Backward Bounded Model Checking in CPAchecker

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About Me

- Currently MSc Logic @ ILLC, University of Amsterdam
  - Interested in mathematical logic and theoretical CS
- Participant in GSoC '23 @ SoSy Lab, LMU Munich
  - Summer program for contributing to open-source software
  - Supervised by Nian-Ze Lee

Key Points

- Improved support for any backward analysis in CPAchecker

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- Implemented backward BMC algorithm in CPAchecker
  - Handling pointer aliasing improves performance
  - Backward BMC can complement regular BMC
- Empirical evidence for proof that backward BMC and (plain) k-induction are equivalent [2]
- Want to identify limiting factors of backward BMC performance
  - Backward formula construction and SMT solving

Backward Bounded Model Checking

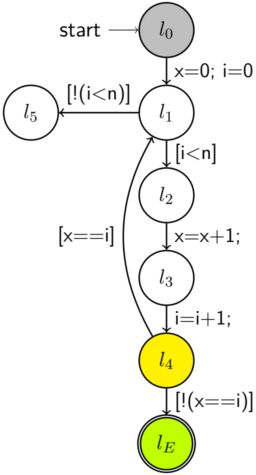
Backward Analysis

- We study the *error location reachability problem*
  - Forward analysis unrolls a program starting from the *main entry* to the *error locations*
  - Backward analysis unrolls a program starting from the *error locations* to the *main entry*

Backward Bounded Model Checking

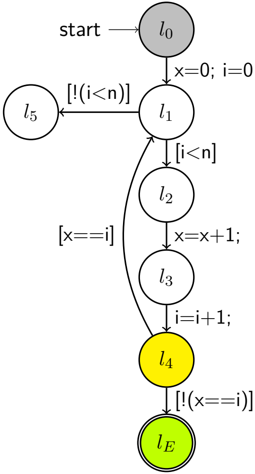
- Based on paper *Backward Symbolic Execution with Loop Folding*, M. Chalupa and J. Strejček [2]
- They claim that BBMC is equivalent to *k*-induction by showing:
  - For a CFA A, let P be the set of all satisfiable paths from the error location. Then both algorithms, when executed on CFA A,
    - return FALSE if P contains a path to the entry location;
    - return TRUE if P is finite and contains no path to the entry location;
    - do not terminate if P is infinite and contains no path to the entry location.

Example: *k*-Induction



Base Case	Step Case
$(l_0, -1)$	$(l_4, 0)$
$\downarrow$	$\downarrow$
$(l_1, -1)$	$(l_1, 0)$
$\downarrow$	$\downarrow$
$(l_2, -1)$	$(l_2, 0)$
$\downarrow$	$\downarrow$
$(l_3, -1)$	$(l_3, 0)$
$\downarrow$	$\downarrow$
$(l_4, 0)$	$(l_4, 1)$
$\downarrow$	$\downarrow$
$(l_E, 0)$	$(l_E, 1)$

Example: BBMC



$$(l_E, \top)$$
$$\uparrow$$
$$(l_4, x \neq i)$$
$$\uparrow$$
$$(l_3, x \neq i + 1)$$
$$\uparrow$$
$$(l_2, x + 1 \neq i + 1)$$
$$\uparrow$$
$$(l_1, i < n \wedge x + 1 \neq i + 1) \longleftarrow (l_0, \bot)$$
$$\uparrow$$
$$(l_4, \bot)$$

Backward Analysis in CPAchecker

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- Some support for backward analysis exists:
  - Backward PredicateCPA (partial support)
    - Backward formula construction
  - Backward CallstackCPA
  - Backward LocationCPA

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- Some support for backward analysis exists:
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  - Backward CallstackCPA
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- Missing support for backward analysis:
  - Exporting witness from backward analysis
  - Backward LoopBoundCPA
  - Handling of pointer aliasing by PredicateCPA

Contributions to CPAchecker

- Implemented support for backward analysis for WitnessExporter
  - MR1

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- Implemented support for LoopBoundCPA and the BBMC algorithm in the `BackwardBMCAlgorithm` class
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- Implemented support for backward analysis for WitnessExporter
  - MR1
- Implemented support for LoopBoundCPA and the BBMC algorithm in the `BackwardBMCAlgorithm` class
  - MR2
- Implemented support for handling pointer aliasing for backward analysis (WIP)
  - MR3
  - Some language features are not yet supported:
    - `union`
    - Pointers to `struct`

Experimental Setup

- On revision 44369 of CPAchecker
  - Branch backward-bmc-algorithm
- Algorithms:
  - BBMC (pointer aliasing disabled)
  - BBMC+PA (pointer aliasing enabled)
  - BMC
  - Plain *k*-induction
- 5652 *ReachSafety* programs of SV-COMP '23 [1]
  - Removed programs with unsupported features for backward pointer aliasing
    - *ProductLines*
    - *LinuxDrivers*

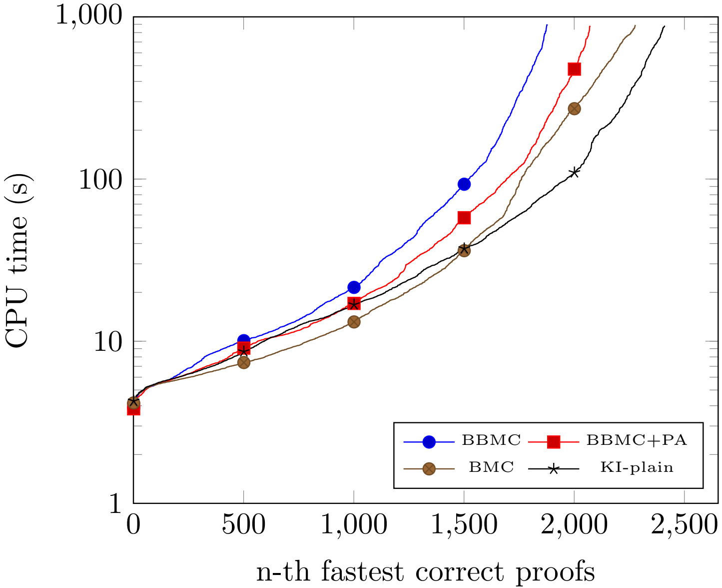
Results

Algorithm	**BBMC**	**BBMC+PA**
Correct True	727	959
Correct False	1152	1113
Incorrect True	10	47
Incorrect False	383	7

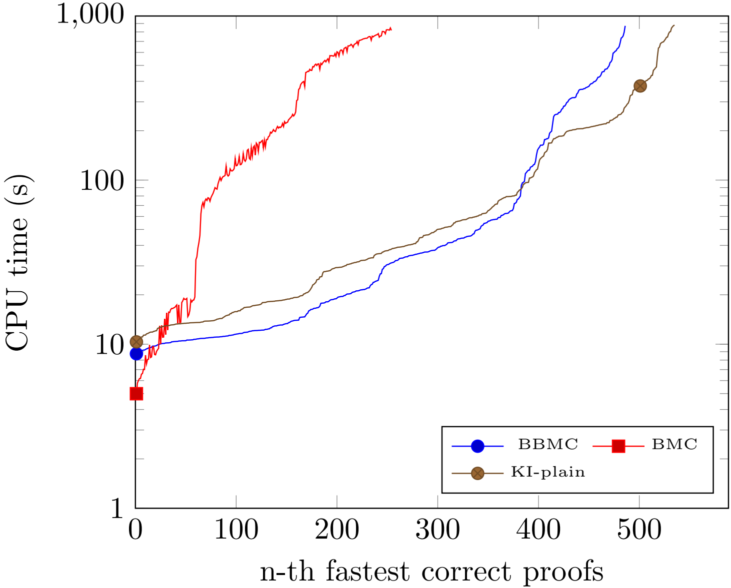
Table: Results of BBMC on 5652 *ReachSafety* programs

- Adding support for backward pointer aliasing solves most false alarms and improves performance by 11%
- However, we get more false proofs
  - These programs have unsupported language features

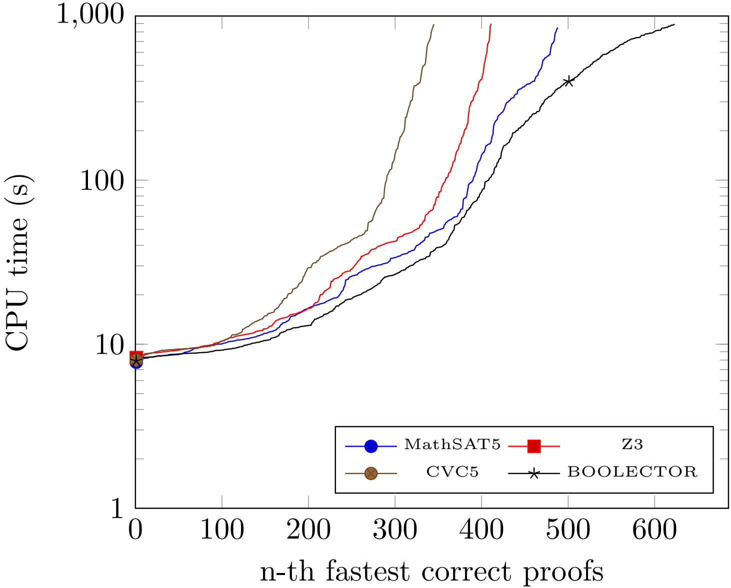
Quantile Plot: All Tasks



Quantile Plot: ECA Tasks



BBMC on ECA Solver Comparison



Observations

- BBMC *complements* BMC on certain program sets
- BBMC and *k*-induction achieve their results at the same loop unrolling bound
- Their results differ only when one algorithm times out before reaching the “required” bound to solve the program
  - Suggests that BBMC and *k*-induction are equivalent on *ReachSafety-ECA*
- On certain programs, BBMC takes a lot of time compared to *k*-induction
  - Likely due to SMT solving phase
  - Solvers make a difference

Conclusion

- Implemented BBMC and further support for backward analysis
- BBMC performs quite well, especially on certain subsets
  - BBMC and k-induction seem to be equivalent, at least on *ReachSafety-ECA*
  - BBMC can benefit from faster performance
- Future work:
  - Identify bottlenecks of BBMC performance (backward formula construction?)
  - Evaluate BBMC vs k-induction further

Technical Challenges

- JavaScript error when generating report
  - `TypeError: simplifiedGraphMap is undefined`
- Improve support for backward pointer aliasing
  - `union`
  - Pointers to `struct`

```c
struct Point { int x; };
// Expected result: FALSE
int test1() {
  struct Point p;
  struct Point *pt = &p;
  pt->x = 2;
  p.x = pt->x - 1;
  if (p.x == 1) {
    reach_error();
    return -1;
  }
  return 0;
}
```

```c
union Data { int a; int b; };
// Expected result: FALSE
int test2() {
  union Data d;
  d.a = 6;
  d.b = d.a + 1;
  if (d.b == 7) {
    reach_error();
    return -1;
  }
  return 0;
}
```

References I

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