Software Verification with CPAchecker

The CPAchecker Team
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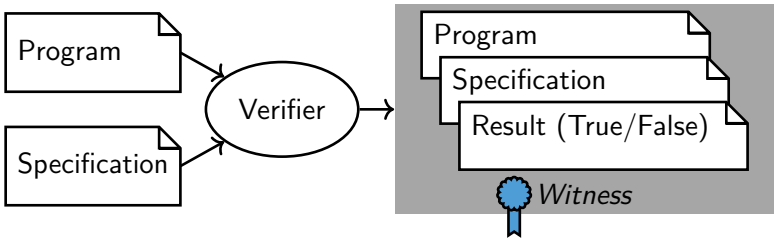
Outline

- Overview of Concepts and Architecture
- Installation and Tutorial Examples
- Overview of the Usage, Inputs, Outputs
- Verification Witnesses

Overview of CPAchecker

Software Verification



CPAchecker History: BLAST

- 2002: BLAST with lazy abstraction refinement [1, 2]
- 2003: Multi-threading support [3]
- 2004: Test-case generation, interpolation, spec. lang. [1, 4]
- 2005: Memory safety, predicated lattices [5, 6]
- 2006: Lazy shape analysis [7]
- Maintenance and extensions became extremely difficult because of design choices that were not easy to revert
- 2007: Configurable program analysis [8, 9], CPAchecker was started as complete reimplementation from scratch [10]

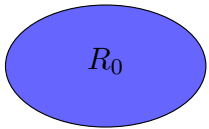
CPAchecker History (2)

- 2009: Large-block encoding [11, FMCAD '09]
- 2010: Adjustable-block encoding [12, FMCAD '10]
- 2012: Conditional model checking [13, FSE '12],
  PredAbs vs. Impact [14, FMCAD '12]
- 2013: Explicit-state MC [15, FASE '13],
  BDDs [16, STTT '14],
  precision reuse [17, FSE '13]
- ...

Software Verification by Model Checking

[18, 19, Clarke/Emerson, Queille/Sifakis 1981]

Iterative fixpoint (forward) post computation



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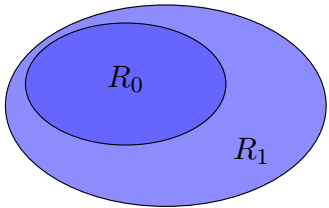

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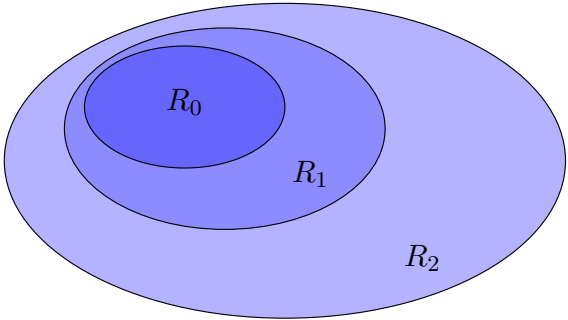

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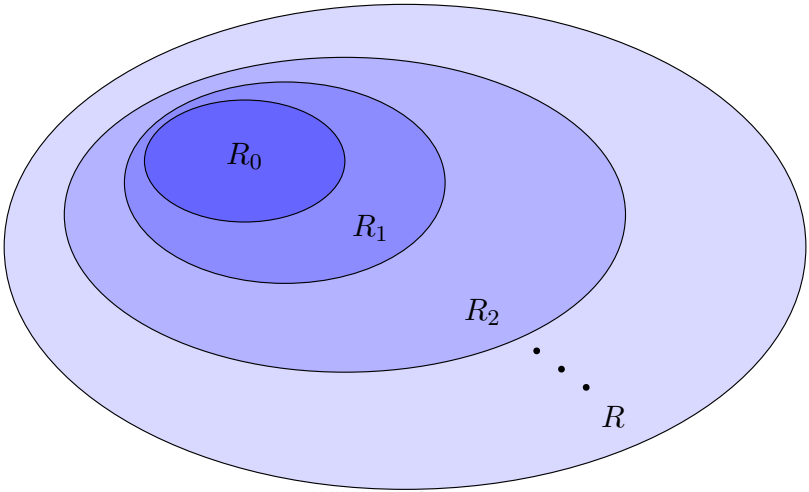
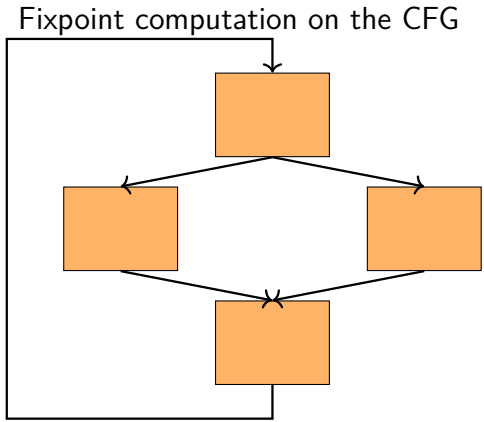


Software Verification by Data-Flow Analysis

[20, Kildall 1973]



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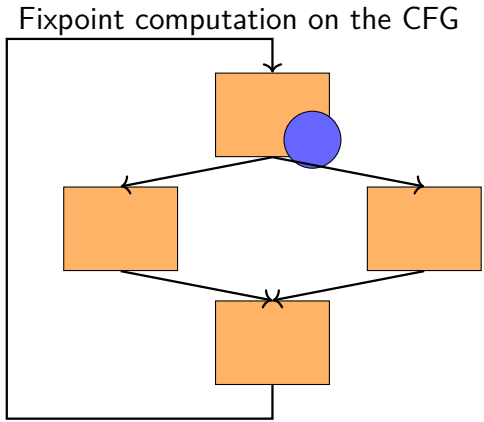

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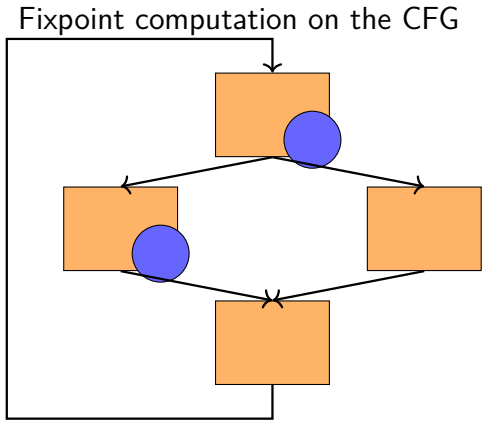

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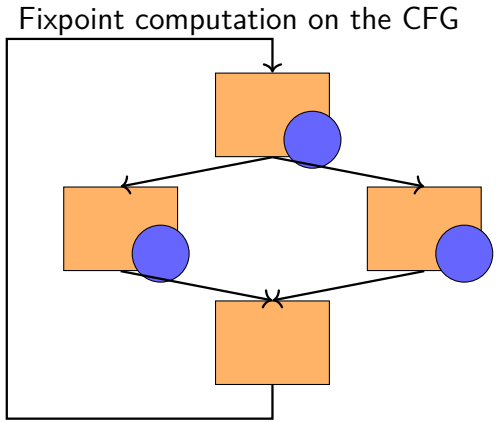

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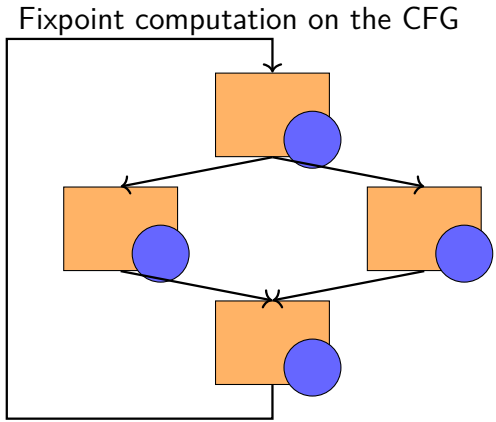

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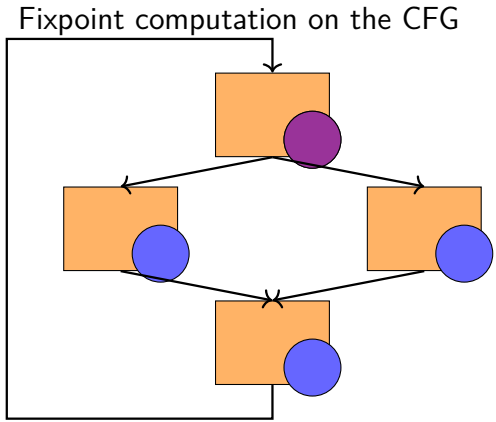

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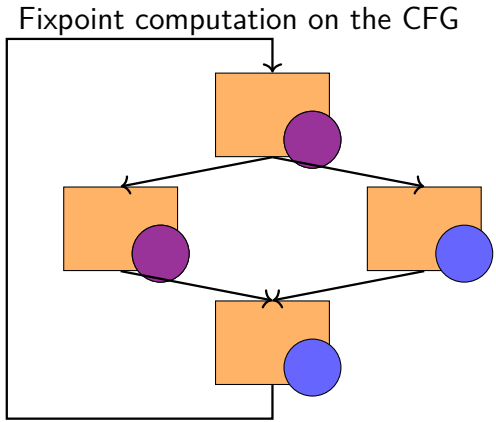

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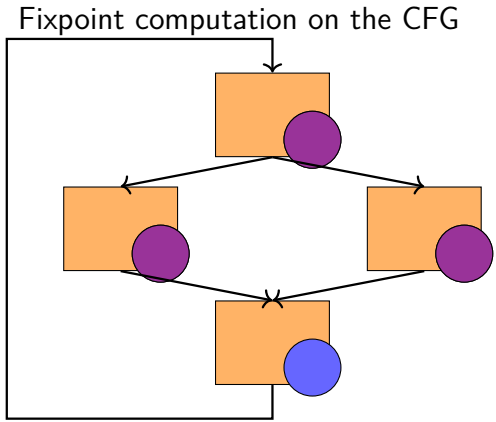

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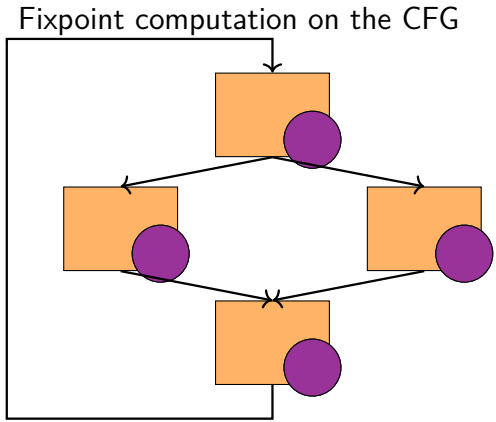
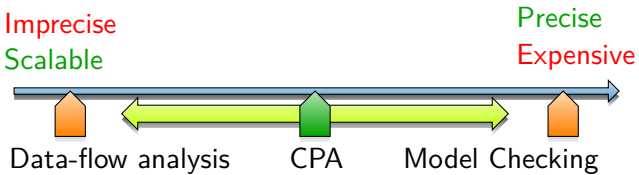


Configurable Program Analysis

[8, Beyer/Henzinger/Theoduloz CAV '07]

- Better combination of abstractions
  → Configurable Program Analysis



Unified framework that enables intermediate algorithms

Dynamic Precision Adjustment

Lazy abstraction refinement: [21, Henzinger/Jhala/Majumdar/Sutre POPL '02]

- Different predicates per location and per path
- Incremental analysis instead of restart from scratch after refinement

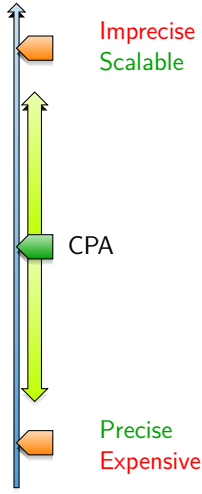
Dynamic Precision Adjustment

Better fine tuning of the precision of abstractions
$\rightarrow$ Adjustable Precision
[9, Beyer/Henzinger/Theoduloz ASE'08]

Unified framework enables:

- switch on and off different analysis, and can
- adjust each analysis separately

- Not only **refine**, also **abstract**!

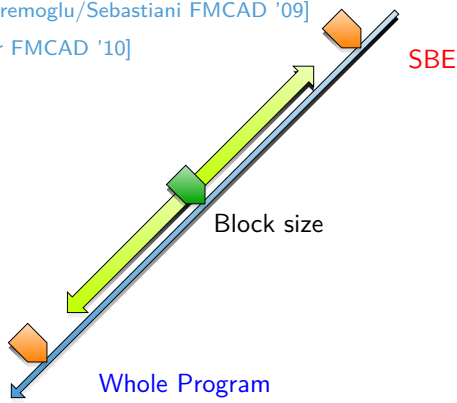


Adjustable Block-Encoding

- Handle loop-free blocks of statements at once
- Abstract only between blocks
  (less abstractions, less refinements)

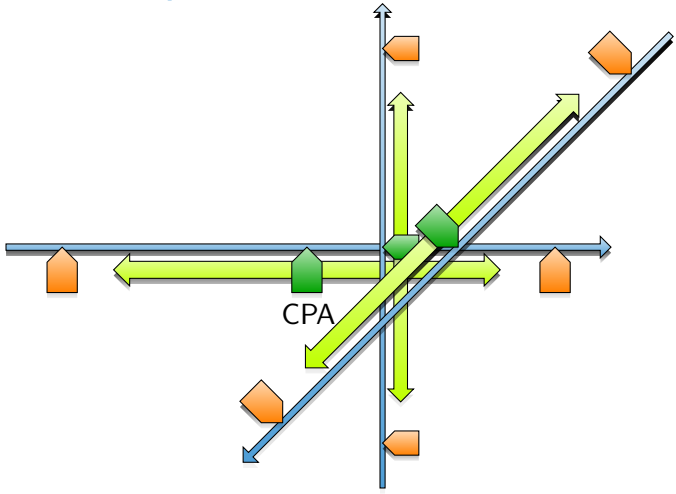
  [11, Beyer/Cimatti/Griggio/Keremoglu/Sebastiani FMCAD '09]

  [12, Beyer/Keremoglu/Wendler FMCAD '10]



CPAchecker

[10, Beyer/Keremoglu CAV '11]



CPA – Summary

- Unification of several approaches
  $\rightarrow$ reduced to their essential properties
- Allow experimentation with new configurations that we could never think of
- Flexible implementation CPAchecker

- Framework for Software Verification — current status
  - Written in Java
  - Open Source: Apache 2.0 License
  - ~131 contributors so far from 15 universities/institutions
  - 572.195 lines of code
    (410.470 without blank lines and comments)
  - Started 2007

https://cpachecker.sosy-lab.org

CPAchecker: Features

- Input language C (experimental: Java)
- Web frontend available:
  `https://vcloud.sosy-lab.org/cpachecker/webclient/run`
- Counterexample output with graphs
- Benchmarking infrastructure available
  (with large cluster of machines)
- Cross-platform: Linux, Mac, Windows

CPAchecker: Achievements

- Among world's best software verifiers:
  https://sv-comp.sosy-lab.org/2021/results/
- Continuous success in competition since 2012
  (66 medals: 19x gold, 22x silver, 25x bronze)
- Awarded Gödel medal
  by Kurt Gödel Society

- Used for Linux driver verification
  with dozens of real bugs found and fixed in Linux [22, 23]

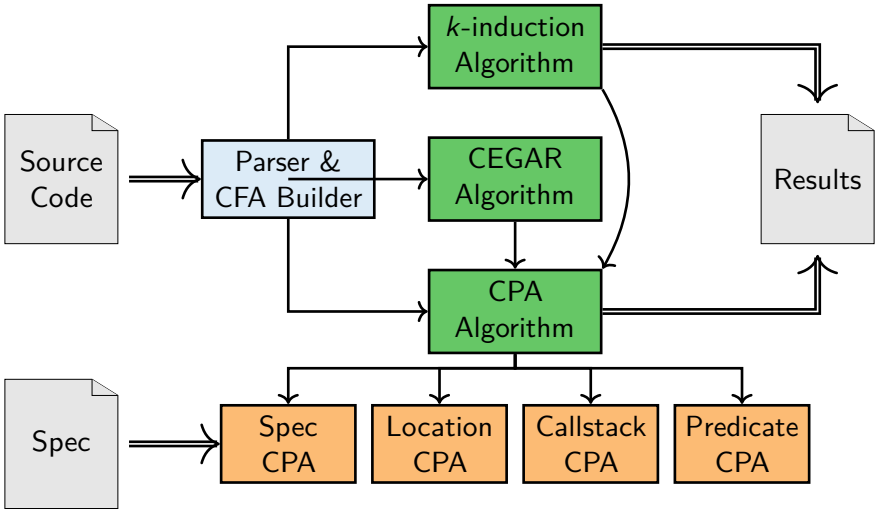
CPAchecker: Concepts

- Included Concepts:
  - CEGAR [24] Interpolation [15, 25]
  - Configurable Program Analysis [8, 9]
  - Adjustable-block encoding [12]
  - Conditional model checking [13]
  - Verification witnesses [26, 27]
  - Various abstract domains: predicates, intervals, BDDs, octagons, explicit values
- Available analyses approaches:
  - Predicate abstraction [11, 12, 9, 17]
  - Impact algorithm [28, 14, 25]
  - Bounded model checking [29, 25]
  - k-Induction [30, 25]
  - IC3/Property-directed reachability [31]
  - Explicit-state model checking [15]
  - Interpolation-based model checking [32]

CPAchecker: Concepts

- Completely modular, and thus flexible and easily extensible
- Every abstract domain is implemented as a "Configurable Program Analysis" (CPA)
- E.g., predicate abstraction, explicit-value analysis, intervals, octagon, BDDs, memory graphs, and more
- Algorithms are central and implemented only once
- Separation of concerns
- Combined with Composite pattern

CPAchecker: Architecture



Getting Started with CPAchecker

Tutorial available at doi:10.1007/978-3-031-71177-0_30

Overview of the First Steps

All the necessary files can be downloaded online.

- We provide multiple ways on how to get CPAchecker:
  - a pre-compiled version from Zenodo,
  - as a docker image,
  - via FM-Weck,
  - installation through `.deb` file,
  - as an online service.
- Please download or copy an artifact with all the examples.
- We will show how to run your first analysis.

Example Verification Task example-safe.c

- Download the examples from:
  https://doi.org/10.5281/zenodo.13612338

```
extern unsigned
    __VERIFIER_nondet_uint();
extern void __assert_fail();
int main() {
  unsigned n =
      __VERIFIER_nondet_uint();
  unsigned x =
      __VERIFIER_nondet_uint();
  unsigned y = n - x;
  while(x > y) {
    x--; y++;
    if (x + y != n) {
      __assert_fail();
    }
  }
  return 0;
}
```

Commands to verify the program:

```
cd <folder of unzipped artifact>
cpachecker ./examples/example-safe.c
```

The expected output:

```
Verification result: TRUE.
No property violation
found by chosen configuration.
More details about the verification
run can be found in the directory "./output".
Graphical representation
included in the file "./output/Report.html".
```

Overview of the Usage, Inputs, Outputs


Program
Specification
Configuration
CPA
Verdict
Report
Tests

Input Program

```
#include<assert.h>




extern int input();



int foo() {
  int a = input();
  int b = input();
  assert(a == b);
}
```

Input Program

```
#include<assert.h>
```
← Must be preprocessed (--preprocess)

```
extern int input();

int foo() {
  int a = input();
  int b = input();
  assert(a == b);
}
```

Input Program

```
extern void __assert_fail (const char *__assertion, const char *__file,
      unsigned int __line, const char *__function)
     __attribute__ ((__nothrow__ , __leaf__)) __attribute__ ((__noreturn__));



extern int input();



int foo() {
  int a = input();
  int b = input();
  if (a != b) __assert_fail(..);
}
```

Input Program

```
extern void __assert_fail (const char *__assertion, const char *__file,
     unsigned int __line, const char *__function)
    __attribute__ ((__nothrow__ , __leaf__)) __attribute__ ((__noreturn__));
```

```
extern int input();
```

← CPAchecker assumes undefined functions to be **pure** (with configurable exceptions)

```
int foo() {
  int a = input();
  int b = input();
  if (a != b) __assert_fail(..);
}
```

Input Program

```
extern void __assert_fail (const char *__assertion, const char *__file,
     unsigned int __line, const char *__function)
    __attribute__ ((__nothrow__ , __leaf__)) __attribute__ ((__noreturn__));

extern int __VERIFIER_nondet_int(); ← New nondet value on each call

int input() {
  return __VERIFIER_nondet_int();    ← Model for input()
}

int foo() {
  int a = input();
  int b = input();
  if (a != b) __assert_fail(..);
}
```


Program
Specification
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CPA
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Demo

Predicate Analyses

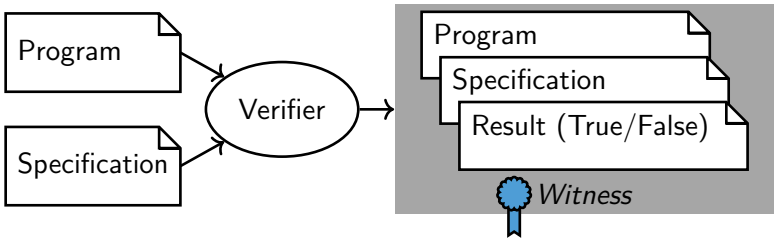
- Many analyses in CPAchecker [25, 32, 33]
  based on predicates and SMT solvers
  (Predicate Abstraction, k-Induction, Interpolation-Based Model Checking, ISMC, DAR, BMC, Impact)
- Symbolic and precise encoding of program semantics
  (bitvectors, floats, dynamic memory; can be configured if necessary)
- Many SMT solvers supported thanks to JavaSMT [34]:
  MathSAT5, Cvc5, SMTInterpol, Princess, z3
- Default solver is MathSAT5 (academic license)
  due to its strength in bitvectors and interpolation

Demo: Predicate Abstraction

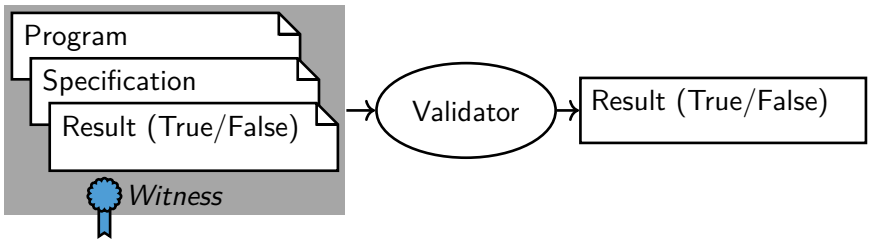
- Example program `example-safe.c`
- Command line:
  `cpachecker --predicateAnalysis examples/example-safe.c`
- Relevant output:
  `expected-outputs/section-4.5-1/output-files/`:
  `Report.html`, `witness-2.0.yml`, `invariants.txt`, `predmap.txt`
- Abstract state 25 in ARG covered by abstract state state 16: fixpoint found
- Invariant visible in witness

Support of Verification Witnesses 2.0

Software Verification



Witness Validation



- Validate untrusted results
- Easier than full verification

Purpose of Witnesses

- Provide insights into the verification process
- Validate verification results
- Enable use of untrusted resources or algorithms
- Exchange information between different tools

Software-Verification Witnesses

Correctness Witnesses:

- Aids in reconstructing the proof
- Contains invariants

Violation Witnesses:

- Aids in replaying a violation
- Represents a set of paths
- At least one is a violation path

Correctness Witnesses 2.0

Concept

- a correctness witness is a list of *invariants* for a given program
- invariants do not have to be inductive
- two *types* of invariants:
  - *loop invariants*: valid before each evaluation of the loop condition
  - *location invariants*: valid before each evaluation of the corresponding statement

Correctness Witnesses 2.0

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Format 2.0

- based on YAML
- supports only C programs
- each invariant has a given *type*, *location*, *value*, and *format* (c_expression)
- *location* = a place in the C program source code
- *value* = a side-effect-free C expression over variables in the current scope

Example

```
1  void reach_error(){}
2  extern unsigned char __nondet_uchar(void);
3  int main() {
4    unsigned char n = __nondet_uchar();
5    if (n == 0) {
6      return 0;
7    }
8    unsigned char v = 0;
9    unsigned int  s = 0;
10   unsigned int  i = 0;
11   while (i < n) {
12     v = __nondet_uchar();
13     s += v;
14     ++i;
15   }
16   if (s < v) {
17     reach_error();
18     return 1;
19   }
20   return 0;
21 }
```

```
- entry_type: invariant_set
  metadata: <...>
  content:
    - invariant:
        type: loop_invariant
        location:
          file_name: "foo.c"
          line: 11
          column: 1
          function: main
        value: "s <= i*255 && 0 <= i && i <= 255"
        format: c_expression
```

Format Support

Support

- many verifiers participating in SV-COMP can produce such witnesses
- these validators can validate such witnesses
  - CPAchecker
  - Goblint
  - LIV
  - MetaVal(++)
  - Mopsa
  - UAutomizer
  - UReferee

Relevant Extensions in Witness Format 2.1

Ghost variables

- to better support concurrent programs
- ghost variables can be both local and global
- definitions and updates of ghost variables associated to program locations (similarly to invariants)
- ghost variables can be used in invariants

Relevant Extensions in Witness Format 2.1

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Function contracts

- another type of invariants
- contract says what the function requires and what it ensures
- uses ACSL expressions

Relevant Extensions in Witness Format 2.1

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Function contracts

- another type of invariants
- contract says what the function requires and what it ensures
- uses ACSL expressions

Transition invariants for termination witnesses

Demo Verification Witnesses

Verification (correct example):

```
cpachecker --predicateAnalysis examples/example-safe.c
```

Validation (with correctness witness):

```
cpachecker --witnessValidation --witness output/witness-2.0.yml
examples/example-safe.c
```

Verification (buggy example):

```
cpachecker --predicateAnalysis examples/example-unsafe.c
```

Latest Development: Distributed Summary Synthesis

Motivation:

- Context: (Automatic) Software Model Checking
- We need low response time.
- Therefore, we need massively parallel approaches.
- Solution: Decomposition into blocks, construct contracts automatically
- Goal: Scalable and Distributed Software Verification

Solution: Distributed Summary Synthesis

Based on [35]:

Dirk Beyer, Matthias Kettl, Thomas Lemberger:

Decomposing Software Verification using Distributed Summary Synthesis

Proc. ACM on Software Engineering, Volume 1, Issue FSE, 2024.
https://doi.org/10.1145/3660766

Overview of Decomposition

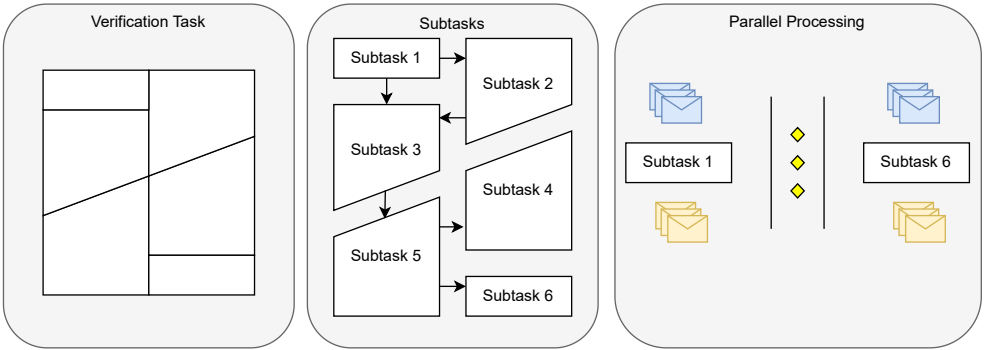


Figure: Overview of the *DSS* approach

Example: Control-Flow Automaton

```
1 int main() {
2   int x = 0;
3   int y = 0;
4   while (n()) {
5     x++;
6     y++;
7   }
8   assert(x == y);
9 }
```

Figure: Safe program

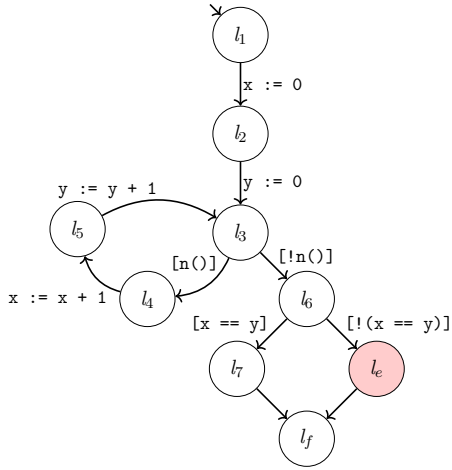


Figure: CFA of program

Decomposition

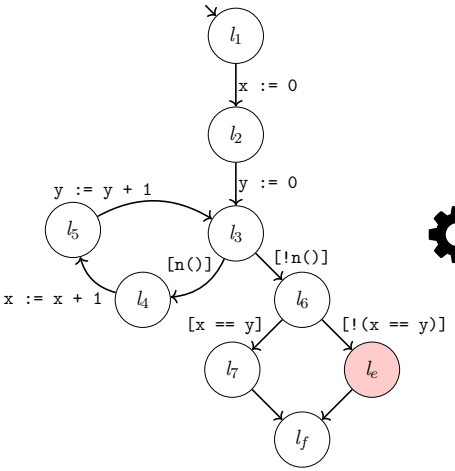
We split a large verification task into multiple smaller subtasks.

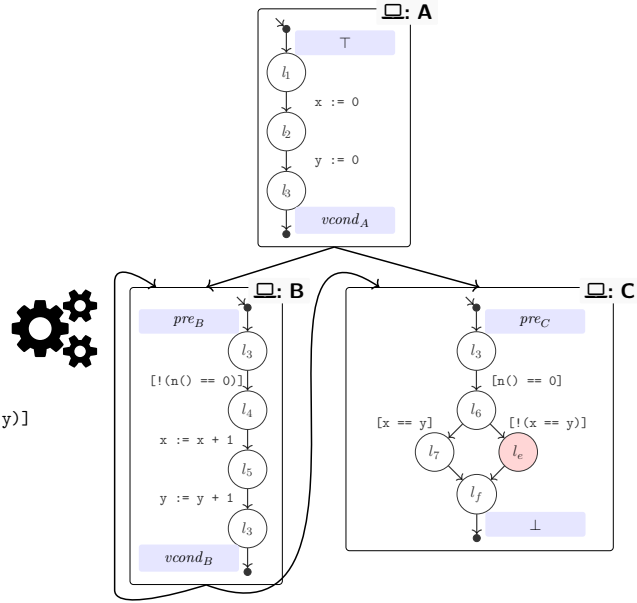
Requirements for eligible decompositions:

- Each block has exactly one entry and one exit location.
- Loops should be reflected as loops in the block graph.
- Blocks should as large as possible.
- Blocks not bound to functions.

Approach: We decompose the CFA similar to large-block encoding [11].

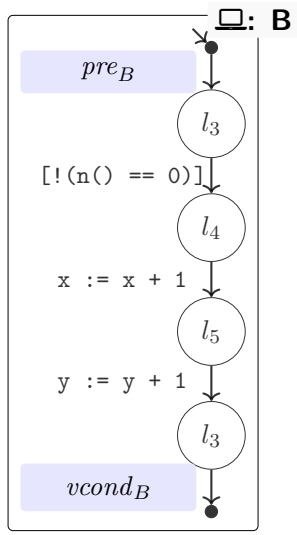
Example: Decomposition





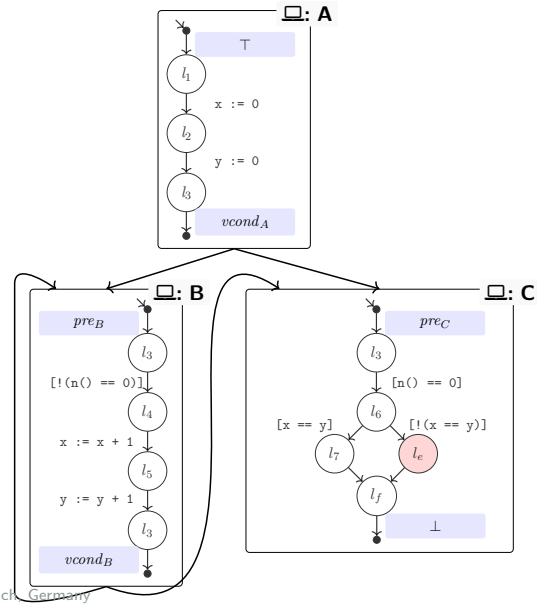
Workers

- Each worker runs independently in an own compute thread/node.
- Preconditions describe good entry states of a block (over-approximating).
- Violation condition needs to be refuted to prove a program safe.
- Preconditions are refined until all violation conditions are refuted or at least one is confirmed.



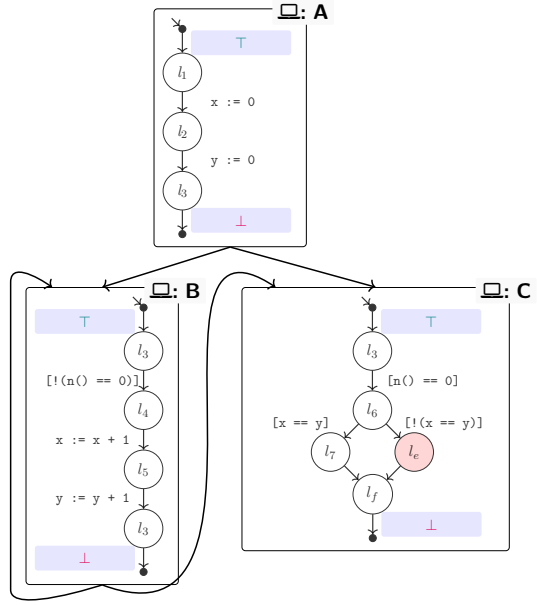
Communication Model

- Workers know their successor and predecessors.
- Workers maintain a list of preconditions, violation conditions, and their subtask.



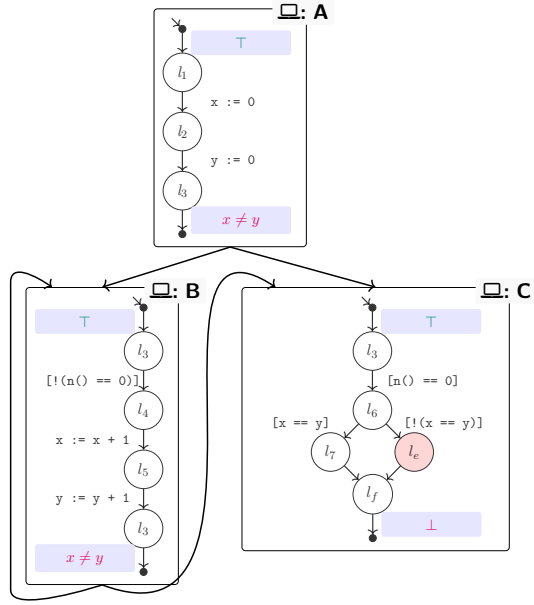
Verification with *DSS* 1

Block	Result
A	$\downarrow\!\boxtimes_{B,C} : \top$
B	$\downarrow\!\boxtimes_{B,C} : \top$
C	$\uparrow\!\boxtimes_{A,B} : x \neq y$



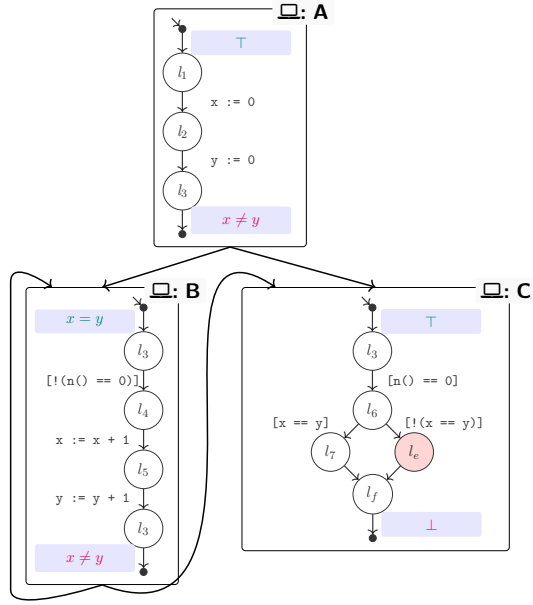
Verification with *DSS* 2

Block	Result
A	$\downarrow\!\boxtimes_{B,C} : x = y$
B	$\uparrow\!\boxtimes_{A,B} : x \neq y$
C	*idle*



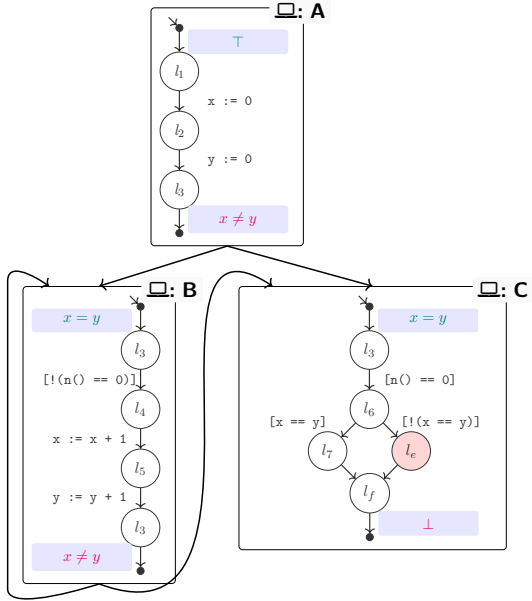
Verification with *DSS* 3

Block	Result
A	$\downarrow\!\boxtimes_{B,C} : x = y$
B	$\downarrow\!\boxtimes_{B,C} : x = y$
C	*idle*



Verification with *DSS* 4

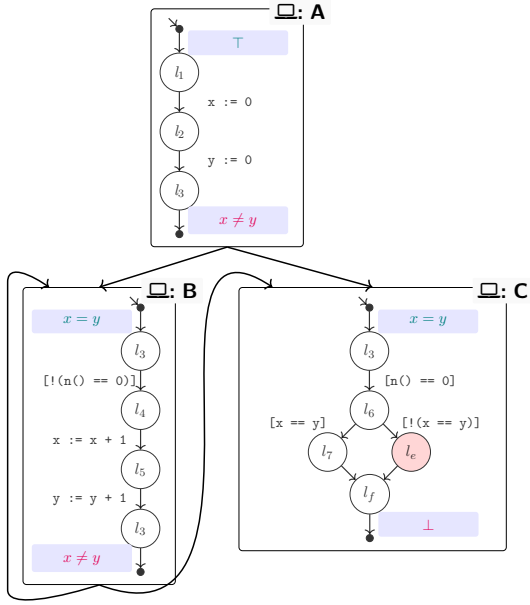
Block	Result
A	*idle*
B	*idle*
C	$\downarrow\!\boxtimes_{\emptyset} : \top$



Verification with *DSS* 5

Block	Result
A	*idle*
B	*idle*
C	*idle*

⇒ Fix-point reached, program safe.



Evaluation: Setup

Benchmark Setup:

- We evaluate *DSS* on the subcategory *SoftwareSystems* of the SV-COMP '23 benchmarks.
- We focus on the 2 485 safe verification tasks.
- We use the SV-COMP [36] benchmark setup:
  15 GB RAM and an 8 core Intel Xeon E3-1230 v5 with 3.40 GHz.

Evaluation: Results

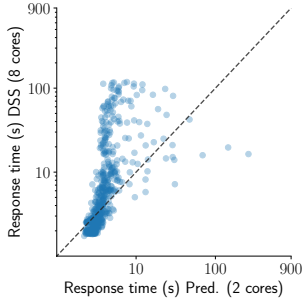


Figure: Response time of predicate abstraction (x-axis) vs. *DSS* (y-axis).

DSS introduces overhead which only pays-off for more complex tasks.
A parallel portfolio combines the best of both worlds.

Evaluation: Distribution of Workload

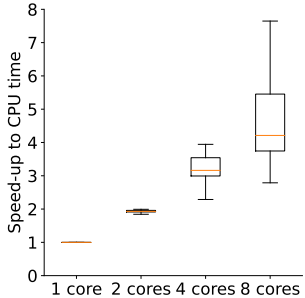


Figure: The ratio of the CPU time and the response time for 1, 2, 4, and 8 cores.

The workload is distributed effectively to multiple processing units.

Evaluation: Outperforming Predicate Analysis

Task	$\text{CPU}_{\mathbb{P}}(s)$	$\text{CPU}_{DSS}(s)$	$\text{RT}_{\mathbb{P}}(s)$	$\mathbf{RT}_{DSS}(s)$	# threads
leds–leds-regulator...	44.8	33.2	30.8	7.18	92
rtc–rtc-ds1553.ko-l...	49.0	64.6	30.3	14.0	164
rtc–rtc-stk17ta8.ko...	46.7	67.9	28.9	15.1	162
watchdog–it8712f_w...	86.8	50.3	69.0	15.9	216
ldv-commit-tester/m0...	50.1	103	28.8	21.0	230

DSS introduces overhead which only pays-off for more complex tasks.
A parallel portfolio combines the best of both worlds.

Related Approaches

Existing approaches have limitations that distributed summary synthesis solves, most importantly the potential to scale to many nodes:

- INFER [37, 38] scales well but reports many false alarms.
  ⇒ *DSS* inherits all properties of the underlying analysis.
- BAM [39] has nested blocks that are not parallelizable.
  ⇒ *DSS* parallelizes as much as possible.
- HIFROG [40] is bound to SMT-based model-checking algorithms.
  ⇒ *DSS* is domain-independent.

Conclusion DSS

- *DSS* can decompose a verification task into independent smaller tasks.
- *DSS* is domain-independent.
- *DSS* effectively distributes the workload to multiple processing units.

Supplementary webpage

Conclusion CPAchecker

CPAchecker has

- many features, abstract domains, algorithms
- replicated most important algorithms for SV
- contribute new concepts and algorithms
- long-living software eco-system
- good results in yearly evaluations at SV-COMP

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