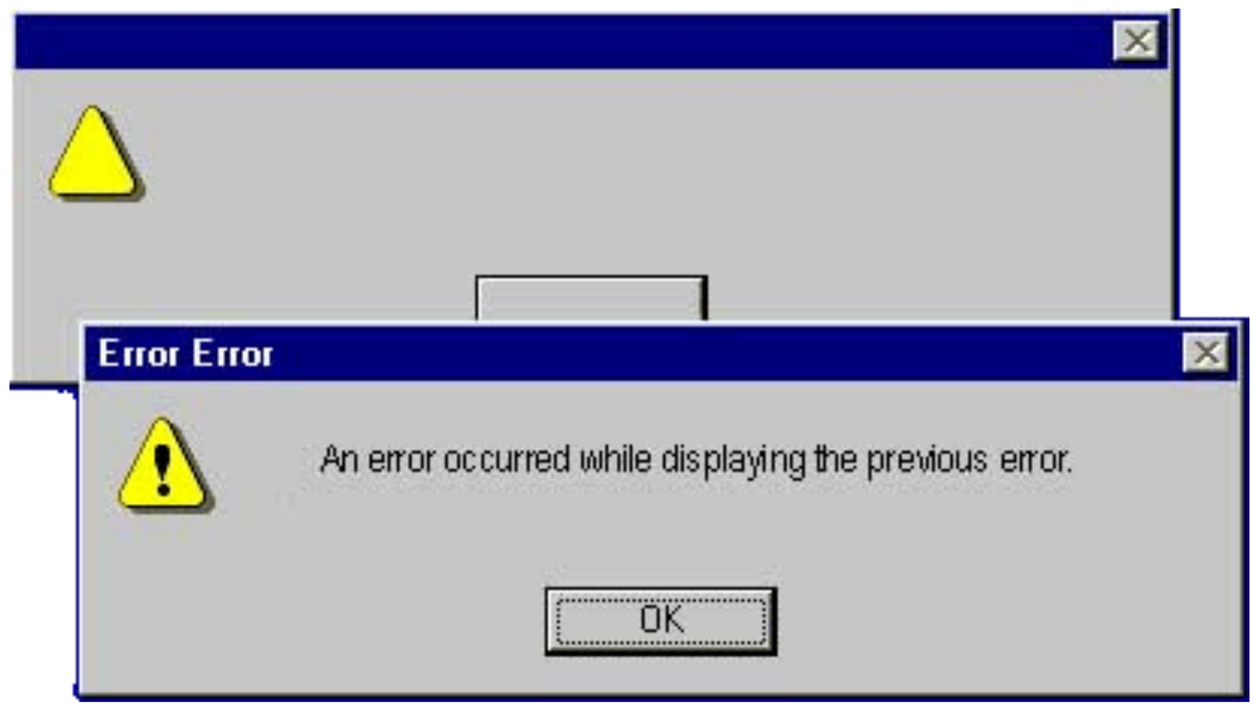

Towards Counterexample-guided *k*-Induction for Fast Bug Detection

Mikhail R. Gadelha
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26th ACM Joint European Software Engineering Conference and Symposium
on the Foundations of Software Engineering

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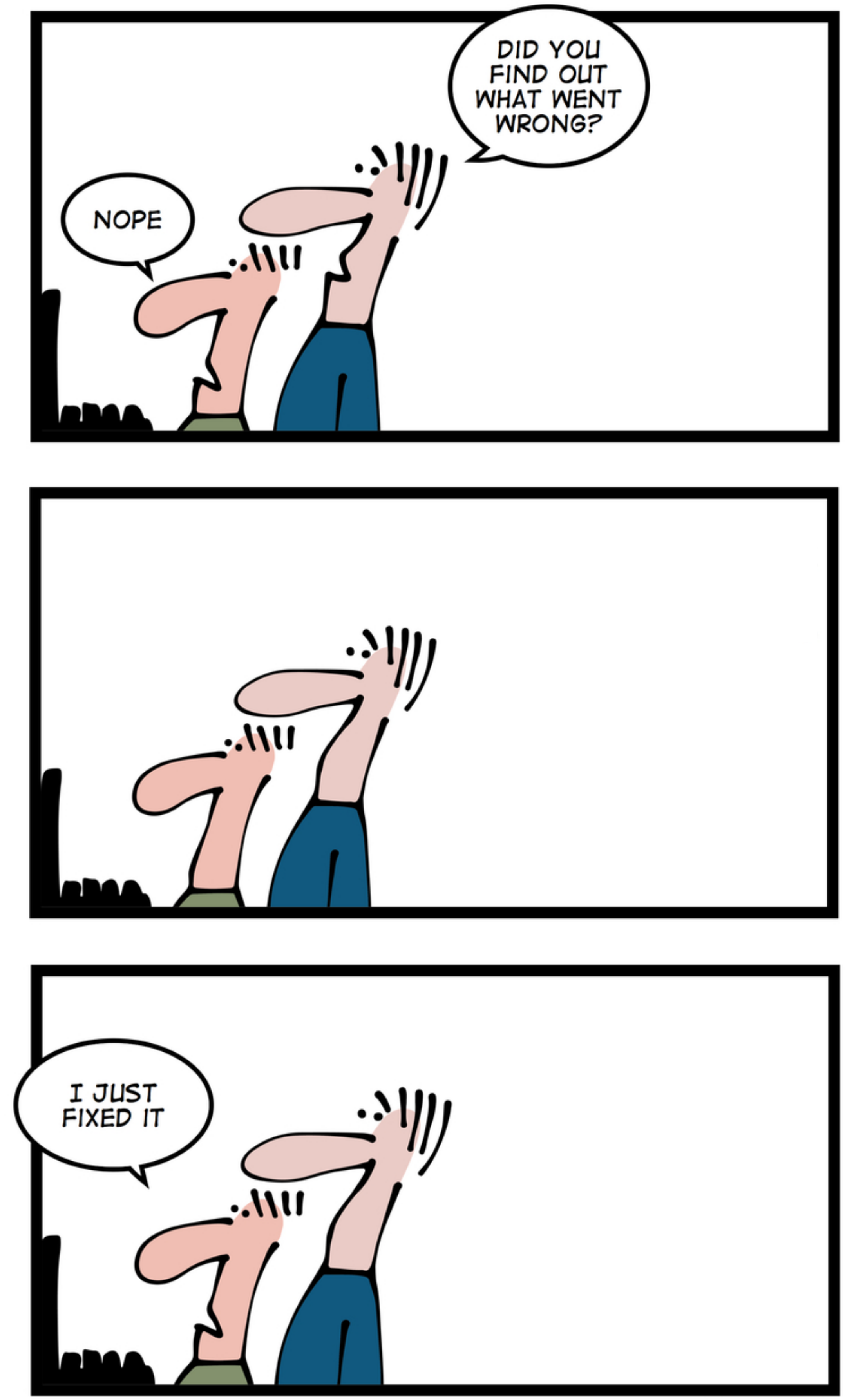
Motivation

Why should we invest in software reliability?



Why should we invest in software reliability?

- The ubiquity of embedded systems drives a need to **test and validate a system** before releasing it to the market, in order to protect against **system failures.**

"Formal automated reasoning is one of the investments that AWS is making in order to facilitate continued simultaneous growth in both functionality and security."

- Byron Cook, FLoC, 2018.

Why should we invest in software reliability?

- Embedded software must be as robust and bug-free as possible, given that **even subtle system bugs can have drastic consequences:**

    - In April 2014, the **Heartbleed** was publicly disclosed, a security bug in the OpenSSL cryptography library, which is a widely used implementation of the Transport Layer Security (TLS) protocol.

    - “*When it is exploited it leads to the leak of memory contents from the server to the client and from the client to the server.*”

      – Synopsys Inc., 2014.

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  - *"When it is exploited it leads to the leak of memory contents from the server to the client and from the client to the server."*

    – Synopsys Inc., 2014.

  - In September 2018, attackers exploited three **Facebook** vulnerabilities and stole access tokens from as many as 50 million users, in order to take over their accounts.

Our main goal is to…

Propose a faster approach to detect bugs and prove correctness of a program

We demonstrate in this paper how to…

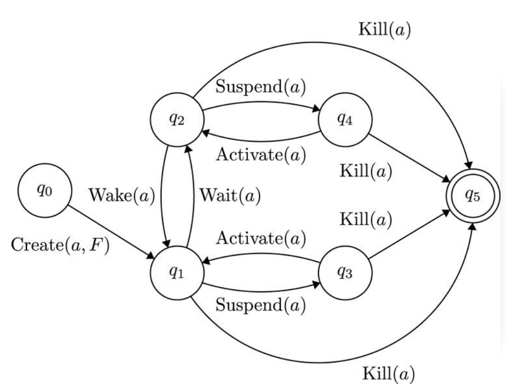
Improve the *k*-induction algorithm to work as a meet-in-the-middle bidirectional search by using the information from the counterexample

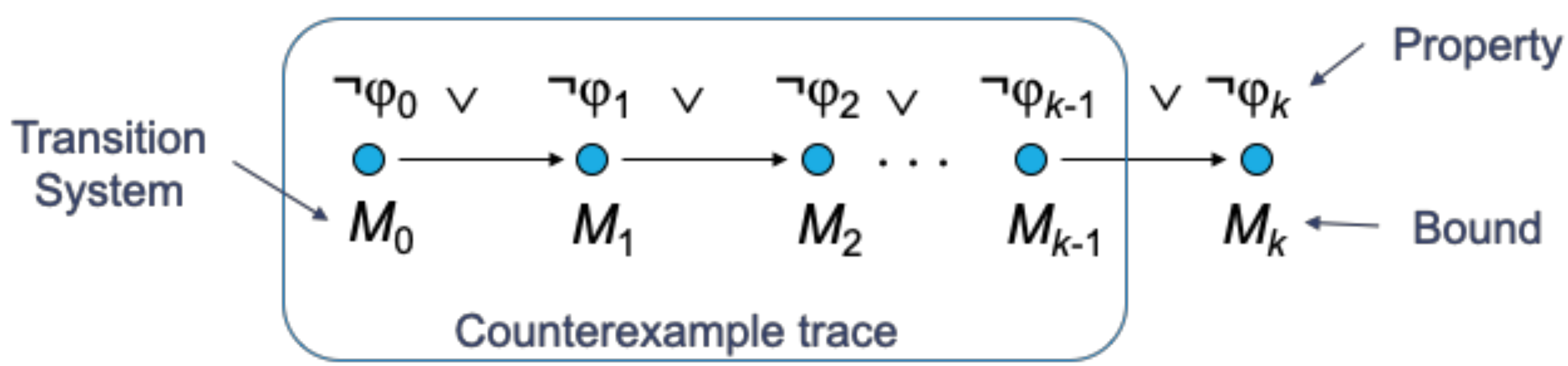
Background

The *k*-Induction Algorithm

Bounded Model Checking

- Basic Idea: given a transition system *M*, check negation of a given property ϕ up to given depth *k:*





- Translated into a VC ψ such that: **ψ is satisfiable iff ϕ has counterexample of max. depth *k*.**
- BMC tools are aimed at finding bugs; they cannot prove correctness, unless the bound *k* safely reaches all program states.

```c
int main() {
    uint32_t n;
    uint64_t sn = 0;
    for (uint64_t i = 1; i <= n; i++) {
        sn = sn + 2;
        assert(sn == i * 2);
    }
    assert(sn == n*2 || sn == 0);
}
```

```c
1  int main() {
2      uint32_t n;
3      uint64_t sn = 0;
4      for (uint64_t i = 1; i <= n; i++) {
5          sn = sn + 2;
6          assert(sn == i * 2);
7      }
8      assert(sn == n*2 || sn == 0);
9  }
```

```c
1  uint64_t i = 1;
2  /* n copies of this if statement */
3  if(i <= n) {
4    sn = sn + 2;
5    assert(sn == i * 2);
6    i++;
7  }
8  /* unwinding assertion */
9  assert(!(i<=n));
```

BMC tools such as CBMC, ESBMC or LLBMC typically reproduce the loop *k* times (lines 4 – 7) and are unable to verify that program unless the loop is fully unrolled, *i.e.*, the unwinding assertion fails if *k < (2^32 – 1)*

The *k*-induction Algorithm

I. Base case: usual BMC algorithm, tries to find a property violation.

- Explores all states up to a bound *k*. Cannot prove correctness.

II. Forward Condition: checks the completeness threshold (if all loops were unrolled).

- Cannot find bugs.

III. Inductive Step: over-approximates loops so all states can be checked without unrolling them completely.

- Might return spurious counterexamples.

Approach and Uniqueness

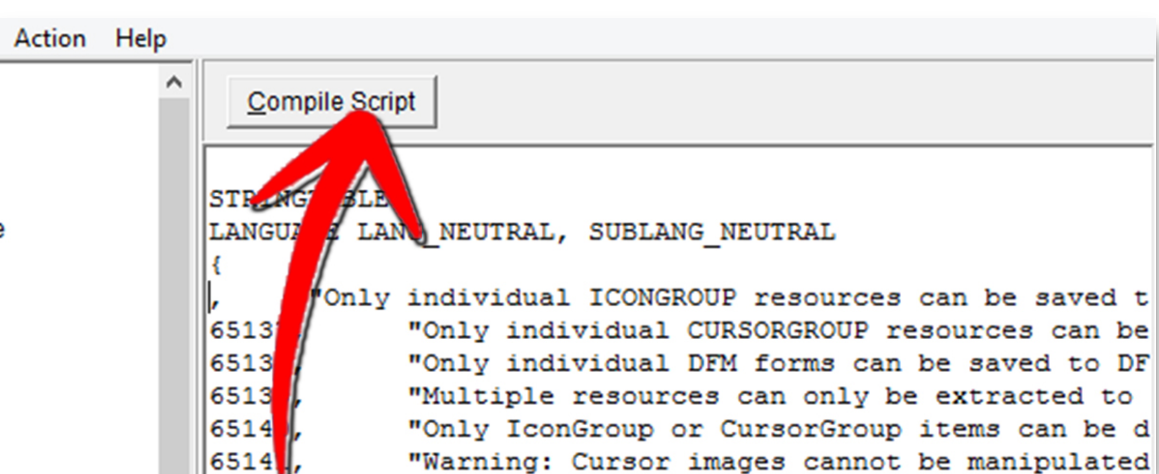
Counterexample-Guided
k-Induction

Counterexample-Guided *k*-Induction

- The biggest limitation of *k*-induction is the fact that it performs three checks for each *k* (*i.e.*, base case, forward condition and inductive step).

- The **inductive step is the most computationally expensive one**; it is an over-approximation, forcing the SMT solver to find a set of assignments in a larger state space than the original program.

- Moreover, the computation is ***wasted*** if a counterexample is found by the inductive step, as it is assumed to be spurious.



Counterexample-Guided *k*-Induction

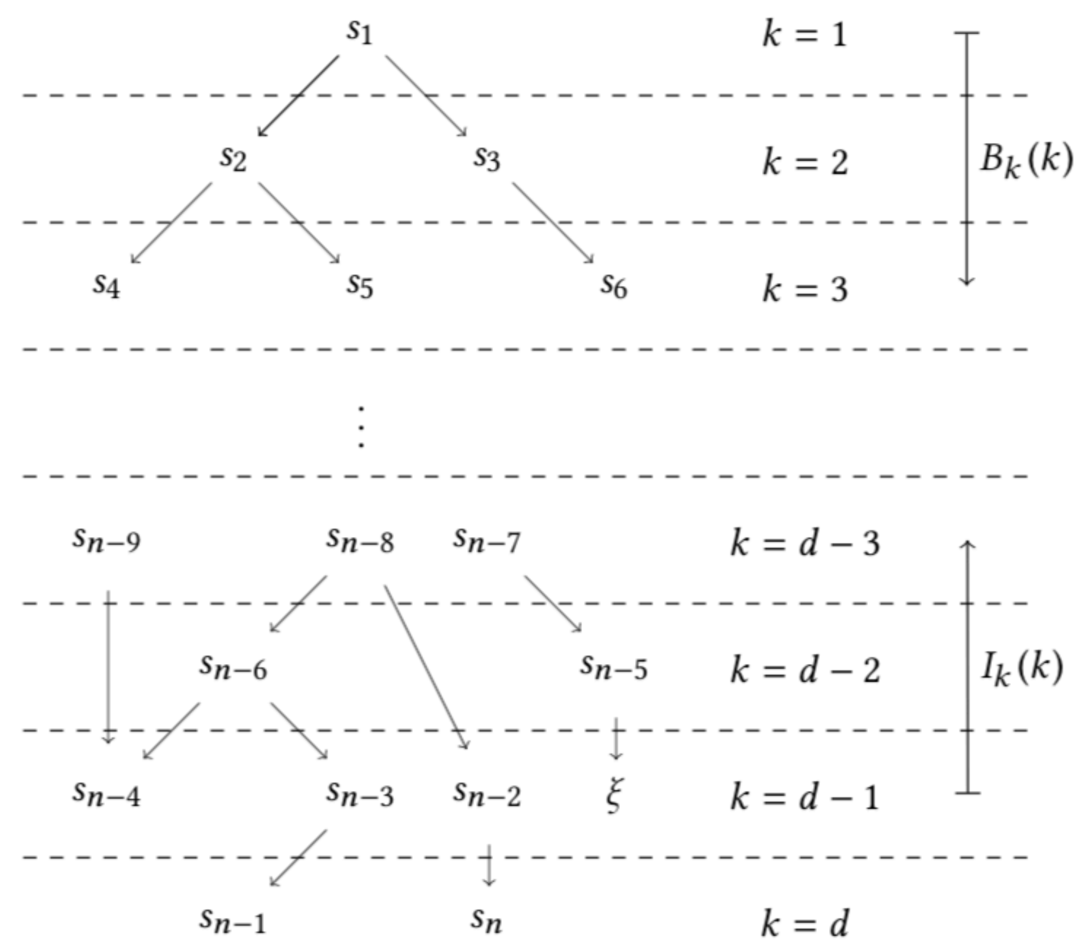
- We propose to use the ***counterexample*** generated by the ***inductive step*** to ***speed up*** the bug finding check (*i.e.*, the base case).

- Our extension converts the *k*-induction algorithm into a **bidirectional search approach** by searching simultaneously:

  i. both forward (*i.e.*, from the initial state);

  ii. backward (*i.e.*, from the error state ξ detected in the inductive step);

  iii. stop if both searches meet in the middle.



Running Example

Original Program

```c
unsigned int a = 1;
while(1)
{
  if(a == 6)
    assert(0);
  a++;
}
```

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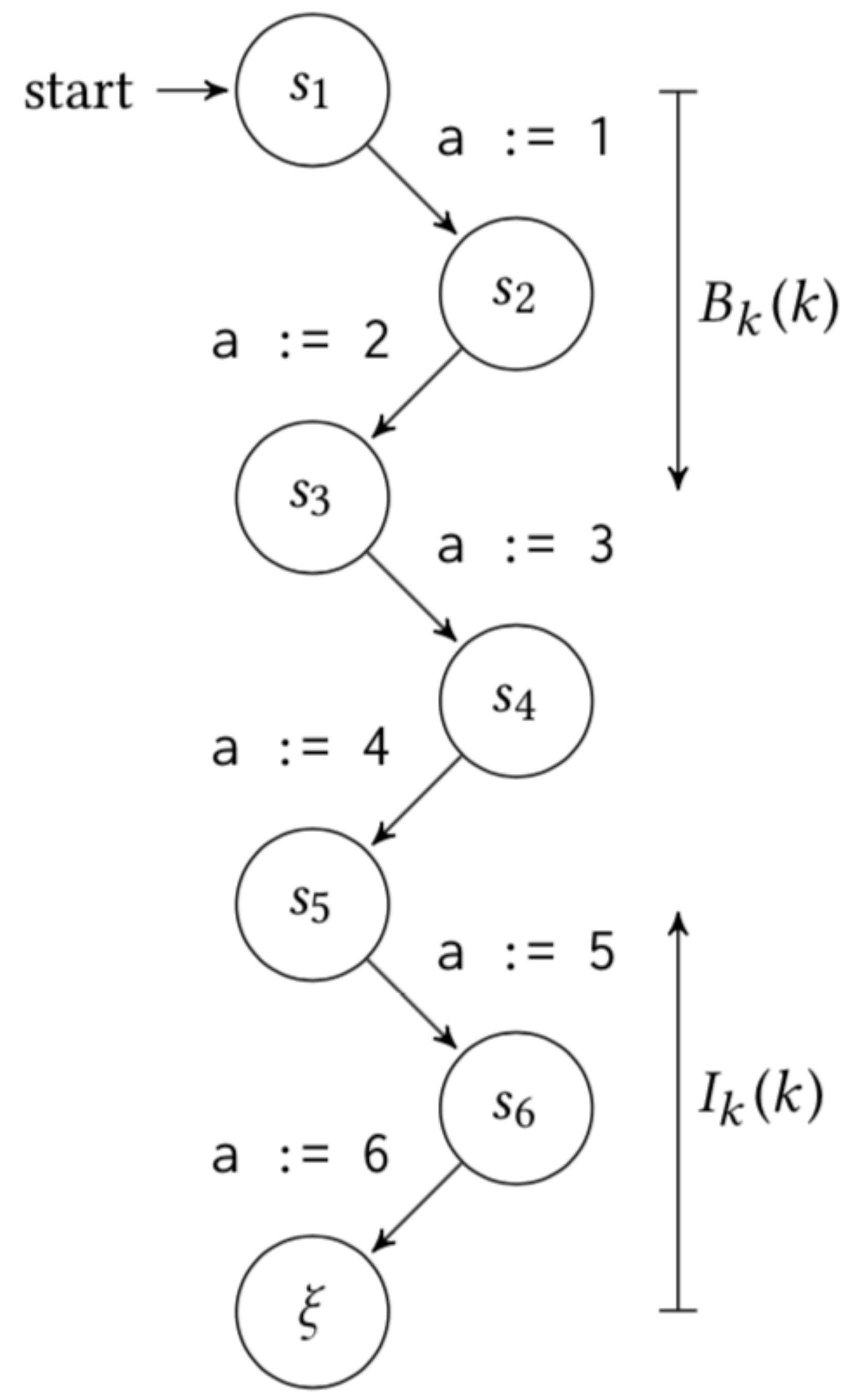


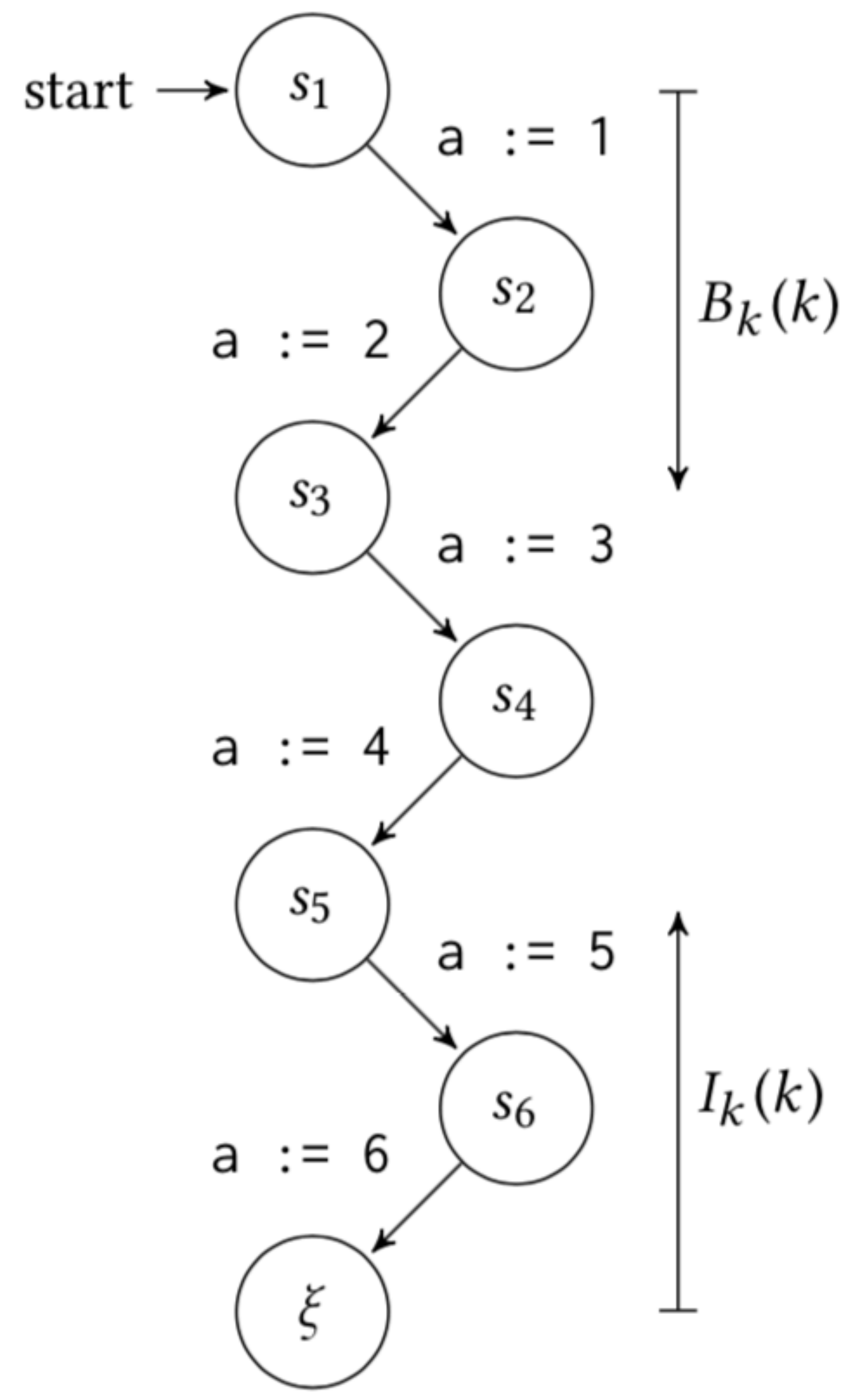
Running Example

Original Program

```c
unsigned int a = 1;
while(1)
{
  if(a == 6)
    assert(0);
  a++;
}
```

Modified Program

```c
unsigned int a = 1;
while(1)
{
  if(a == 6)
    assert(0);
  a++;
  // added assertion
  assert(a != 5);
}
```



Preliminary Results

Evaluate our *k*-induction algorithm extension

Experiments

- In order to evaluate our *k*-induction algorithm extension, we selected a number of benchmarks from the **International Competition on Software Verification 2018.**
- We compare the results from the original k-induction and our extended version.

Experimental setup. All experiments were conducted on a computer with an Intel Core i7-2600 running at 3.40GHz and 24GB of RAM under Fedora 25 64-bit. We used **ESBMC v5.0** and no time or memory limit was set for the verification tasks.

Availability of data & tools. Our experiments are based on a set of publicly available benchmarks. All tools, benchmarks, and the results of our evaluation are available on our web page http://esbmc.org/

Preliminary Results

- Preliminary evaluation over the SV-COMP 2018 benchmarks.

Benchmark	LOC	k-induction T(s)	k-induction M(MB)	k-induction k	Extended k-induction T(s)	Extended k-induction M(MB)	Extended k-induction k
sum04.c	19	**1**	38.7	9	**1**	38.7	5
sum01.c	18	**1**	38.9	11	**1**	38.8	6
sum03.c	25	3	39.1	11	**1**	38.8	6
diamond1.c	24	13	43.6	51	**6**	39.1	26
rangesum.c	64	7	66.2	4	**1**	39.0	2
rangesum05.c	59	11	72.3	6	**1**	65.4	3
rangesum10.c	59	28	78.2	11	**16**	47.5	6
Problem01_label15.c	594	7	87.3	5	**5**	70.3	4
rangesum20.c	59	101	99.9	21	**26**	78.2	12
rangesum40.c	59	847	269.5	41	**90**	113.9	22
const.c	20	2606	796.6	1025	**890**	253.2	513
rangesum60.c	59	80272	1106.9	61	**159**	134.6	32
Average	88	6991	228.1	104	**99**	79.8	53
Total	1059	83897	2737.2	1255	**1197**	957.5	638

Preliminary Results

verification time is not related to the number of steps or the program size

- Preliminary evaluation over the SV-CO

Benchmark	LOC	k-induction			Extended k-induction		
		T(s)	M(MB)	k	T(s)	M(MB)	k
sum04.c	19	1	38.7	9	**1**	38.7	5
sum01.c	18	1	38.9	11	**1**	38.8	6
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Preliminary Results

- Preliminary evaluation over

our extension to the *k*-induction algorithm potentially cuts the verification time considerably in cases where the state space explored is large

Benchmark	*LOC*	*k*-induction			Extended *k*-induction		
		T(s)	*M*(MB)	*k*	*T*(s)	*M*(MB)	*k*
sum04.c	19	**1**	38.7	9	**1**	38.7	5
sum01.c	18	**1**	38.9	11	**1**	38.8	6
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Preliminary Results

- Preliminary evaluation over

for small cases, our extension does not slow things down or use more memory than the original *k*-induction

Benchmark	*LOC*	*k*-induction *T*(s)	*M*(MB)	*k*	Extended *k*-induction *T*(s)	*M*(MB)	*k*
sum04.c	19	**1**	38.7	9	**1**	38.7	5
sum01.c	18	**1**	38.9	11	**1**	38.8	6
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Preliminary Results

for large cases, the gains are substantial (*e.g.*, the verification time of `rangesum60.c` is 504x faster)

- Preliminary evaluation over

Benchmark	*LOC*	*k*-induction			Extended *k*-induction		
		T(s)	*M*(MB)	*k*	*T*(s)	*M*(MB)	*k*
sum04.c	19	**1**	38.7	9	**1**	38.7	5
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Preliminary Results

the speed up comes from requiring roughly half the number of steps to find a property violation

- Preliminary evaluation over

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		T(s)	*M*(MB)	*k*	*T*(s)	*M*(MB)	*k*
sum04.c	19	**1**	38.7	9	**1**	38.7	5
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Contributions

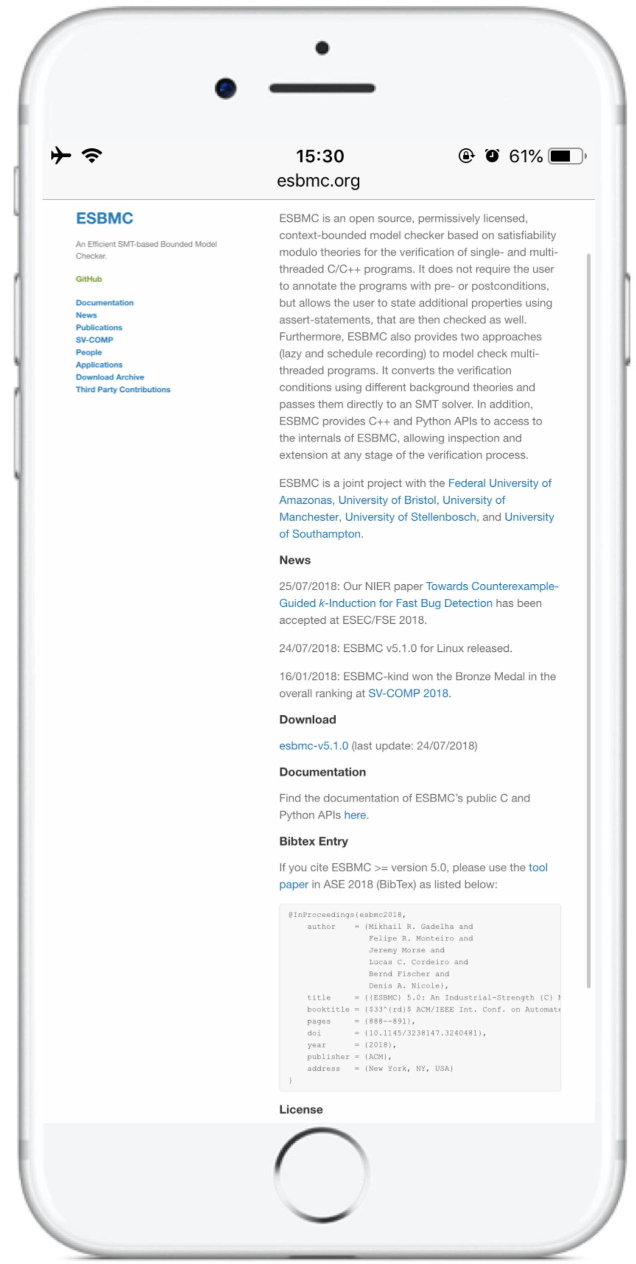
A novel extension to the *k*-induction algorithm

Contributions

- Our main contribution is **a novel extension to the *k*-induction algorithm**, to perform a bidirectional search instead of the conventional iterative deepening search:
  - the preliminary results show that the extension has the potential to substantially improve the verification time for problems with large state space, while maintaining a small verification time for small programs.
- As **future work**, we plan to expand our evaluation over the SV-COMP benchmarks, where the original k-induction algorithm already proved to be the state-of-art, if compared to other *k*-induction tools

"**The main challenge is scalability**: real-world software systems not only include complex control and data structure, but depend on much "context" such as libraries and interfaces to other code, including lower-level systems code. As a result, proving a software system correct requires much more effort, knowledge, training, and ingenuity than writing the software in trial-and-error style."

–E. M. Clarke et al., Handbook of Model Checking, 2018.



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