How to Win SV-COMP with Symbolic Execution

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KLEE Workshop 2022

SV-COMP

SV-COMP = Competition on Software Verification

- organized by Dirk Beyer since 2012
- task = to decide whether a given C (or Java) program satisfies a given property (and produce a witness)
- considered properties
  - reachability safety
  - memory safety
  - no overflows
  - termination
- resources: 8 cores, 900 s of CPU time, 15 GB of memory

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SV-COMP 2022

- 15 648 verification tasks
- 40 verification tools (including 12 hours concours)
- 12 of them use symbolic execution

Symbiotic at SV-COMP

- participating since 2013 (every year except 2015)
- 4 gold medals in MemSafety (2018, 2019, 2021, 2022)
- 3 gold medals in SoftwareSystems (2020, 2021, 2022)
- overall winner of SV-COMP 2022

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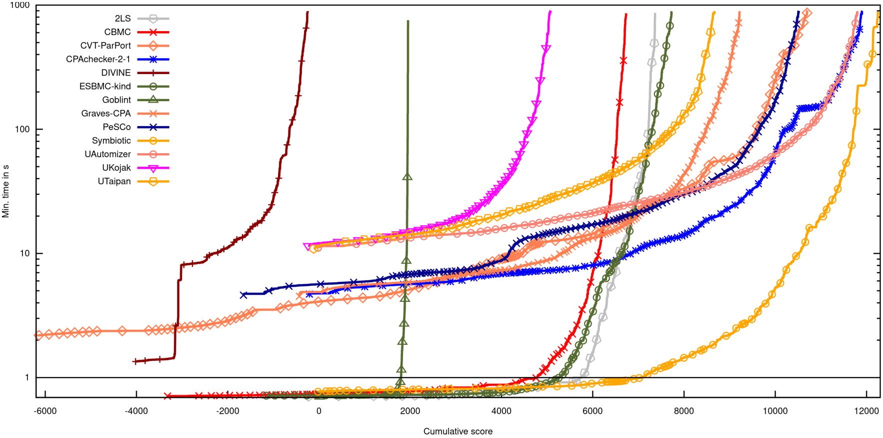

source: `https://sv-comp.sosy-lab.org/2022/results/results-verified/`

why Symbiotic uses symbolic execution

Jiří Slabý

Marek Trtík

why SYMBIOTIC uses symbolic execution

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pros

+ no false alarms
+ KLEE is available
+ KLEE easily finds bugs

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– path explosion problem
– struggles with program loops
– rarely finishes on real programs
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outline

1. how Symbiotic works
   - Chalupa and Strejček: *Symbiotic: Slice and Verify*. Under review.
   - Chalupa, Mihalkovič, Řechtáčková, Zaoral, and Strejček: *Symbiotic 9: String Analysis and Backward Symbolic Execution with Loop Folding*. TACAS 2022.

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2. what SLOWBEAST does
   - backward symbolic execution (BSE) $=$ k-induction
   - BSE $+$ loop folding (BSELF)
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JetKlee

- our fork of Klee optimized for verification
- analysis of all possible runs is more important than speed
- `https://github.com/staticafi/JetKlee`

	Klee	JetKlee
symbolic pointers	✓	✓
symbolic-sized allocations	✗	✓
symbolic addresses	✗	✓

JetKlee and Slowbeast

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Slowbeast

- symbolic executor implemented by Marek Chalupa in Python
- https://gitlab.fi.muni.cz/xchalup4/slowbeast

	Klee	JetKlee	Slowbeast
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symbolic-sized allocations	✗	✓	✓
symbolic addresses	✗	✓	✓
symbolic floats	✗	✗	✓
parallel programs	✗	✗	✓
backward symbolic exec. (BSE)	✗	✗	✓
BSE + loop folding (BSELF)	✗	✗	✓
invariant generation	✗	✗	✓

program slicing

```
n = input();
i = 0;
while (i != n) {
  c = input();
  if (i == 0) {
    min = c;
    max = c;
  }
  if (c < min)
    min = c;
  if (c > max)
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  i = i + 2;
}
assert(min <= c);
assert(even(n));
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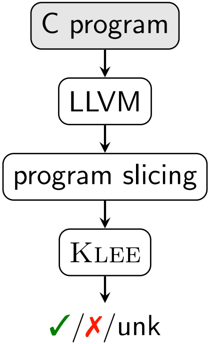
first workflow of SYMBIOTIC for reachability safety



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standard control dependence (SCD)

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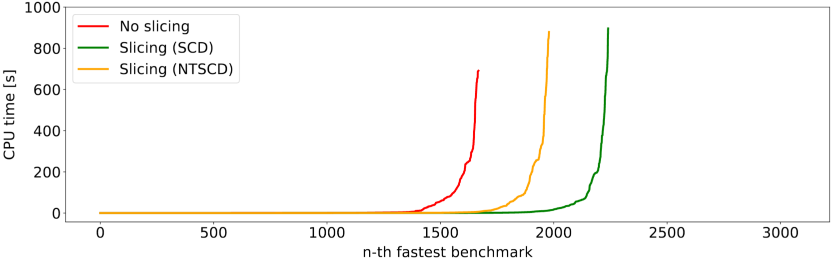
non-termination sensitive control dependence (NTSCD)

influence of slicing on performance of KLEE

correct verification results produced by KLEE with slicing on reachability safety tasks of SV-COMP 2019



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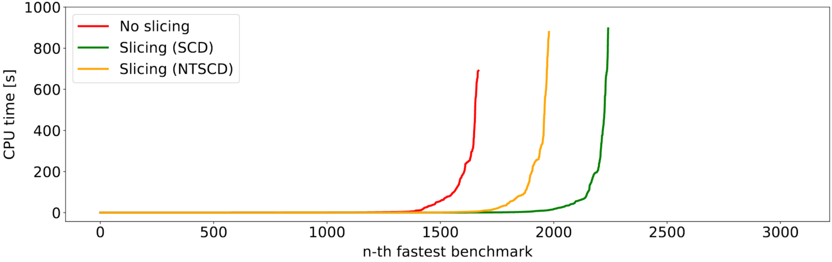
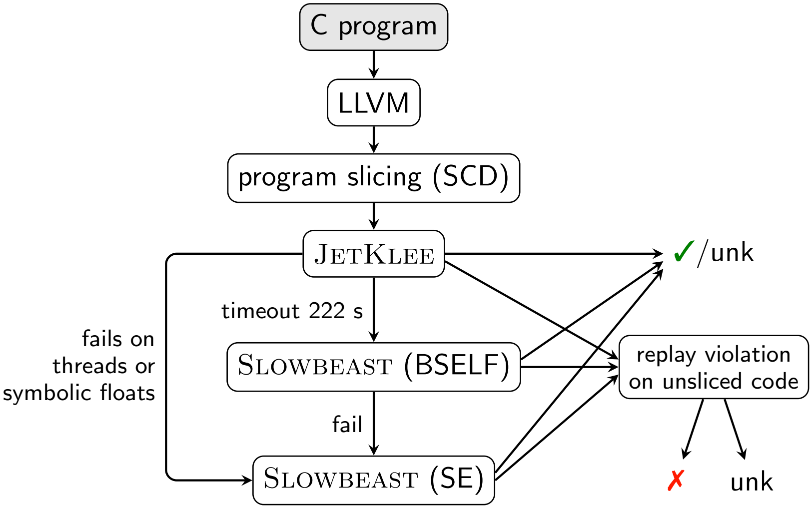


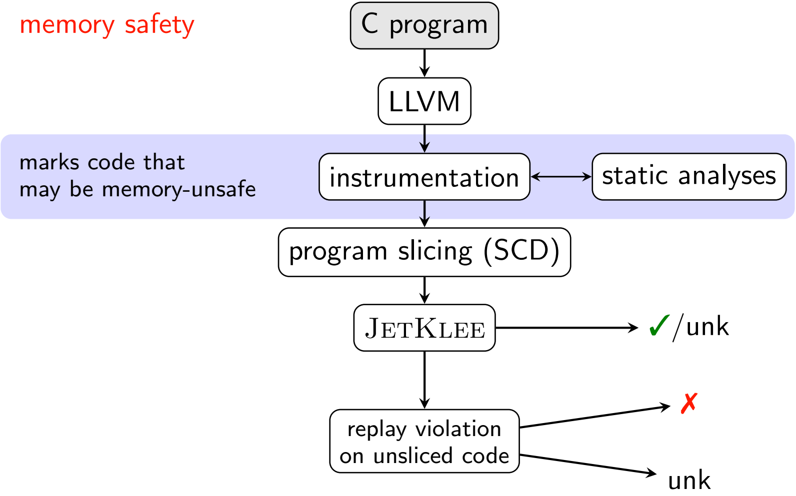
- slicing (SCD) also brought 43 incorrect verification results ✗
- Chalupa and Strejček: *Evaluation of Program Slicing in Software Verfication*. iFM 2019.

current workflow of Symbiotic for reachability safety



current workflow of Symbiotic for other properties

memory safety



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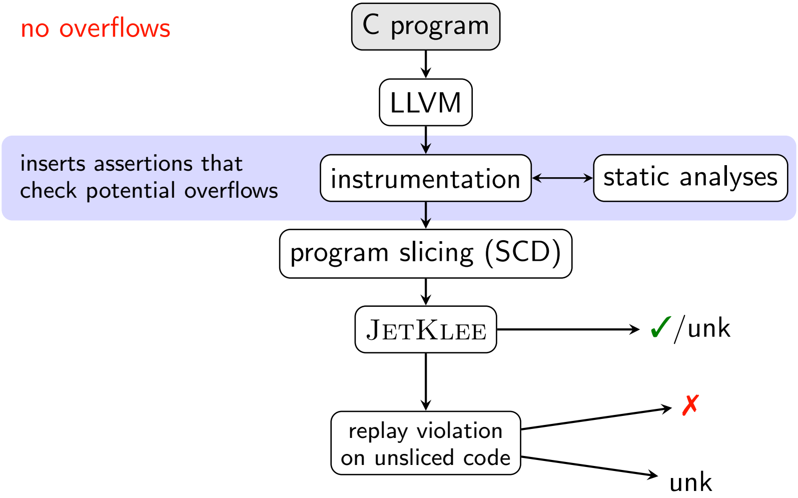

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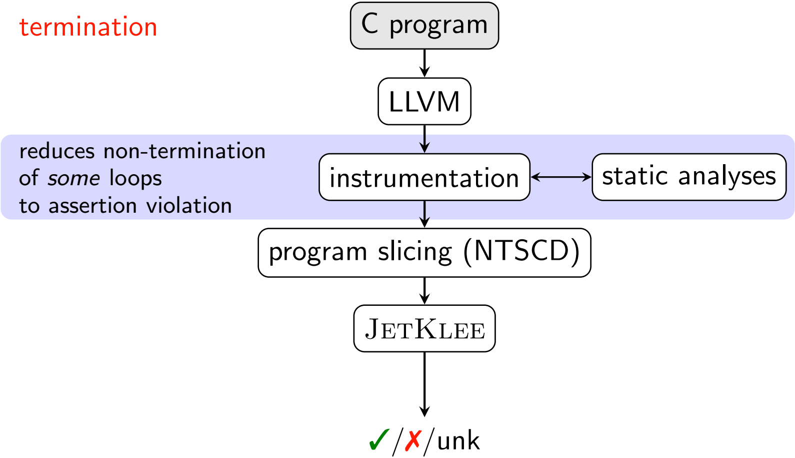
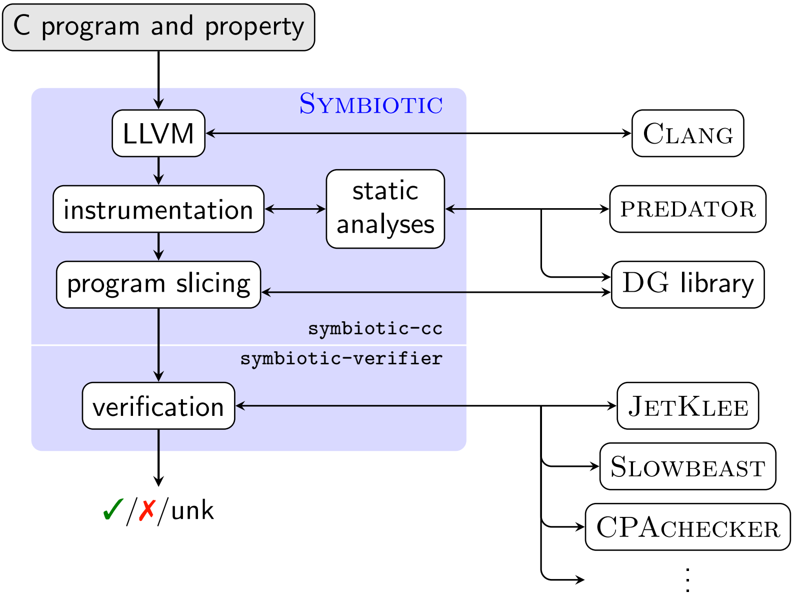
termination



general structure of Symbiotic



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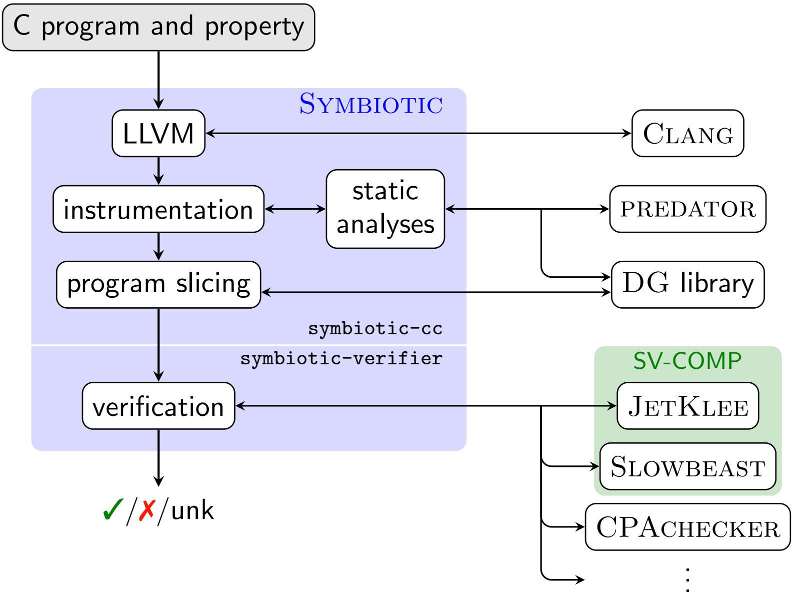

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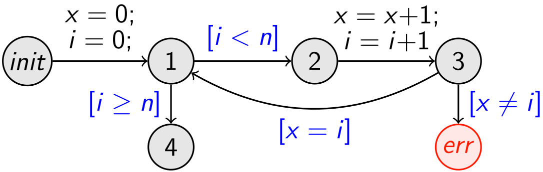

control flow automata (CFA)

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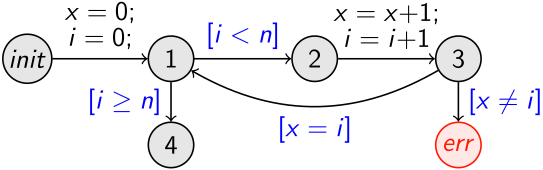

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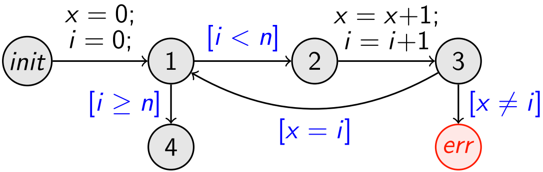

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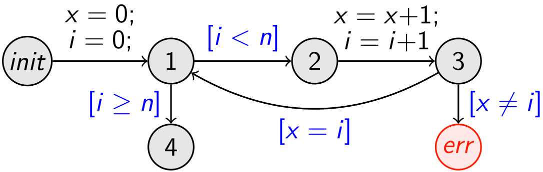

- *err* has no successors
- a path is feasible if it can be entirely executed
- a path is unsafe if it is feasible and ends in *err*, it is safe otherwise
- a CFA is correct if all paths starting in *init* are safe, it is incorrect otherwise

symbolic execution (SE)

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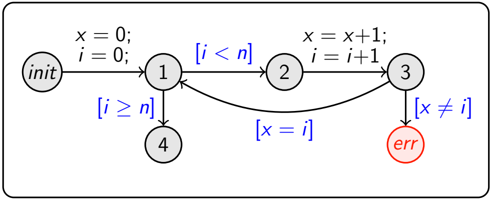

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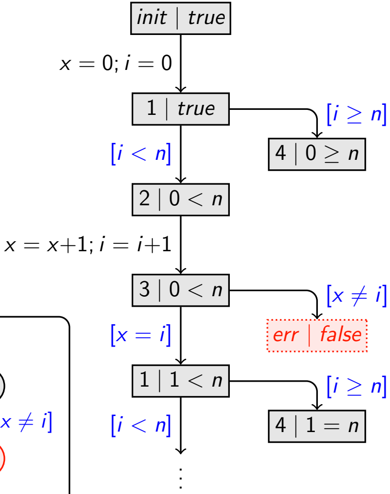

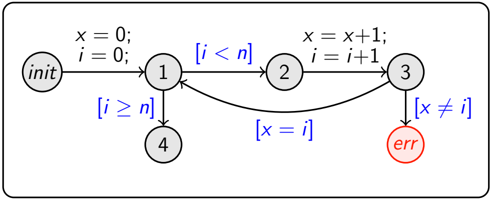

backward symbolic execution (BSE)

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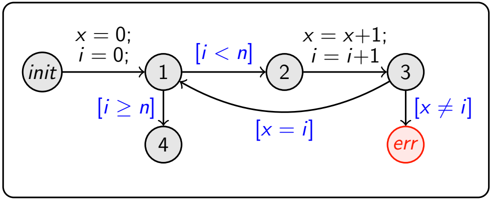

backward symbolic execution (BSE)

err | *true*

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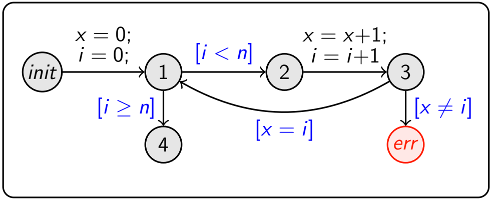

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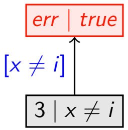

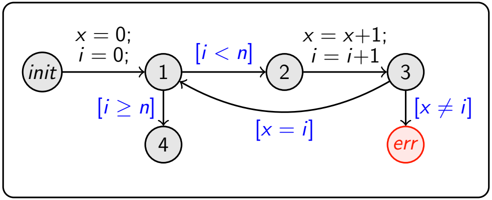

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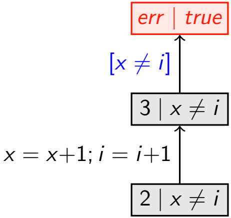

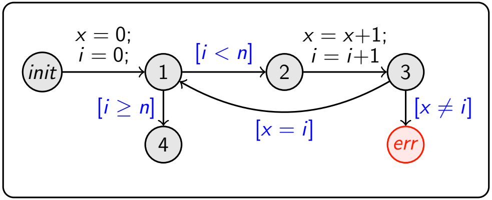

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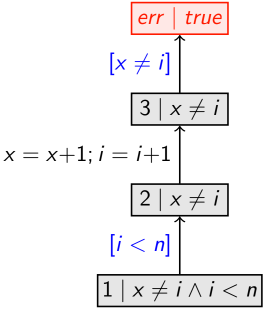

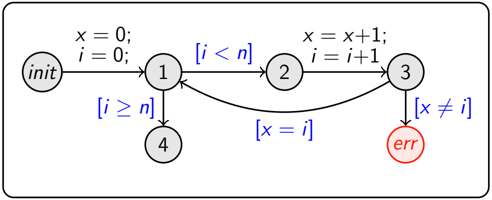

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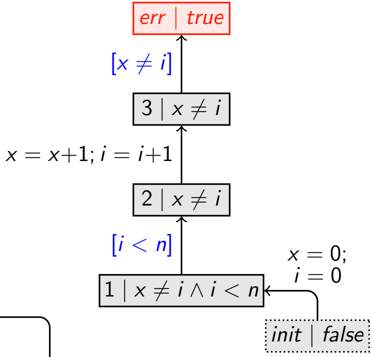

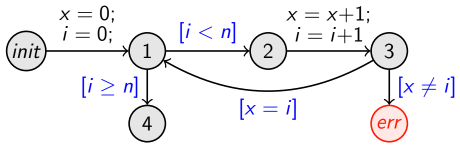

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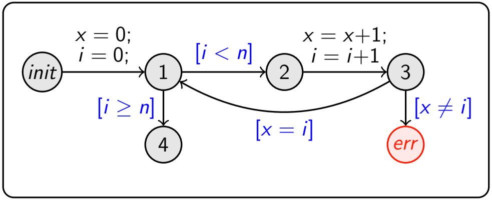

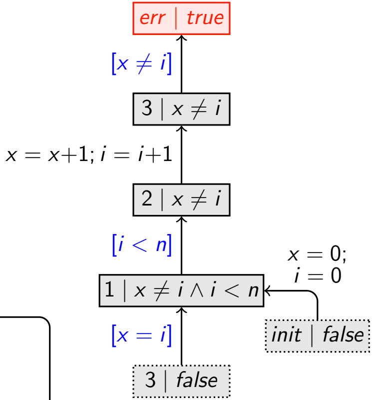

k-induction for CFA

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A CFA is correct if the following holds for some $k > 0$.

1. base case
   All paths of length at most k starting in *init* are safe.
2. induction step
   Each path of length $k + 1$ that has a safe prefix of length k is also safe.

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verification algorithm

1. $k \leftarrow 1$
2. <u>if</u> base case does not hold <u>then</u> <u>return</u> incorrect
3. <u>if</u> induction step holds <u>then</u> <u>return</u> correct
4. $k \leftarrow k + 1$
5. <u>goto</u> 2

relating *k*-induction and BSE

base case

All paths of length at most *k* starting in *init* are safe.

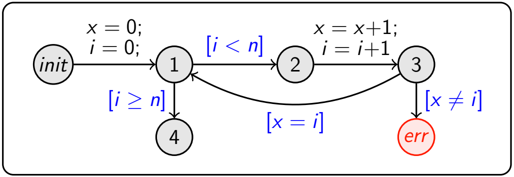
- i.e. there is no feasible path from *init* to *err* of length at most *k*

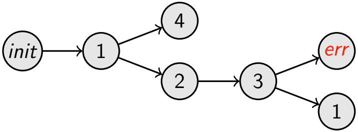
relating k-induction and BSE

base case

All paths of length at most k starting in *init* are safe.

- i.e. there is no feasible path from *init* to *err* of length at most k
- we can either search all relevant paths starting in *init*



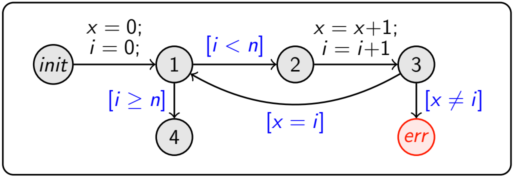


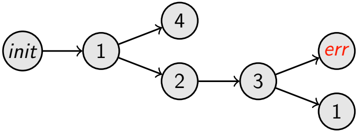
relating k-induction and BSE

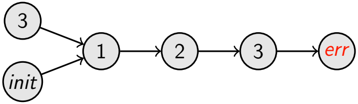
base case

All paths of length at most k starting in *init* are safe.

- i.e. there is no feasible path from *init* to *err* of length at most k
- we can either search all relevant paths starting in *init*
- or search all relevant paths leading to *err*







relating k-induction and BSE

induction step

Each path of length $k + 1$ that has a safe prefix of length k is also safe.

- i.e. there is no unsafe path of length $k + 1$ with a safe prefix of length k
- but a proper prefix of each unsafe path is safe
- i.e. there is no feasible path to *err* of length $k + 1$
- i.e. the BSE tree is finite

relating k-induction and BSE

Theorem (BSE = k-induction)

If a CFA is incorrect, then the k-induction algorithm detects it and BSE tree will contain an unsafe path from init.
If a CFA is correct, then k-induction algorithm detects it if and only if the BFS tree is finite and contains no init node.

Both approaches fail to detect correctness of a CFA that contains an unsafe path of length k for each $k > 0$ (i.e. BSE tree is infinite).

BSE with Loop Folding (BSELF)

- BSE (and k-induction) is incomplete

```
int n; // input
int x = 0;
int i = 0;
while (i < n) {
  ++x;
  ++i;
  assert(x == i);
}
```

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BSE with Loop Folding (BSELF)

- BSE (and k-induction) is incomplete
- invariants in loops can help
- loop folding computes loop invariants from BSE states

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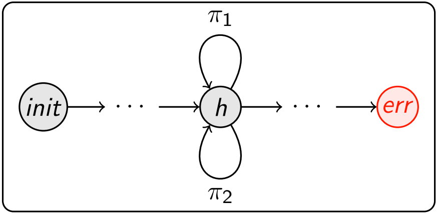

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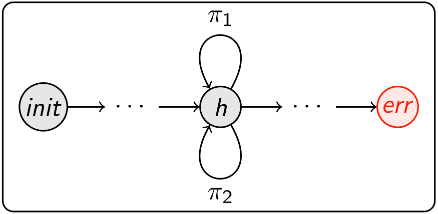

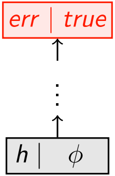

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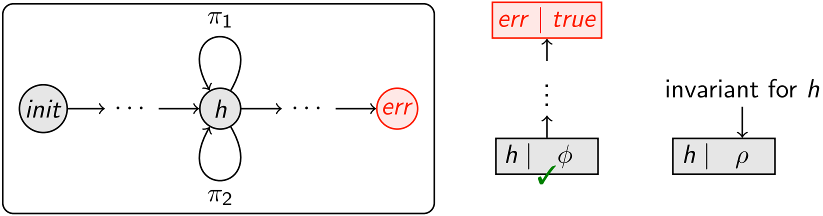
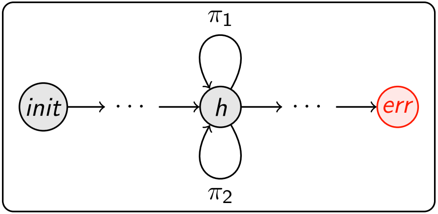
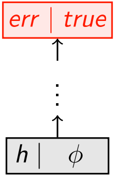


- when BSE reaches a node $h \mid \phi$ where h is a loop header, we try to find an invariant ρ for h satisfying $\rho \implies \neg\phi$
- if we succeed, we can drop this path

BSE with Loop Folding (BSELF)

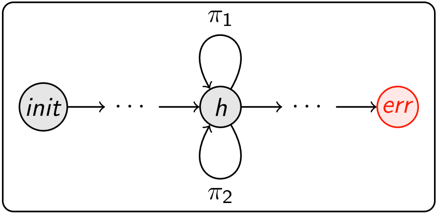


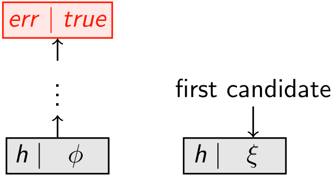


- we gradually create invarant candidates
- each candidate ξ satisfies $\xi \implies \neg\phi$ and is inductive, i.e.

  if $h \mid \xi$ $\longrightarrow \cdots \longrightarrow$ $h \mid \xi'$ then $\xi' \implies \xi$

BSE with Loop Folding (BSELF)





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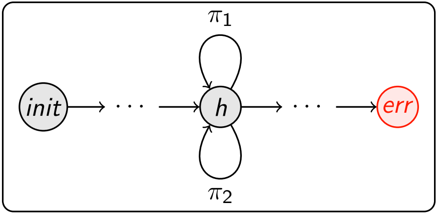
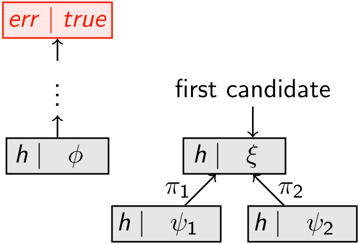
- each candidate ξ satisfies $\xi \implies \neg\phi$ and is inductive, i.e.

  if [h | ξ] $\longrightarrow \cdots \longrightarrow$ [h | ξ'] then $\xi' \implies \xi$

1. find first invariant candidate ξ such that location h cannot be reached again from [h | ξ]

BSE with Loop Folding (BSELF)





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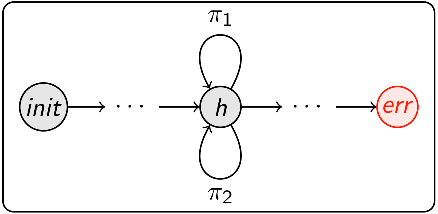
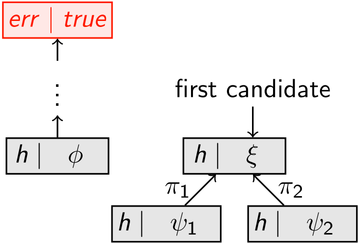
2. if ξ is not an invariant, then compute ψ_1, ψ_2

BSE with Loop Folding (BSELF)





- we gradually create invarant candidates
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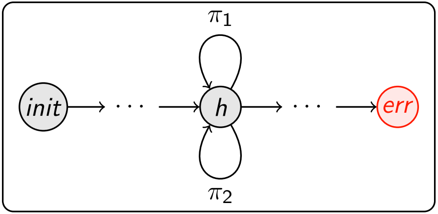
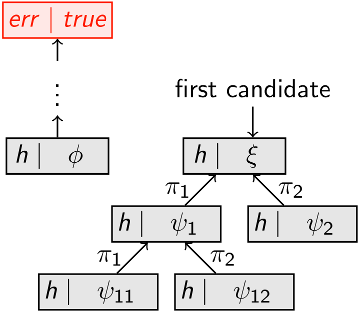
  if $\boxed{h \mid \xi} \longrightarrow \cdots \longrightarrow \boxed{h \mid \xi'}$ then $\xi' \implies \xi$

1. find first invariant candidate ξ such that location h cannot be reached again from $\boxed{h \mid \xi}$
2. if ξ is not an invariant, then compute ψ_1, ψ_2
3. if $\psi_i \implies \neg\phi$, then $\psi_i \vee \xi$ is also a candidate

   ⋮

BSE with Loop Folding (BSELF)



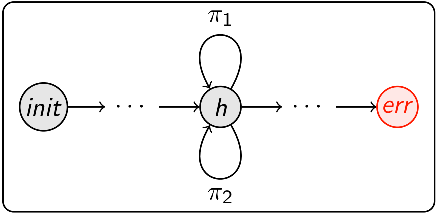


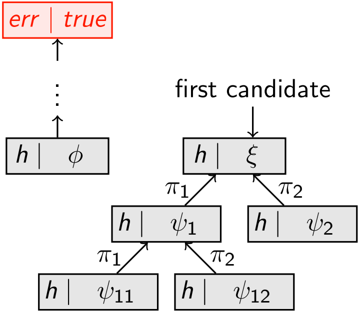
⋮

- candidates $\psi_{11} \vee \psi_1 \vee \xi$ and $\psi_{12} \vee \psi_1 \vee \xi$

⋮

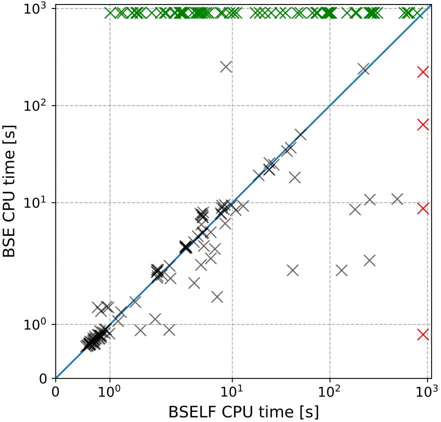
BSE with Loop Folding (BSELF)





- we also apply overapproximation to candidates
- searching for an invariant is restricted to not get stuck
- if invariant is not found, we continue with BSE
- but candidates are saved and used for the construction of the first candidate when we enter *h* next time

BSE vs. BSELF on reachability safety tasks
from the Loops subcategory of SV-COMP 2021
(only benchmarks solved by BSE or BSELF)



conclusion

to win SV-COMP with symbolic execution

- first use static analyses and slicing to reduce the program
- tune symbolic executor to handle various code features precisely
- combine SE with BSE and potentialy other techniques
- fix all bugs

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Thank you.