Incremental Slicing
CEGAR + Program Slicing

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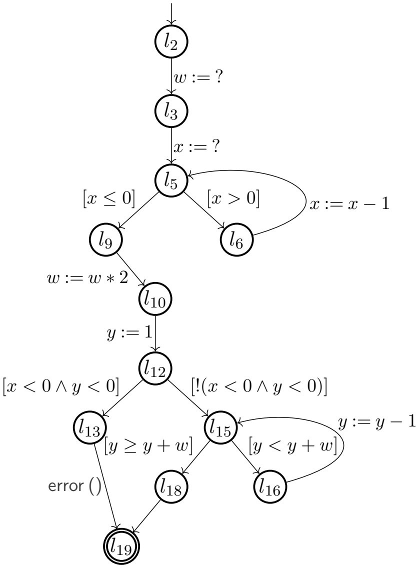
The Evil Loop Program

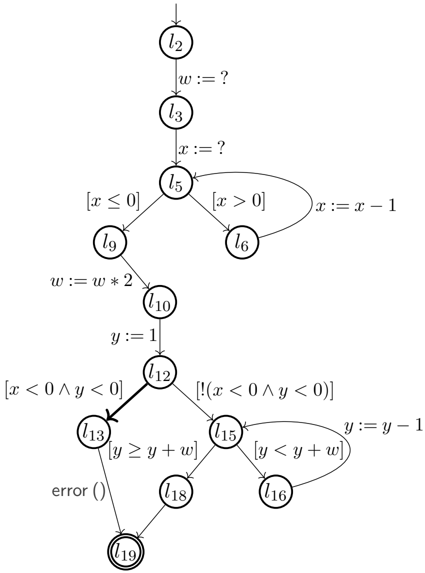
```
int main() {
    int w = ?;
    int x = ?;

    while (x > 0) {
        x--;
    }

    int w = w * 2;
    int y = 1;

    if (x < 0 && y < 0) {
        error();
    } else {
        while (y < y + w) {
            y--;
        }
    }
}
```



Symbolic Execution

1. Symbolic memory: Stores (symbolic) variable assignments.
   $v : X \mapsto \mathcal{Z} \cup \mathcal{S}$
2. Path constraints: Constrain symbolic values.
   $pc \in 2^{\mathcal{P}}$

Path Explosion ruins the day



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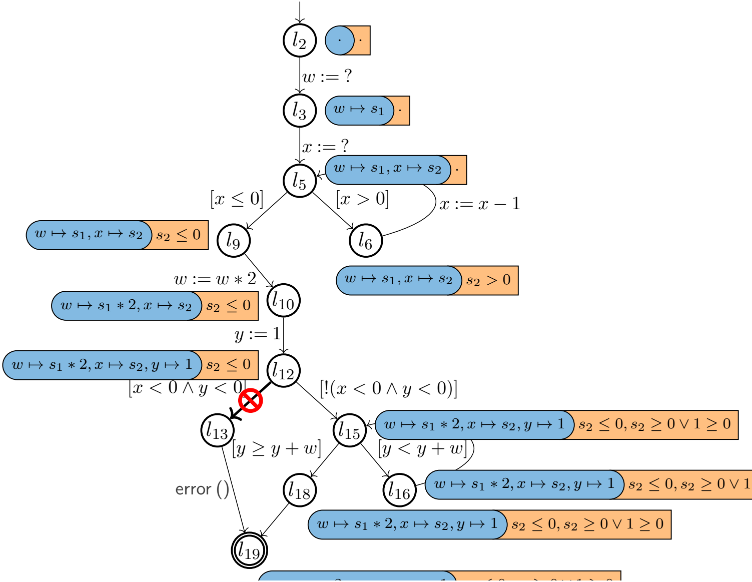

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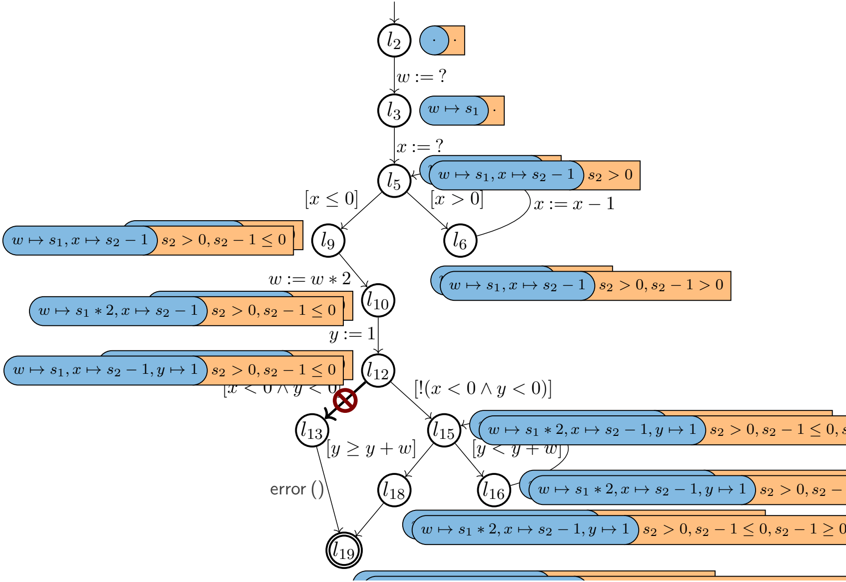

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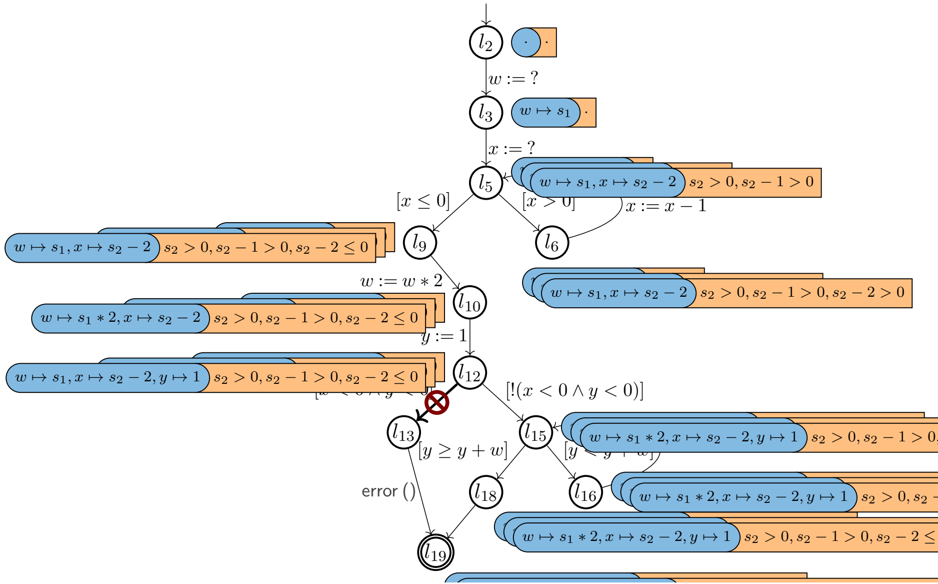

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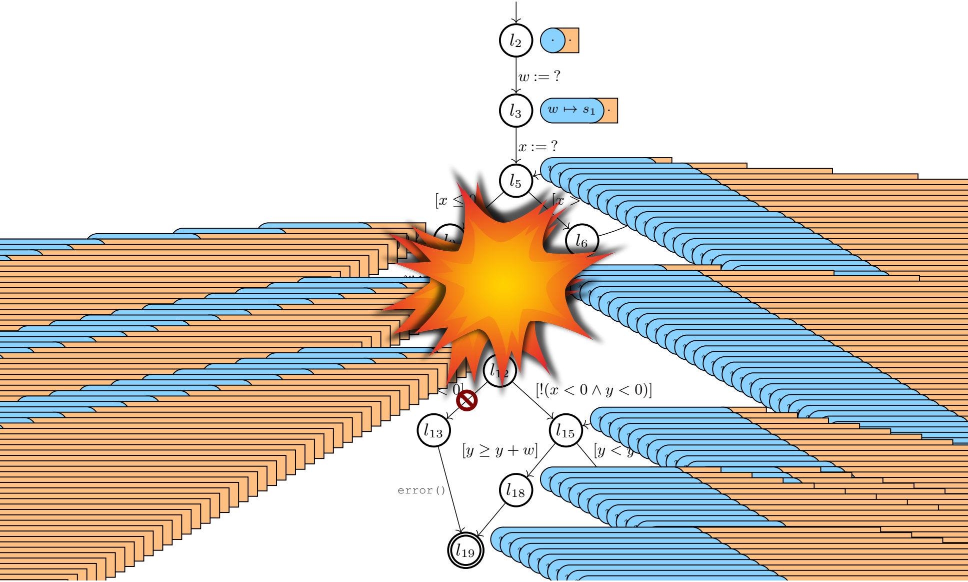
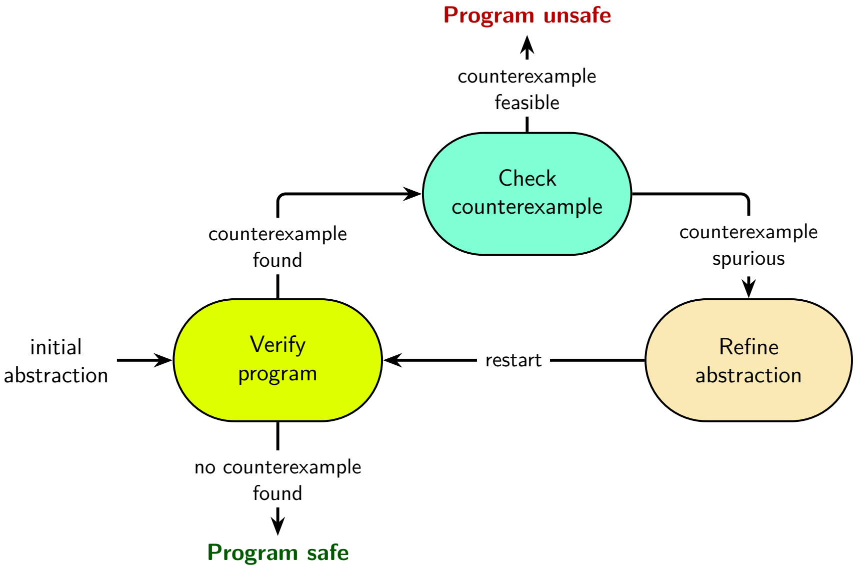


Abstraction with CEGAR

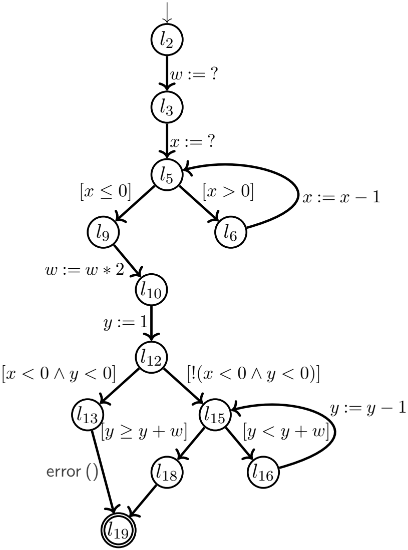


Issues with CEGAR

- CEGAR *only* keeps information that is necessary
- Often many refinements needed to get similar information at different locations
- Solution for some abstract domains: *Scoped precisions*
  - Example explicit-state model checking:
  - Scoped precision needs 7x less refinements than location-based precision
- But: Scoped precision may be too coarse

Scoped CEGAR fails

First iteration: $\pi = \emptyset$



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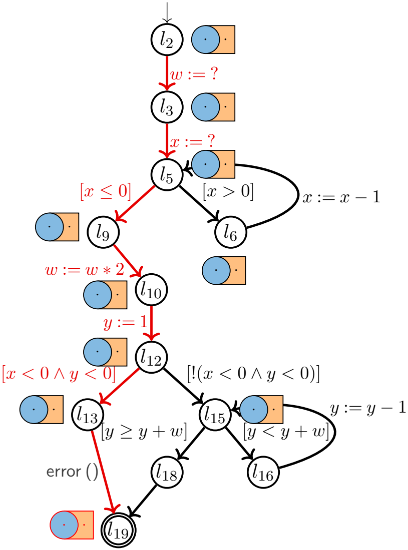
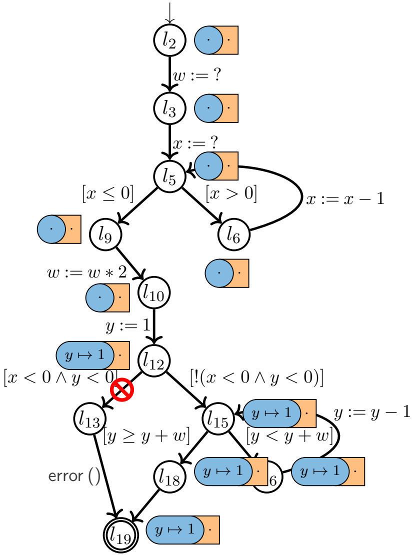


Scoped CEGAR fails

Second iteration: $\pi = \{y\}$



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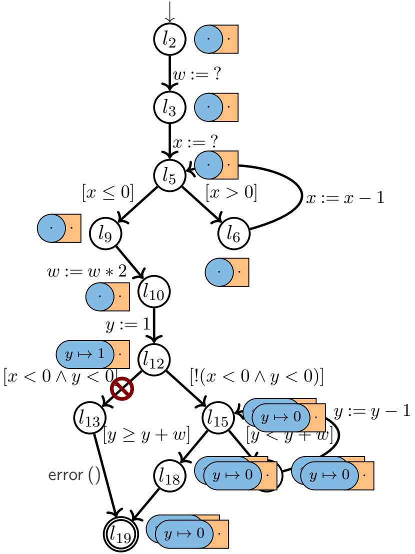

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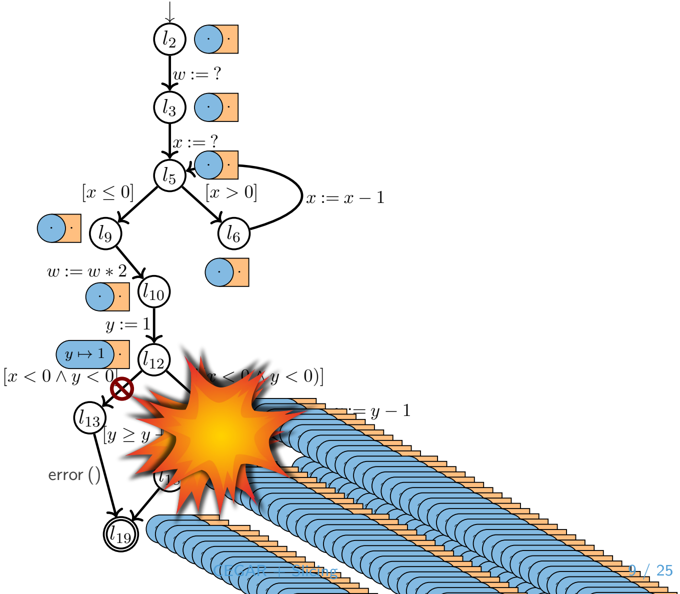

Next Try: Static Slicing

- Goal: Slice $P/g \subseteq P$ behaviorally equivalent to P regarding CFA edge $g = (l, op, l')$
  - Whenever P exits on an input I, P/g also exits on I, and the values of all program variables at l' are equal for P and P/g.
- Procedure: Replace irrelevant CFA edges (l, op, l') with $(l, \texttt{noop}, l')$
- Relevant edges computed through *dependence graph*
  - Data and control dependences

Dependence Graph: Data Dependence

CFA edge $g_2 = (l_2, op_2, l'_2)$ data dependent on edge $g_1 = (l_1, op_1, l'_1)$ for variable $x \in X$, if:

1. g_1 defines x
2. g_2 uses x
3. a path between the two exists without a new definition of x

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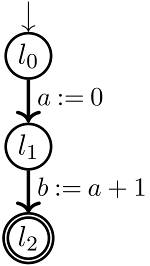

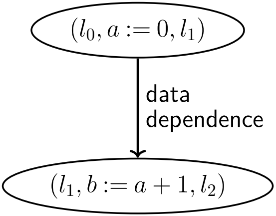

Dependence Graph: Control Dependence

CFA edge g_2 control dependent on edge g_1, if
g_1 is a program branch that must be entered at the time of its encounter to get to g_2.

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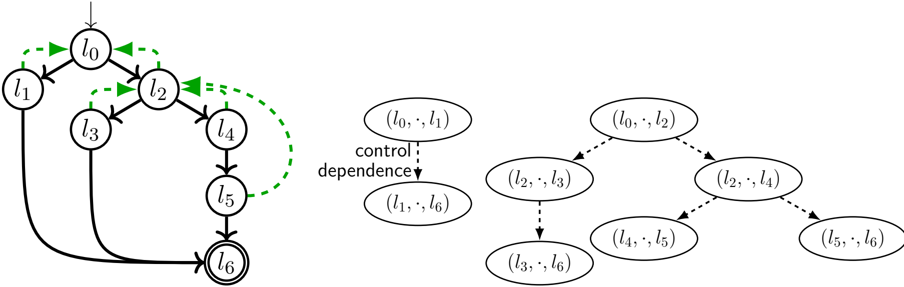
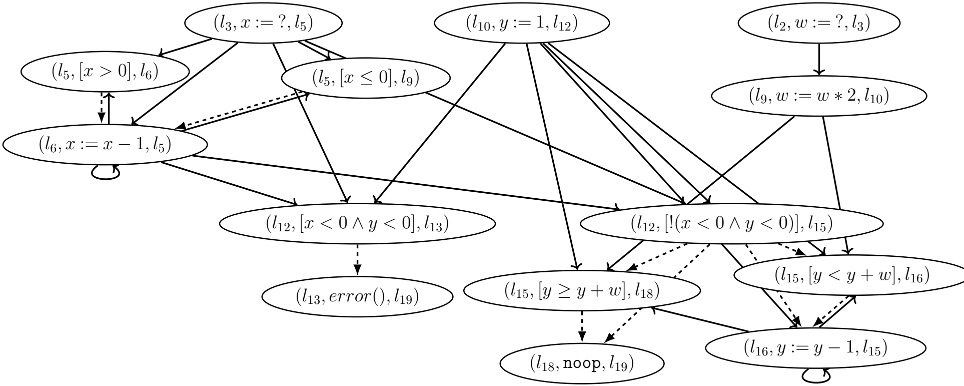


Slice Computation

- Backwards-search through dependence graph, starting at slicing criterion g
- Slice consists of all reachable CFA edges



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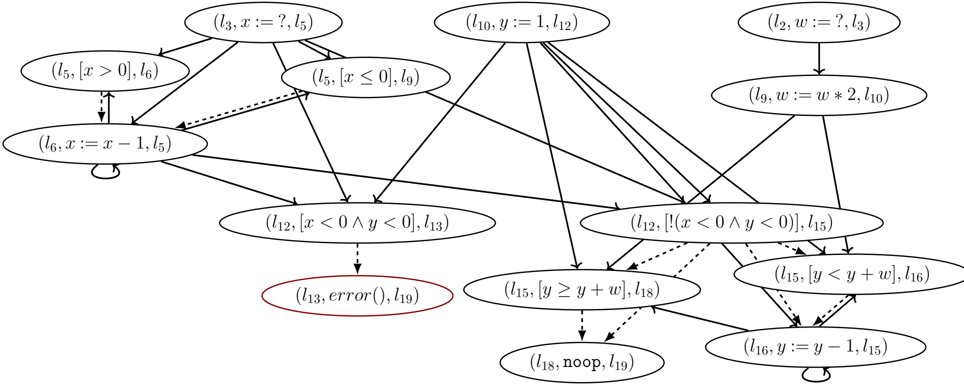

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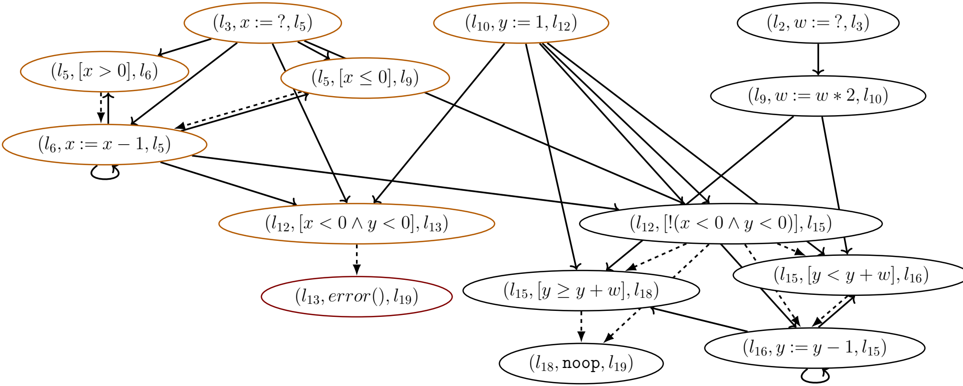
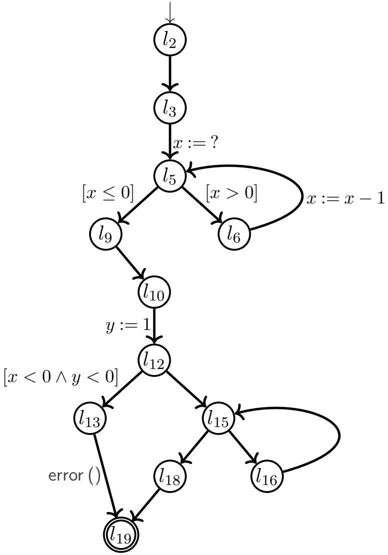


Slicing also fails!



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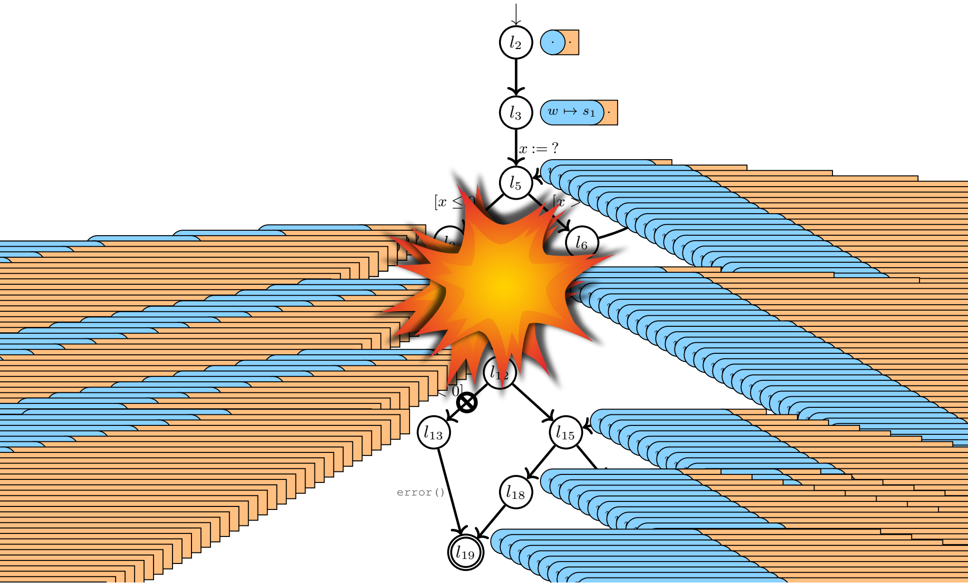
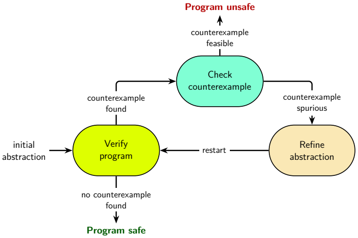


Problem of CEGAR and Slicing

- CEGAR:
  - Location-based precisions too fine-grained
  - Scoped precision too coarse (information could be tracked at unfortunate locations)
- Slicing:
  - Doesn't consider semantics (too coarse)
  - Only done for fixed slicing criteria

Incremental Slicing

- Combine CEGAR and static slicing
- Create dynamic approach to static program slicing
- Consider program operations as they become necessary



Incremental Slicing in CPAchecker

1. Dependence Graph
2. Slicing CPA
3. Slice Refinement

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Slicing CPA

- Reminder: CPA $A = (D, \Pi, \rightsquigarrow, \text{merge}, \text{stop}, \text{prec})$
- Slicing CPA $\mathbb{SC}$ wraps other CPA
- Always runs on original CFA
- Precision represents slice: $\Pi_{\mathbb{SC}} = 2^G$
- $\mathbb{SC}$ modifies CFA edge g before passing it to wrapped CPA

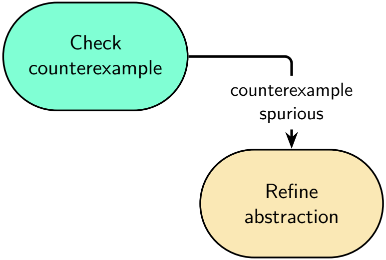
For $g = (l, op, l')$,

$$g' = \begin{cases} g & \text{if } g \in \pi_{\mathbb{SC}} \\ (l, \texttt{noop}, l') & \text{otherwise} \end{cases}$$

and

$$e \overset{g}{\rightsquigarrow}_{\mathbb{SC}} e' \text{ if } e \overset{g'}{\rightsquigarrow} e'$$

Slice Refinement



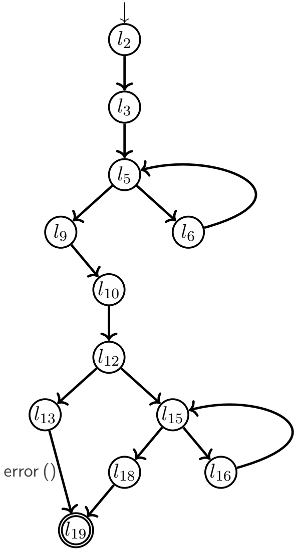
- Counterexample check: Run wrapped CPA on counterexample without slicing
- Abstraction Refinement: $\pi'_{\mathbb{SC}} = \pi_{\mathbb{SC}} \cup (P/g_e)$
- Initial abstraction: $\pi_{\mathbb{SC}_0} = \emptyset$

Combination: Slicing and wrapped CEGAR

- Combination possible: Slicing CPA with CEGAR + wrapped CPA with CEGAR
- Goal: Use scoped precision of wrapped CPA, but avoid easy mistakes through slicing

Combination: Slicing and wrapped CEGAR

First iteration: $\pi = \emptyset$



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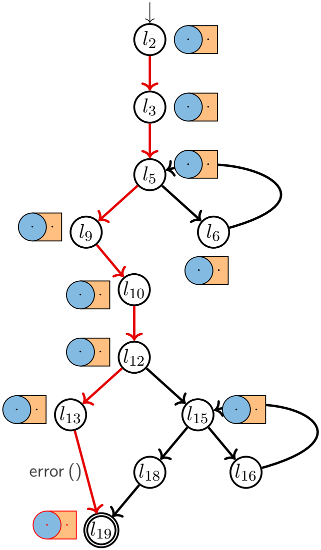

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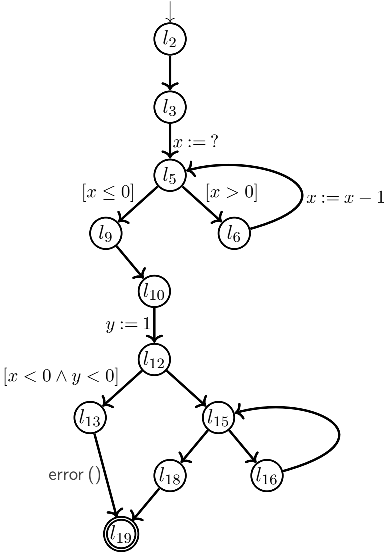

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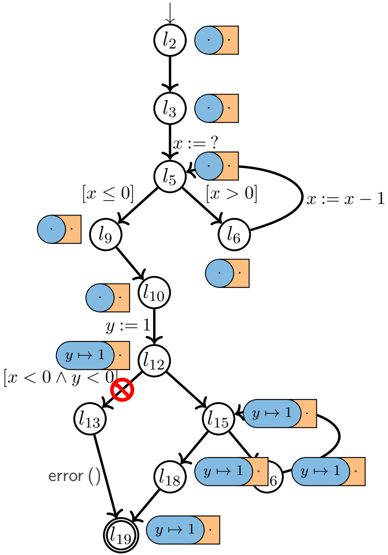


Evaluation

Table: Results over ReachSafety + LDV (5 590 tasks)

	SymEx	SymEx_{S}	SymEx_{C}	$\text{SymEx}_{\text{S+C}}$
Correct	726	1398	**2398**	2000
Correct proof	190	1147	**2108**	1794
Correct alarm	**536**	251	290	206

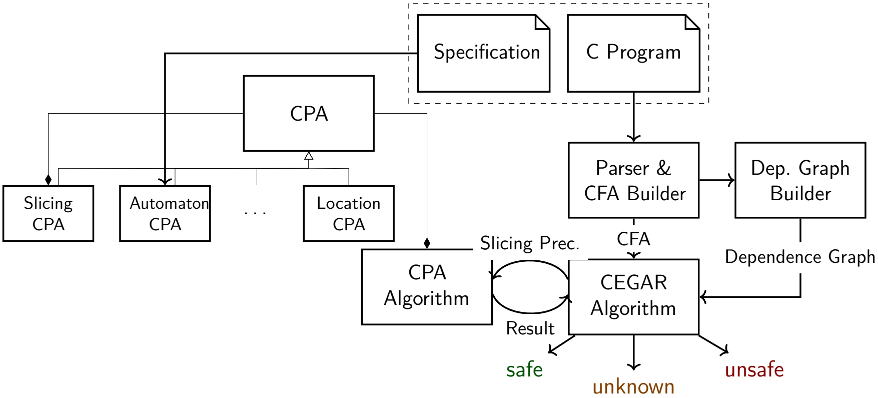
At the current state +17 correct proofs and +19 correct alarms

Conclusion

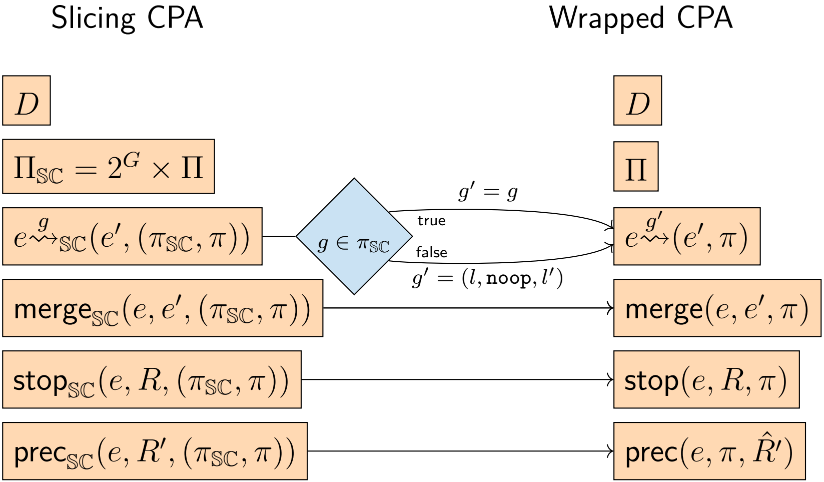
- Incremental slicing not competitive to CEGAR (yet?)
- Program slicing can complement CEGAR-approaches
- Flexible framework for dependence graph computation/slicing

Appendix

Incremental Slicing in CPAchecker



Slicing CPA Definition



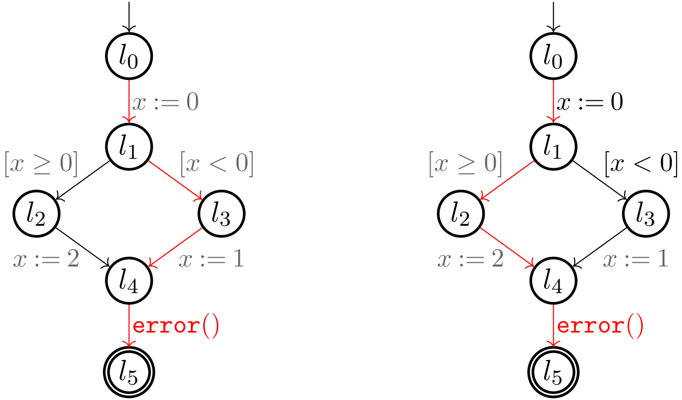
Details: Dependence Graph Construction

1. Data Dependence Computation:
   - Reaching Definitions + Variable Uses
   - Abstract State: Data Dependences + Reaching Definitions per State

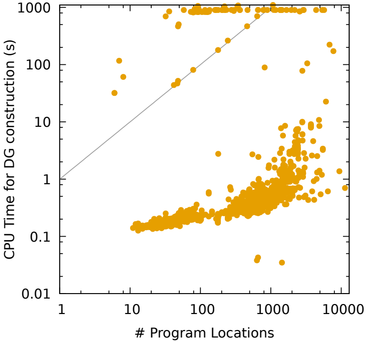
     (S, d) with $S \subseteq X \times G$, set G of CFA edges, and $d \subseteq G \times X \times G$
   - Example: $(g_1, x, g_2) \Rightarrow g_1$ is, through use of x, data dependent on g_2.
2. Control Dependence Computation:
   - Post-Dominator Computation: Backwards-run of dominator computation (pseudo-CPA)
   - Abstract State: Set of candidate dominator locations for corresponding program location

     $D \subseteq L$ with set L of program locations
   - Pseudo-merge when control flow meets: $\delta \sqcup_D \delta' = \delta \cap \delta'$
   - Transfer relation: $\delta \overset{g}{\rightsquigarrow} \delta \cup \{l\}$ for $g = (l, \cdot, l')$

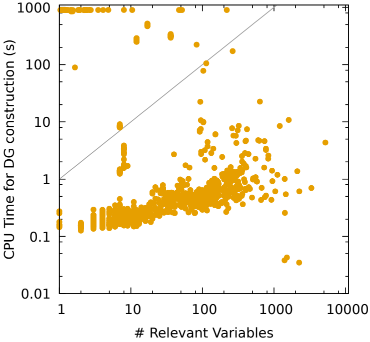
Why we need target-path slicing



Dependence Graph Construction Time Correlation



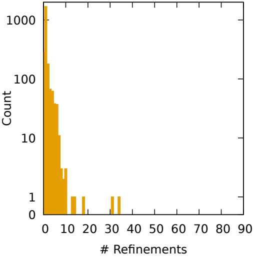
(a) Number of program locations to construction time



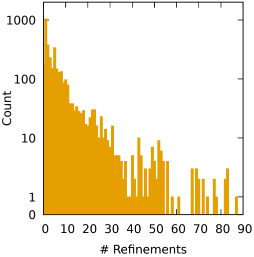
(b) Number of relevant variables to construction time

Figure: Indicators for the CPU time required for dependence graph construction

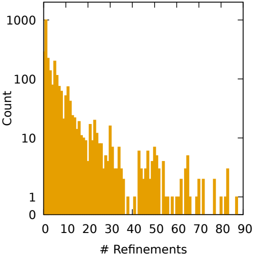
Number of Refinements Performed



(a) SYMEX$_{S}$



(b) SYMEX$_{C}$



(c) SYMEX$_{S+C}$