LoopInvGen: Data-Driven Loop Invariant Inference using Learned Features

SyGuS-COMP 2017

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Verification

C/C++ Code

```
int n, x = 0, m = 0;

while (x < n) {
  if (rand()) m = x;
  x = x + 1;
}

if(n > 0)
  assert (0 <= m && m <= n );
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SyGuS-INV Problem

```
(define-fun pre-f ((x Int) (n Int) (m Int)) Bool
                  (and (= x 0) (= m 0)))

(define-fun trans-f ((x Int) (n Int) (m Int)
                     (x! Int) (n! Int) (m! Int)) Bool
                    (or (and (and (and (< x n) (= x! (+ x 1)))
                                  (= n! n)) (= m! m))
                        (and (and (and (< x n) (= x! (+ x 1)))
                                  (= n! n)) (= m! x))))

(define-fun post-f ((x Int) (n Int) (m Int)) Bool
                   (not (and (and (>= x n) (> n 0))
                             (or (<= n m) (< m 0)))))

(inv-constraint inv-f pre-f trans-f post-f)
```

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inv-f:

```
(and (>= x m)
     (or (and (> n m) (> m 0))
         (= 0 m)))
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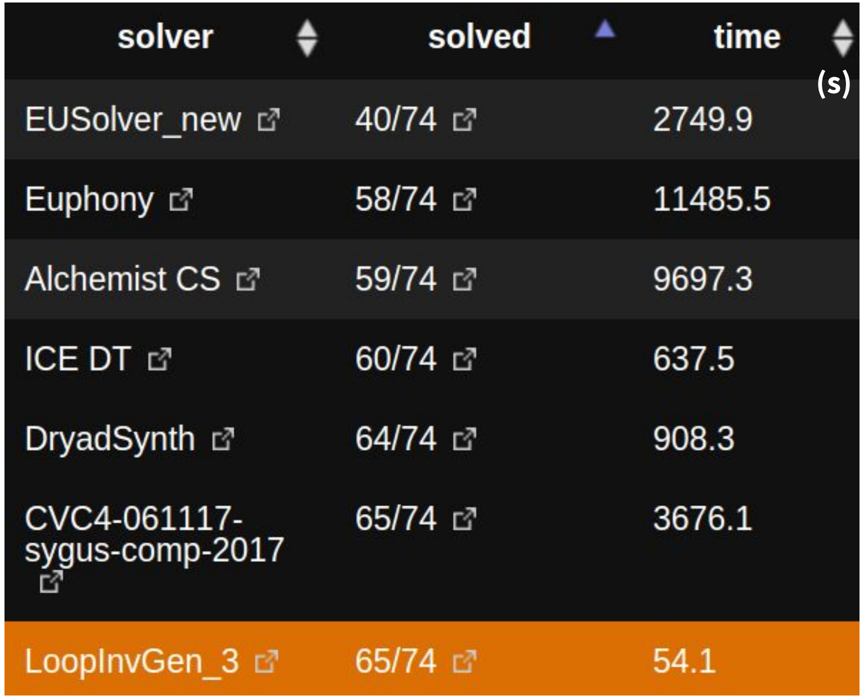
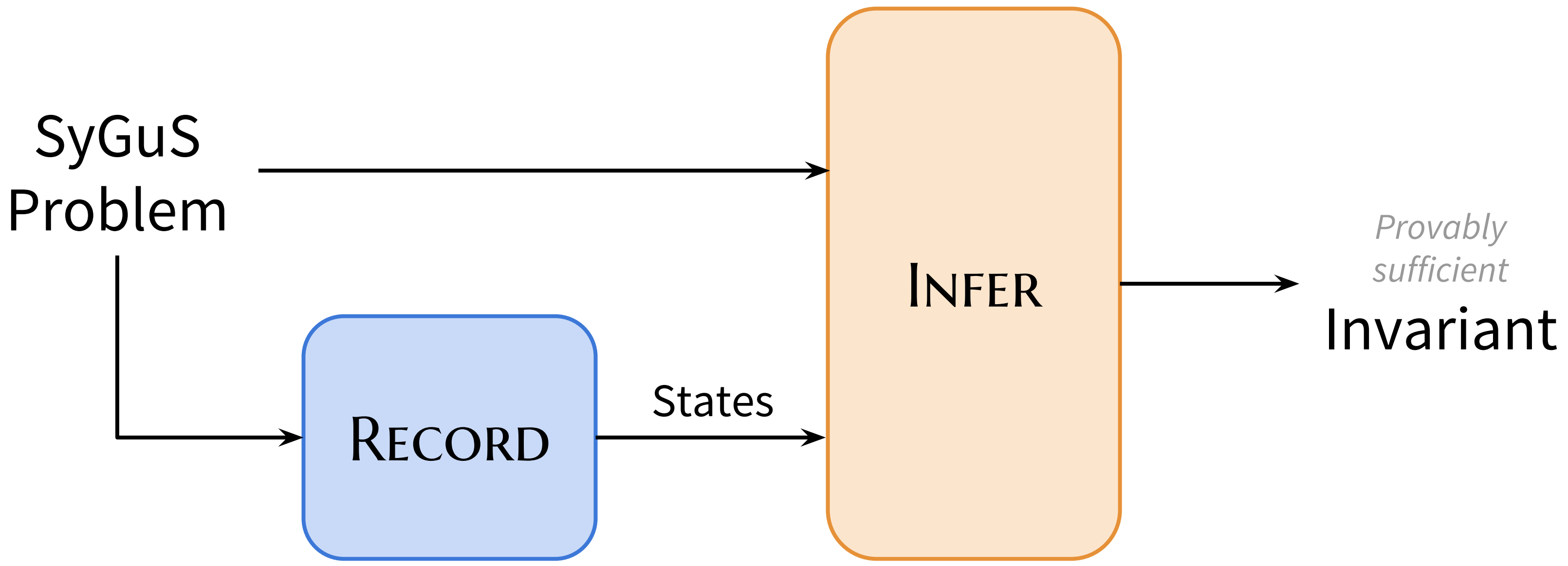


solver	solved	time (s)
EUSolver_new	40/74	2749.9
Euphony	58/74	11485.5
Alchemist CS	59/74	9697.3
ICE DT	60/74	637.5
DryadSynth	64/74	908.3
CVC4-061117-sygus-comp-2017	65/74	3676.1
LoopInvGen_3	65/74	54.1

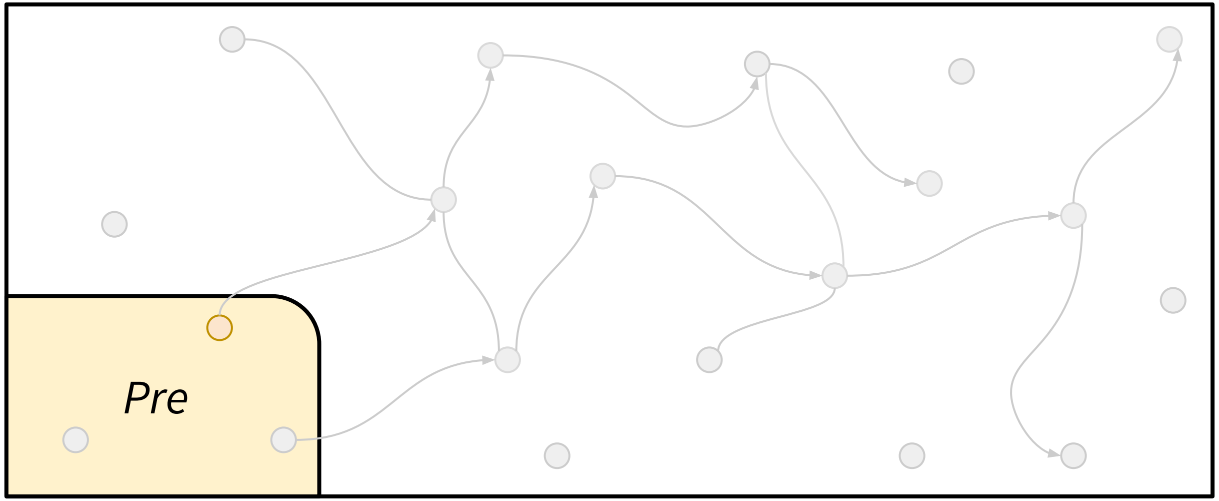
* The remaining 9 benchmarks have no solution

Overview


SyGuS Problem
Record
States
Infer
Provably sufficient
Invariant

Record-ing Reachable States

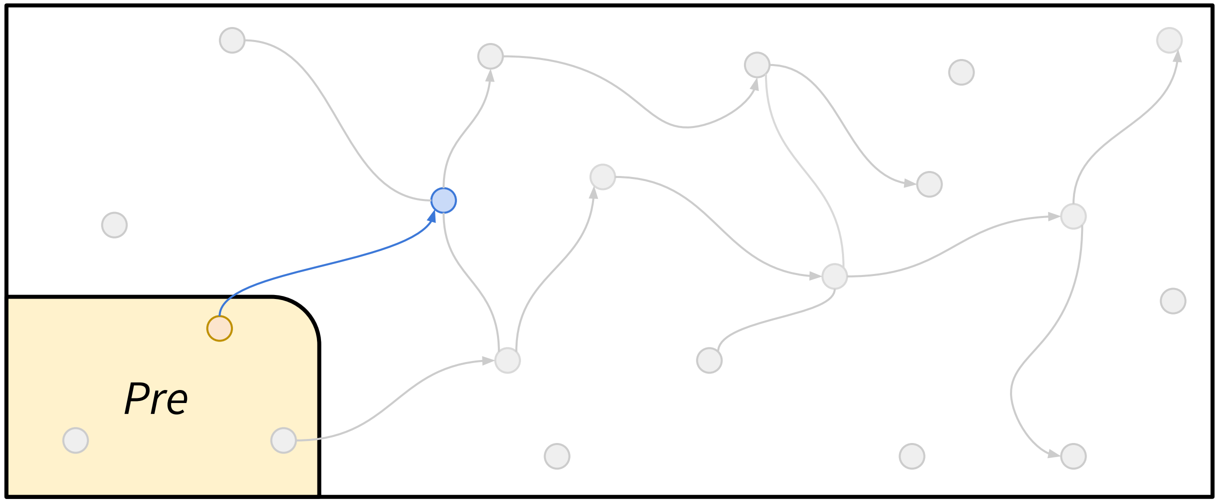
SyGuS Problem (Pre, Trans, Post) →List of variable assignments



1. Pick state s, s.t. Pre(s)

RECORD-ing Reachable States

SyGuS Problem (Pre, Trans, Post) →List of variable assignments



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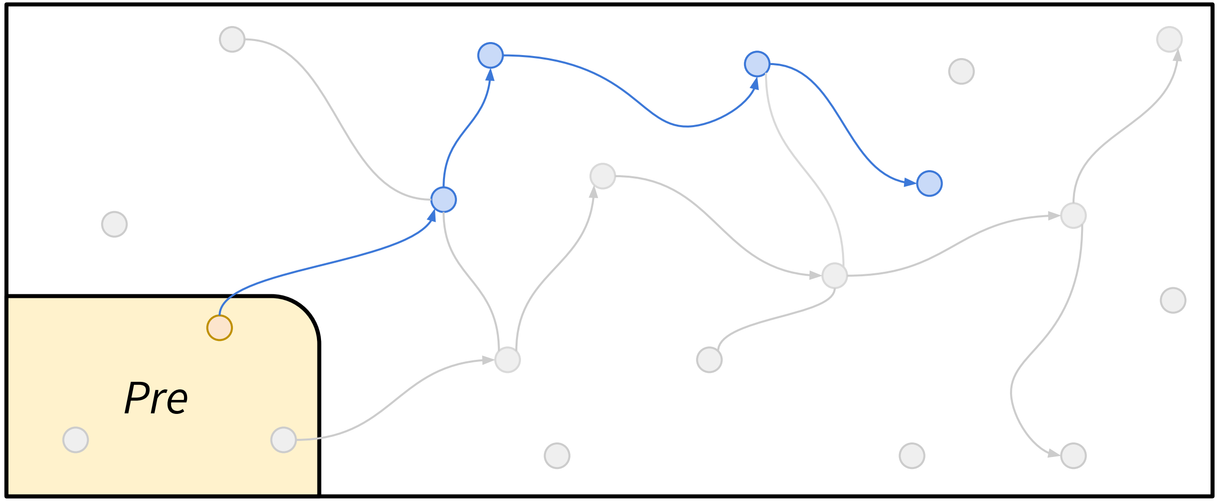

1. Pick state s, s.t. Pre(s) 2. Obtain state t, s.t. Trans(s,t) 3. Set s ← t and repeat (2)

RECORD-ing Reachable States

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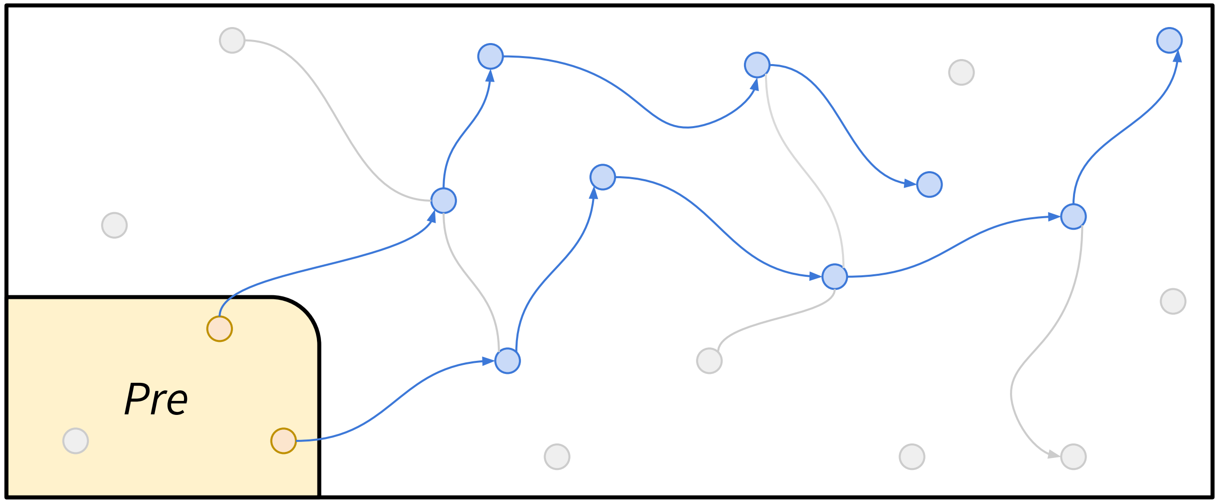

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4. Repeat (1,2,3) till the desired number of states has been collected

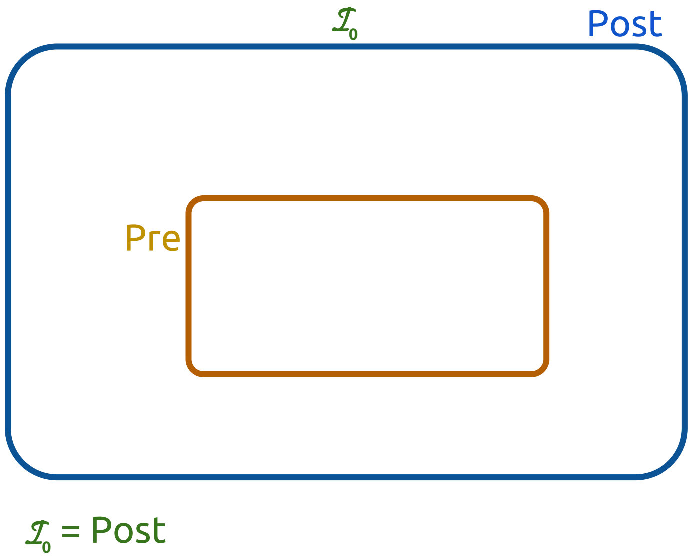
INFER-ing Sufficient Invariants

→ $\forall$ s: Pre(s) $\Rightarrow$ $\mathcal{I}$(s)

→ $\forall$ s, t: $\mathcal{I}$(s) $\wedge$ Trans(s,t) $\Rightarrow$ $\mathcal{I}$(t)

→ $\forall$ s: $\mathcal{I}$(s) $\Rightarrow$ Post(s)

1. Start with the weakest candidate



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→ $\forall$ s, t: $\mathcal{I}$(s) $\land$ Trans(s,t) $\Rightarrow$ $\mathcal{I}$(t)

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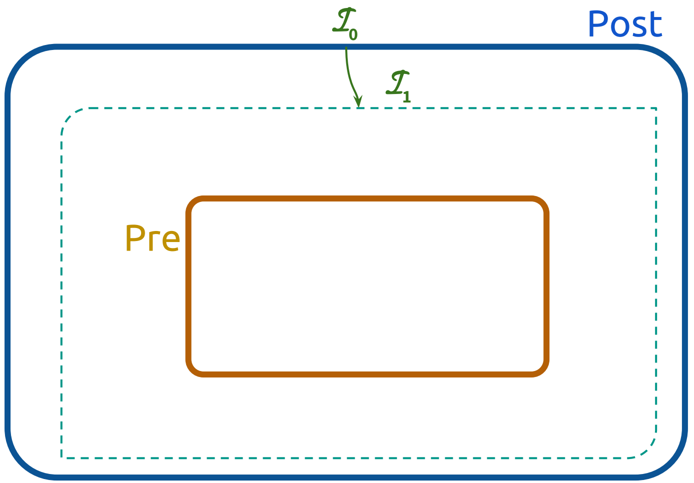
1. Start with the weakest candidate
2. Iteratively strengthen for inductiveness (data-driven precondition inference)



$\mathcal{I}_0$ = Post

$\mathcal{I}_1 = \delta_0 \land \mathcal{I}_0$

$\delta_0 \Rightarrow (\mathcal{I}_0 \land \text{Trans} \Rightarrow \mathcal{I}_0')$

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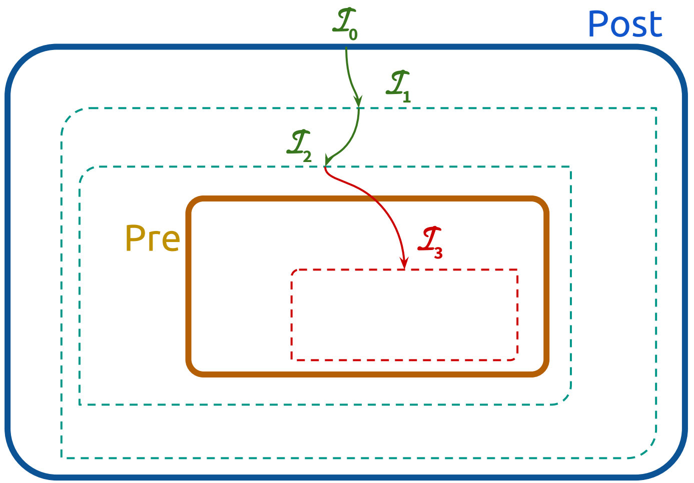

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$\mathcal{I}_1 = \delta_0 \wedge \mathcal{I}_0$

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$\vdots \quad \vdots \qquad\qquad \vdots \qquad \vdots$

$\mathcal{I}_n = \delta_{n-1} \wedge \mathcal{I}_{n-1} = \mathcal{I}_{n-1}$

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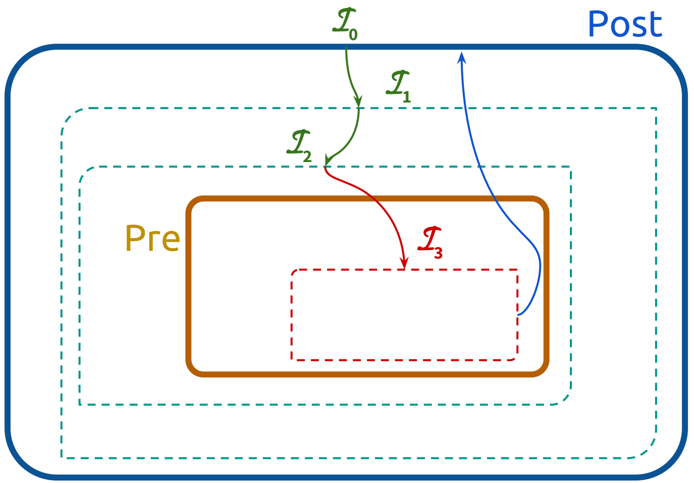
→ $\forall$ s, t: $\mathcal{I}$(s) $\wedge$ Trans(s,t) $\Rightarrow \mathcal{I}$(t)

→ $\forall$ s: $\mathcal{I}$(s) $\Rightarrow$ Post(s)

1. Start with the weakest candidate
2. Iteratively strengthen for inductiveness (data-driven precondition inference)
3. If the invariant is too strong, restart from (1) after augmenting the recorded states with appropriate counterexamples



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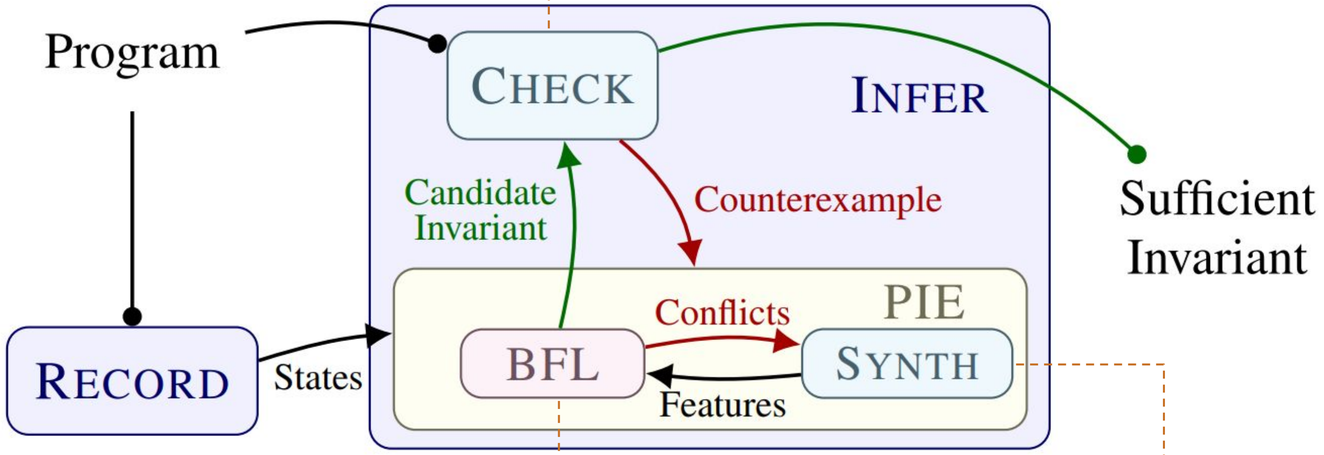
$\mathcal{I}_n = \delta_{n\text{-}1} \wedge \mathcal{I}_{n\text{-}1} = \mathcal{I}_{n\text{-}1}$

LoopInvGen Architecture

Z3 Theorem Prover [de Moura et al 2008]



Escher Synthesizer [Albarghouthi et al 2013]

Standard PAC algo for Learning k-CNF formulas

Thanks! ☺

Code + Benchmarks:

https://github.com/SaswatPadhi/LoopInvGen

Reach me at:

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