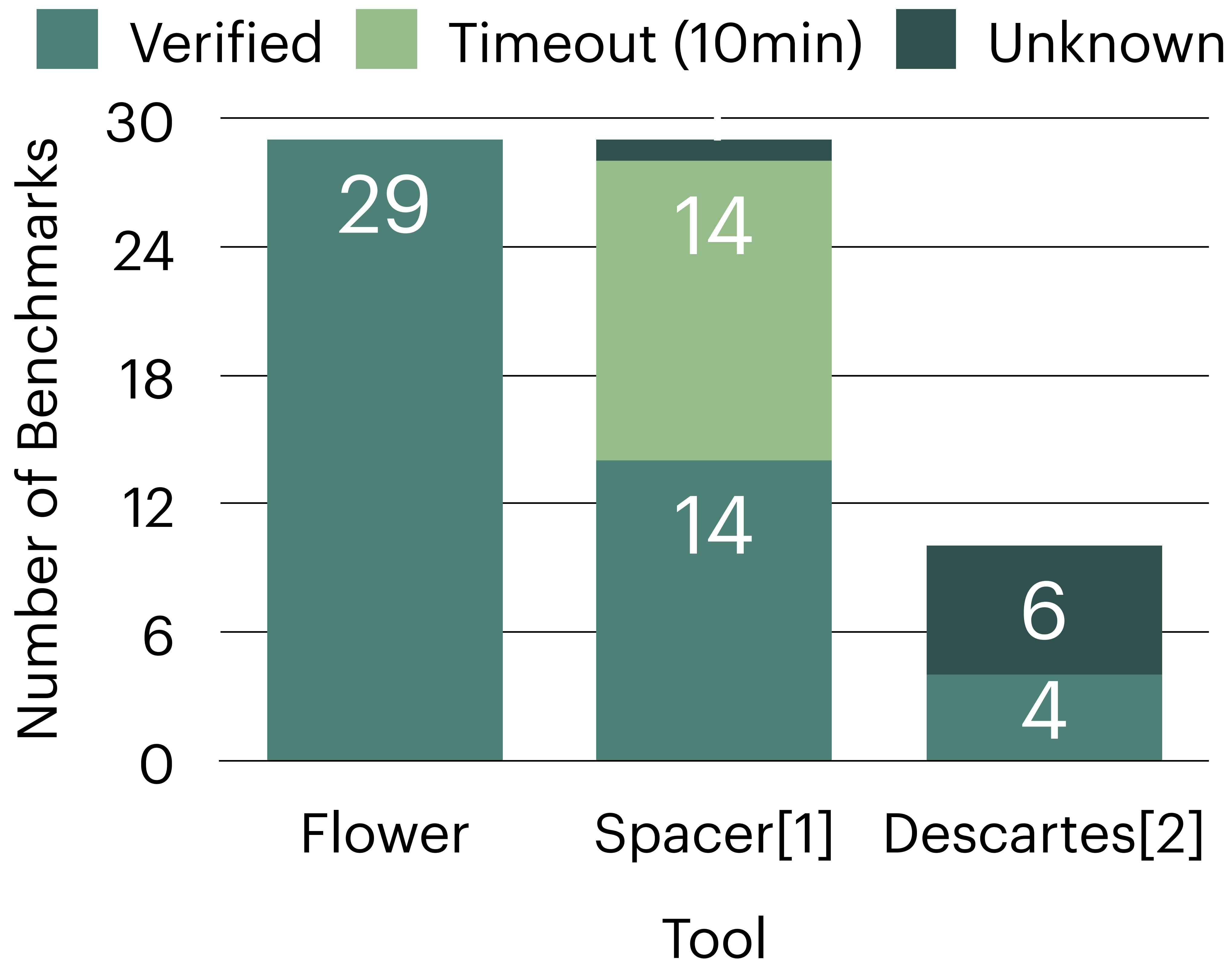

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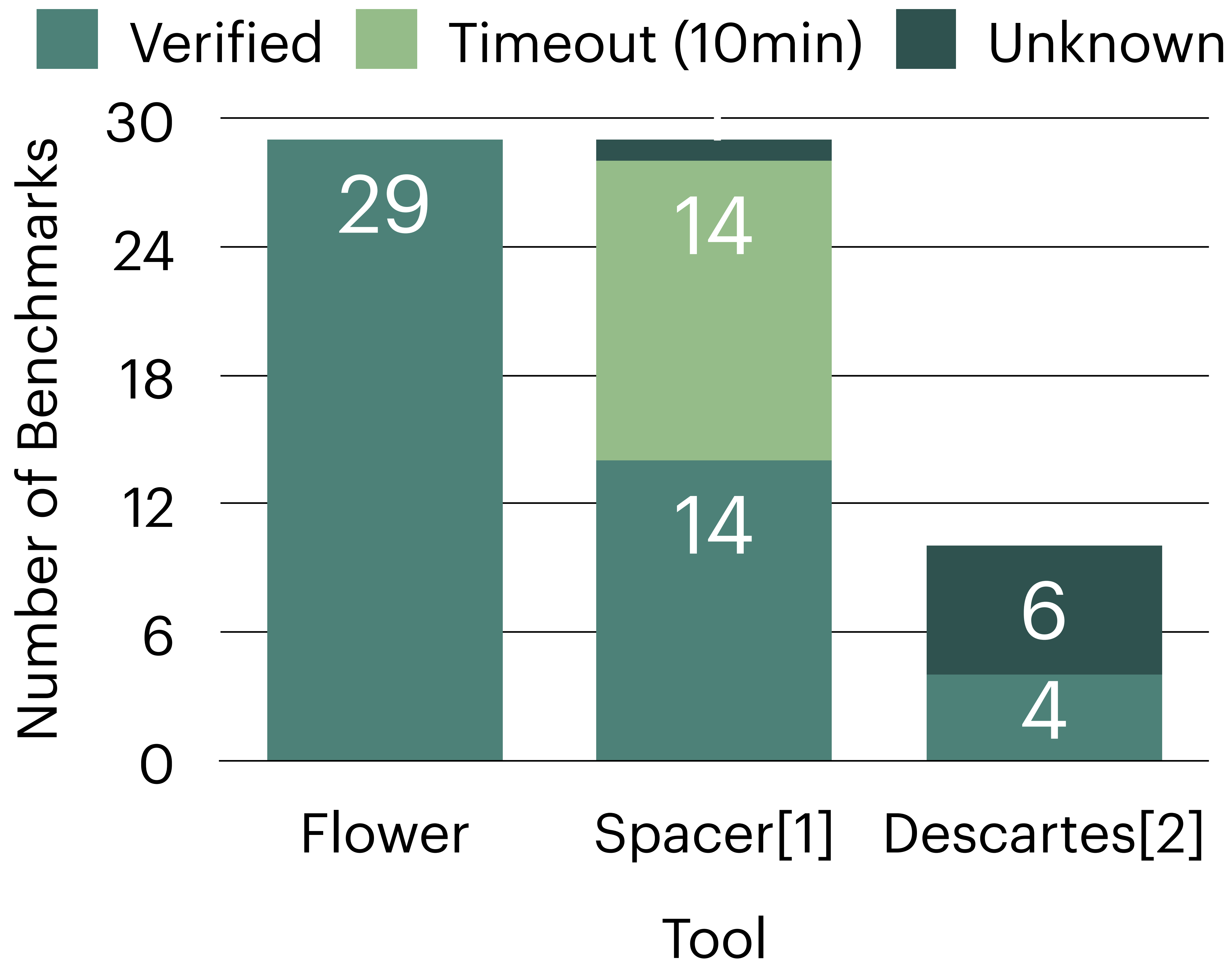

Unknown indicates inferred invariants too weak

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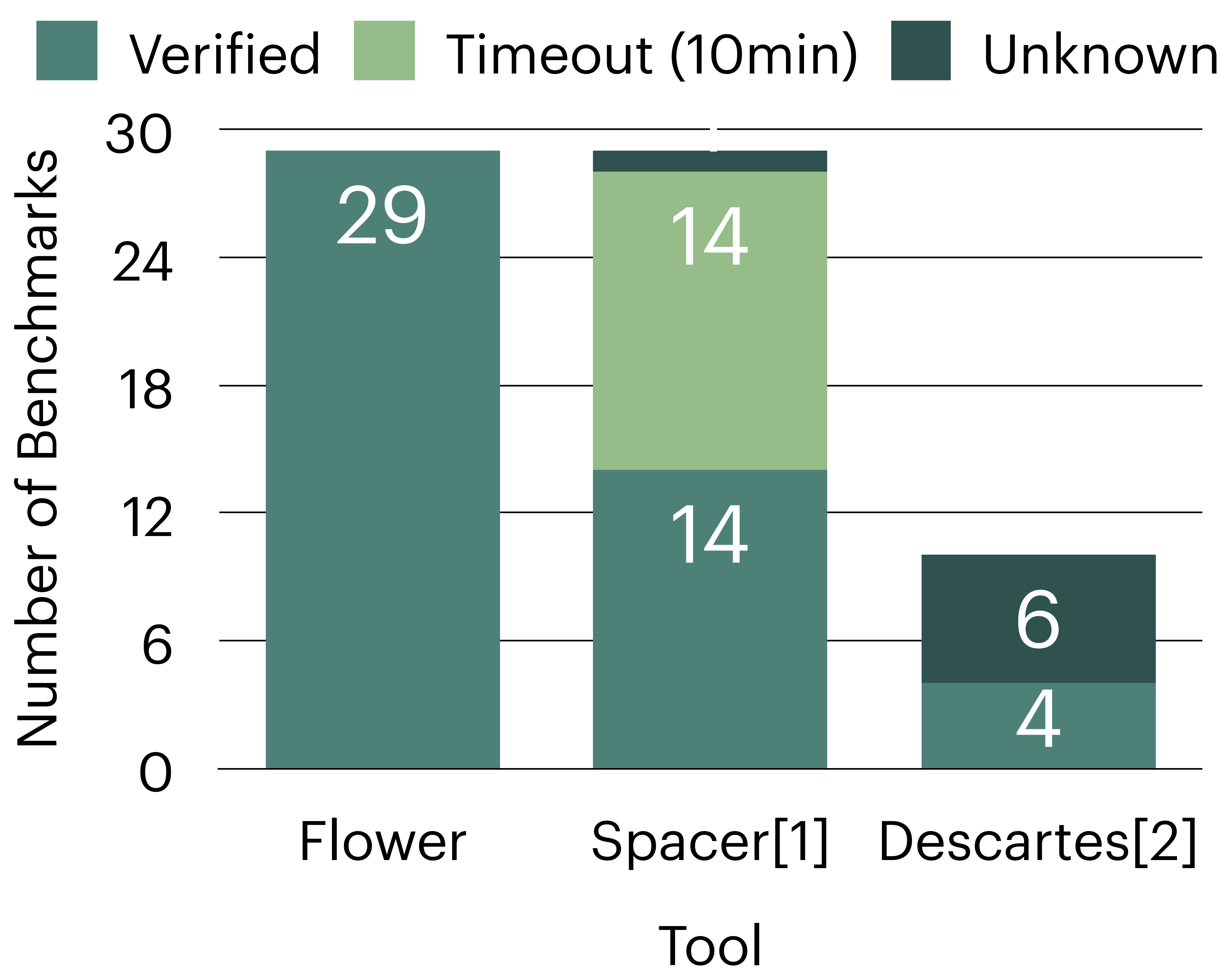

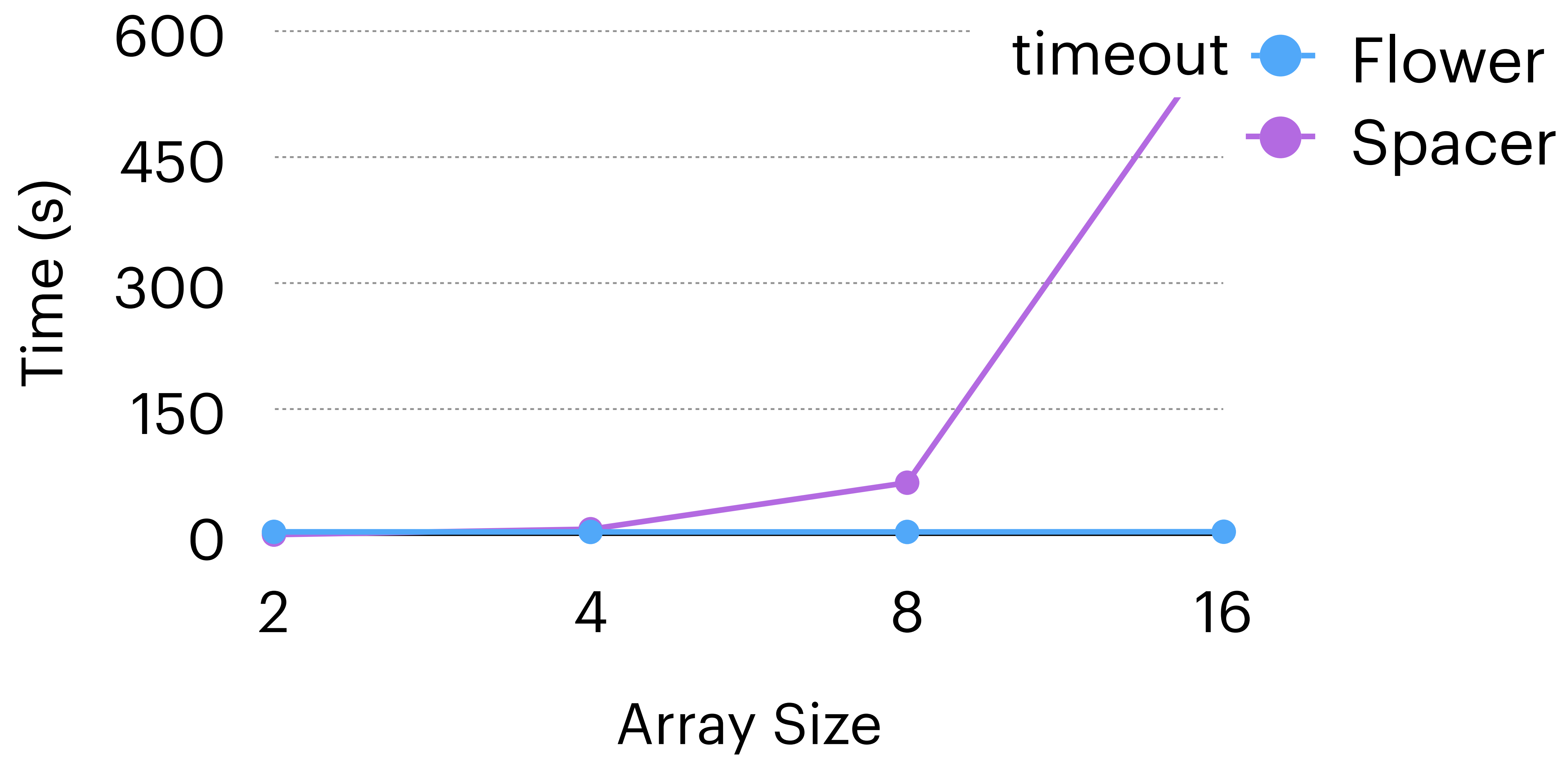

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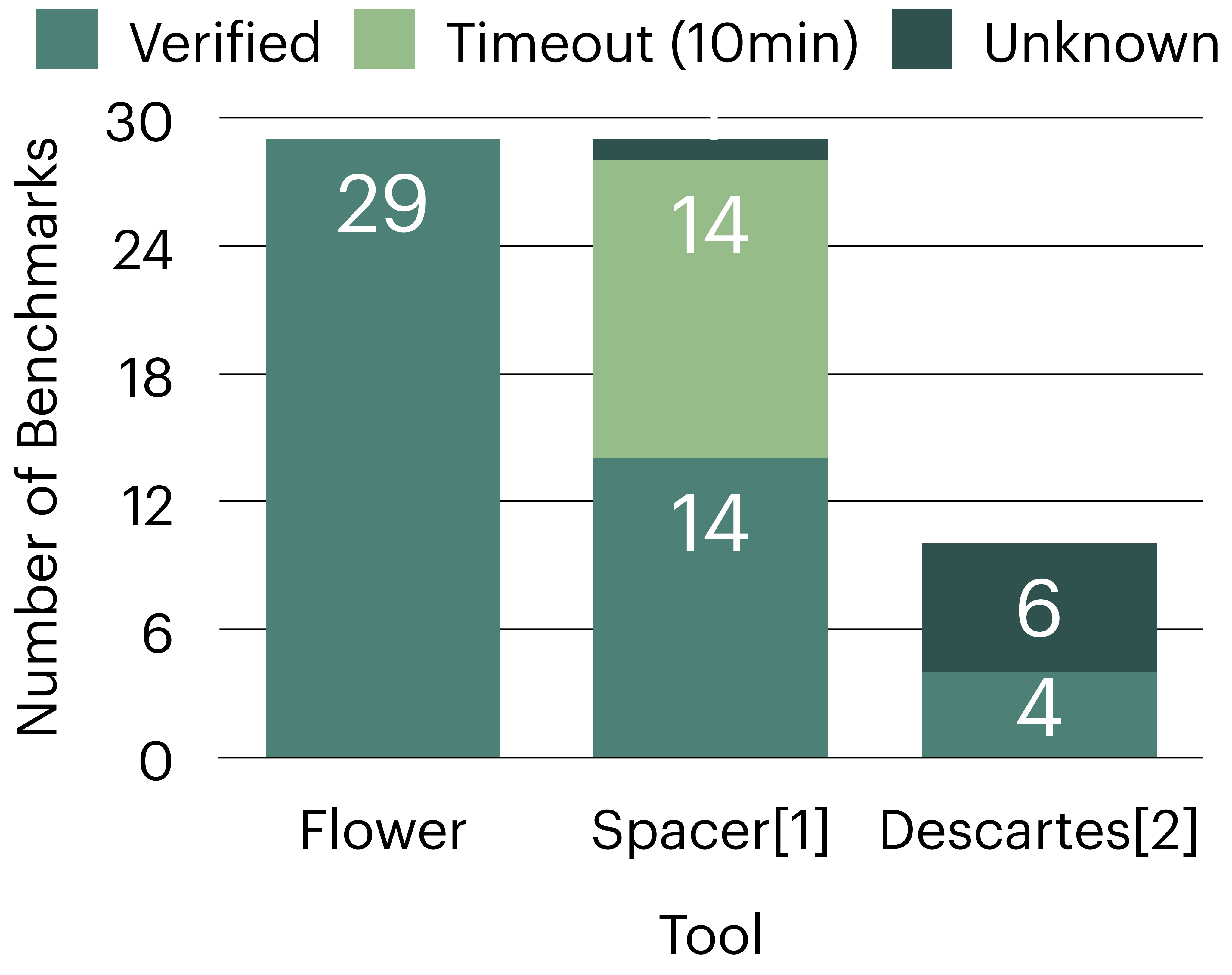

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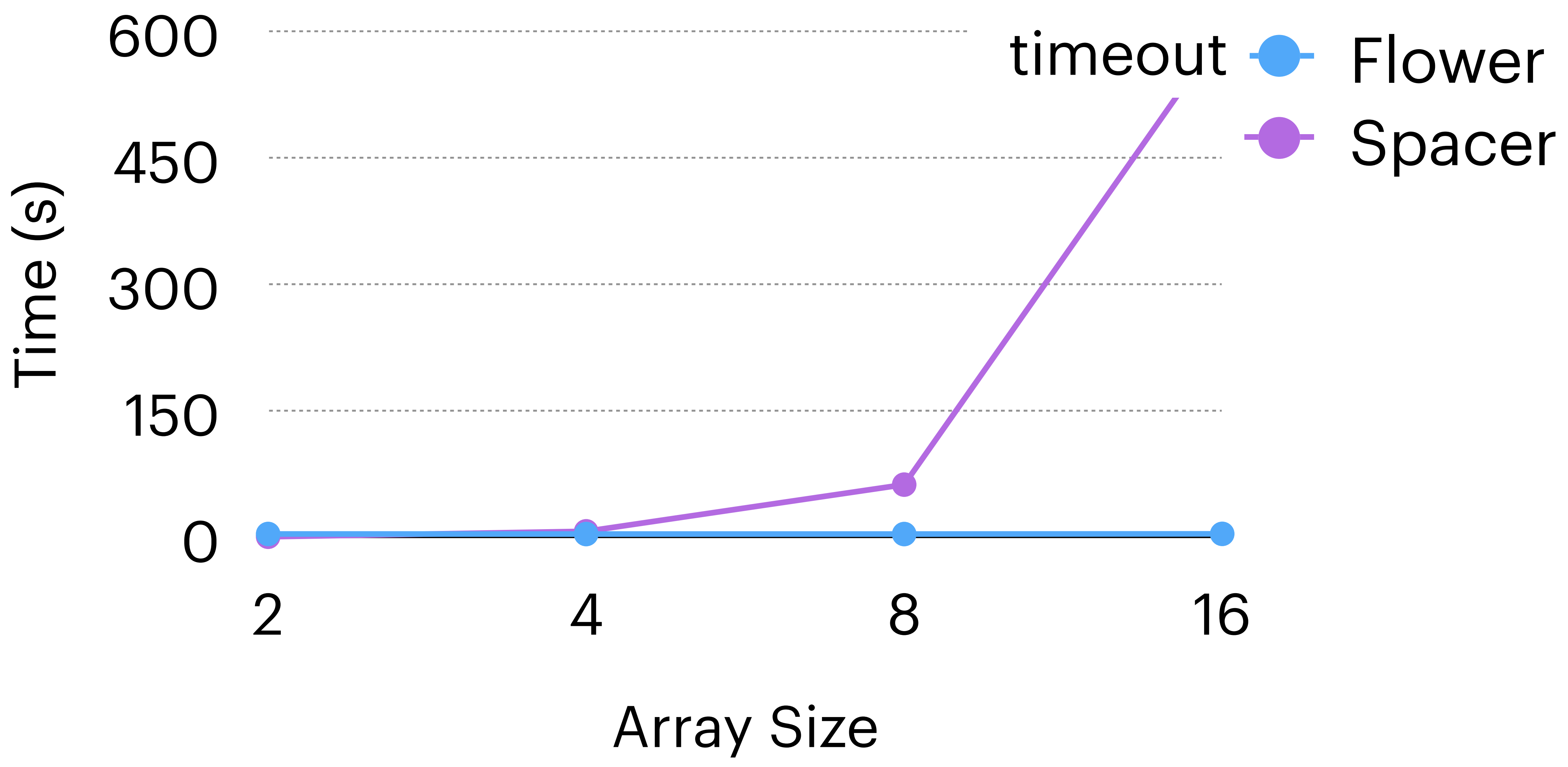

Parametrizable benchmark shows array size does not affect Flower's performance because of quantified template

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Related Work

Relational Program Verification	Information-Flow Checking

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Information-Flow Checking

Non-modular approaches

[Barthe et al., CSFW'04] [Terauchi and Aiken, SAS'05] [Banerjee et al., FSTTCS'16]

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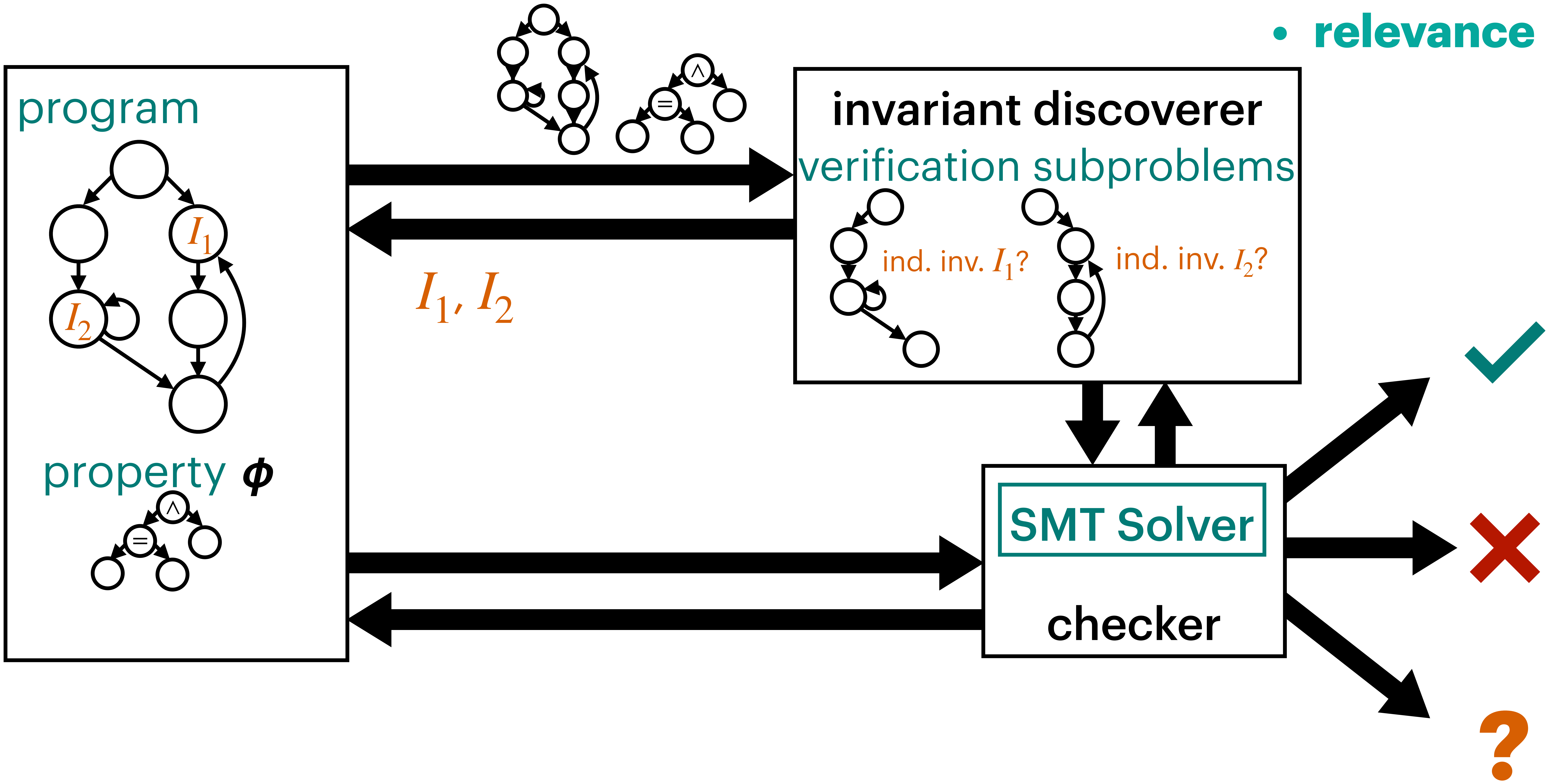
Syntax-Guided Synthesis for Quantified Array Invariants

[Fedyukovich et al., CAV'19]

Structure and Syntax

Structural info about programs and properties can help with:

- **performance**
- **scalability**
- **relevance**



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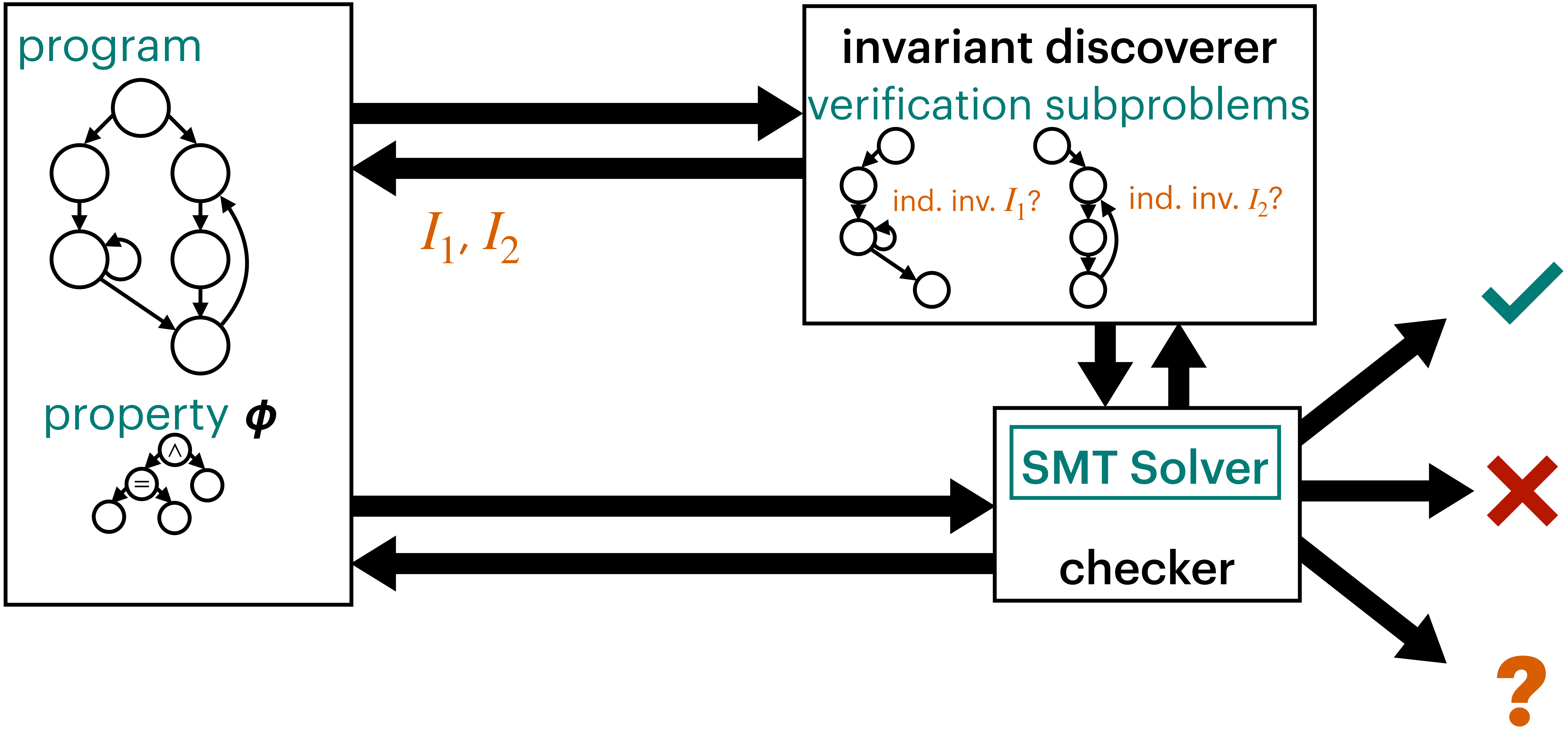

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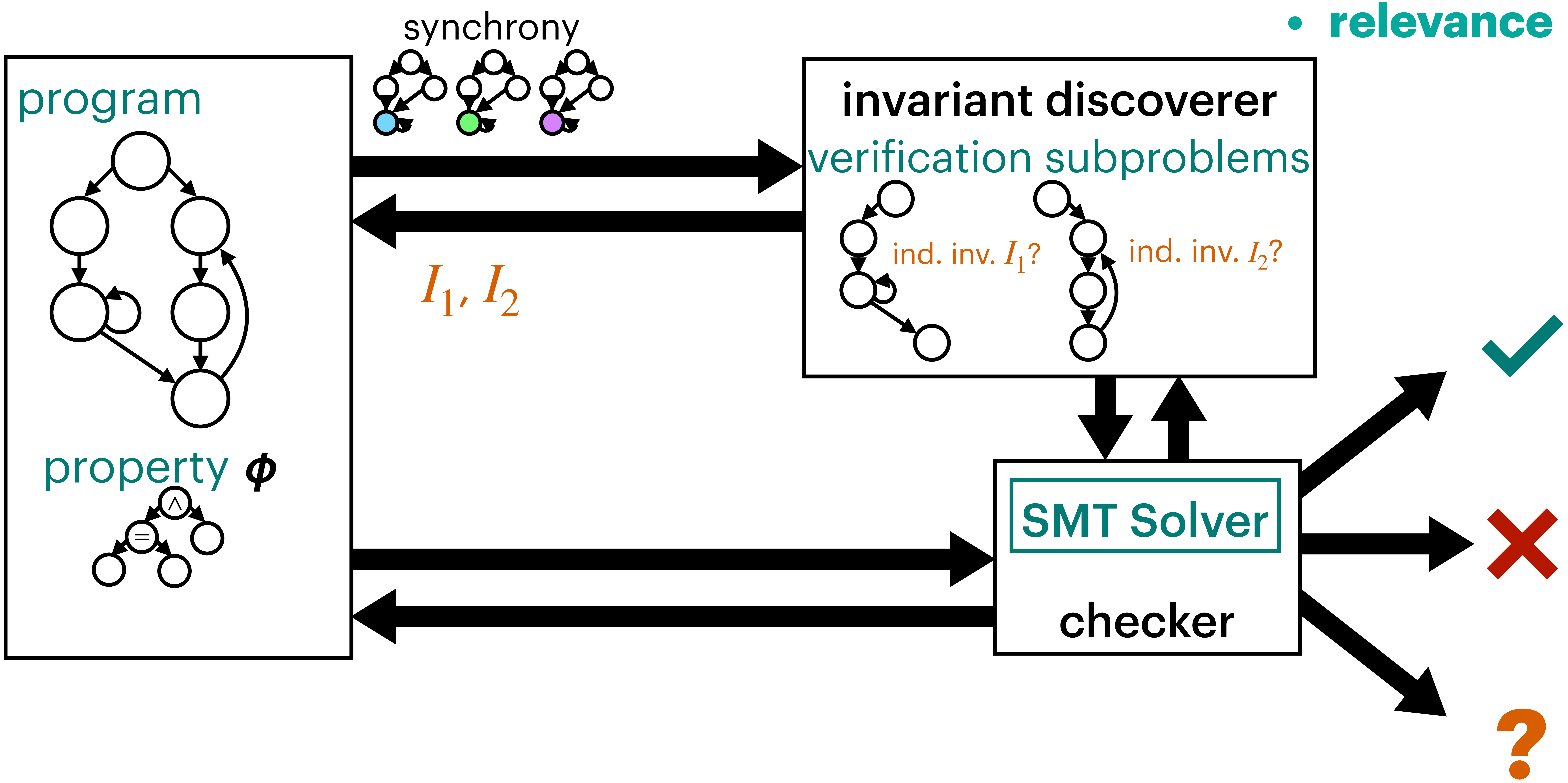

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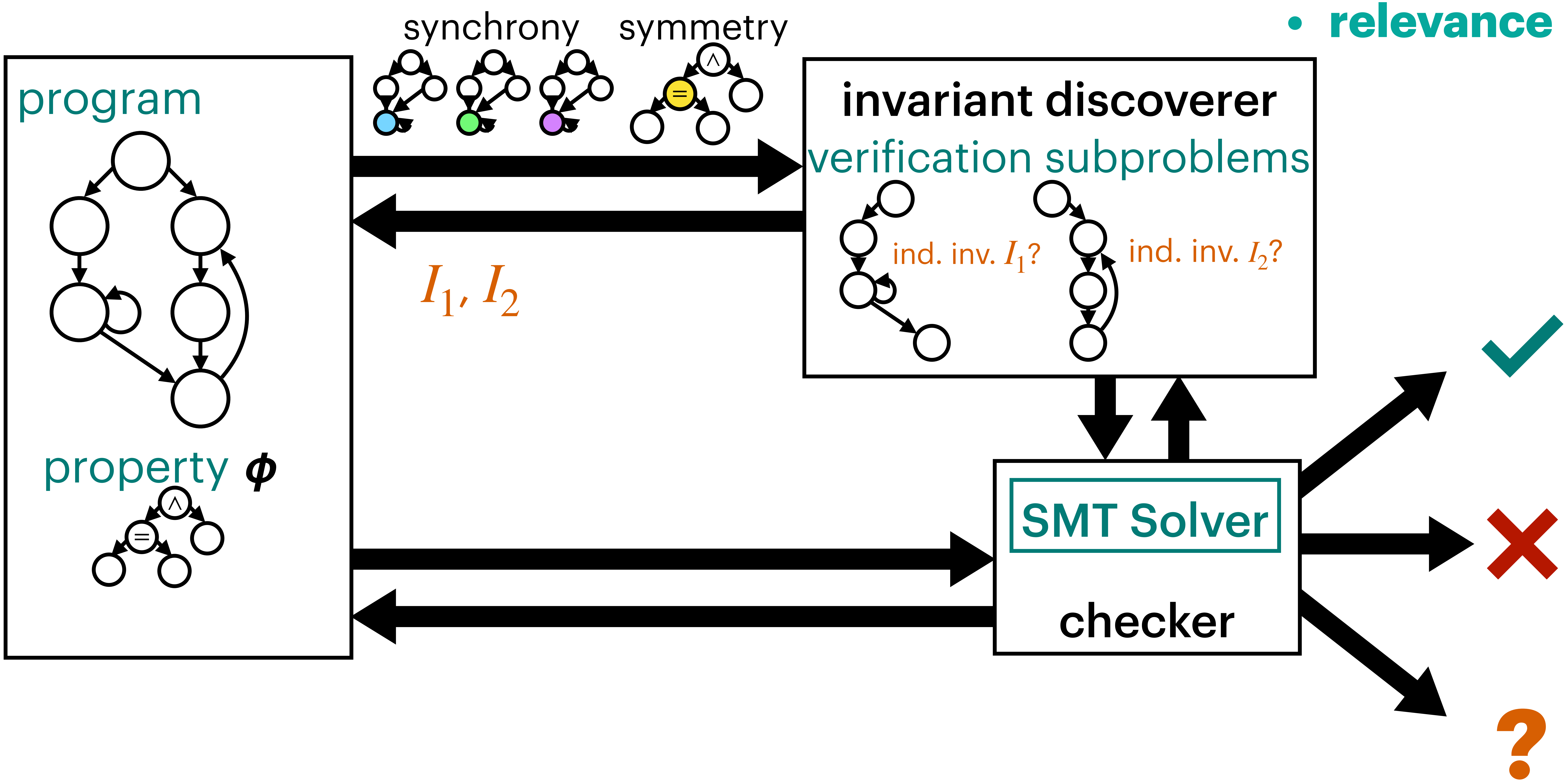

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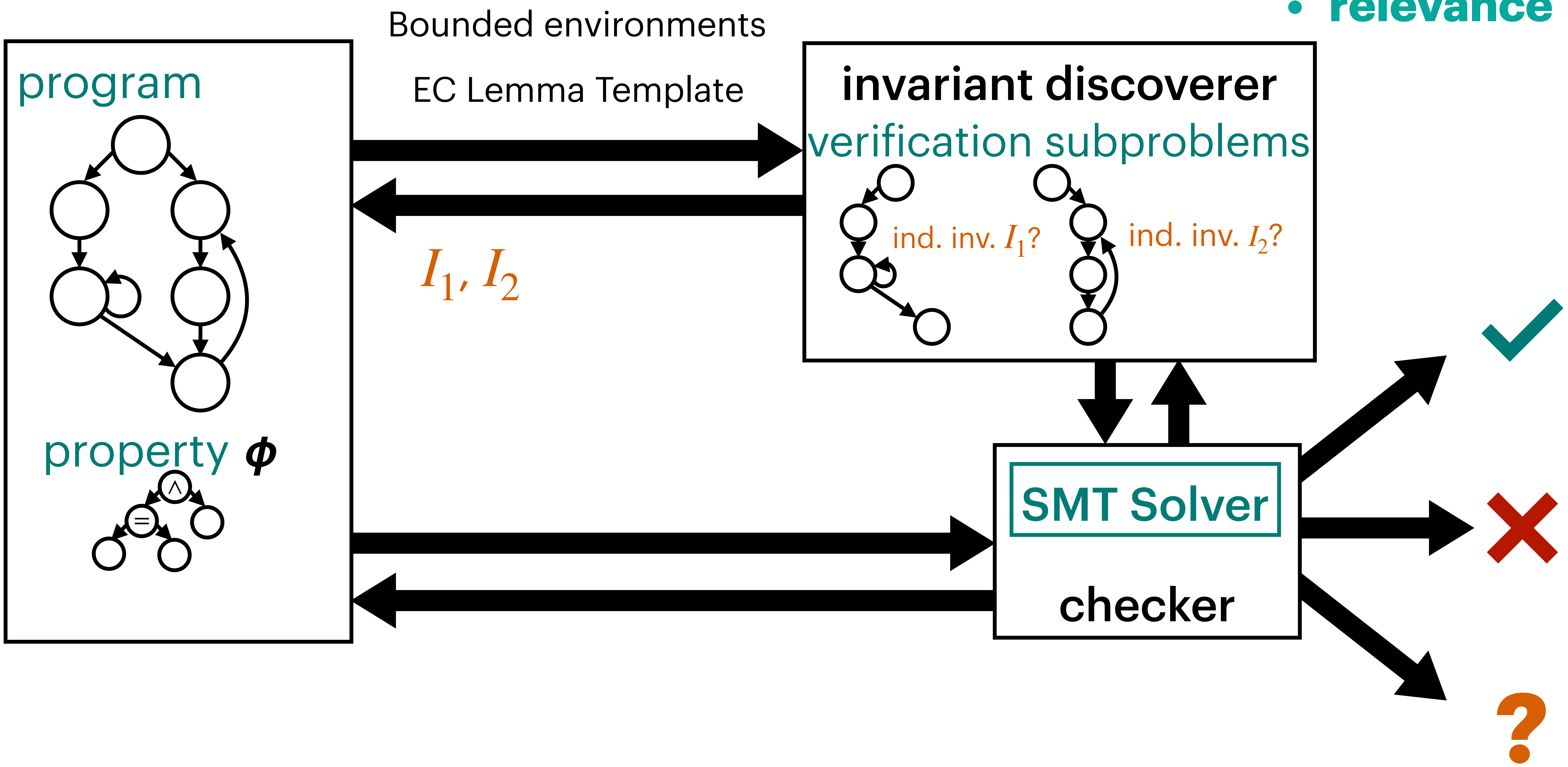

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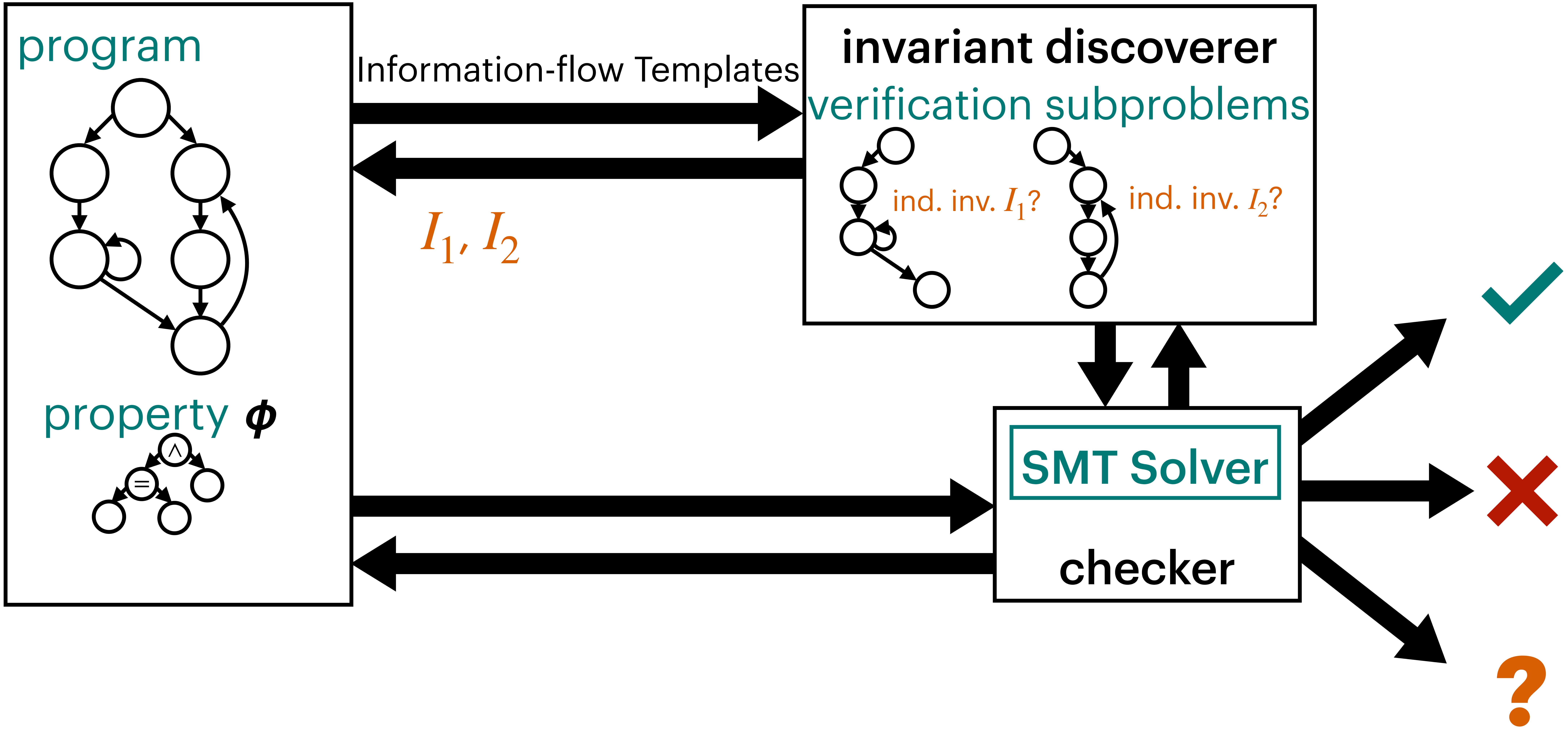

Contributions

How to exploit **structure** of both **programs** and **properties**
to infer and leverage **invariants** that improve **scalability** and **performance**
in SMT-based automated verification.

Future Work

I. *k*-safety Verification
Cartesian Hoare Logic [2]

Symmetry-breaking for Constrained Horn Clauses

II. Interprocedural Program Verification
Constrained Horn Clauses

III. Information-Flow Verification
Constrained Horn Clauses

Handle heaps: Constrained Horn Clauses + heaps [1]

[1] Towards an SMT-Lib Theory of Heap, Esen and Rümmer, IJCAR'20
[2] Cartesian Hoare Logic, Sousa and Dillig, PLDI'16

Extra slides

Invariants

How to make it easy to **infer** relational properties with symmetries?

invariant synthesizer

Invariants

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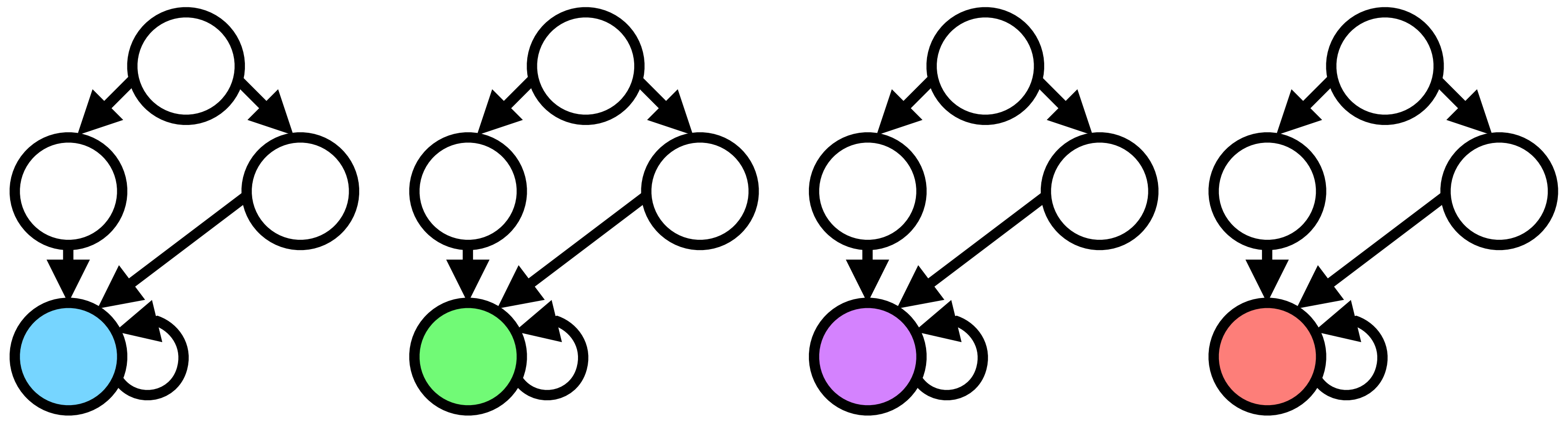
synchronize (align) structurally similar parts
(e.g., control-flow graph nodes)



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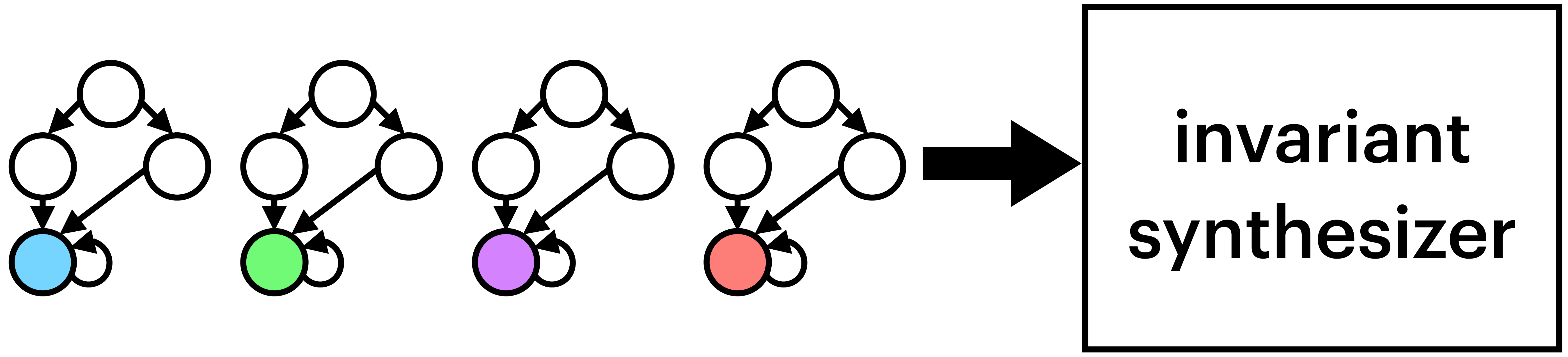

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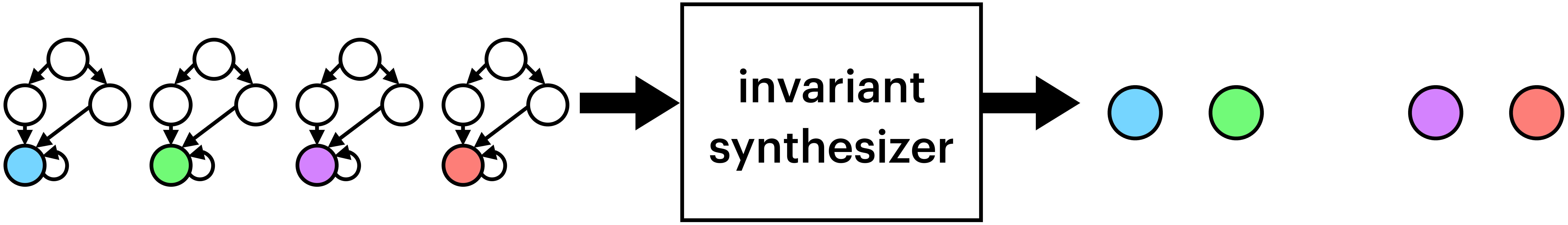

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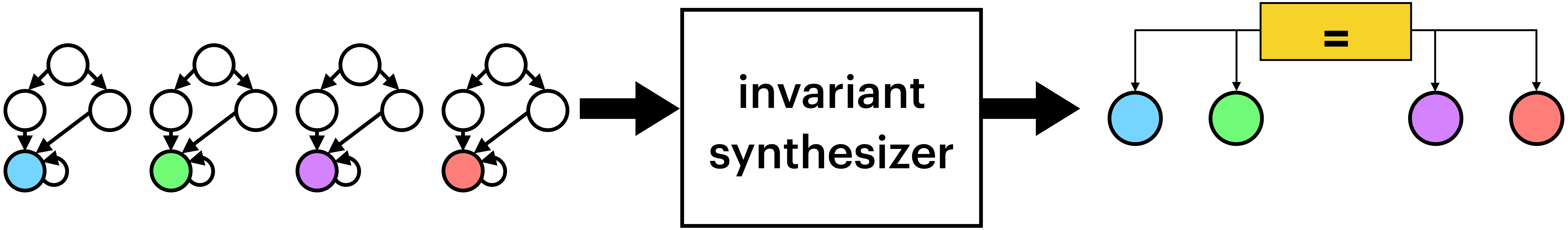

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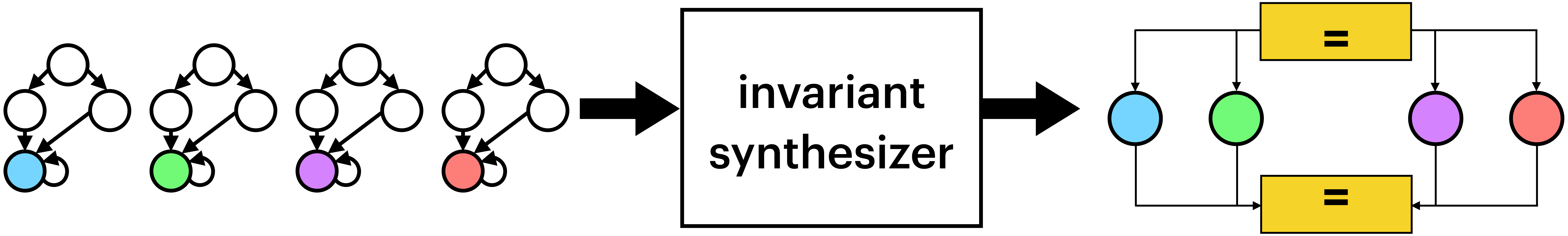

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Synchrony for Loops

How to make it easy to infer relational loop invariants?

[Barthe et al., 2011]
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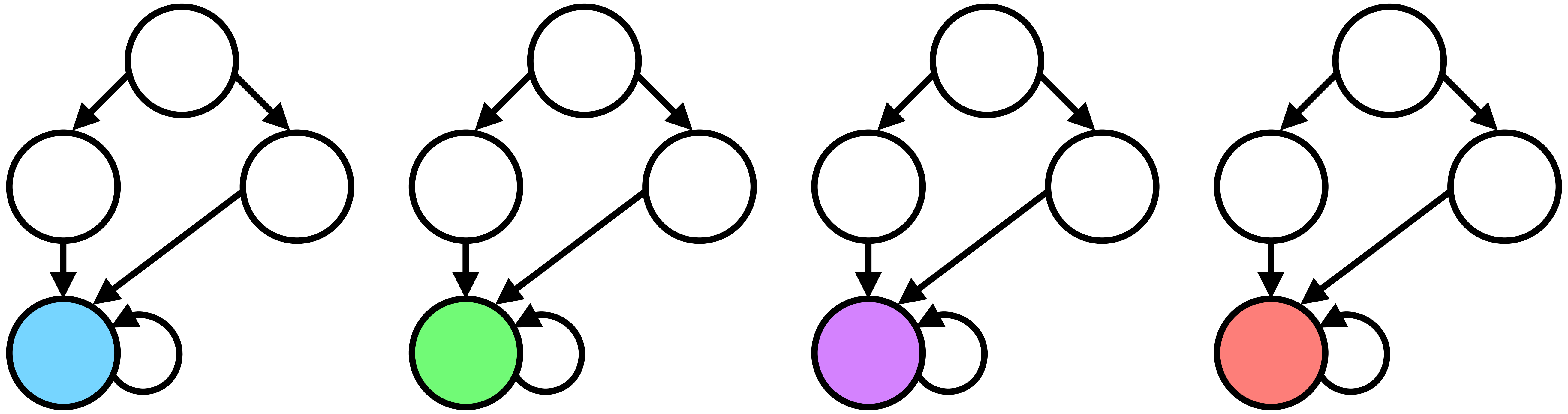

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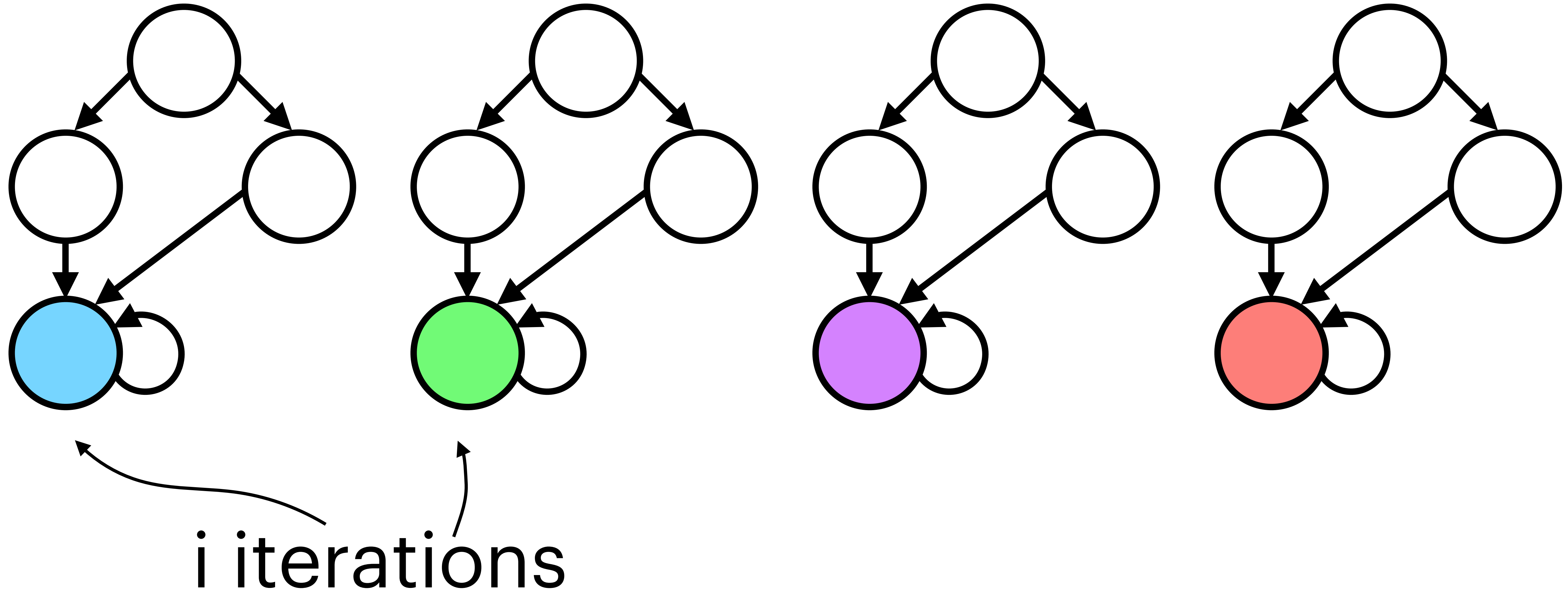

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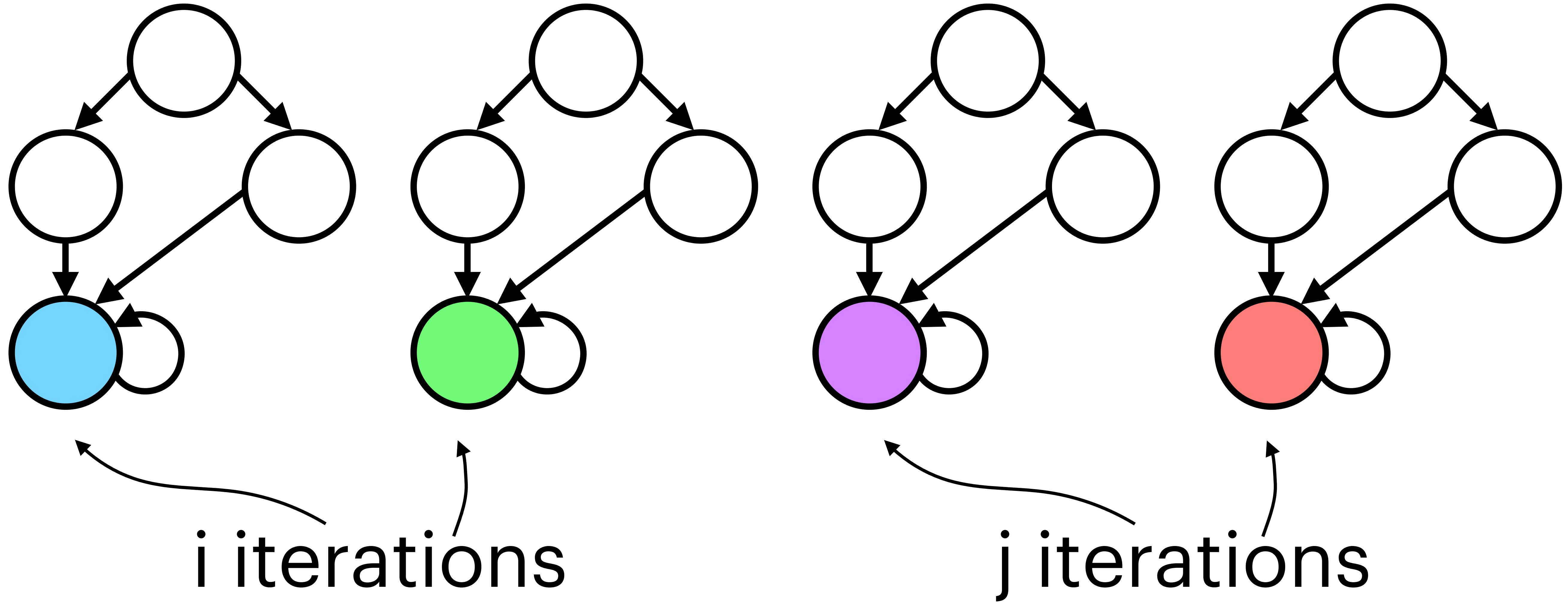

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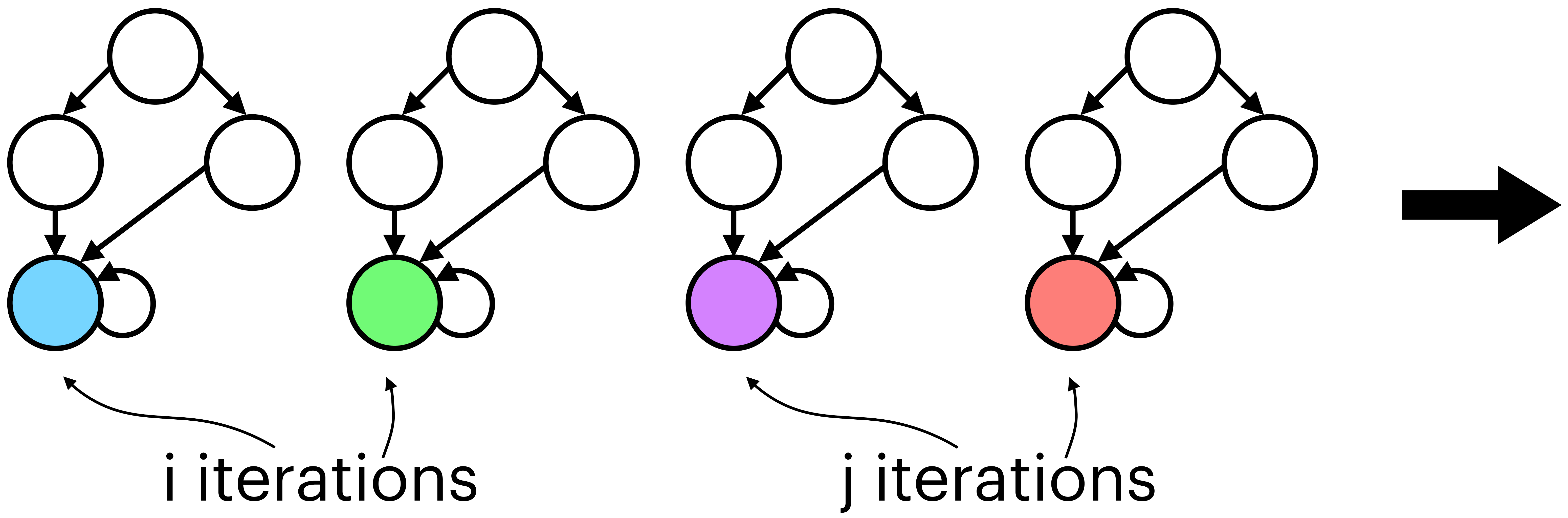

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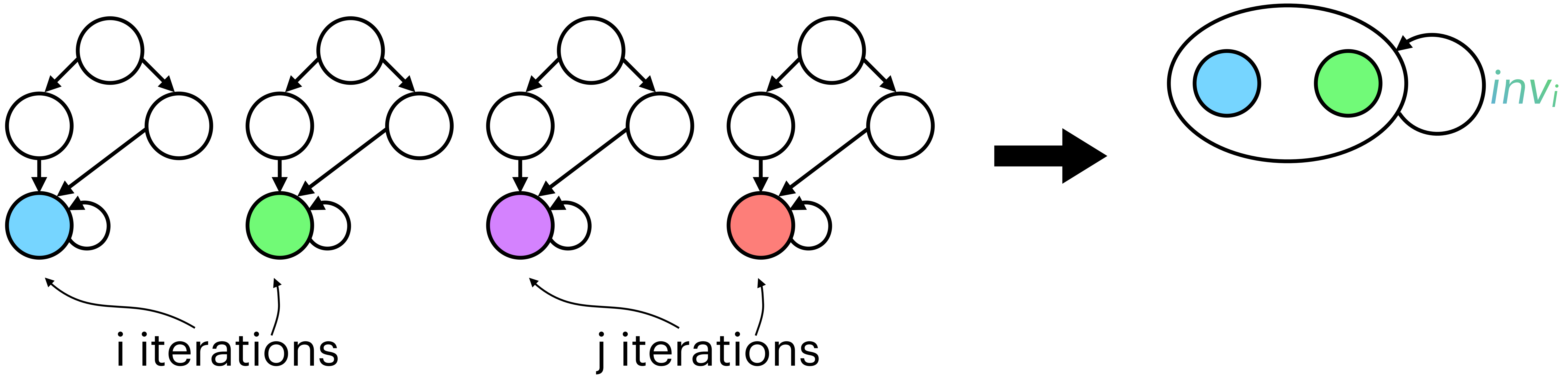

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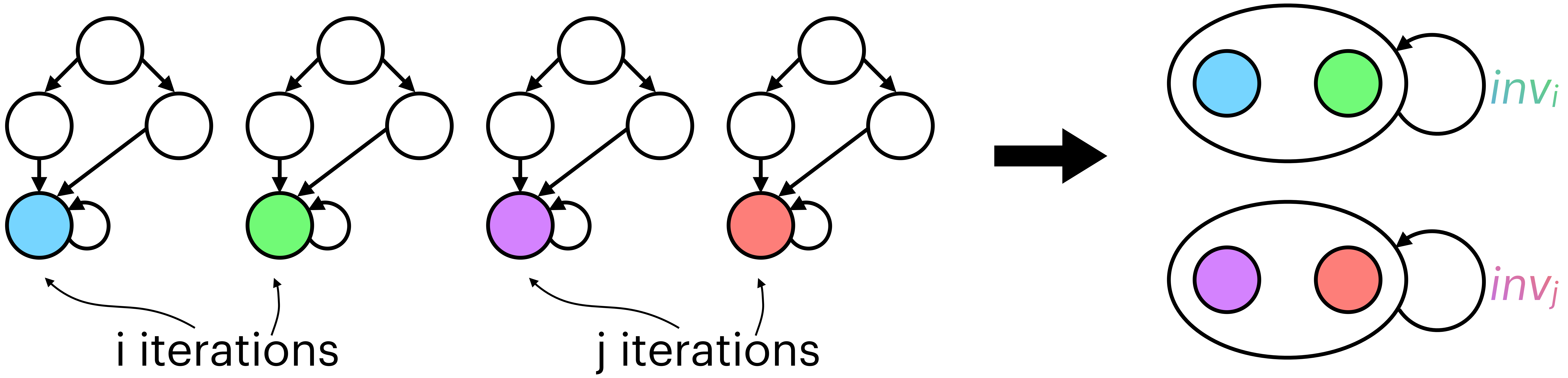

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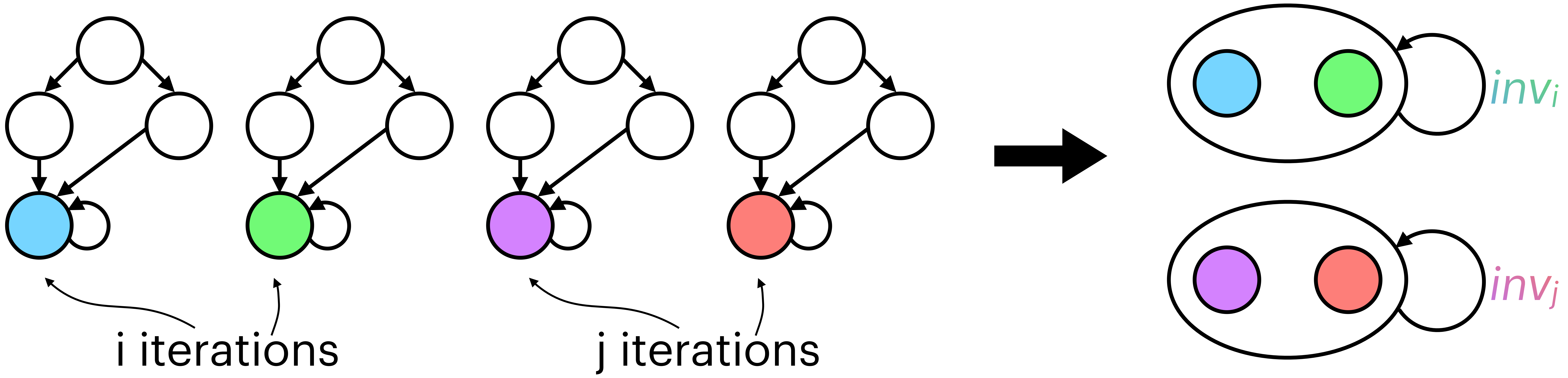

Use one simple relational loop invariant per set of “lockstep” loops.

[Barthe et al., 2011]
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Maximal Lockstep Loop Detection

Synthesize simple relational invariant I, then do partition-refinement:

At each step, ask:

[Pick et al., 2018]

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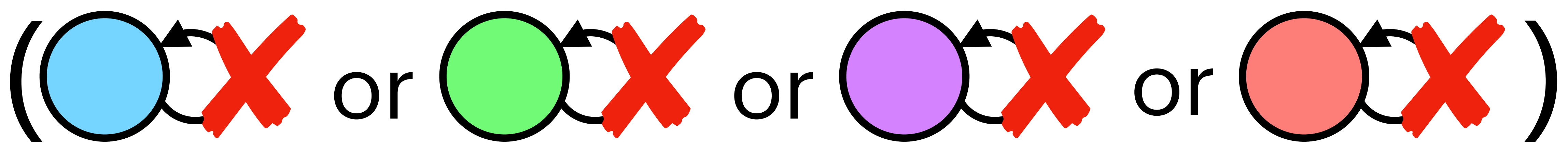
I and 

One loop terminated

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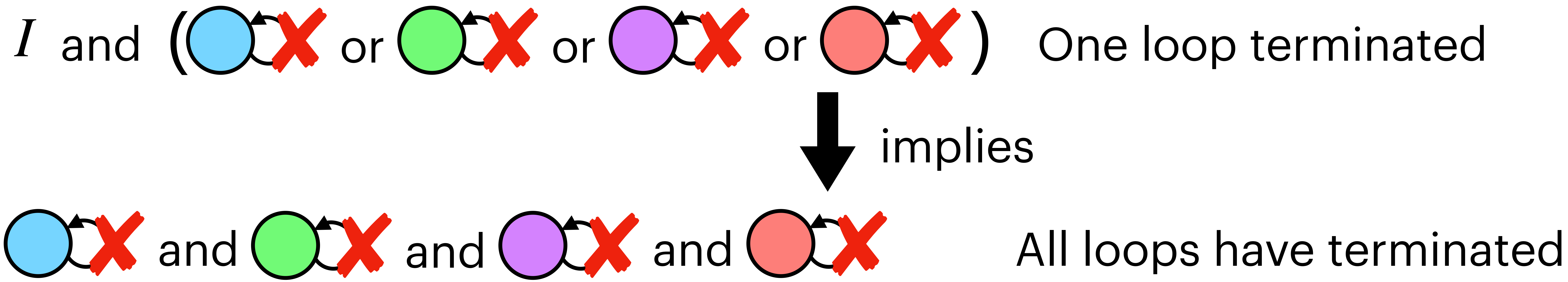

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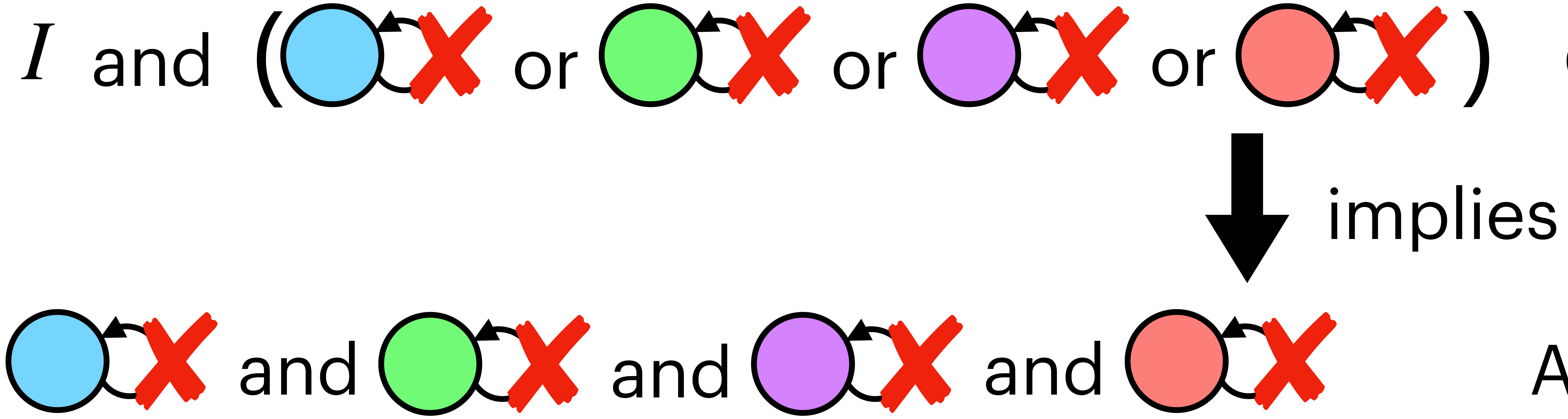

One loop terminated

All loops have terminated

Ask as SMT query, and use model to partition

[Pick et al., 2018]

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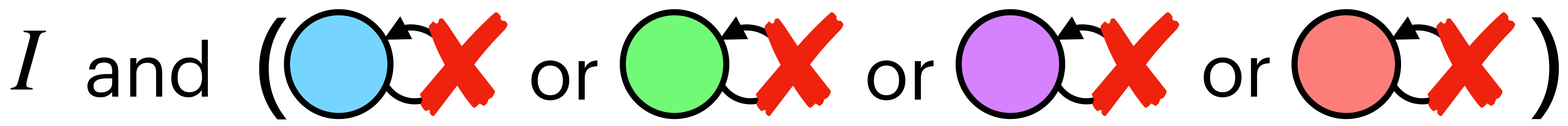

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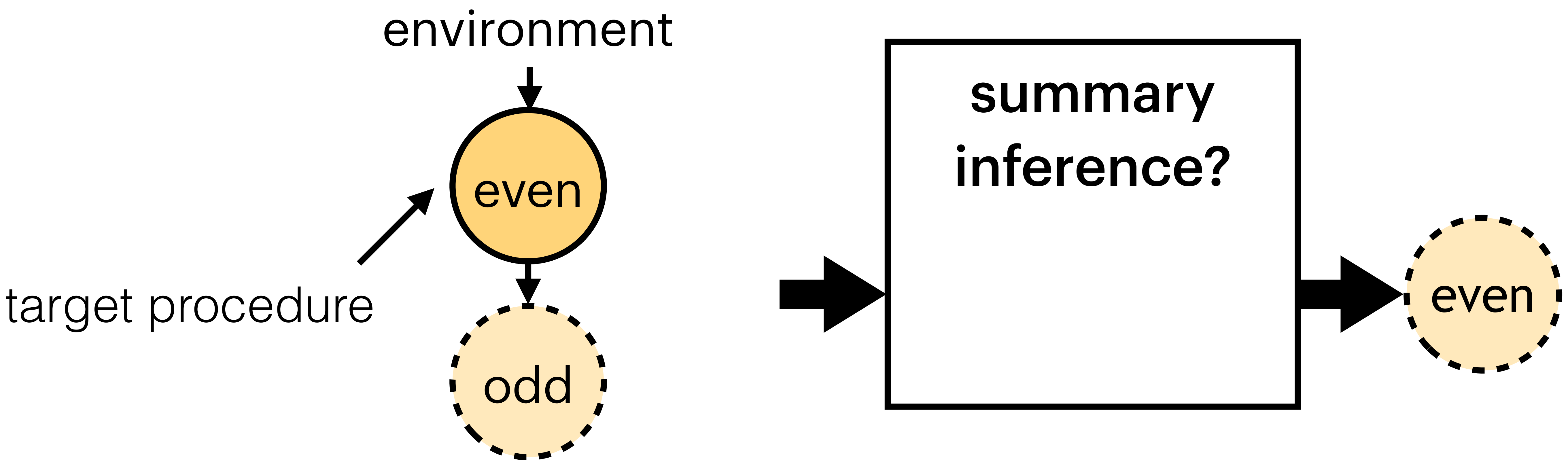

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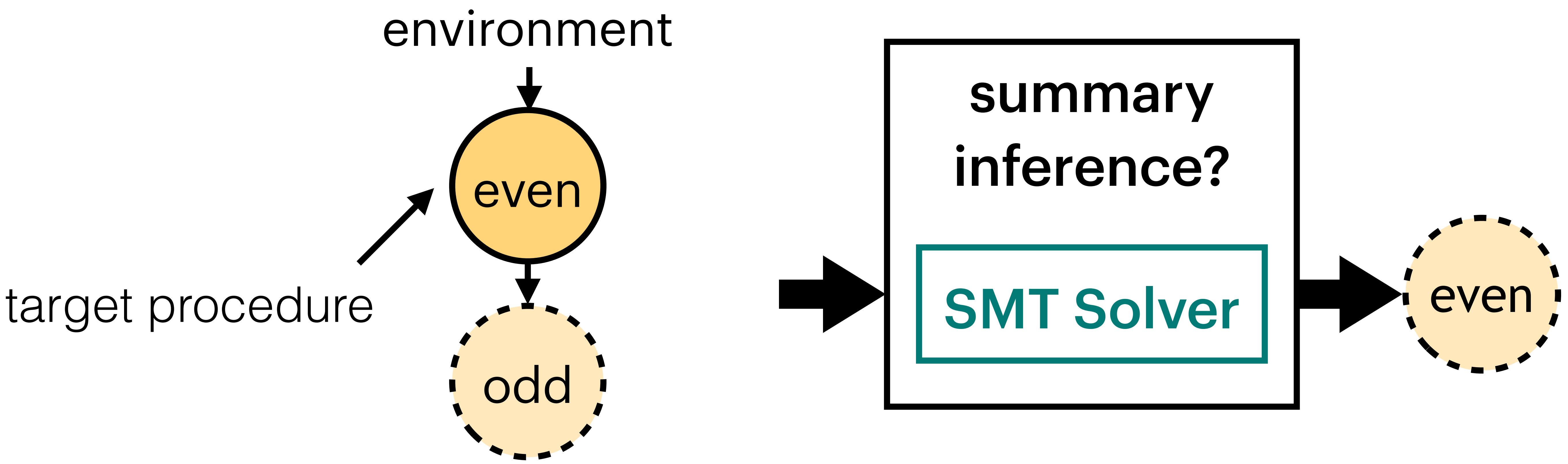

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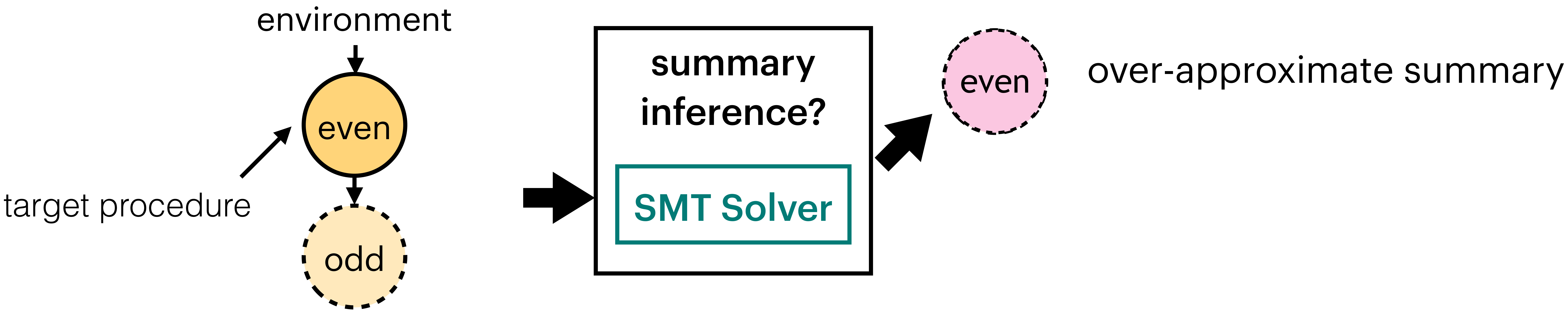

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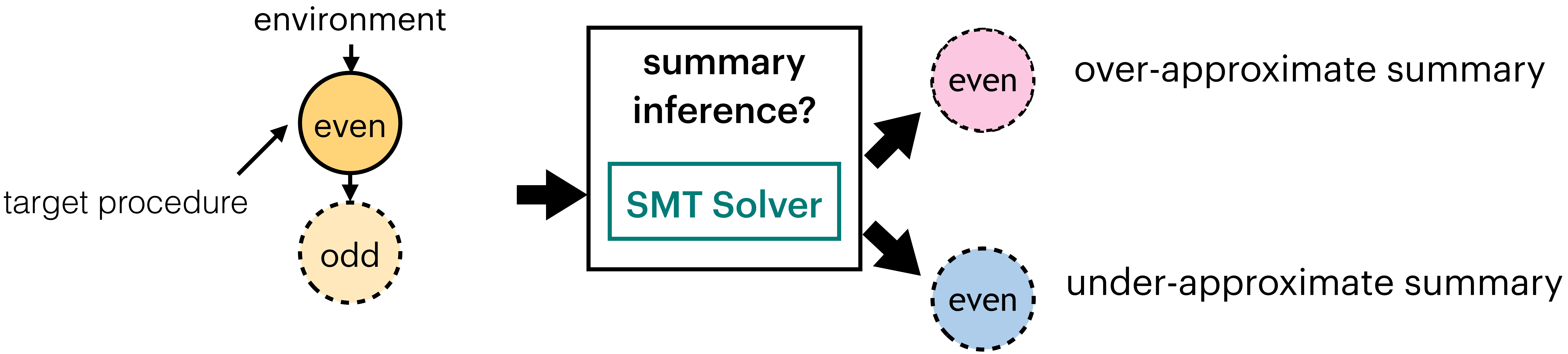
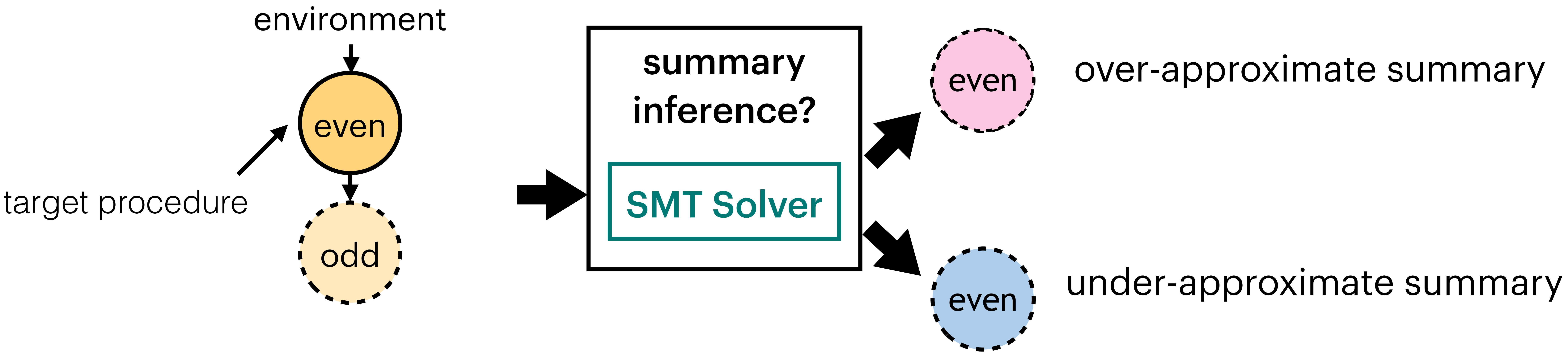


Summary Inference

example: $y \leftarrow 2x + 2$



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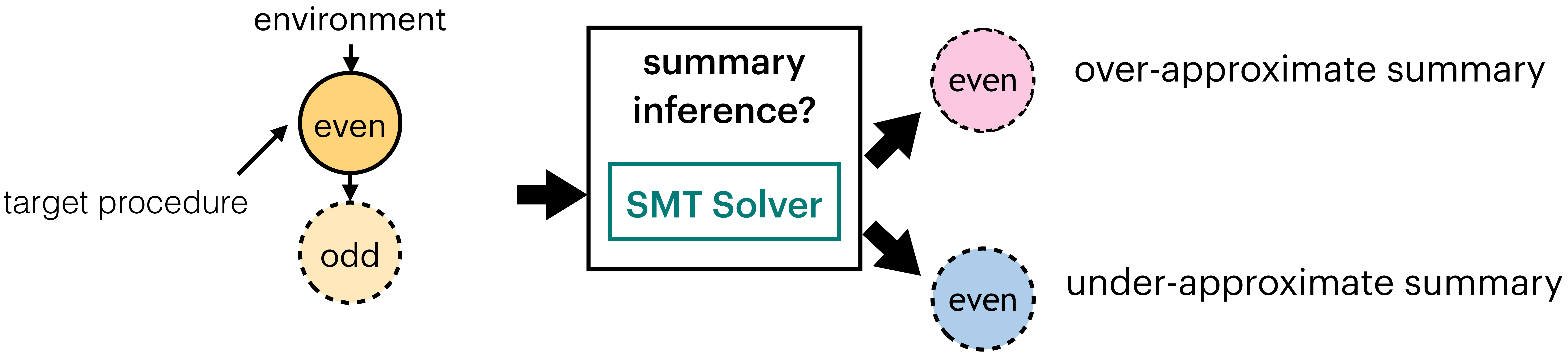

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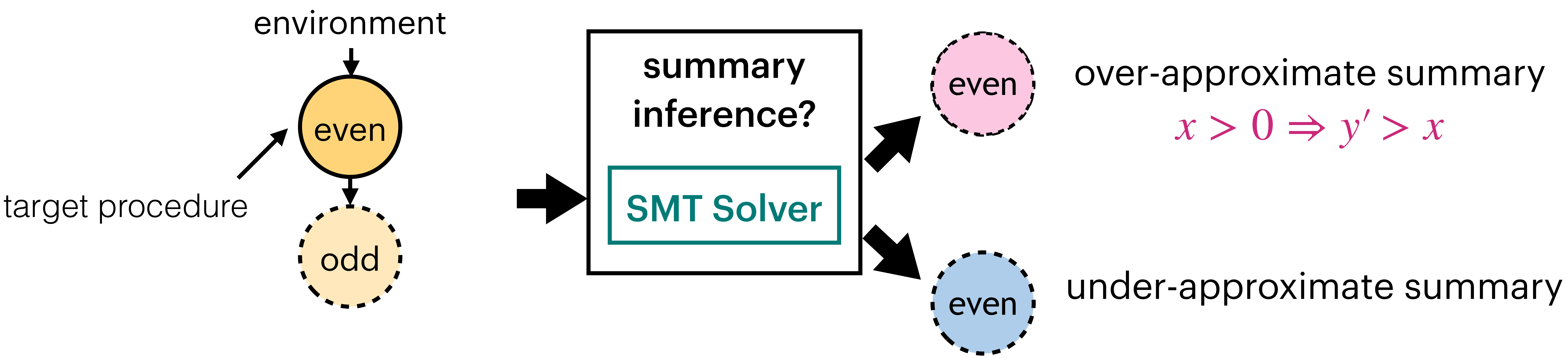

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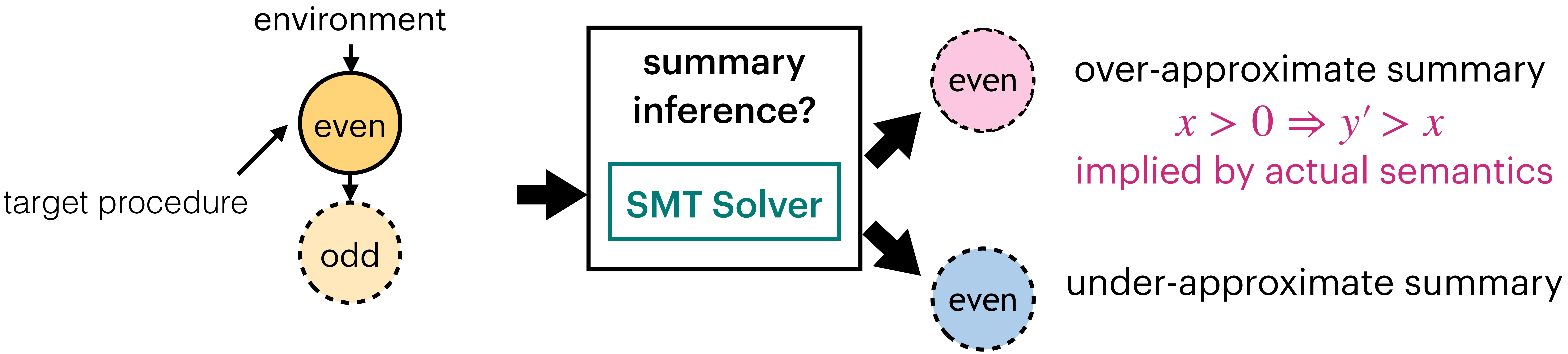

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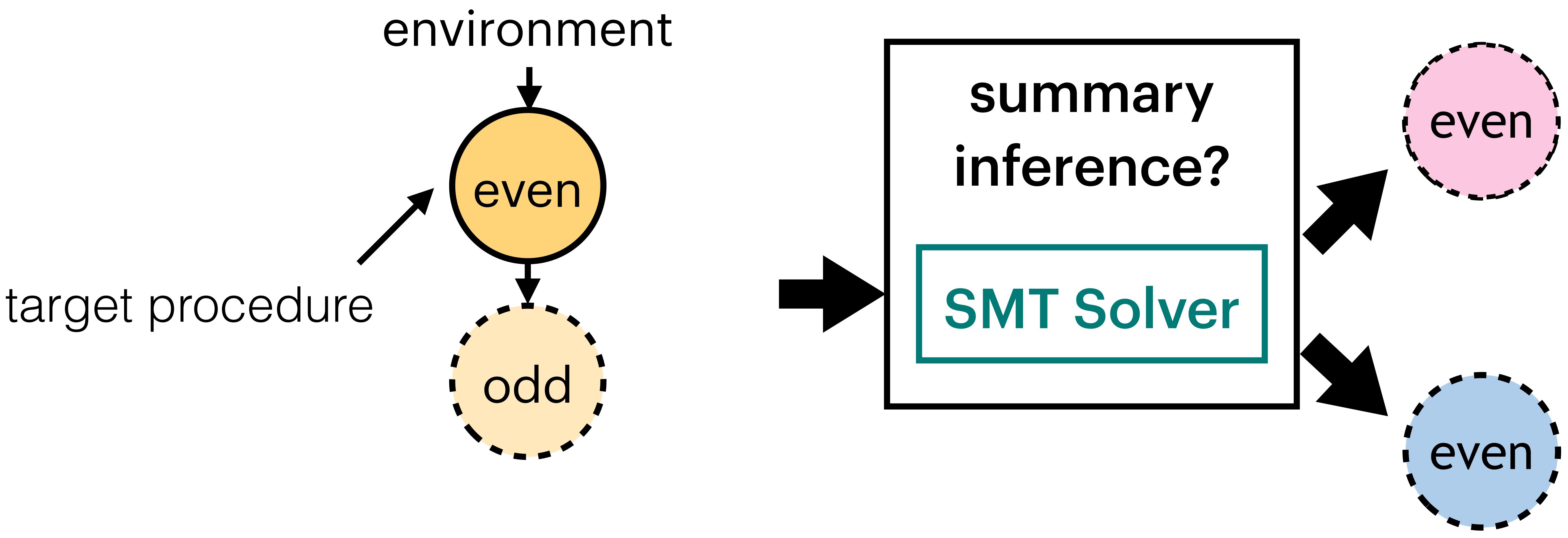


over-approximate summary

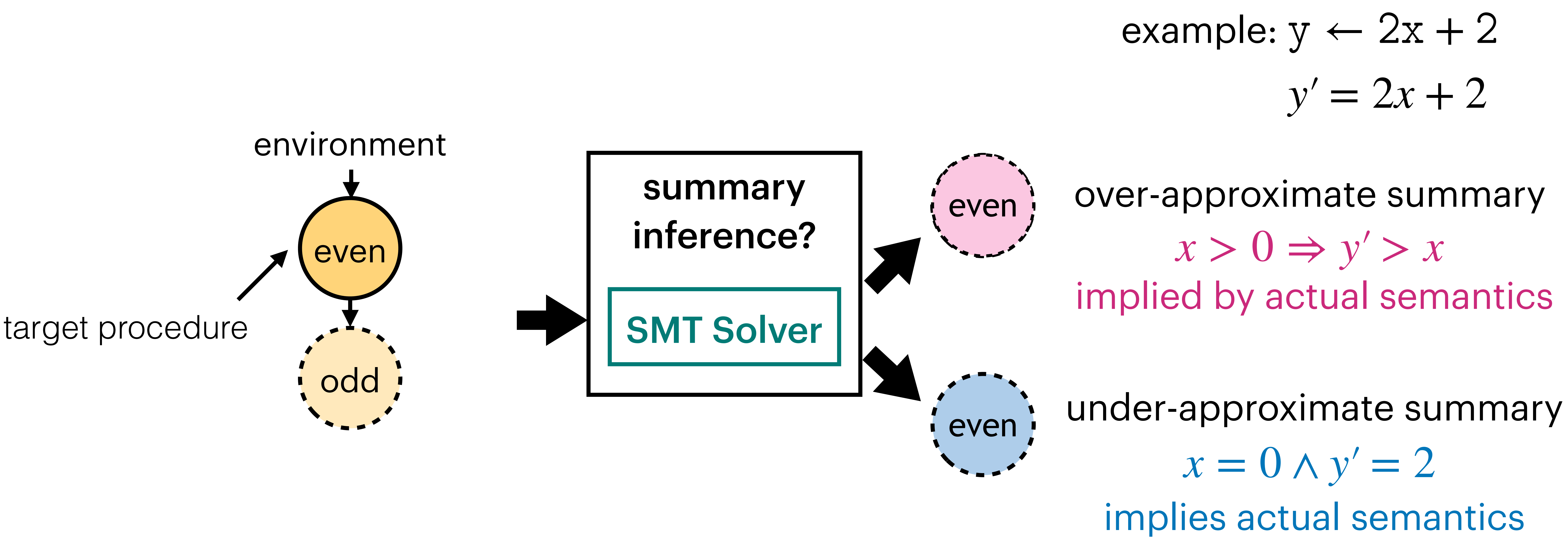
$x > 0 \Rightarrow y' > x$

implied by actual semantics

under-approximate summary

$x = 0 \wedge y' = 2$

Summary Inference



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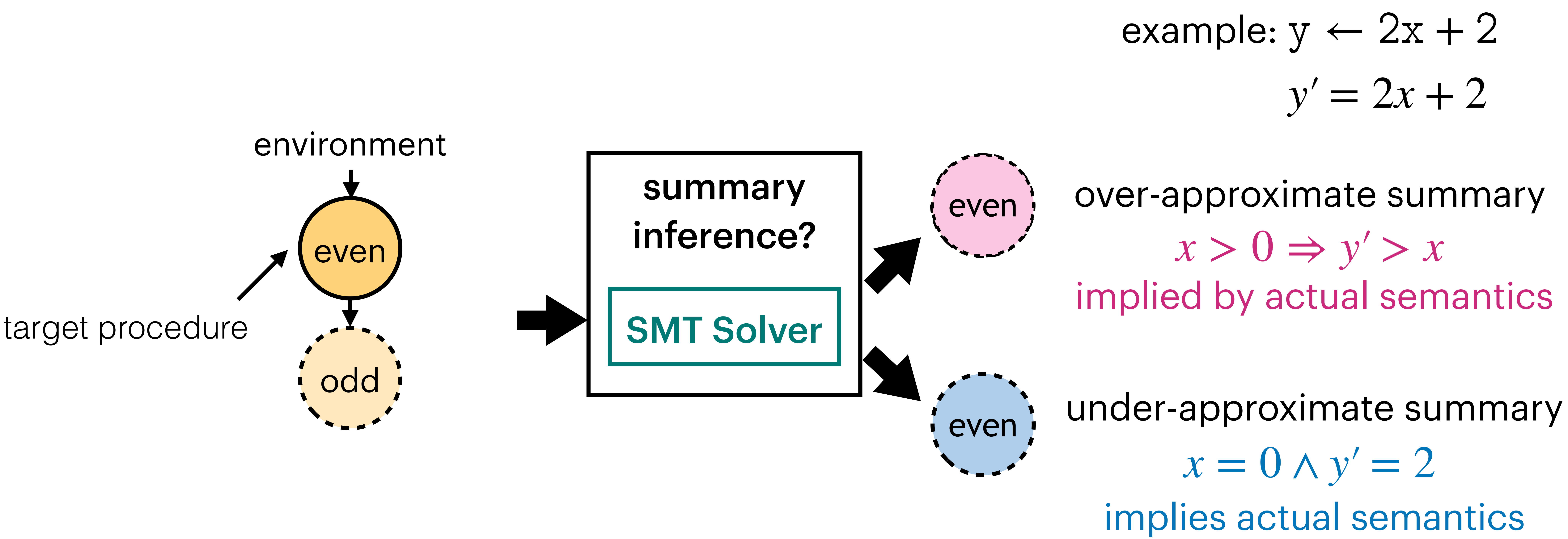
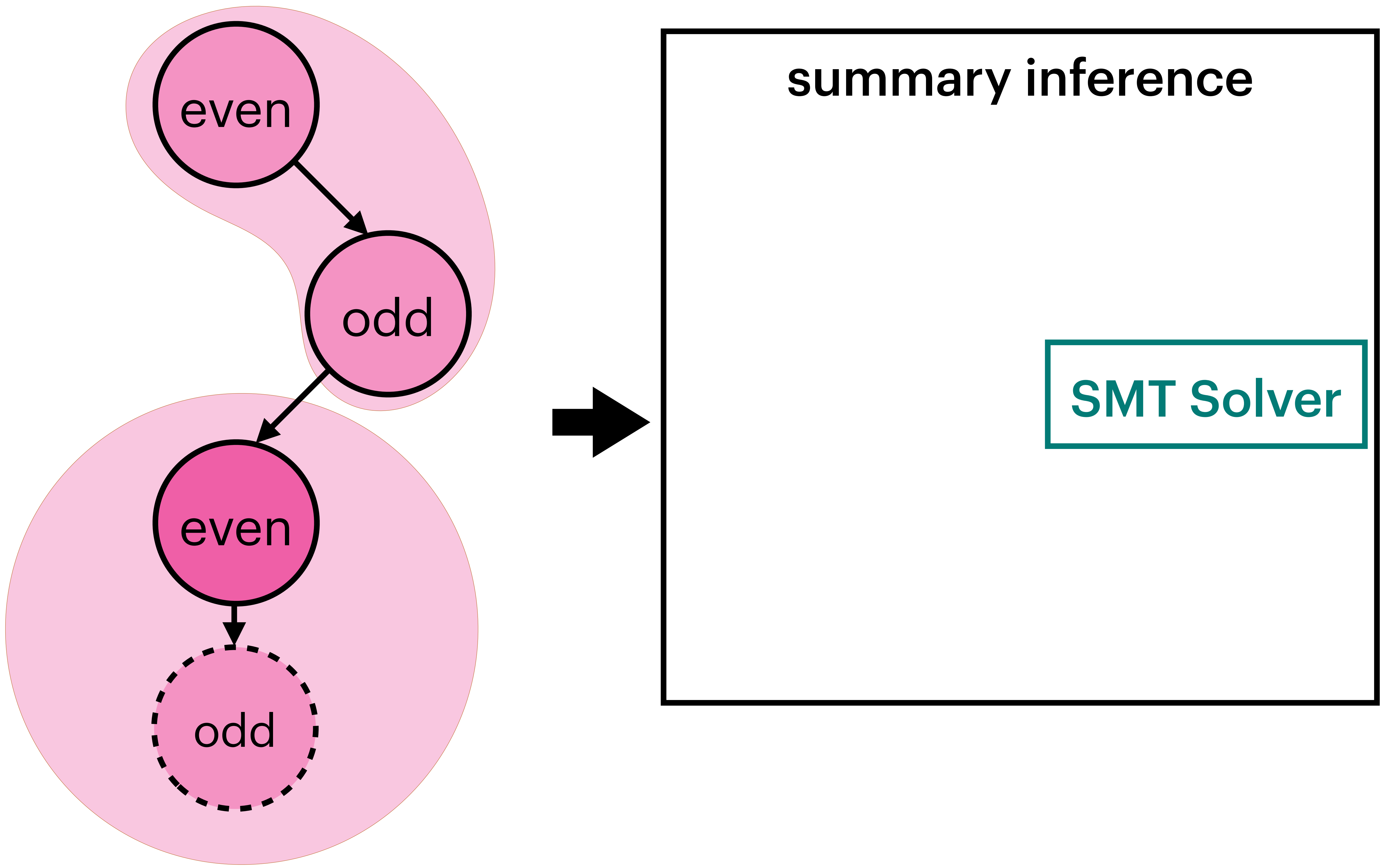
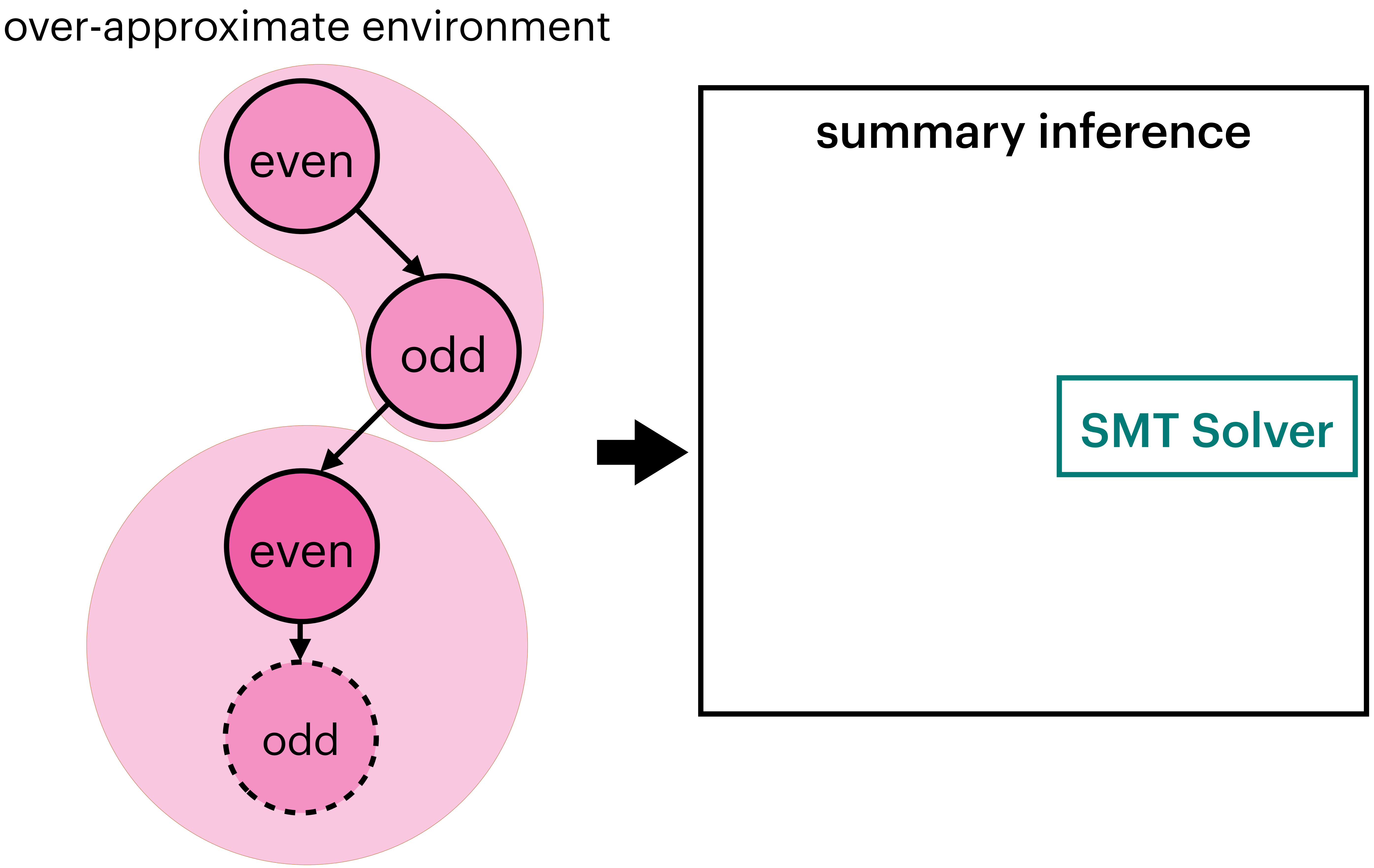


Will make four SMT queries, over- and under-approximating both environment and target procedure

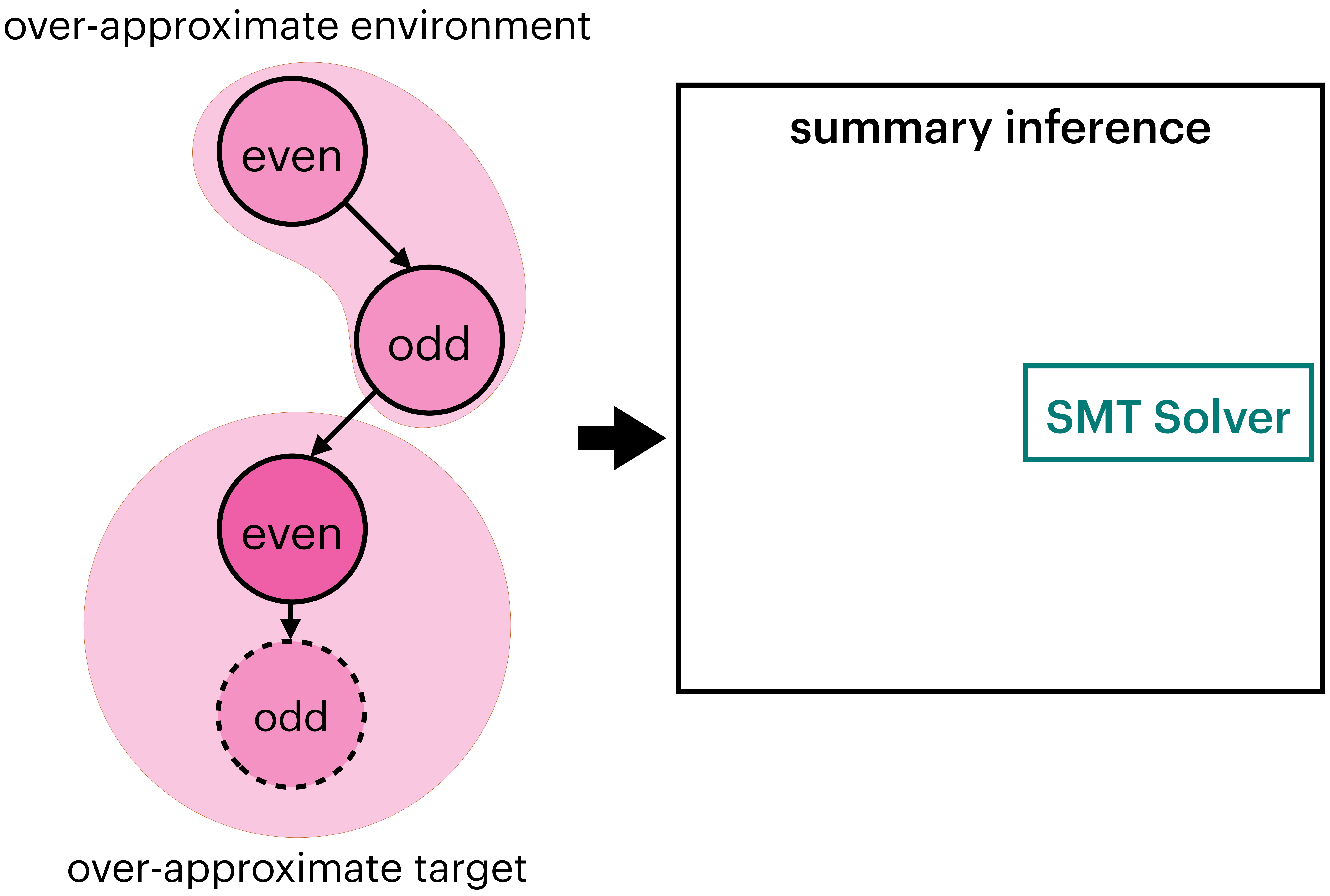
Over-Approximate Summary Inference



Over-Approximate Summary Inference



Over-Approximate Summary Inference



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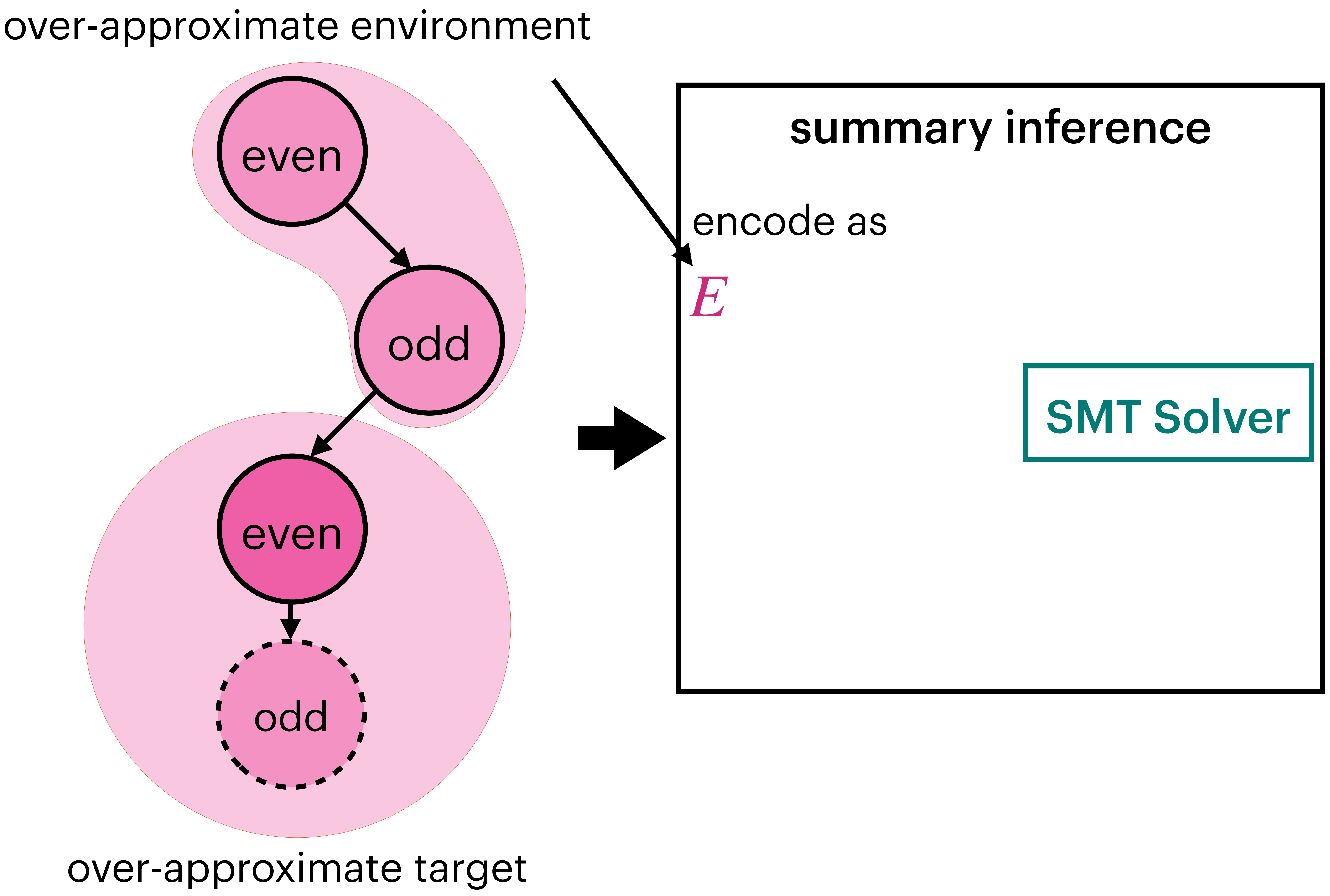

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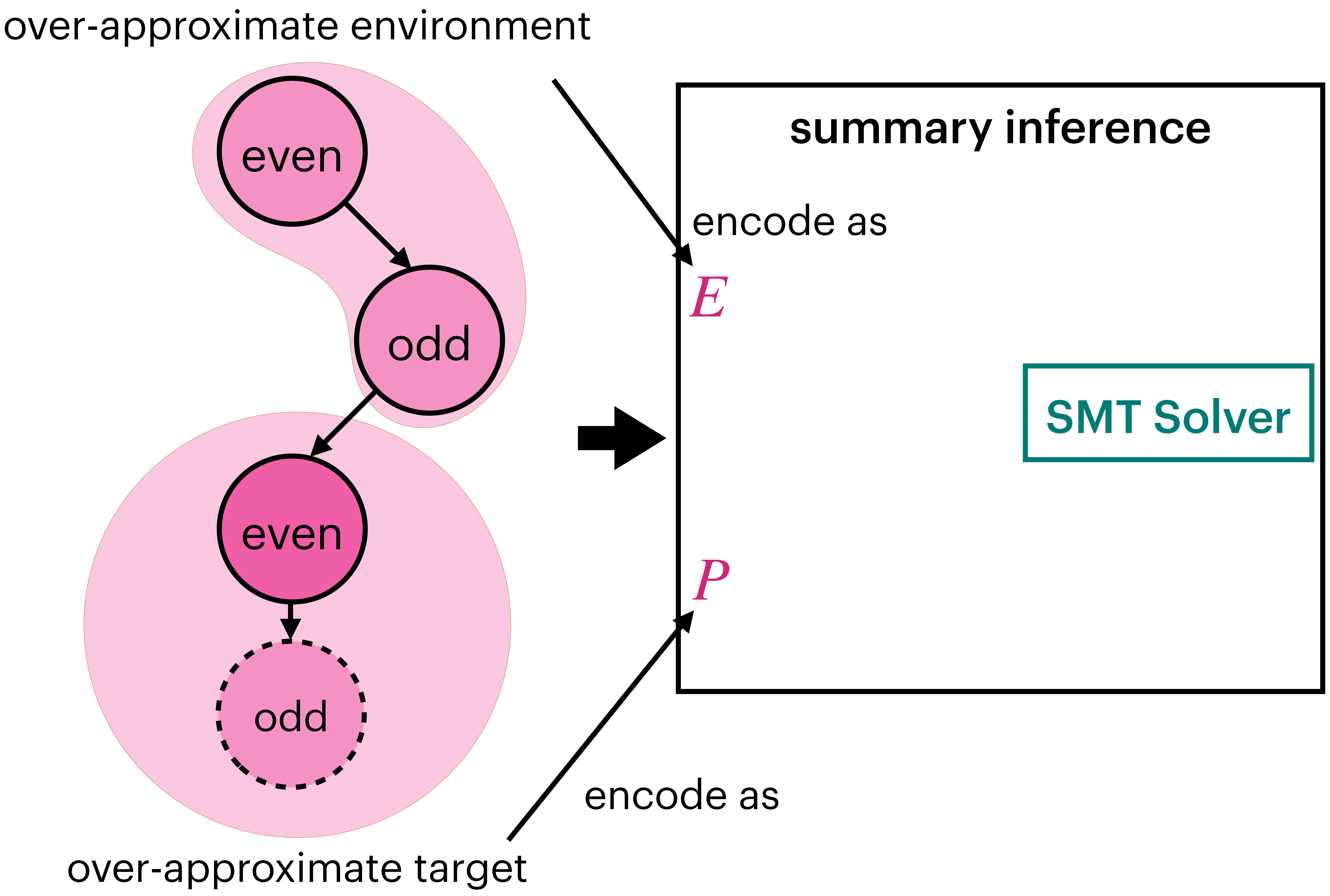

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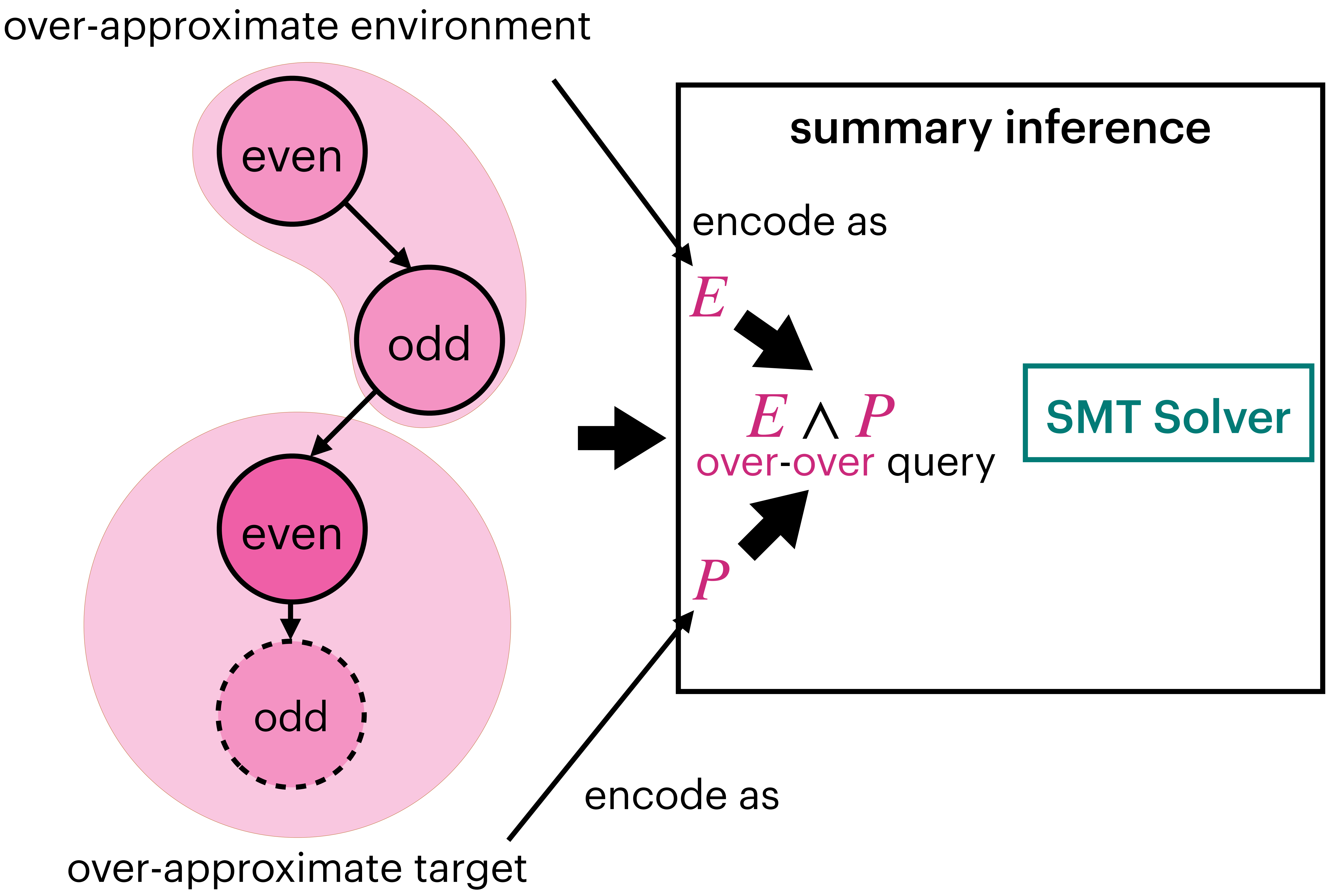

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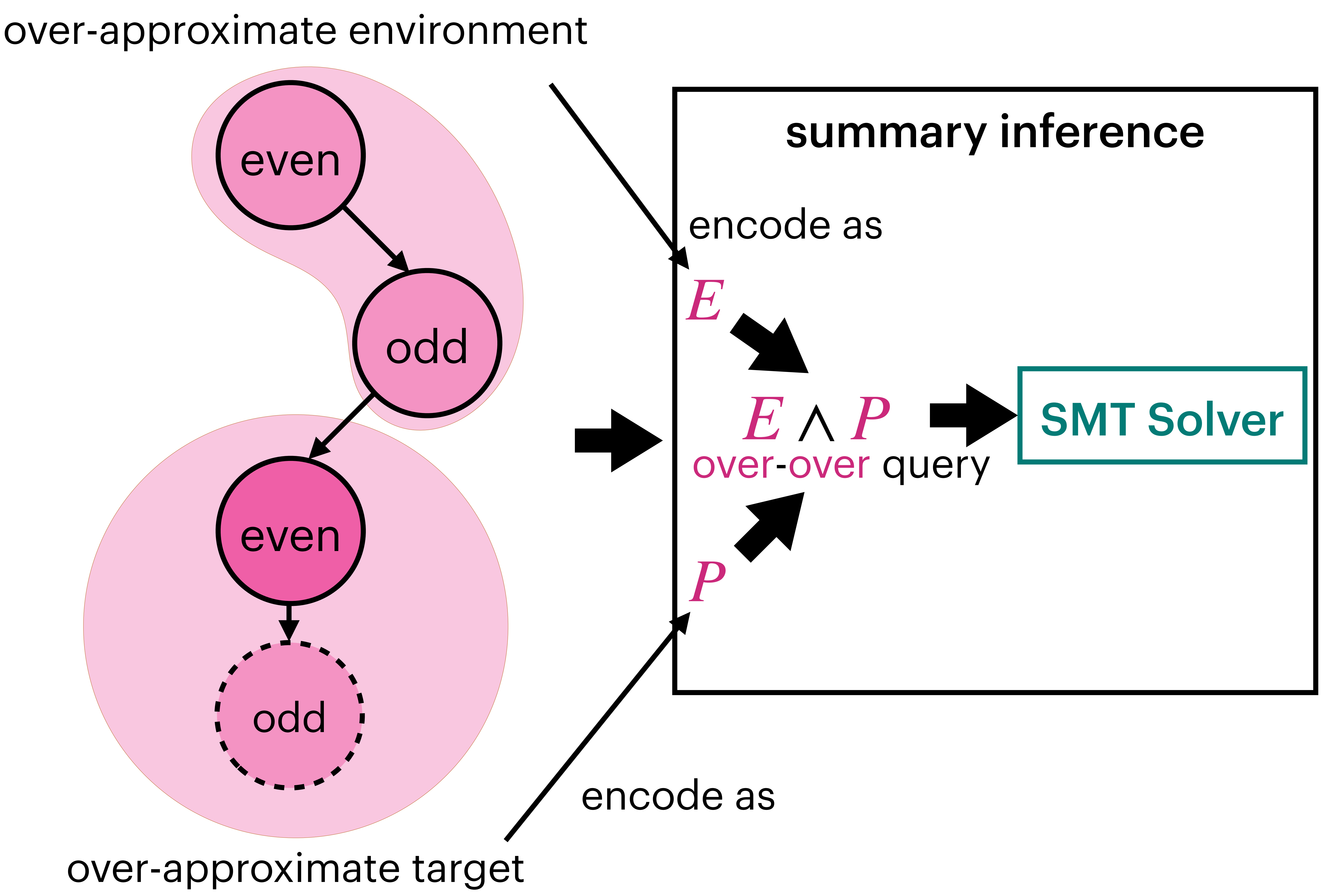

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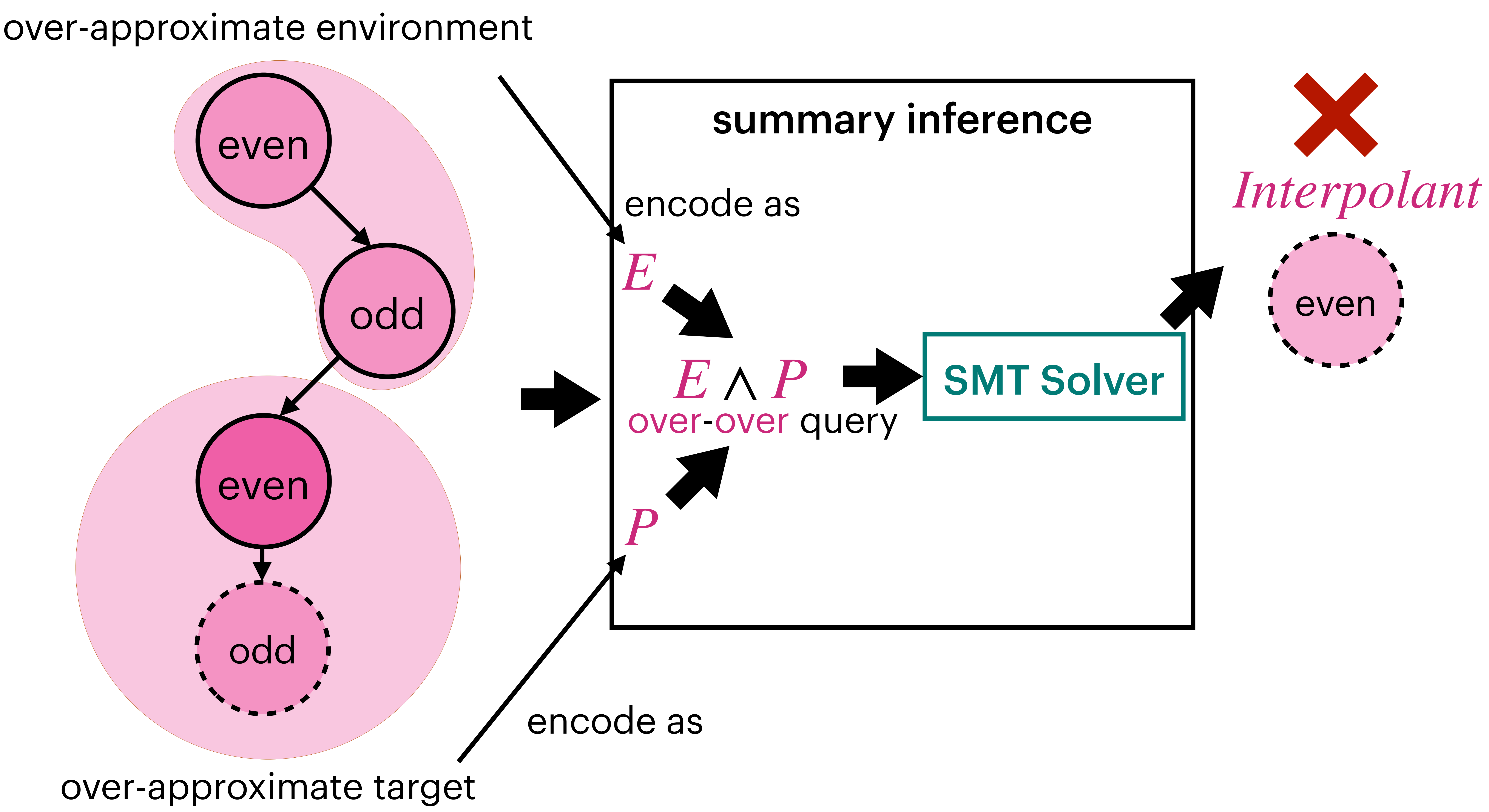

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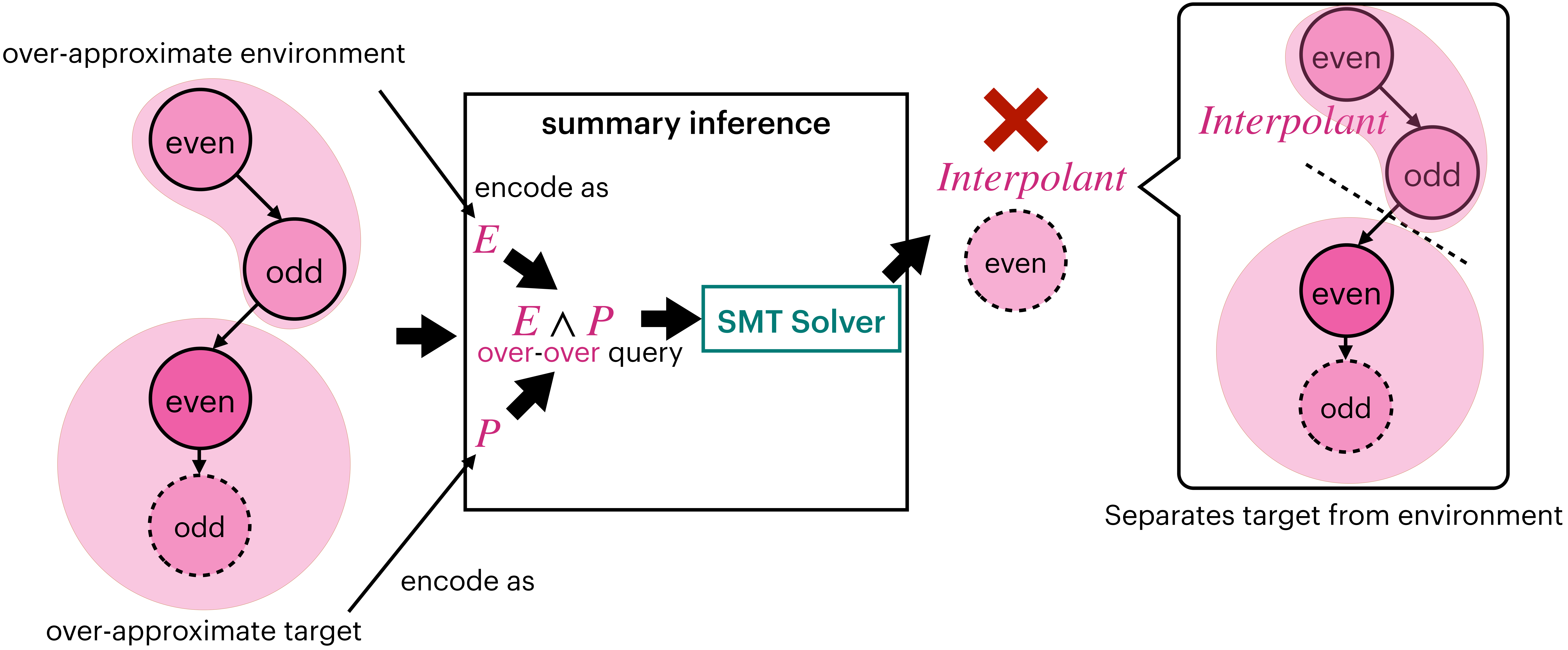

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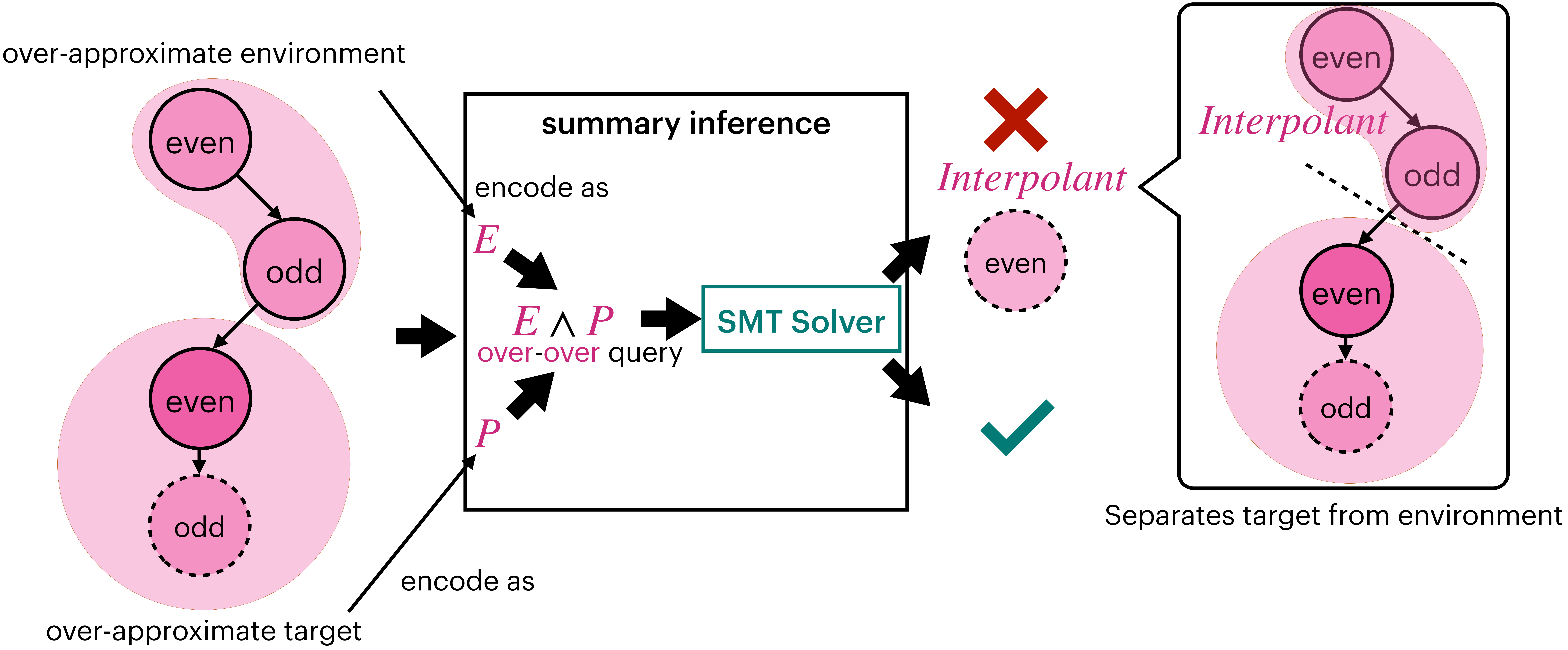

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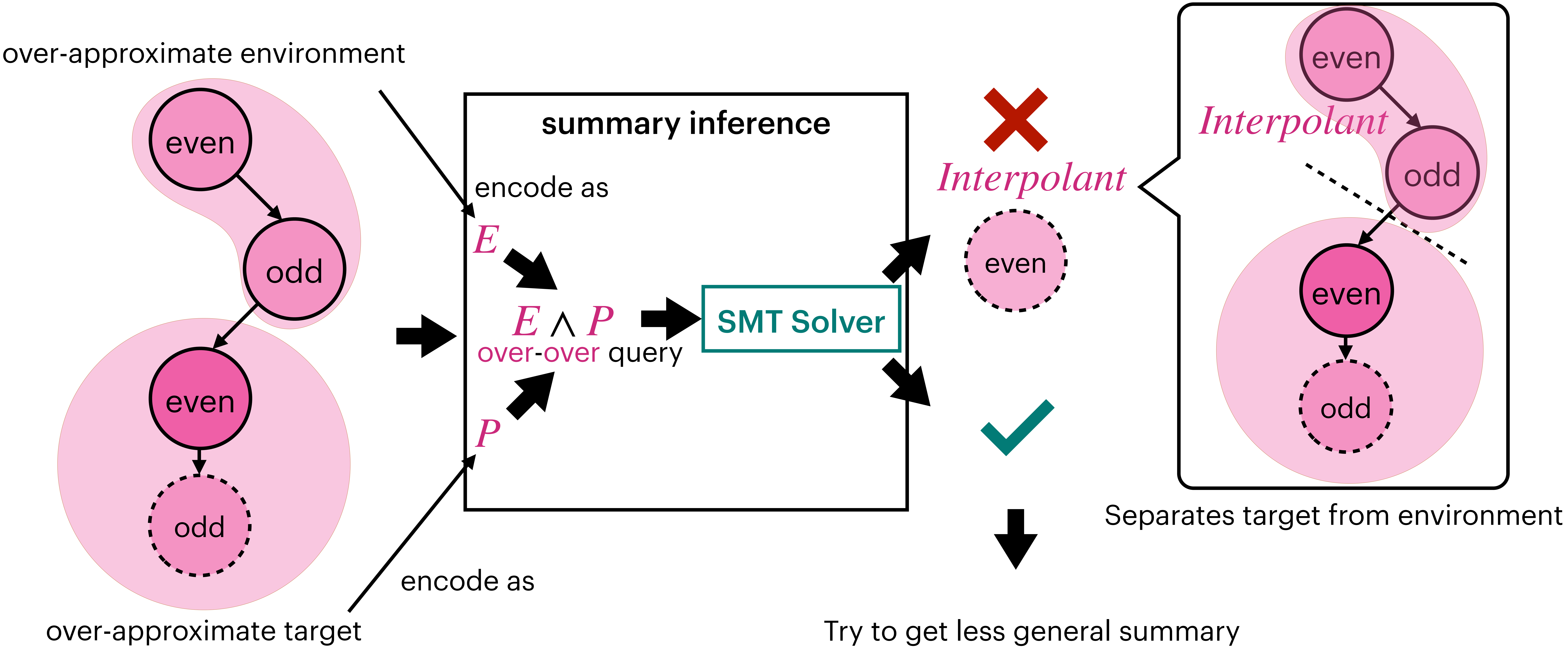

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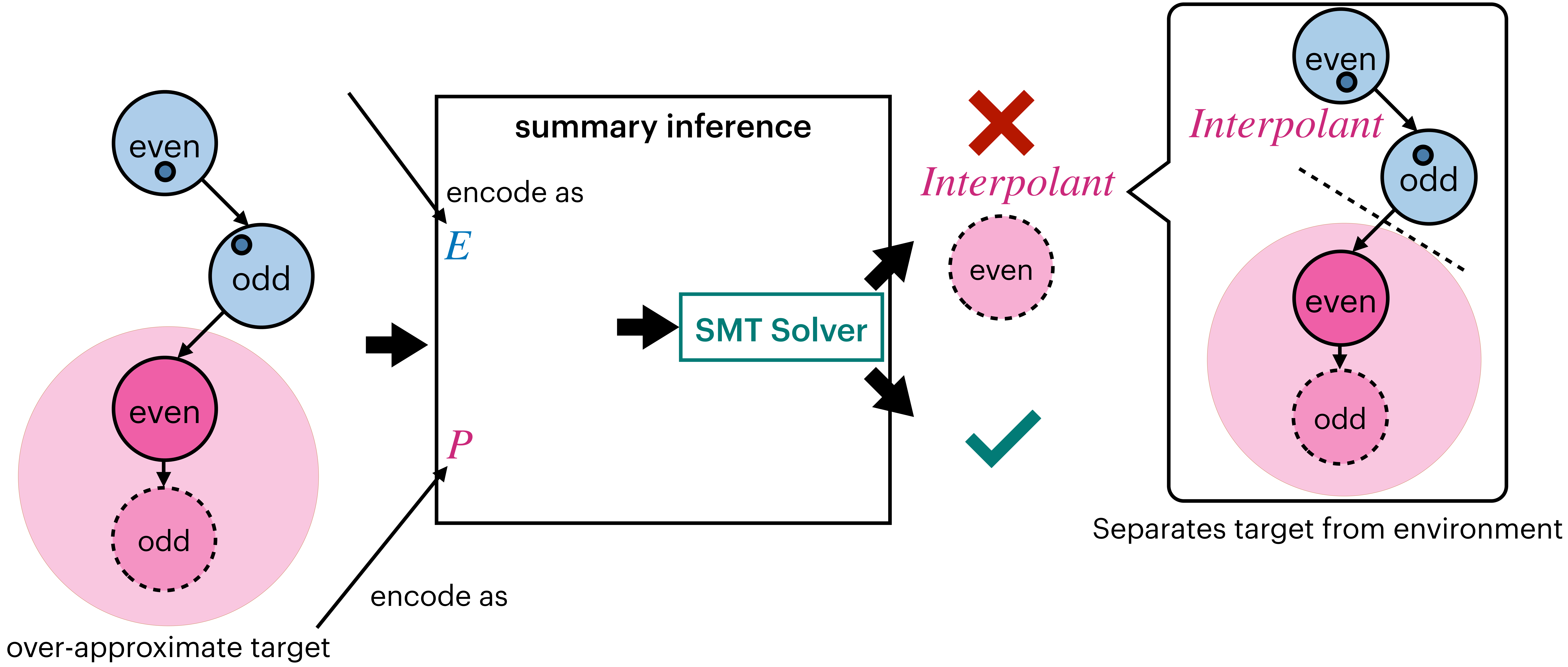

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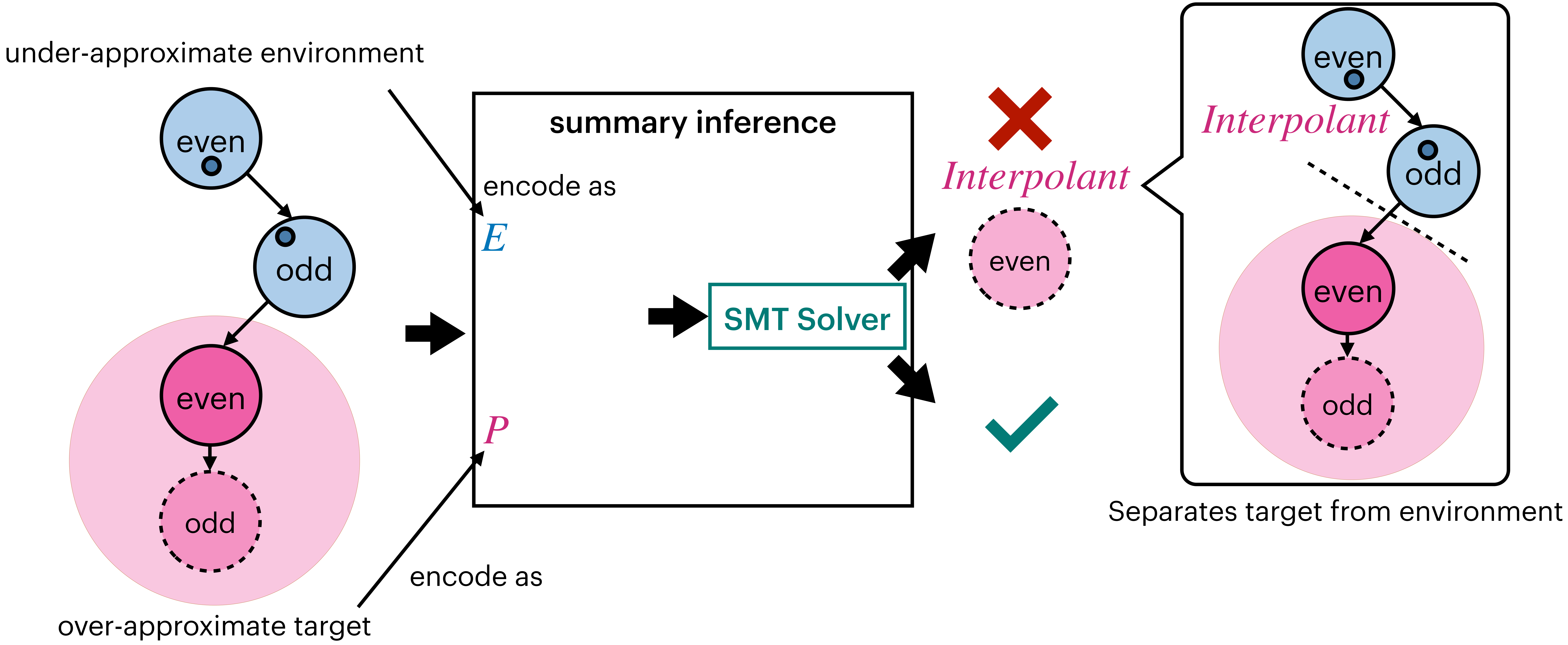

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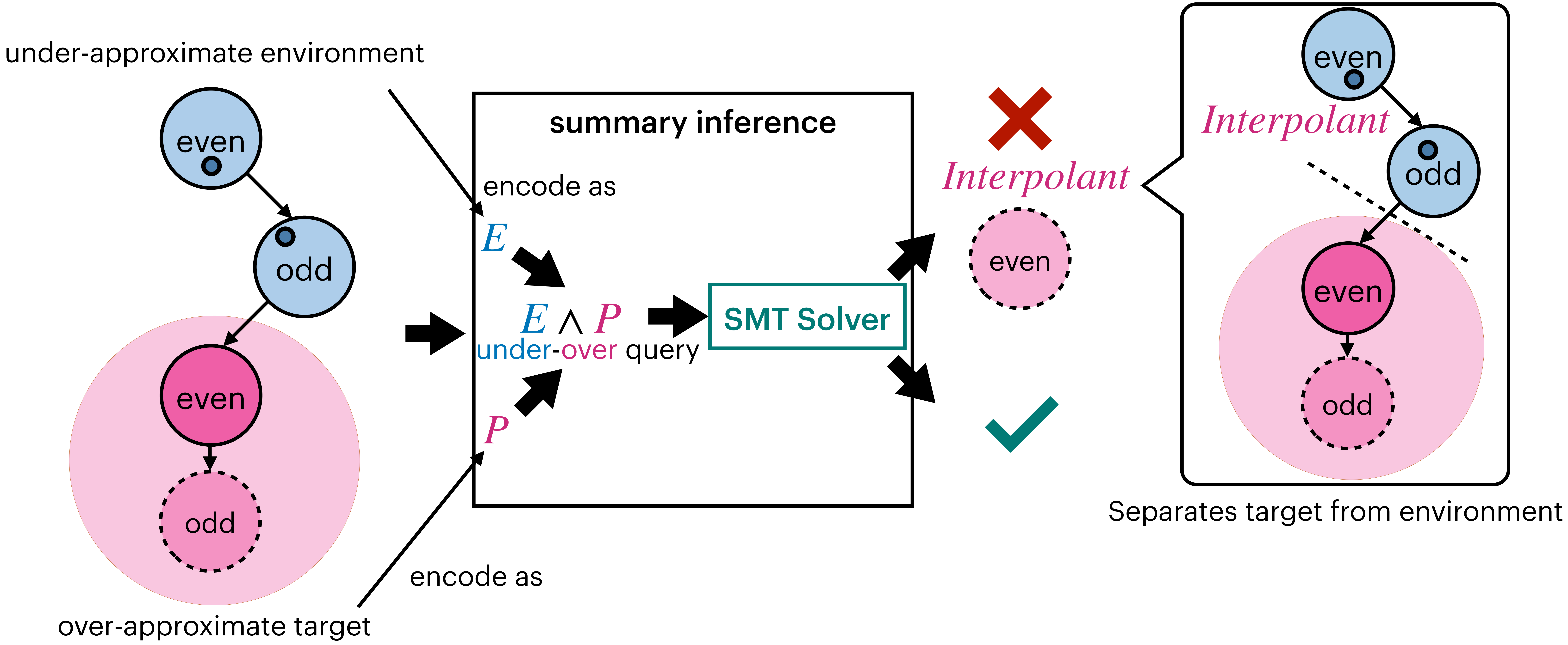
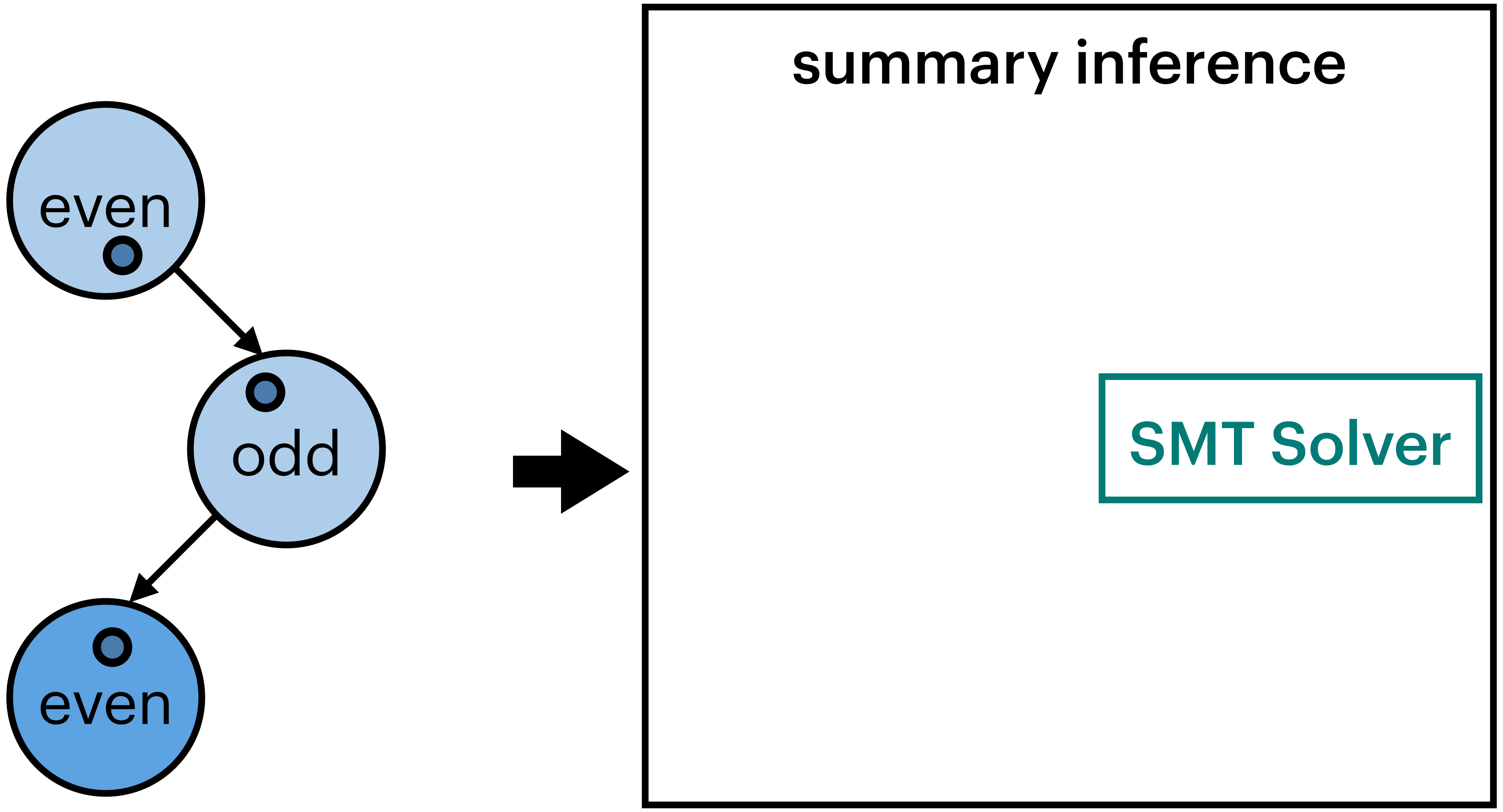
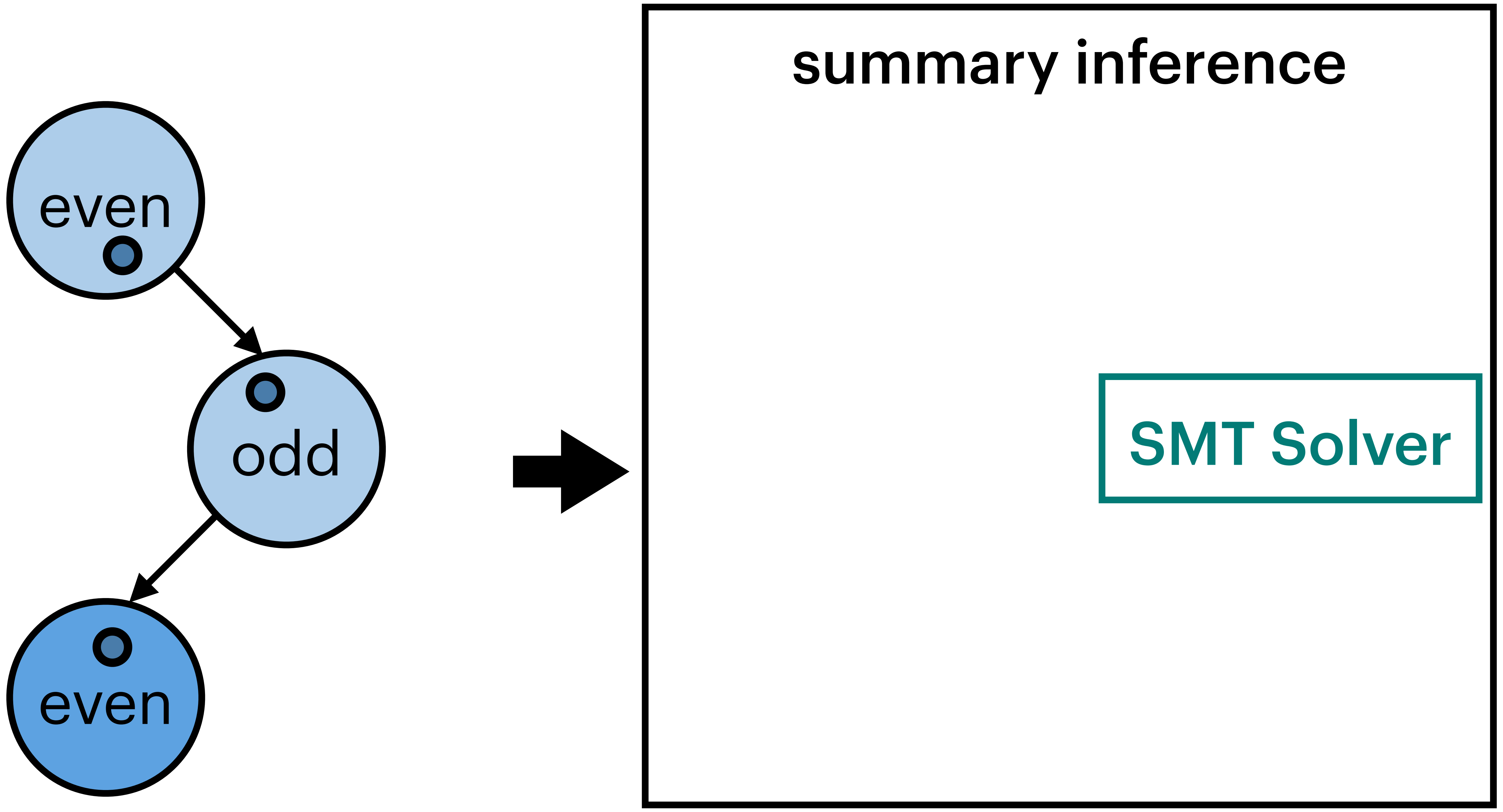


Under-Approximate Summary Inference



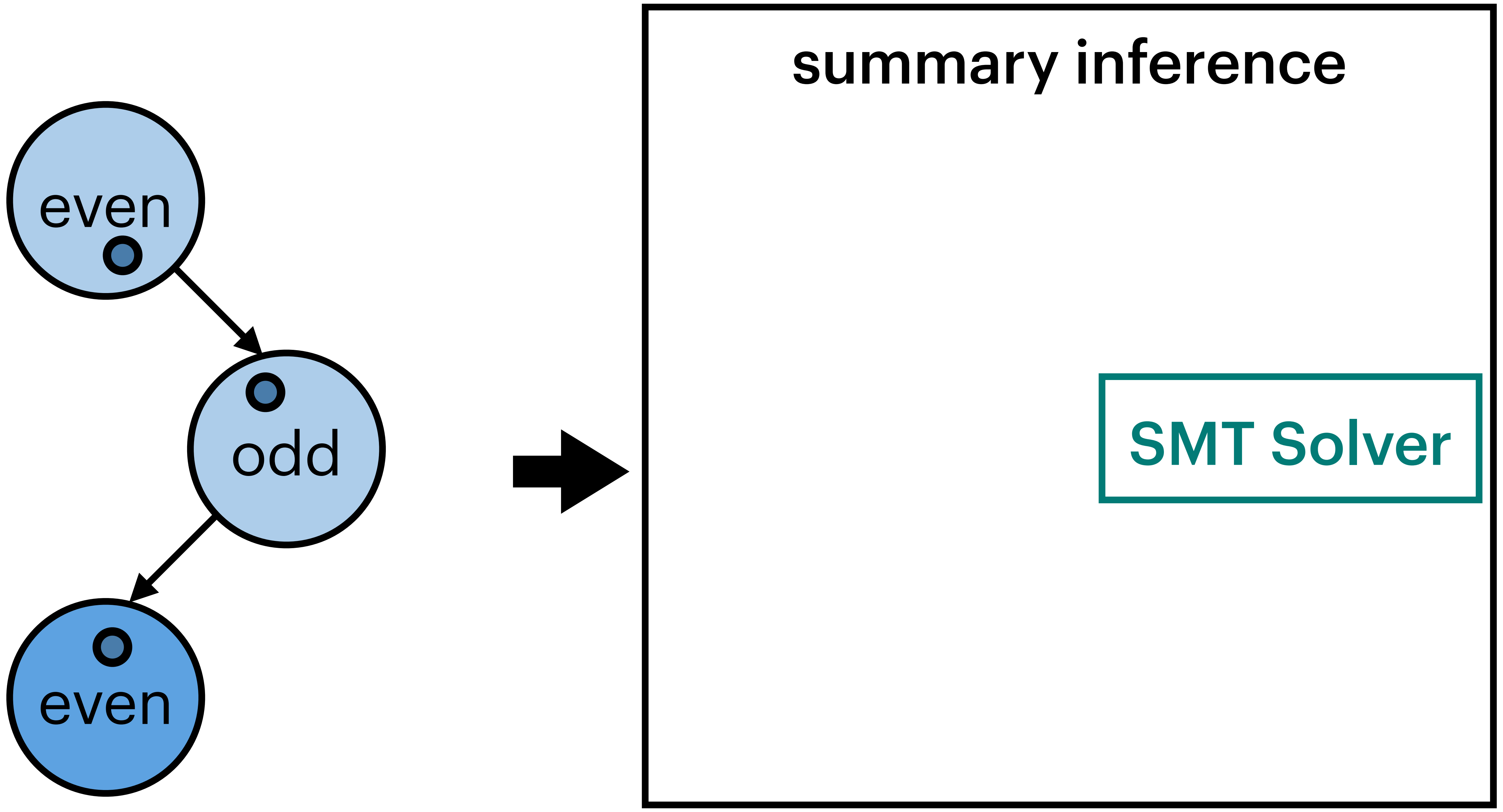
Under-Approximate Summary Inference

under-approximate environment



Under-Approximate Summary Inference

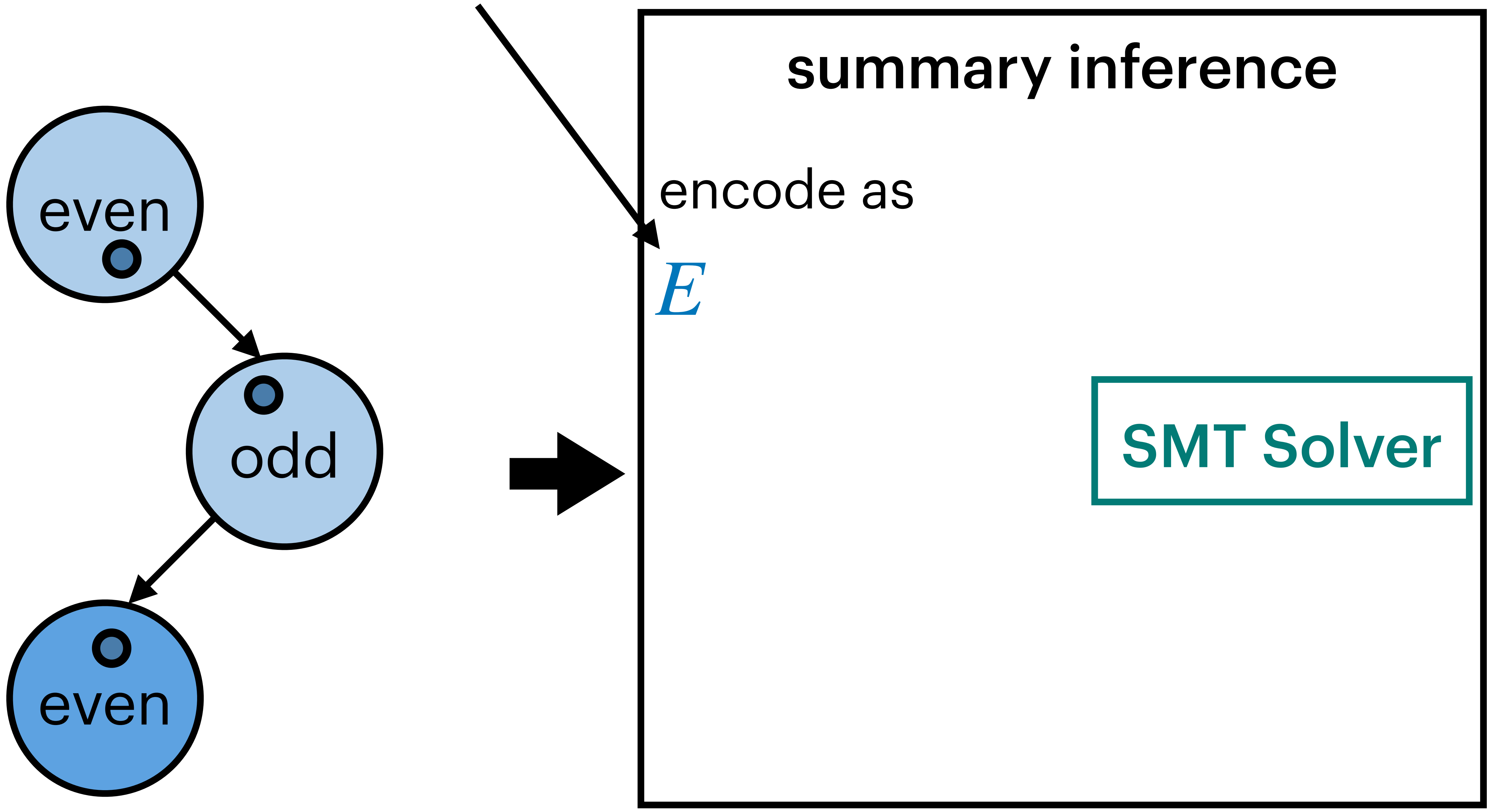
under-approximate environment



under-approximate target

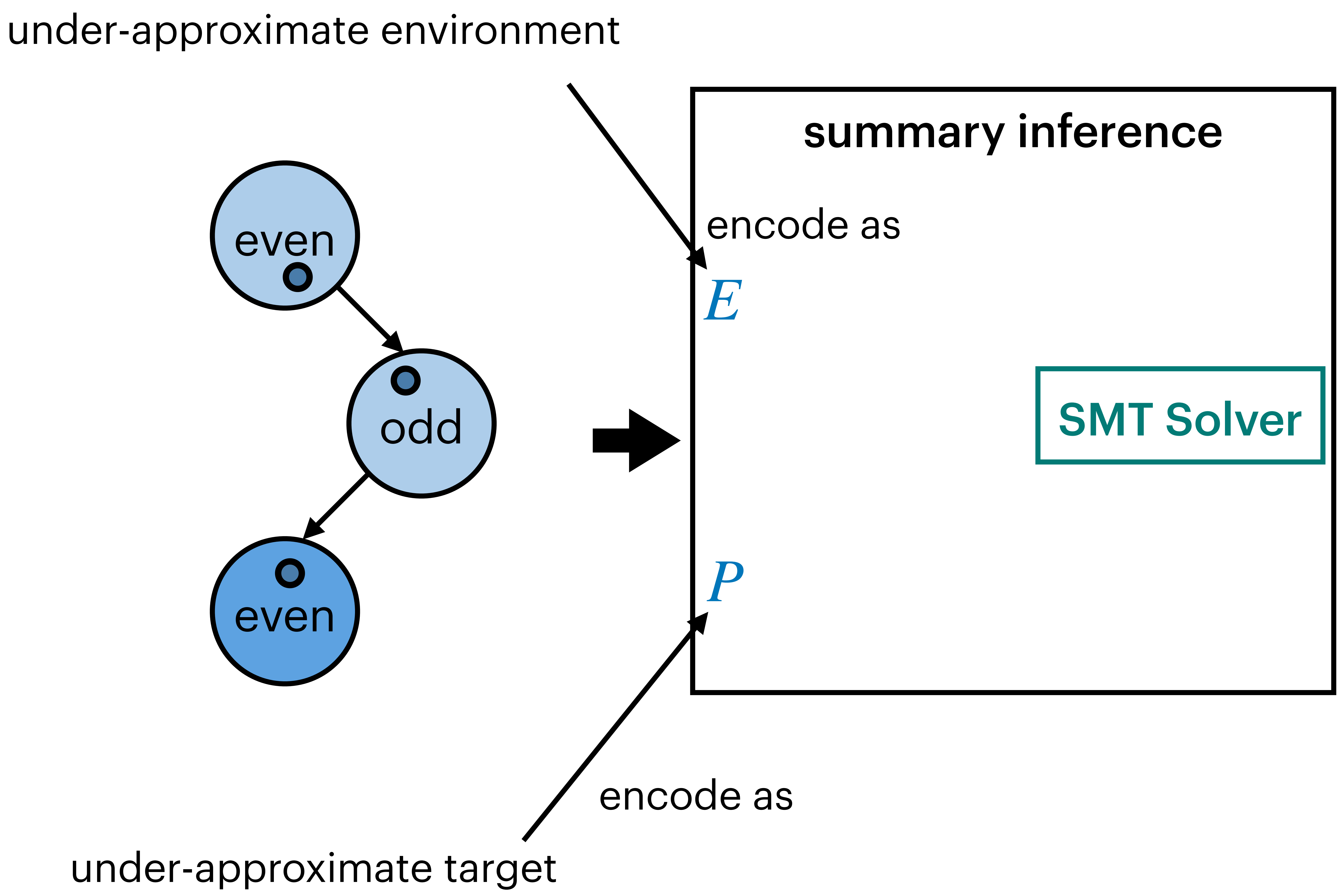
Under-Approximate Summary Inference

under-approximate environment



under-approximate target

Under-Approximate Summary Inference



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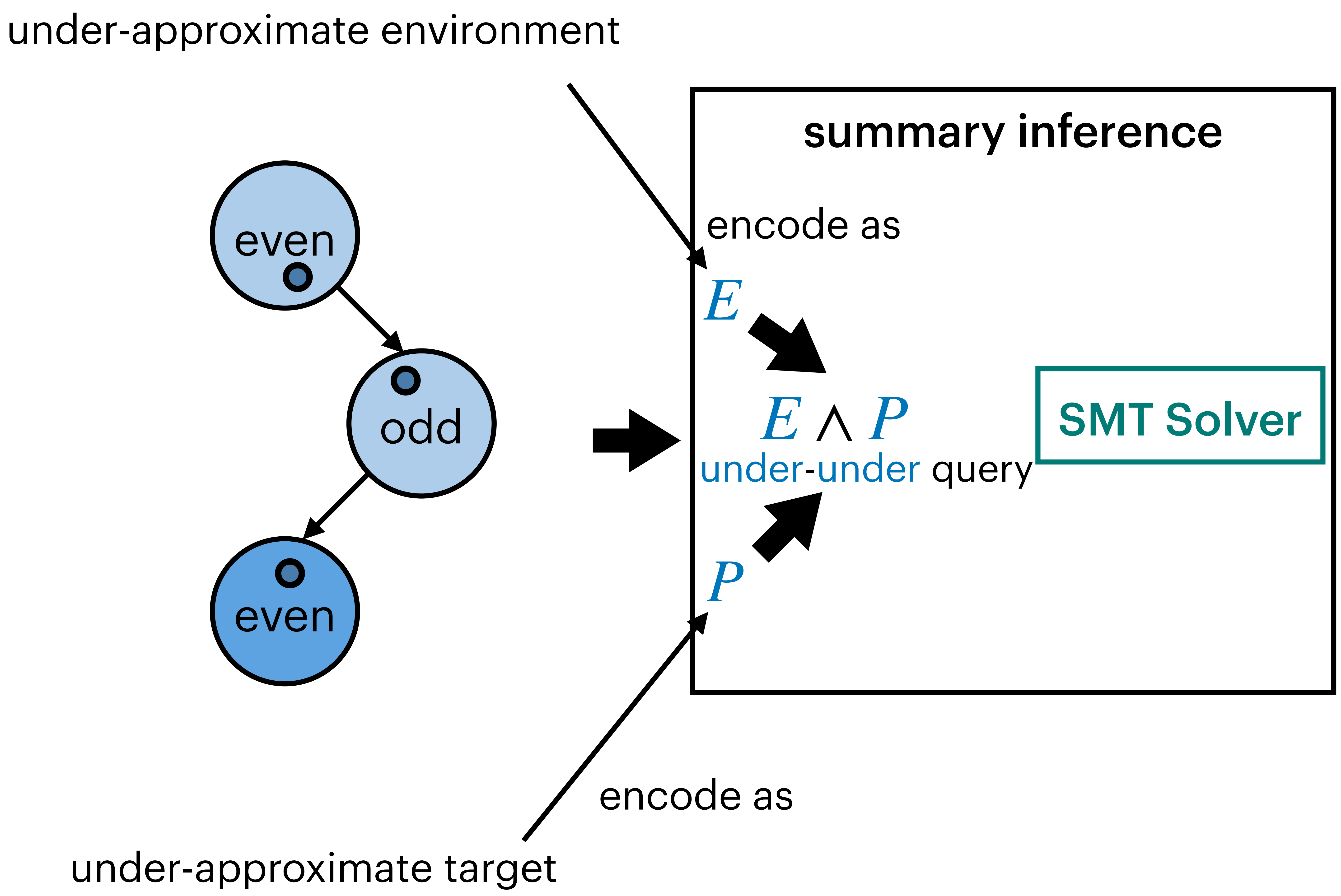

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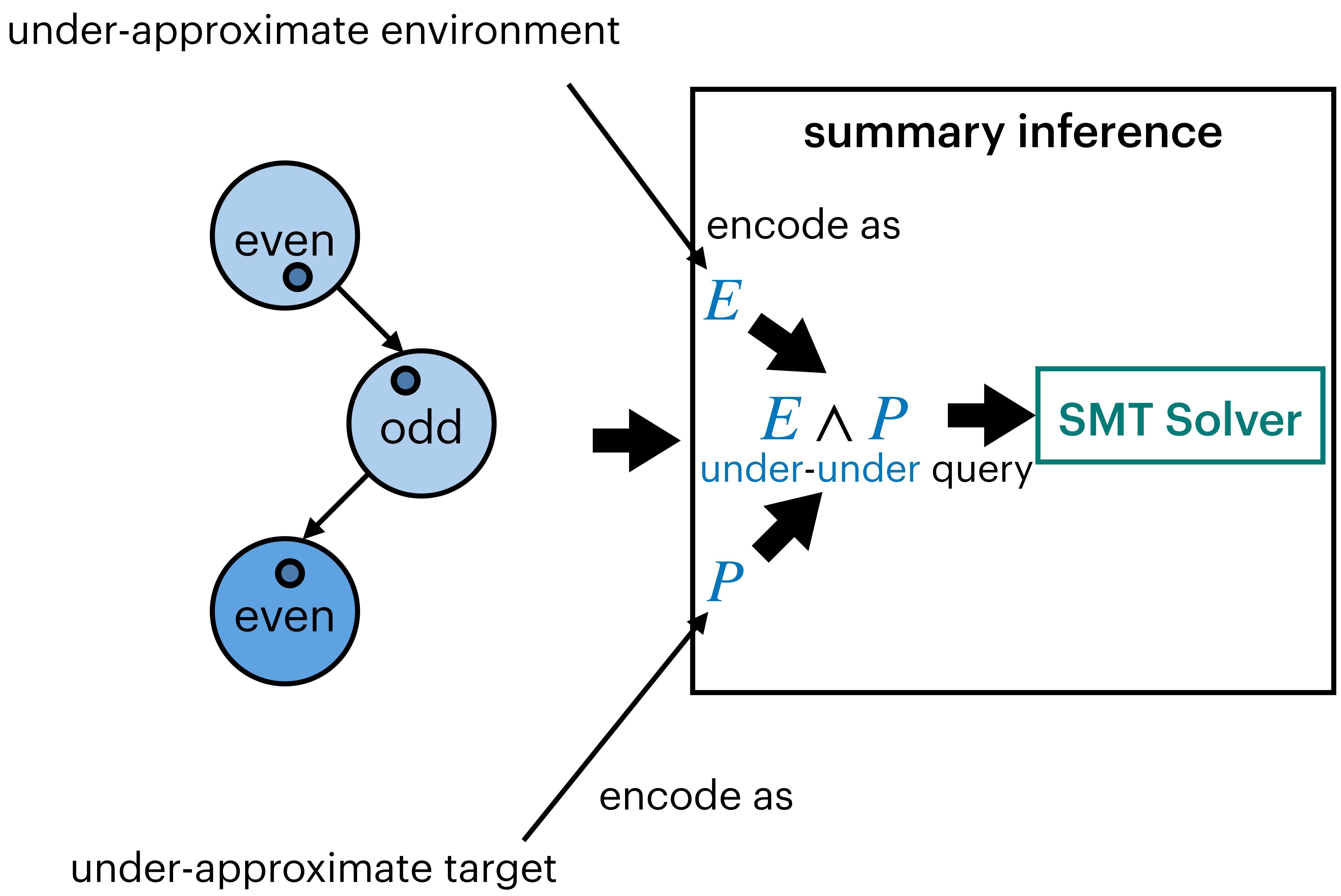

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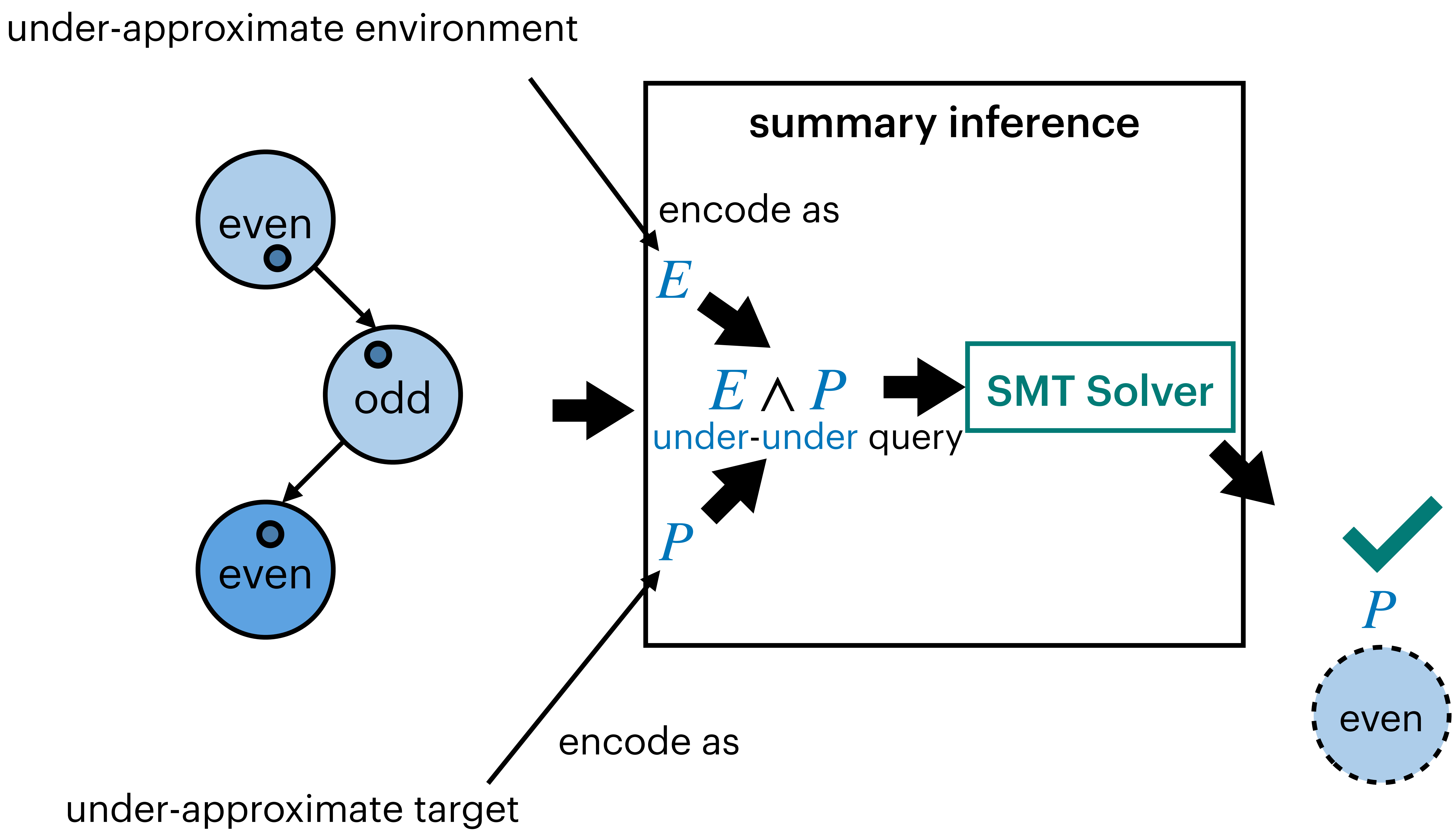
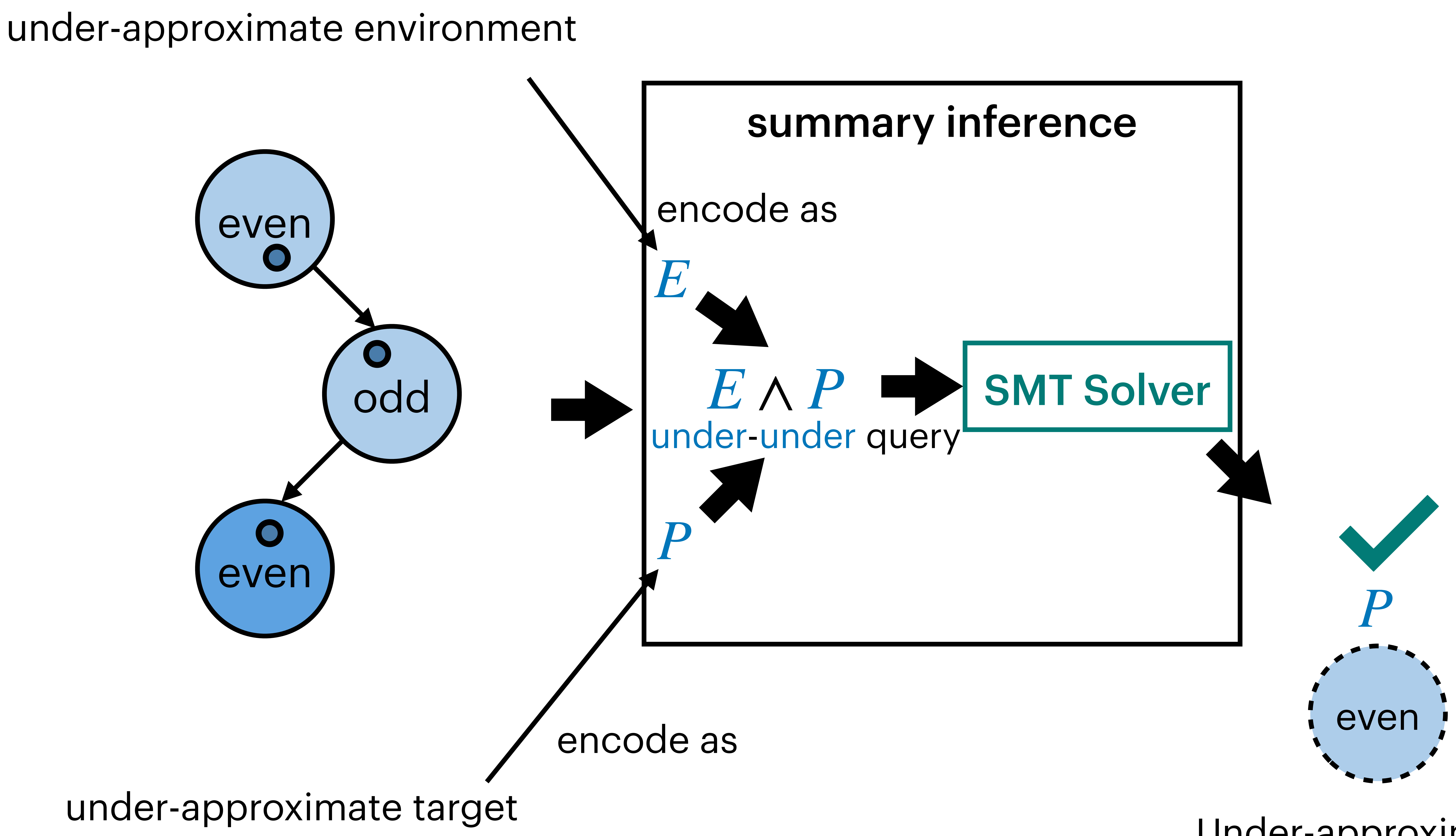
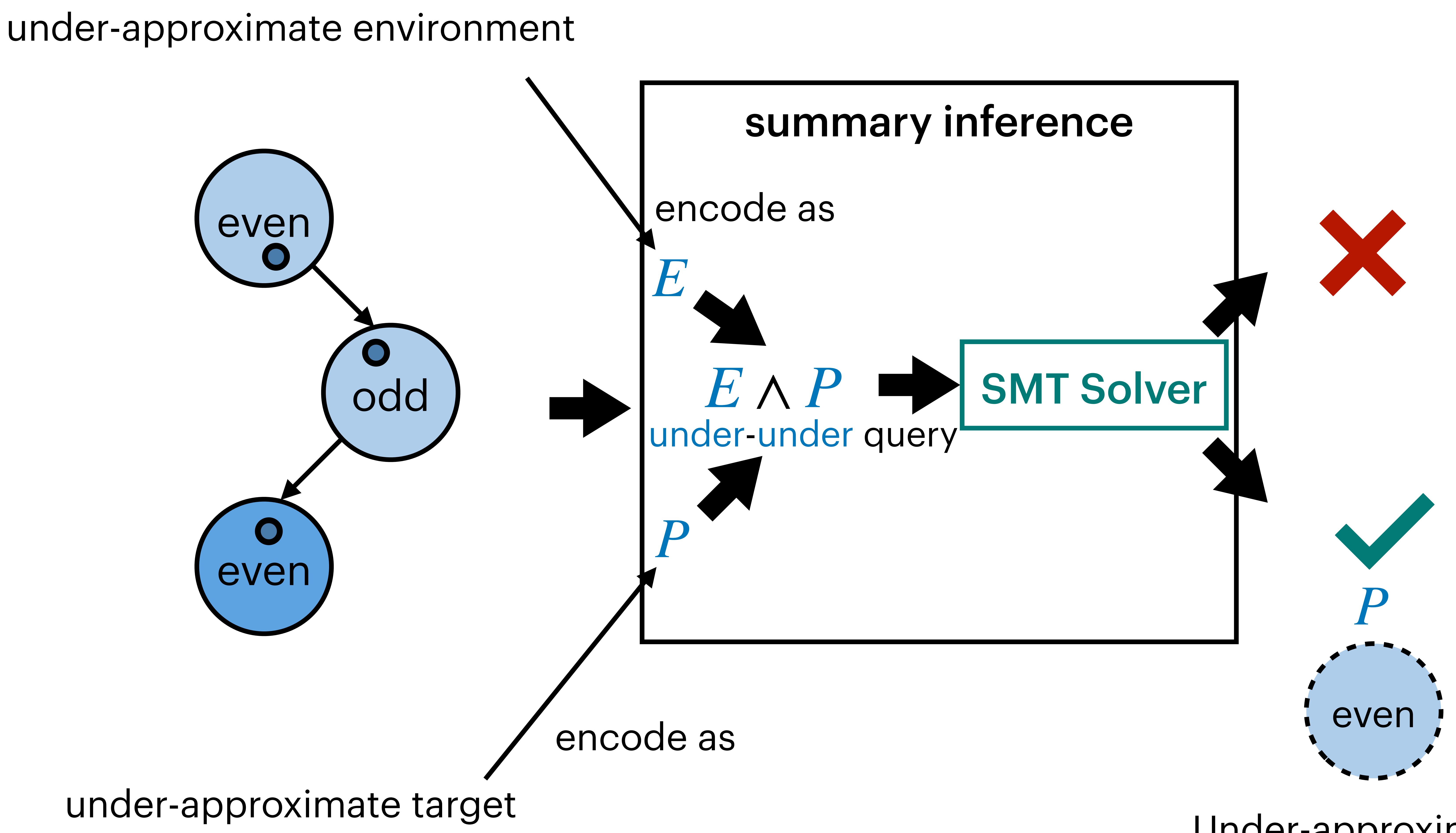


Under-Approximate Summary Inference



Under-approximation **must** occur in the environment, so worth remembering

Under-Approximate Summary Inference



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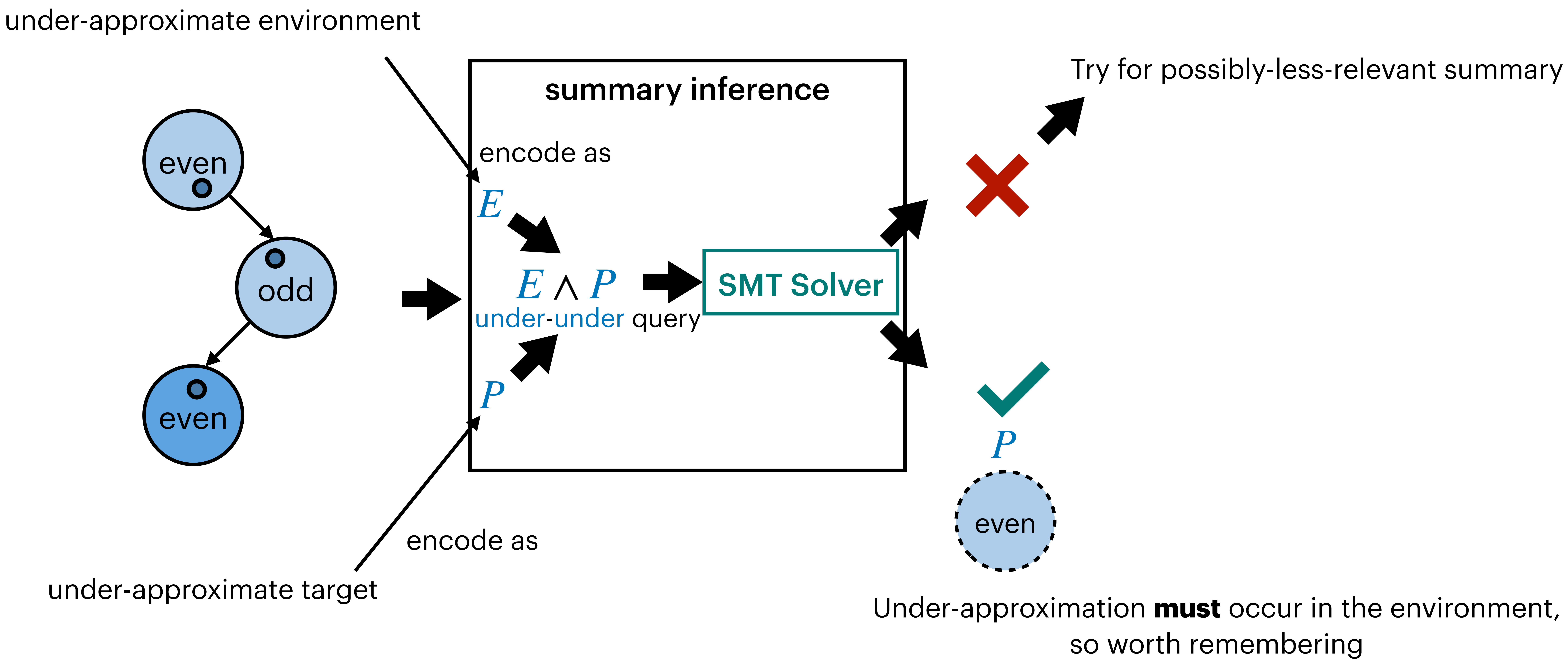

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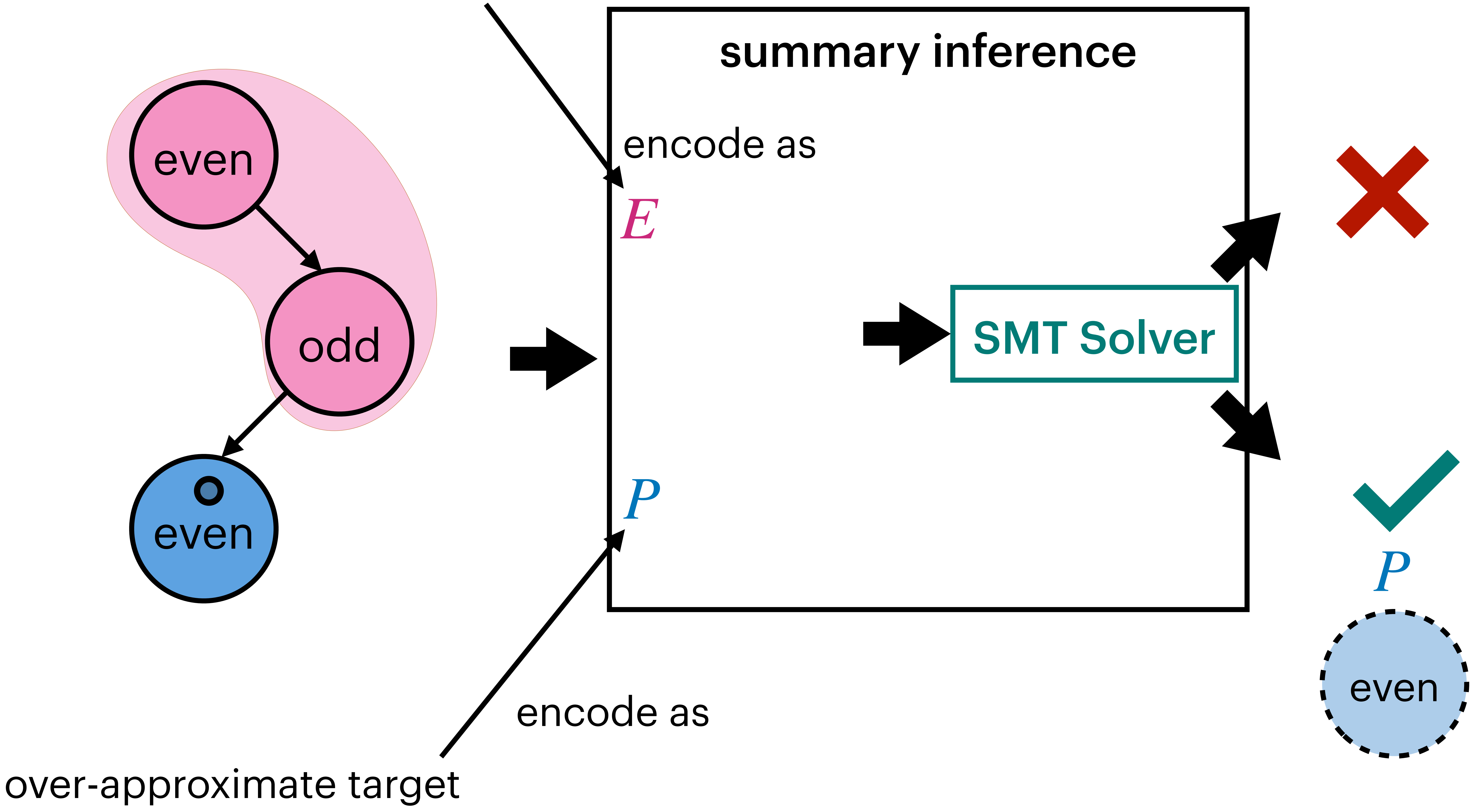

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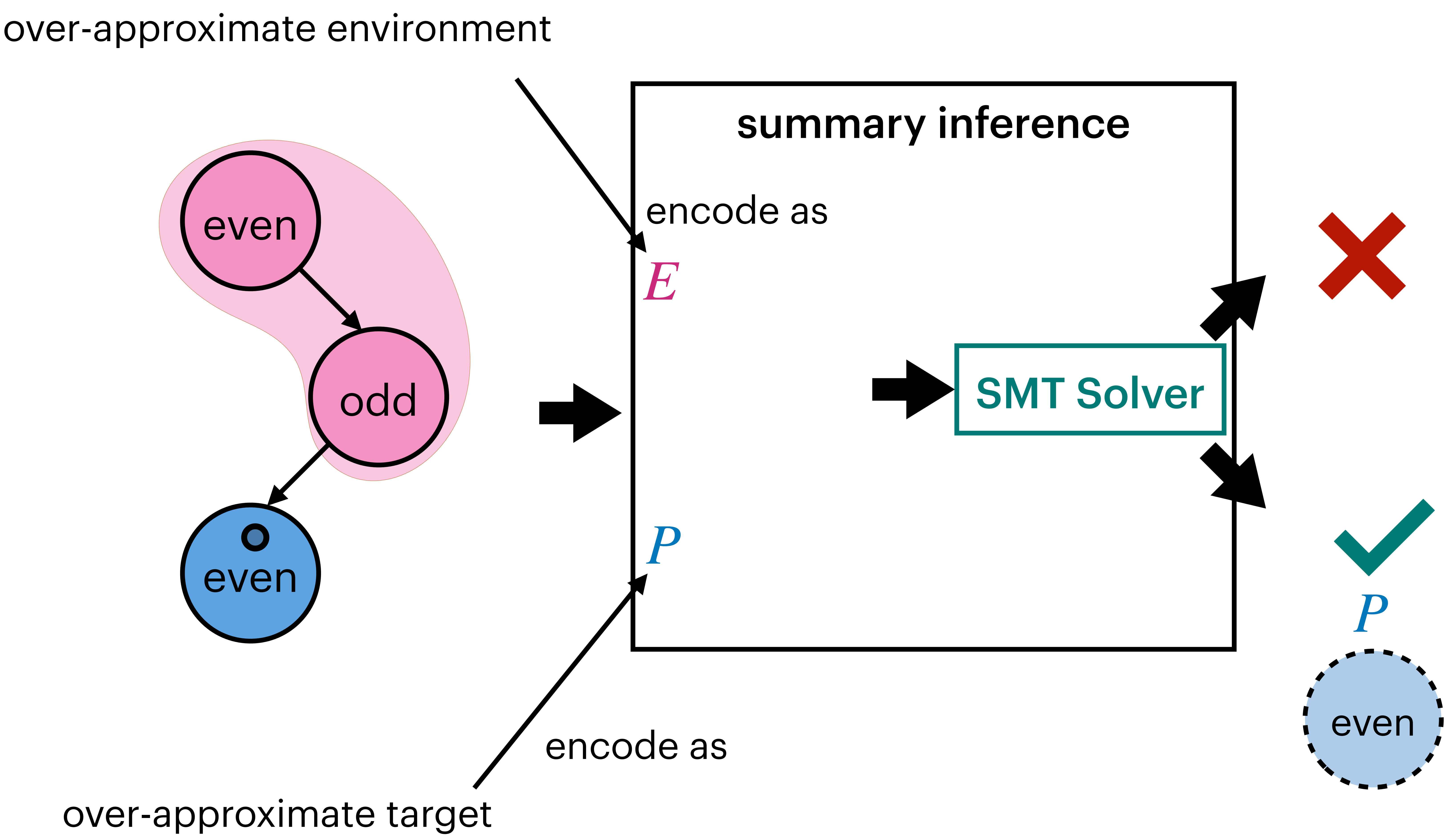

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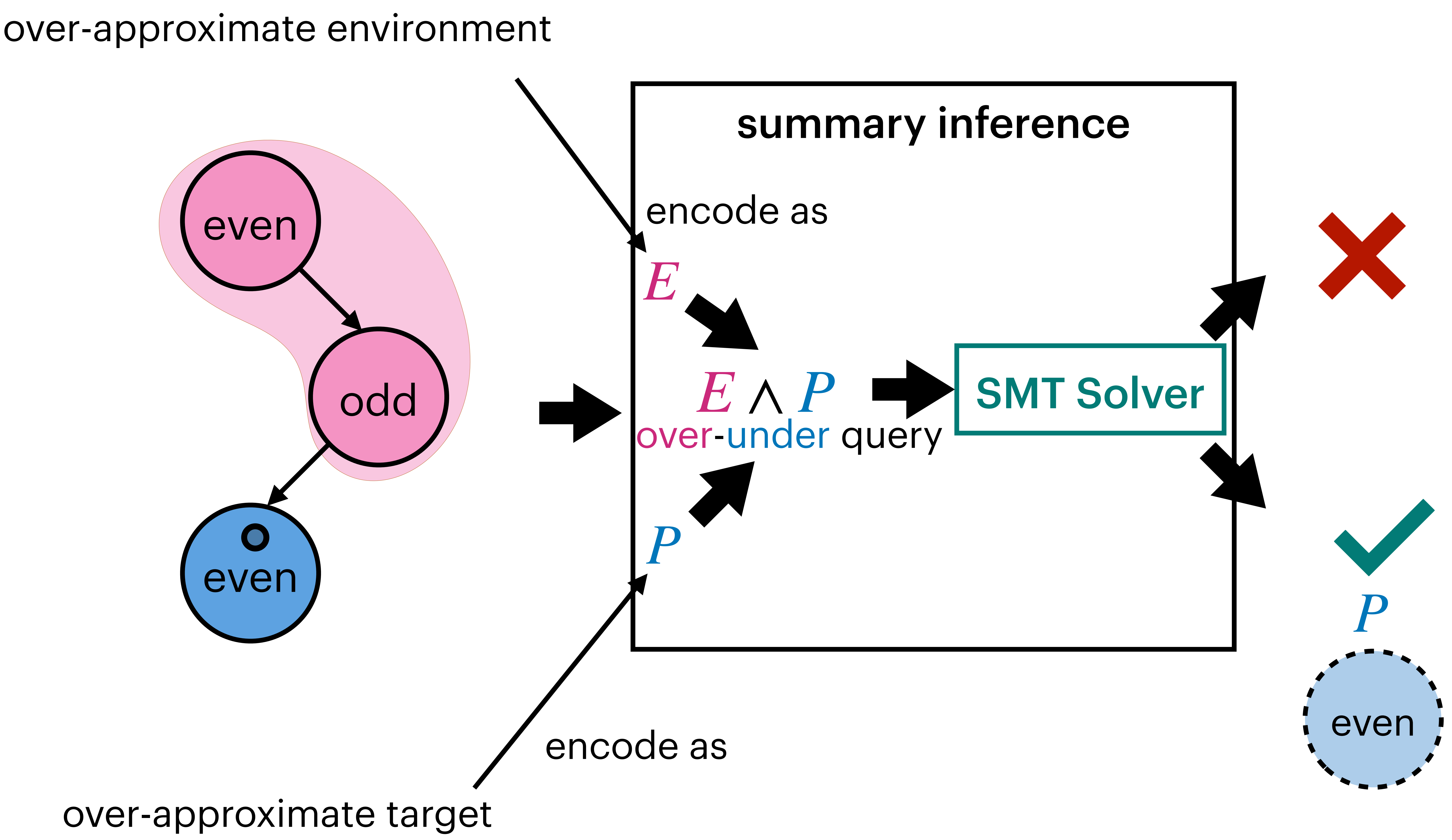
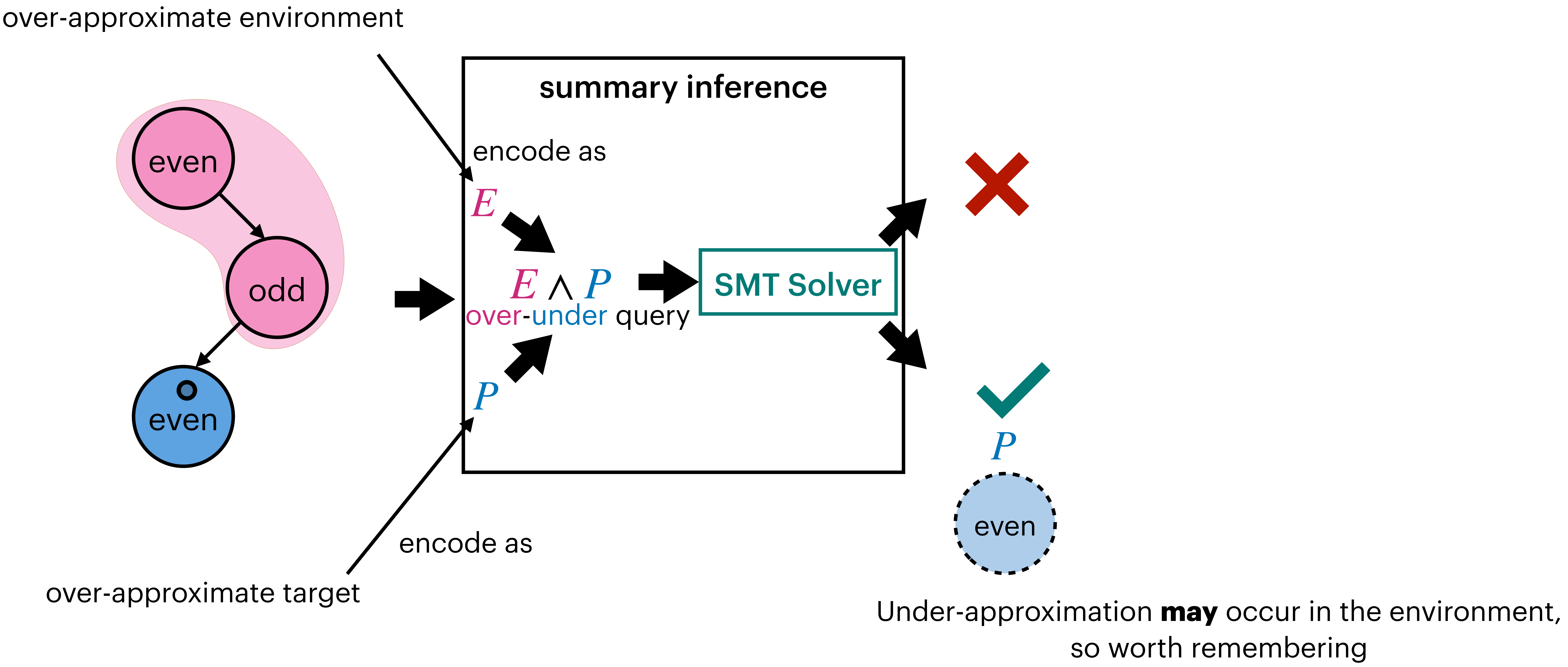
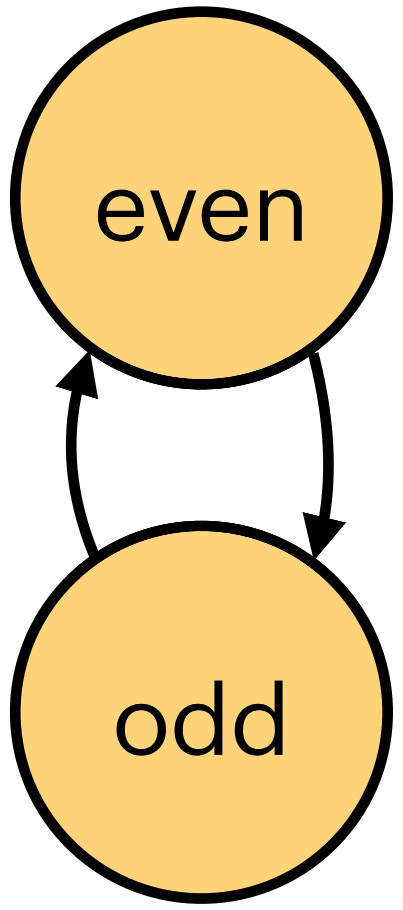


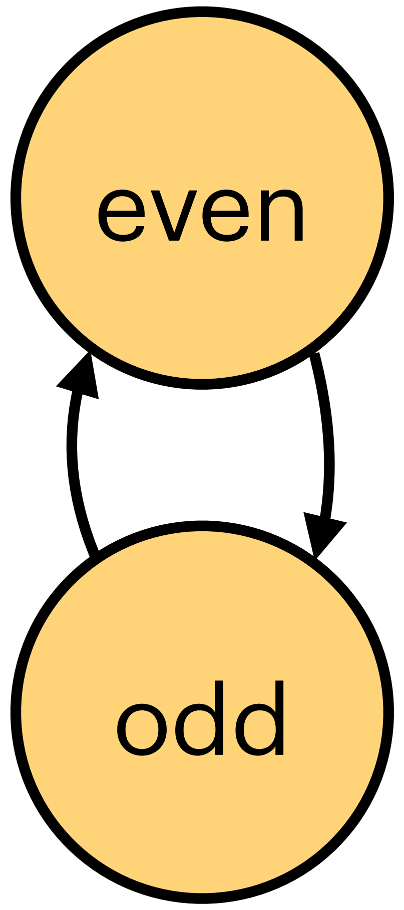
Under-Approximate Summary Inference



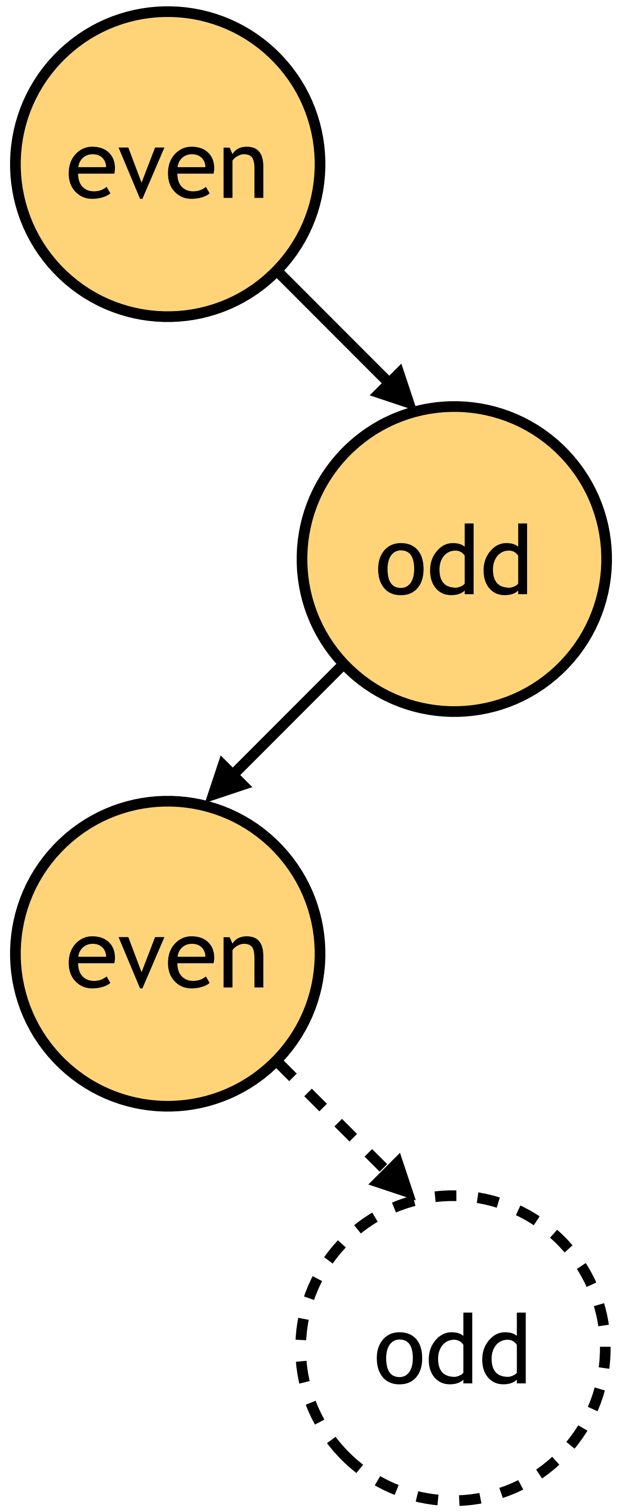
Mutual Recursion



Mutual Recursion



Unfolding:



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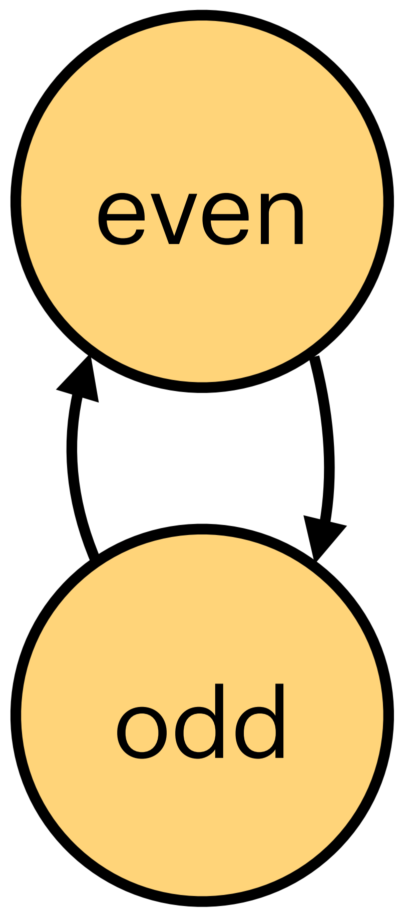

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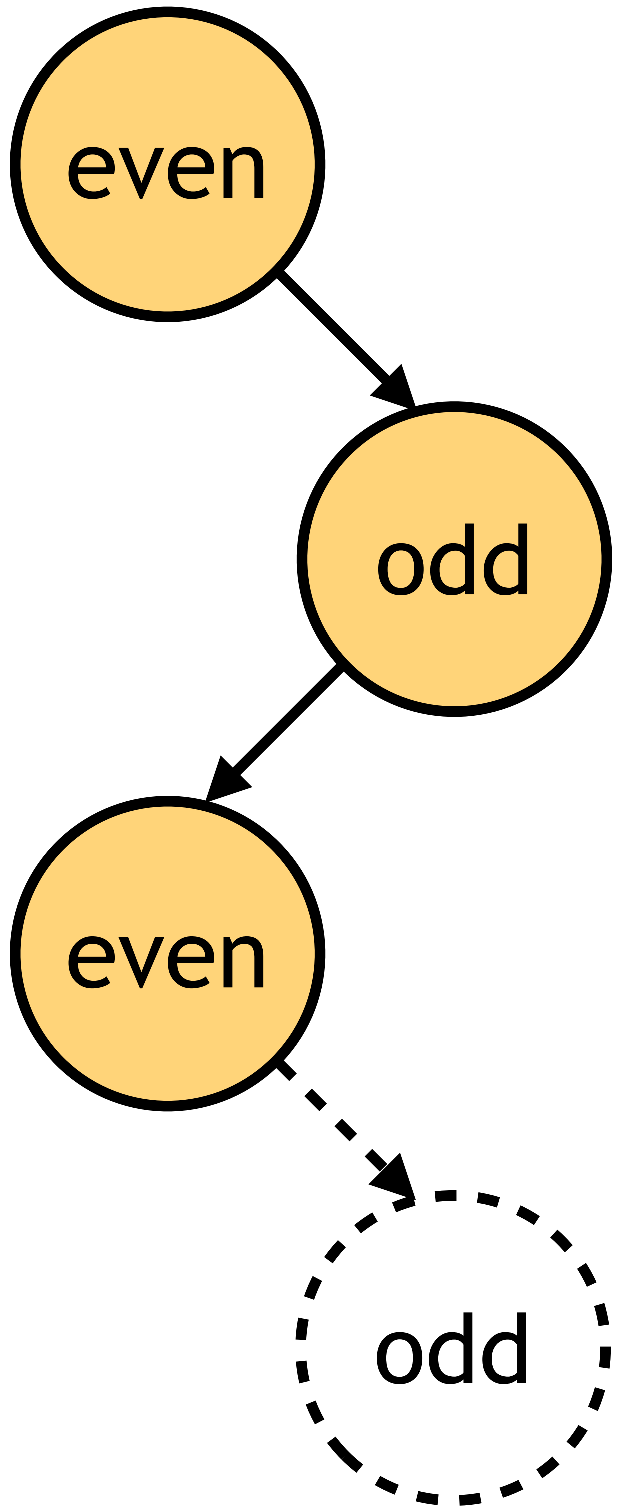
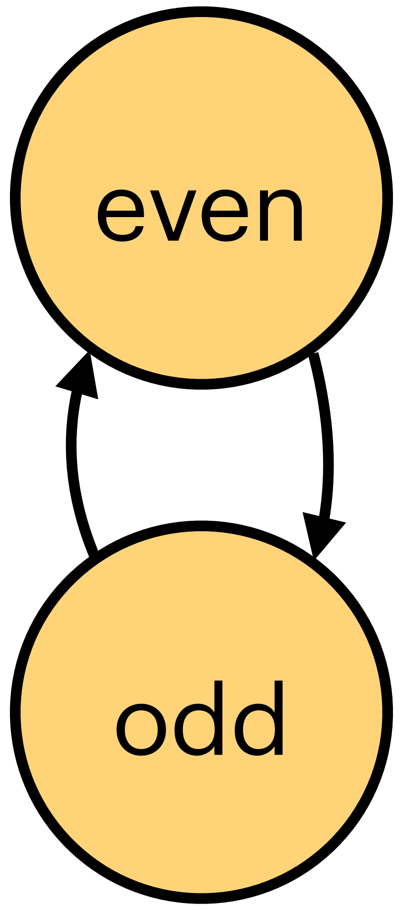


How much to unfold?

Mutual Recursion



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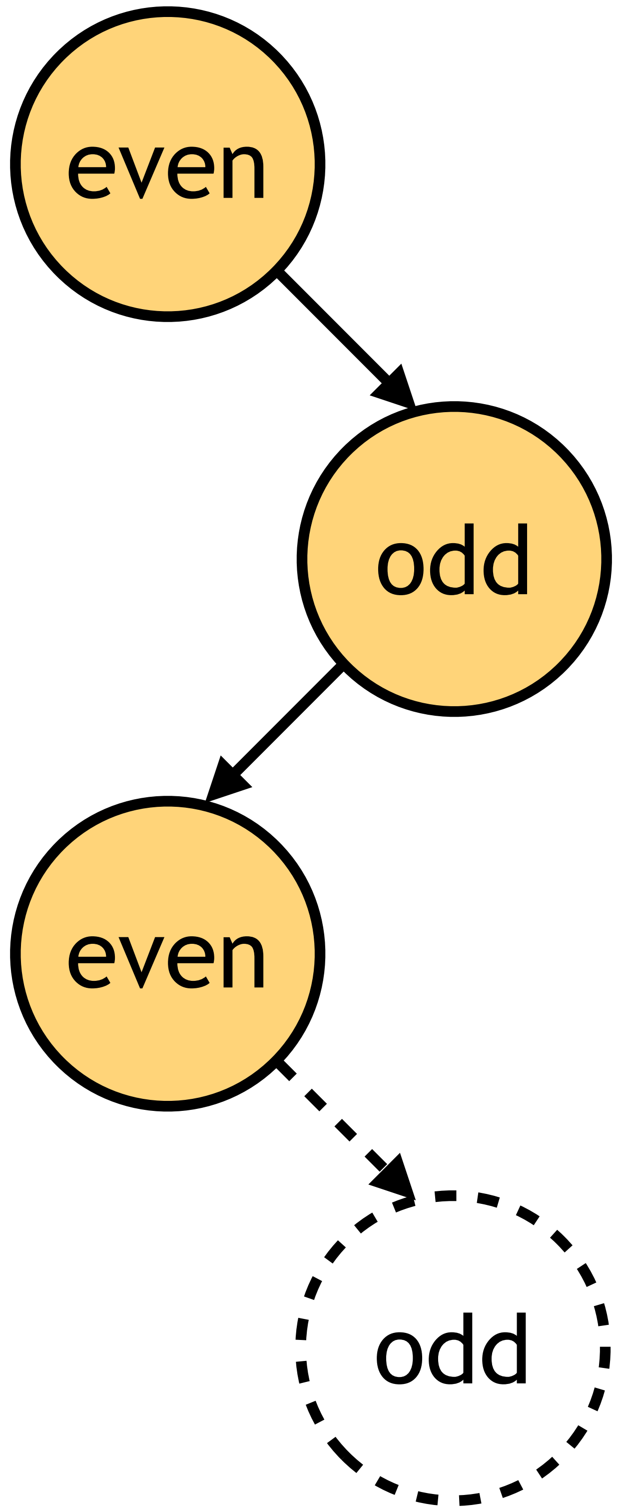
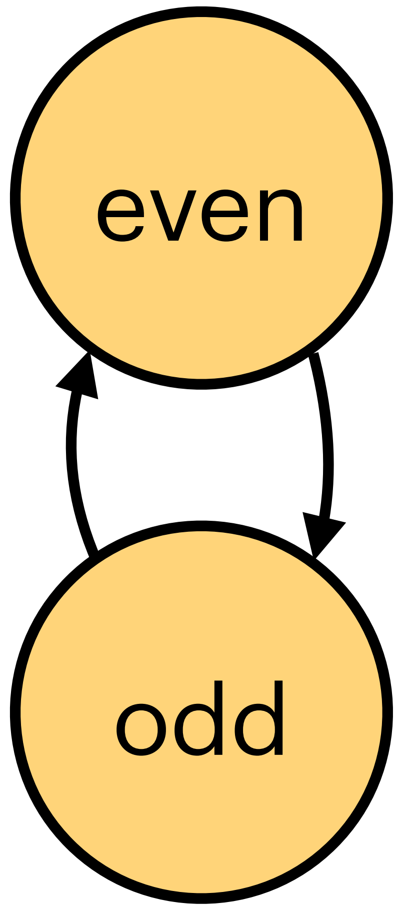


How much to unfold?

Can’t do induction directly on even

Mutual Recursion



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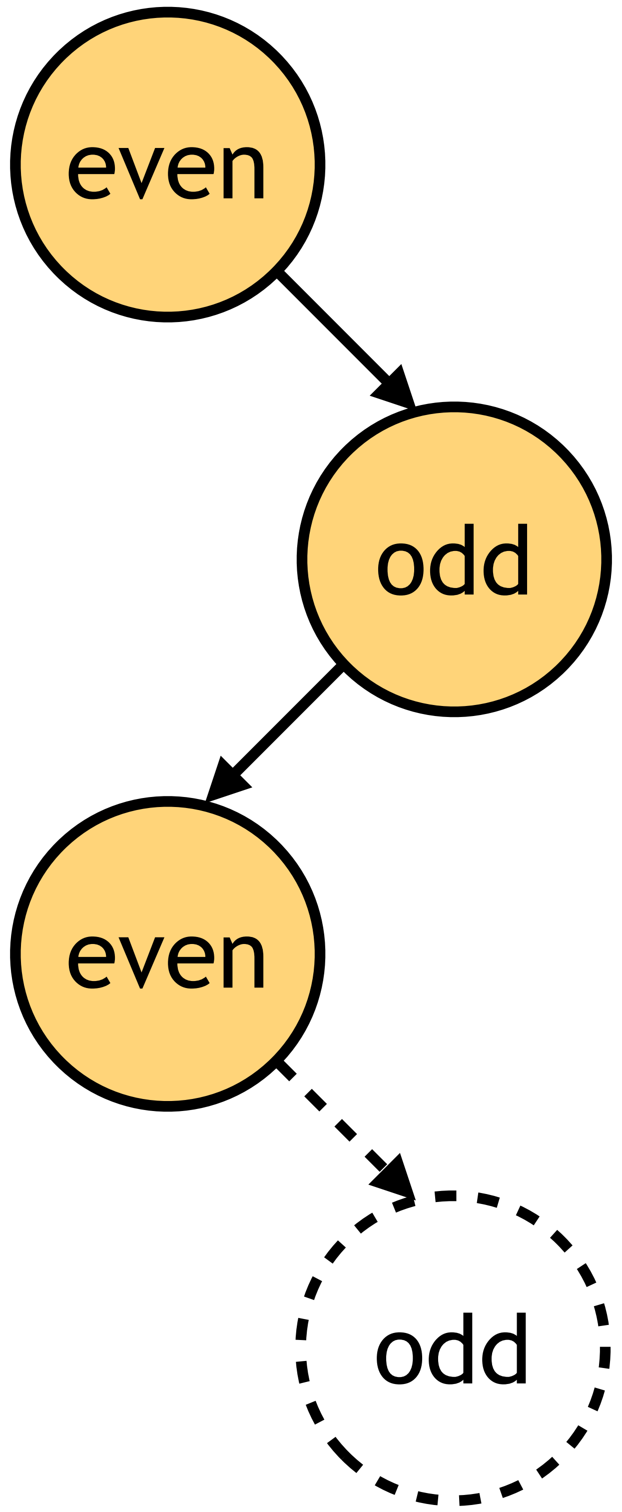
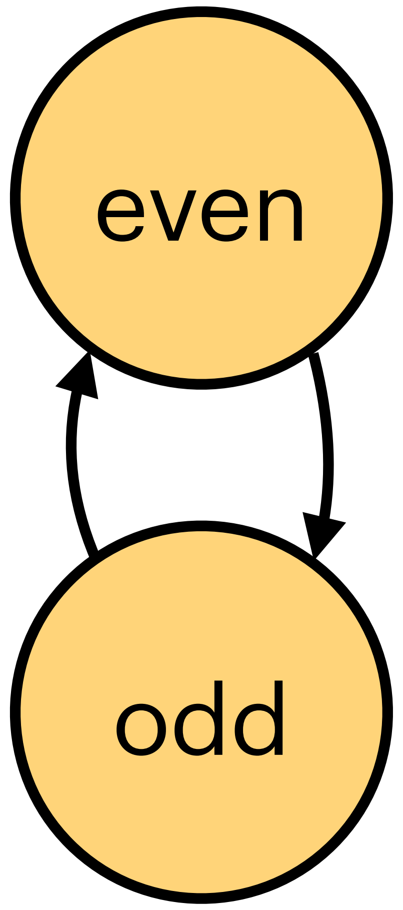


Inlining:

How much to unfold?

Can't do induction directly on even

Mutual Recursion



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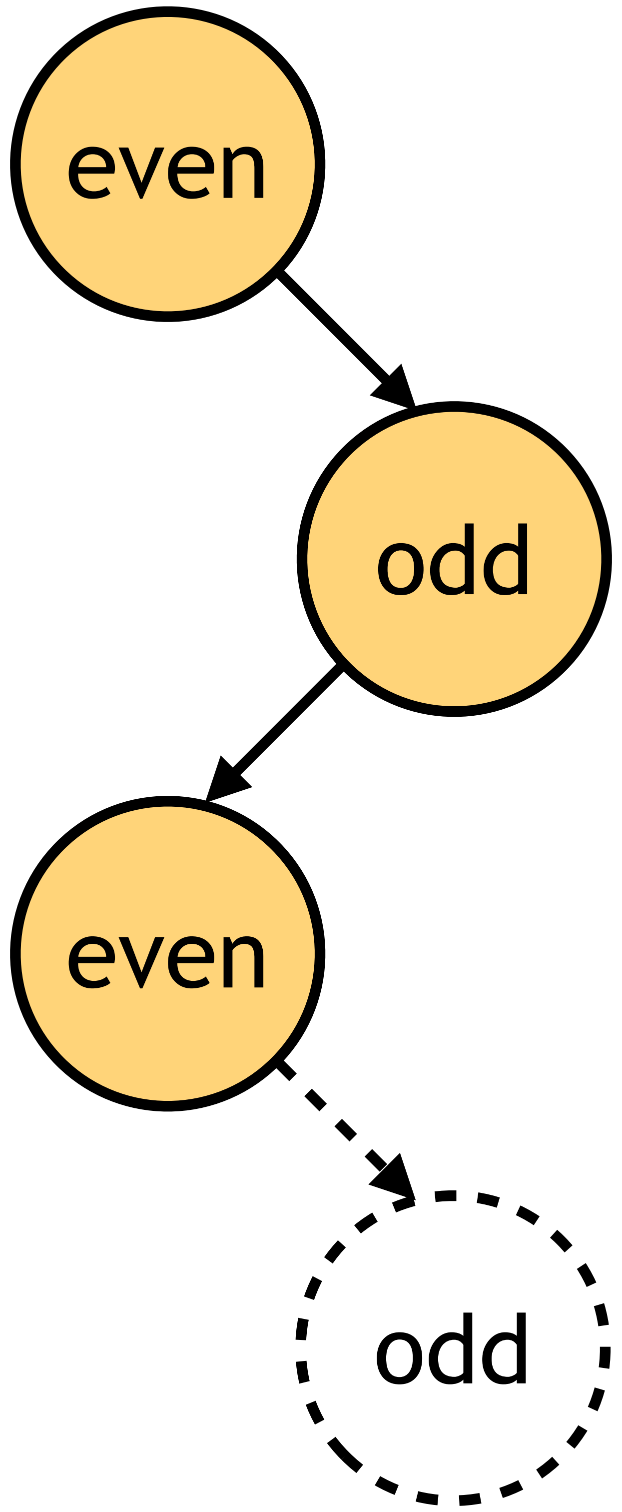


How much to unfold?

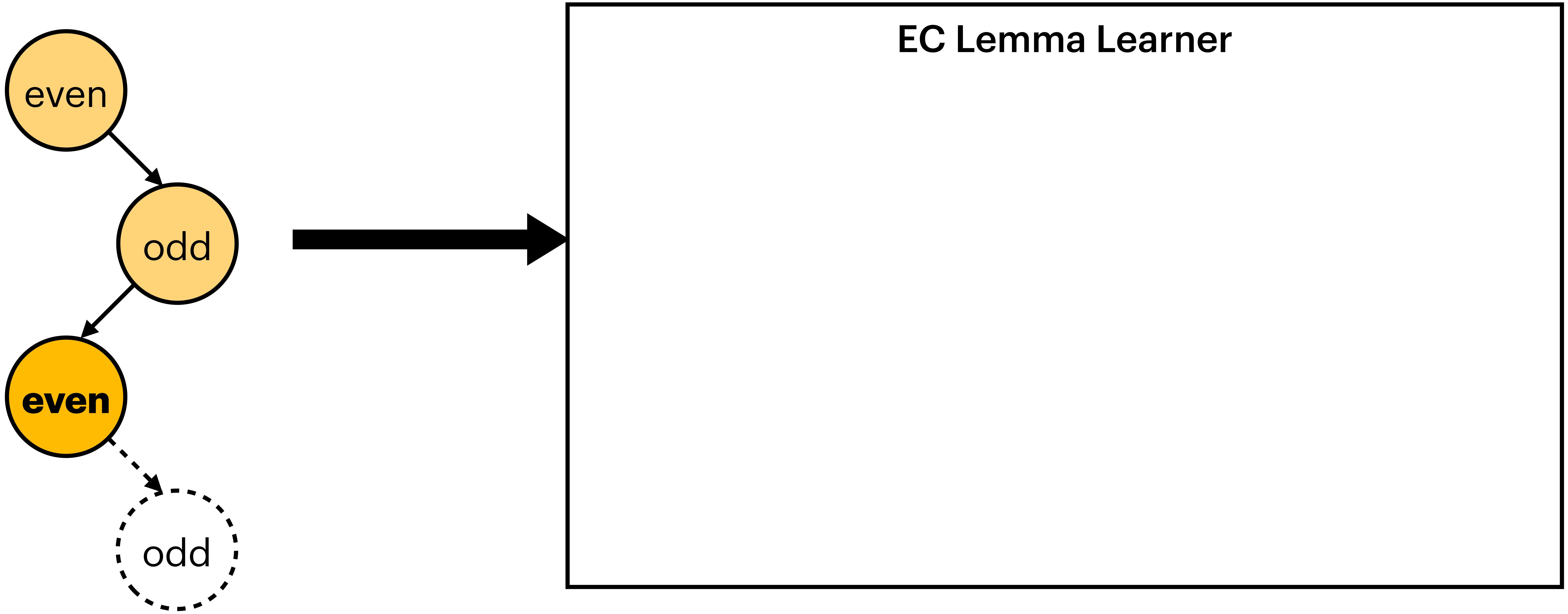
Can’t do induction directly on even

Inlining:

No summary for odd

Environment-Callee (EC) Lemmas

Express relationships between summaries of procedures on the same call path in a program



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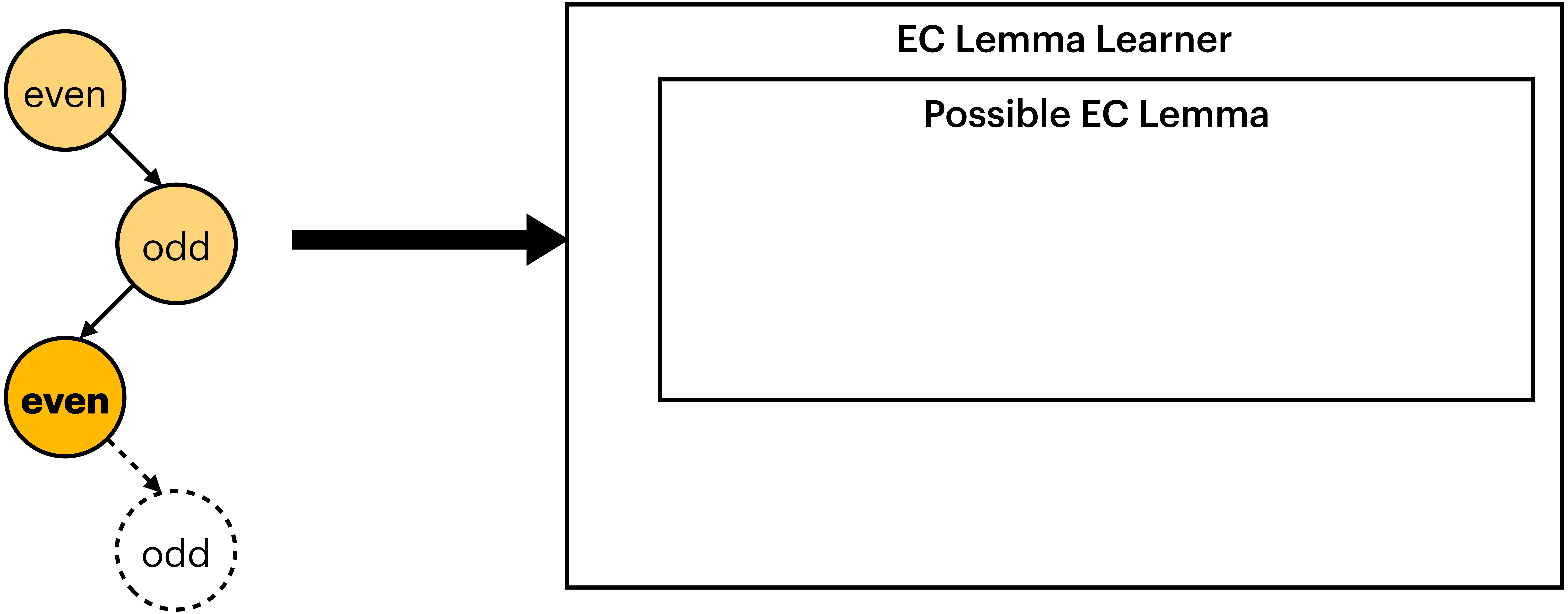

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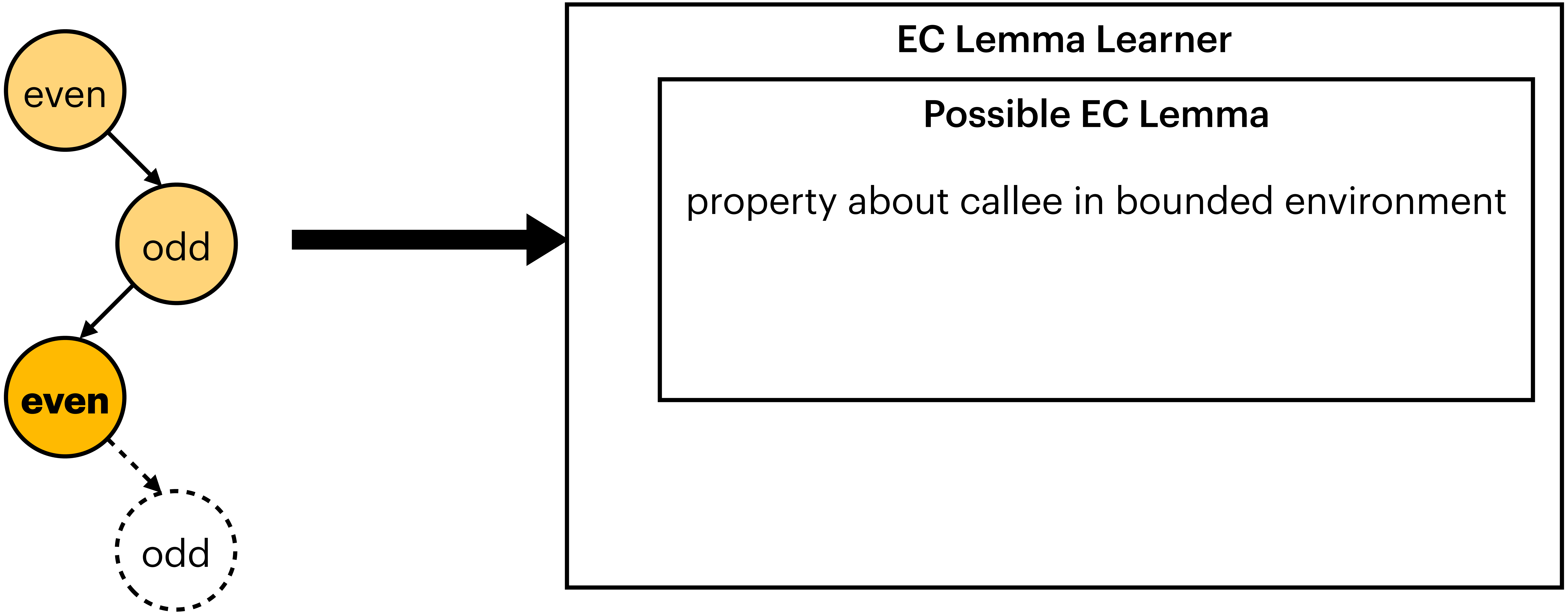

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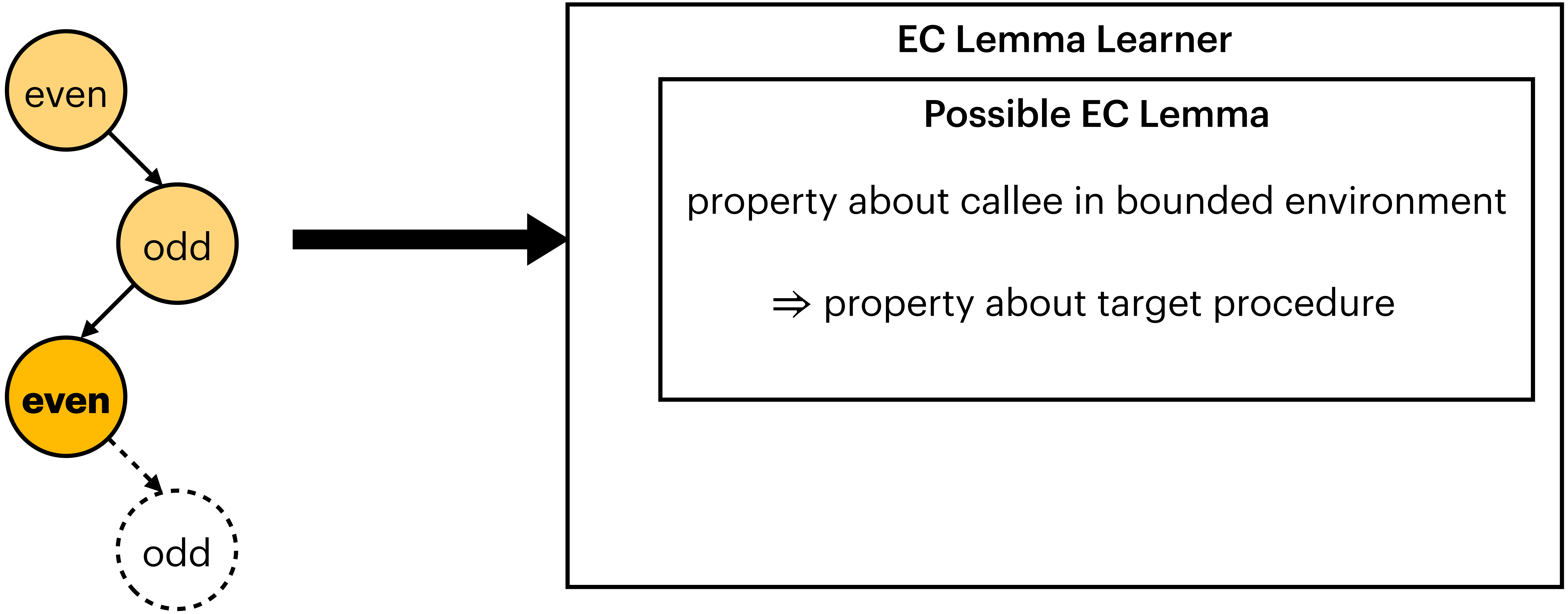

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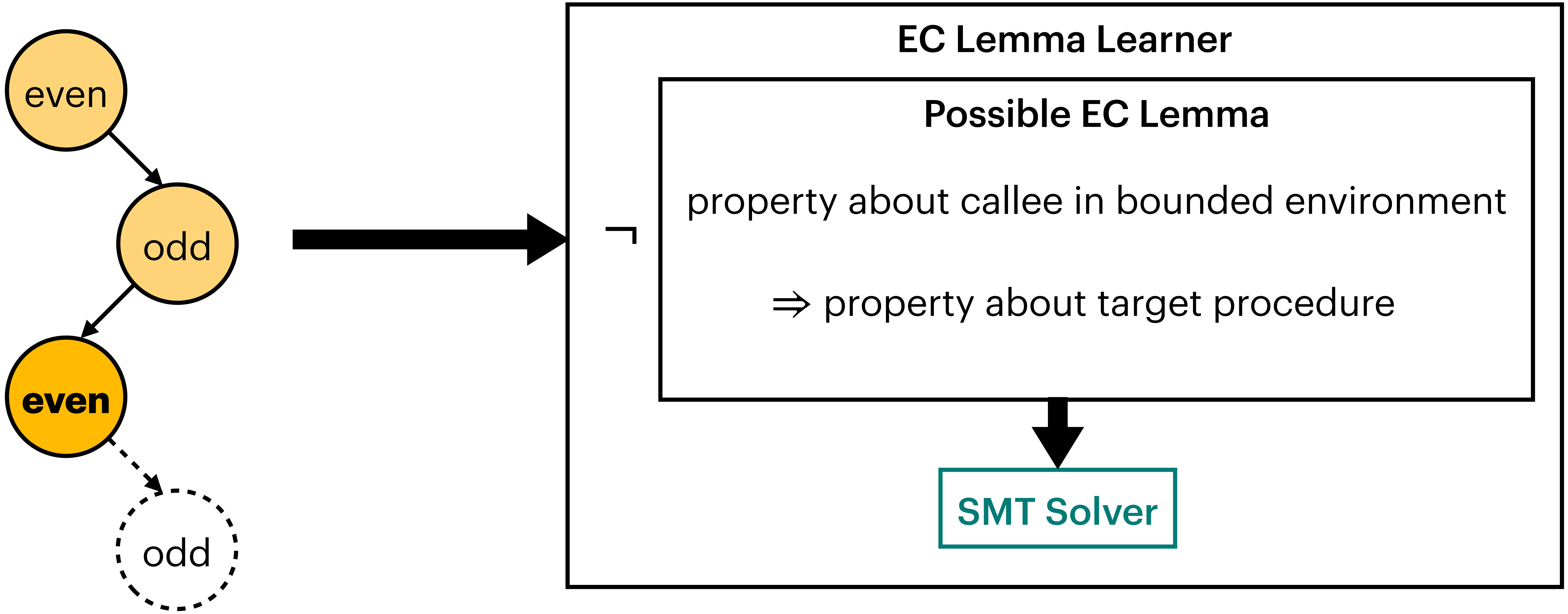

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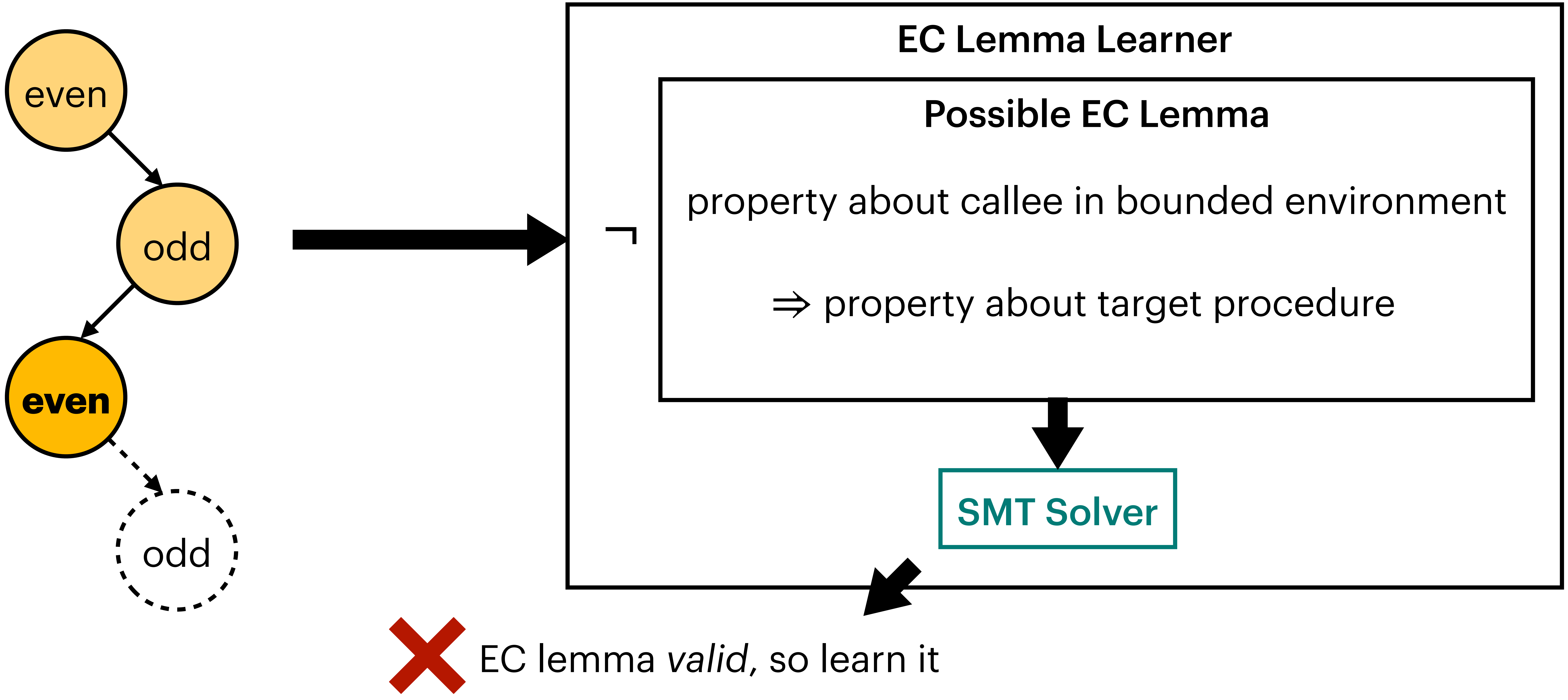

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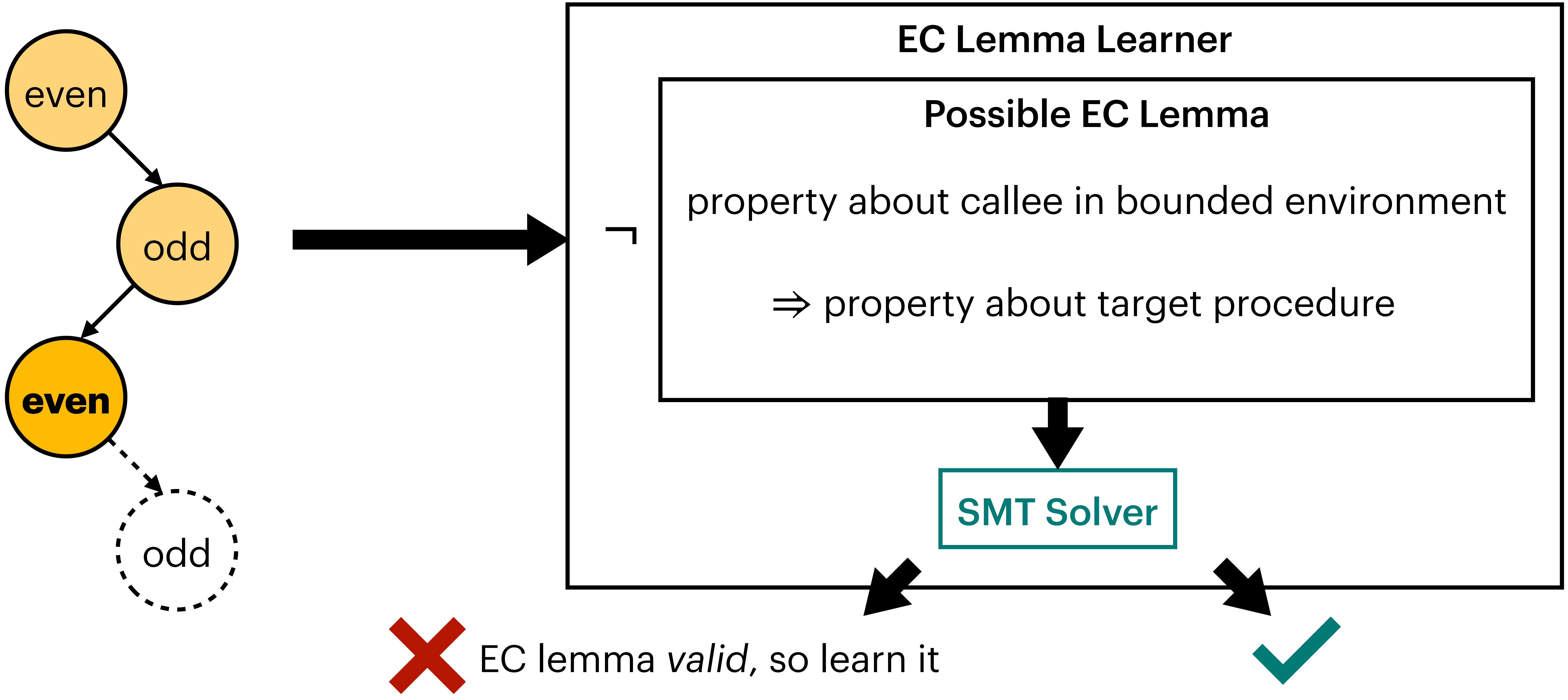

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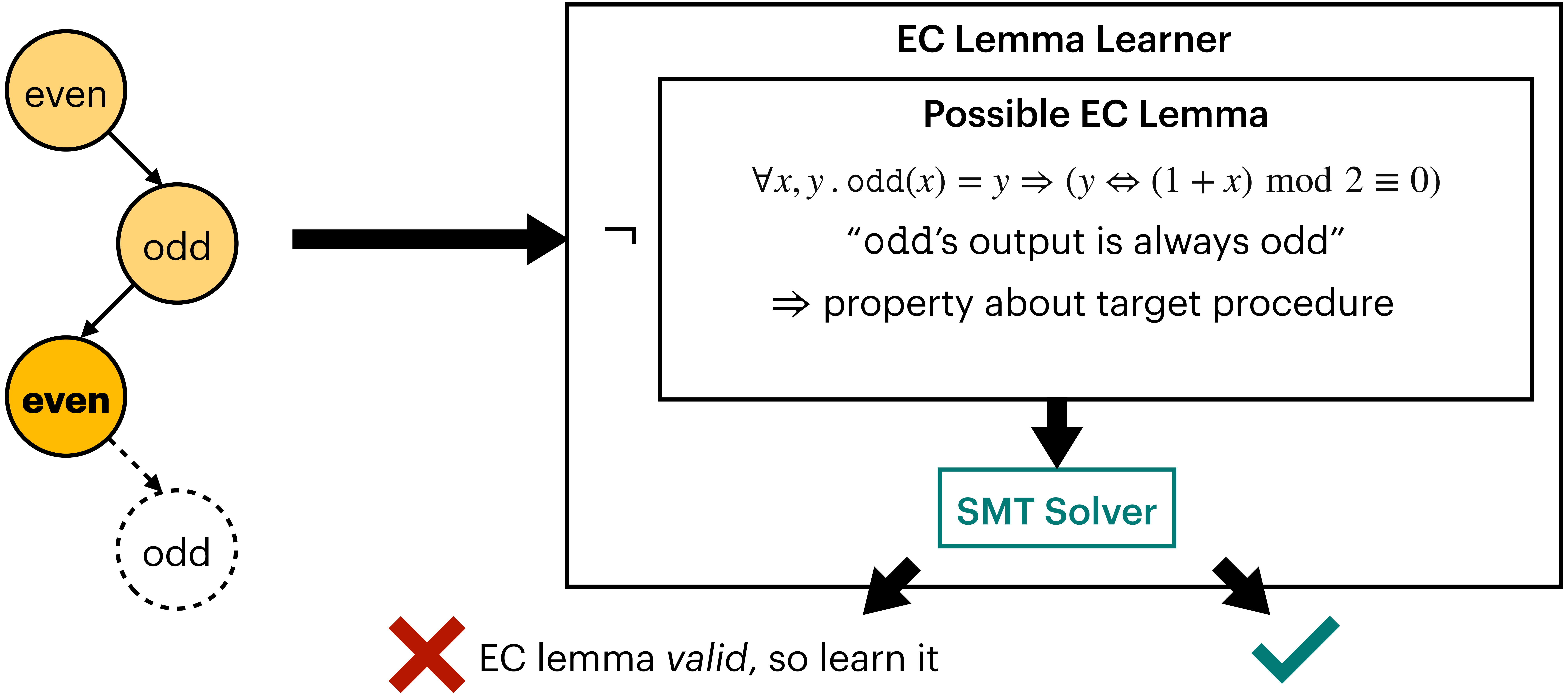

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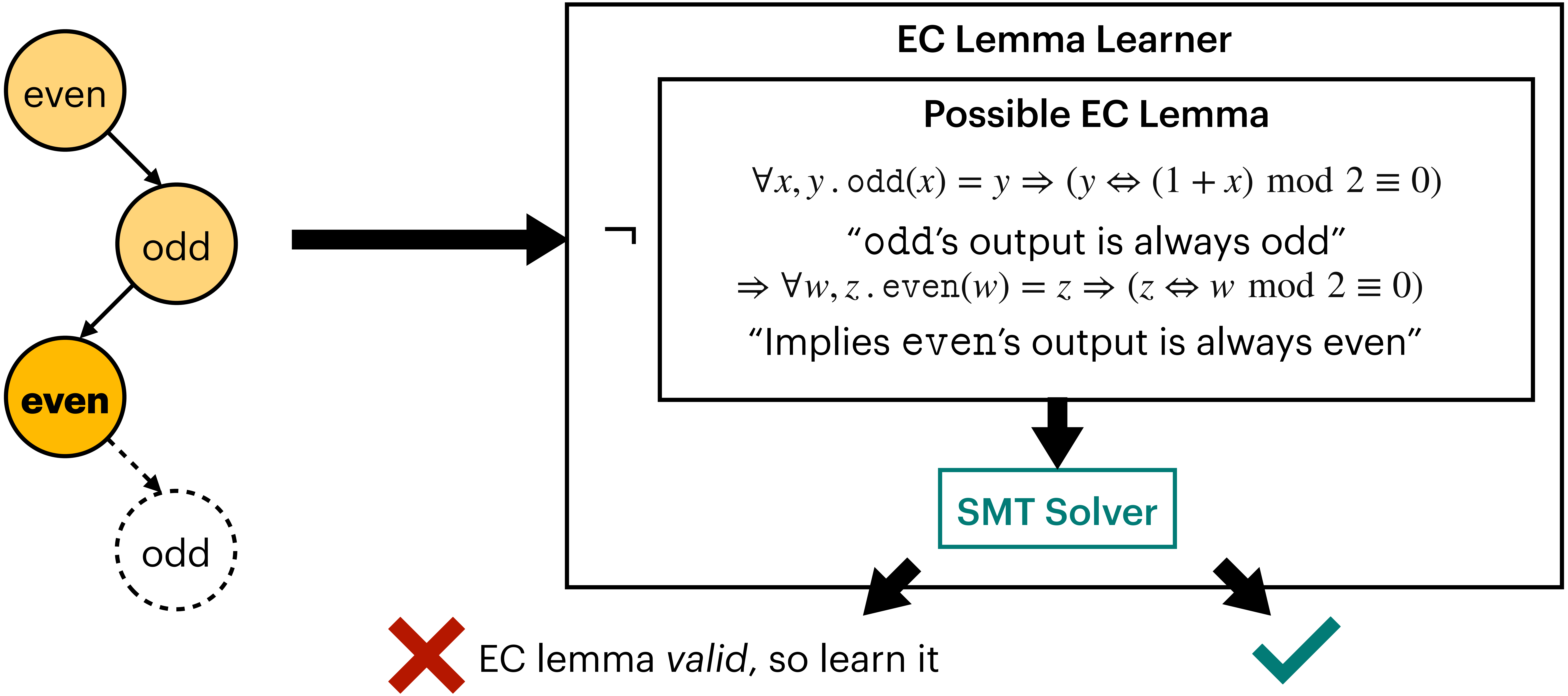

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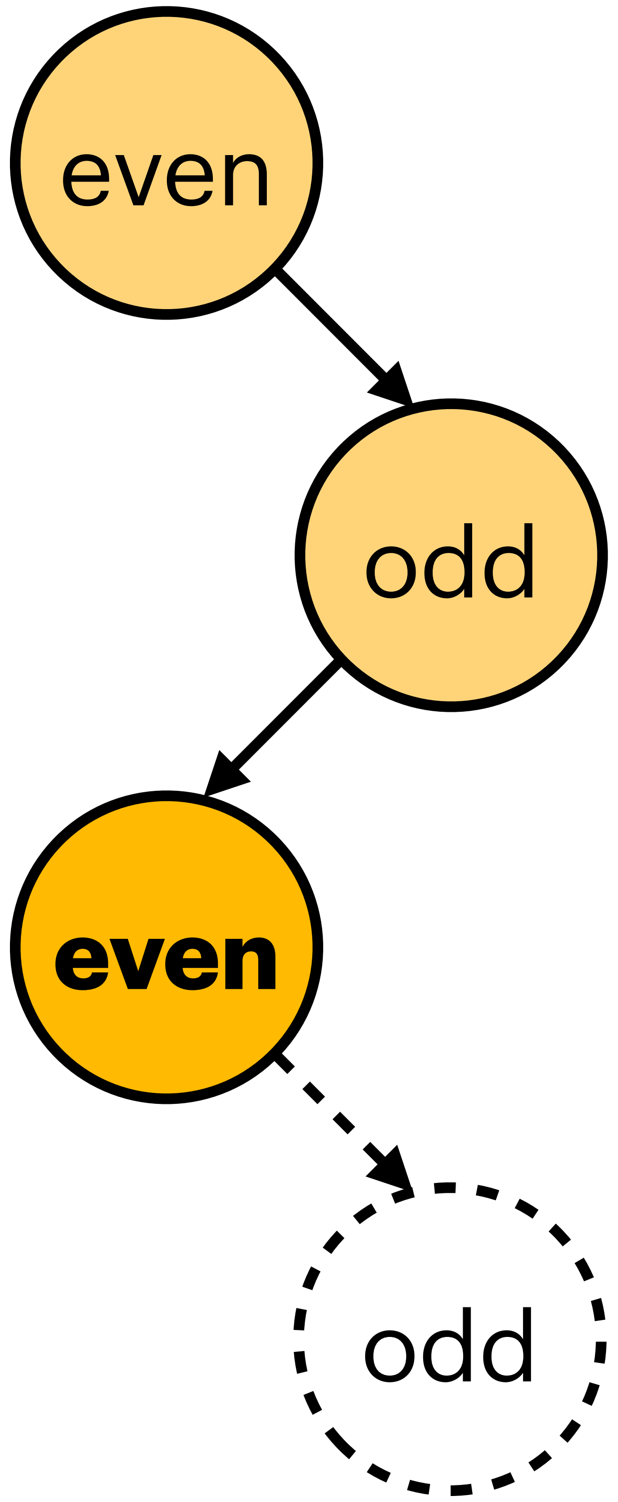

EC Lemma Learner

Possible EC Lemma

$$\neg \quad \forall x, y\,.\,\texttt{odd}(x) = y \Rightarrow (y \Leftrightarrow (1 + x) \bmod 2 \equiv 0)$$

"odd's output is always odd"

$$\Rightarrow \forall w, z\,.\,\texttt{even}(w) = z \Rightarrow (z \Leftrightarrow w \bmod 2 \equiv 0)$$

"Implies even's output is always even"

SMT Solver

✗ ✓

EC lemma *valid*, so learn it

learn: "odd's output always being odd implies that even's output is always even"