Effcient Software Model Checking with Block-Abstraction Memoization

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LUDWIG-
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MÜNCHEN

SoSy-Lab
Software Systems

Outline

Introduction and Background

Block-Abstraction Memoization

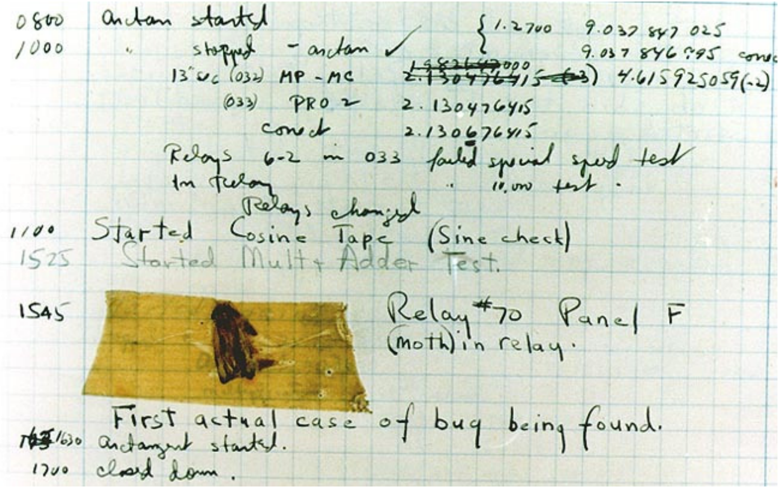
1. Parallel Block-Abstraction Memoization

2. Refinement for Block-Abstraction Memoization

3. Interprocedural Block-Abstraction Memoization

Conclusion

Software Quality



Computer's log of Mark II Aiken Relay Calculator, Grace Hopper, 1947

(Automated) Software Verification

Computer Program

```
int main() {
    int a = foo();
    int b = bar(a);
    if (a != b) error();
}
```

Specification

LTL(G ! call(error()))

Verification Tool

TRUE
i.e., specification is satisfied
→ proof

FALSE
i.e., bug found
→ counterexample

Configurable Program Analysis (CPA)

[Beyer/Henzinger/Théoduloz, 2007]

Fixed-point algorithm for exploring reachable abstract states

- termination based on coverage

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- *transfer*: successor computation
- *merge*: combination of two abstract states
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domain	abstract state
location	l_3
callstack	$[f_1, f_2]$
explicit value	$\{a = 3, b = 5\}$
predicate	$(l < 4 \land m = 5) \lor n \neq 0$

Block-Abstraction Memoization

[Wonisch/Wehrheim, 2012]

Challenge:

- X computation of the complete abstract state space is expensive
- X analysis is not modular

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- reuse intermediate results

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Our contribution:

- ✓ independence of domain
- ✓ modular design and implementation

Block Abstraction

- input-output relation for a block

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Examples for several domains:

domain	abstract input state	abstract output state
location	l_3	l_5
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explicit value	$\{a = 3, b = 5\}$	$\{a = 4, b = 6, c = 9\}$
predicate	$(l < 4 \wedge m = 5) \vee n \neq 0$	$(l < 4 \wedge m = 6) \vee n > l + 1$

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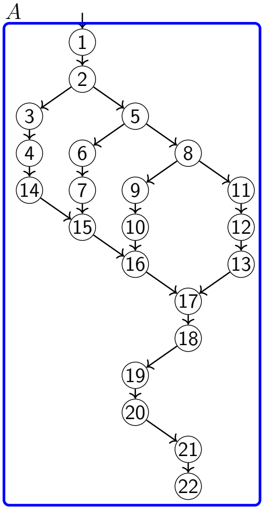
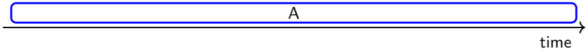
Schematic Example of an Analysis



State-Space Exploration



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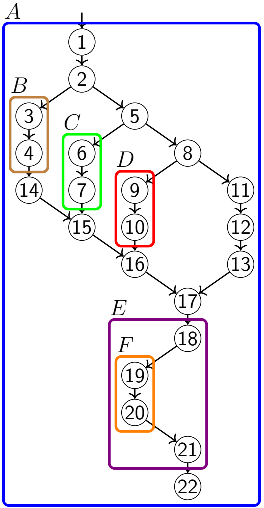

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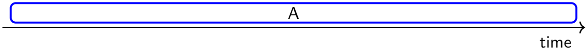

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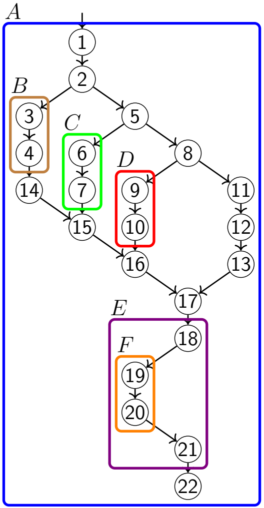

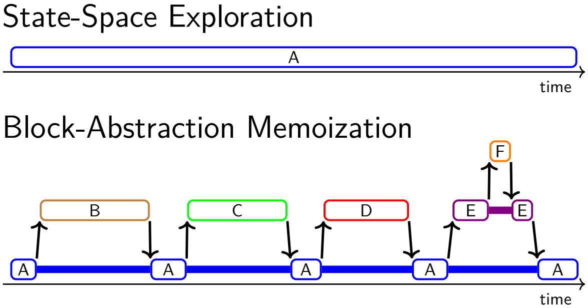

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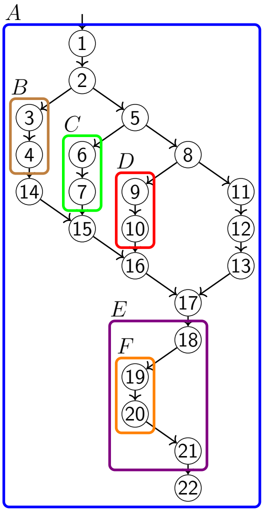

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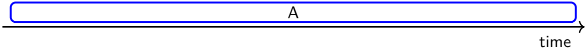
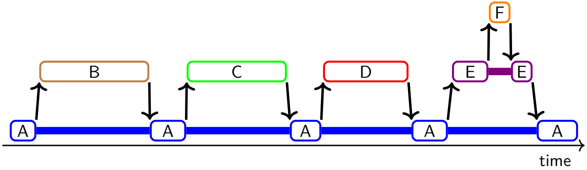
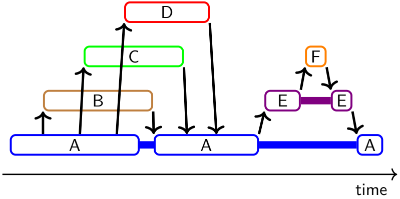


Block-Abstraction Memoization



Parallel Block-Abstraction Memoization



Parallel Block-Abstraction Memoization

[Beyer/Friedberger, 2018]

Challenges with an efficient parallel algorithm:

- X program analysis strictly sequential (per block!)
- X control-flow dependencies between block abstractions

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- ✗ control-flow dependencies between block abstractions

Our contribution: Parallel Block-Abstraction Memoization

- ✓ combination of the existing CPA concept and a parallel application

Evaluation for Parallel Block-Abstraction Memoization

Research questions

- ? 1 processing unit: overhead of the parallel approach
- ? performance with more processing units

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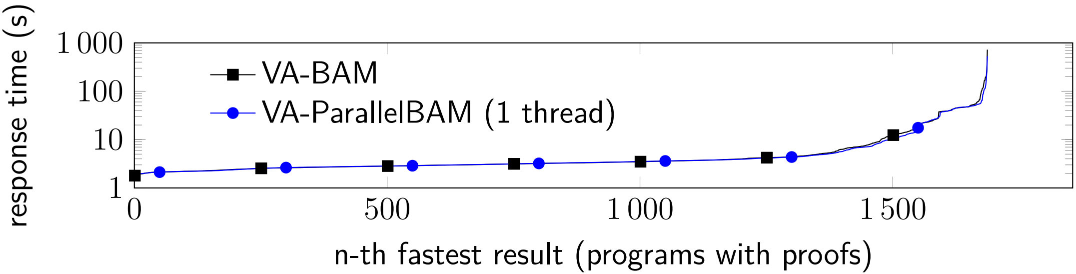
Configuration (CPAchecker r28809)

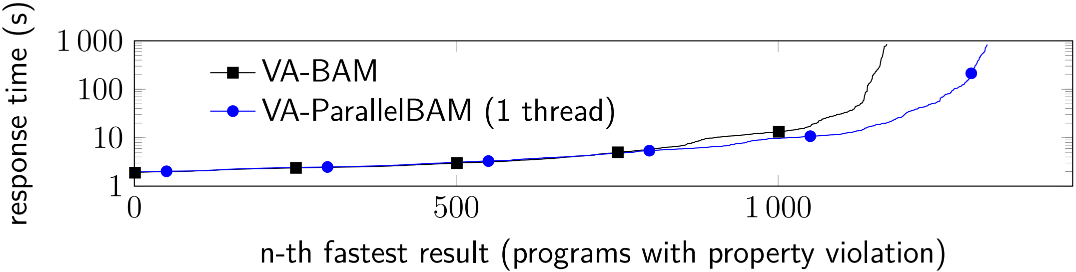
- explicit-value analysis (VA) with BAM or with ParallelBAM

Environment and tasks

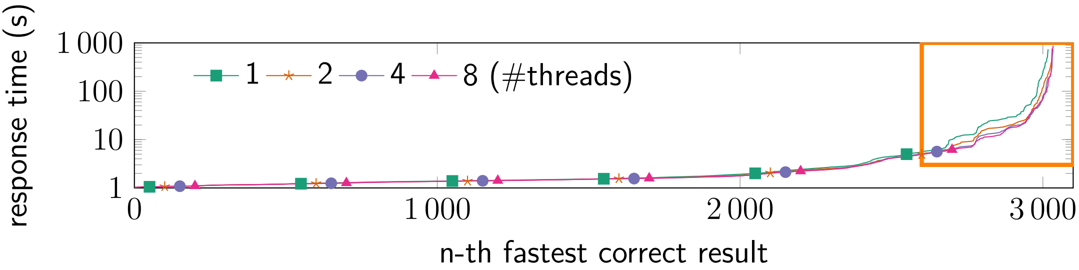
- Intel Xeon E3-1230 v5 with 3.40 GHz and 4 physical cores
- limitation of 15 GB RAM and 15 min of runtime
- 5400 tasks from SV benchmark suite

Evaluation: Sequential vs. Parallel Approach





Evaluation: More Processing Units



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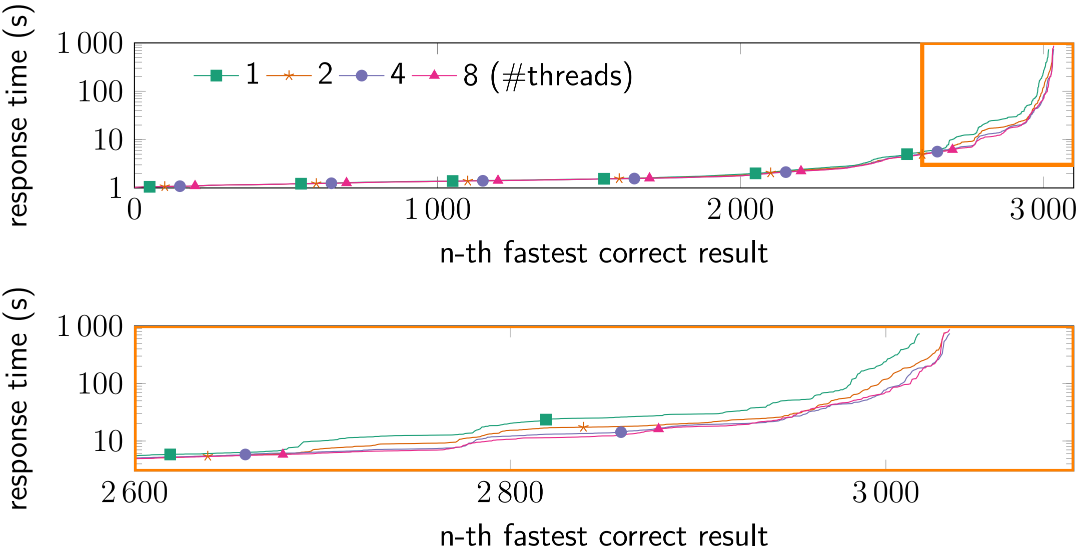

Refinement for Block-Abstraction Memoization

Counterexample-guided Abstraction Refinement (CEGAR)

- granularity of the analysis
- domain-independent approach

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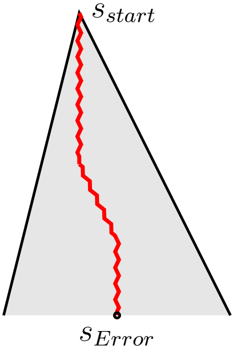

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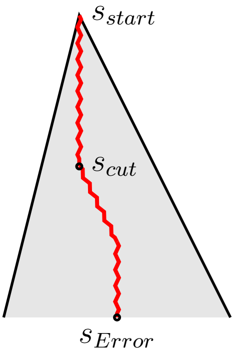

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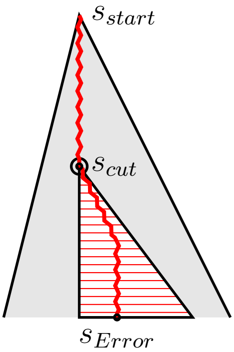

CEGAR with Lazy Refinement (with BAM)

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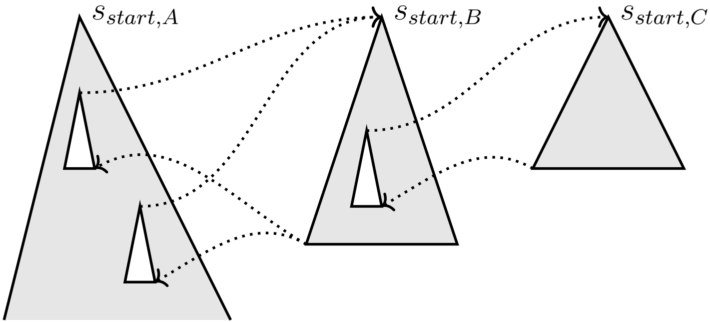

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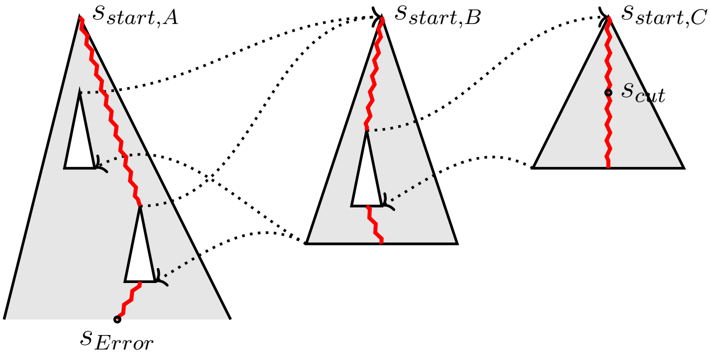

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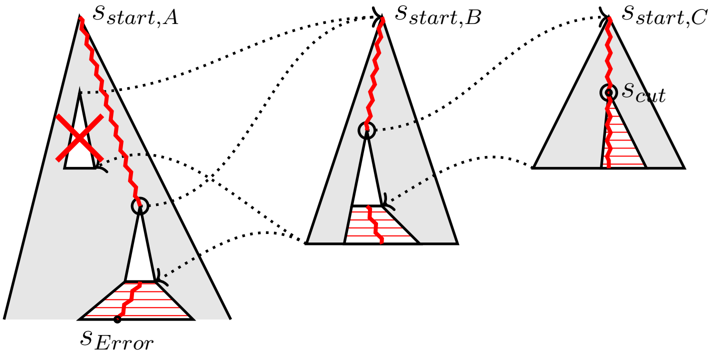

Challenges with *In-Place* Refinement

[Beyer/Friedberger, 2018]

Missing information after the refinement

- ? re-compute nested blocks or take partial results from cache?

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Missing information after the analysis

- X export of incomplete data (witnesses, explored state space, statistics)
- X no guarantee for progress in the analysis

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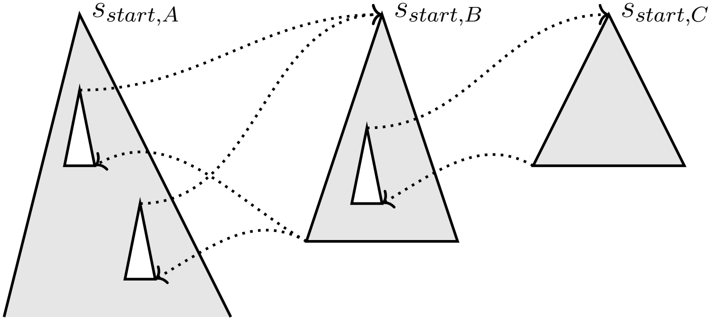
Our contribution: *Copy-on-Write* refinement for BAM

- no deletion of computed block abstractions

Copy-on-Write Refinement Strategy



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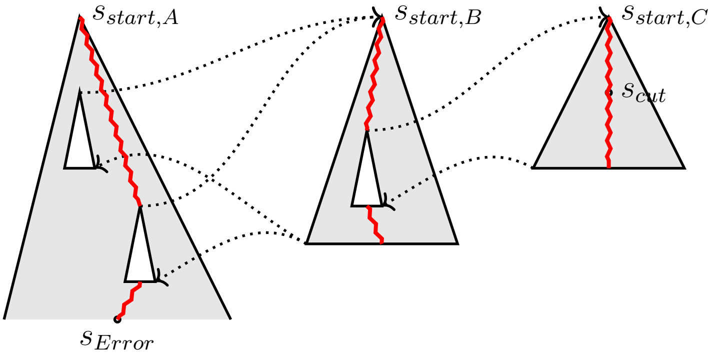

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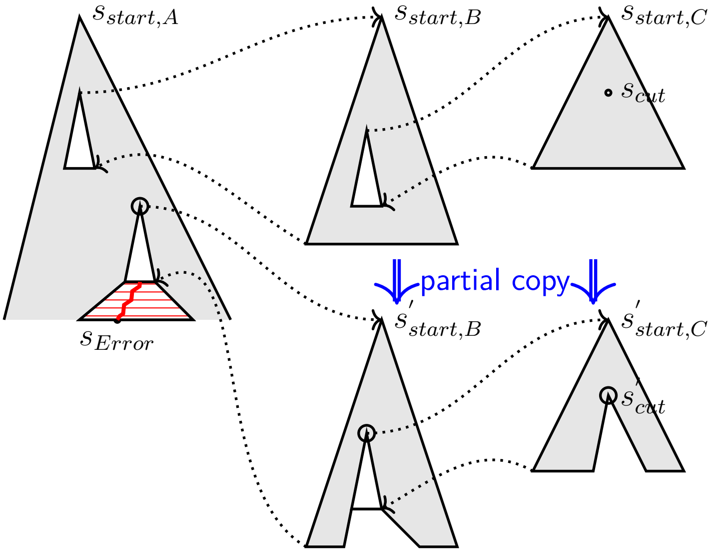

Evaluation

Research questions

- ? different runtime for the analysis?
- ? different number of refinements?

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Configuration (CPAchecker r29066)

- BAM with predicate analysis (PA) and BAM with explicit-value analysis (VA)
- *in-place* vs. *copy-on-write* refinement

Environment and tasks

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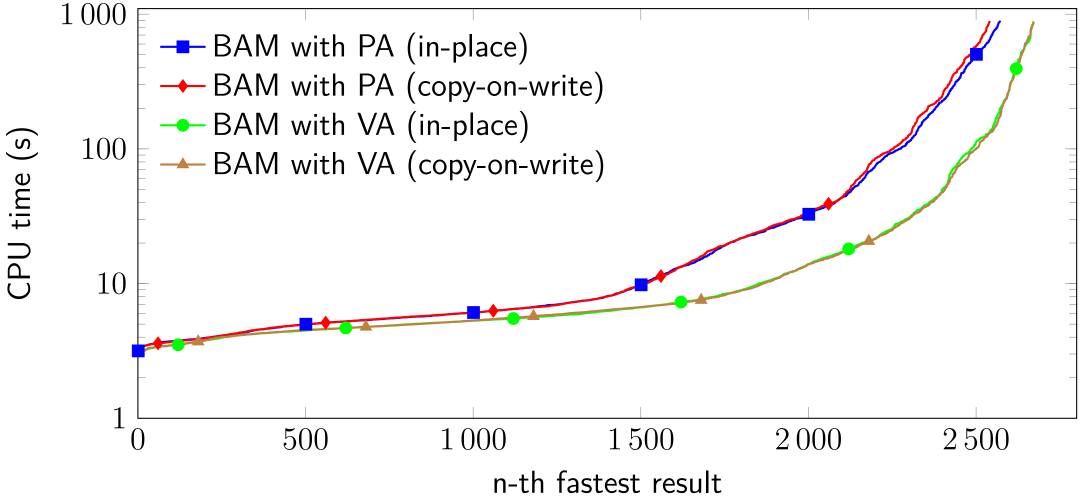
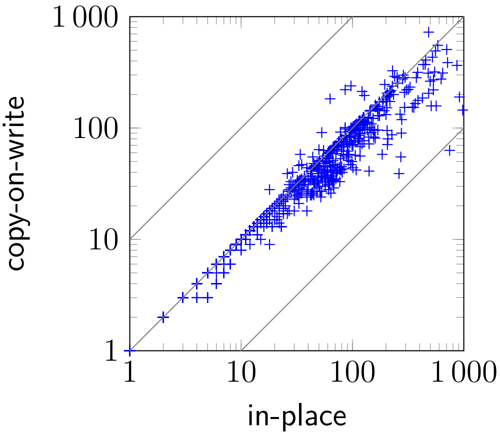
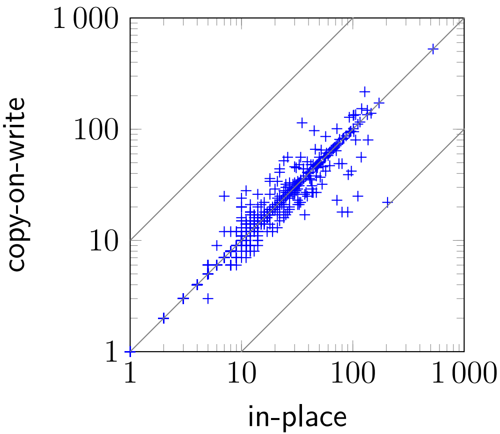
Evaluation: Runtime of Different Refinement Approaches



Evaluation: #Refinements for Different Analyses





Number of refinements for (1) predicate analysis and (2) explicit-value analysis

Interprocedural Block-Abstraction Memoization

[Beyer/Friedberger, 2020]

Challenges with (**intra**procedural) block abstractions:

- X dependent on program context
- X missing support for recursive procedures

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Our contribution: **Inter**procedural Block-Abstraction Memoization

- block abstractions are (mostly) independent of the calling context
- fixed-point algorithm for soundly analyzing recursive procedures

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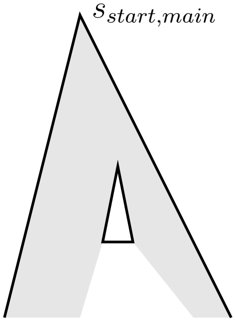
✓ based on Intraprocedural Block-Abstraction Memoization

Analysis of Recursive Procedures



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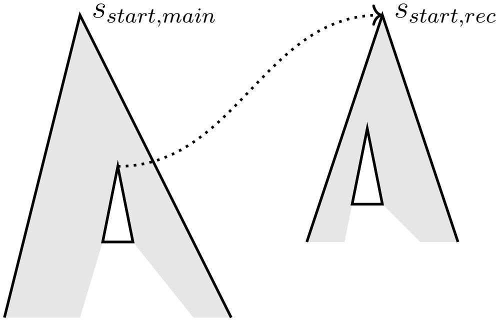

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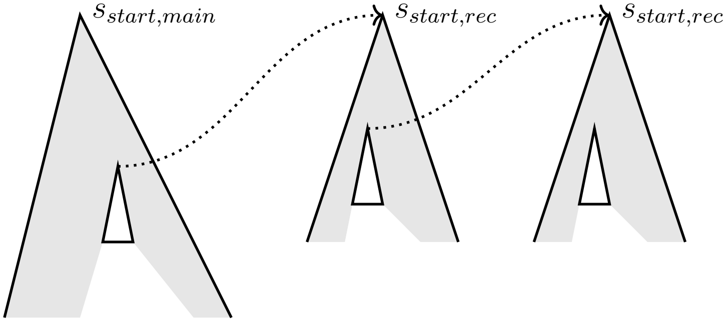

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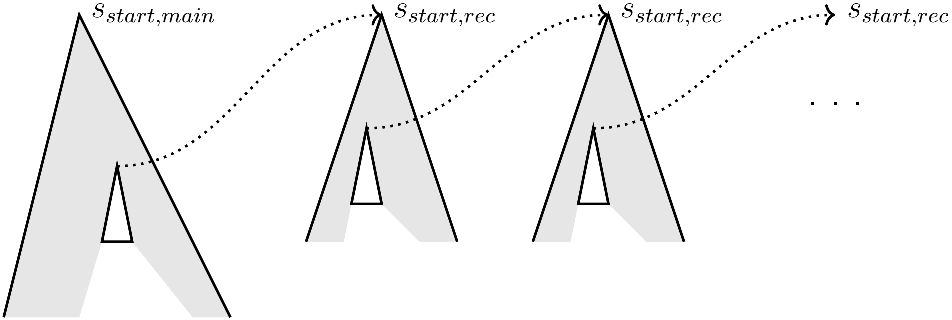
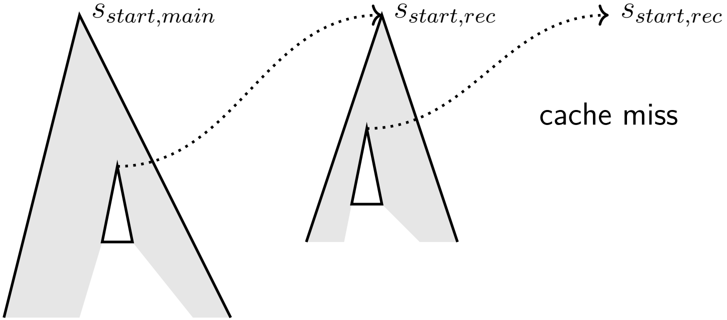


Analysis of Recursive Procedures (Interprocedural BAM)



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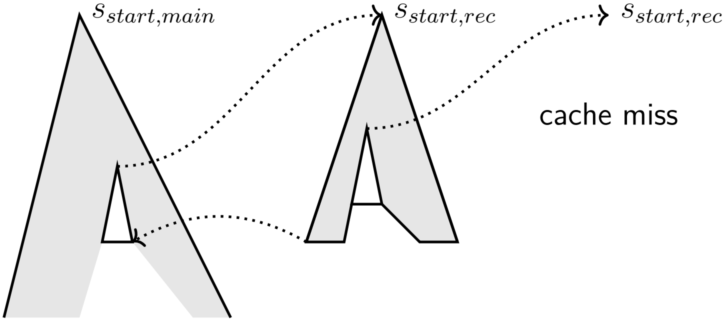

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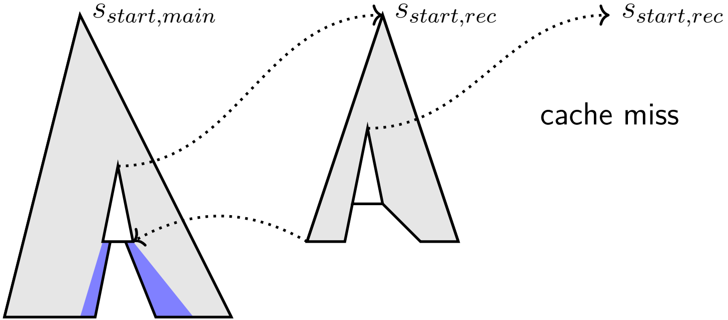

cache miss

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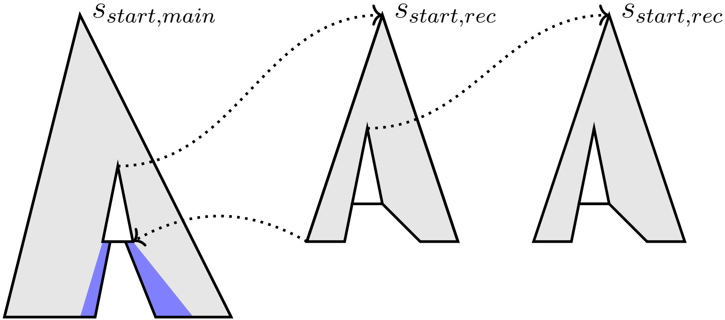

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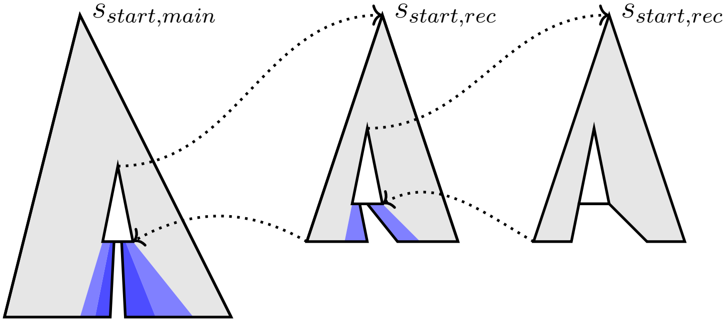

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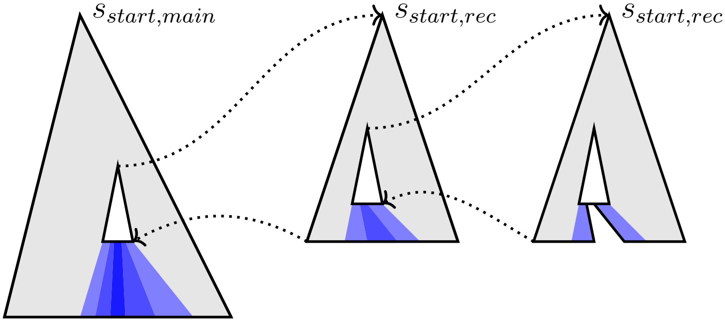

Evaluation

Research questions

- ? effectiveness and efficiency against **Intra**procedural BAM
- ? effectiveness and efficiency against other state-of-the-art tools

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- ? effectiveness and efficiency against **Intra**procedural BAM
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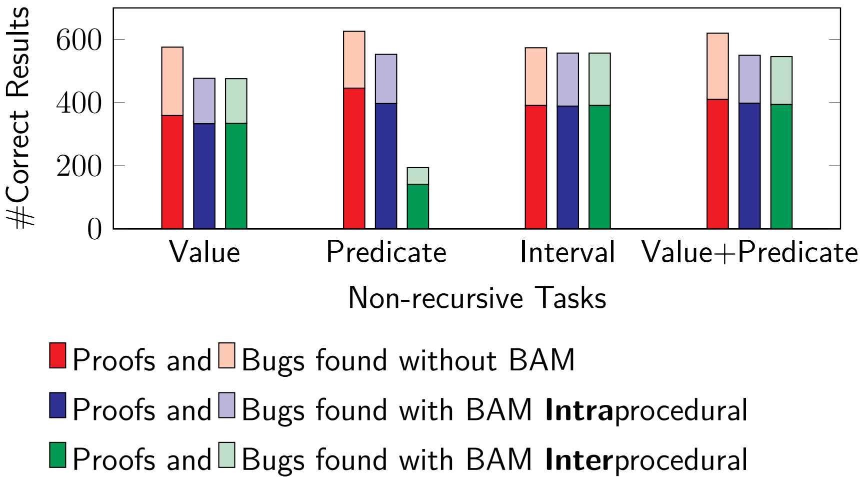
Tools and configurations

- CPAchecker v1.9 with different analyses and different domains
- several participants of SV-COMP'20

Environment and tasks

- Intel Xeon E3-1230 v5 with 3.40 GHz and 4 physical cores
- limitation of 15 GB RAM and 15 min of runtime
- $>$1000 non-recursive tasks from SV benchmark suite
- $>$100 recursive tasks from SV benchmark suite

Evaluation: CPAchecker with Different Analyses



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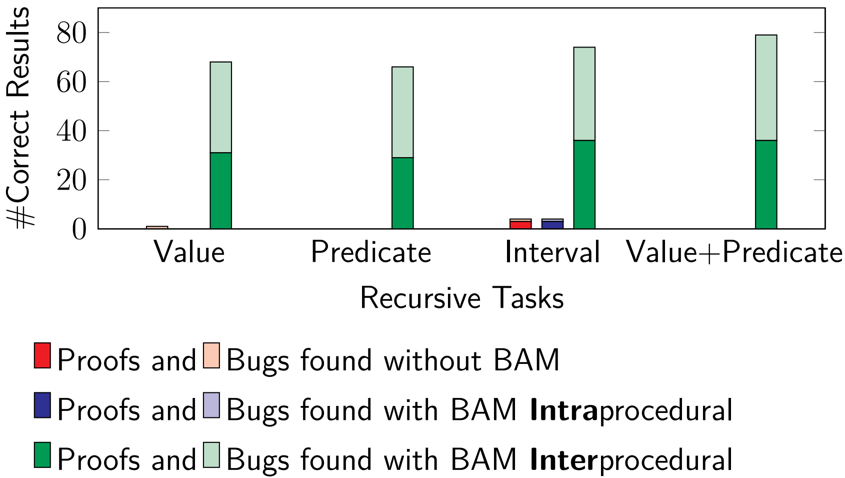


Evaluation: CPAchecker vs. Tools of SV-COMP'20 on Recursive Tasks

Verifier	CPU time (s)	Proofs	Bugs
Cbmc	662	32	47
CPAchecker (Value+Predicate)	2 180	37	46
Divine	1 190	32	42
Esbmc	941	33	47
Map2Check	23 600	34	37
Pinaka	237	31	31
Symbiotic	138	33	45
UAutomizer	2 160	41	37
VeriAbs	7 630	41	46

Conclusion

Block Abstraction Memoization

- domain-independent approach for software verification

Parallel Block Abstraction Memoization

- simple and efficient approach

Refinement for Block Abstraction Memoization

- insights into refinement in the context of BAM

Interprocedural Block Abstraction Memoization

- support for recursive procedures
- competitive performance

Ideas and Future Research Directions

Block Abstraction Memoization

- combine with backward analysis for bi-directional state-space exploration
- more domain

Parallel Block Abstraction Memoization

- multiple processes (machines) instead of multiple threads

Interprocedural Block Abstraction Memoization

- pointer handling and heap manipulation is currently unsolved

References and Data Availability

- Domain-Independent Multi-threaded Software Model Checking
  Dirk Beyer and Karlheinz Friedberger, ASE 2018
  Supplement: https://www.sosy-lab.org/research/bam-parallel/

- In-Place vs. Copy-on-Write CEGAR Refinement for Block Summarization with Caching
  Dirk Beyer and Karlheinz Friedberger, ISoLA 2018
  Supplement: https://www.sosy-lab.org/research/bam-cow-refinement/

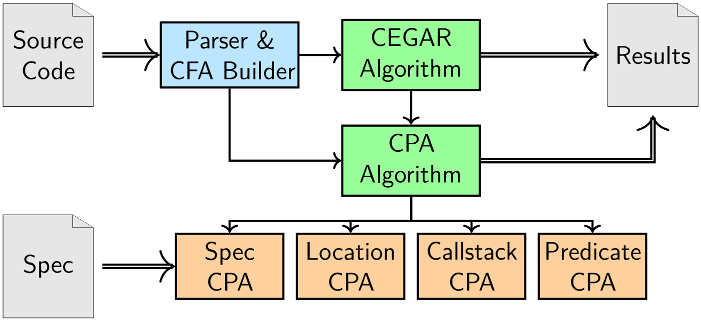
- Domain-Independent Interprocedural Program Analysis using Block-Abstraction Memoization
  Dirk Beyer and Karlheinz Friedberger, FSE 2020
  Reproduction Package: https://doi.org/10.5281/zenodo.4024268

Tools

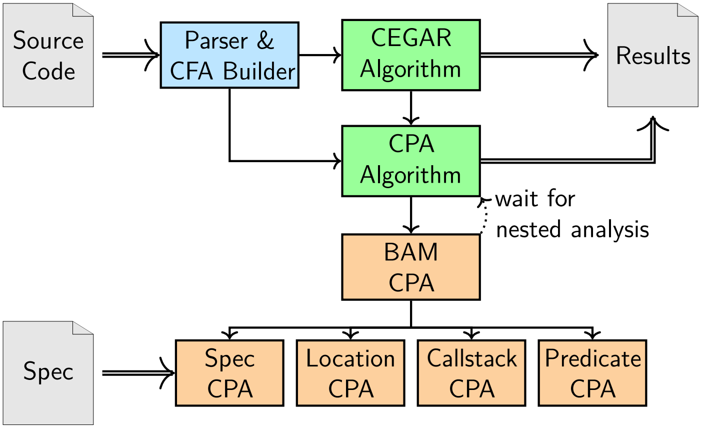
- CPAchecker - The Configurable Software-Verification Platform
  https://cpachecker.sosy-lab.org
- BenchExec - Reliable Benchmarking and Resource Measurement
  https://github.com/sosy-lab/benchexec
- JavaSMT - Unified Java API for SMT Solvers
  https://github.com/sosy-lab/java-smt
- SV-Benchmarks - Collection of Verification Tasks
  https://github.com/sosy-lab/sv-benchmarks

Questions?

CPAchecker Framework



BAM in CPAchecker



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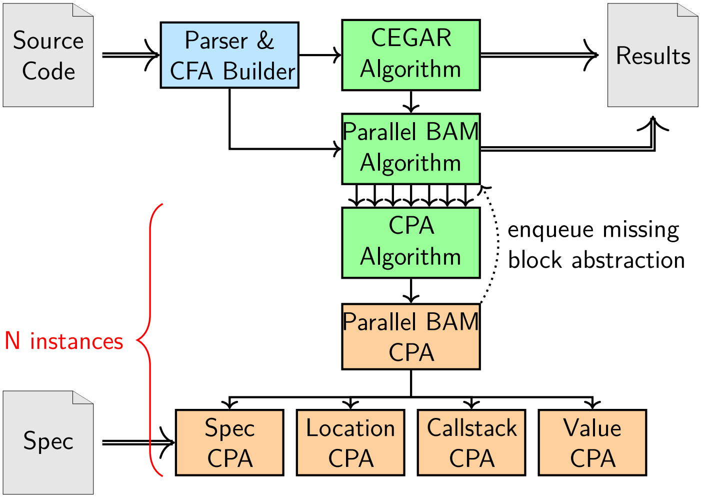
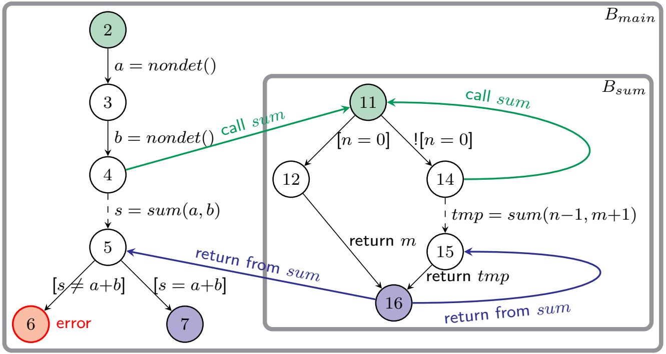


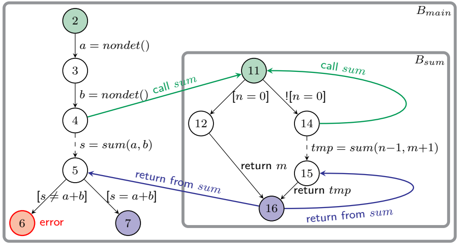
Example of an Analysis

```
void main(void) {
  uint a = nondet();
  uint b = nondet();
  uint s = sum(a, b);
  if (s != a + b) {
    error ();
  }
}

uint sum(uint n, uint m) {
  if (n == 0) {
    return m;
  } else {
    uint tmp = sum(n − 1, m + 1);
    return tmp;
  }
}
```

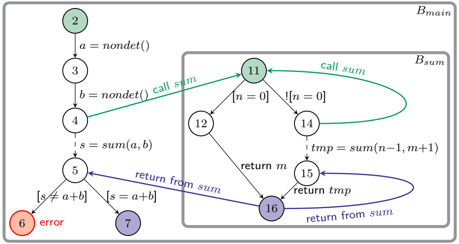


Example of an Analysis

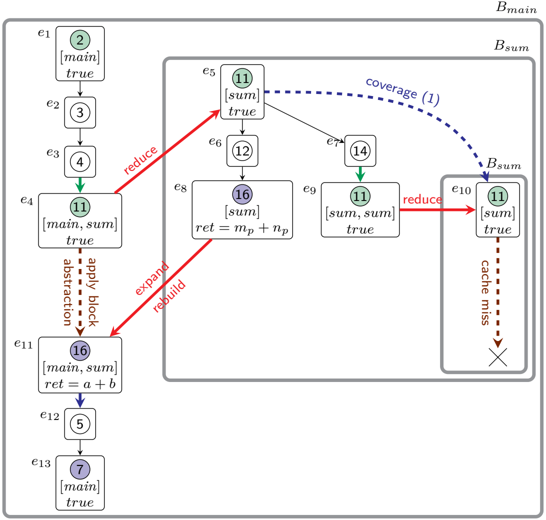


control-flow automaton

Example of an Analysis



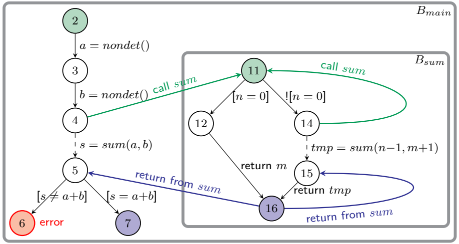
control-flow automaton



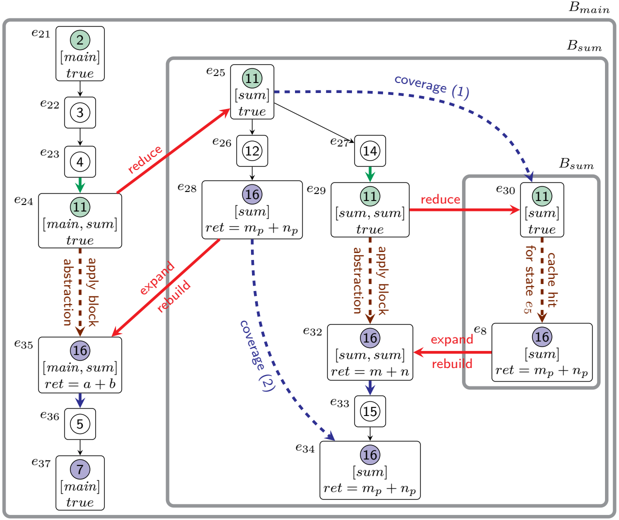
abstract reachability graph

Fixed-point algorithm
(first iteration)

Example of an Analysis



control-flow automaton



abstract reachability graph

Fixed-point algorithm
(second iteration)