Demanded Abstract Interpretation

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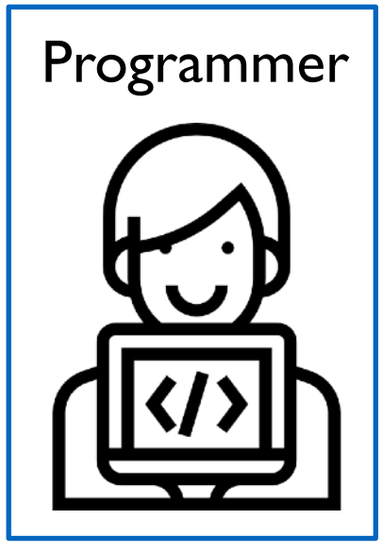
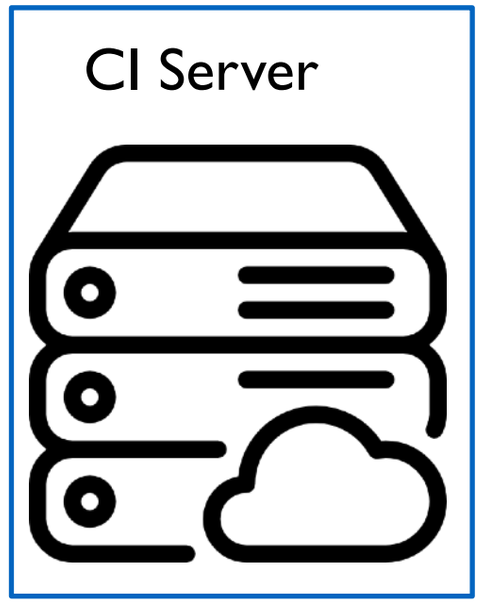
CUPLV

PLDI ‘21

* Bor-Yuh Evan Chang holds concurrent appointments as an Associate Professor at the University of Colorado Boulder and as an Amazon Scholar. This talk describes work performed at the University of Colorado Boulder and is not associated with Amazon.

Batch Static Analysis Workflow





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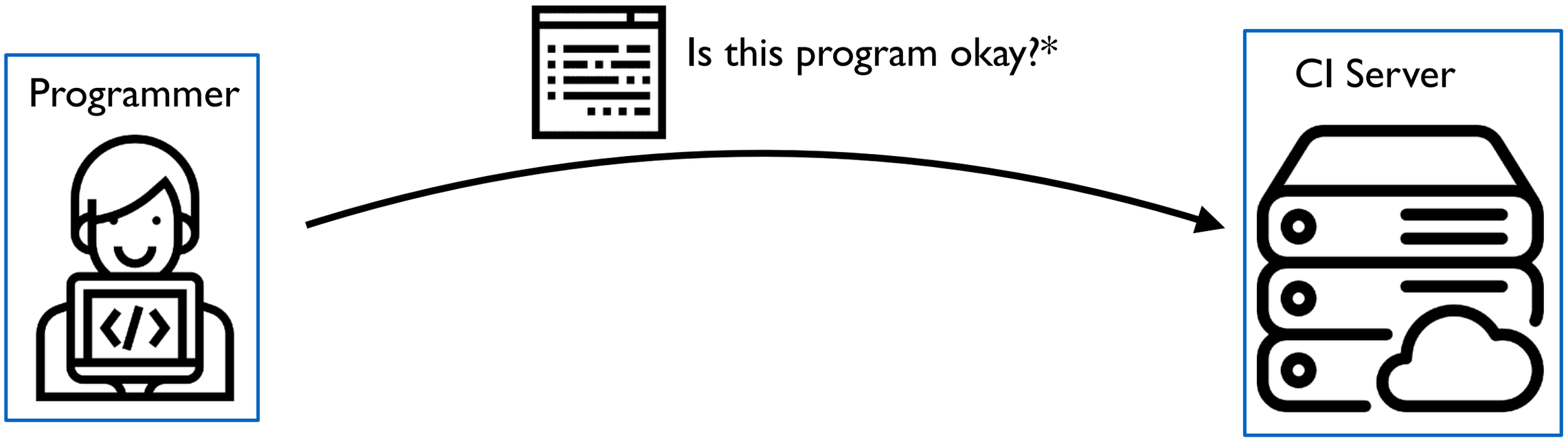

* i.e. safe with respect to some program analyzer

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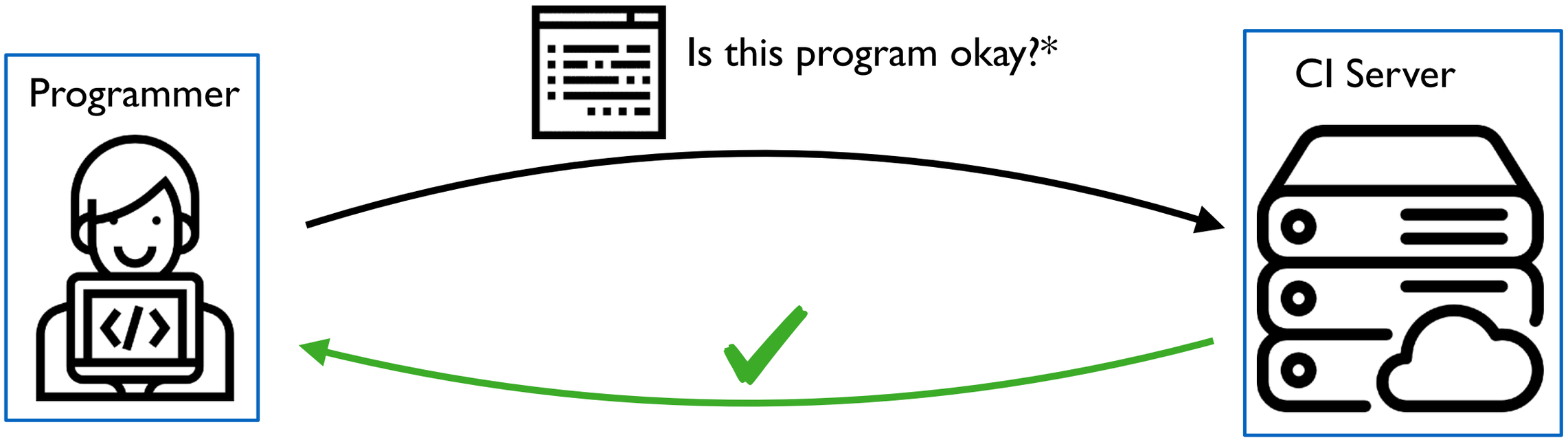

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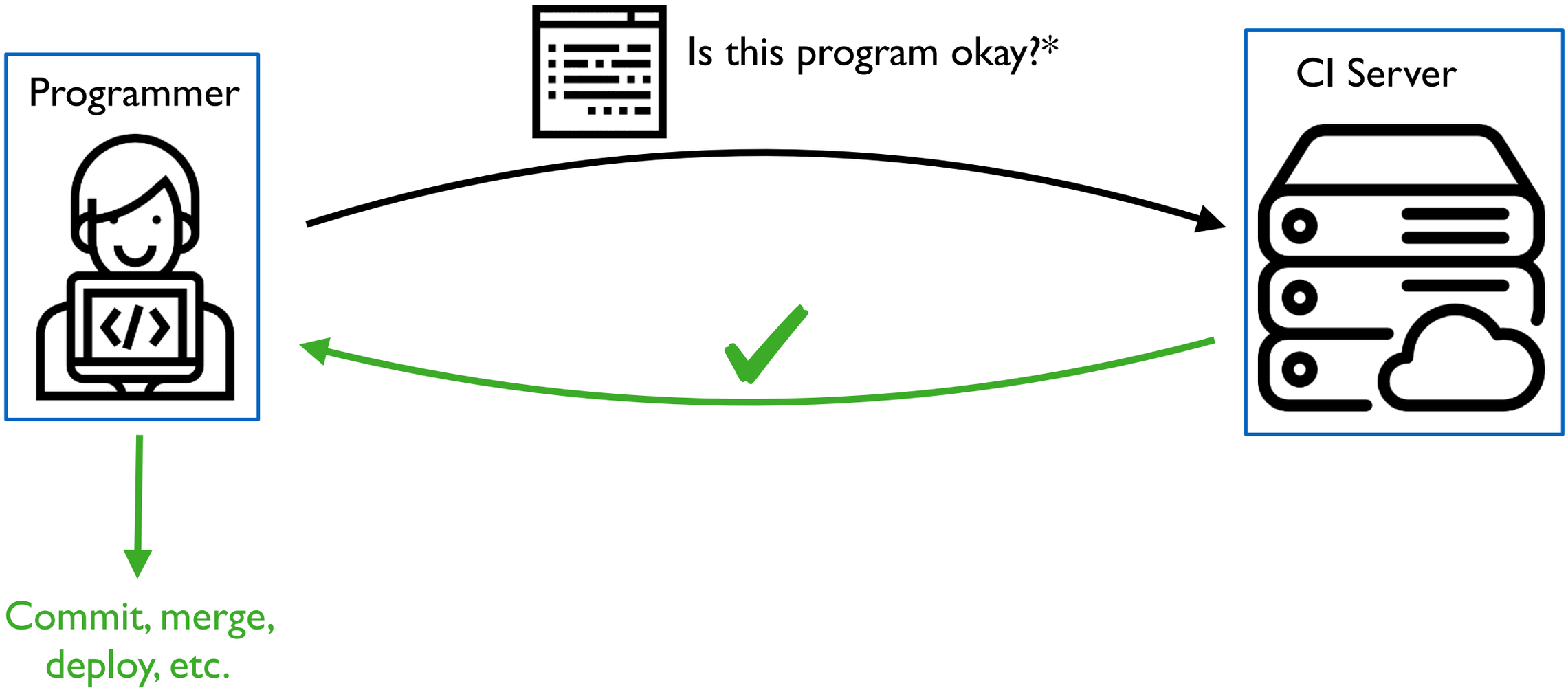

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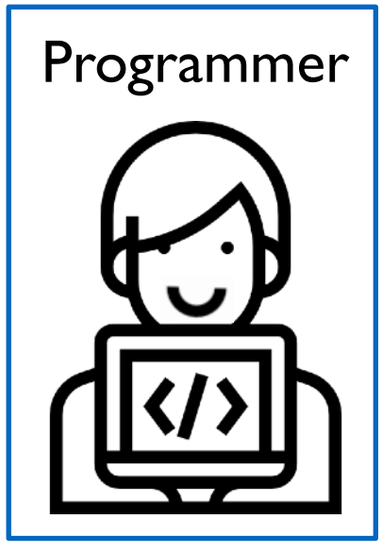

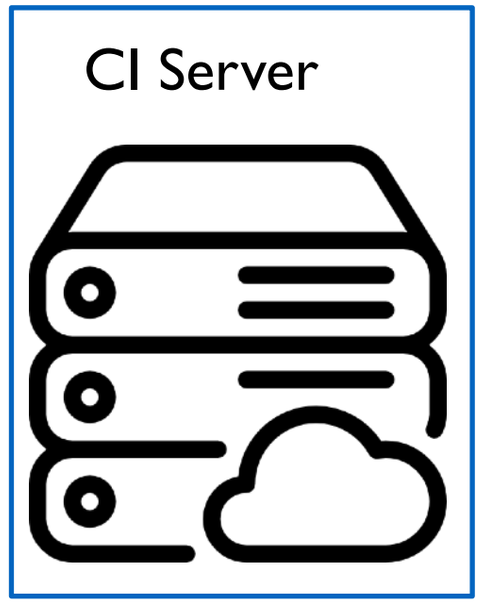

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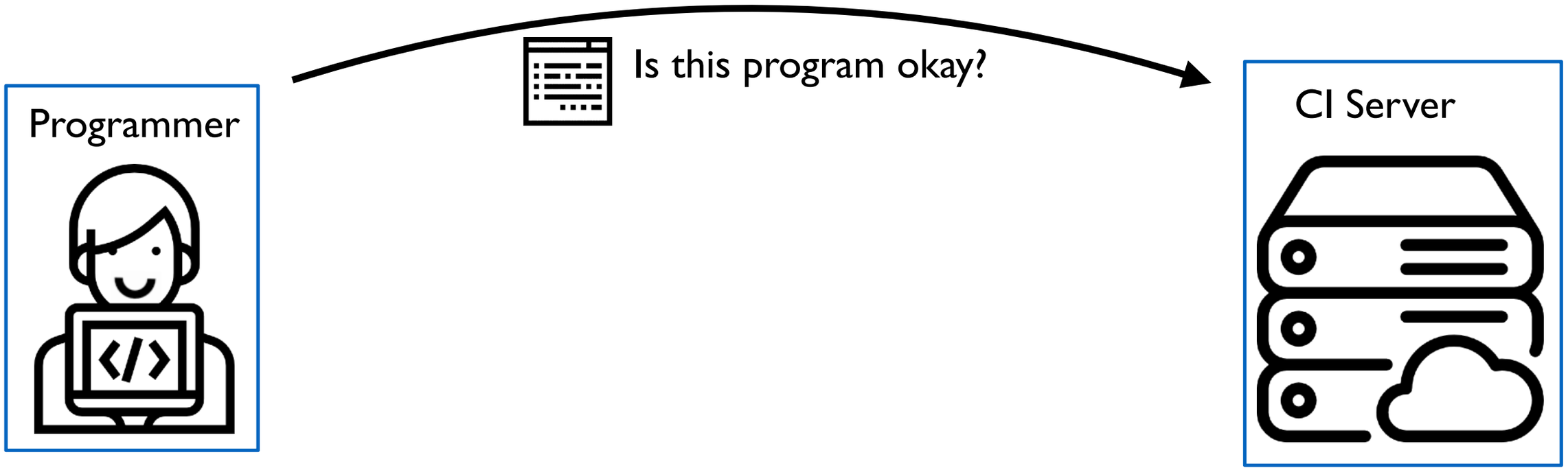

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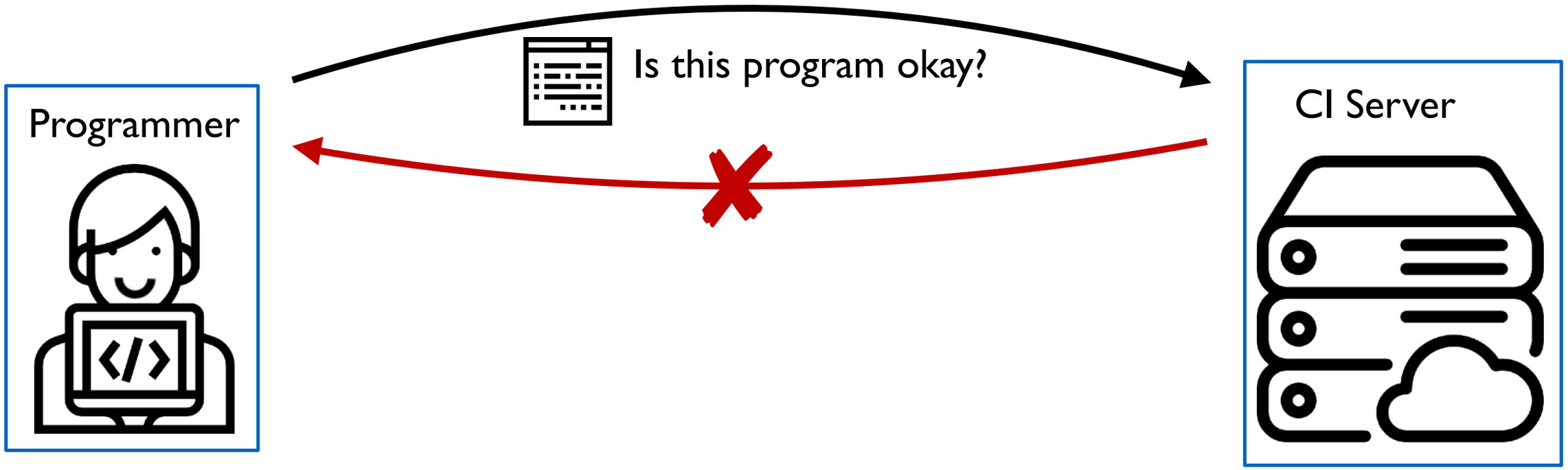

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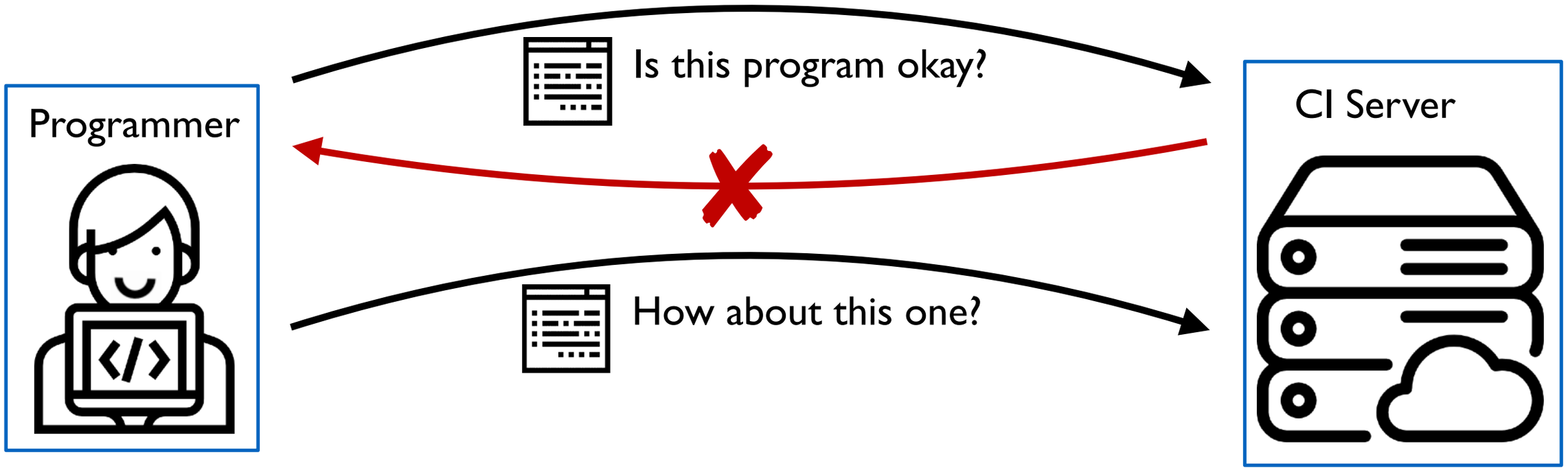

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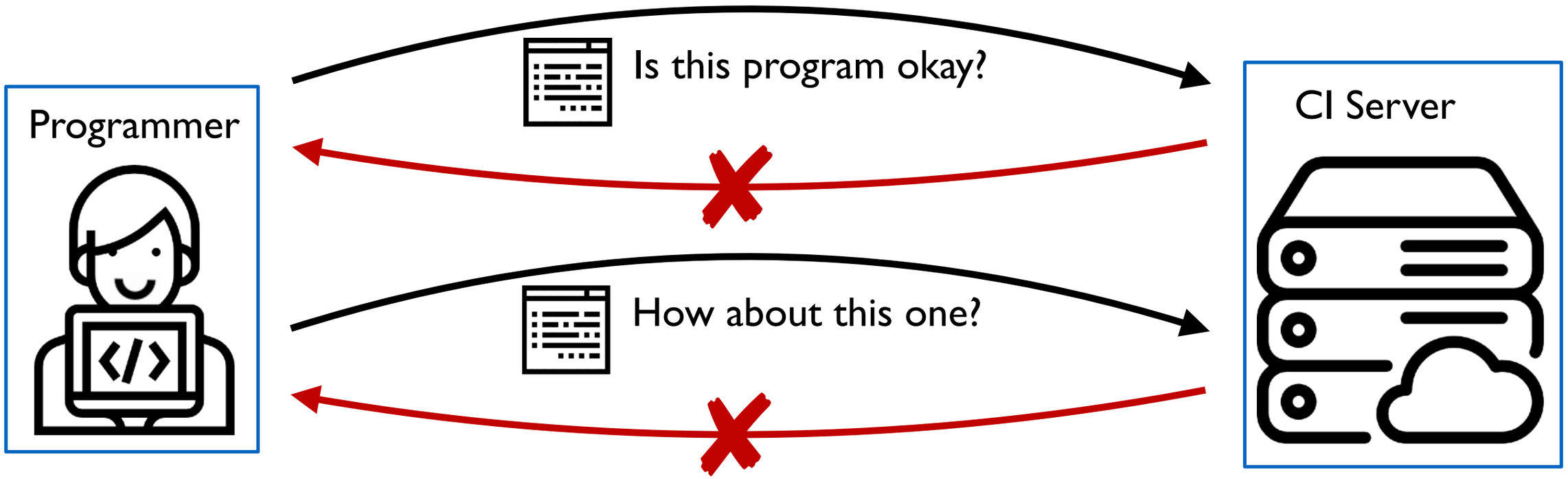

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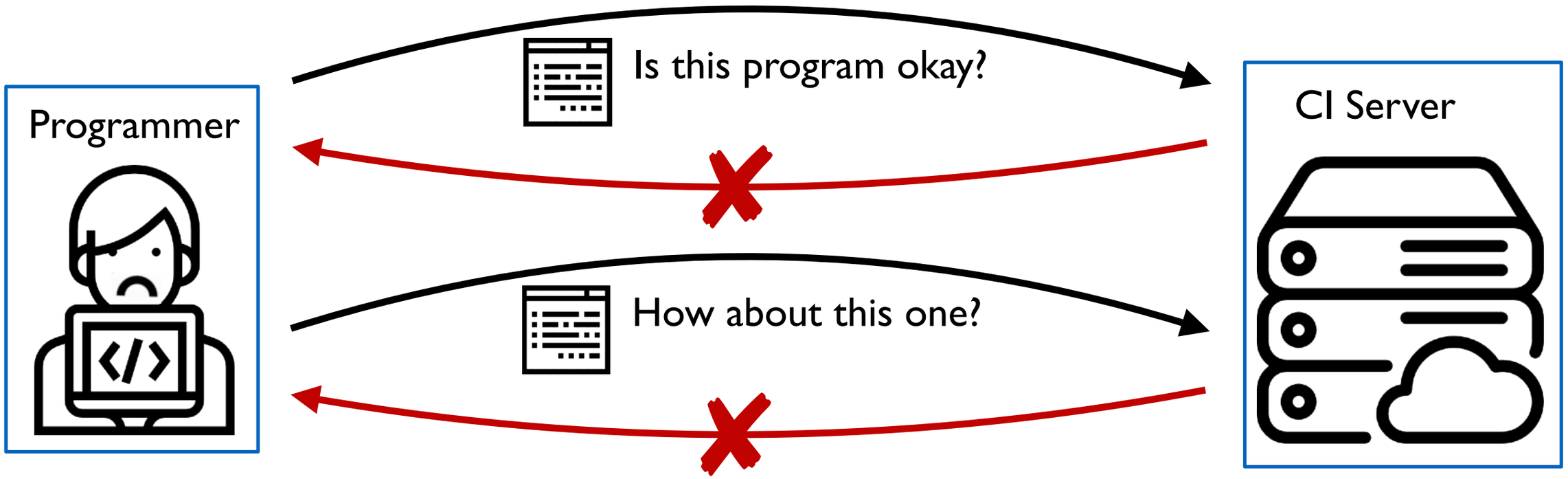

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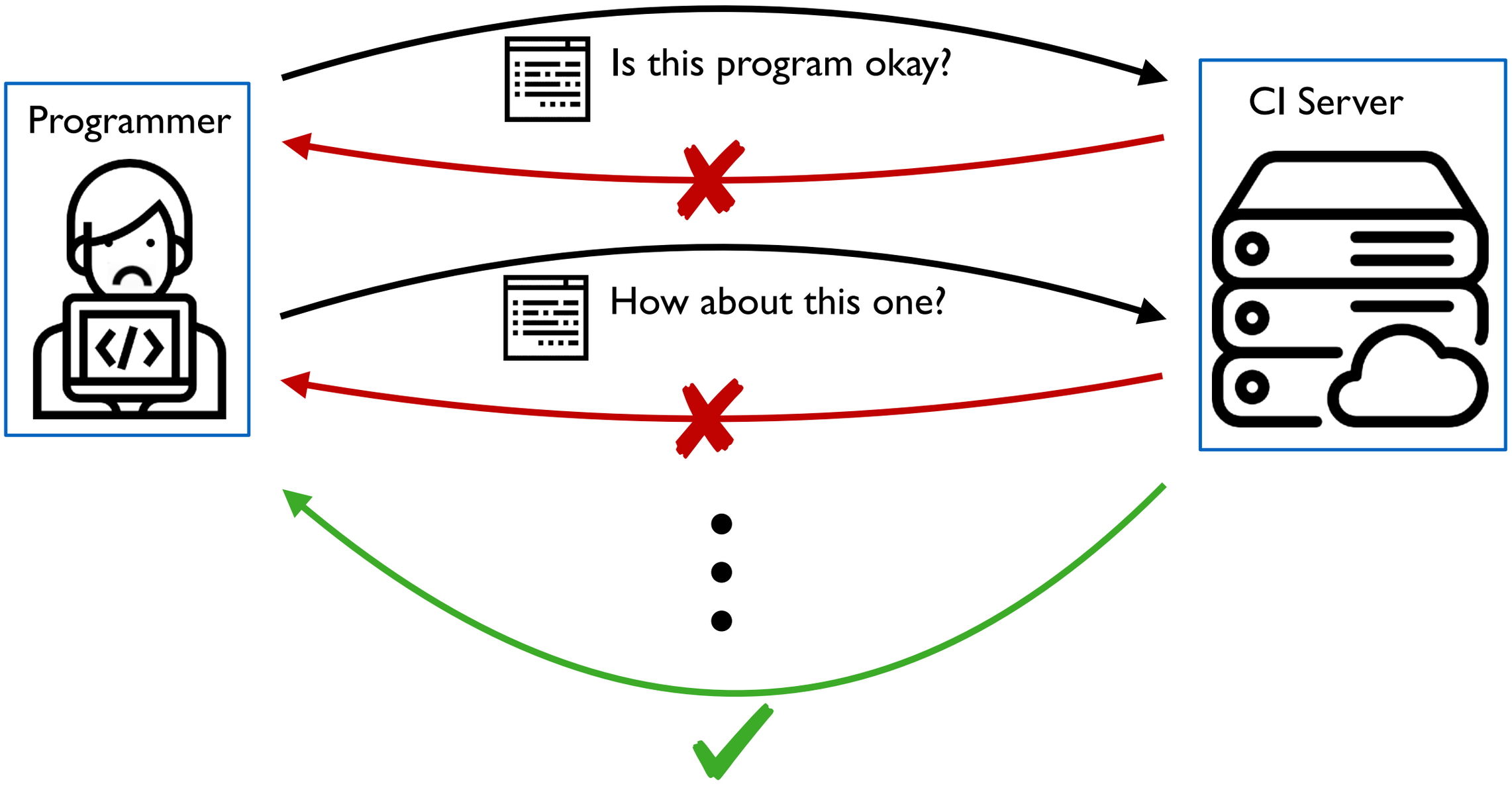

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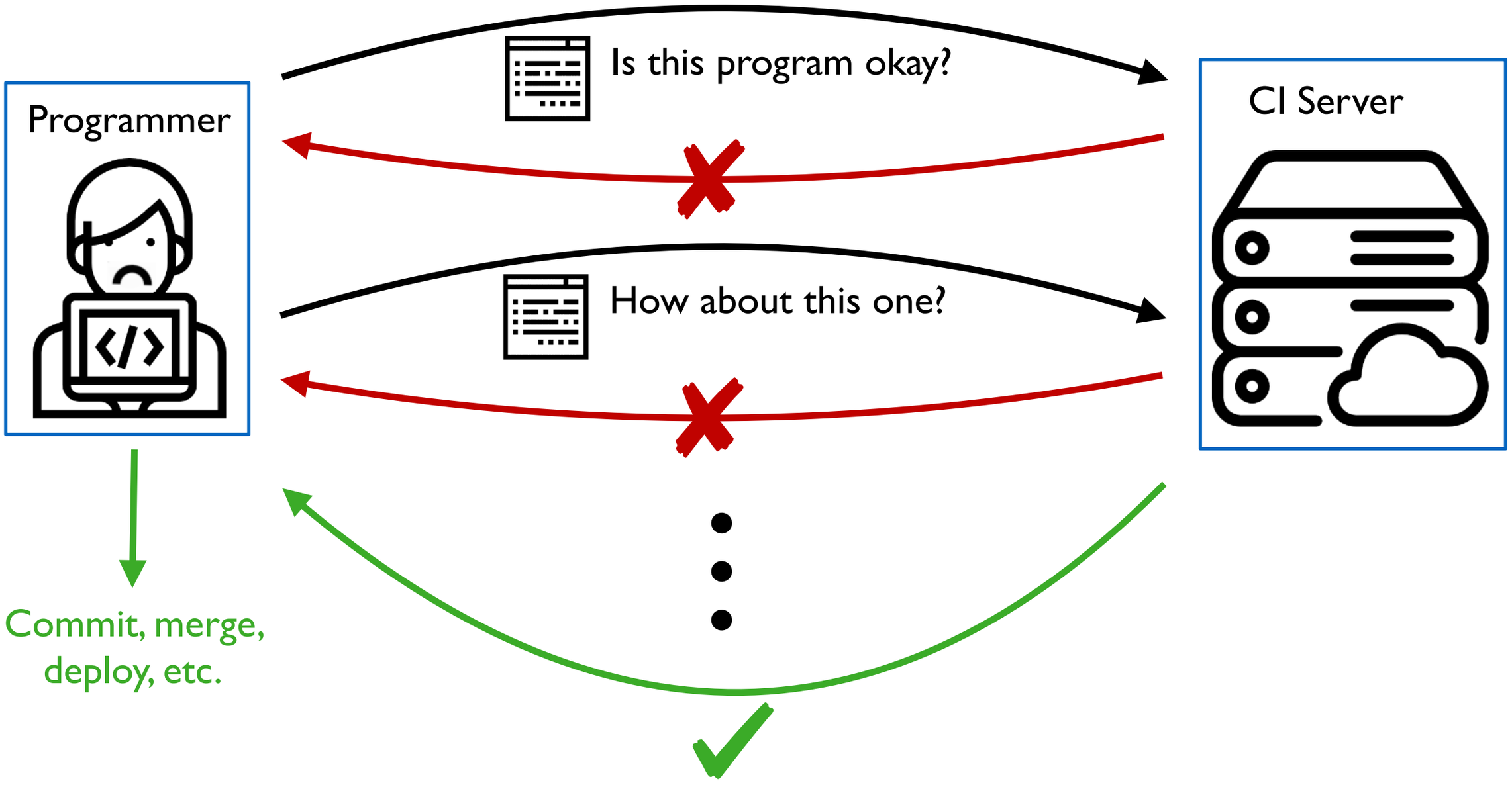

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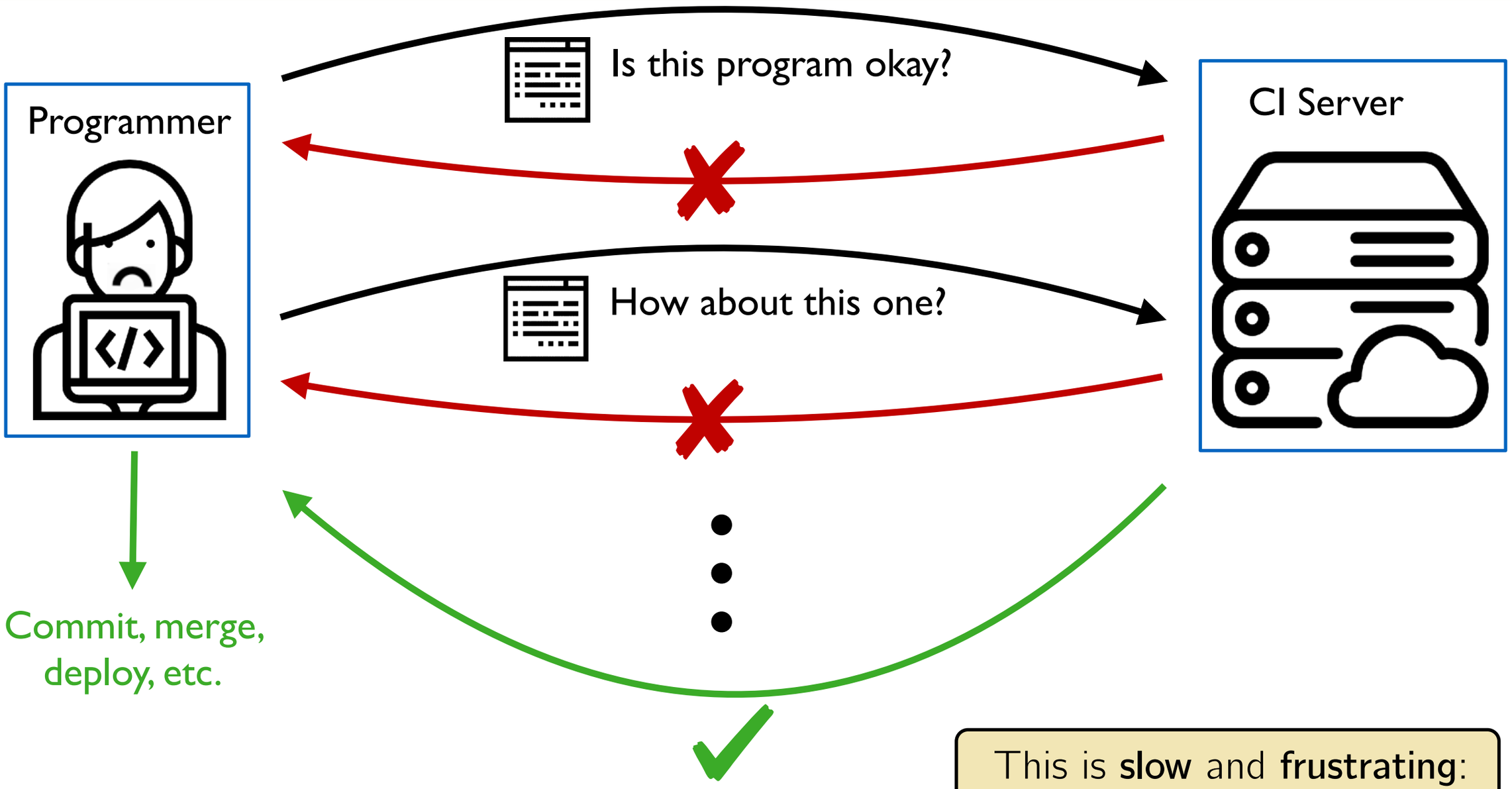
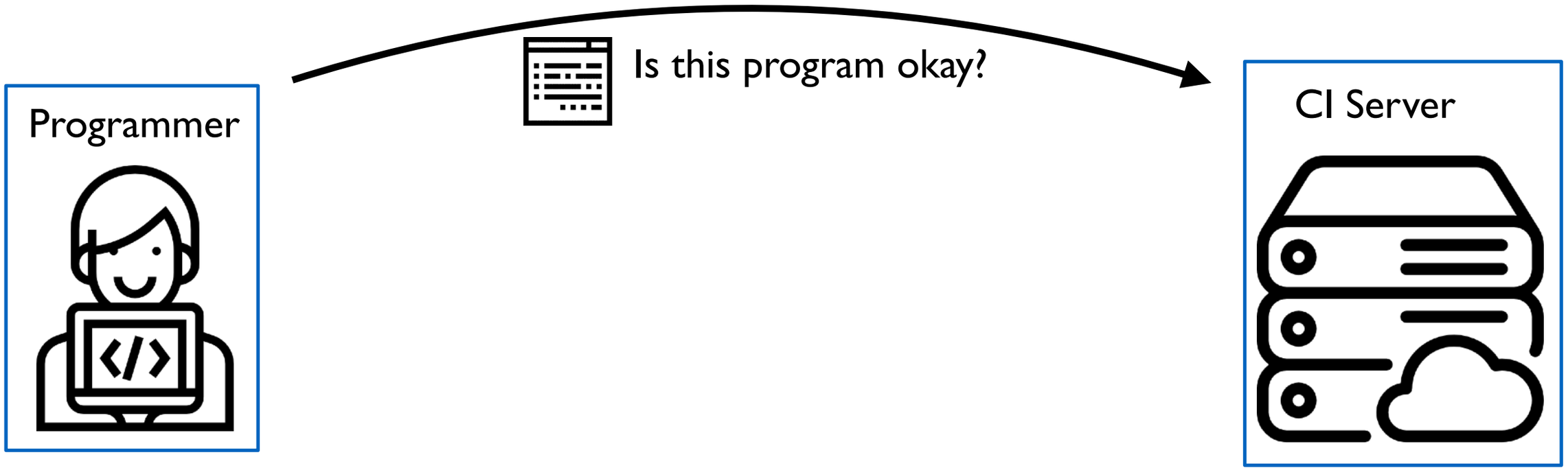


This is **slow** and **frustrating**: each iteration can be on the order of an hour or more.

Interactive Static Analysis Workflow



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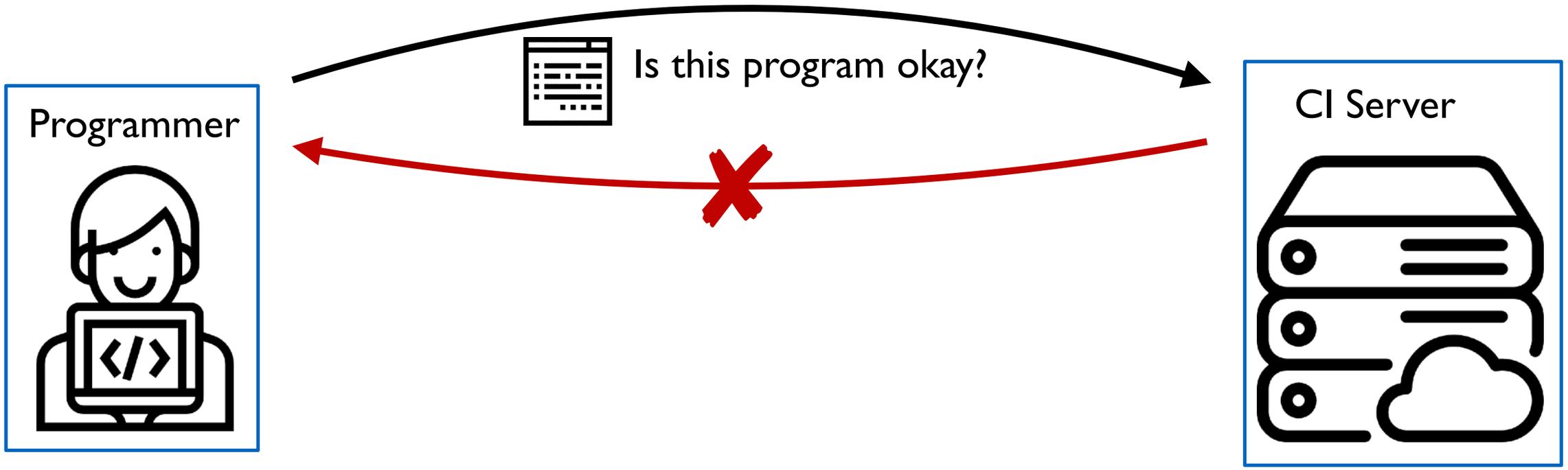

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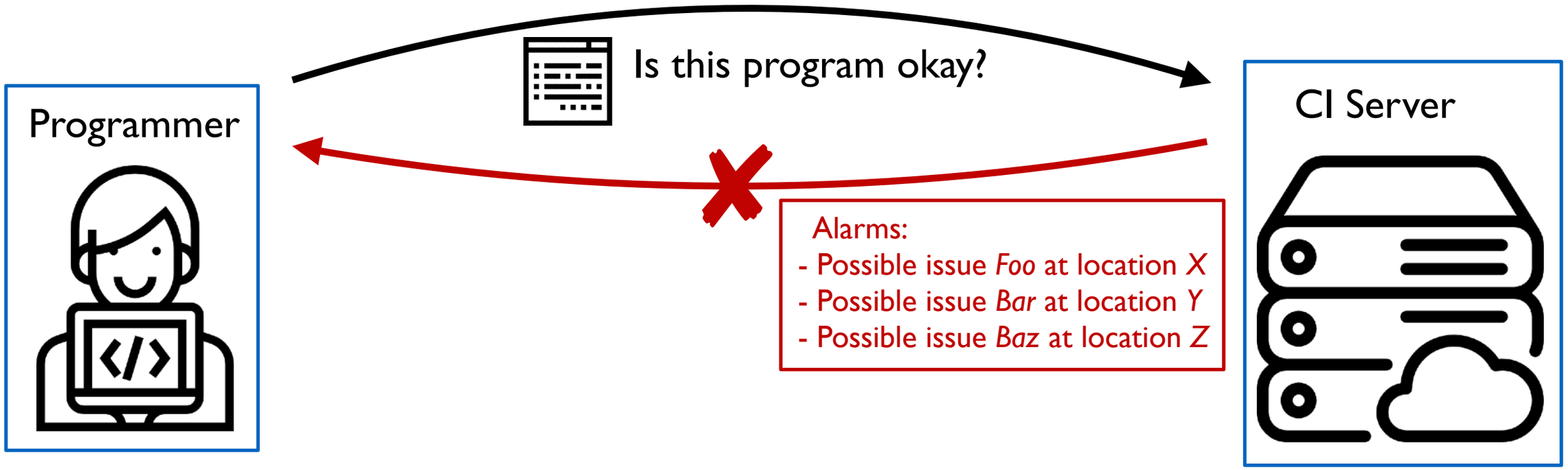

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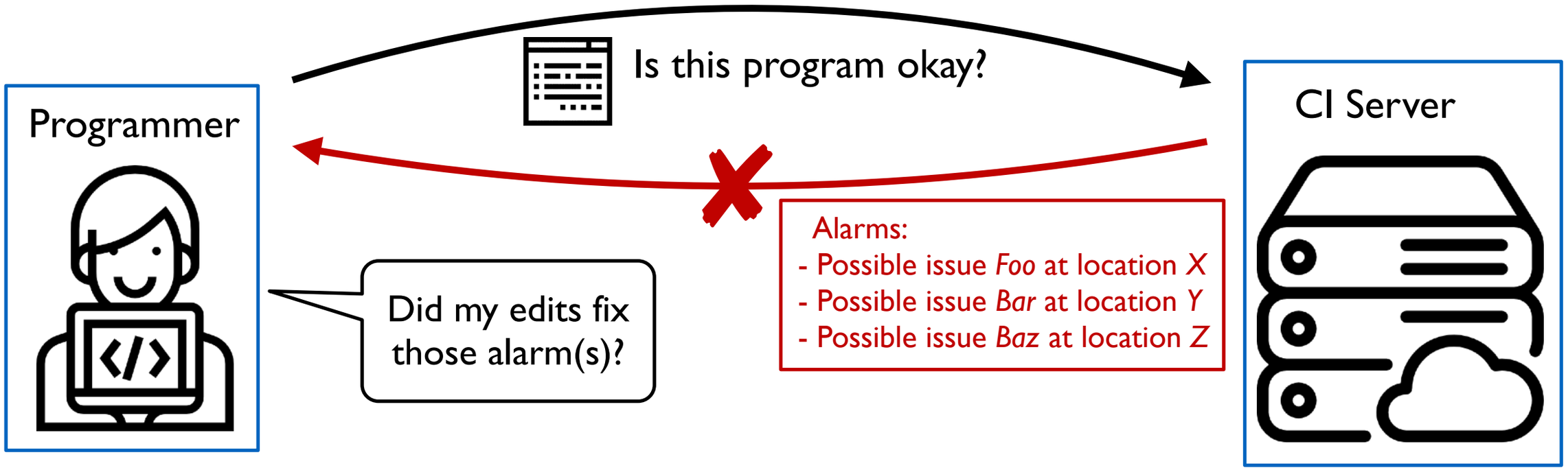

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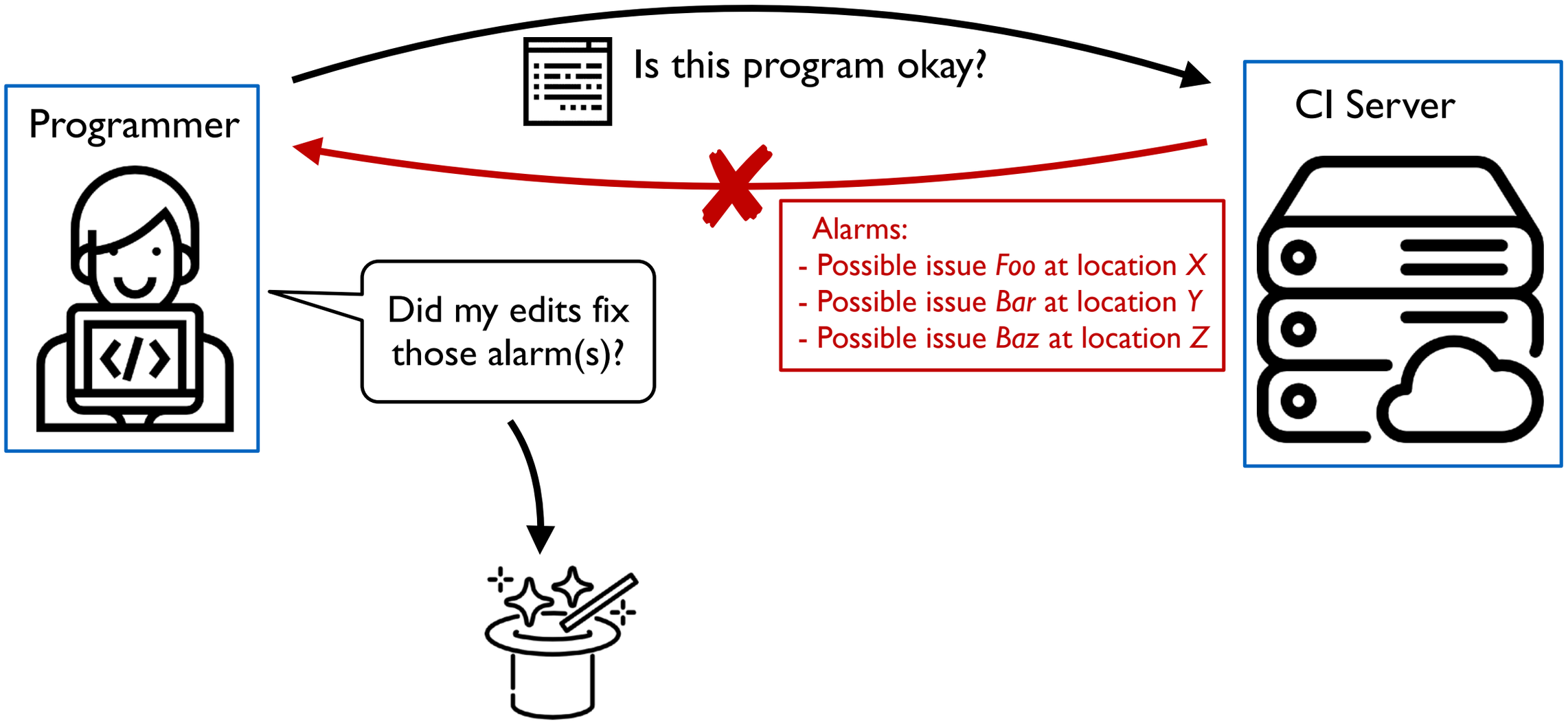

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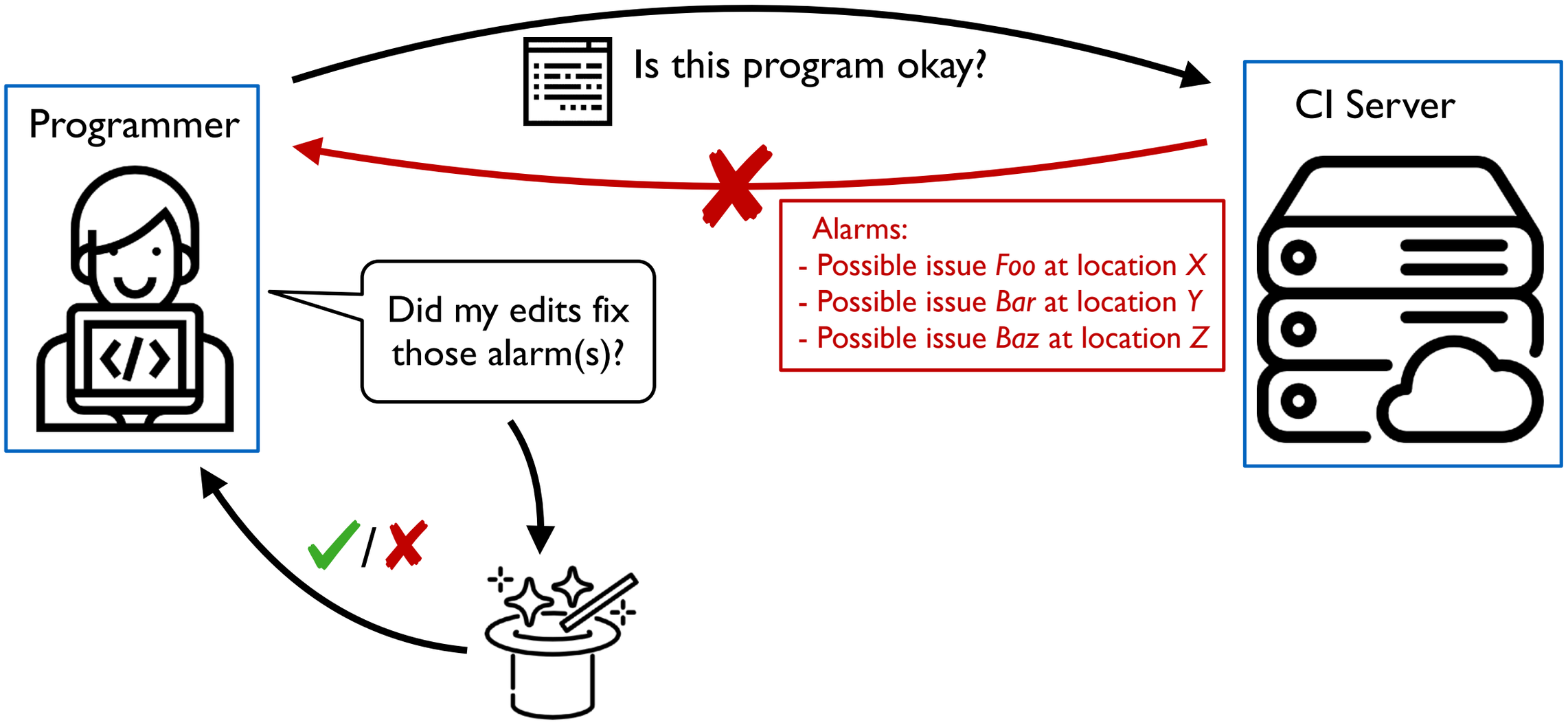

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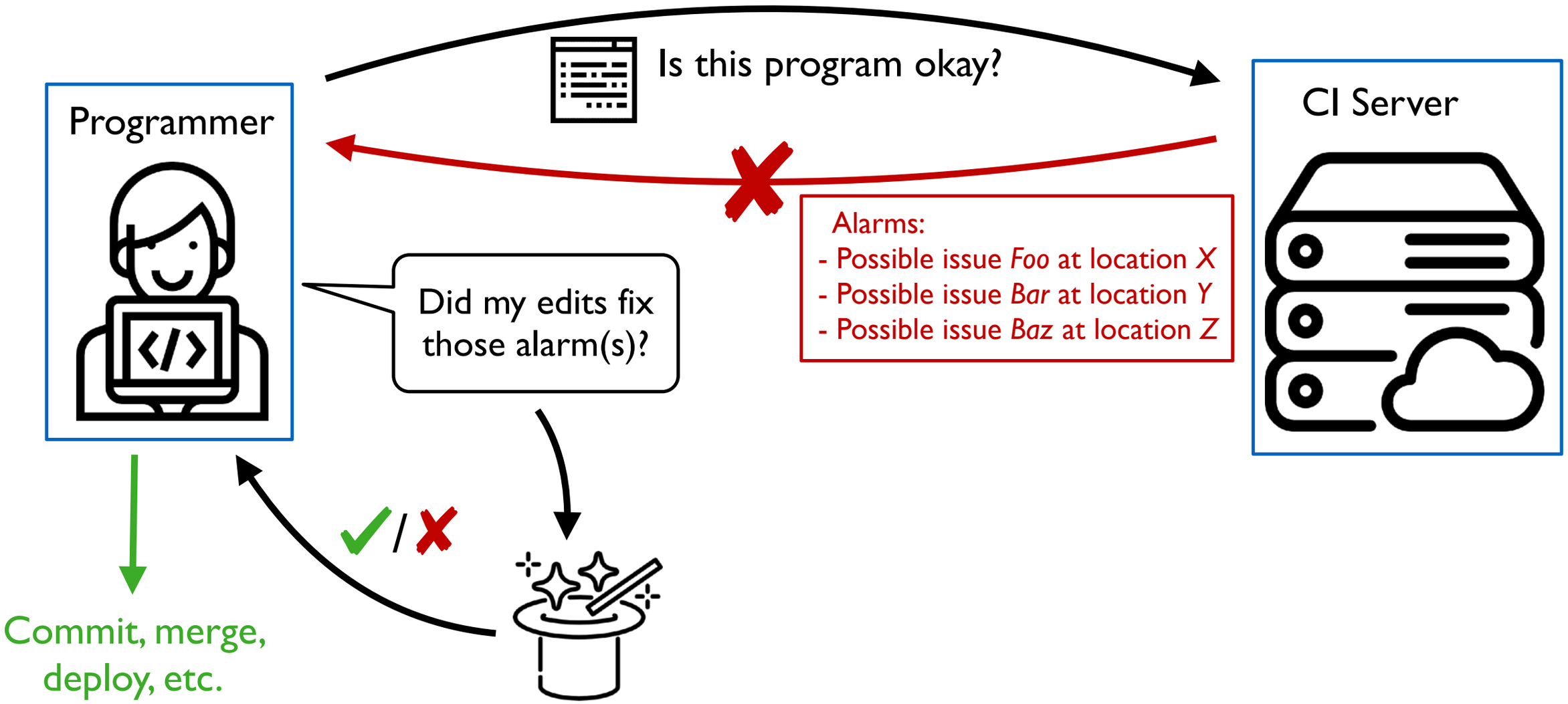

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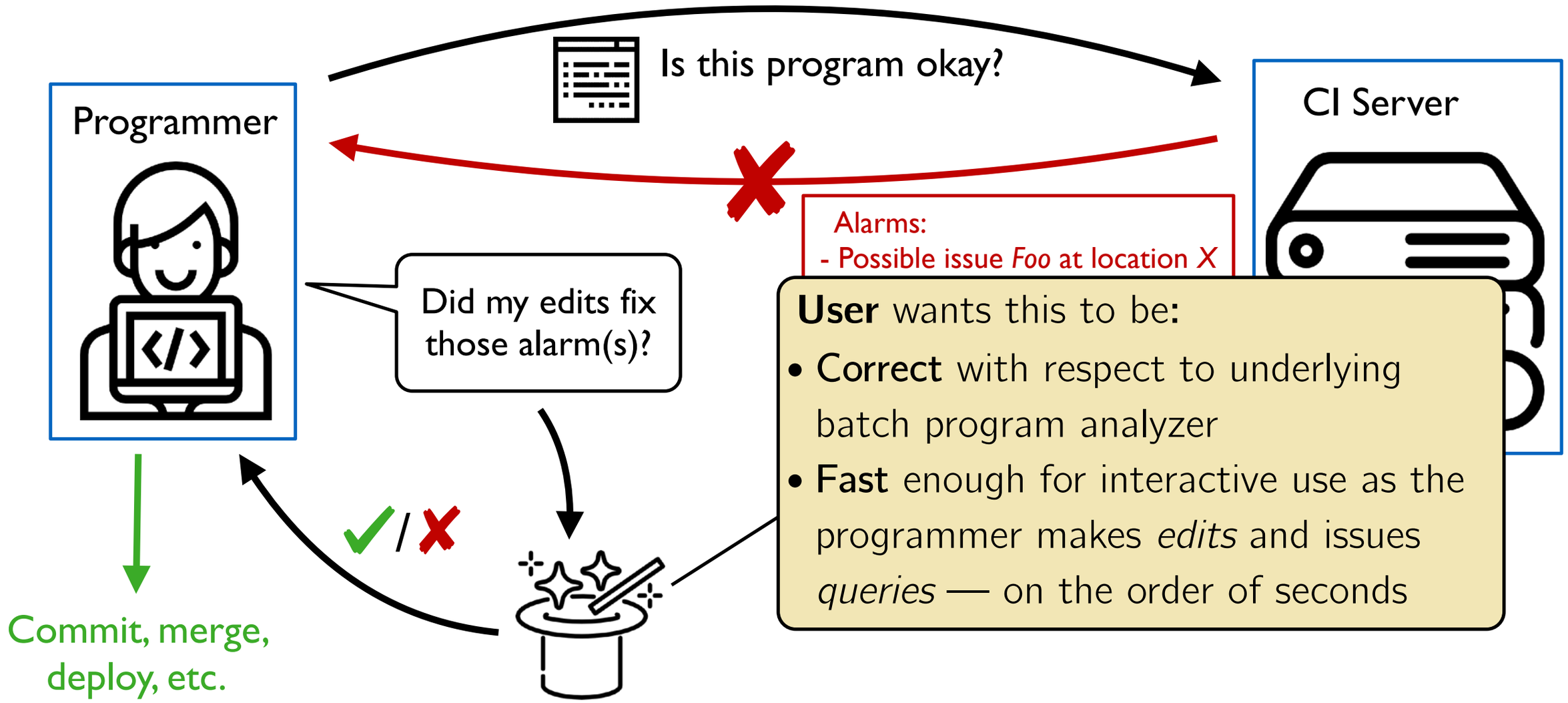

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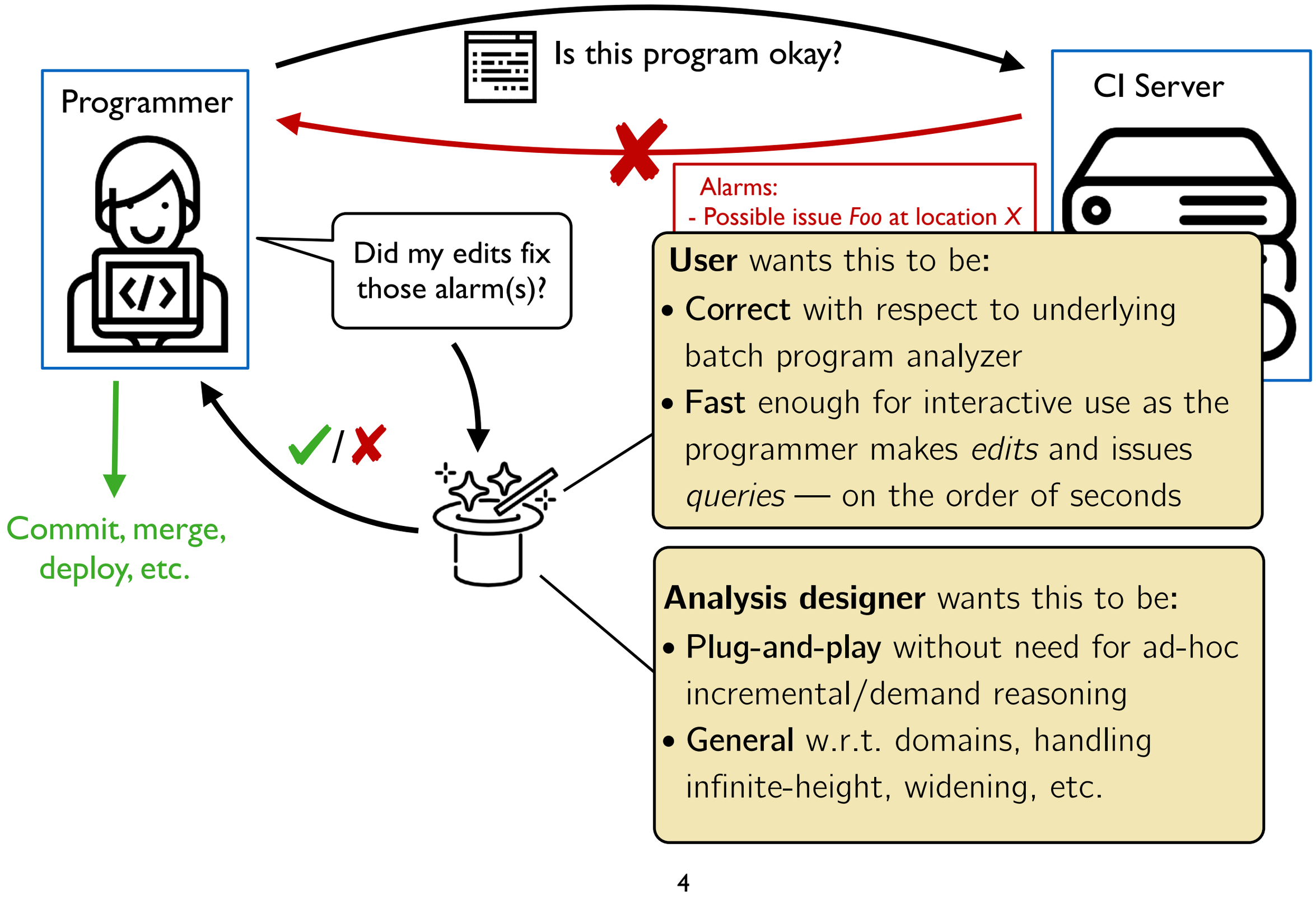

Batch Analysis

Incremental Analysis

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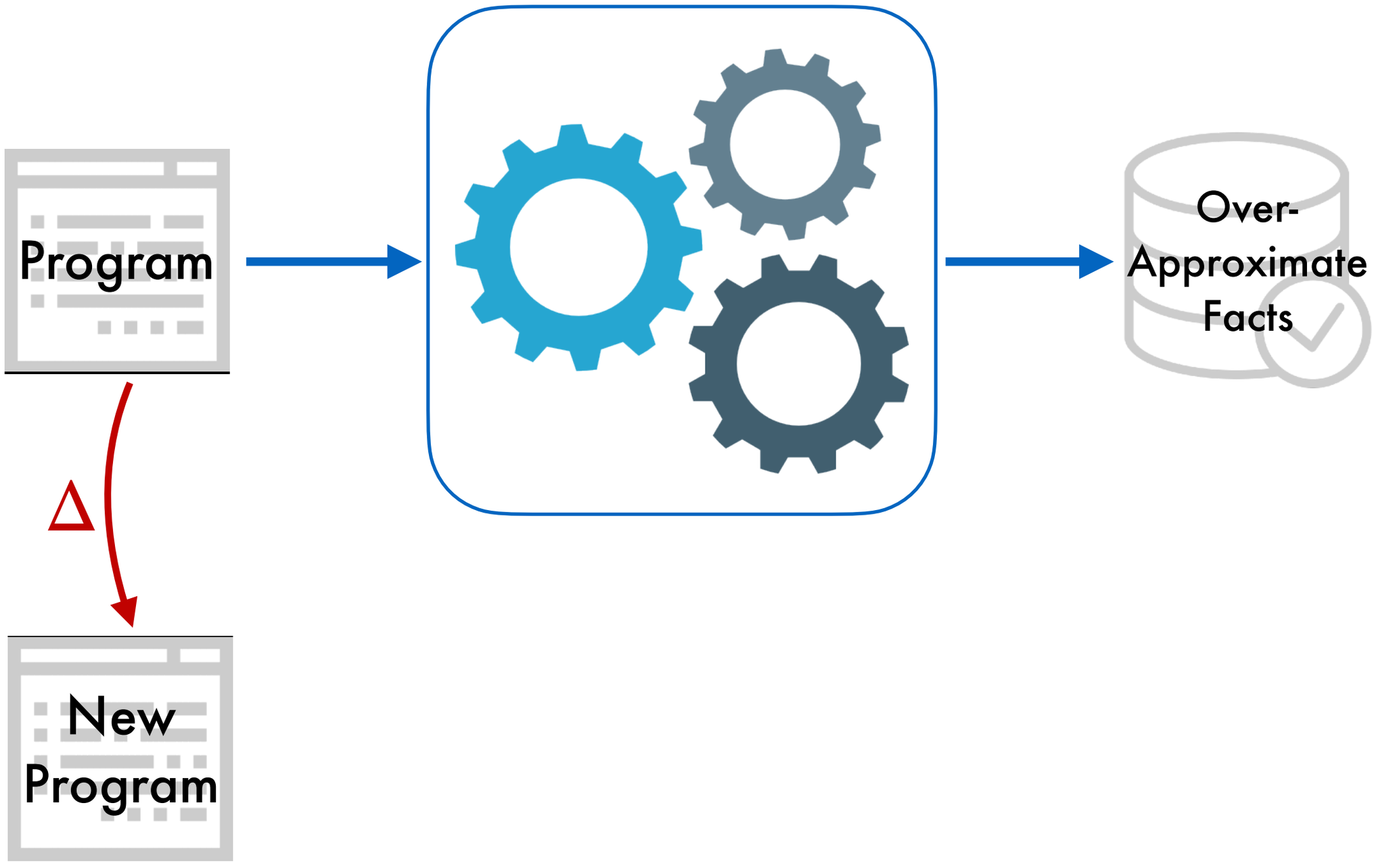

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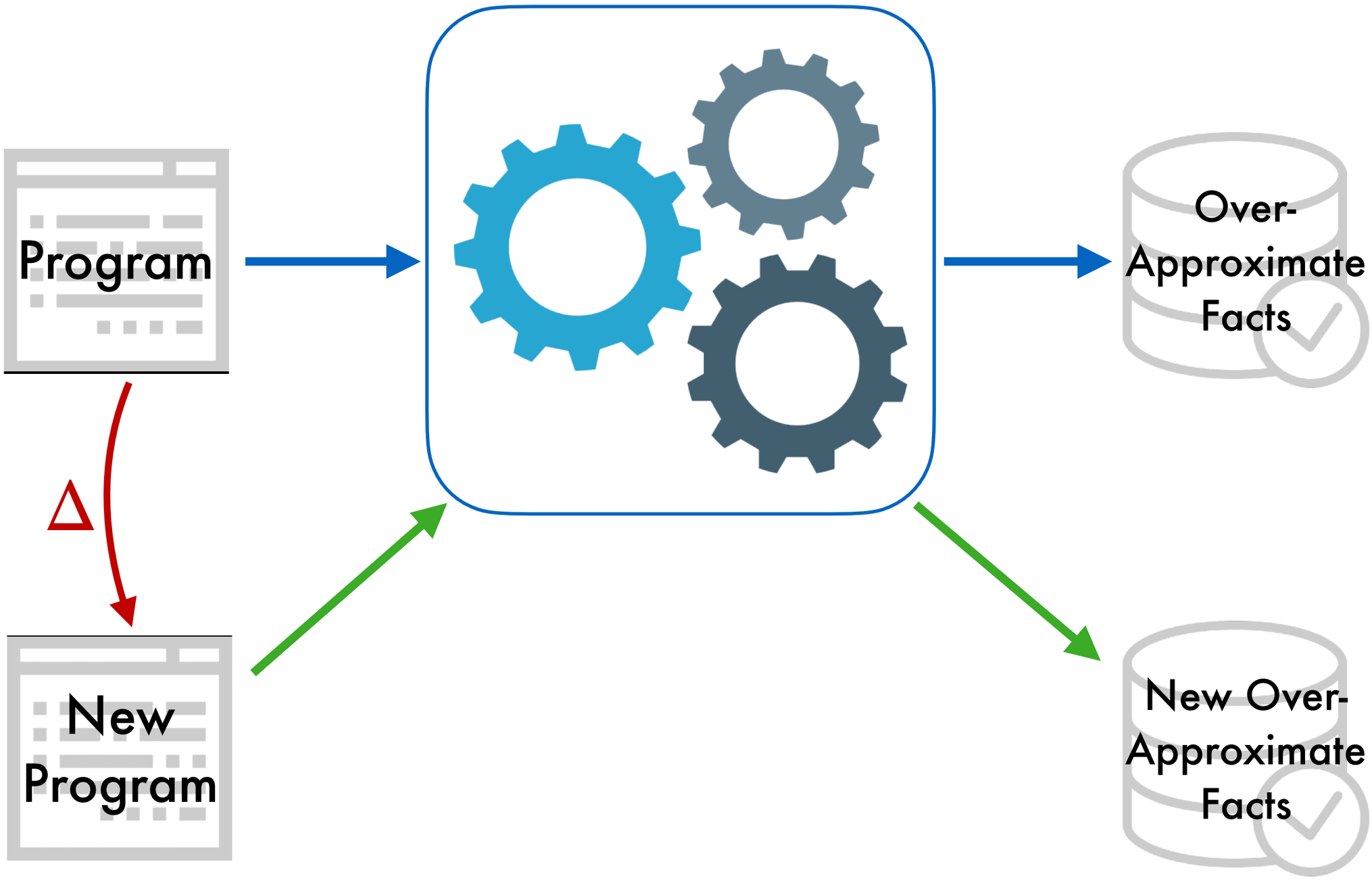

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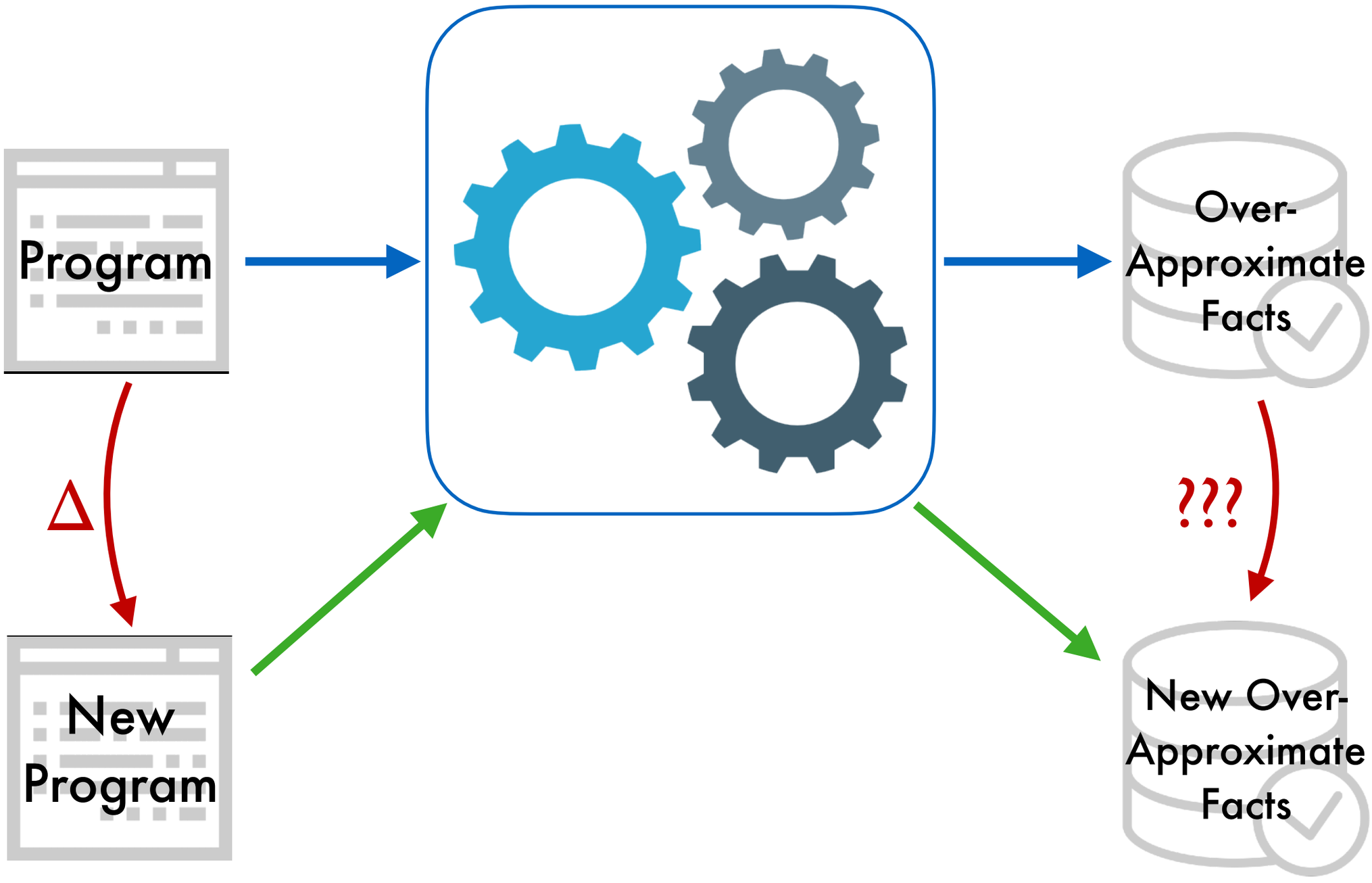
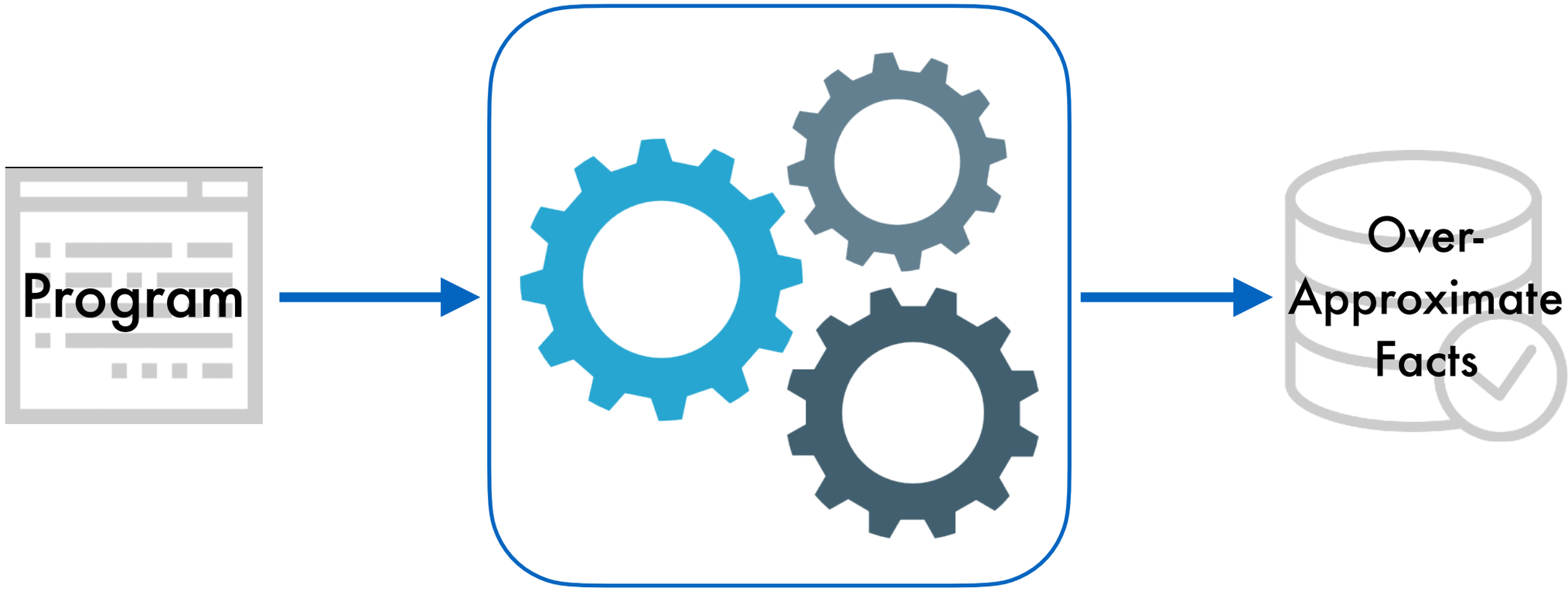


Incremental Analysis

Demand-Driven Analysis



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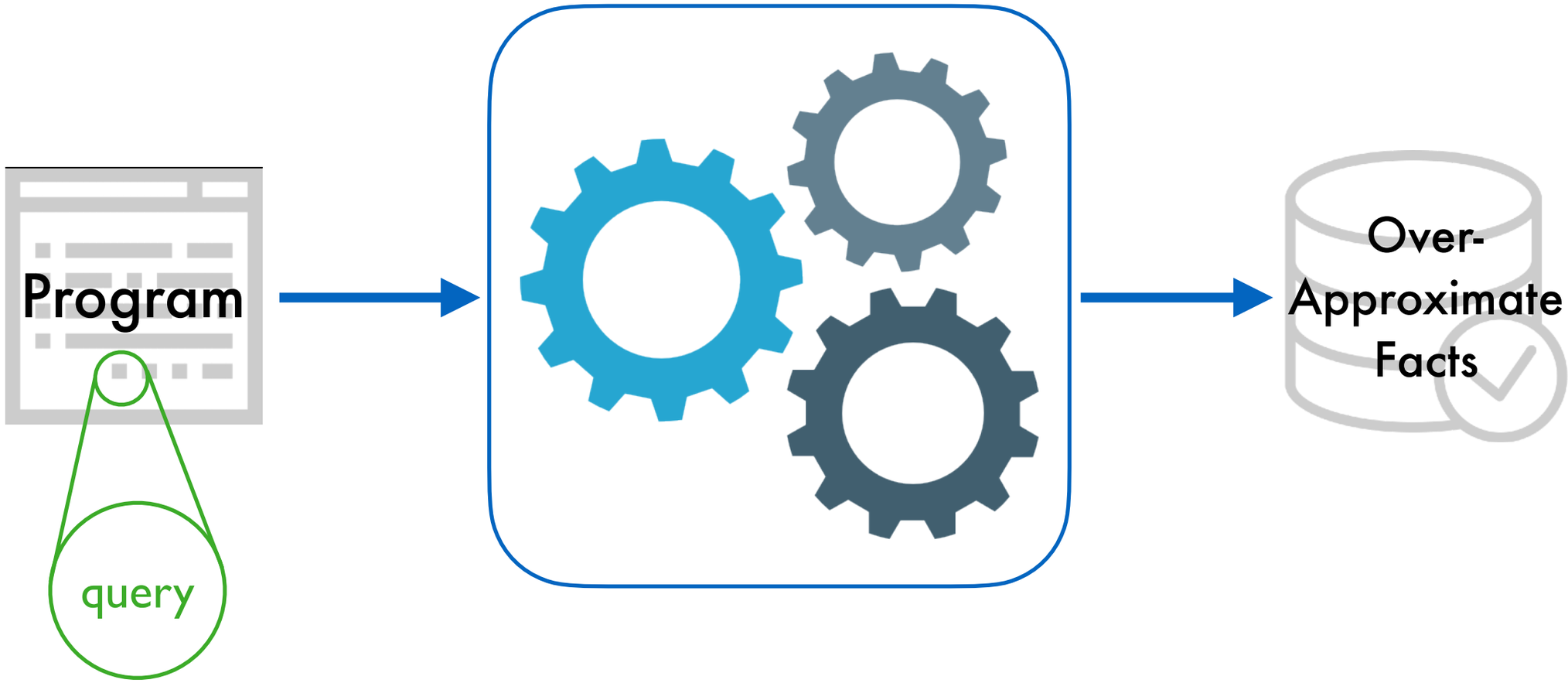

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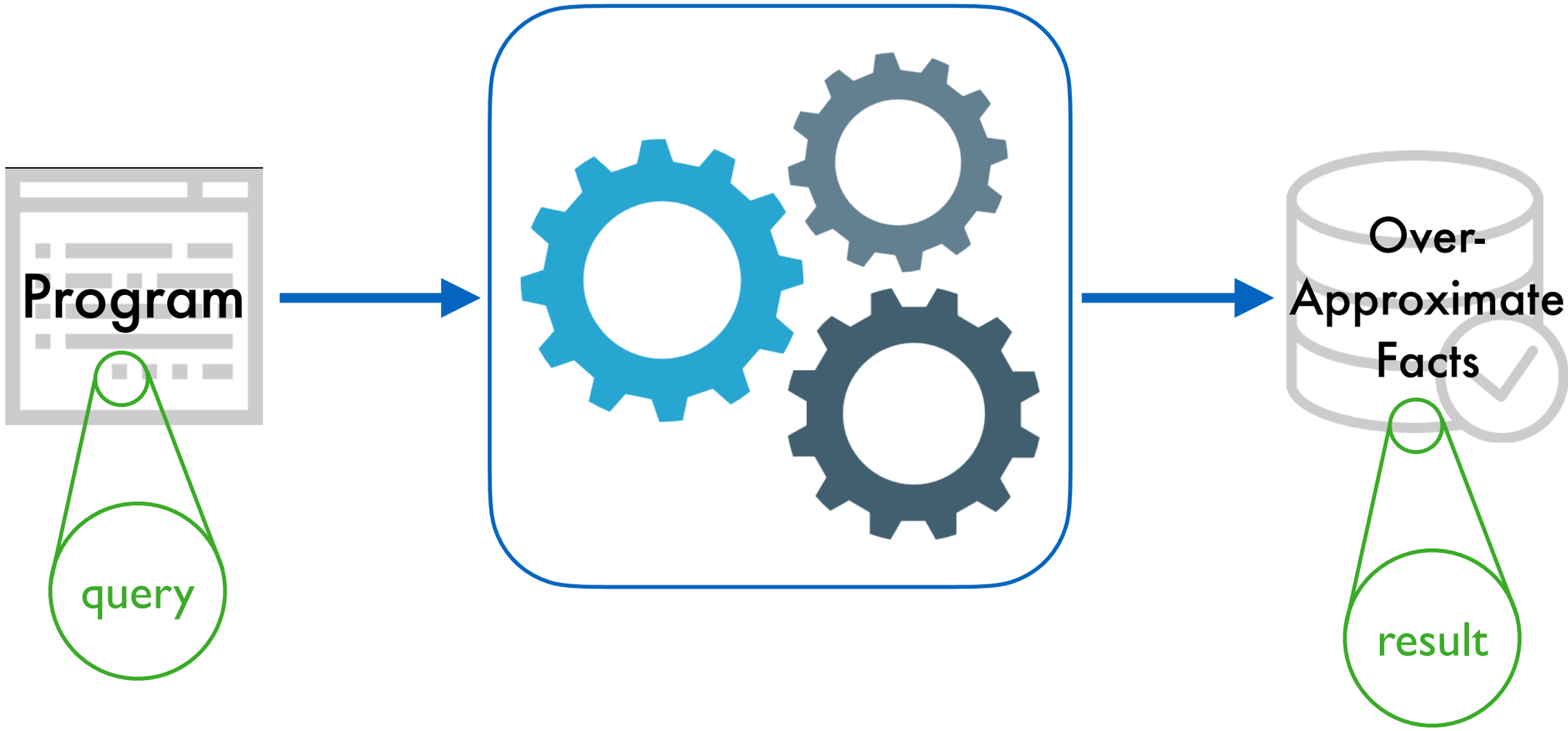

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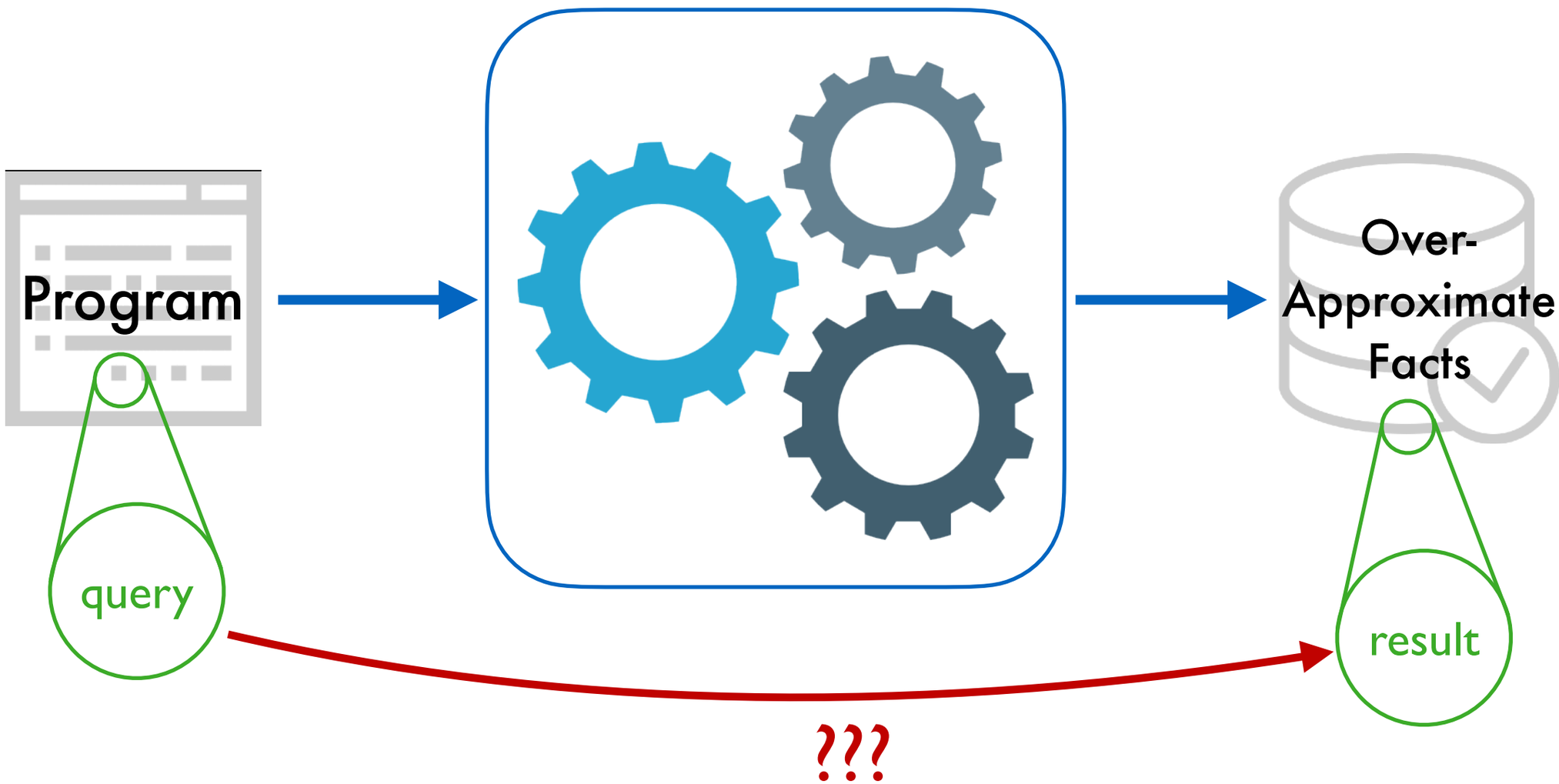
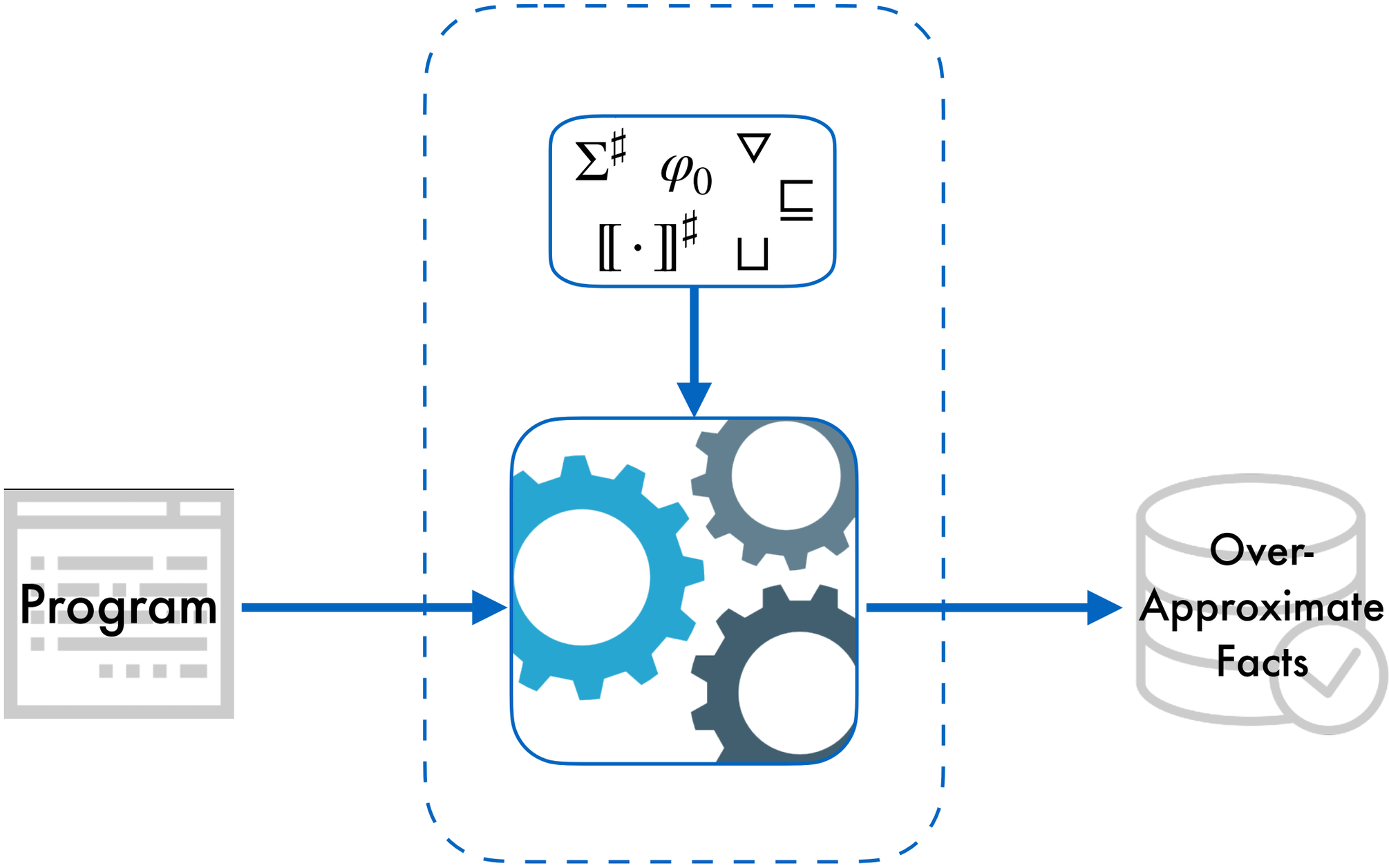


Abstract Interpretation



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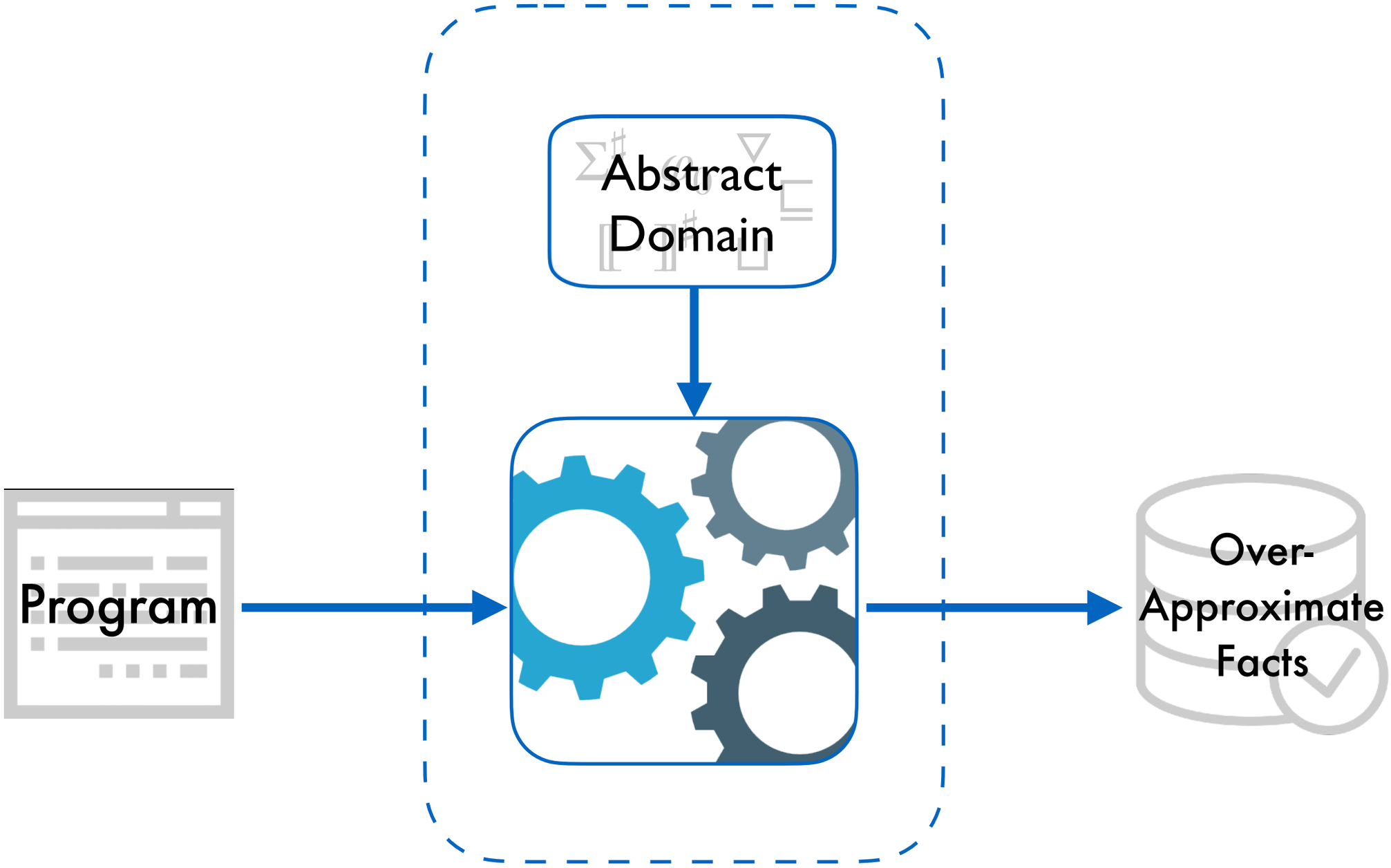

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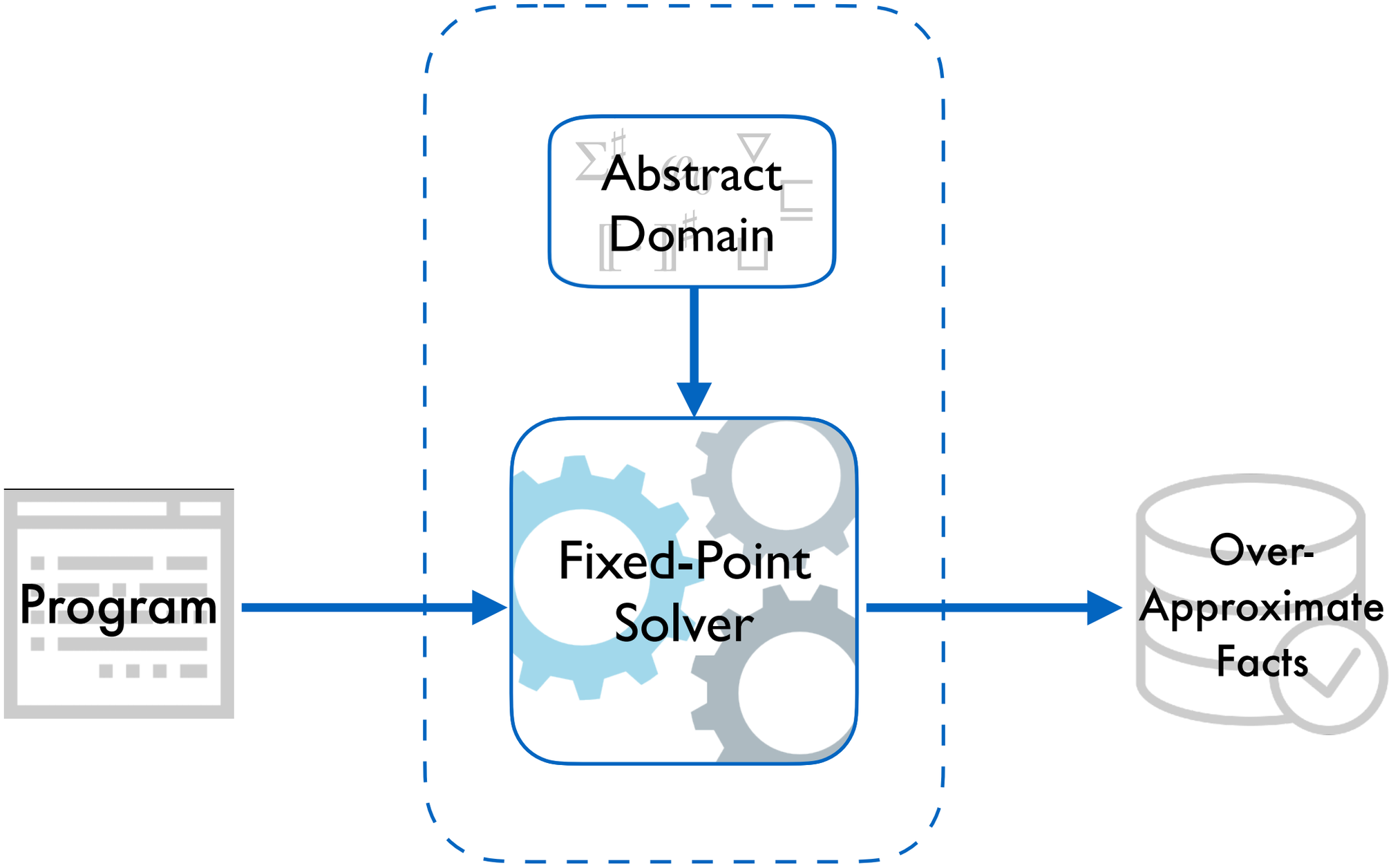
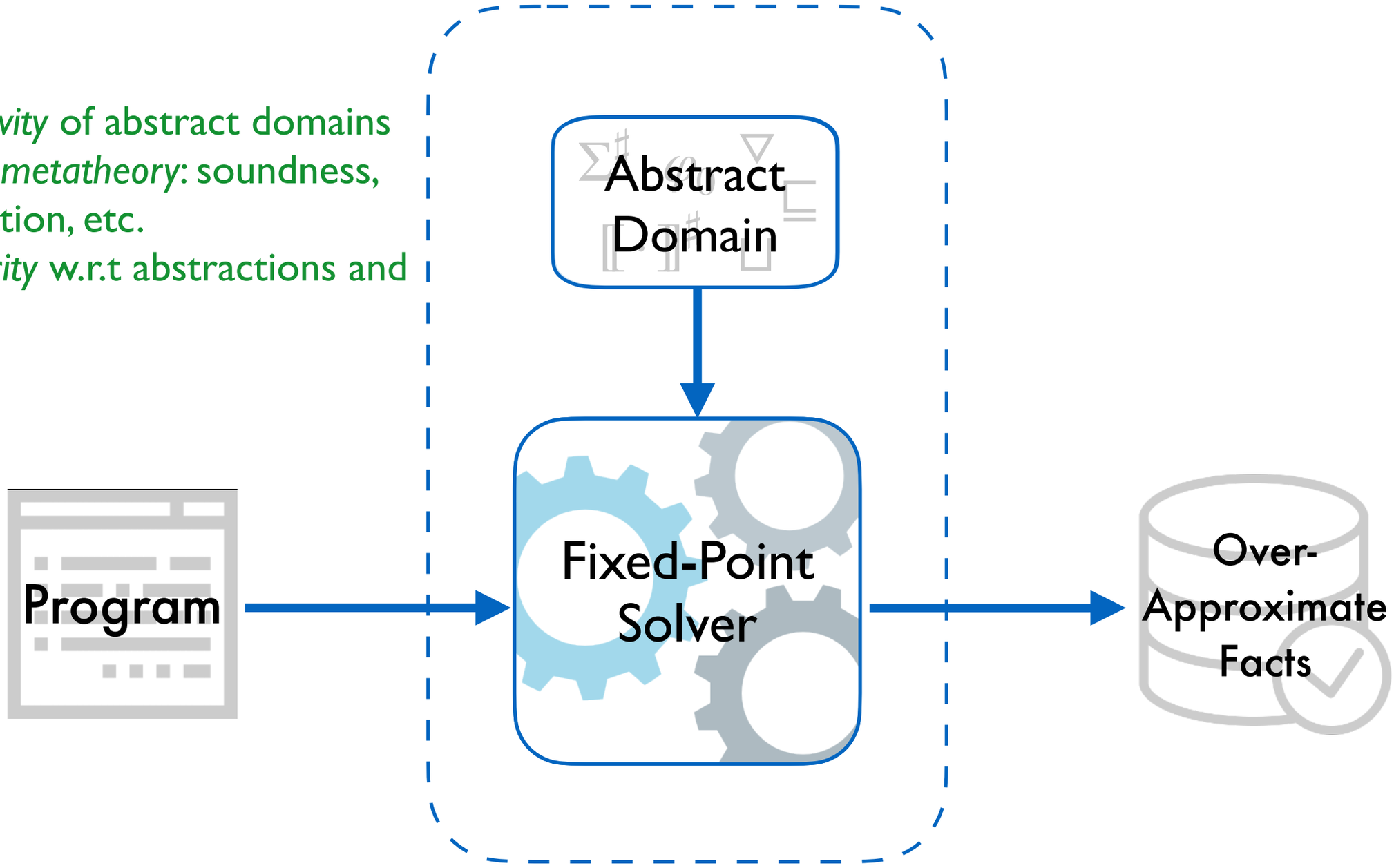


Abstract Interpretation

Pros:

- *Expressivity* of abstract domains
- Robust *metatheory*: soundness, termination, etc.
- *Modularity* w.r.t abstractions and solvers



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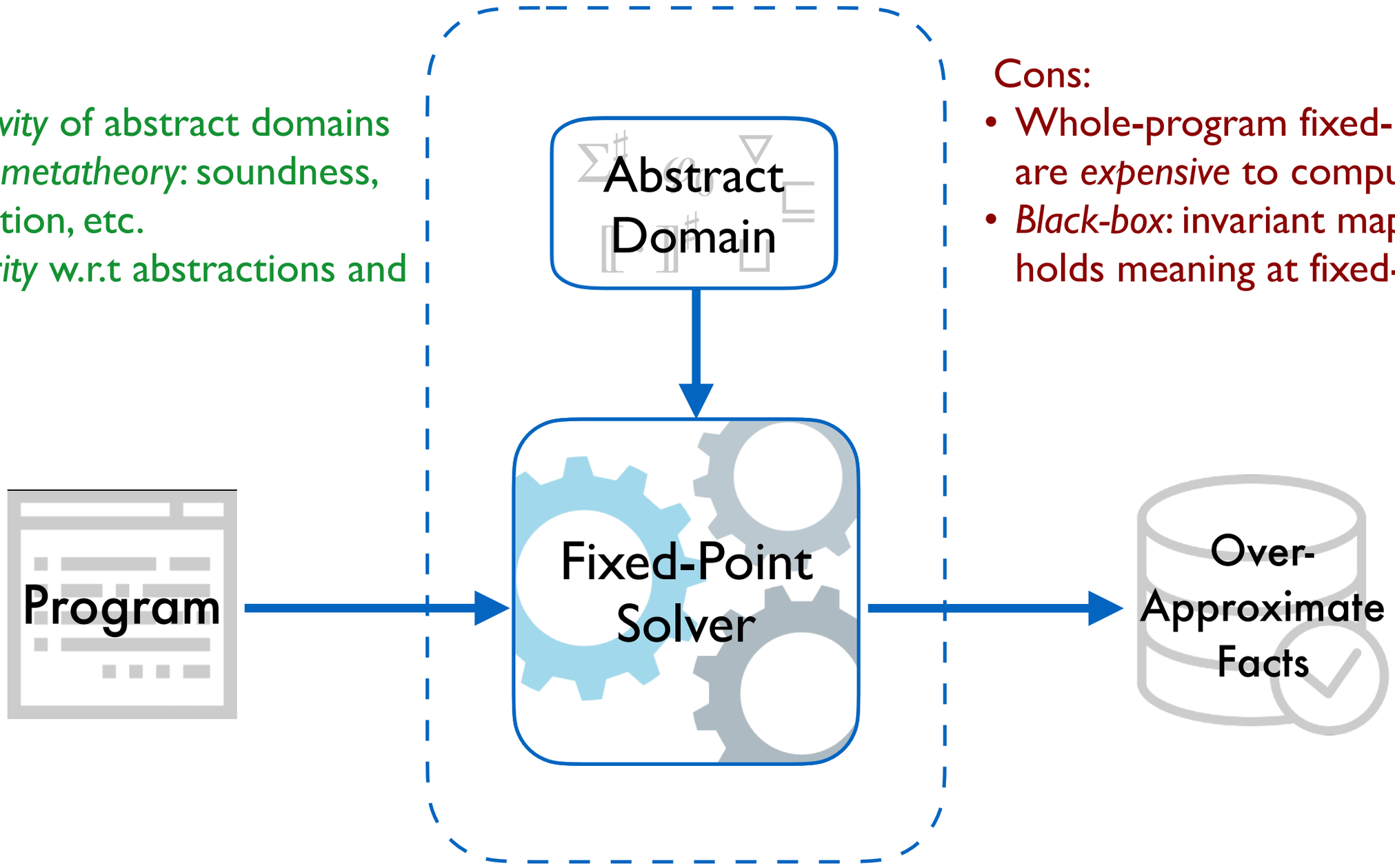
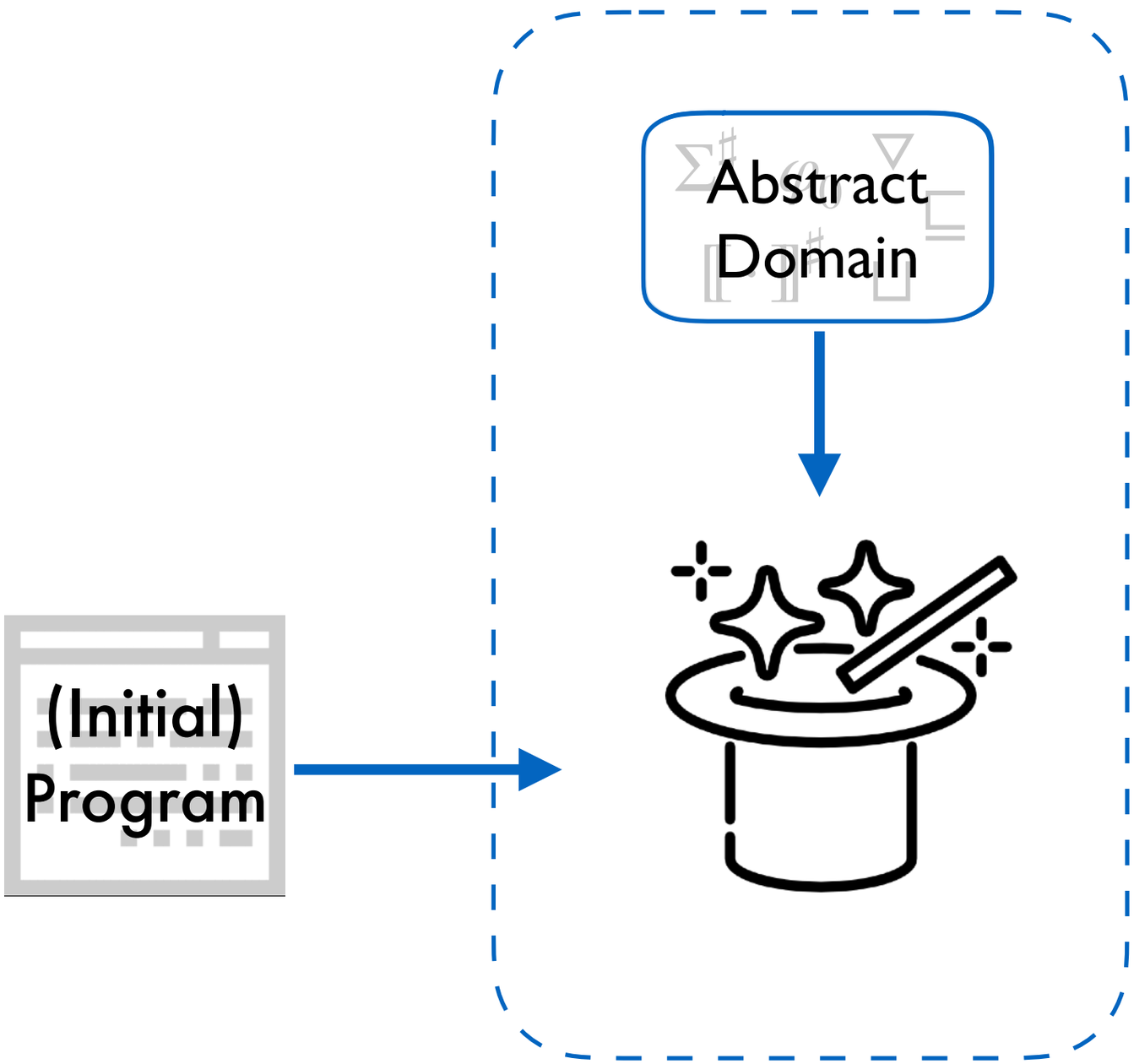


Cons:

- Whole-program fixed-points are *expensive* to compute
- *Black-box*: invariant map only holds meaning at fixed-point

Demanded Abstract Interpretation



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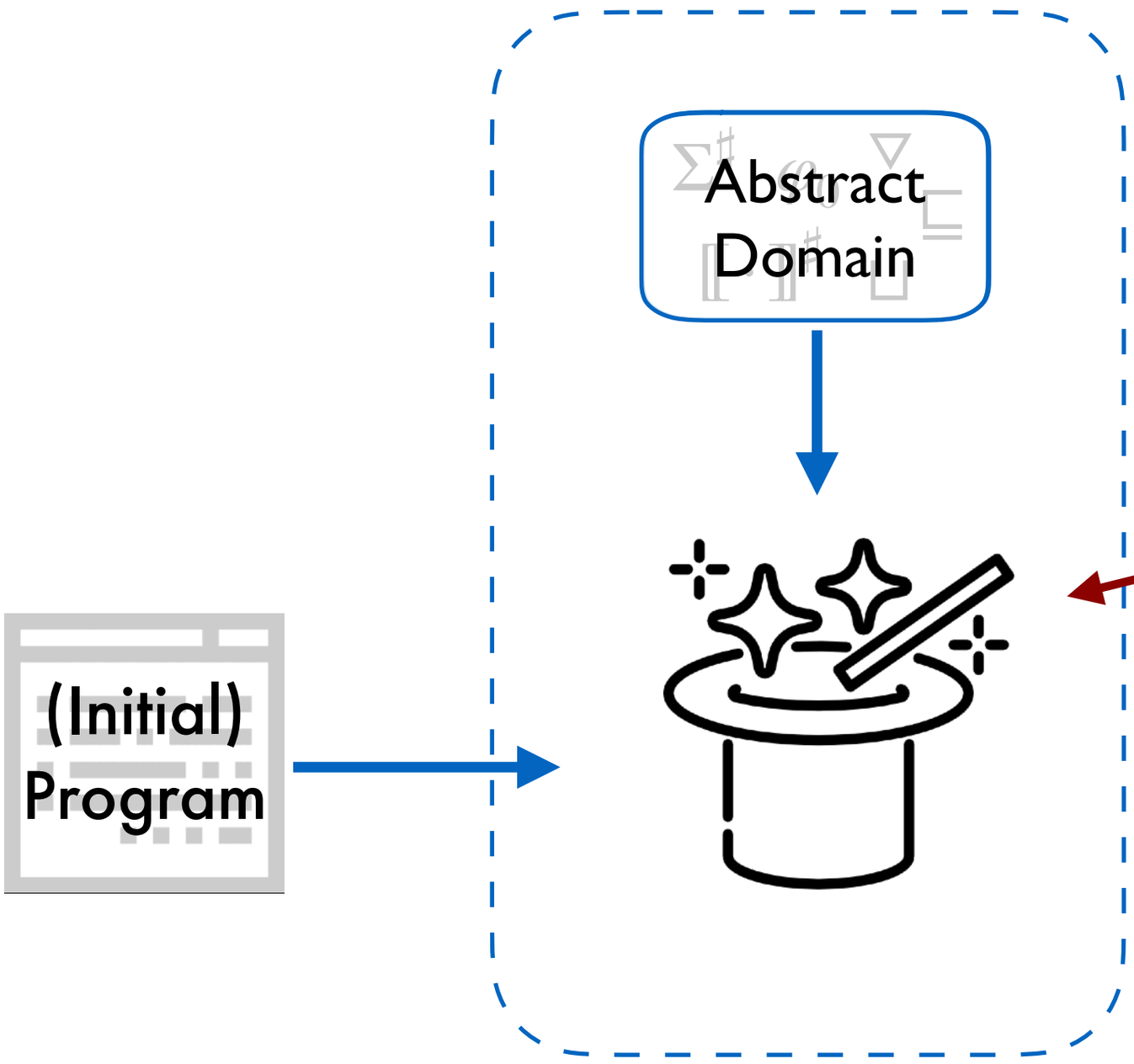

Demand-driven queries
"What is the abstract state at this program location?"

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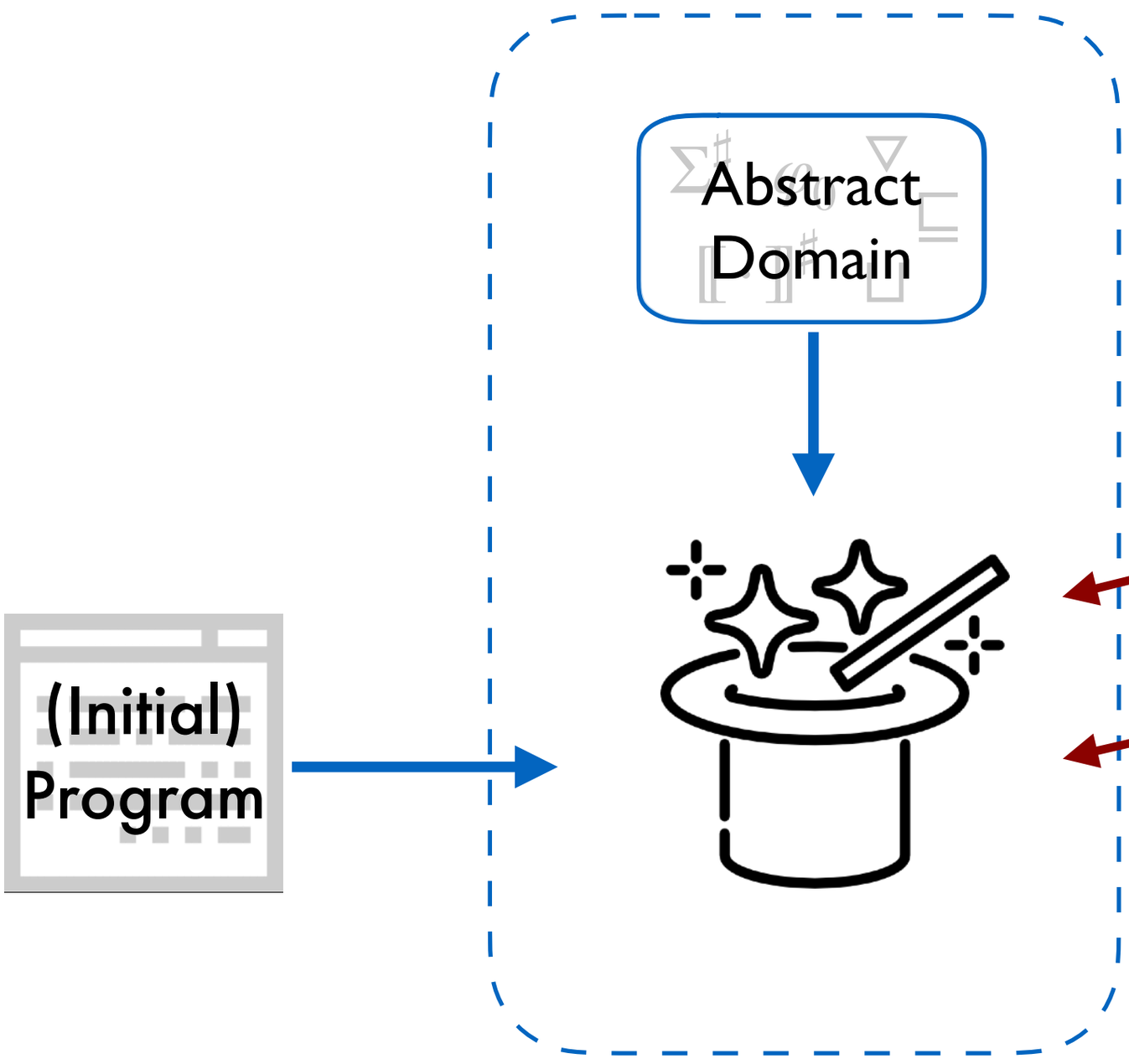

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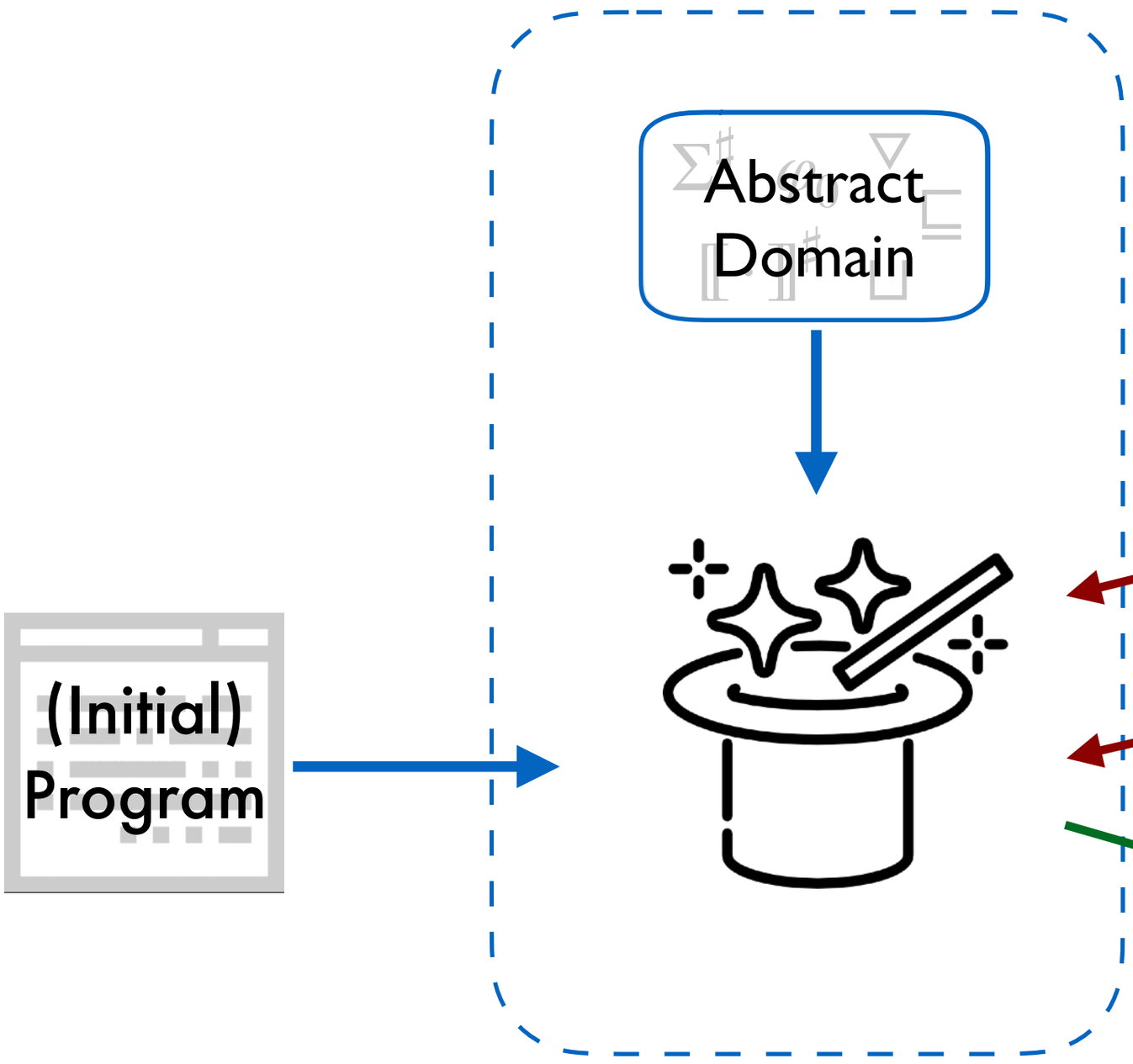

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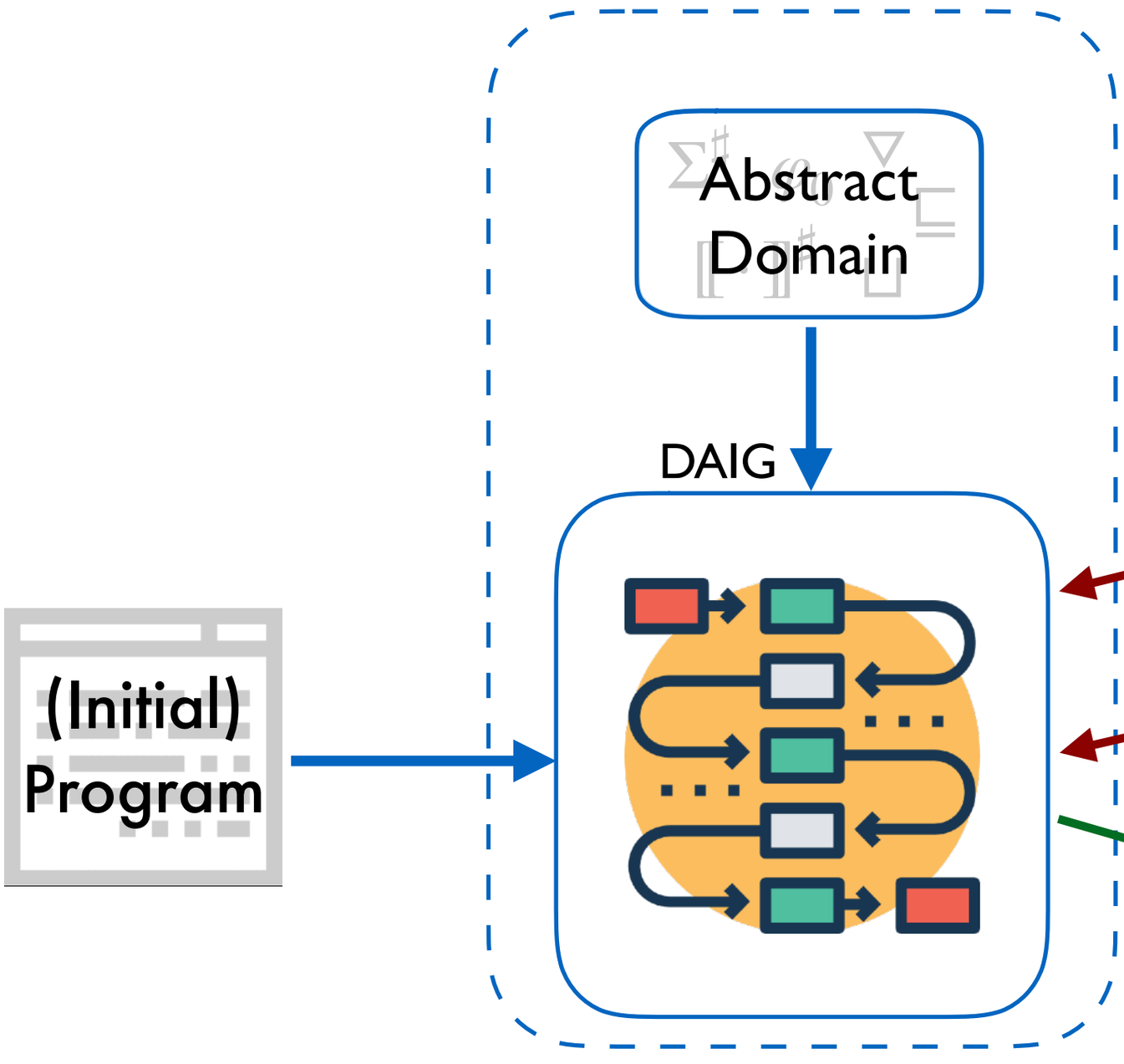
From-scratch consistent results
Query responses are guaranteed identical to batch analysis on current program version

Demanded Abstract Interpretation Graphs (DAIGs)



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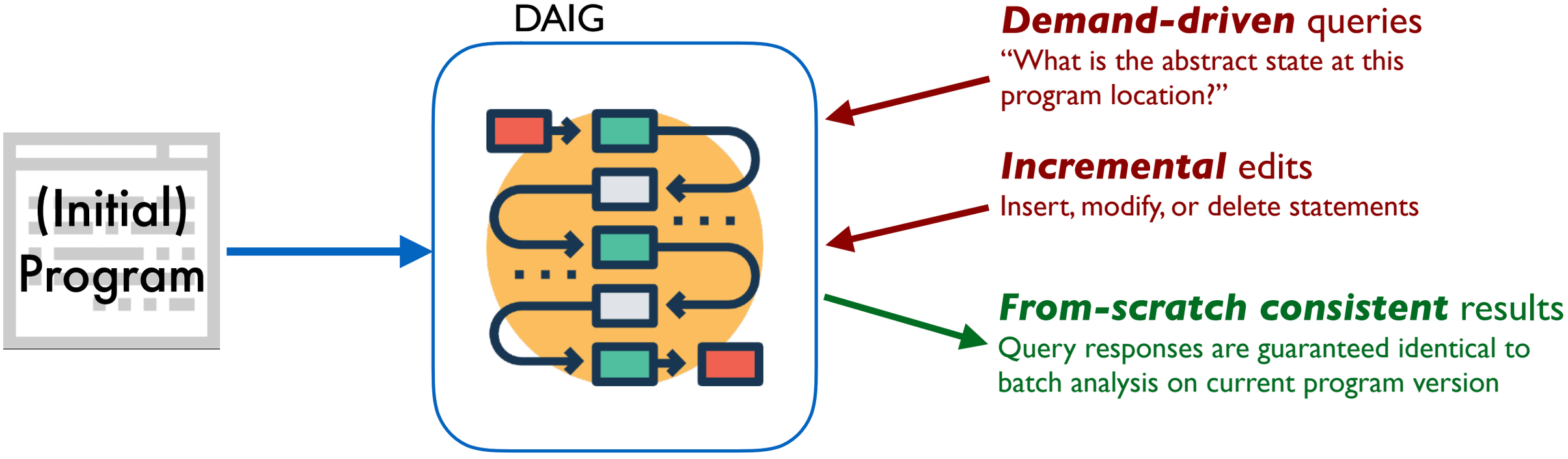
A **DAIG** reifies the *dependency* structure of an abstract interpretation.



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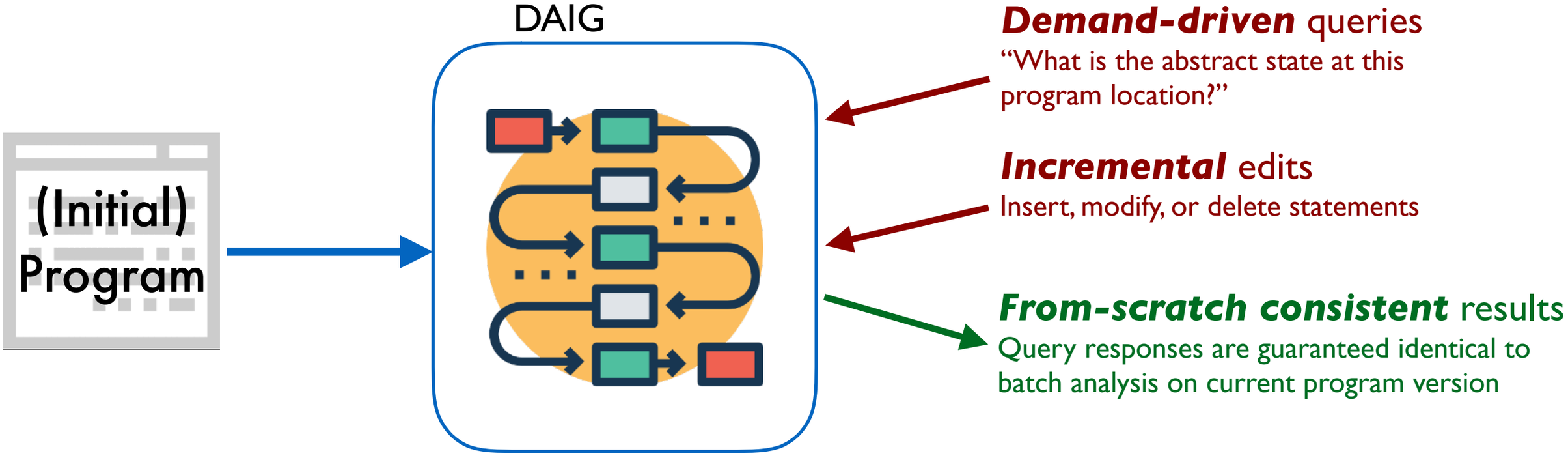
Reference cell vertices...

... contain intermediate analysis results & program syntax

... are uniquely named and potentially empty



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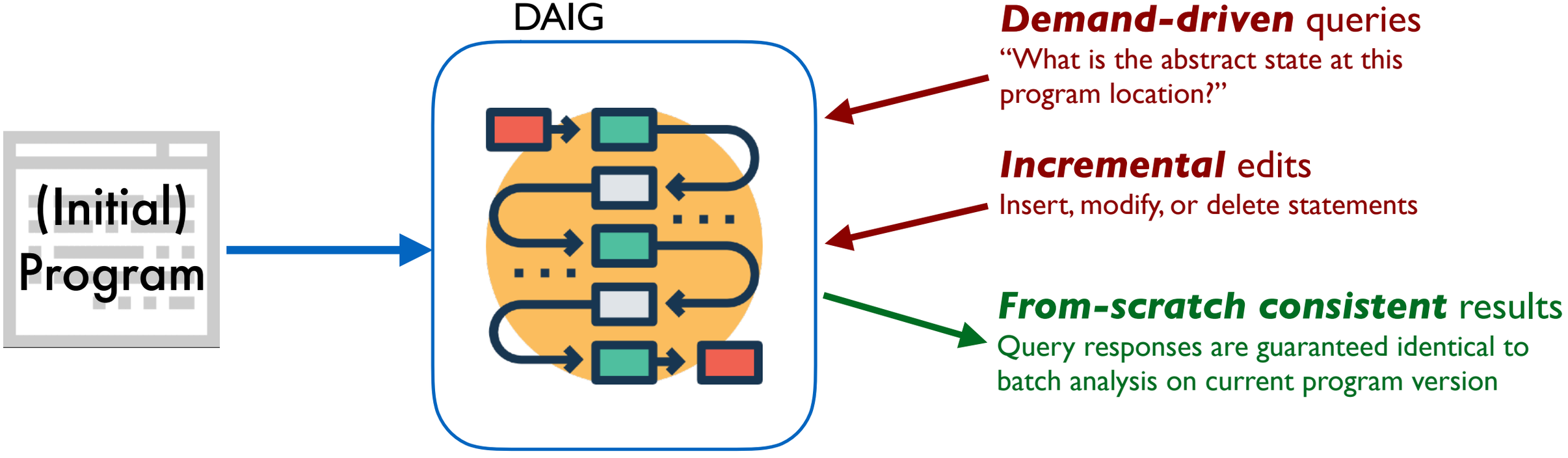
... acyclically connect reference cells

... denote analysis computations (e.g. $[\![\cdot]\!]^\sharp, \sqcup, \nabla$)



Contributions

A **DAIG** reifies the *dependency* structure of an abstract interpretation.

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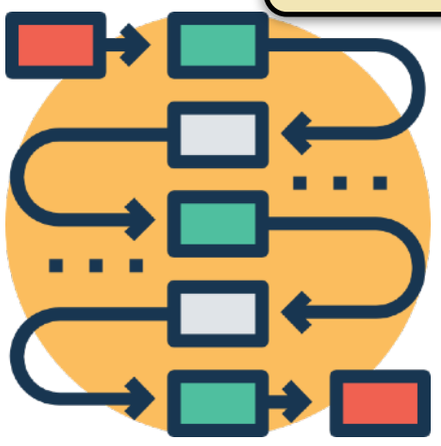
Finite & **acyclic** dependency graph, supporting incremental **and** demand-driven evaluation

ven queries

ct state at this

(Initial) Program

DAIG



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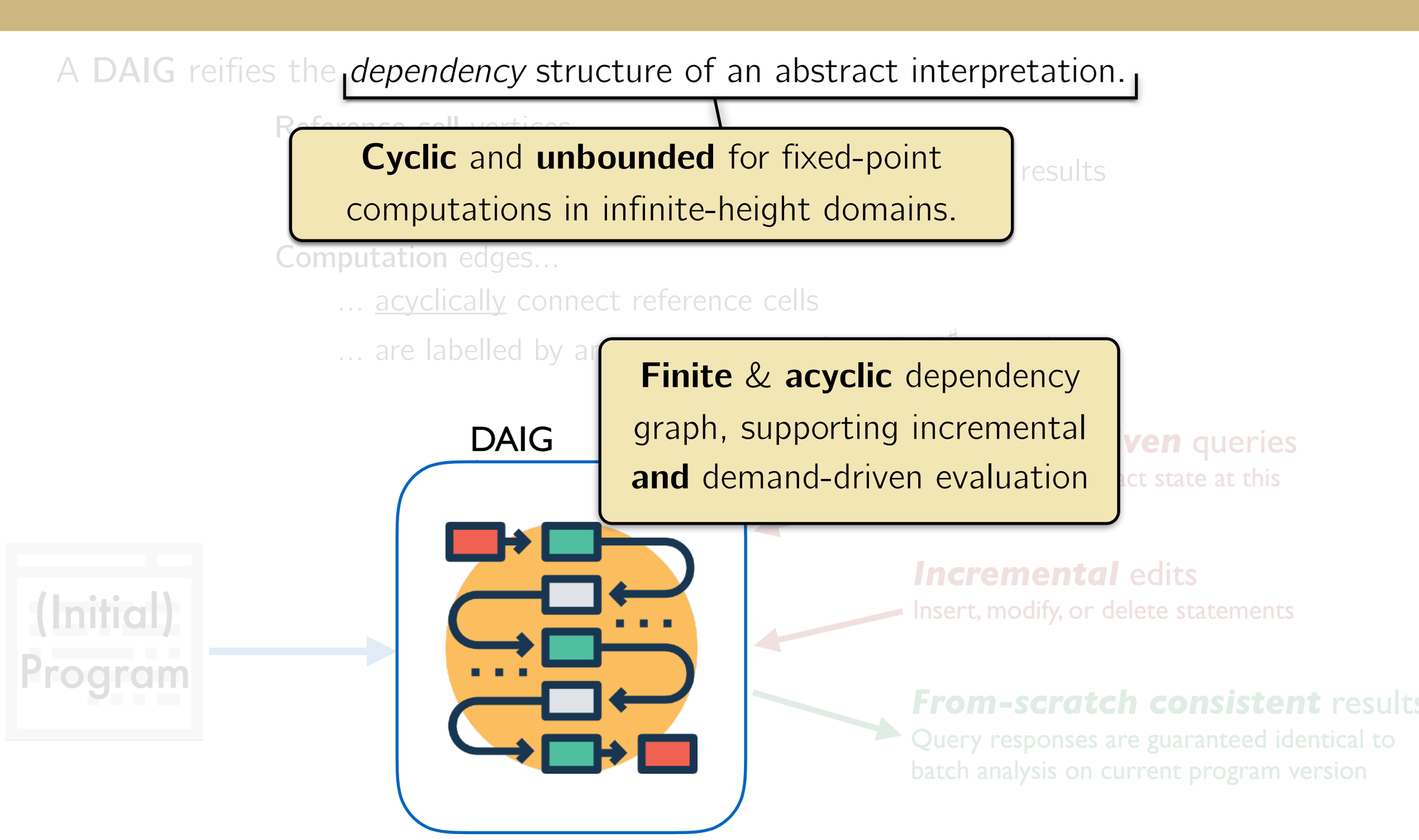
A **DAIG** reifies the *dependency* structure of an abstract interpretation.

Cyclic and **unbounded** for fixed-point computations in infinite-height domains.

Finite & **acyclic** dependency graph, supporting incremental **and** demand-driven evaluation



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Cyclic and **unbounded** for fixed-point computations in infinite-height domains.

via *demanded unrolling* of fixed-point computations

Finite & **acyclic** dependency graph, supporting incremental **and** demand-driven evaluation

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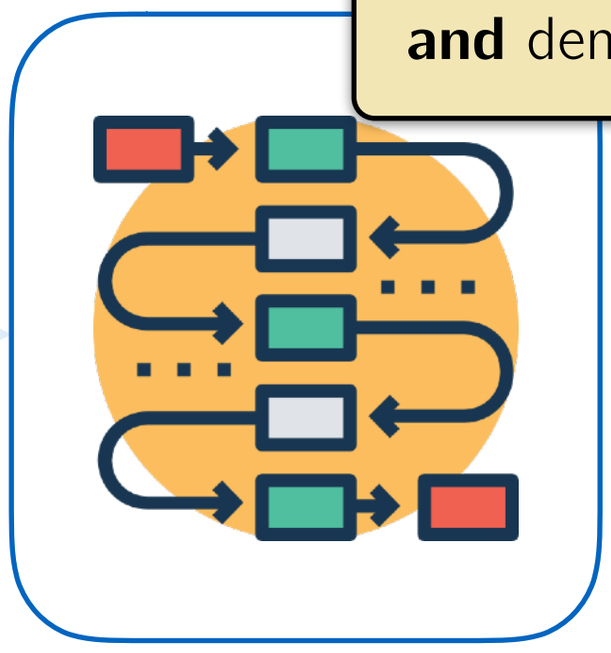

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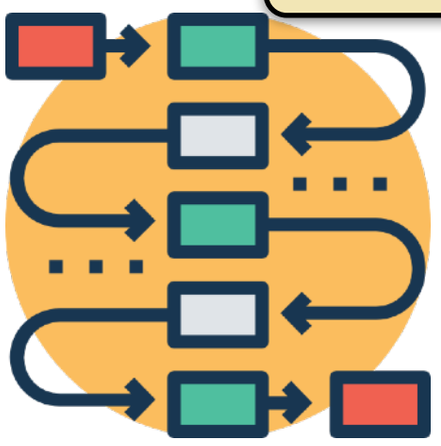

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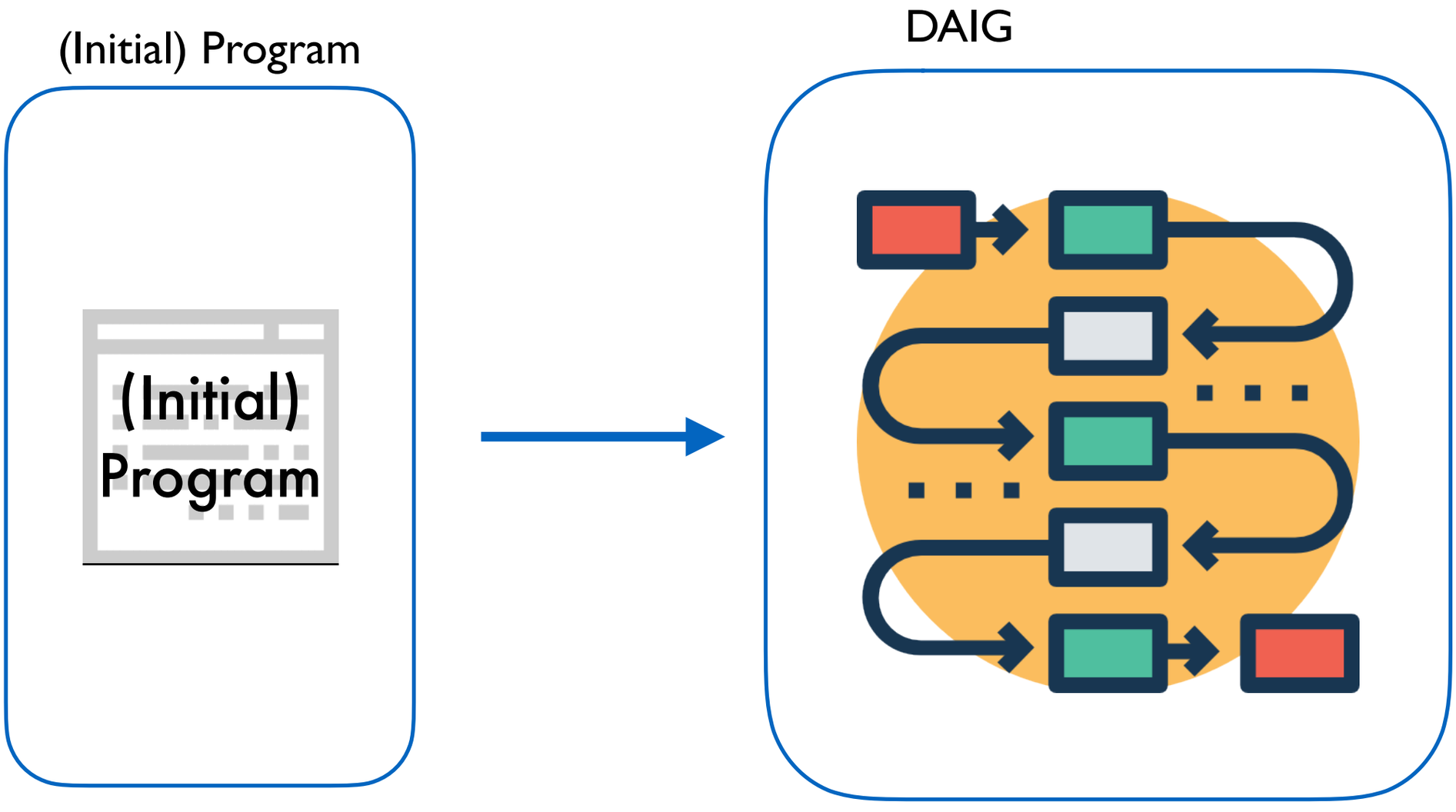
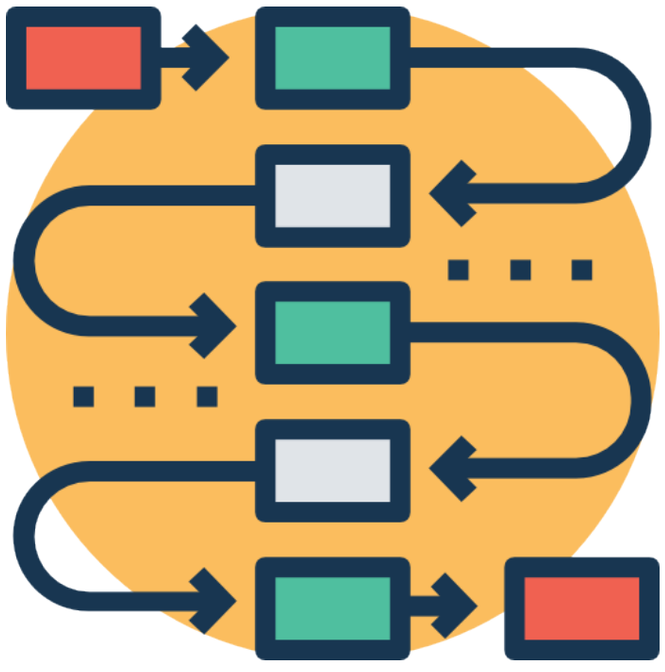


Demanded Abstract Interpretation Graphs (DAIGs)

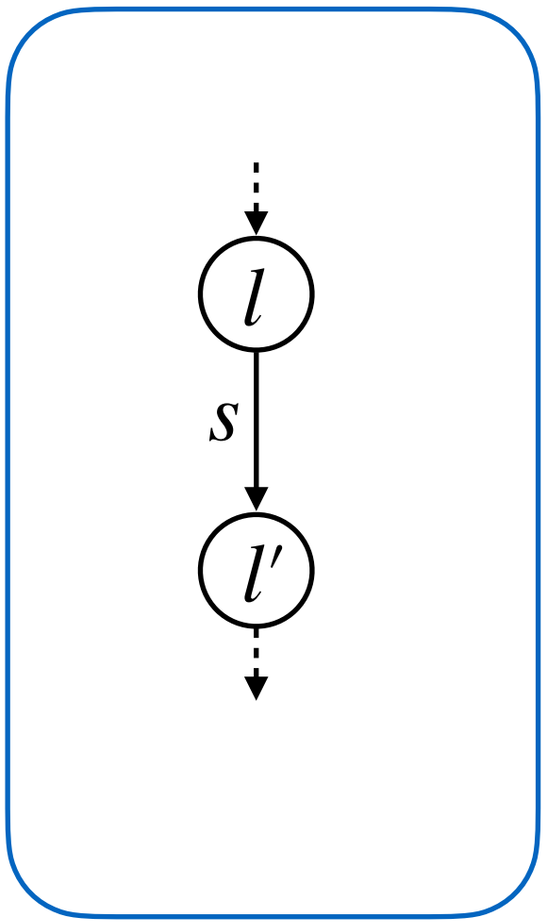
(Initial) Program

DAIG



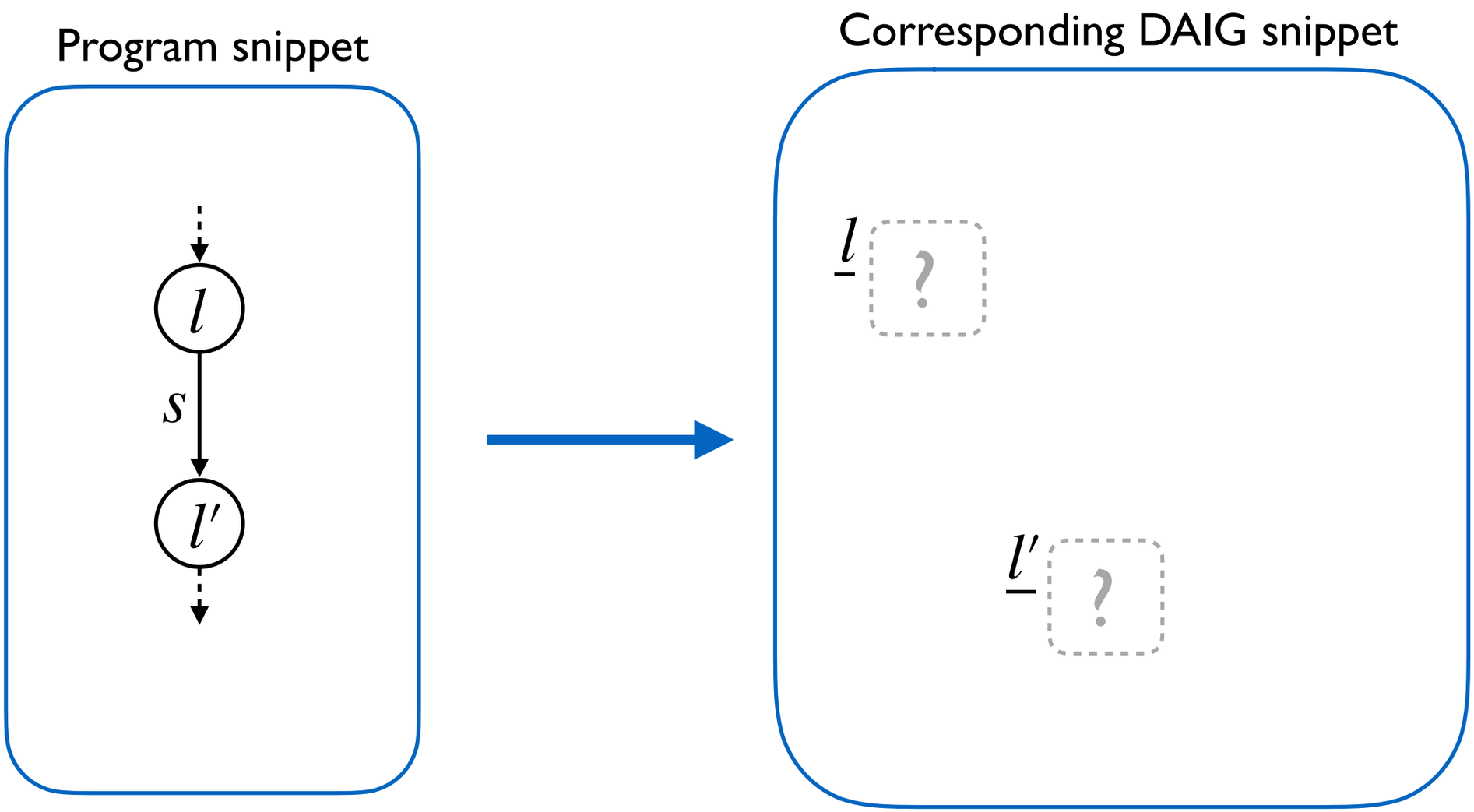
CFG → DAIG Encoding (by example)

Program snippet



Corresponding DAIG snippet

CFG → DAIG Encoding (by example)



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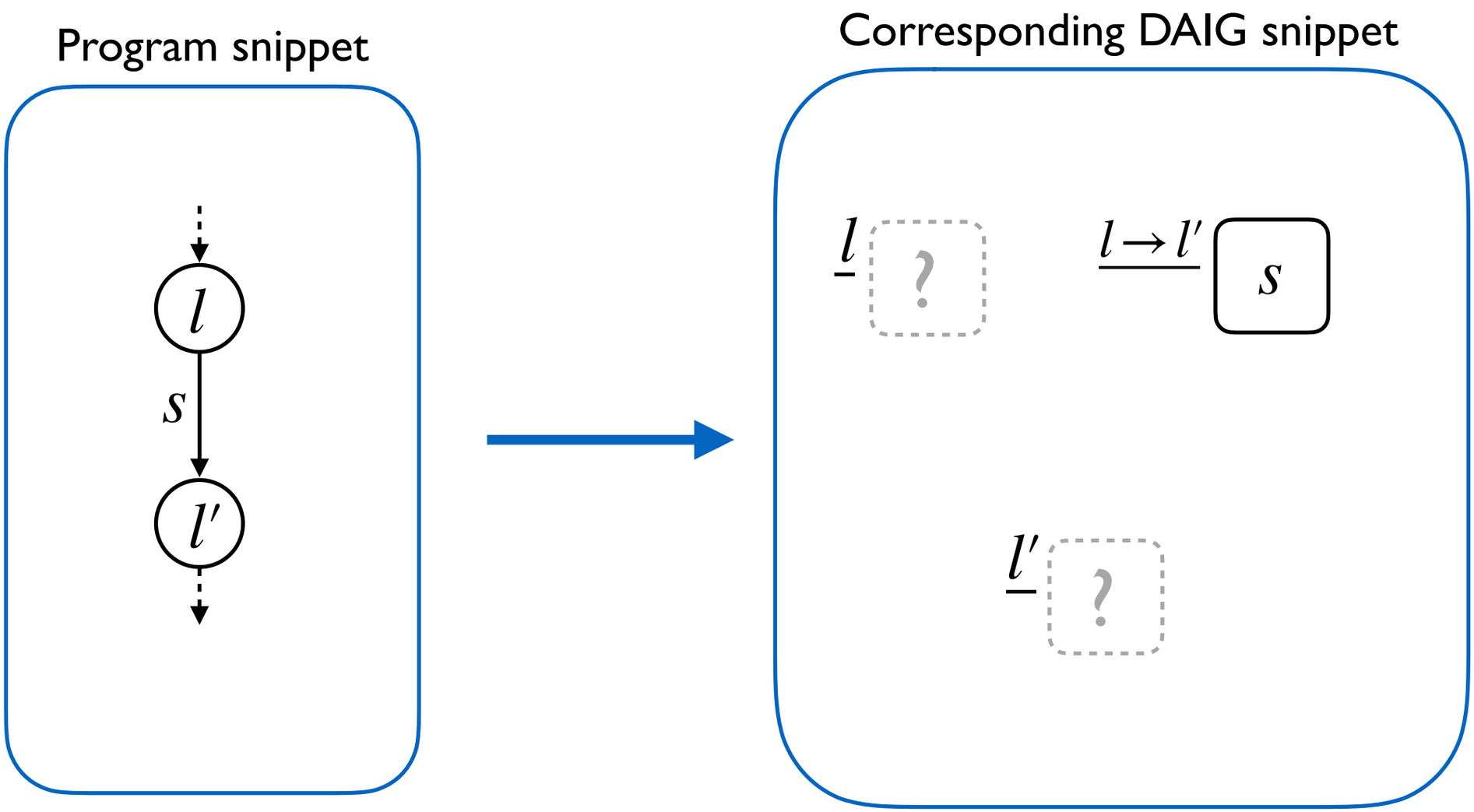

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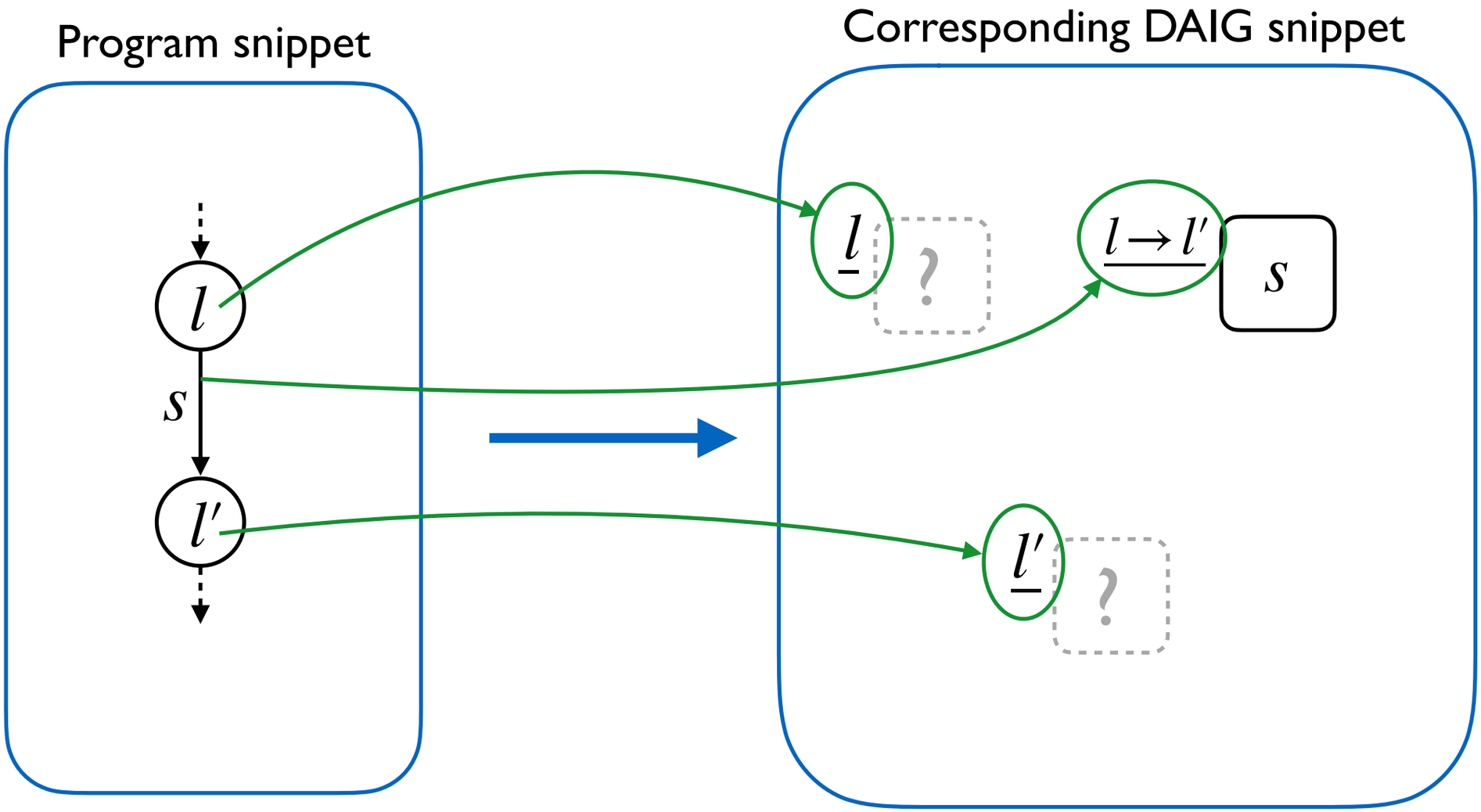
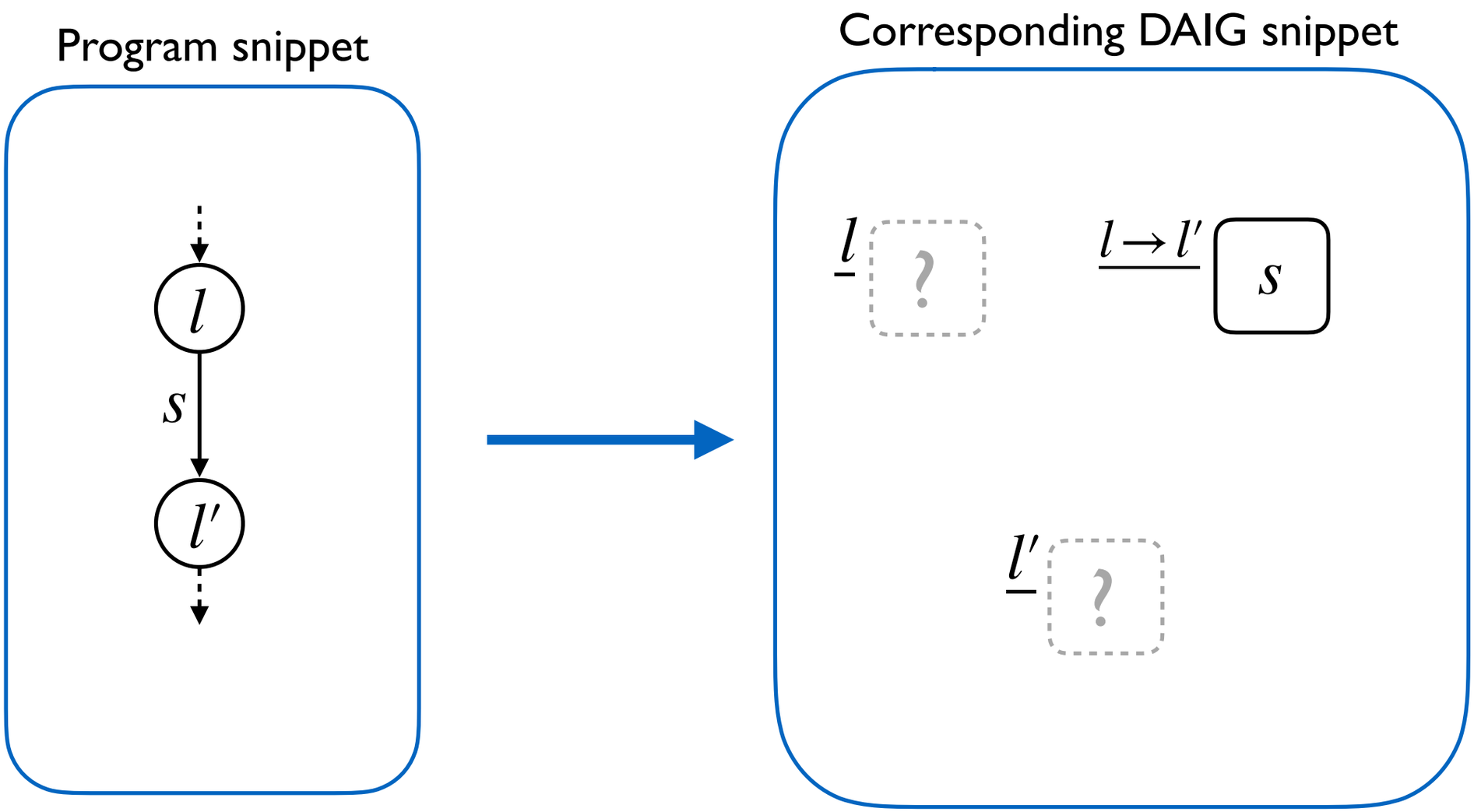


Underlined terms are *names* derived e.g. by hashing

CFG → DAIG Encoding (by example)



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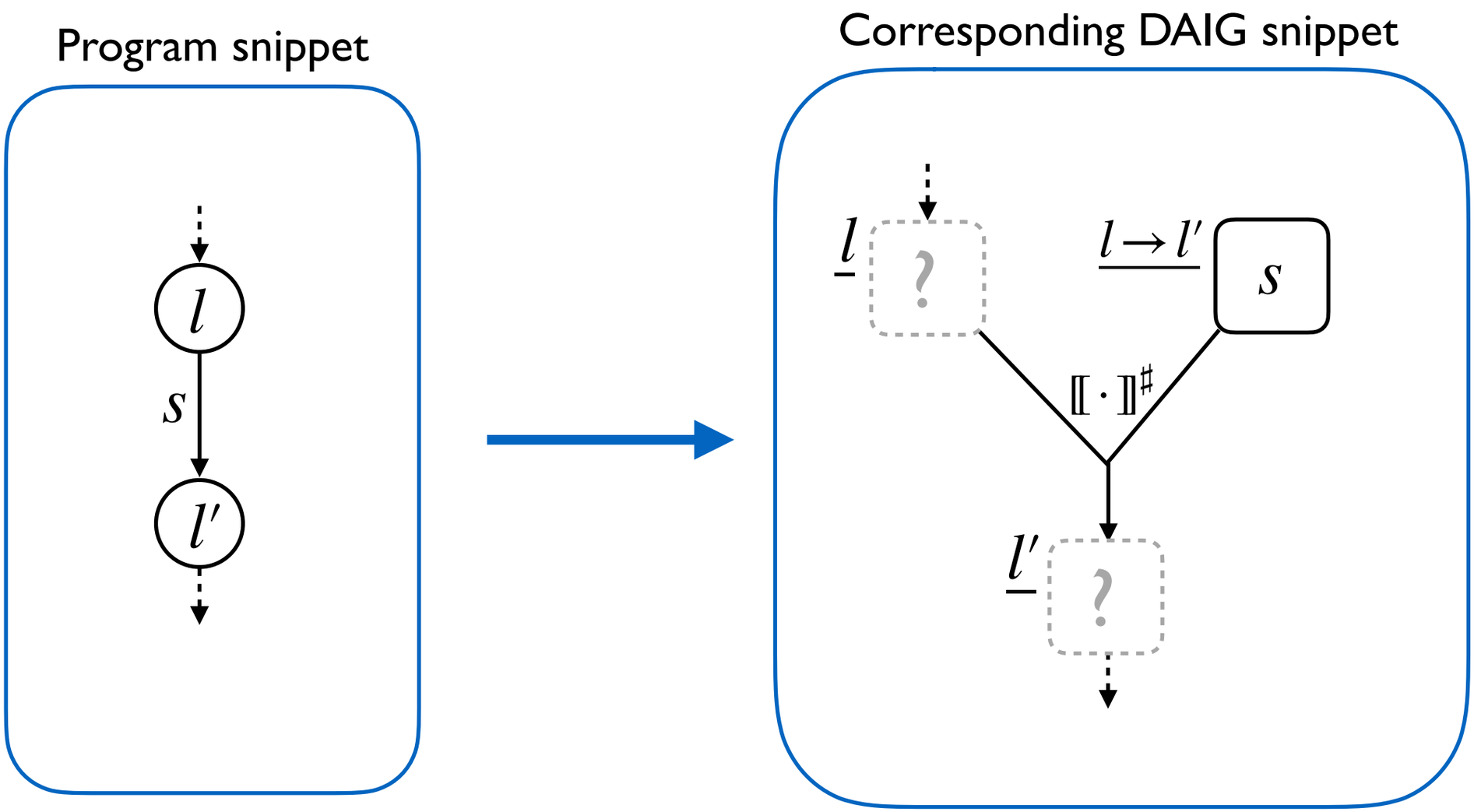
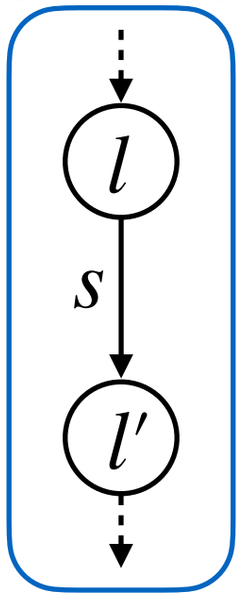
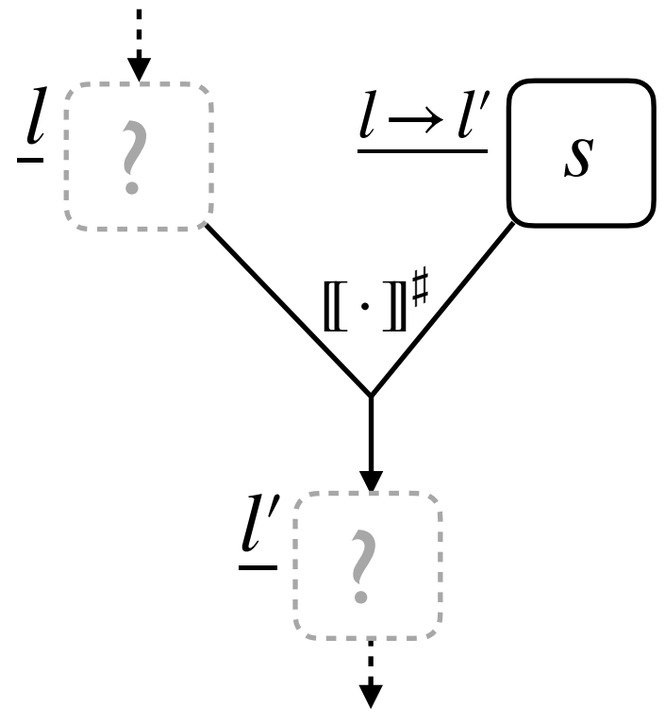


Demand-Driven Query Evaluation

Program snippet





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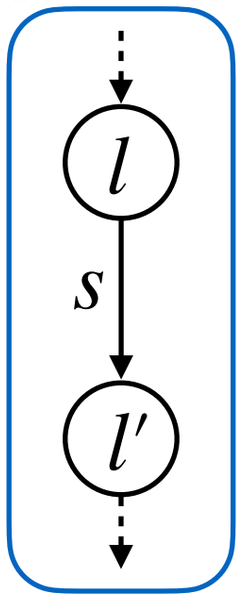
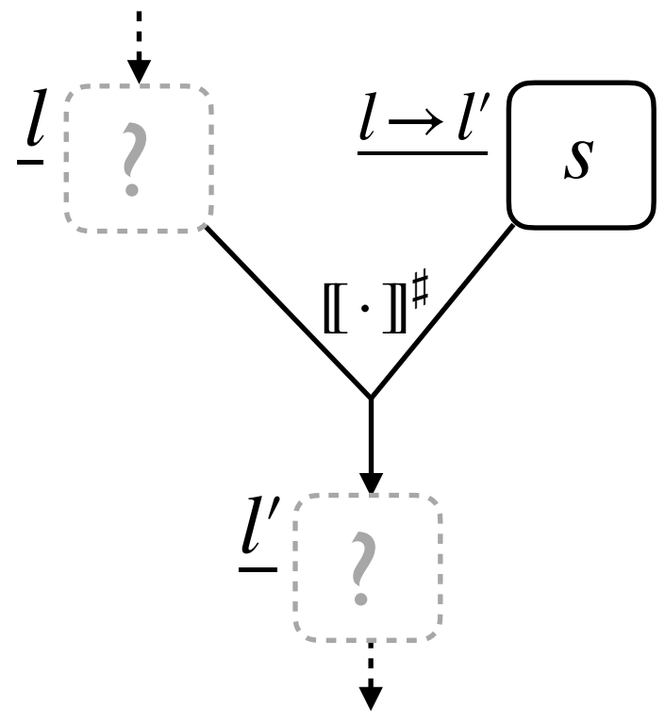




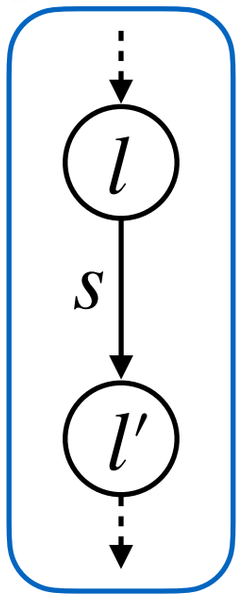
Demand-driven query:

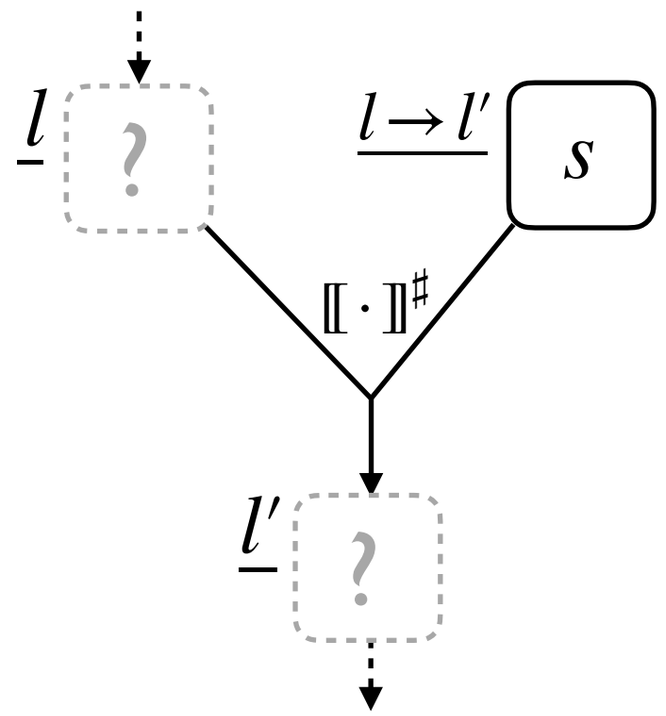
"What is the abstract state at l' ?"

i.e. "What is the value of cell $\underline{l'}$?"

Demand-Driven Query Evaluation

Program snippet





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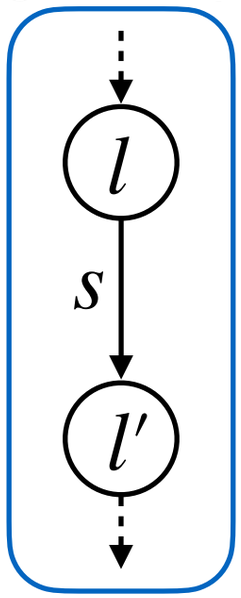
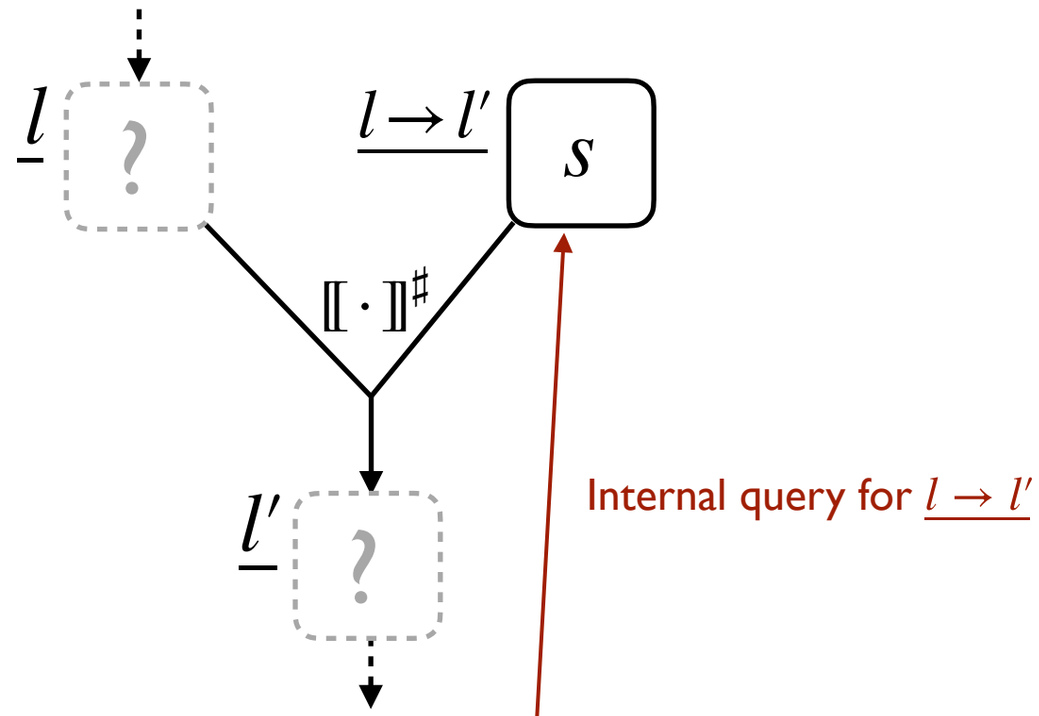
Demand-Driven Query Evaluation

Program snippet





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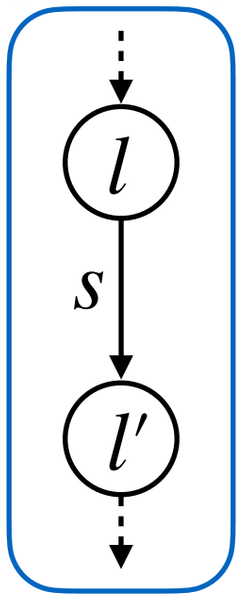
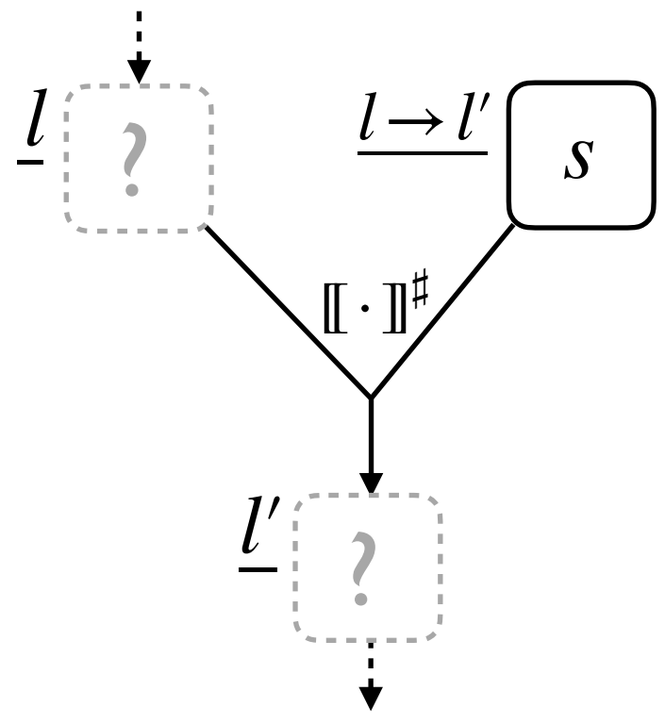
Demand-Driven Query Evaluation

Program snippet





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Demand-Driven Query Evaluation

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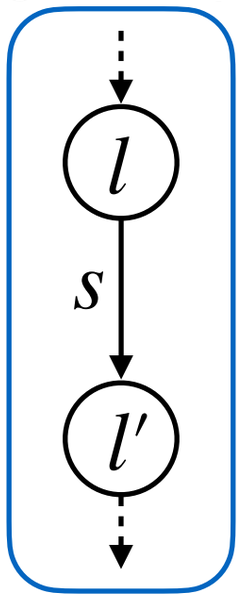

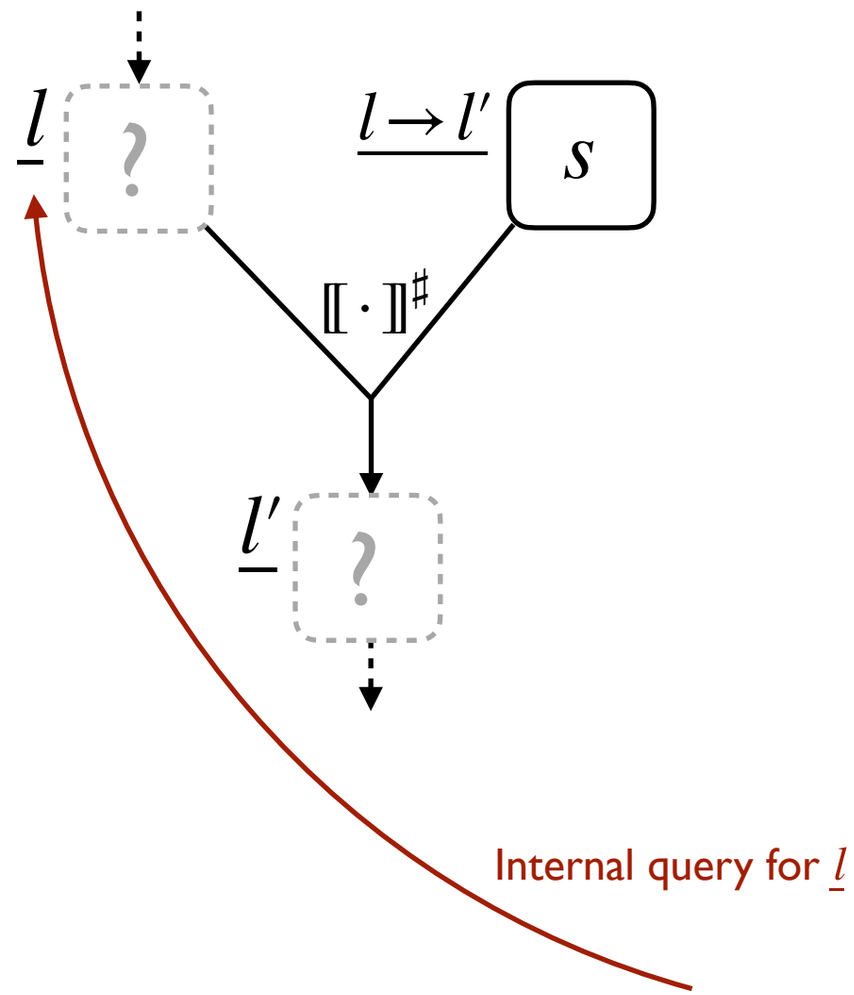

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Demand-Driven Query Evaluation

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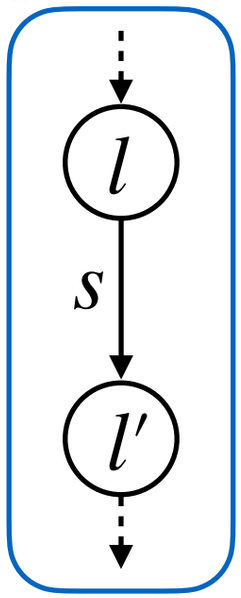

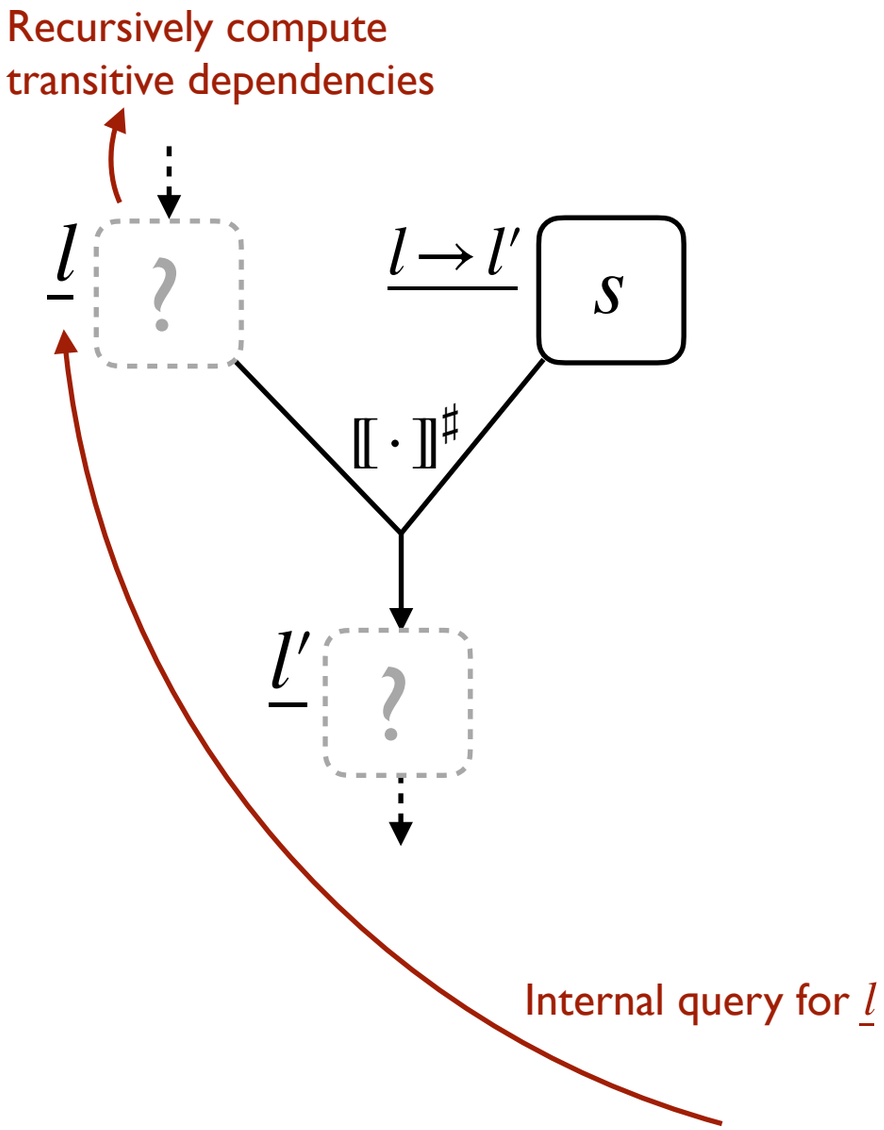

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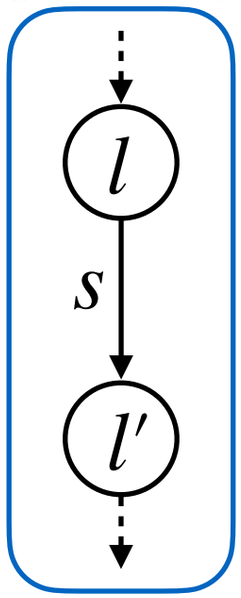
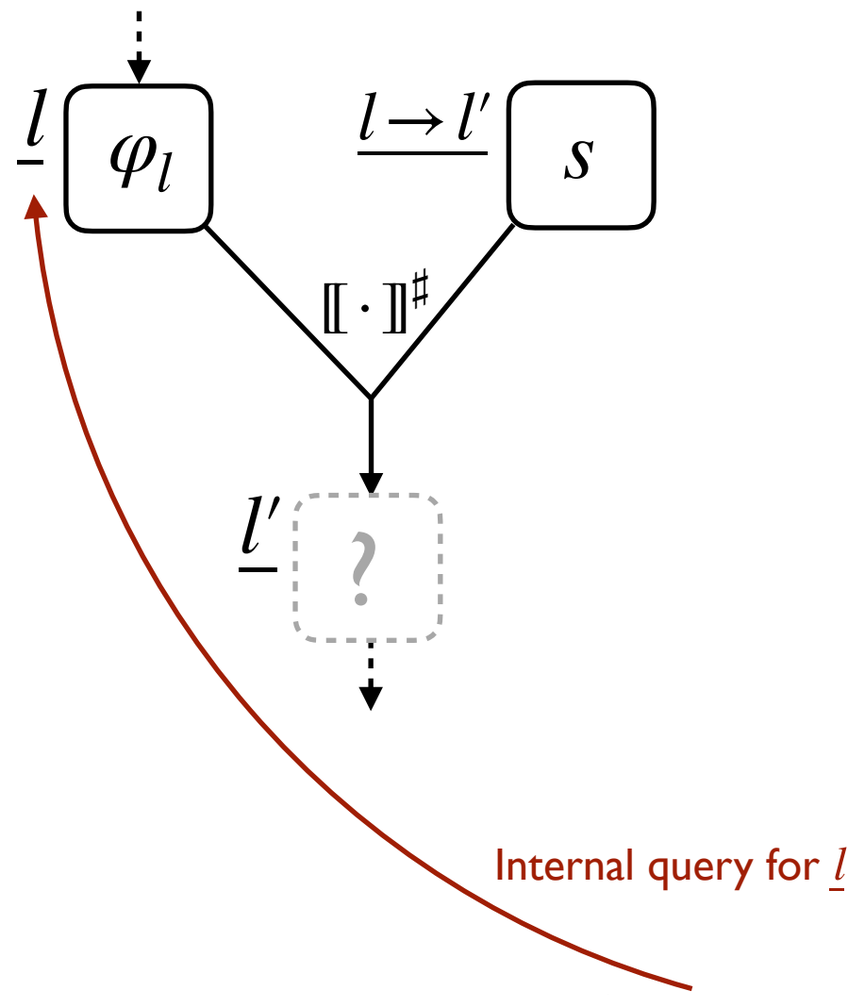
Demand-Driven Query Evaluation

Program snippet





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Demand-Driven Query Evaluation

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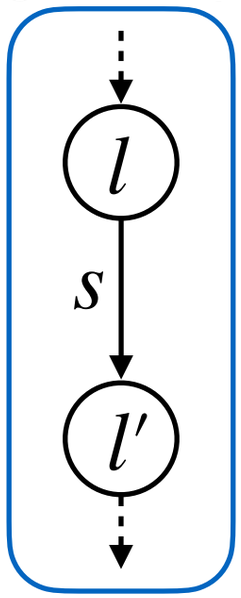

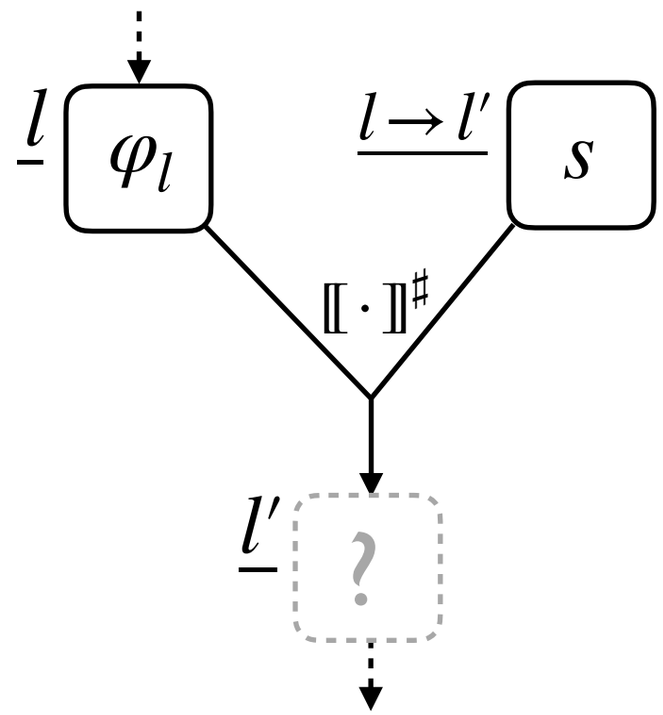

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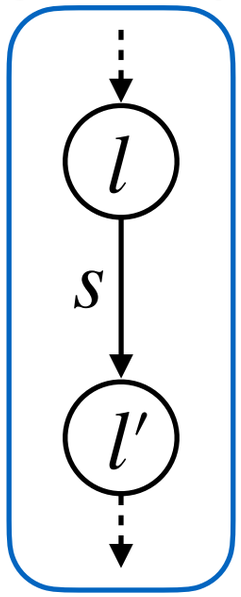
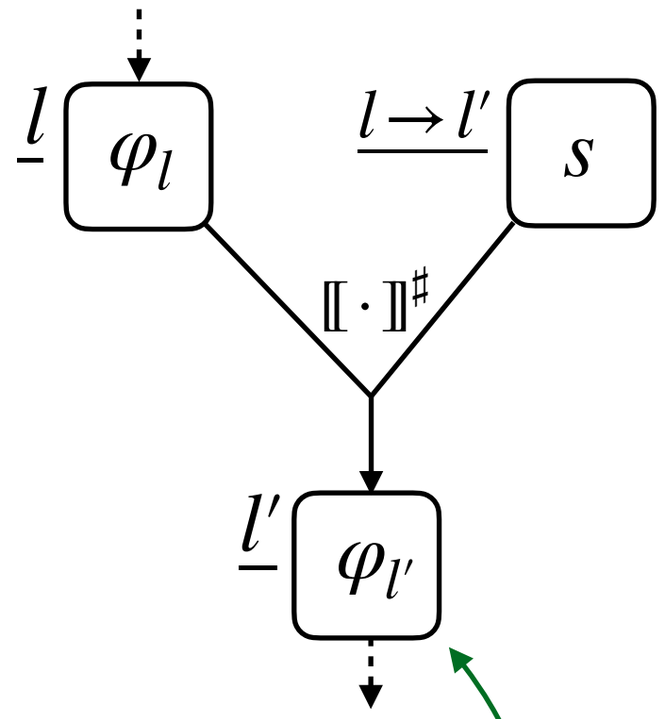
Demand-Driven Query Evaluation

Program snippet





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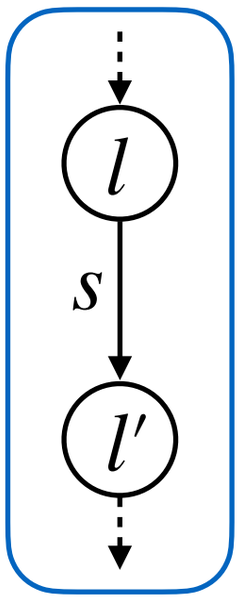
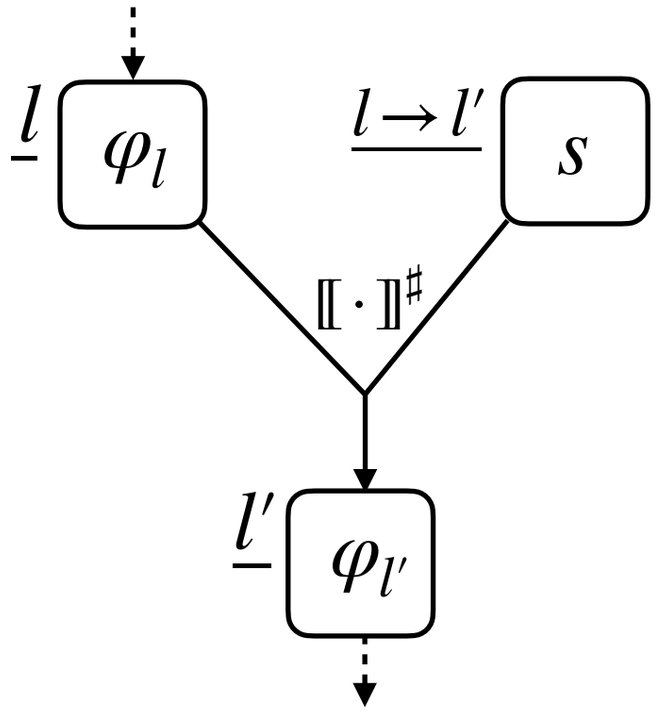
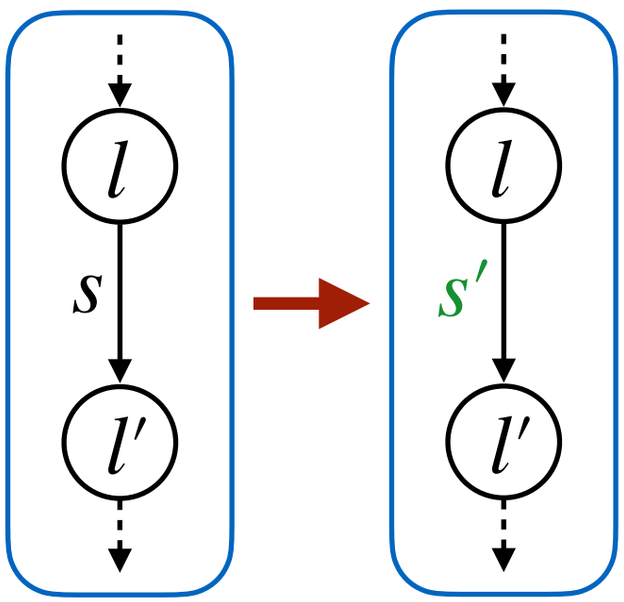
Incremental Change Propagation

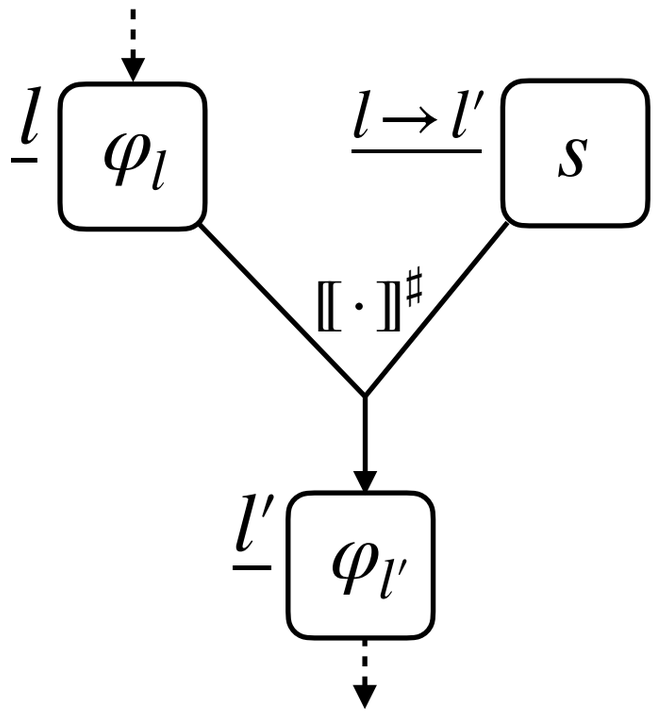




Incremental Change Propagation

Program edit:
Modify statement s to s'





Incremental Change Propagation

Program edit:
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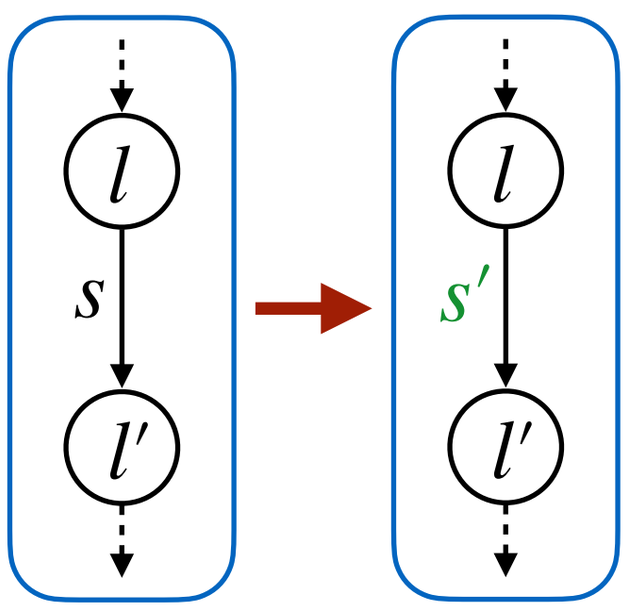
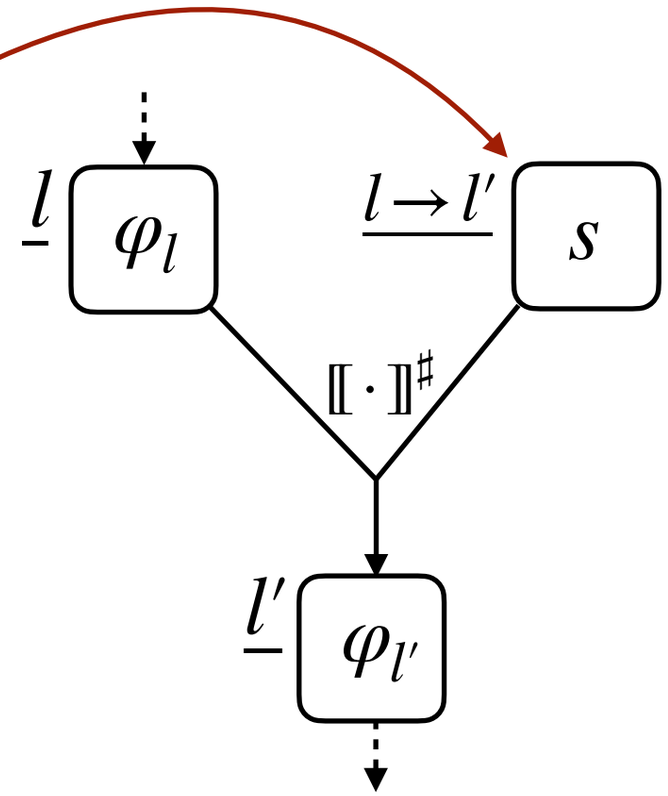
i.e. "Write s' to the cell named $\underline{l \to l'}$"





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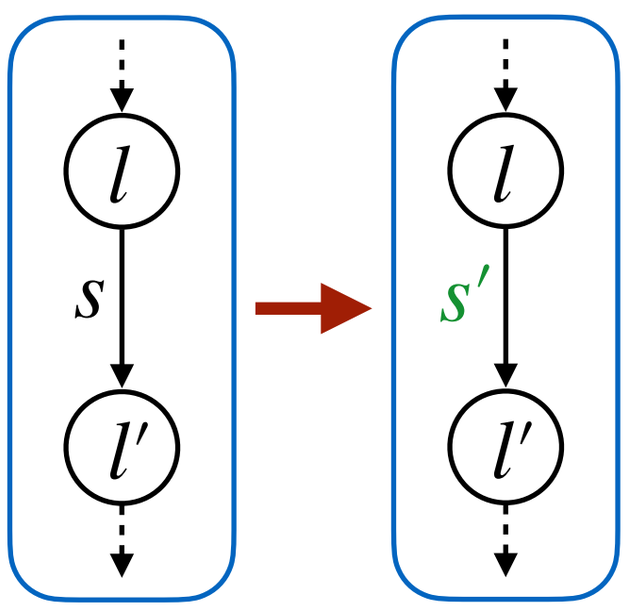

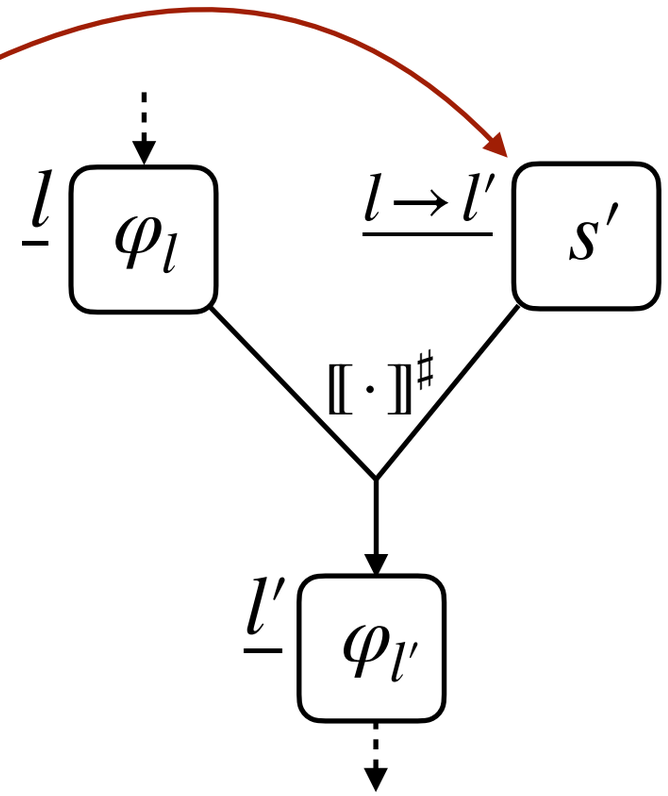

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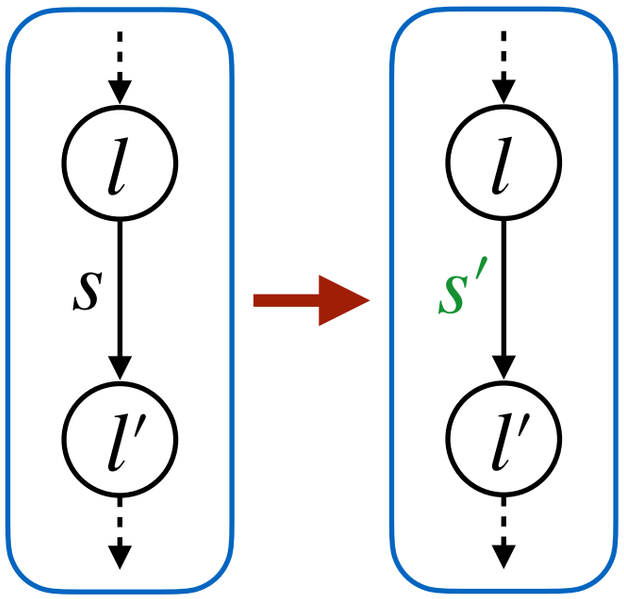

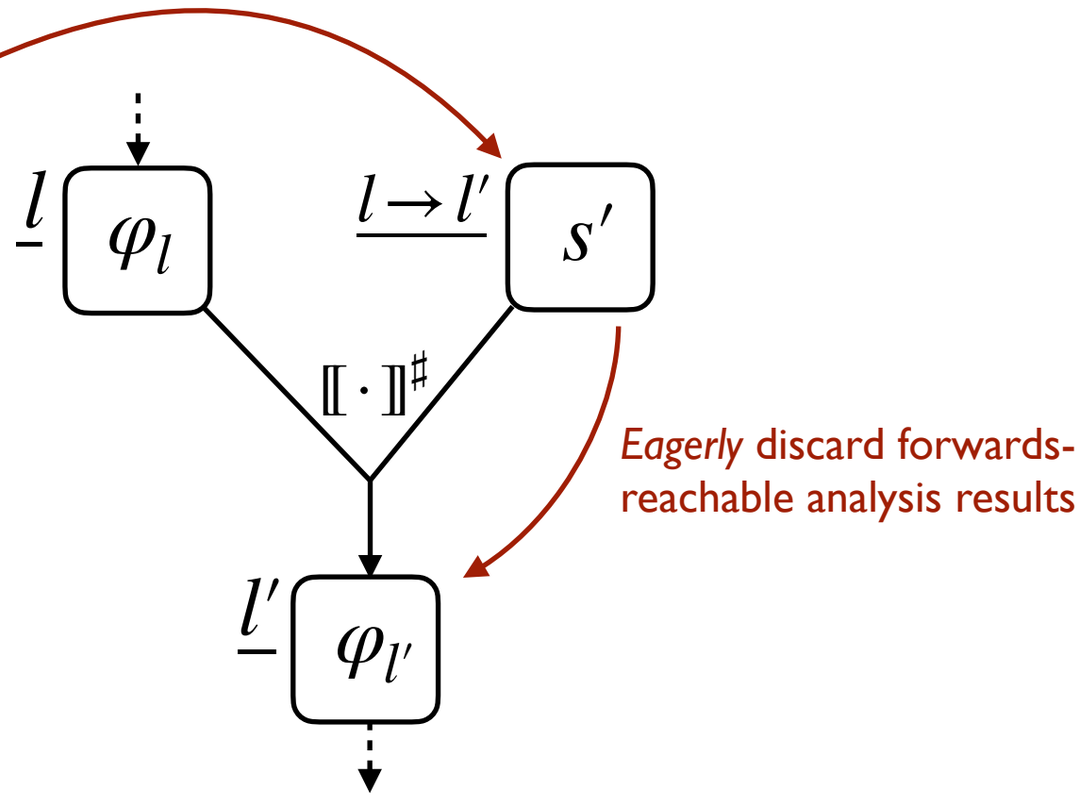

Eagerly discard forwards-reachable analysis results

Incremental Change Propagation

Program edit:
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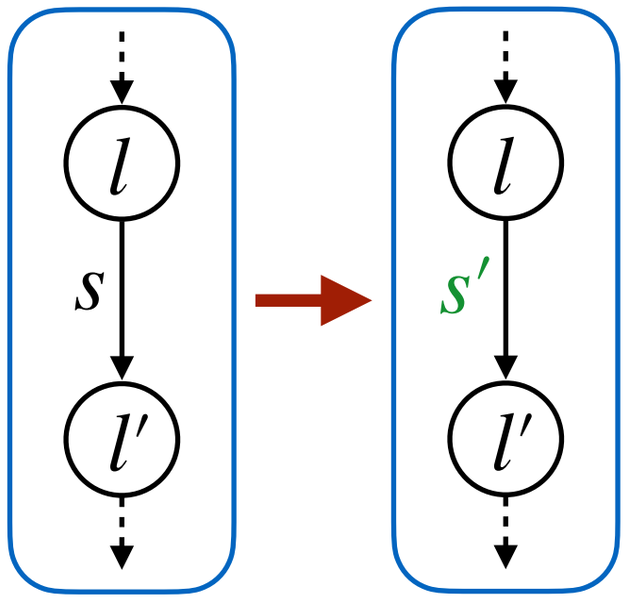

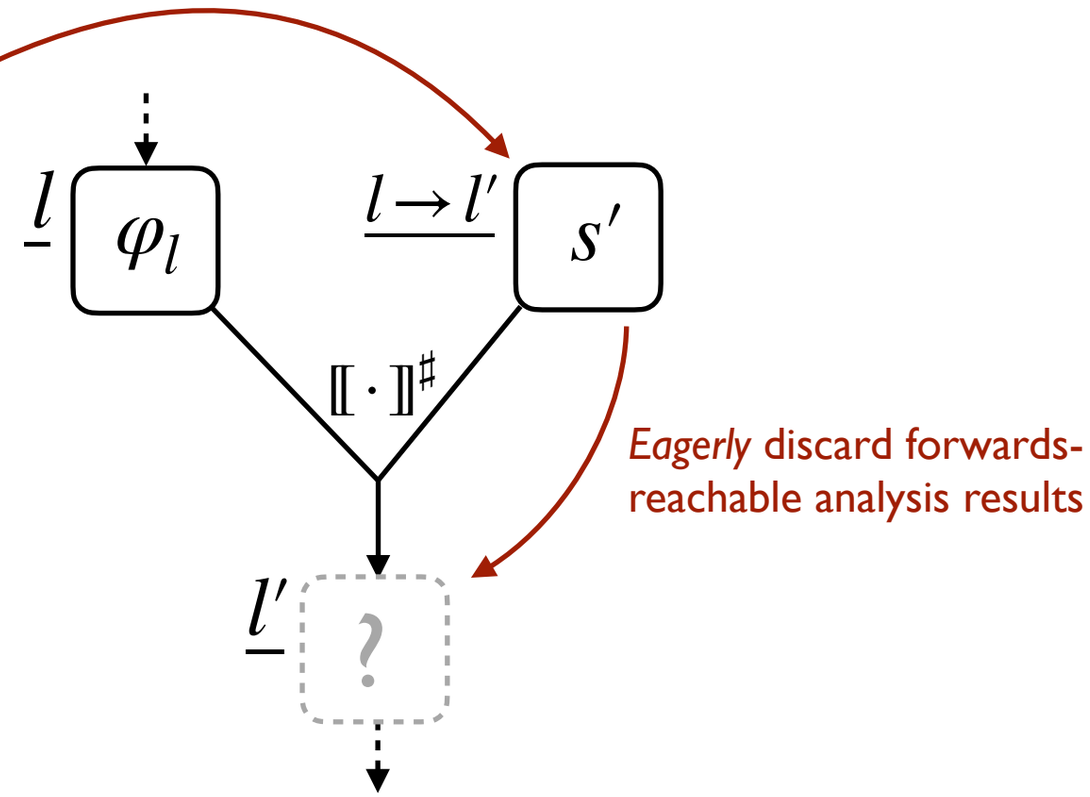

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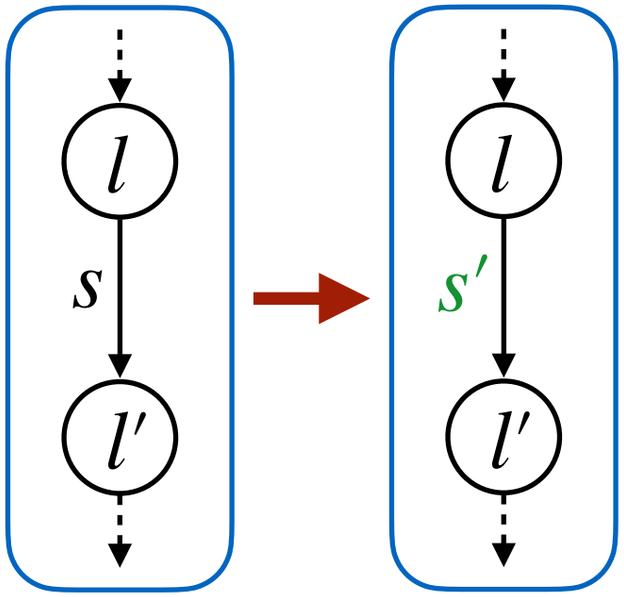

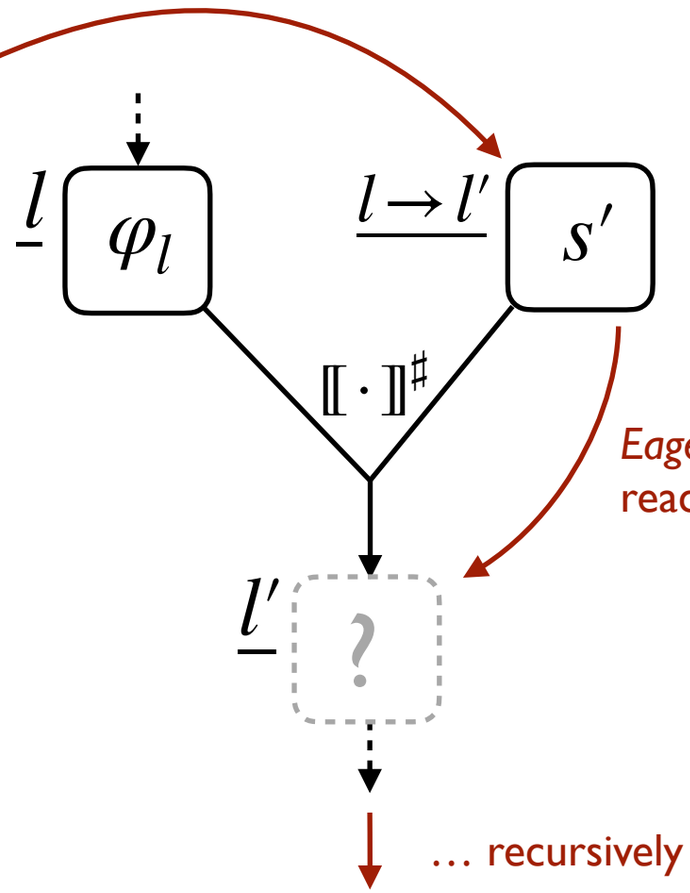

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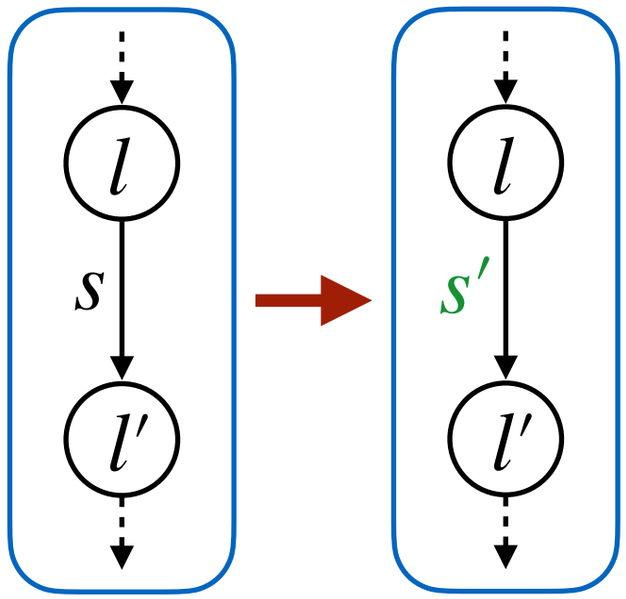
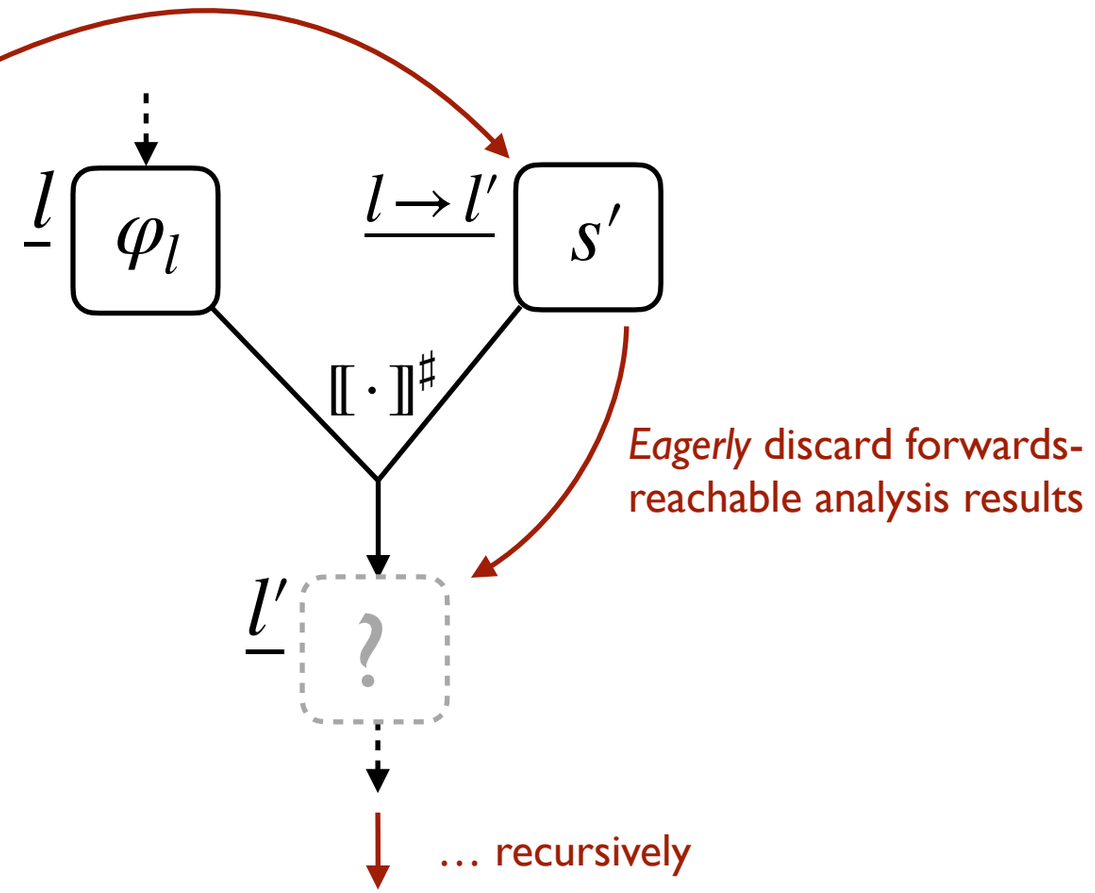


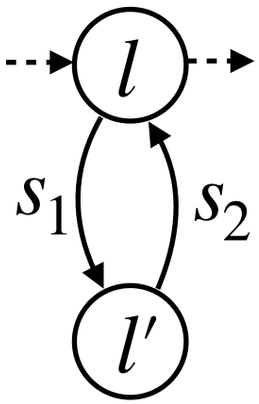


Eagerly discard forwards-reachable analysis results

Subsequent queries only recompute those analysis results potentially affected by the edit!

Cyclic Control Flow

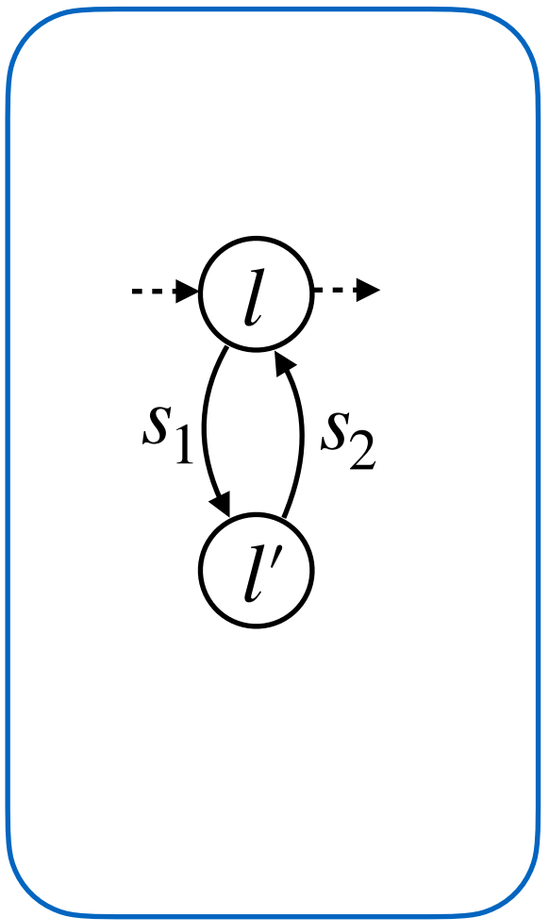
Program snippet



Corresponding DAIG snippet

Cyclic Control Flow

Program snippet



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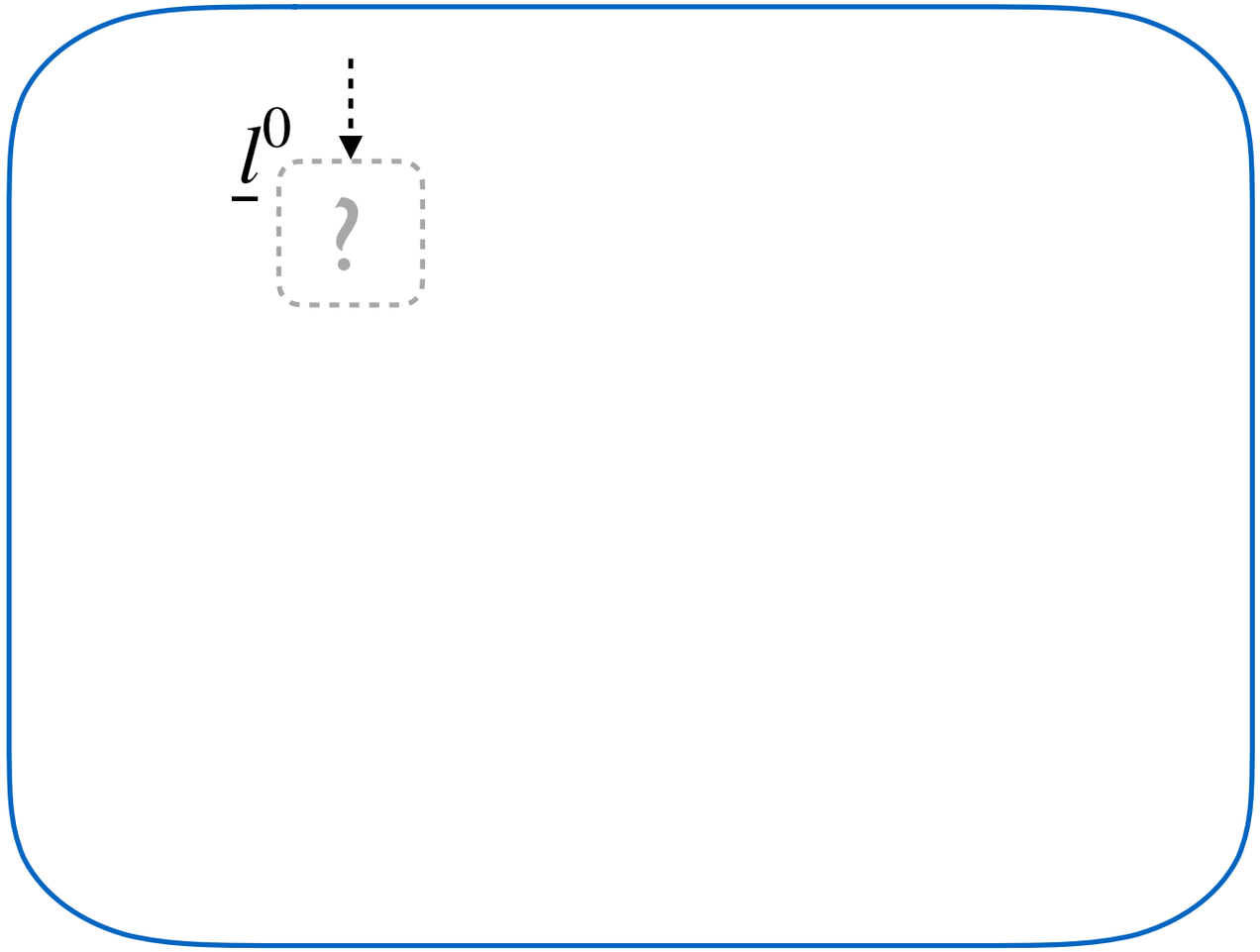
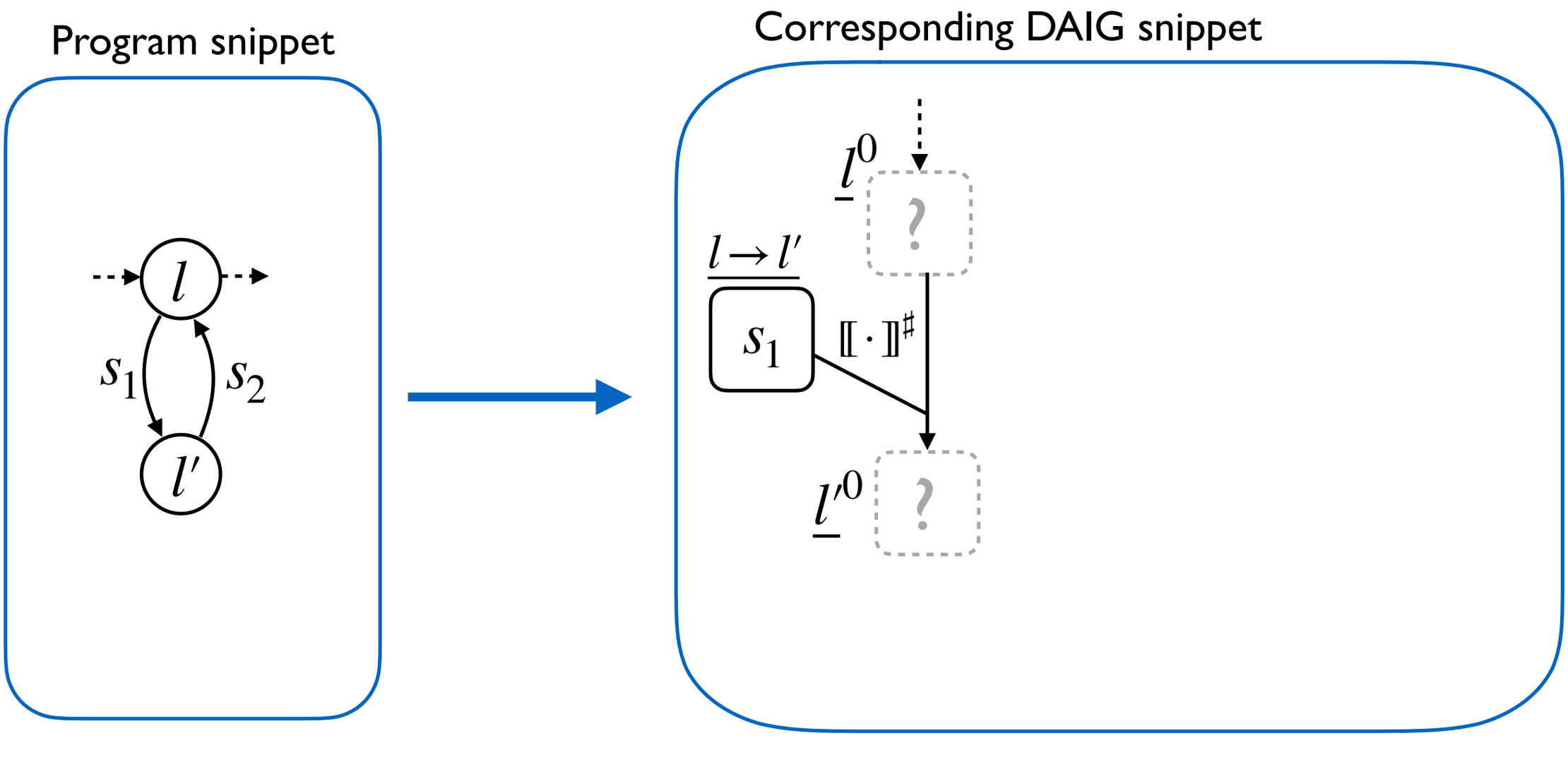


Cyclic Control Flow



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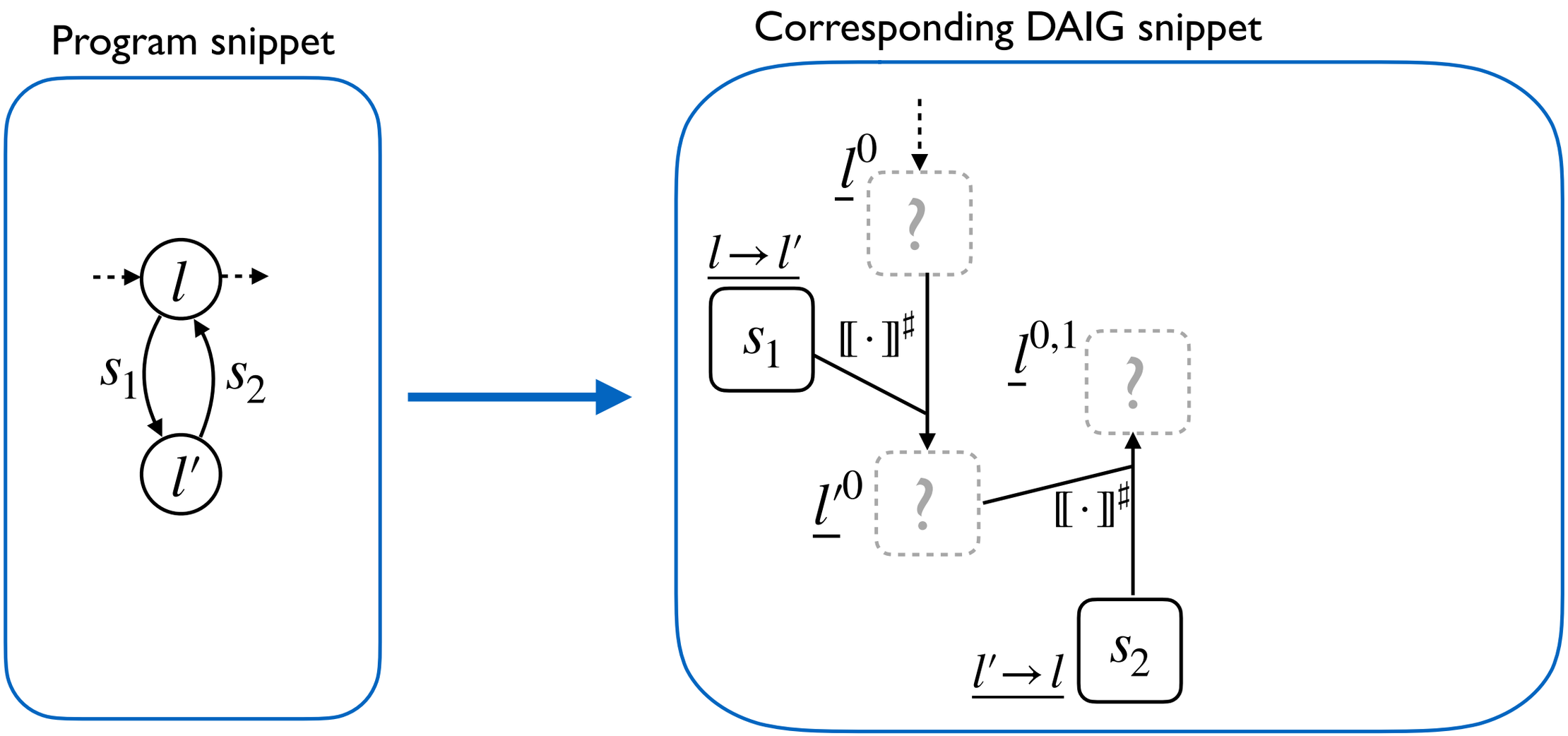
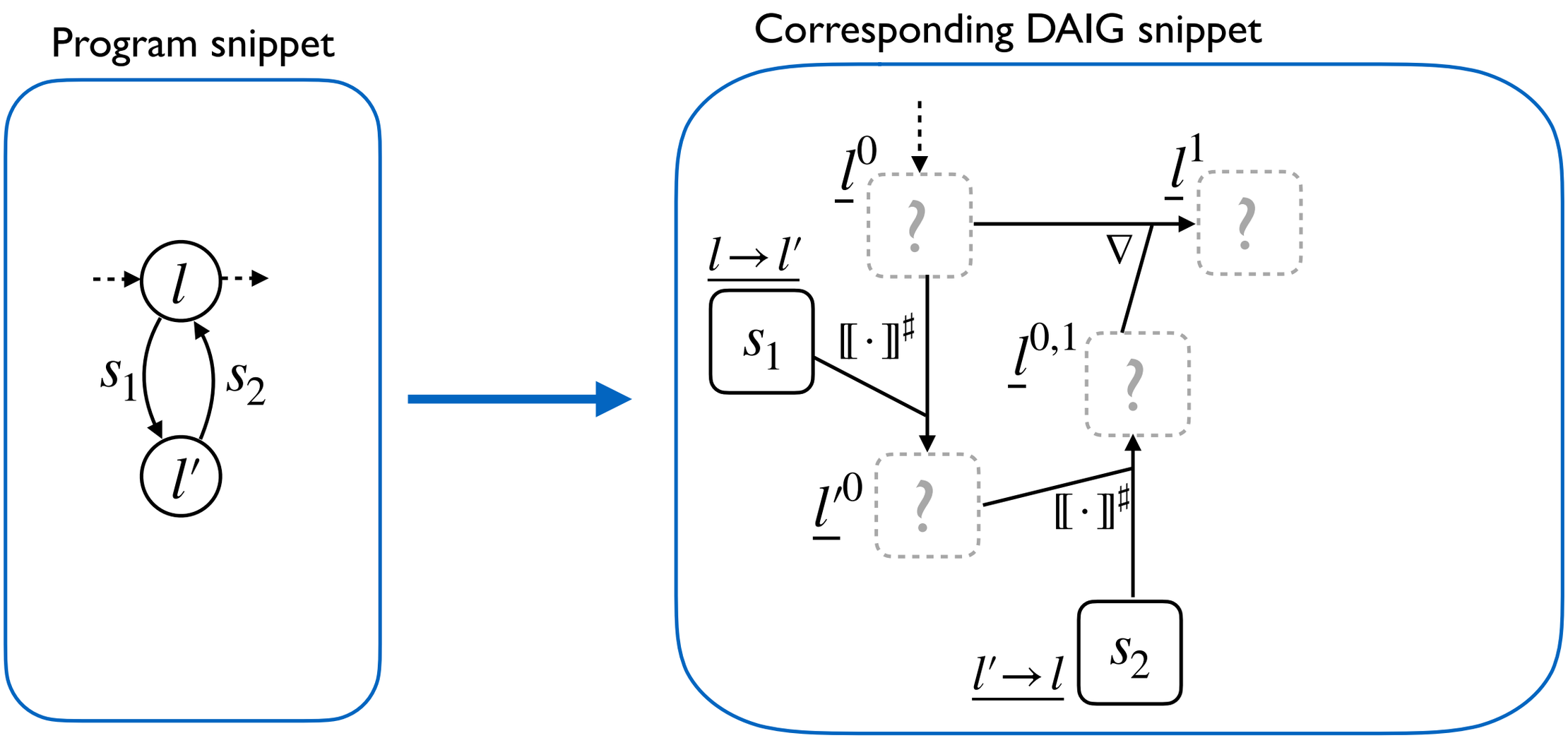
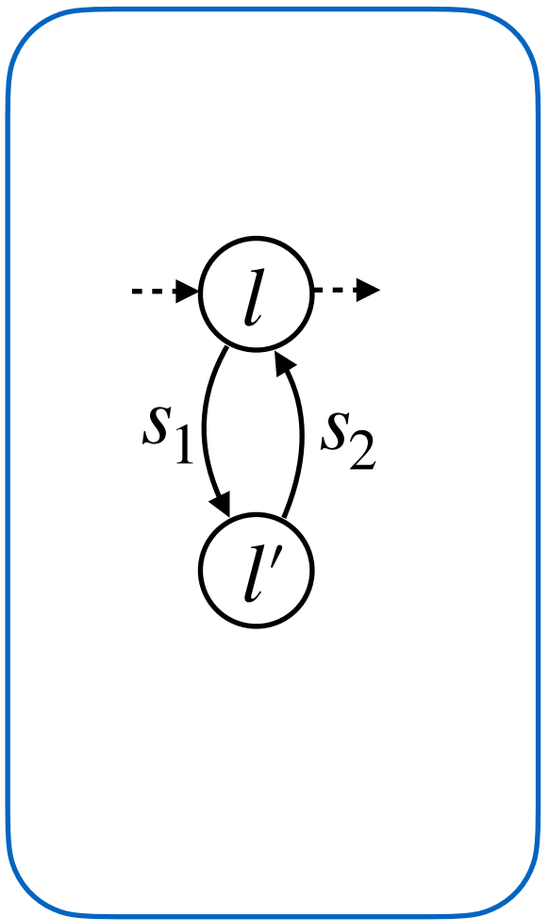


Cyclic Control Flow



Cyclic Control Flow

Program snippet



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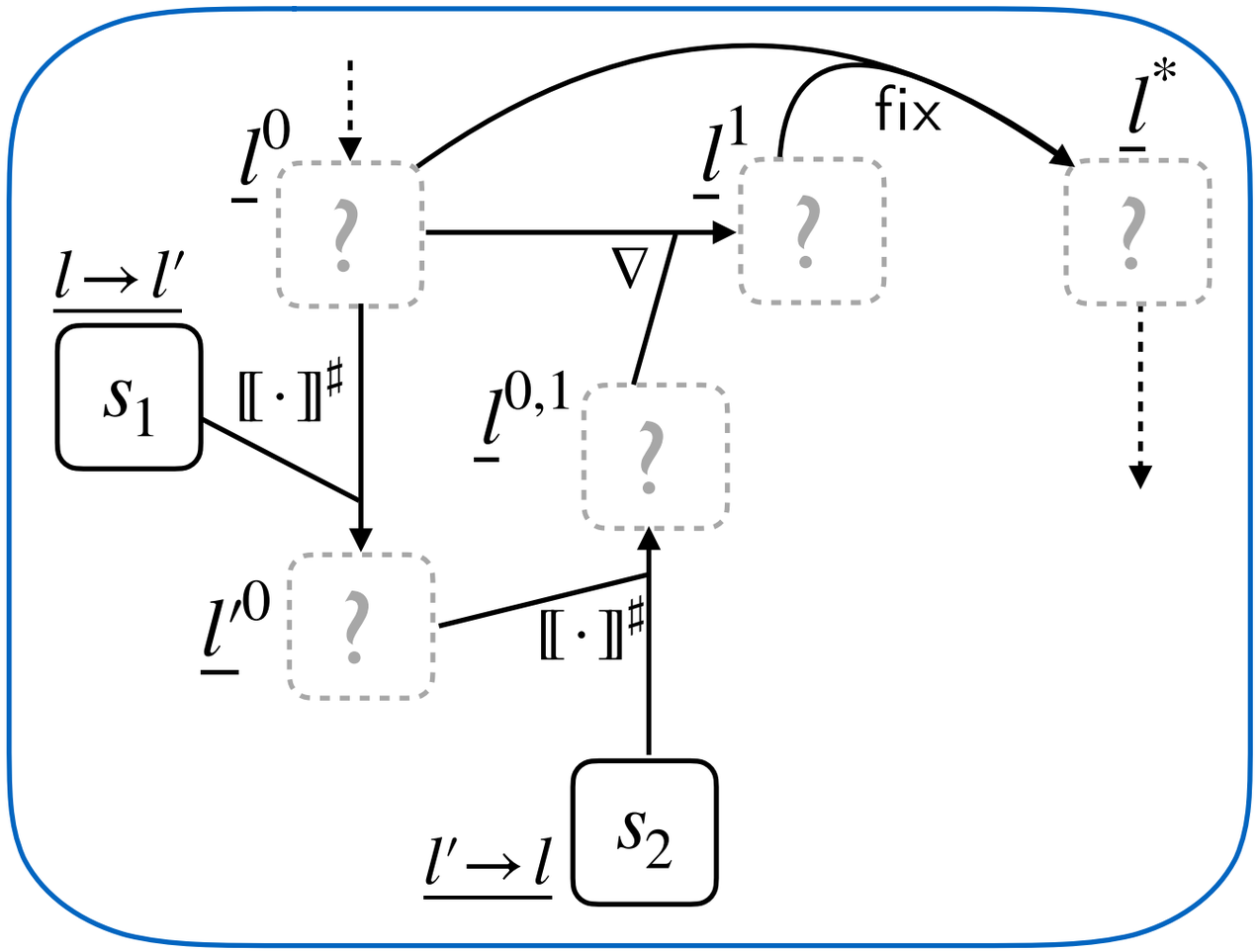
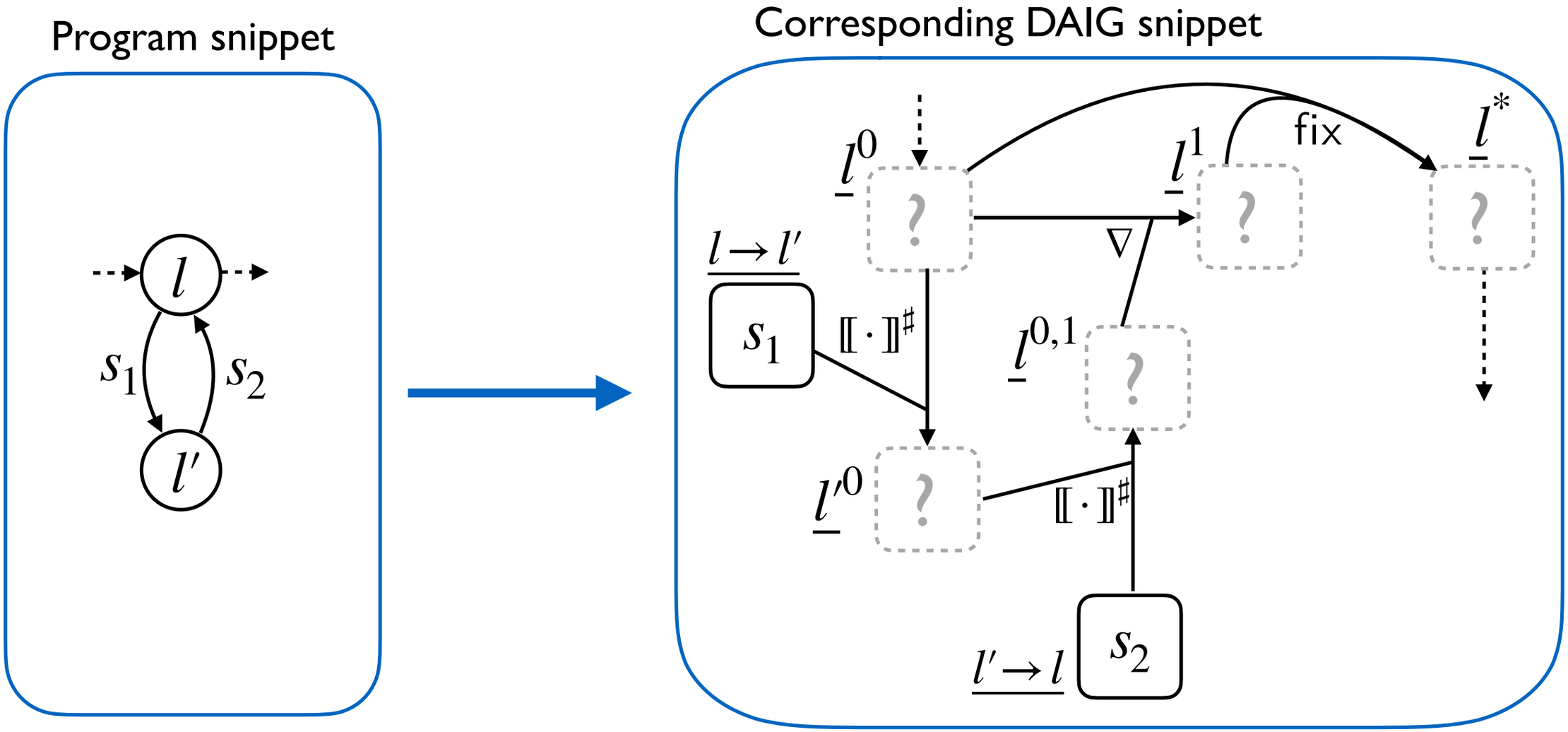
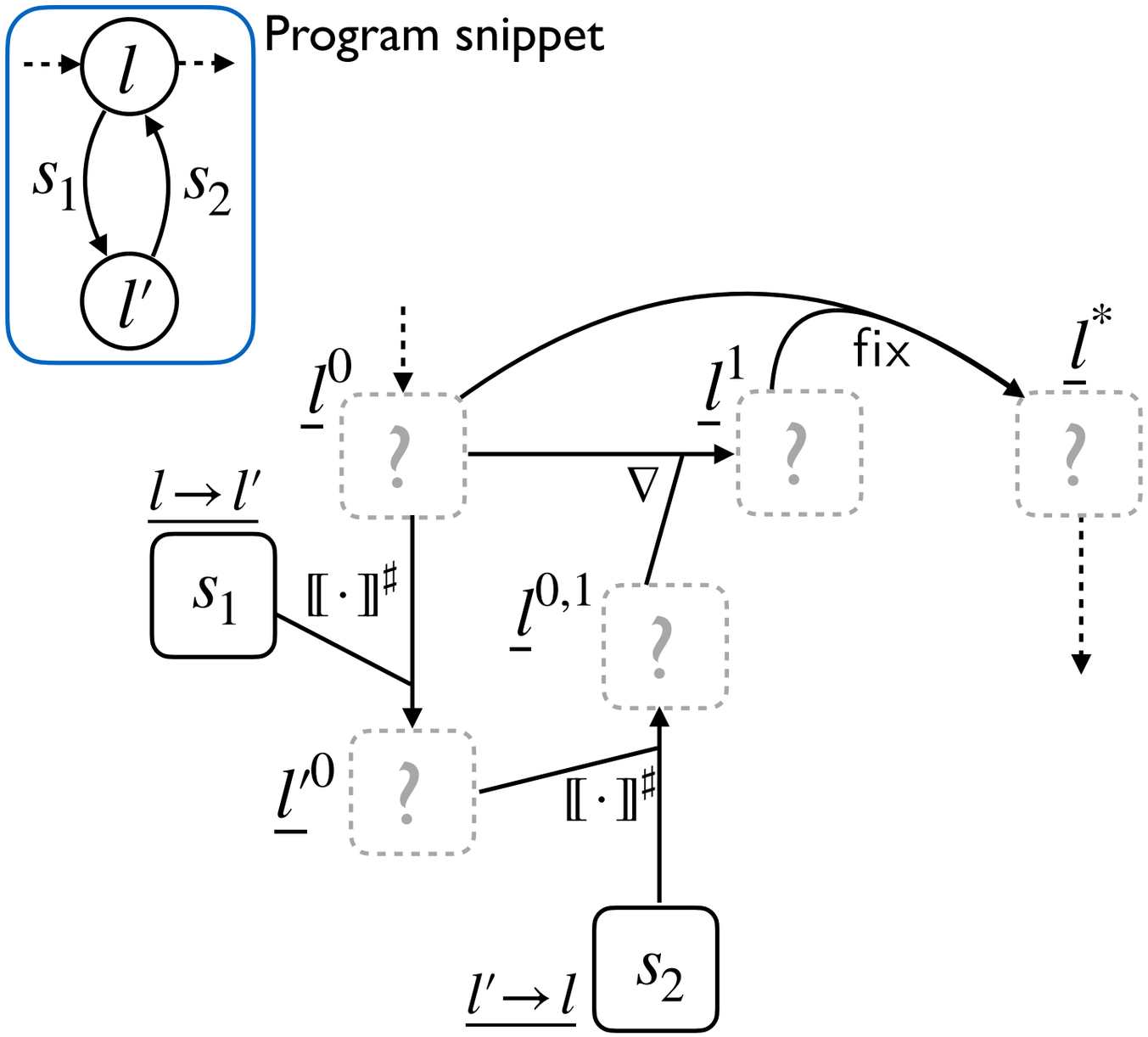


Cyclic Control Flow



DAIG Fixed-point Computation



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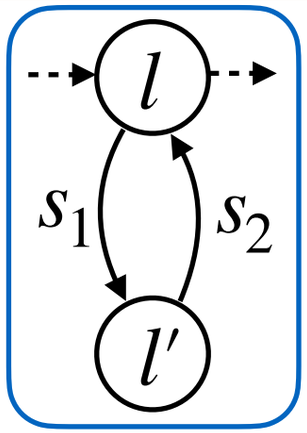
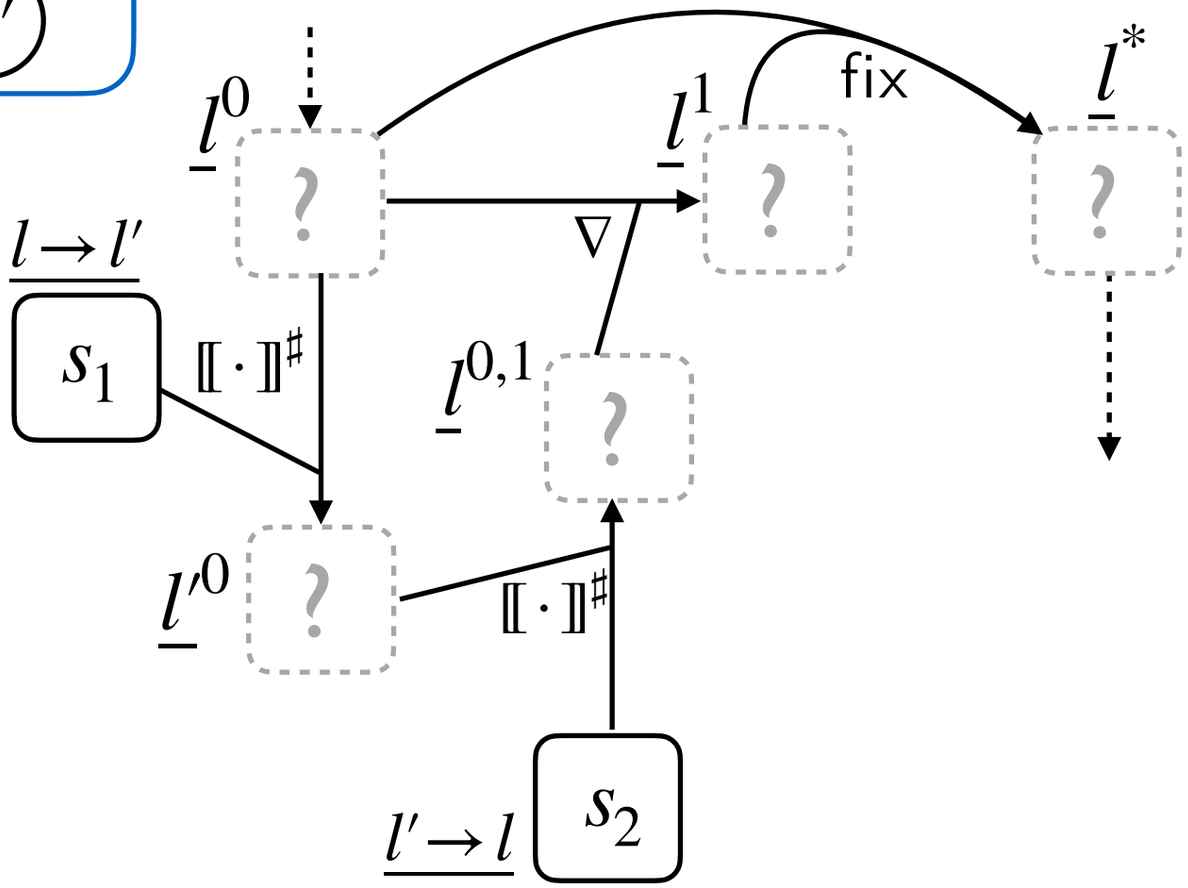
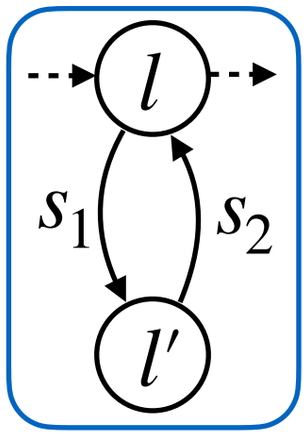


Program snippet

Demand-driven query:
"What is the *fixed-point* abstract state at l ?"



DAIG Fixed-point Computation



Program snippet

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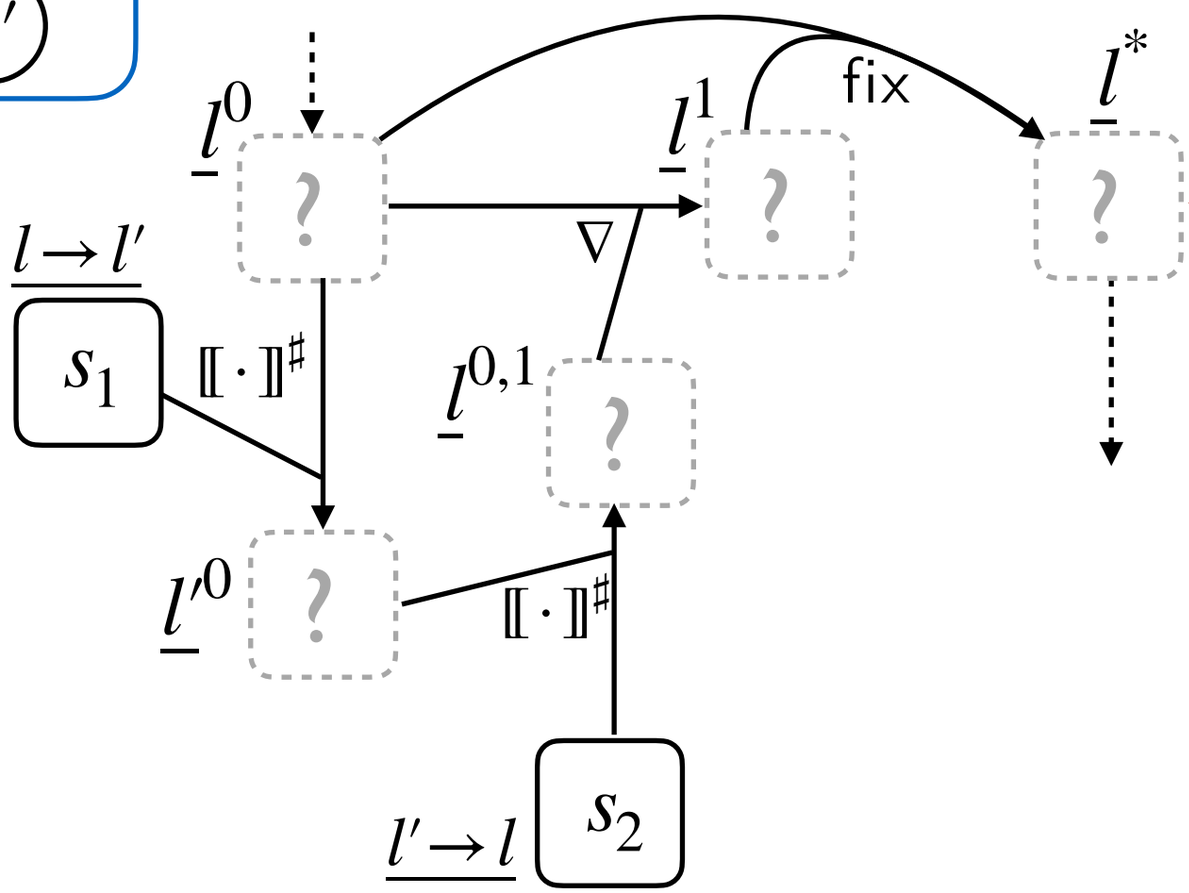

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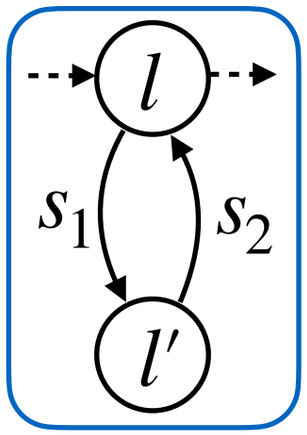

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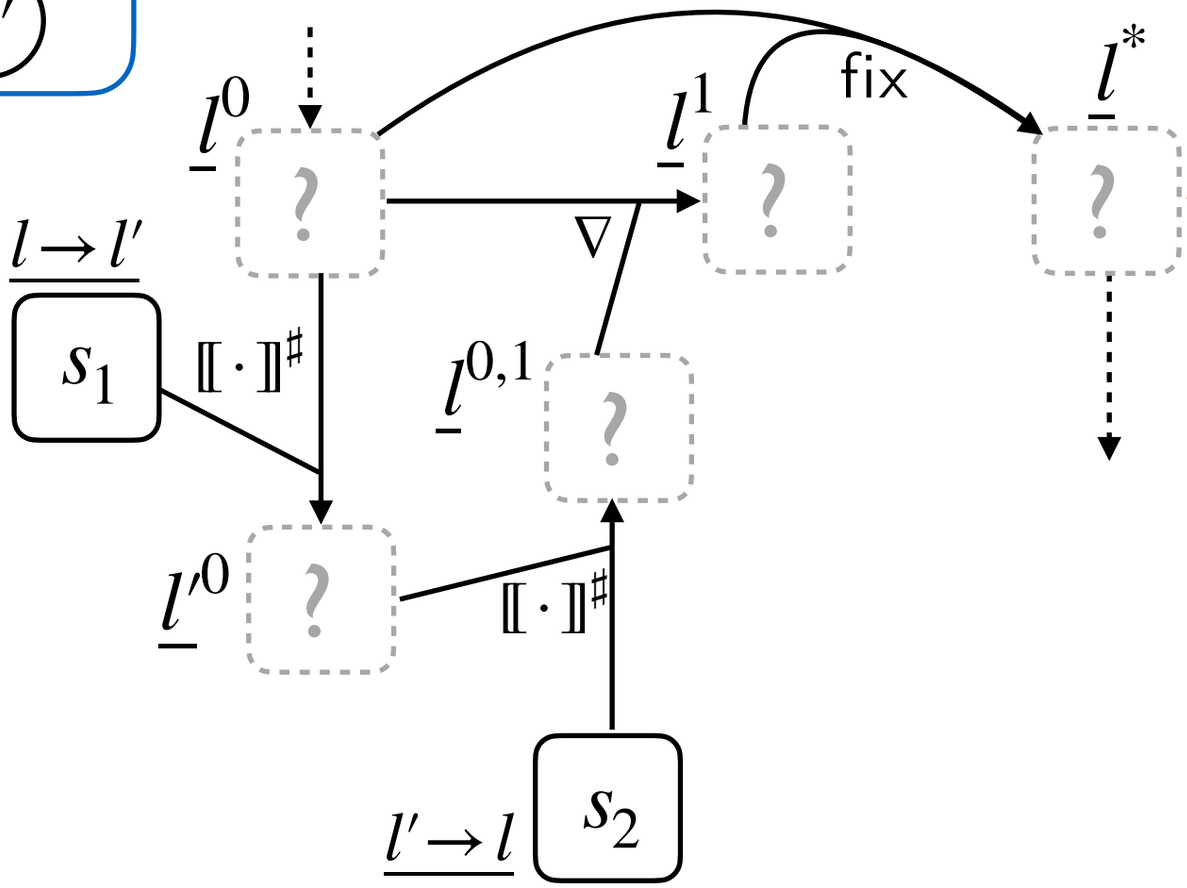
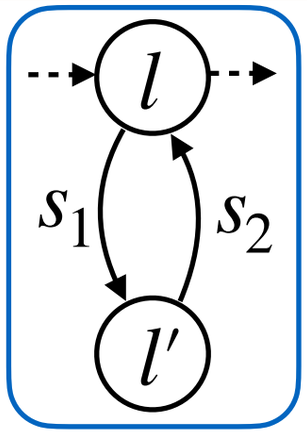


Compute dependencies as normal…

DAIG Fixed-point Computation

Program snippet



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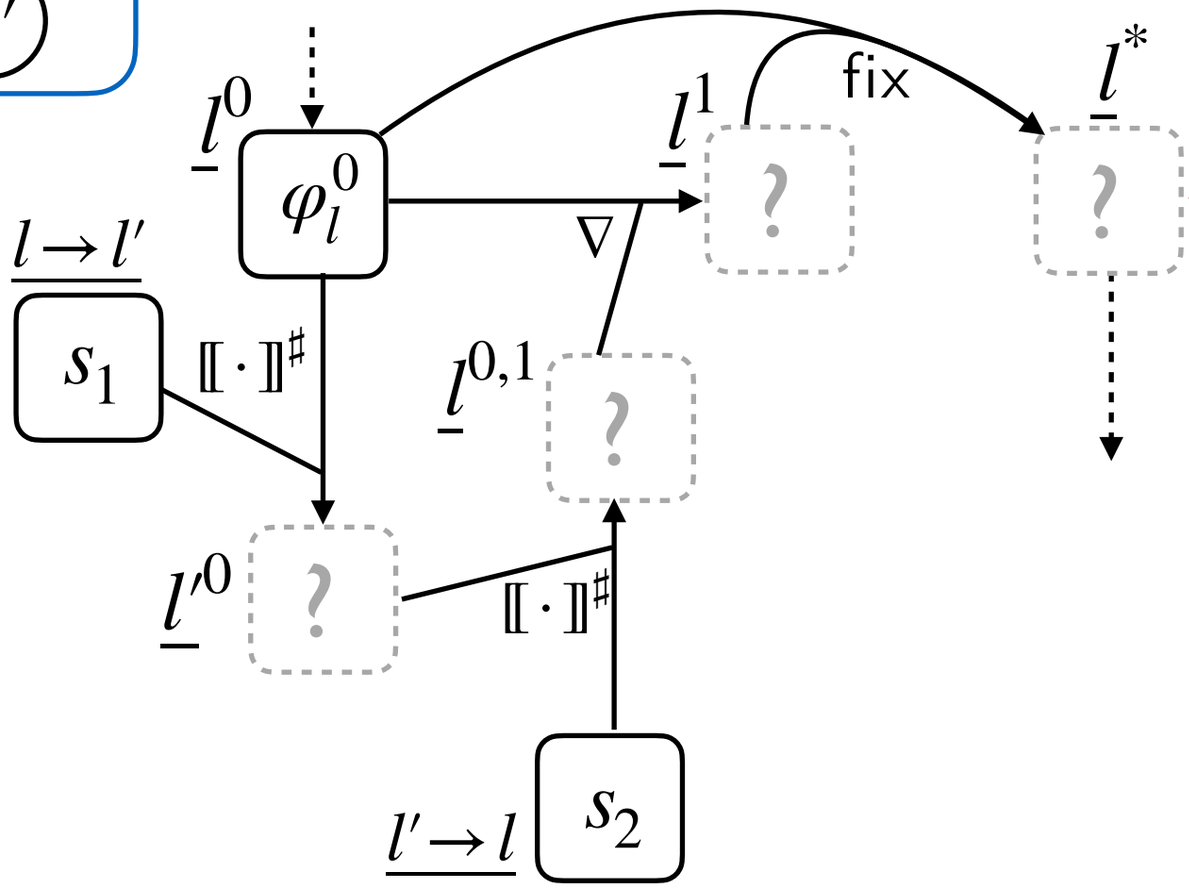

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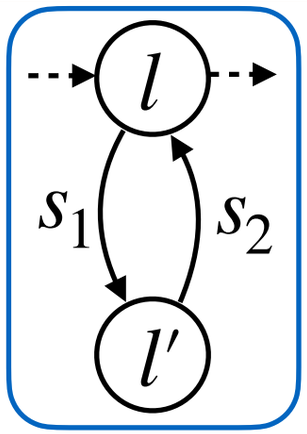

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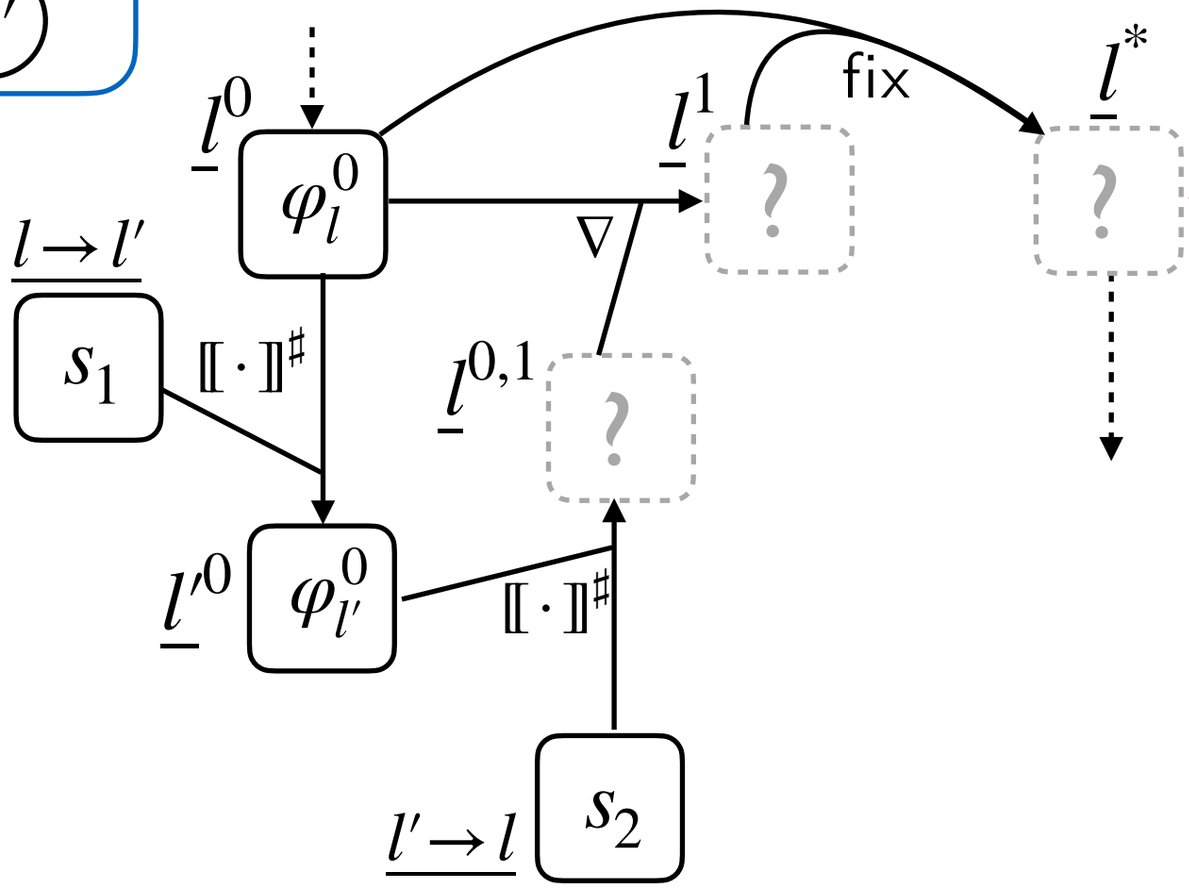

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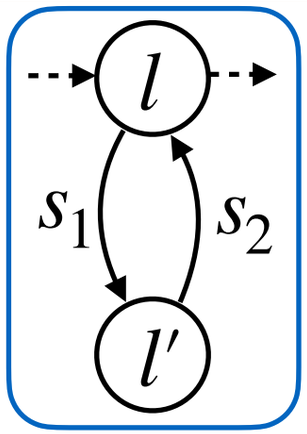

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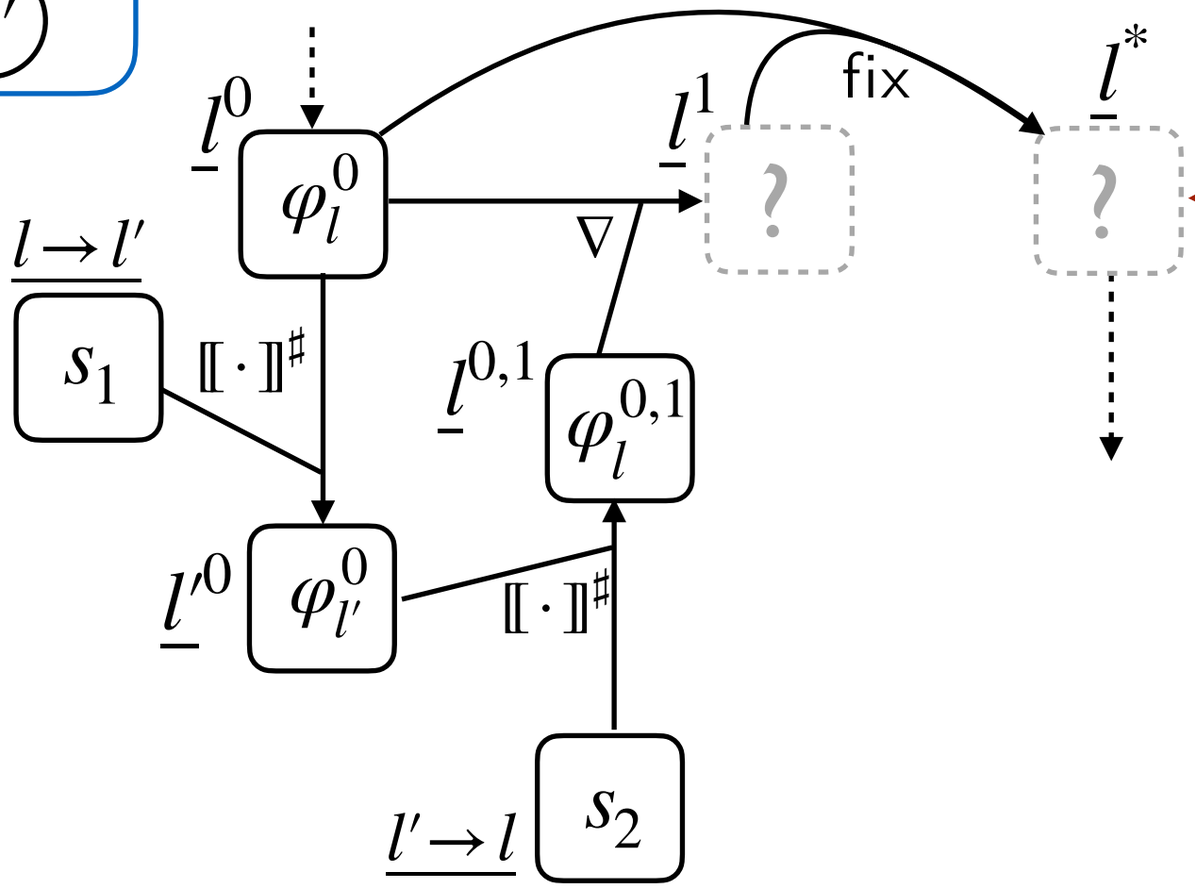

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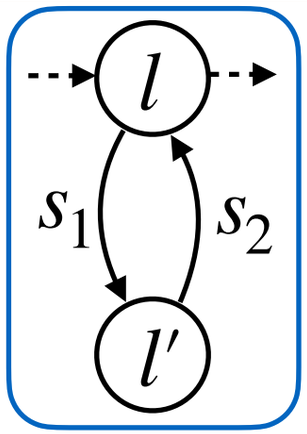

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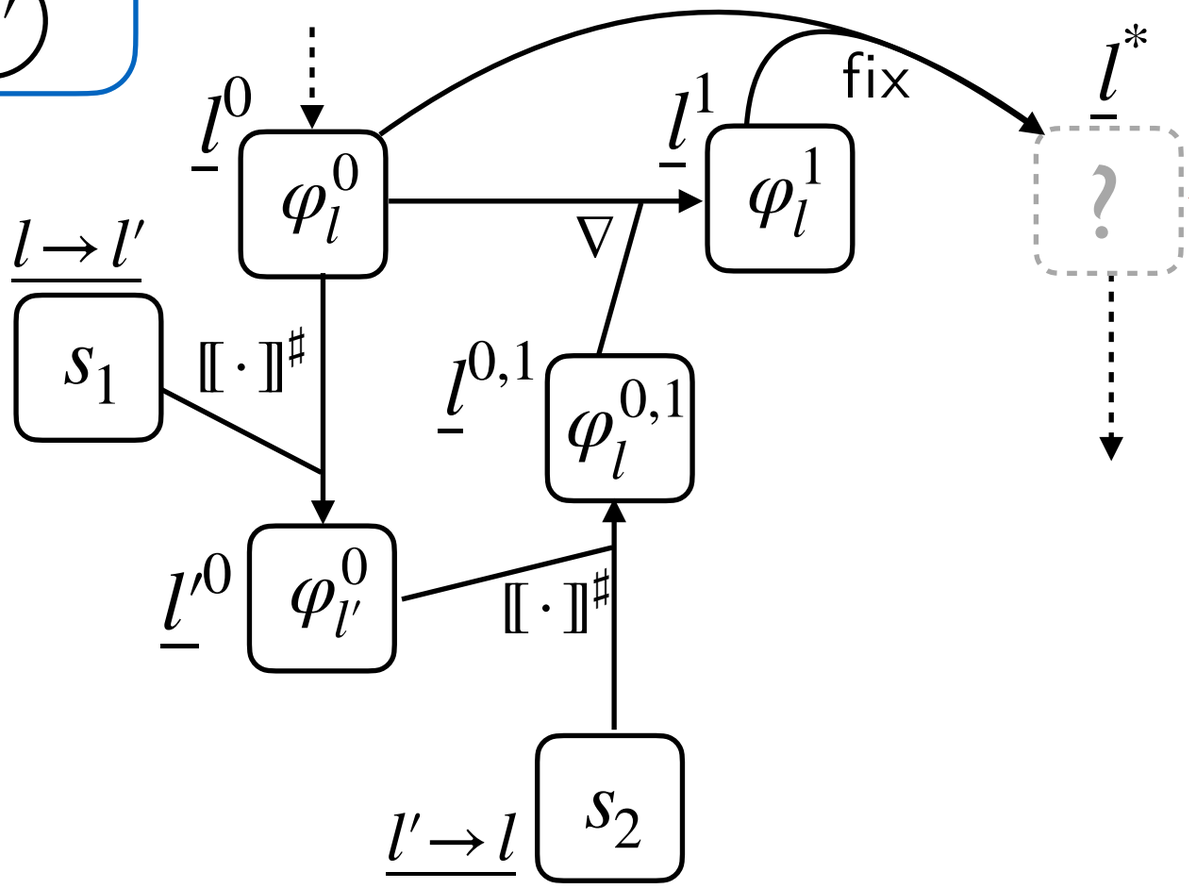

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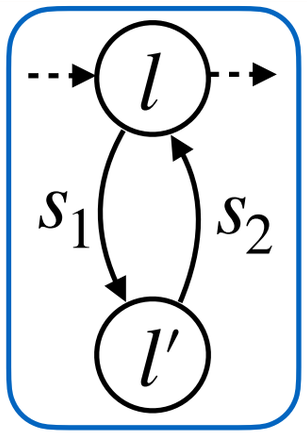

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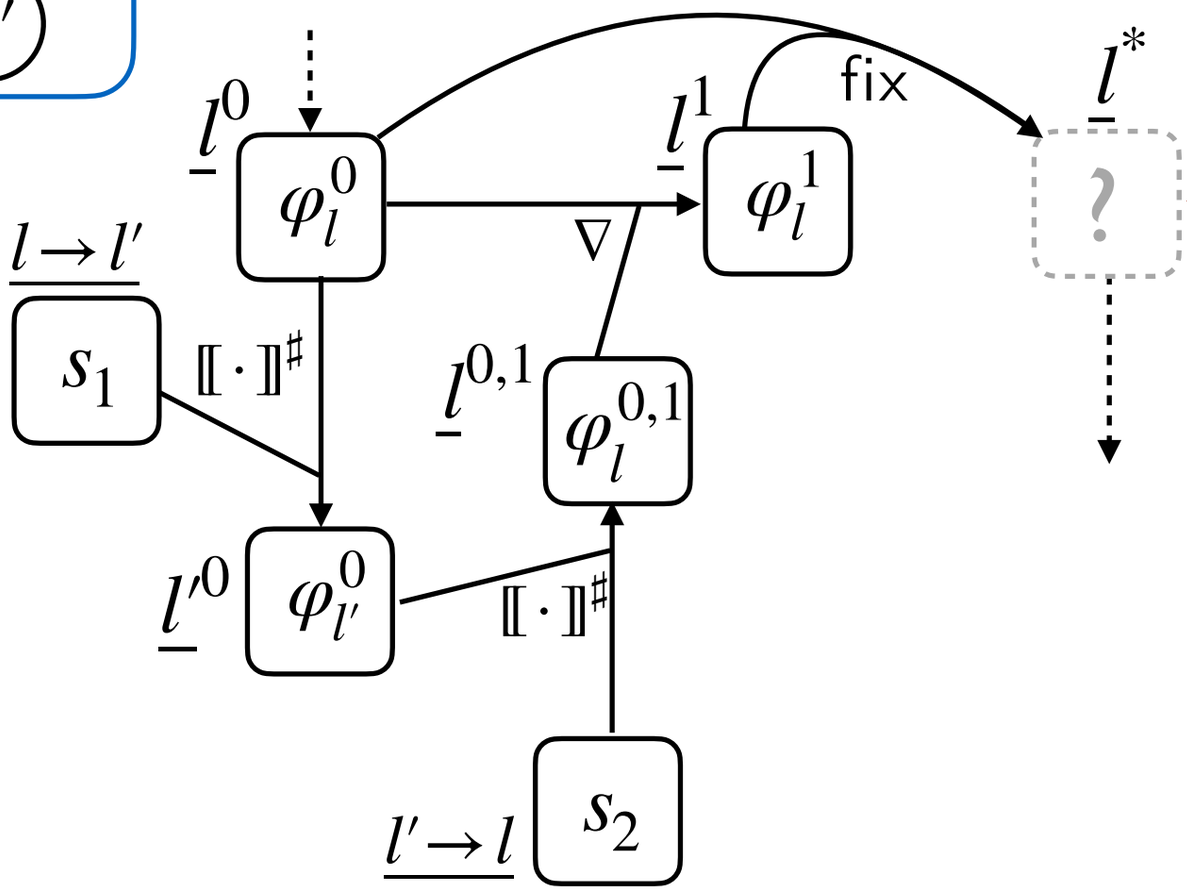
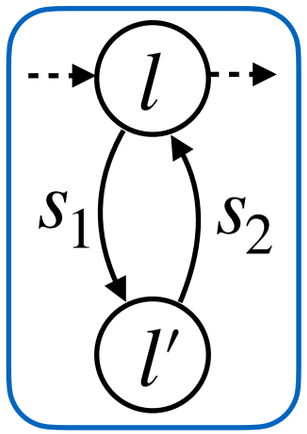


If the zeroth and first abstract iterates are equal (i.e. $\varphi_l^0 = \varphi_l^1$) then that's the fixed point; write to $\underline{l}^*$ and return.

DAIG Fixed-point Computation



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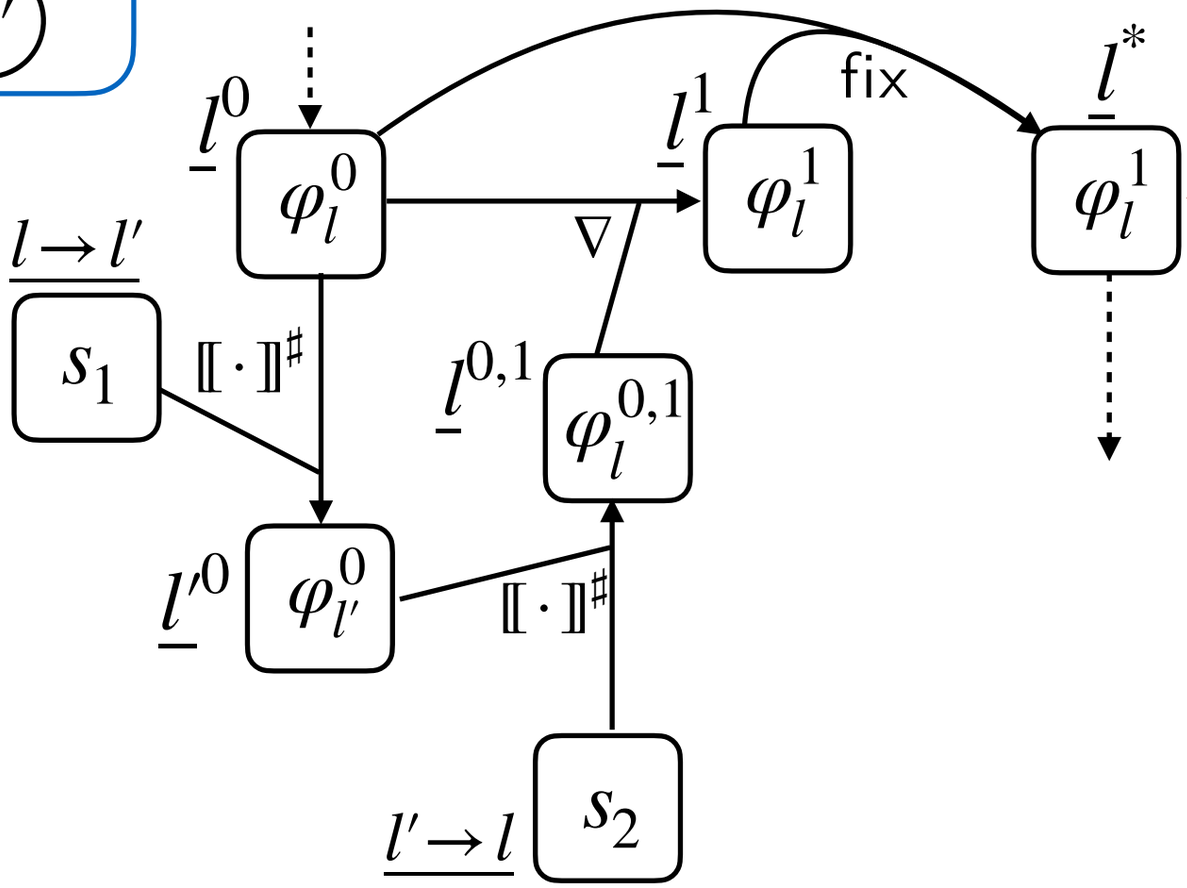

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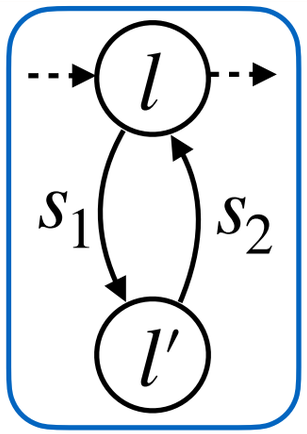

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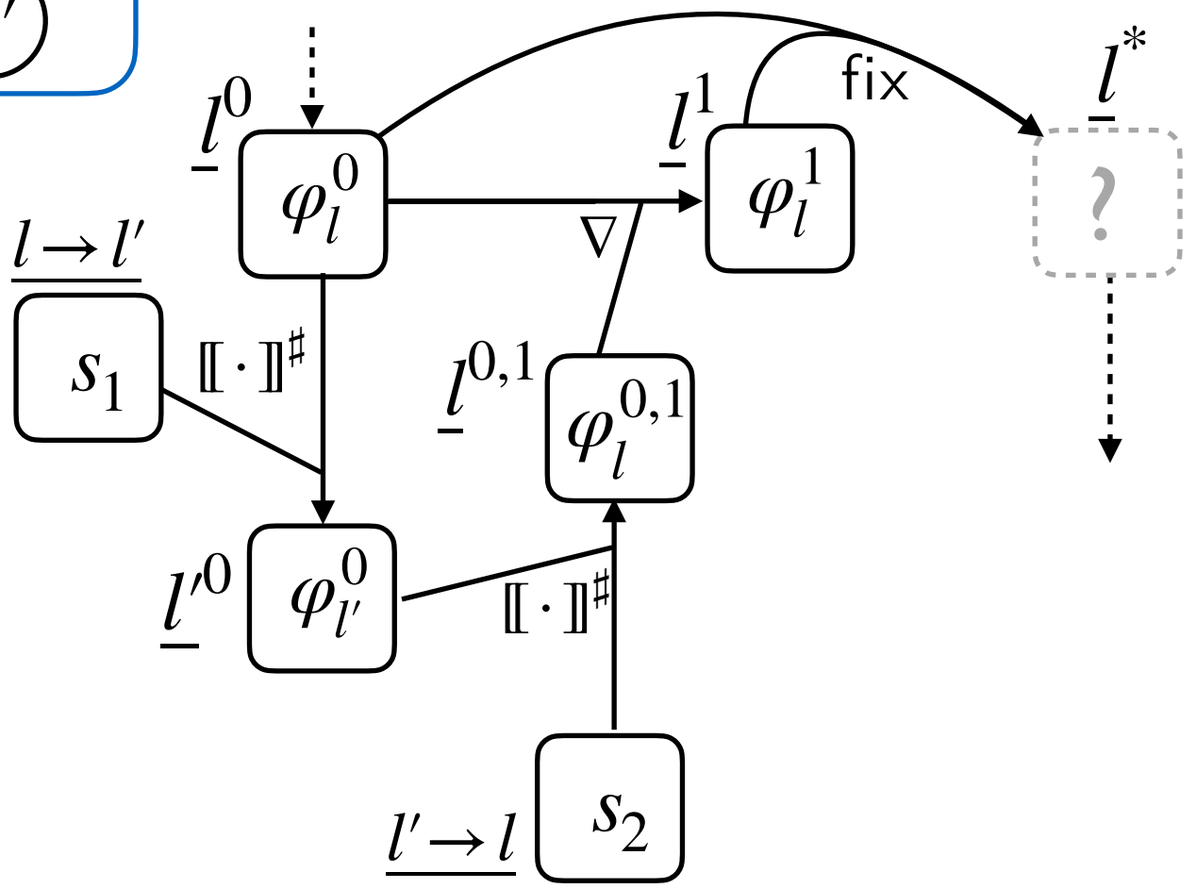
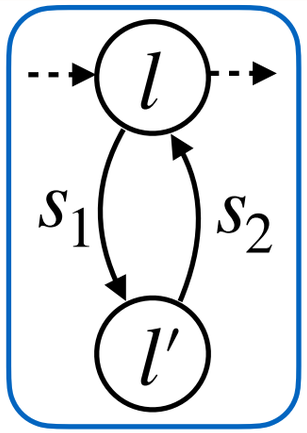


Demand-driven query:
"What is the *fixed-point* abstract state at l ?"

Otherwise, unroll the DAIG's loop representation, re-query, and continue.

DAIG Fixed-point Computation



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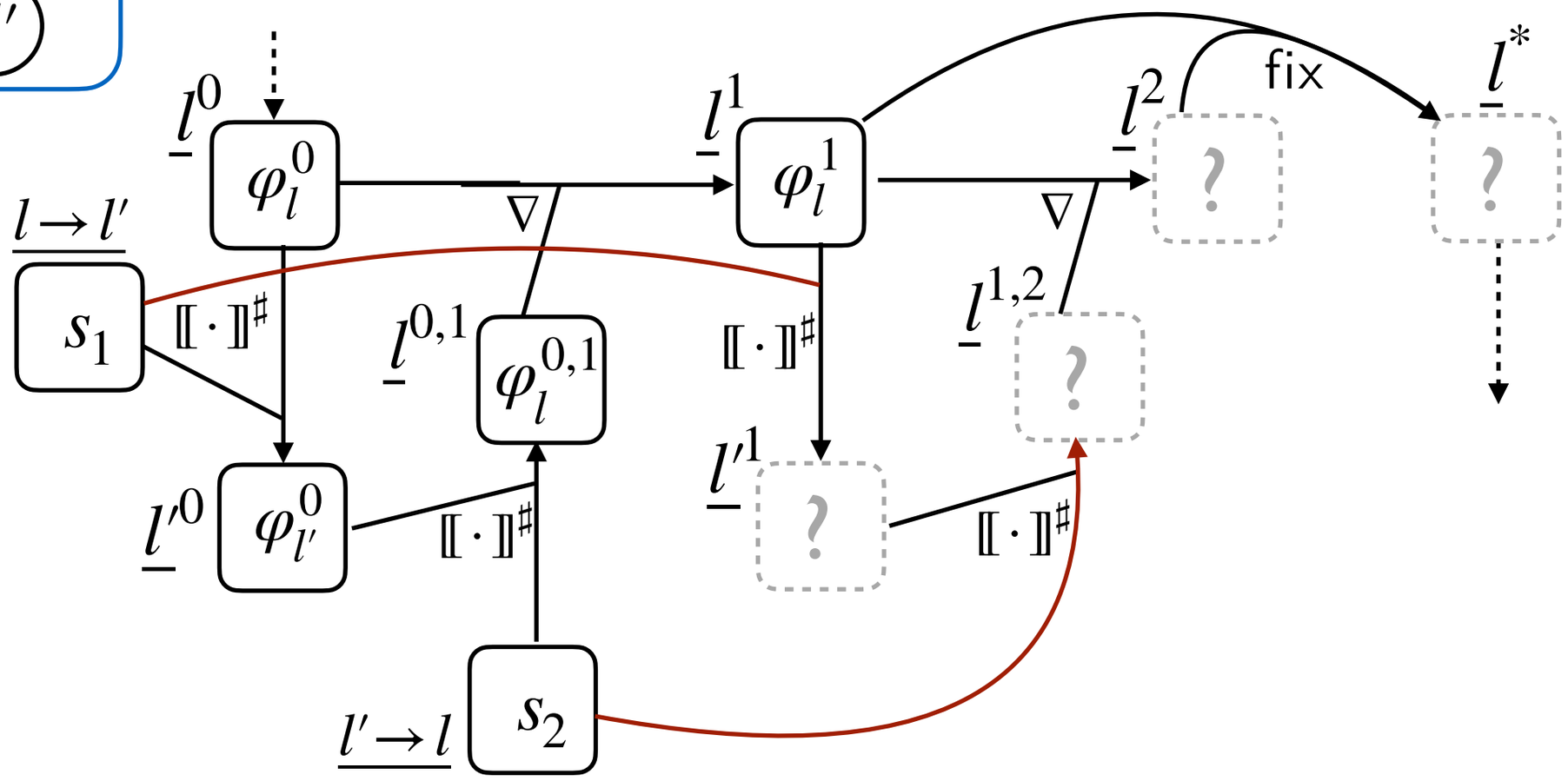

Statement cells not unrolled!

Otherwise, unroll the DAIG's loop representation, re-query, and continue.

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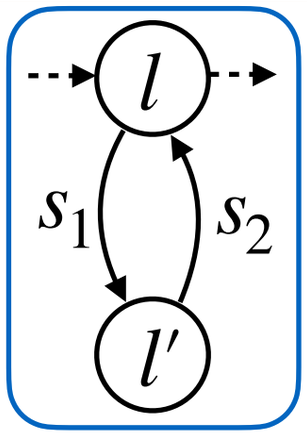

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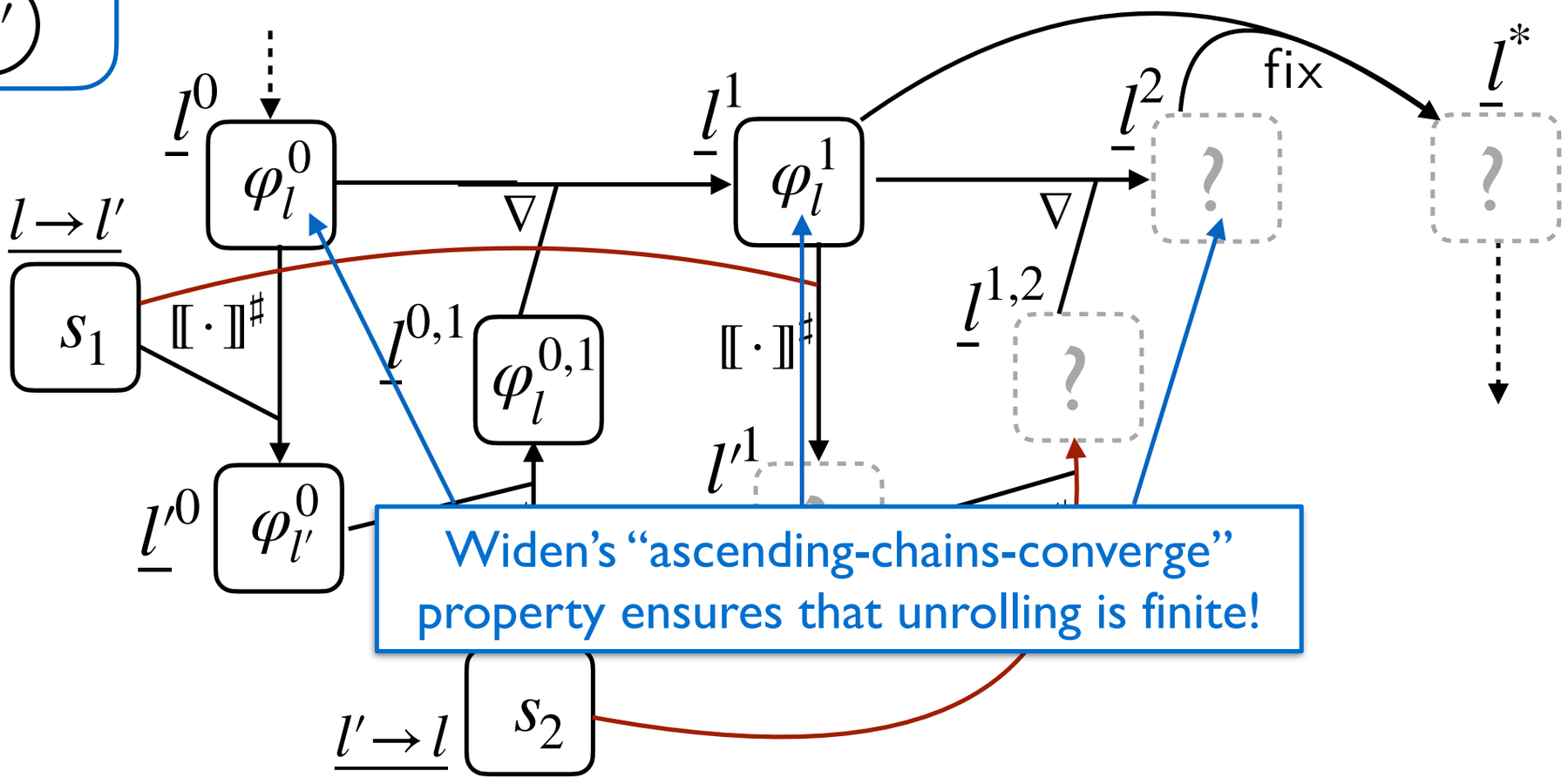

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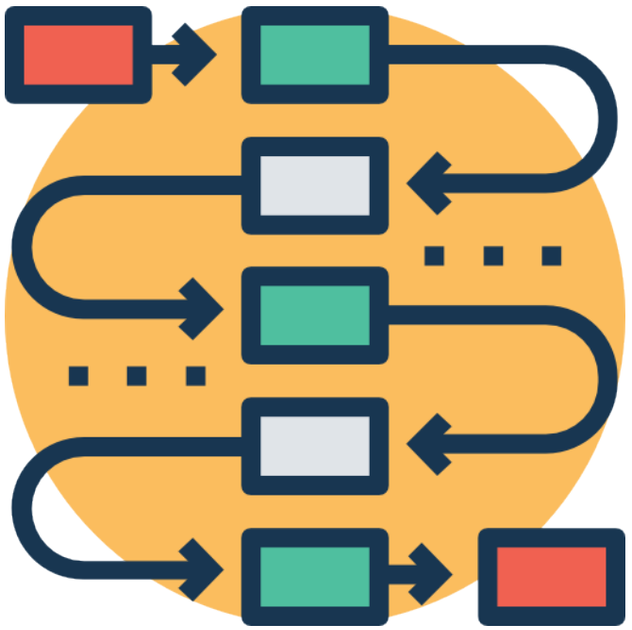
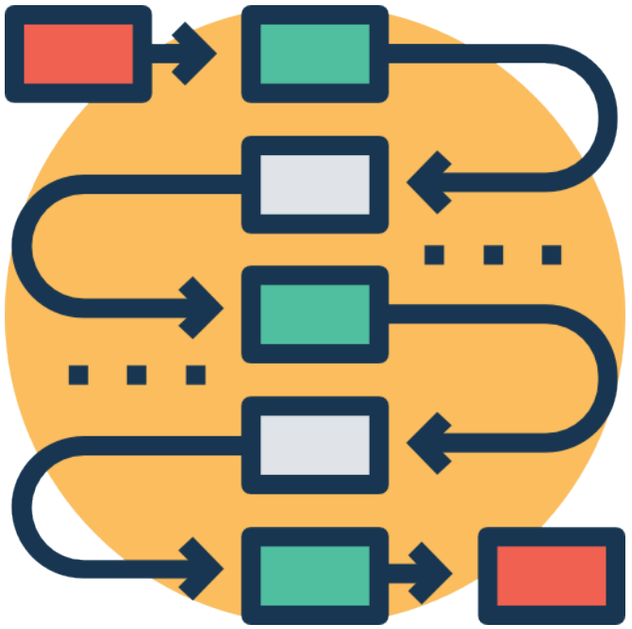
DAIG Formalism



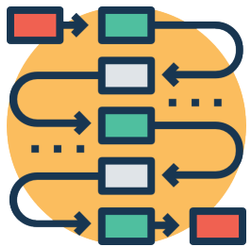
DAIG Formalism

A DAIG is an *explicit* representation of a partially-evaluated abstract interpretation



DAIG Formalism

Query evaluation == (small-step) operational semantics



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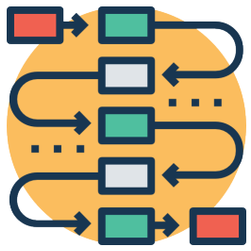

Given an initial DAIG*...

* this elides some details of the actual semantics

DAIG Formalism

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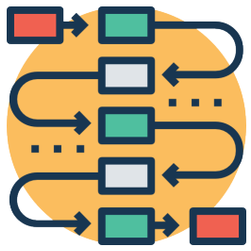

$$\vdash n \Rightarrow v$$

Given an initial DAIG*...

... a query for the value named n yields v...

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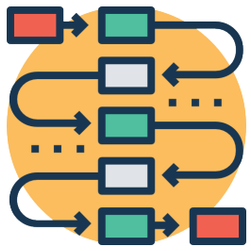
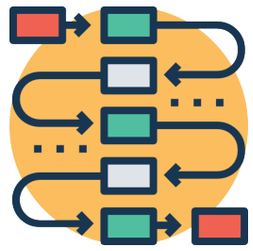
DAIG Formalism

Query evaluation == (small-step) operational semantics



$$\vdash n \Rightarrow v \;;$$



Given an initial DAIG*...

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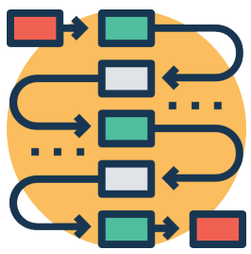

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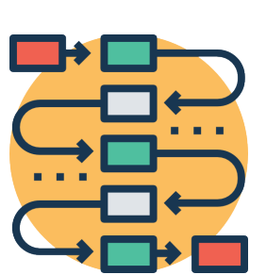

Given an initial DAIG*...

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Edit handling/change propagation is *also* a small-step operational semantics

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DAIG Formalism

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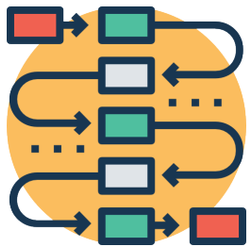

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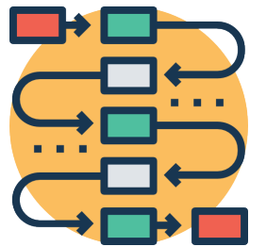

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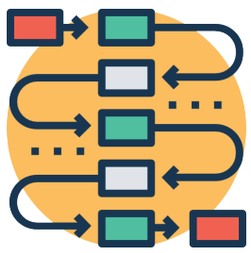

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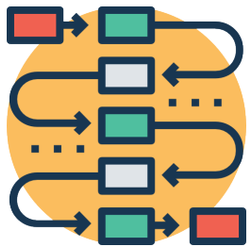

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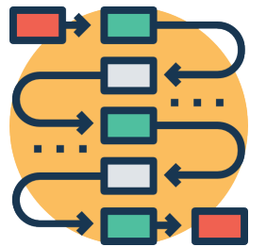

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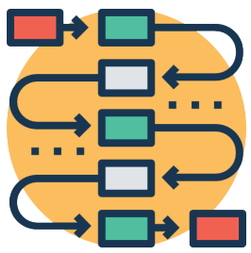

$$\vdash n \Leftarrow v$$

Given an initial DAIG...

... an edit that writes value v to cell n ...

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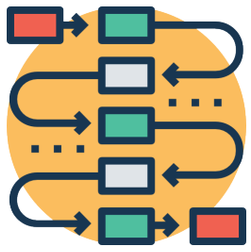
DAIG Formalism

Query evaluation == (small-step) operational semantics



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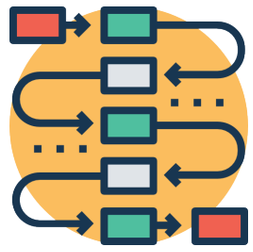

Given an initial DAIG*...

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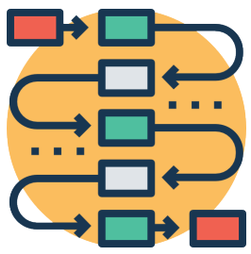
Edit handling/change propagation is *also* a small-step operational semantics



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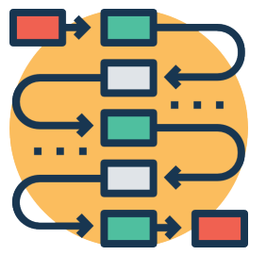

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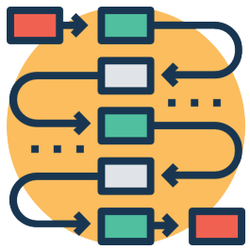
... an edit that writes value v to cell n ...

... yields an updated DAIG.

* this elides some details of the actual semantics

Termination



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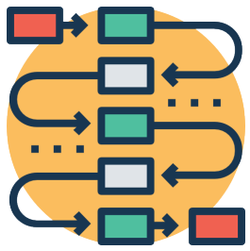
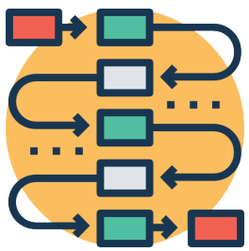


If this initial DAIG is a valid abstract interpretation state for some program...

Termination

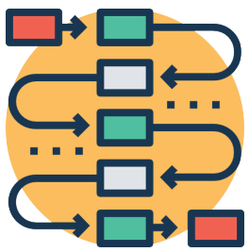


$\vdash n$

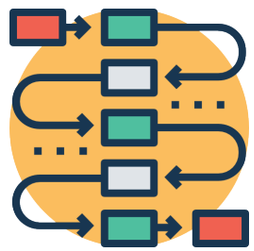
If this initial DAIG is a valid abstract interpretation state for some program...

... then a query for any n therein ...

Termination



$$\vdash n \Rightarrow v \; ;$$



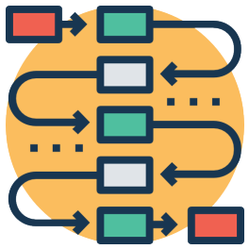
$'$

If this initial DAIG is a valid abstract interpretation state for some program...

... then a query for any n therein ...

... will terminate with some value v and an updated DAIG.

From-Scratch Consistency



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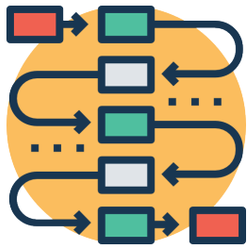

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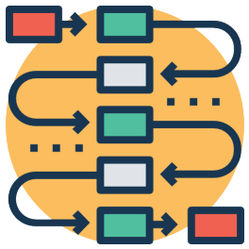
From-Scratch Consistency



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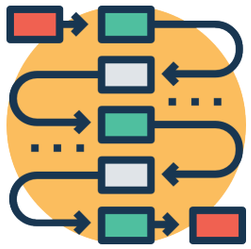
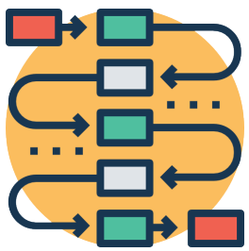


$'$

If the current DAIG is a valid abstract interpretation state for some program…

From-Scratch Consistency



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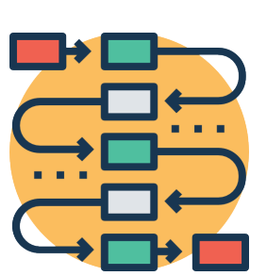

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If the current DAIG is a valid abstract interpretation state for some program...

... and n is the name of the abstract state at a program location l ...

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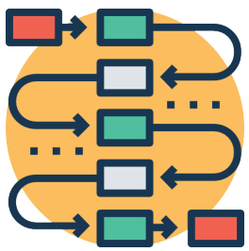

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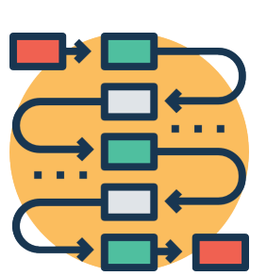

If the current DAIG is a valid abstract interpretation state for some program...

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... then v is *precisely* the same value that a batch abstract interpreter would compute at l.

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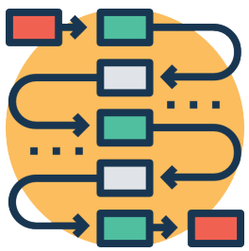

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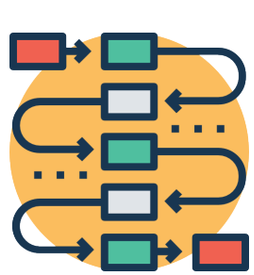

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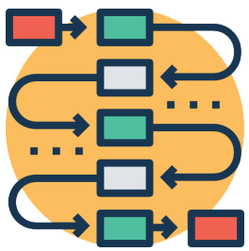

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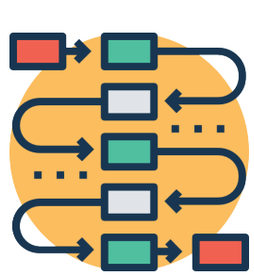

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Corollary: DAIG query results are **sound**.

Expressivity

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Domain implementer doesn't need to reason about incrementality or demand!

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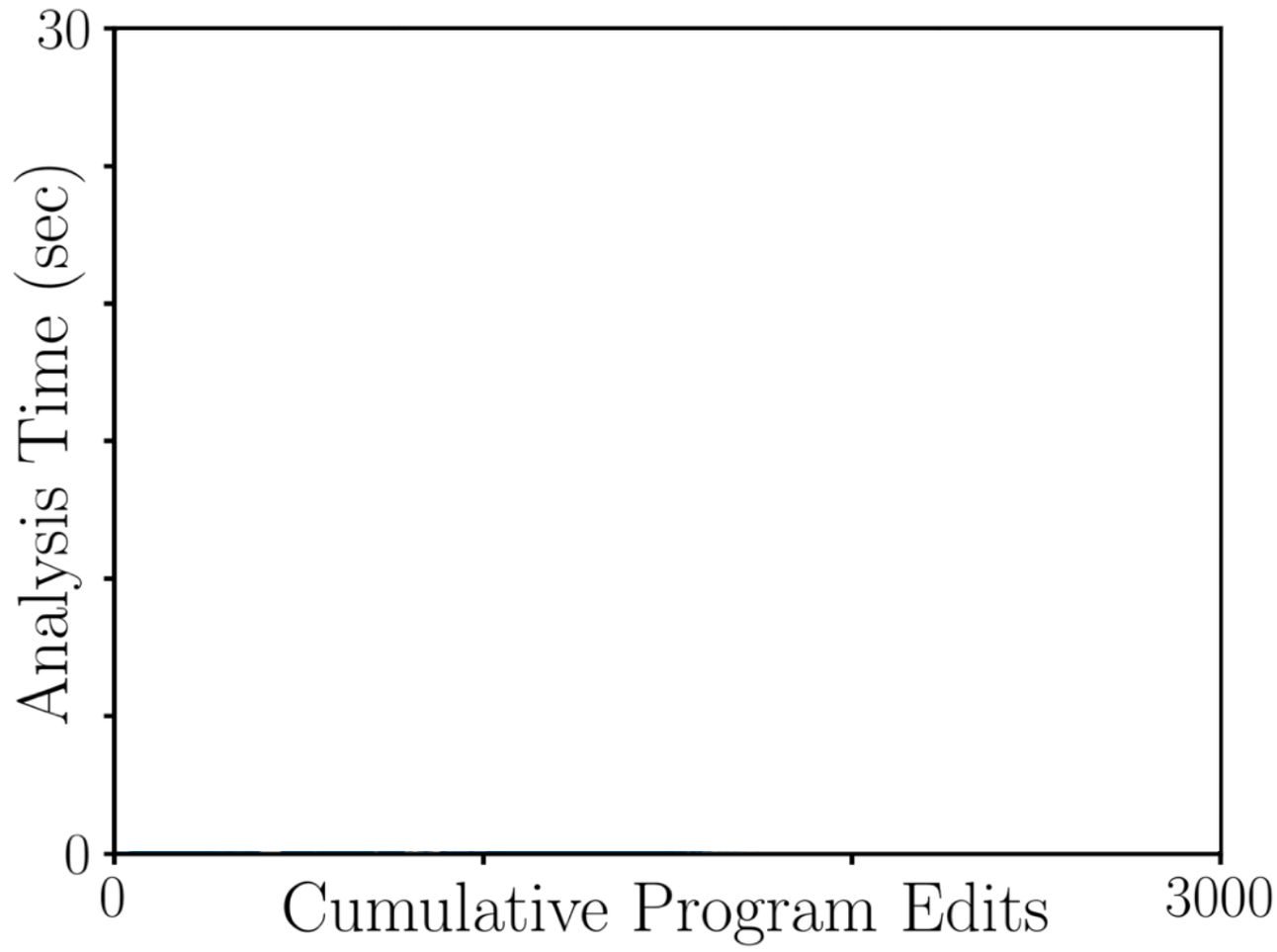
Intervals & Octagons built with APRON — optimized open-source numerical domains in C

Scalability

For these rich analysis domains, what degree of performance improvement can be obtained by performing incremental and/or demand-driven analysis?



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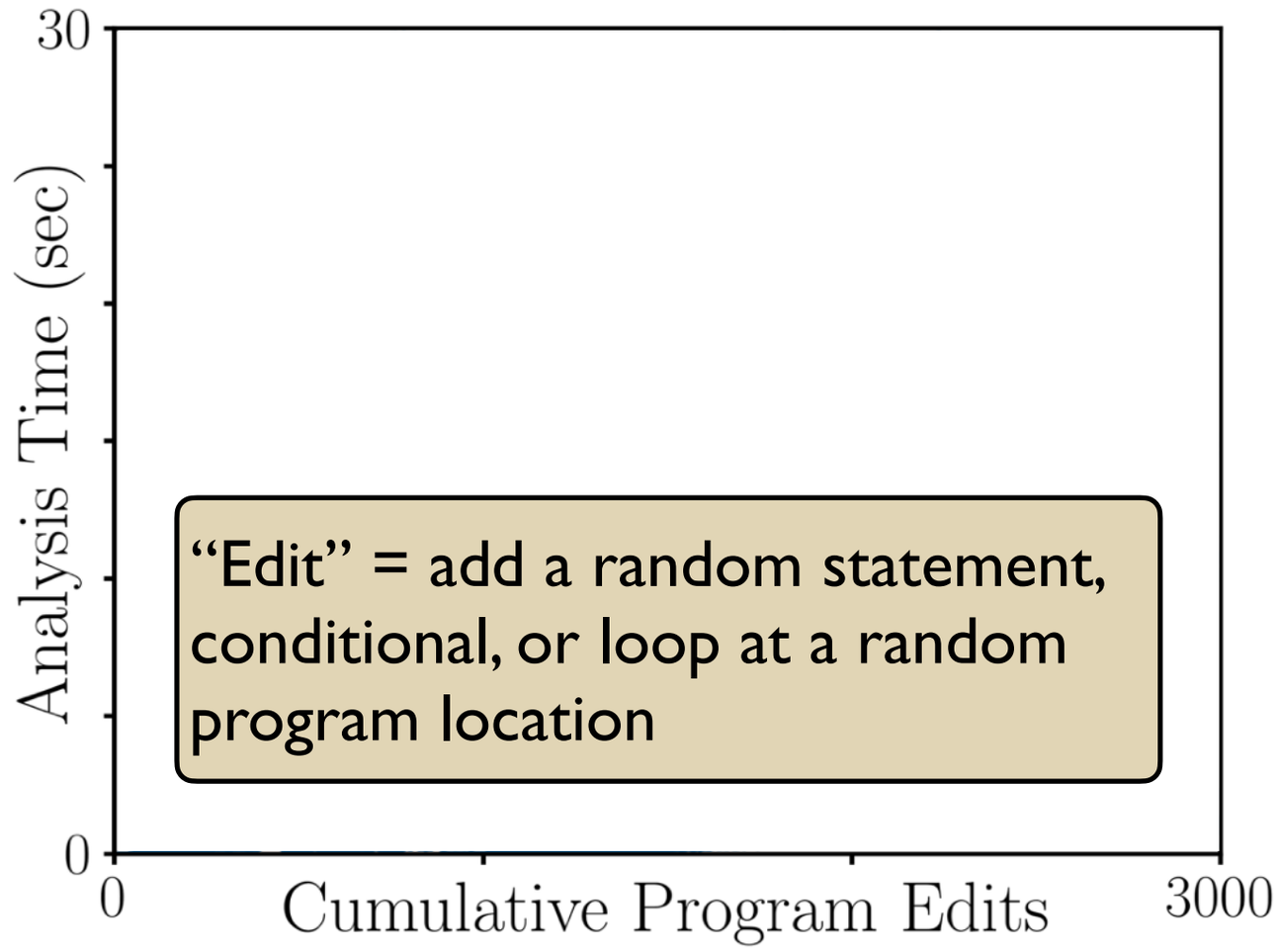

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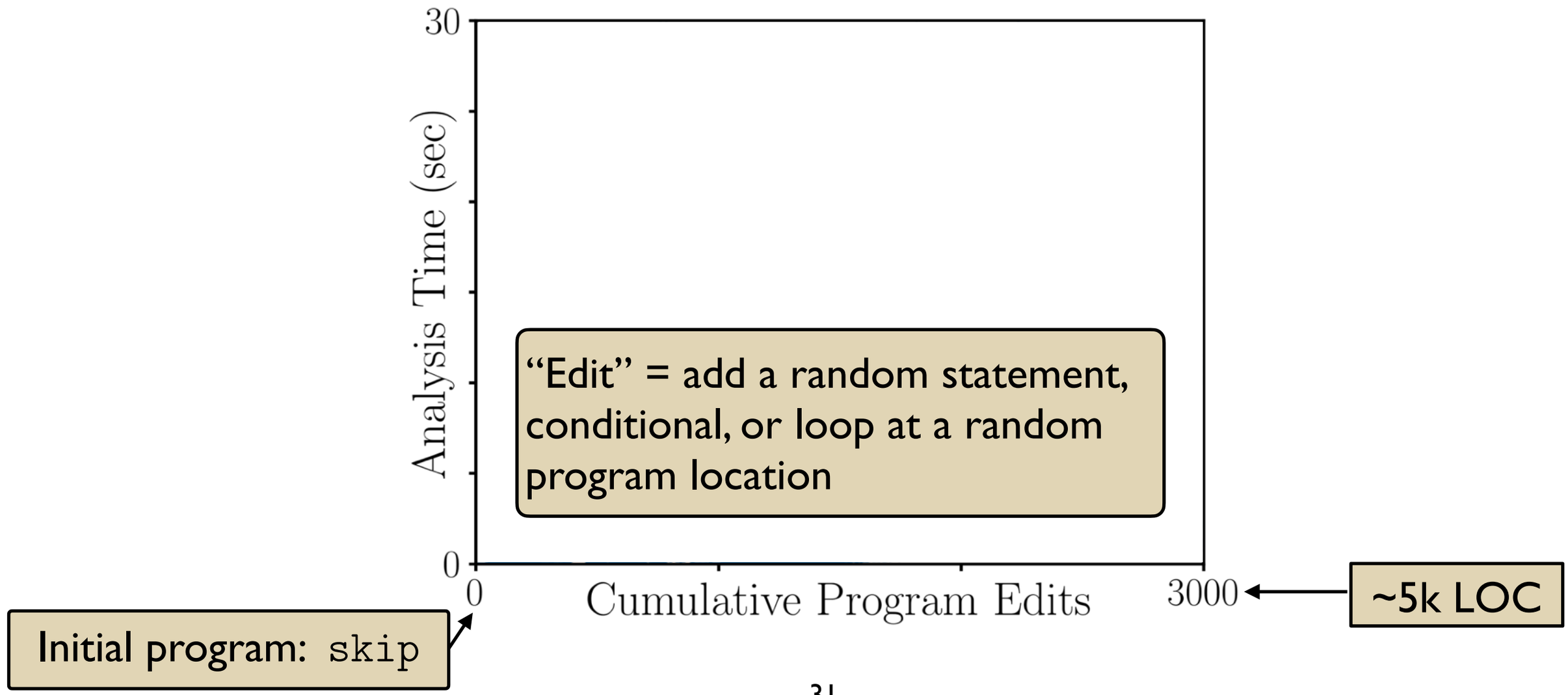

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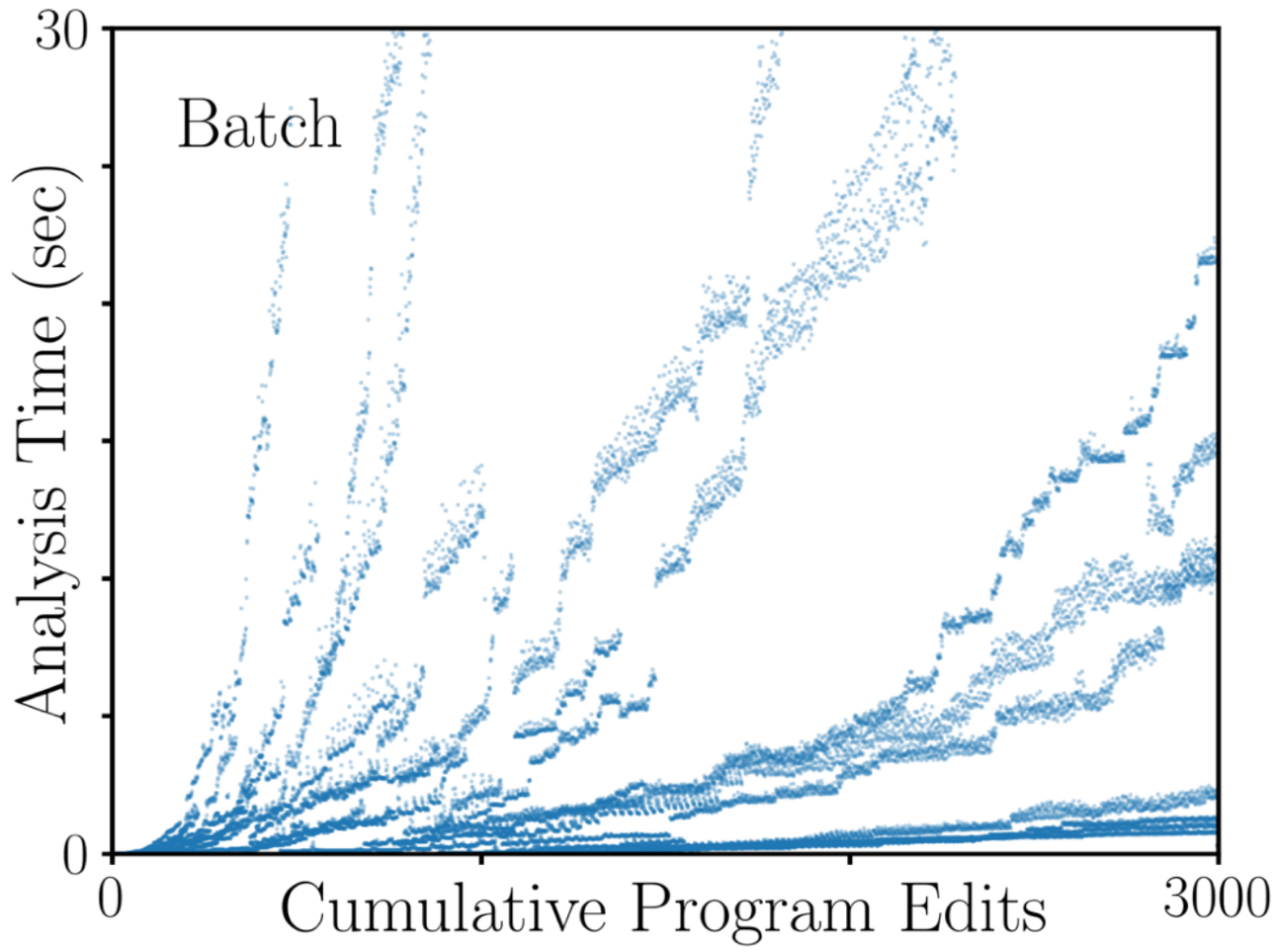

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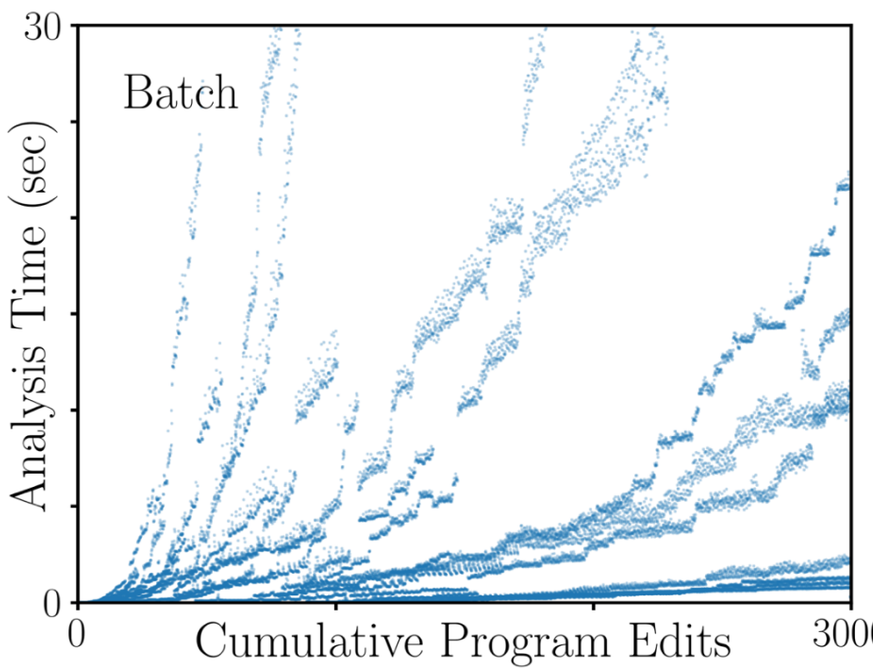

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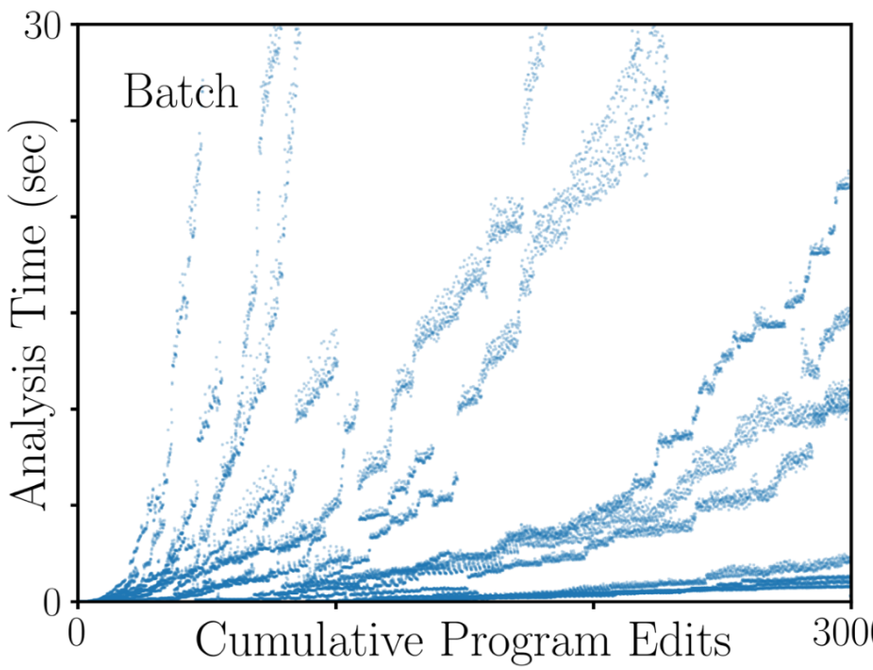

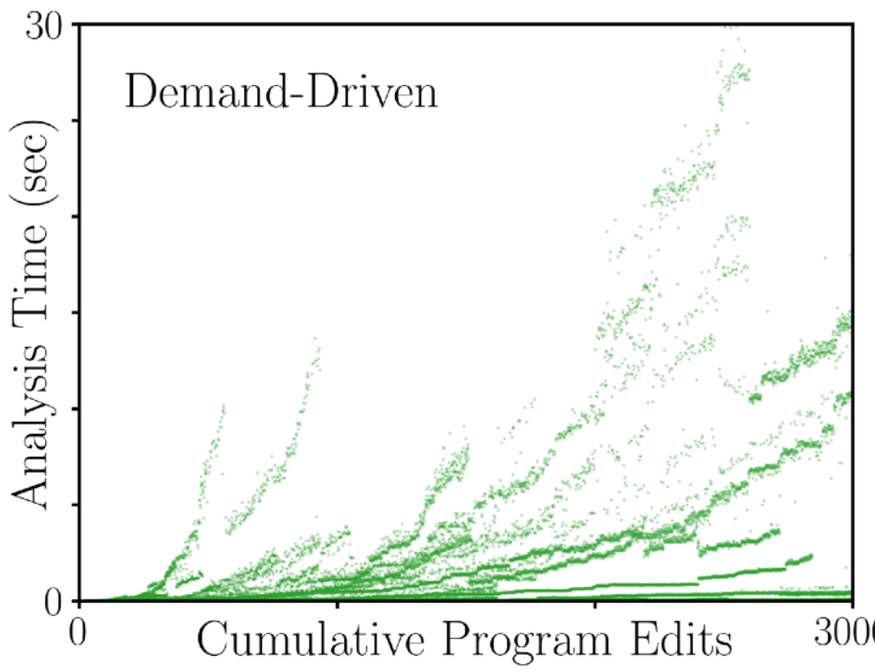

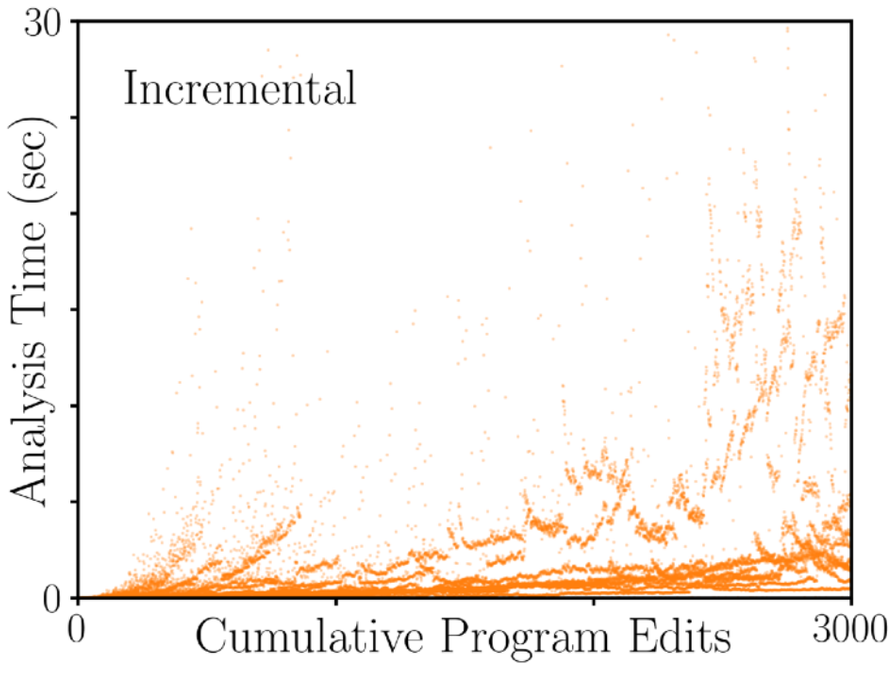

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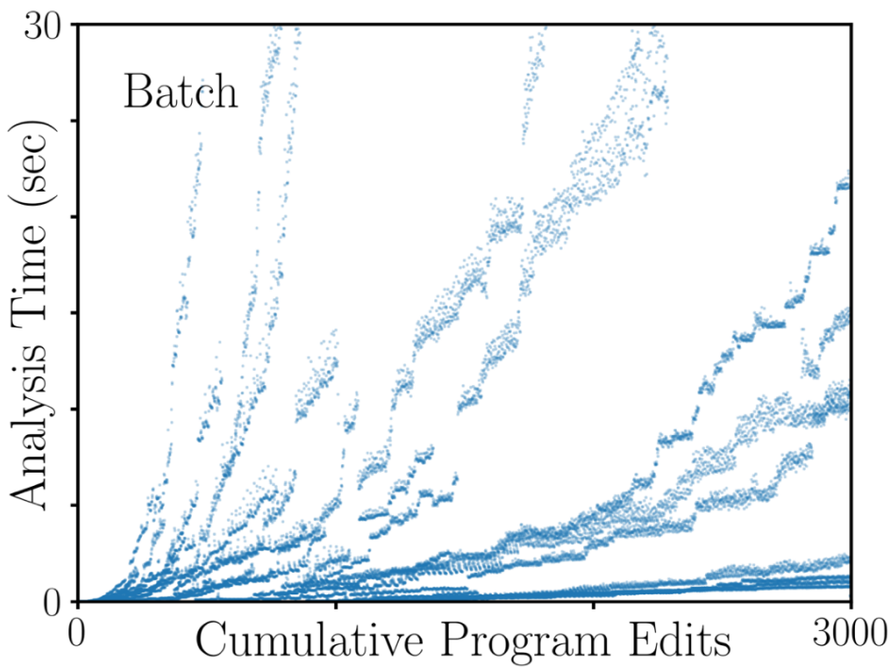

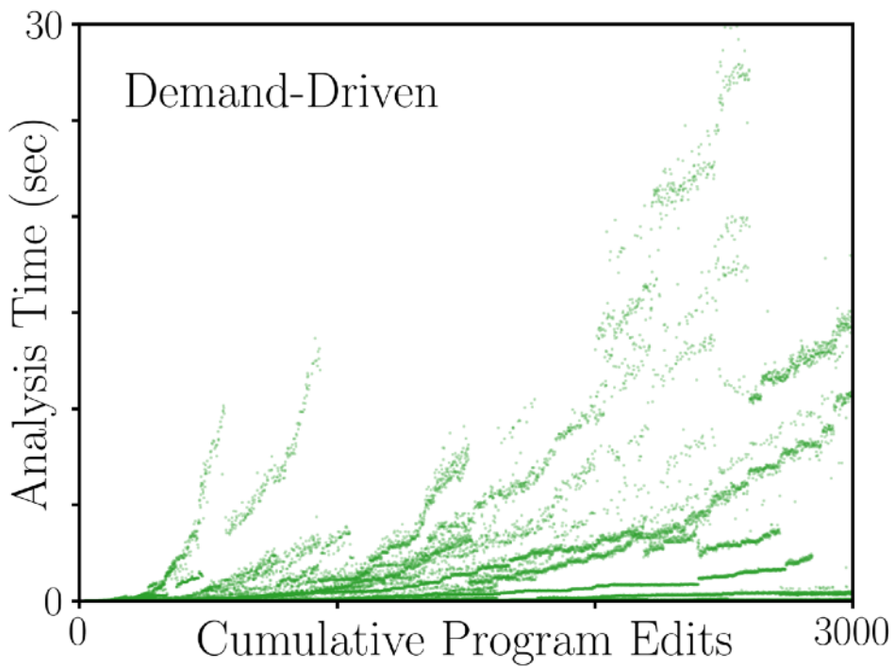

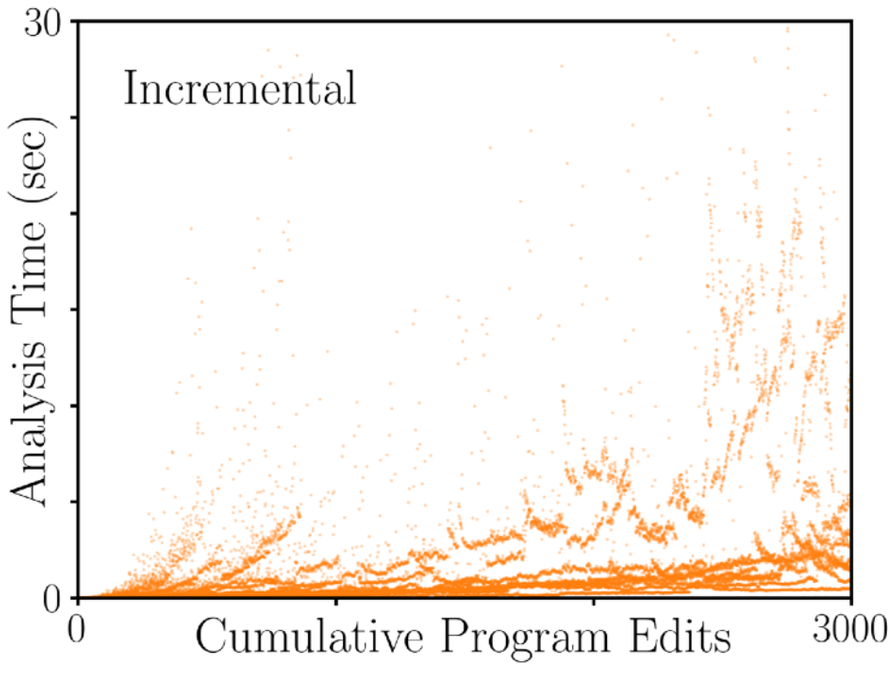

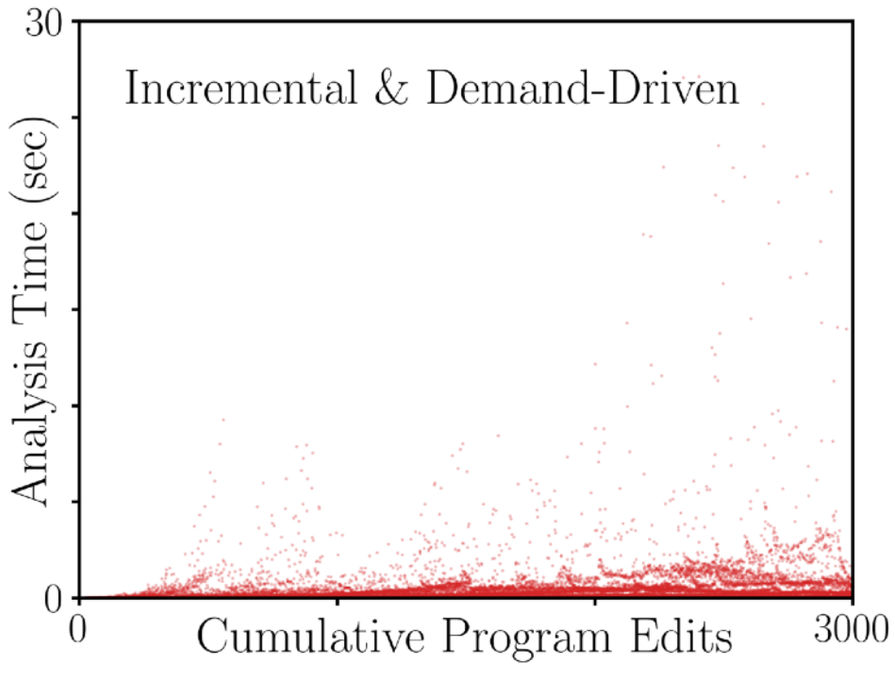

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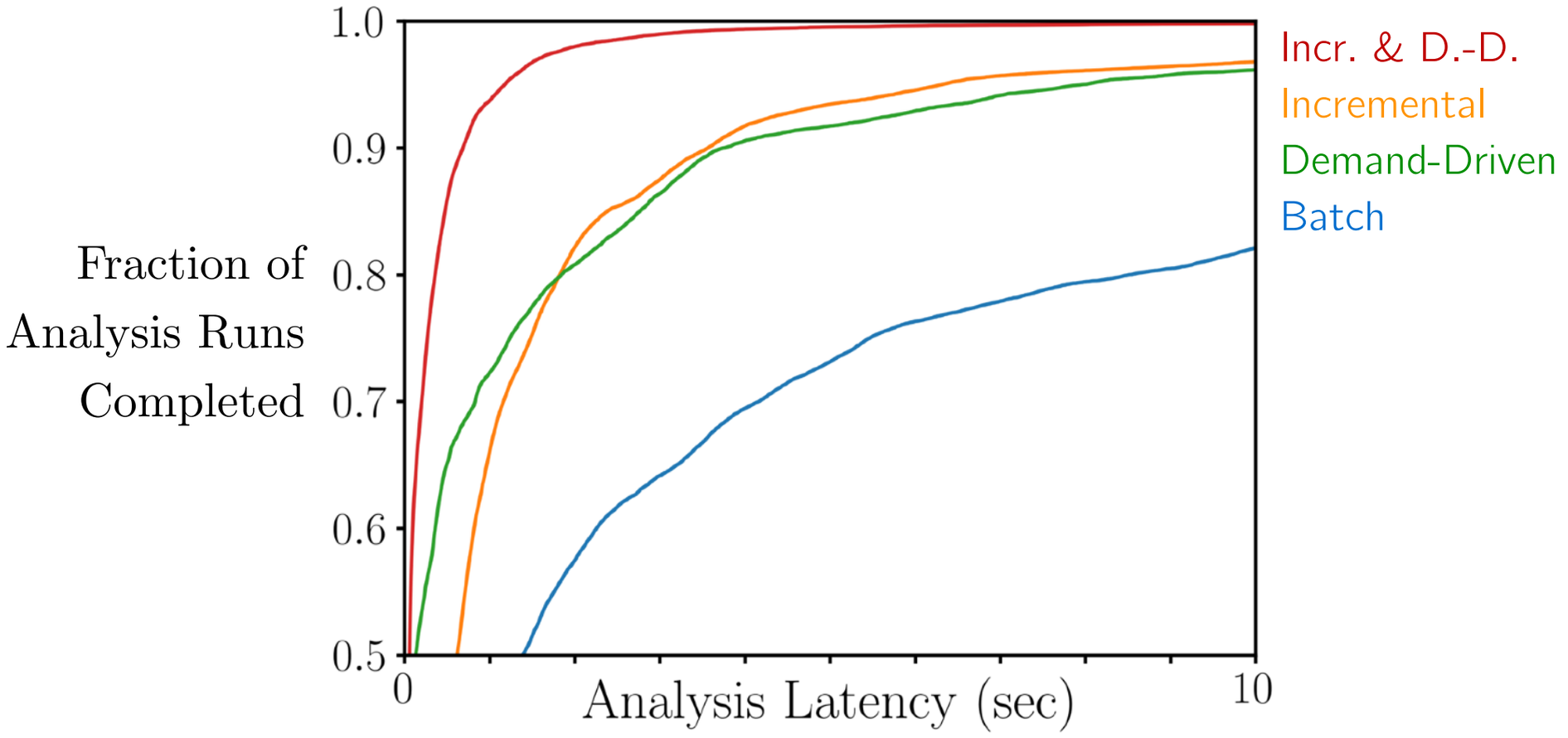
The *combination* of incrementality and demand consistently obtains lower latencies than either incrementality or demand alone.



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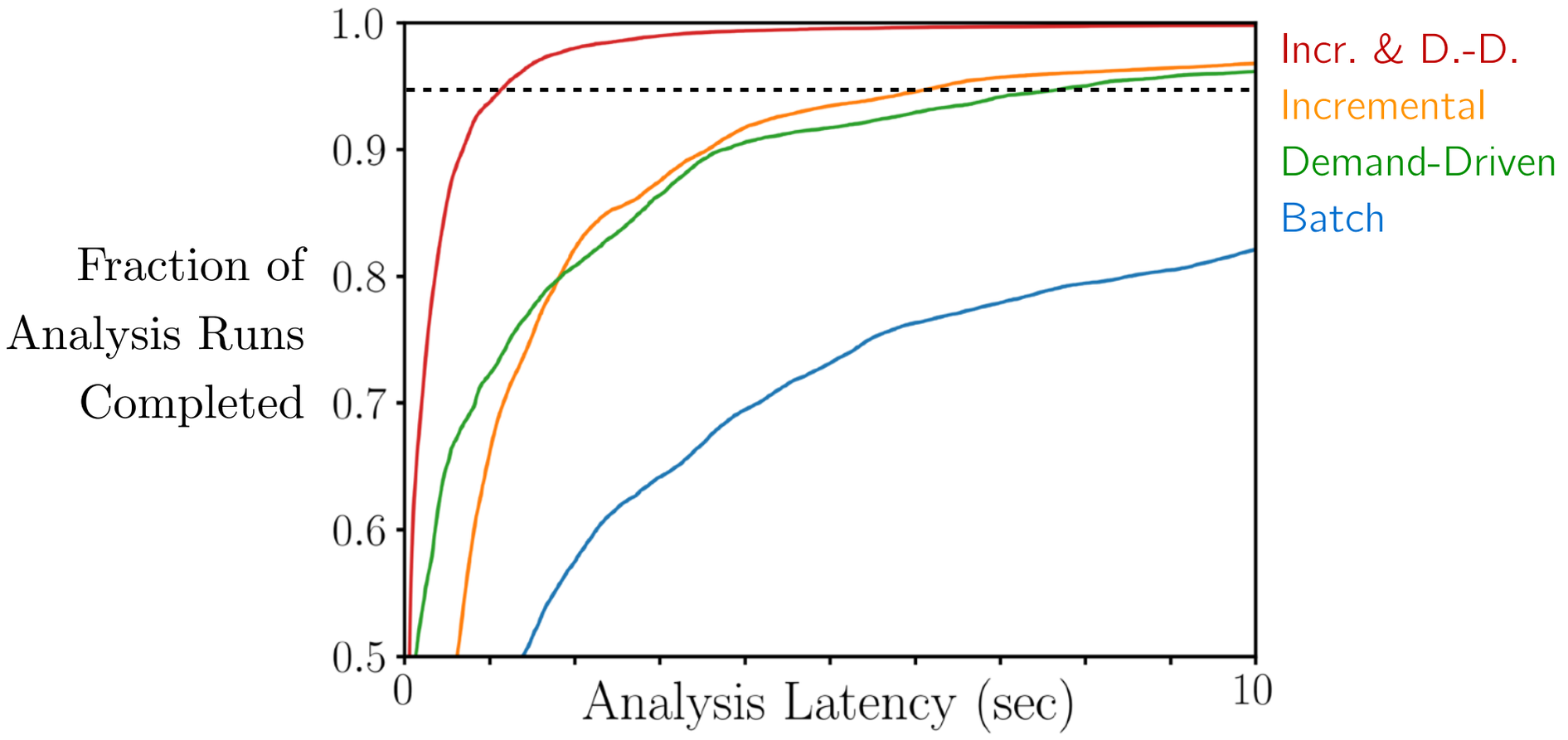

p95: 1.2s ; 6.3s ; 7.9s ; 36.2s

Thanks for watching!

Check out our paper or come chat at the Q&A for more details.

Conclusion:

- Batch whole-program analysis is too costly to support real-time developer interaction, but existing incremental and demand-driven analyses are often limited in expressivity or granularity
- By leveraging graph-based incremental computation techniques, we define an engine for incremental and demand-driven evaluation of *arbitrary* abstract interpreters (and prove it sound & from-scratch consistent)

CUPLV

Benno Stein
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PLDI '21