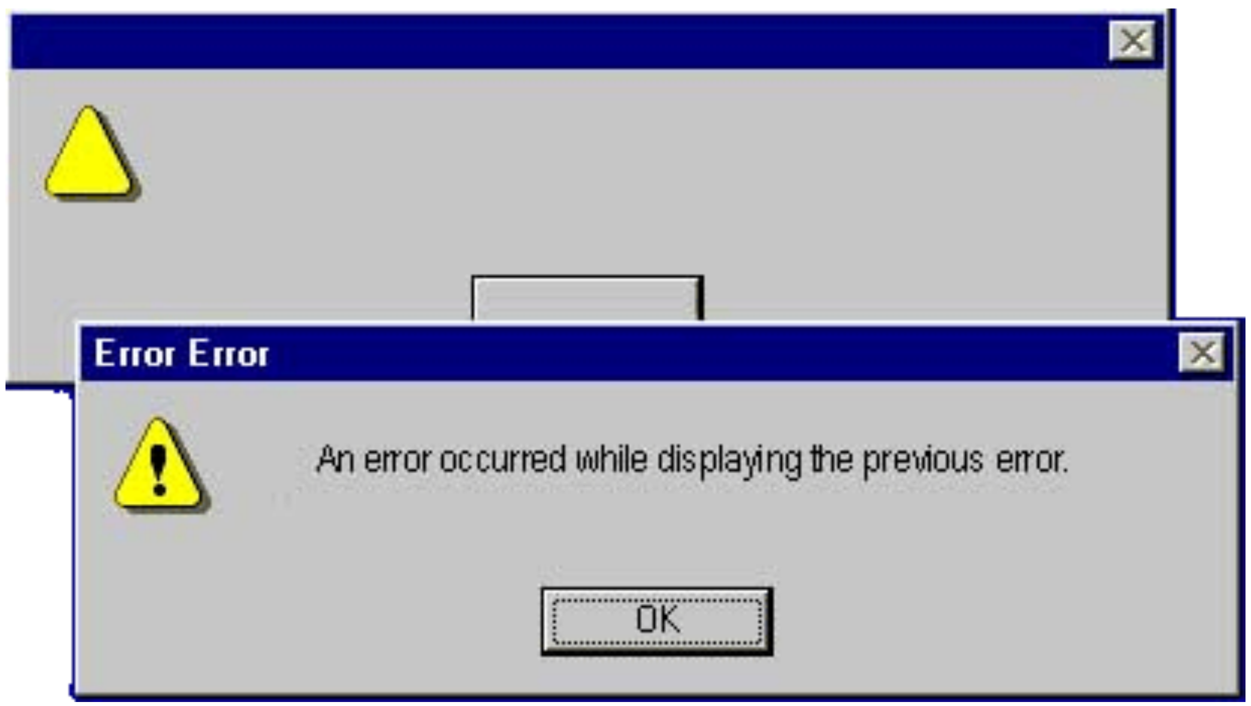


ESBMC v6.0

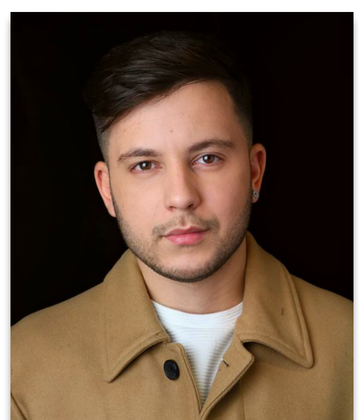
Mikhail R. Gadelha
Felipe R. Monteiro
Lucas C. Cordeiro
Denis A. Nicole

25th Intl. Conference on Tools and Algorithms for the Construction and Analysis of Systems

8th Intl. Competition on Software Verification

ESBMC *v6.0*
Verifying C Programs Using *k*-Induction and Invariant Inference
(Competition Contribution)

Mikhail R. Gadelha, **Felipe R. Monteiro**, Lucas C. Cordeiro, and Denis A. Nicole

ESBMC Gadelha *et al.*, ASE'18

- SMT-based bounded model checker of single- and multi-threaded C/C++ programs

  turned 10 years old in 2018 🎉

- Combines BMC, *k*-induction and abstract interpretation:

  path towards correctness proof

  bug hunting

- Exploits SMT solvers and their background theories

  optimized encodings for pointers, bit operations, unions, arithmetic over- and underflow, and floating-points

ESBMC — Gadelha *et al.*, ASE'18

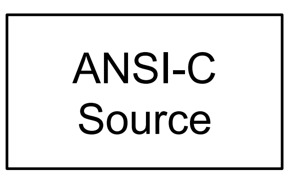
- SMT-based bounded model checker of single- and multi-threaded C/C++ programs

  - arithmetic under- and overflow
  - pointer safety
  - array bounds
  - division by zero
  - memory leaks
  - atomicity and order violations
  - deadlock
  - data race
  - user-specified assertions

  } **built-in properties**

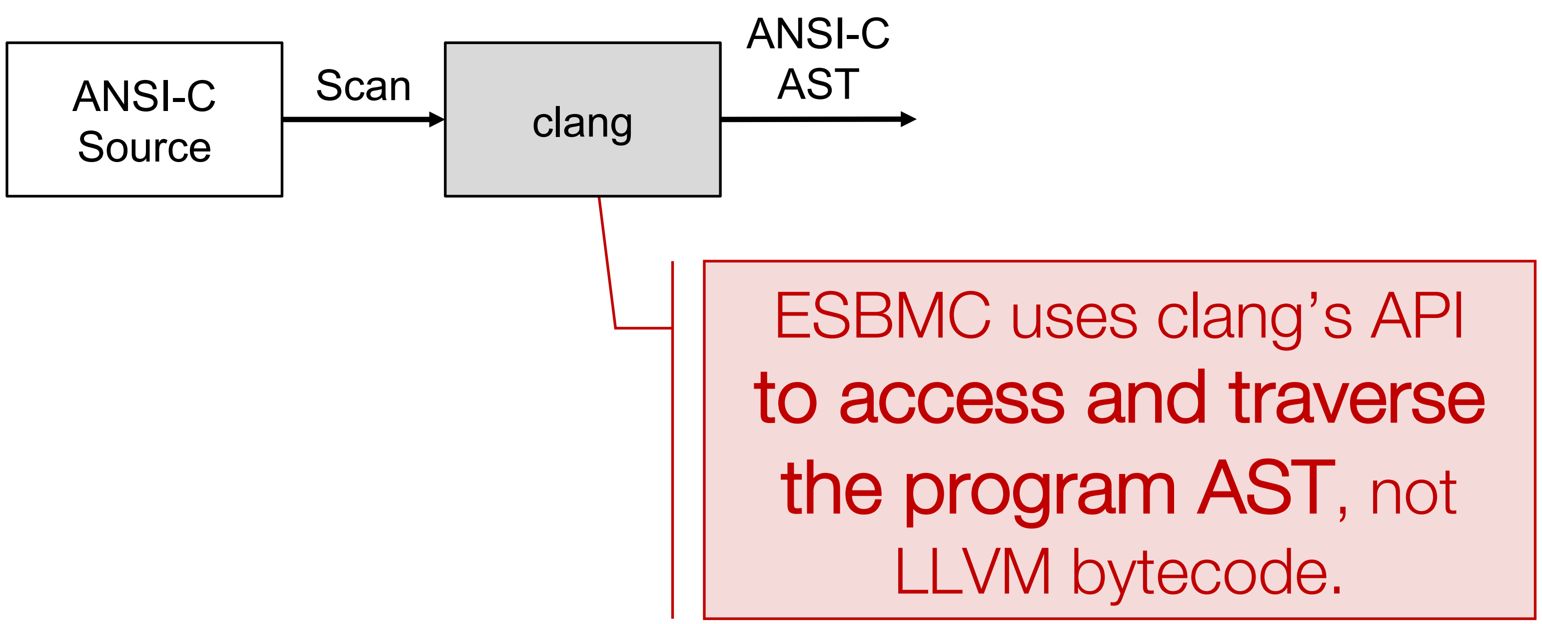
ESBMC Architecture

- ESBMC uses a *k*-induction proof rule to verify and falsify properties over C programs



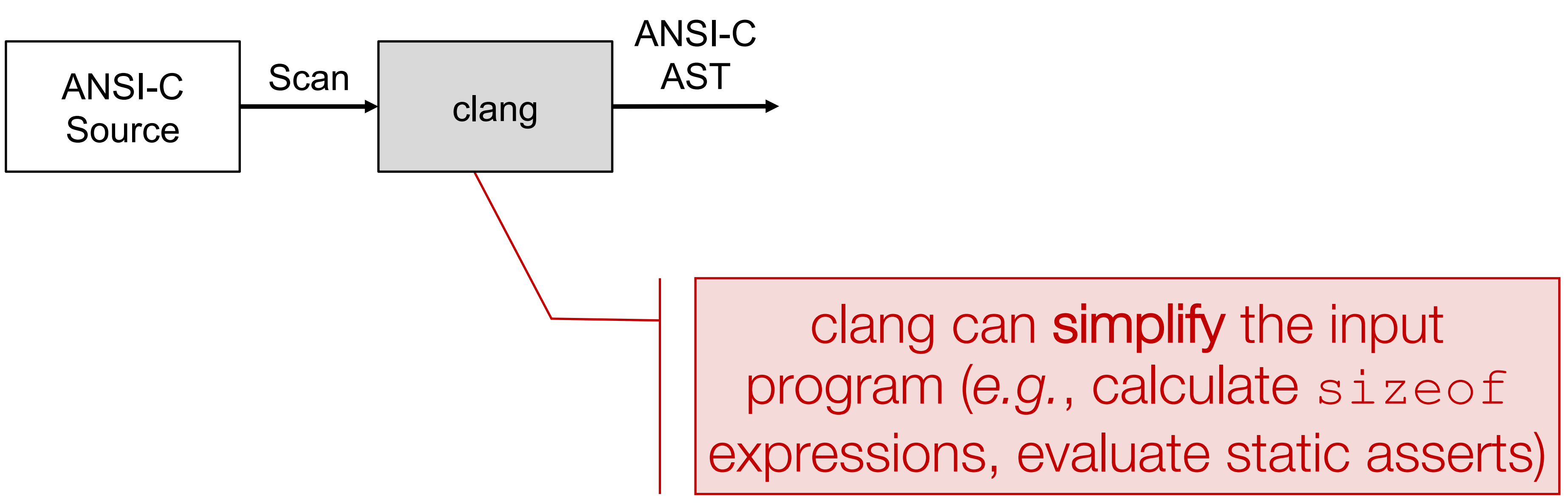
ESBMC Architecture

- ESBMC uses a *k*-induction proof rule to verify and falsify properties over C programs



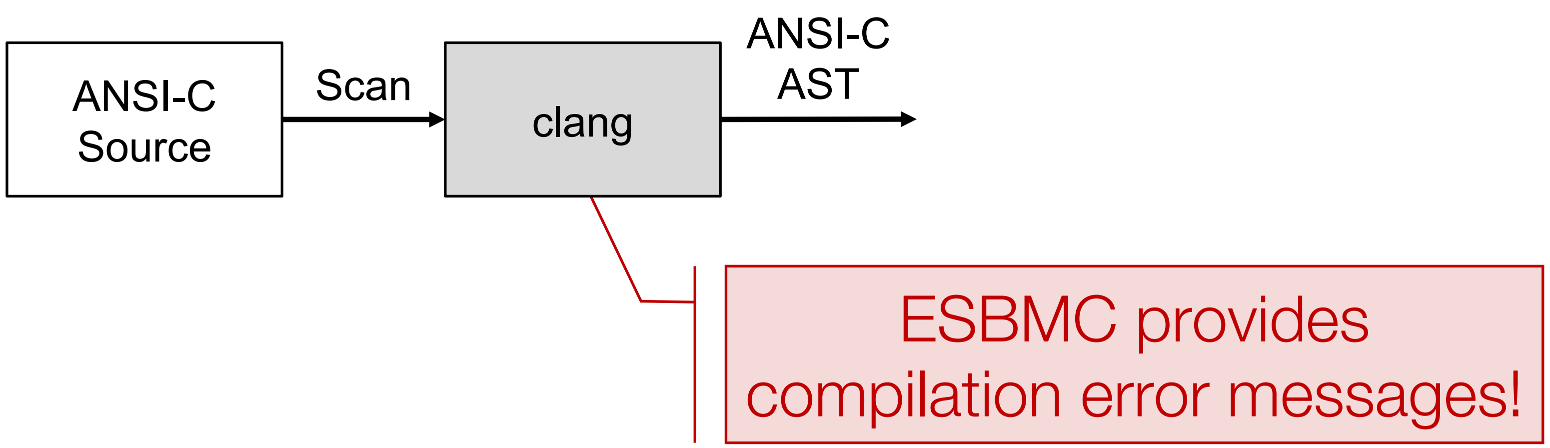
ESBMC Architecture

- ESBMC uses a *k*-induction proof rule to verify and falsify properties over C programs



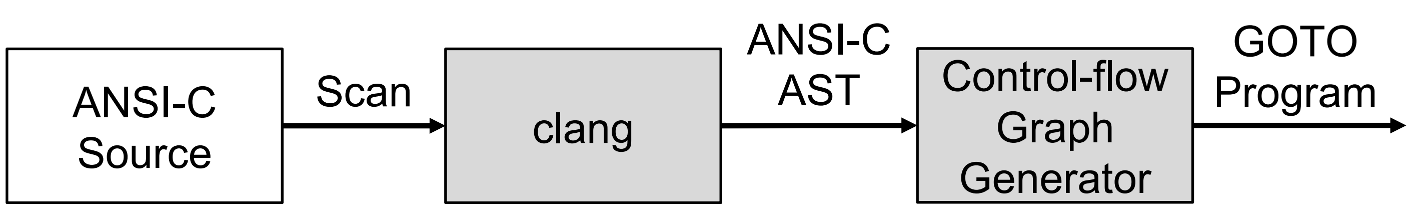
ESBMC Architecture

- ESBMC uses a *k*-induction proof rule to verify and falsify properties over C programs



ESBMC Architecture

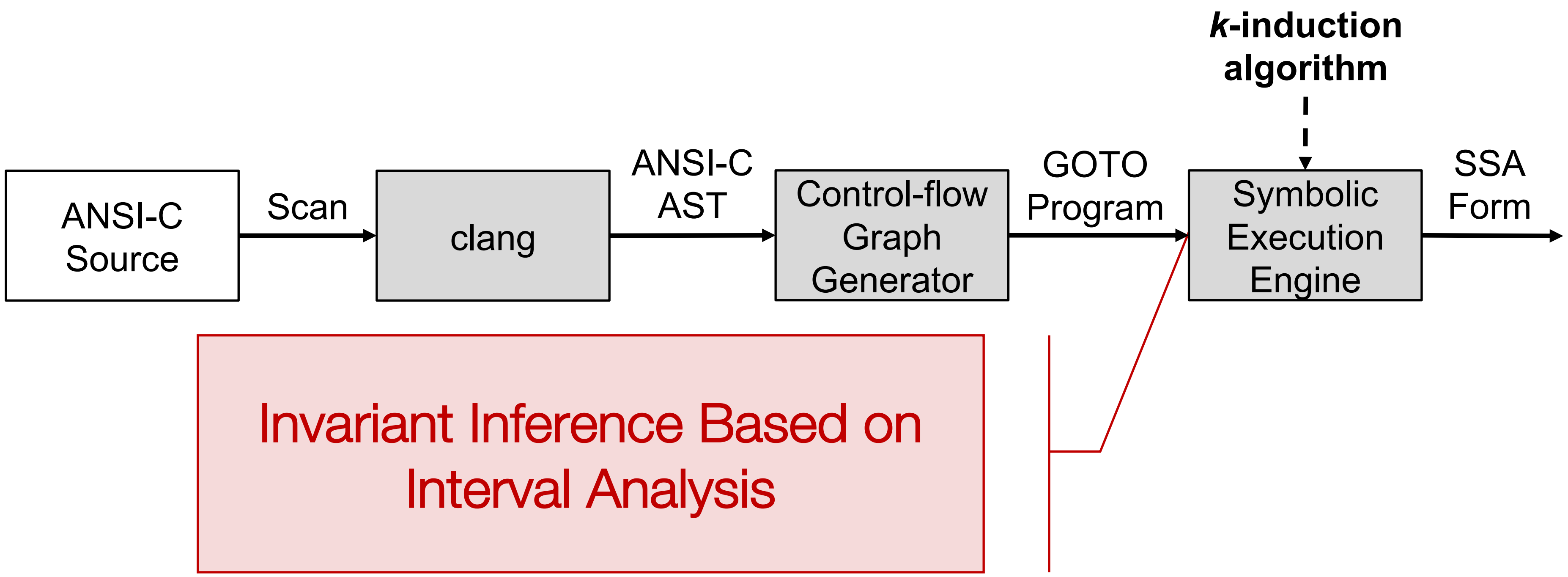
- The CFG generator takes the program AST and transforms it into an equivalent GOTO program
  - only of assignments, conditional and unconditional branches, assumes, and assertions.



ESBMC Architecture

- ESBMC perform a static analysis prior to loop unwinding and (over-)estimate the range that a variable can assume

  "rectangular" invariant generation based on interval analysis (*e.g.*, a ≤ x ≤ b)

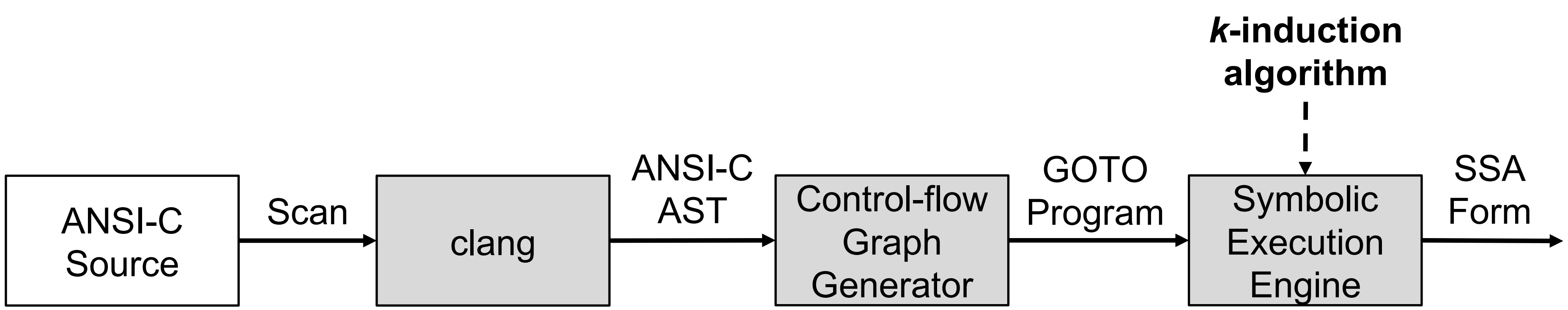


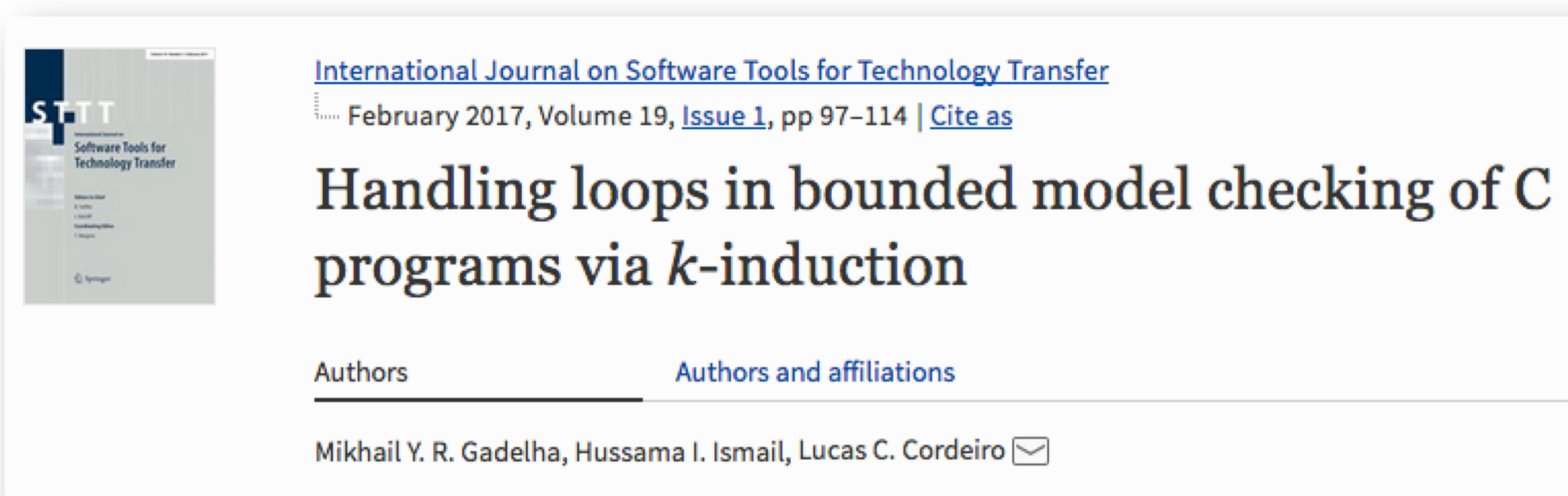
- Abstract-interpretation component from CPROVER
- Only for **integer** variables

ESBMC Architecture

- ESBMC perform a static analysis prior to loop unwinding and (over-)estimate the range that a variable can assume

    "rectangular" invariant generation based on interval analysis (*e.g.*, $a \leq x \leq b$)





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Handling loops in bounded model checking of C programs via *k*-induction

Authors | Authors and affiliations

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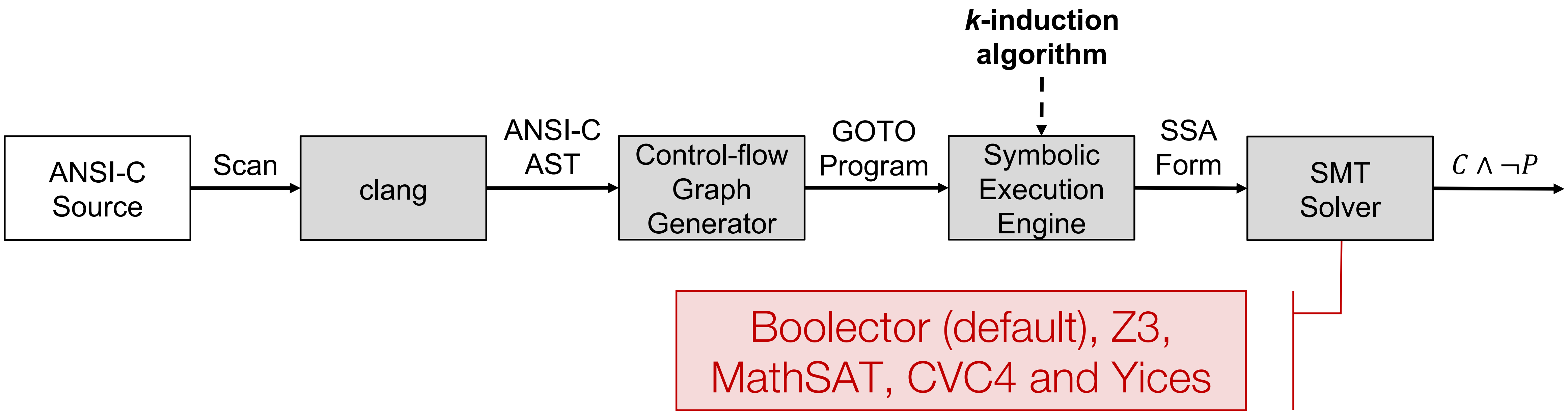
ESBMC Architecture

- The back-end is highly configurable and allows the encoding of quantifier-free formulas

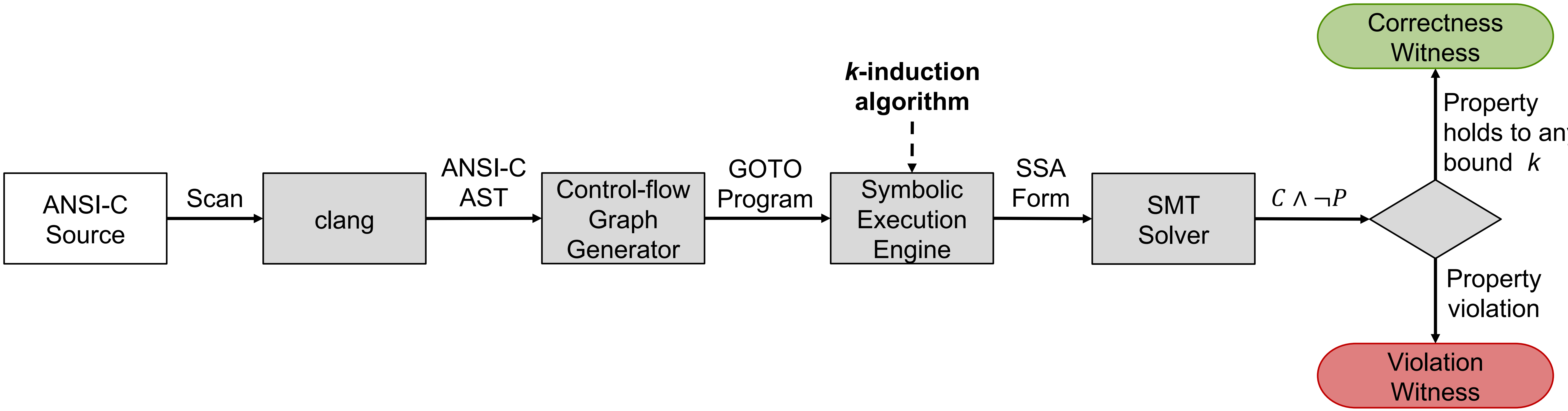
  bitvectors, arrays, tuple, fixed-point and floating-point arithmetic (all solvers), and linear integer and real arithmetic (all solvers but Boolector).



ESBMC Architecture

- The back-end is highly configurable and allows the encoding of quantifier-free formulas

  bitvectors, arrays, tuple, fixed-point and floating-point arithmetic (all solvers), and linear integer and real arithmetic (all solvers but Boolector).



Strengths & Weaknesses

- Strengths
  - Reach-Safety
    - ECA (score: 1113)
    - Floats (score: 790)
    - Heap (score: 300)
    - Product Lines (score: 787)
  - Falsification (score: 1916)
  - Arithmetic, floating point arithmetic
  - User-specified assertions
  - the use of invariants increases the number of correct proofs in ESBMC by about 7%
- Weaknesses
  - need relational analysis that can keep track of relationship between variables

```c
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

Simplified safe program extracted from SV-COMP 2018

```c
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

Program under verification | **Enable *k*-induction instead of plain BMC** | **Enable interval analysis**

```
esbmc main.c --k-induction --interval-analysis
```

without interval analysis

```
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int
    if (input > 5
      return 0;
    } else if (in
      s = 2;
    } else if (in
      s = 3;
    } else if (in
      s = 4;
    } else if (in
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

```
Unwinding loop 1 iteration 49 file svcomp2018.c line 17 function main
Not unwinding loop 1 iteration 50 file svcomp2018.c line 17 function main
Symex completed in: 0.111s (3563 assignments)
Slicing time: 0.008s (removed 2716 assignments)
Generated 1 VCC(s), 1 remaining after simplification (847 assignments)
No solver specified; defaulting to Boolector
Encoding remaining VCC(s) using bit-vector arithmetic
Encoding to solver time: 0.006s
Solving with solver Boolector 3.0.0
Encoding to solver time: 0.006s
Runtime decision procedure: 0.219s
The inductive step is unable to prove the property
Unable to prove or falsify the program, giving up.
VERIFICATION UNKNOWN
```

with interval analysis

ASSUME s <= 5 && 1 <= s

1

```
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

with interval analysis

1. `ASSUME s <= 5 && 1 <= s`
2. `ASSUME s <= 5 && 1 <= s`

```c
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

with interval analysis

```
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

1. `ASSUME s <= 5 && 1 <= s` (at `int main() {`)
2. `ASSUME s <= 5 && 1 <= s` (at `while (1) {`)
3. `ASSUME s <= 5 && 1 <= s && 6 <= input` (at `return 0;`)

with interval analysis

1. `ASSUME s <= 5 && 1 <= s`
2. `ASSUME s <= 5 && 1 <= s`
3. `ASSUME s <= 5 && 1 <= s && 6 <= input`
4. `ASSUME s == 1 && input == 1`

```
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

with interval analysis

1. ASSUME s <= 5 && 1 <= s
2. ASSUME s <= 5 && 1 <= s
3. ASSUME s <= 5 && 1 <= s && 6 <= input
4. ASSUME s == 1 && input == 1
5. ASSUME s == 2 && input == 2

```c
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

with interval analysis

```c
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

1. ASSUME s <= 5 && 1 <= s
2. ASSUME s <= 5 && 1 <= s
3. ASSUME s <= 5 && 1 <= s && 6 <= input
4. ASSUME s == 1 && input == 1
5. ASSUME s == 2 && input == 2
6. ASSUME s == 3 && input == 3

with interval analysis

```c
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

1. ASSUME s <= 5 && 1 <= s
2. ASSUME s <= 5 && 1 <= s
3. ASSUME s <= 5 && 1 <= s && 6 <= input
4. ASSUME s == 1 && input == 1
5. ASSUME s == 2 && input == 2
6. ASSUME s == 3 && input == 3
7. ASSUME s == 4 && input == 4

with interval analysis

```c
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return 0;
    } else if (input == 1 && s == 1) {
      s = 2;
    } else if (input == 2 && s == 2) {
      s = 3;
    } else if (input == 3 && s == 3) {
      s = 4;
    } else if (input == 4 && s == 4) {
      s = 5;
    } else if (input == 5 && s > 5) { // unsatisfiable
      __VERIFIER_error(); // property violation
    }
  }
}
```

1. ASSUME s <= 5 && 1 <= s
2. ASSUME s <= 5 && 1 <= s
3. ASSUME s <= 5 && 1 <= s && 6 <= input
4. ASSUME s == 1 && input == 1
5. ASSUME s == 2 && input == 2
6. ASSUME s == 3 && input == 3
7. ASSUME s == 4 && input == 4
8. ASSUME s <= 5 && 1 <= s && input <= 5

with interval analysis

```
unsigned int s = 1;
int main() {
  while (1) {
    unsigned int input = __VERIFIER_nondet_int();
    if (input > 5) {
      return
    } else i
      s = 2;
    } else i
      s = 3;
    } else i
      s = 4;
    } else i
      s = 5;
    } else i
      __VERI
    }
  }
}
```

1 ASSUME s <= 5 && 1 <= s

2 ASSUME s <= 5 && 1 <= s

3 ASSUME s <= 5 && 1 <= s && 6 <= input

ut == 1

ut == 2

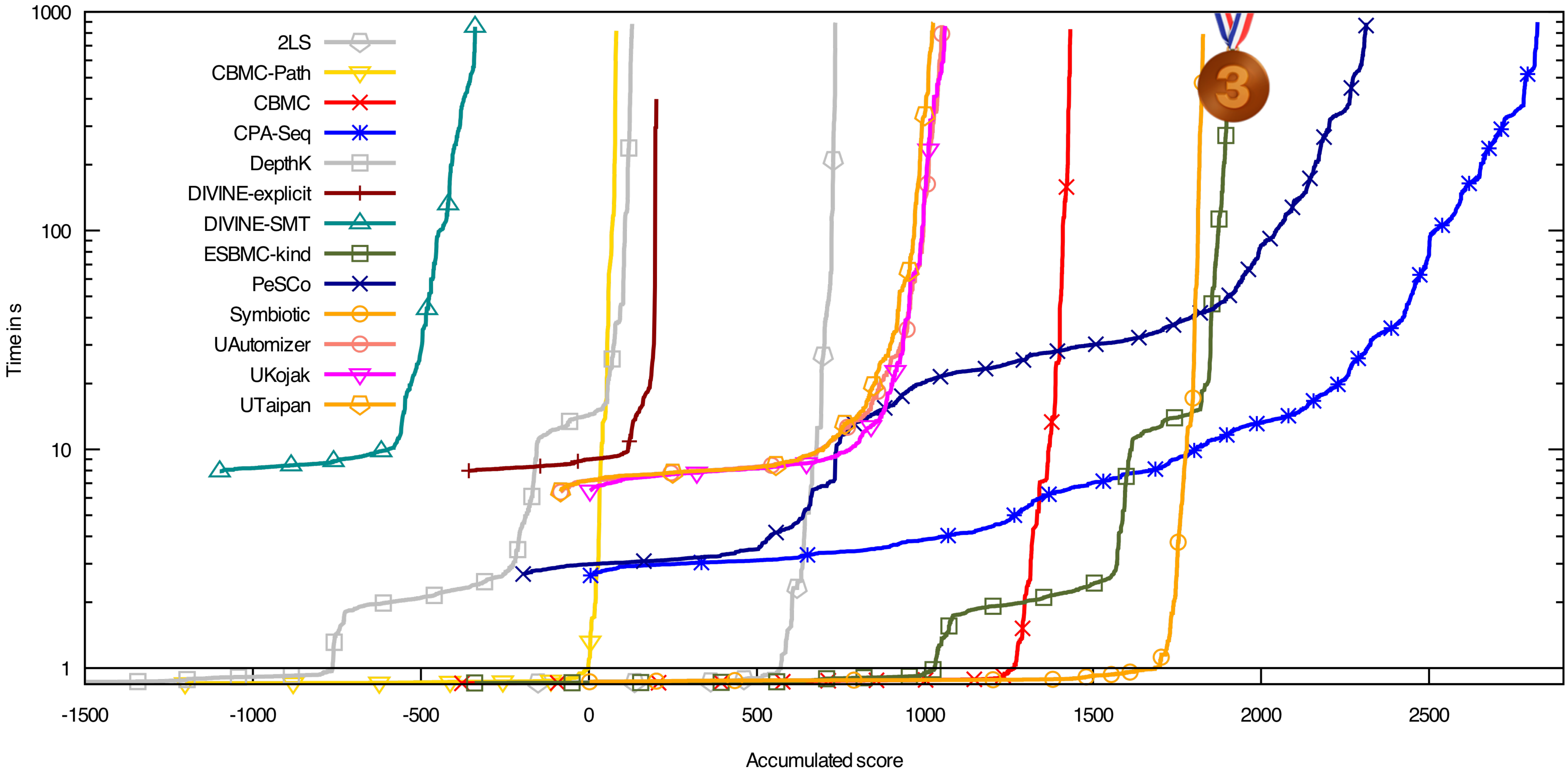
ut == 3

ut == 4

nput <= 5

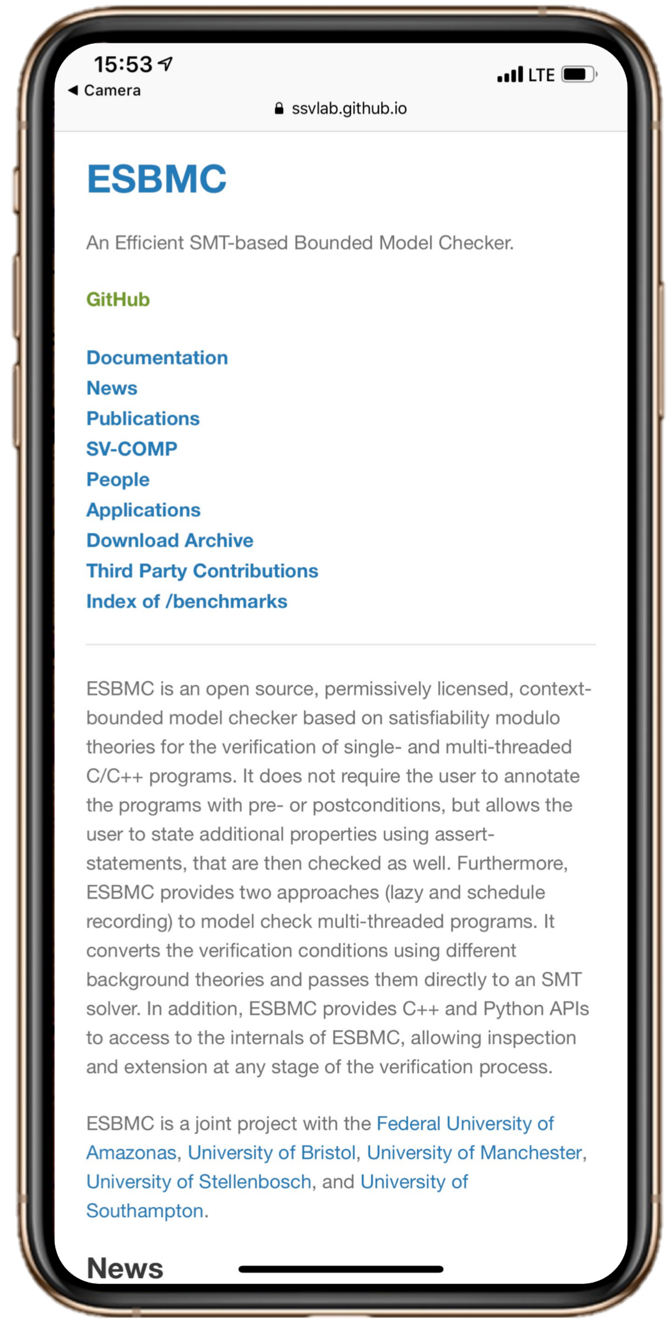
```
*** Checking inductive step
Starting Bounded Model Checking
Unwinding loop 1 iteration 1 file svcomp2018.c line 17 function main
Not unwinding loop 1 iteration 2 file svcomp2018.c line 17 function main
Symex completed in: 0.001s (82 assignments)
Slicing time: 0.000s (removed 22 assignments)
Generated 1 VCC(s), 1 remaining after simplification (60 assignments)
No solver specified; defaulting to Boolector
Encoding remaining VCC(s) using bit-vector arithmetic
Encoding to solver time: 0.000s
Solving with solver Boolector 3.0.0
Encoding to solver time: 0.000s
Runtime decision procedure: 0.001s
BMC program time: 0.003s


VERIFICATION SUCCESSFUL


Solution found by the inductive step (k = 2)
```

Falsification



Thank you!

More information available at http://esbmc.org/



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