# Current Trends in CPAchecker

Dirk Beyer
LMU Munich, Germany

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LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

SoSy-Lab Software Systems

# What is going on?

- Implement more and more approaches in CPAchecker
- Make them available as a configuration of CPAchecker
- Reusable components from CPAchecker independently
- Combination approaches

# CPAchecker [21] Offers a Lot!

- Included Concepts:
  - CEGAR [27] Interpolation [24, 12]
  - Configurable Program Analysis [16, 17]
  - Adjustable-block encoding [22]
  - Conditional model checking [15]
  - Verification witnesses [10, 9]
  - Various abstract domains: predicates, intervals, BDDs, octagons, explicit values
- Available analyses approaches:
  - Predicate abstraction [7, 22, 17, 25]
  - Impact algorithm [40, 26, 12]
  - Bounded model checking [29, 12]
  - k-Induction [11, 12]
  - IC3/Property-directed reachability [8]
  - Explicit-state model checking [24]
  - Interpolation-based model checking [23]

# Competitions in Software Verification

CPAchecker should win SV-COMP. ;-)

# Different Techniques

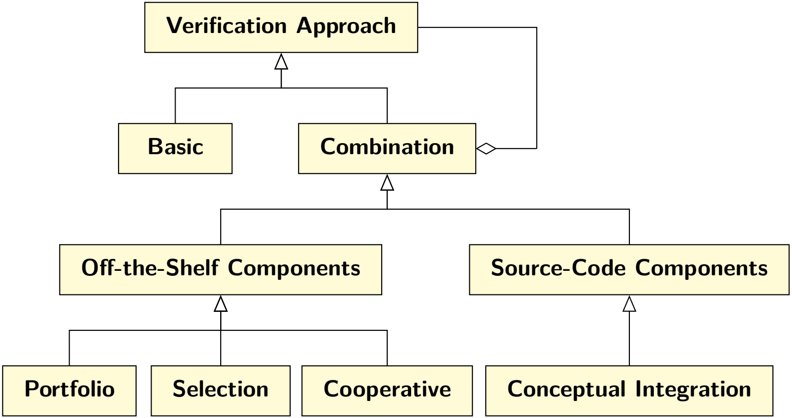
| Participant | CEGAR | Predicate Abstraction | Symbolic Execution | Bounded Model Checking | k-Induction | Property-Directed Reach. | Explicit-Value Analysis | Numeric. Interval Analysis | Shape Analysis | Separation Logic | Bit-Precise Analysis | ARG-Based Analysis | Lazy Abstraction | Interpolation | Automata-Based Analysis | Concurrency Support | Ranking Functions | Evolutionary Algorithms |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2LS | | | | ✓ | ✓ | | | ✓ | | | ✓ | | | | | | ✓ | |
| AProVE | | | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | | | | | | ✓ | |
| CBMC | | | | ✓ | | | | | | | ✓ | | | | | ✓ | | |
| CBMC-Path | | | | ✓ | | | | | | | ✓ | | | | | ✓ | | |
| CPA-BAM-BnB | ✓ | ✓ | | | | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | | | | |
| CPA-Lockator | ✓ | ✓ | | | | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | |
| CPA-Seq | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| DepthK | | | | ✓ | ✓ | | | | | | ✓ | | | | | ✓ | | |
| DIVINE-explicit | | | | | | | ✓ | | | | ✓ | | | | | ✓ | | |
| DIVINE-SMT | | | | | | | ✓ | | | | ✓ | | | | | ✓ | | |
| ESBMC-kind | | | | ✓ | ✓ | | | | | | ✓ | | | | | ✓ | | |
| JayHorn | ✓ | ✓ | | | | ✓ | | ✓ | | | | | ✓ | ✓ | | | | |
| JBMC | | | | ✓ | | | | | | | ✓ | | | | | ✓ | | |
| JPF | | | | ✓ | | | ✓ | ✓ | | | ✓ | | | | | ✓ | | |
| Lazy-CSeq | | | | ✓ | | | | | | | ✓ | | | | | ✓ | | |
| Map2Check | | | | ✓ | | | | | | | ✓ | | | | | | | |
| PeSCo | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| Pinaka | | | ✓ | ✓ | | | | | | | ✓ | | | | | | | |
| PredatorHP | | | | | | | | | ✓ | | | | | | | | | |
| Skink | ✓ | | | | | | ✓ | | | | | | | ✓ | ✓ | | | |
| Smack | ✓ | | | ✓ | | ✓ | | | | | ✓ | | ✓ | | | ✓ | | |
| SPF | | | ✓ | | | | | | ✓ | | | | | | | ✓ | | |
| Symbiotic | | | ✓ | | | | | ✓ | | | ✓ | | | | | | | |
| UAutomizer | ✓ | ✓ | | | | | | | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | |
| UKojak | ✓ | ✓ | | | | | | | | | ✓ | | ✓ | ✓ | | | | |
| UTaipan | ✓ | ✓ | | | | | | | | | ✓ | | ✓ | ✓ | ✓ | | | |
| VeriAbs | ✓ | | | ✓ | ✓ | | ✓ | ✓ | | | | | | | | | | |
| VeriFuzz | | | | ✓ | | | | ✓ | | | | | | | | | | ✓ |
| VIAP | | | | | | | | | | | | | | | | | | |
| Yogar-CBMC | ✓ | | | ✓ | | | | | | | ✓ | | ✓ | | | ✓ | | |
| Yogar-CBMC-Par. | ✓ | | | ✓ | | | | | | | ✓ | | ✓ | | | ✓ | | |

Competition Report [5]
https://doi.org/10.1007/978-3-030-17502-3_9

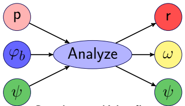
# CPAchecker as Component

- Make CPAchecker usable like a library
- Small tools perspective (Unix philosophy)
- Construct combinations
- More interfaces
  via, e.g., Conditions, Witnesses, Test Suites
- See also: Little Engines [41], Evidential Tool Bus [33]

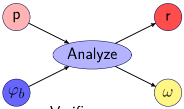
# Approaches for Combinations



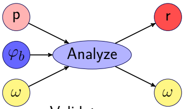
# Graphical Visualization of the Coop Framework



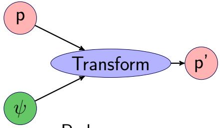
Conditional Verifier



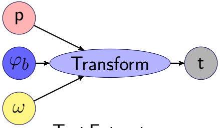
Verifier



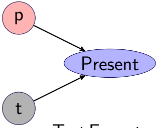
Validator



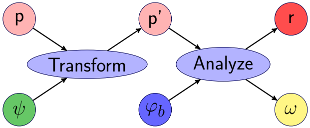
Reducer



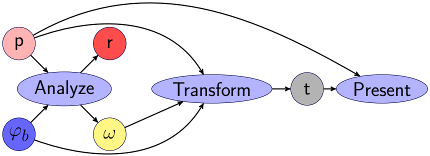
Test Extractor



Test Executor



Conditional Verifier constructed from Reducer and Verifier



Execution-Based Validation constructed from Verifier, Test Extractor, and Test Executor

# Definition of Cooperative Verification

An approach is called **cooperative verification**, if

- identifiable *actors* pass information in form of
- identifiable *artifacts* towards the common objective of
- solving a *verification* problem,

where at least two of these actors are *analyzers*.

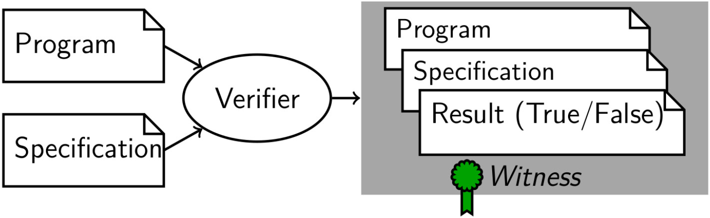
# Definition of Cooperative Verification

Examples for notions:

- Identifiable actor:
  off-the-shelf components, binaries, agents, web services
- Identifiable artifacts:
  programs, witnesses, ARGs, test suites
- Verification problem:
  verification task, test task, feasibility check, refinement

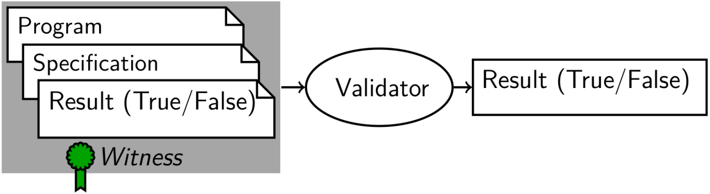
# Software Verification with Witnesses

Witnesses are an important interface between tools.




[10, Proc. FSE 2015] [9, Proc. FSE 2016]

# Witness Validation




- Validate untrusted results
- Easier than full verification

# Example Combination (in DSL CoVeriTeam)

CoVeriTeam: Language and Tool [19, Proc. TACAS 2022]

**Algorithm 1** Witness Validation [10, 9]

**Input:** Program p, Specification s

**Output:** Verdict

```
verifier := Verifier("Ultimate Automizer")
validator := Validator("CPAchecker")
result := verifier.verify(p, s)
if result.verdict ∈ {TRUE, FALSE} then
    result = validator.validate (p, s, result.witness)
return (result.verdict, result.witness)
```

# Simple Combination without Cooperation

Often, even simple combinations help!

Portfolio construction using off-the-shelf verification tools [20, Proc. FASE 2022]

Consider AWS category (177 tasks) in SV-COMP 2022:
CBMC: 69 (8 wrong)
CoVeriTeam-Parallel-Portfolio: 147 (3 wrong)
(improvement did not require any change in a verification tool)

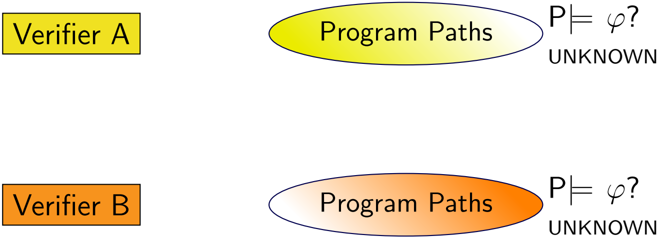
With Nian-Ze Lee and Po-Chun Chien:

- inject invariants (in k-induction, IMC, ISMC)
- parallel portfolio

A lot of improvements are (trivially) possible.

# Facing Hard Verification Tasks

Given: Program P$\models \varphi$?



# Facing Hard Verification Tasks

Given: Program P$\models \varphi$?

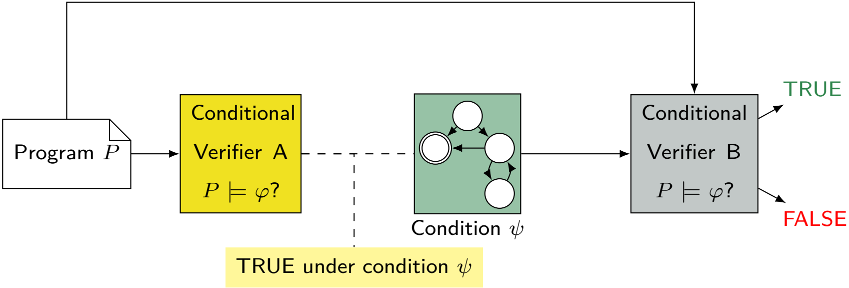
Verifier A — Program Paths — P$\models \varphi$? UNKNOWN

Verifier B — Program Paths — P$\models \varphi$? UNKNOWN

Verifier A + Verifier B — Program Paths — P$\models \varphi$ ✓

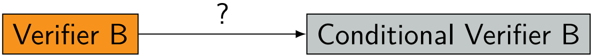
e.g., conditional model checking

# Conditional Model Checking



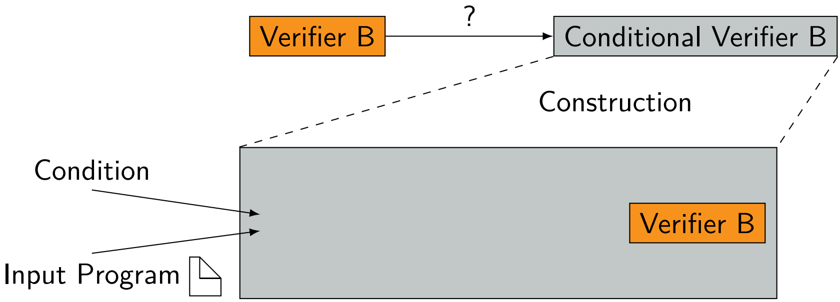

Proc. FSE 2012 [15]

# Reducer-Based Construction



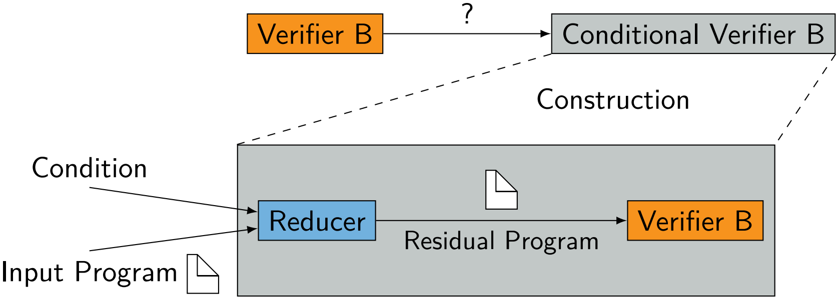

Proc. ICSE 2018 [18]

# Reducer-Based Construction




Proc. ICSE 2018 [18]

# Reducer-Based Construction

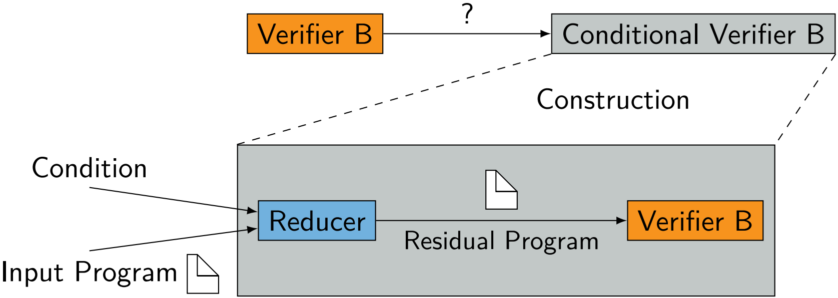



Reducer (preprocessor)

- Builds standard input (C program)
- Representing a subset of paths
- Contains at least all non-verified paths

Proc. ICSE 2018 [18]

# Reducer-Based Construction



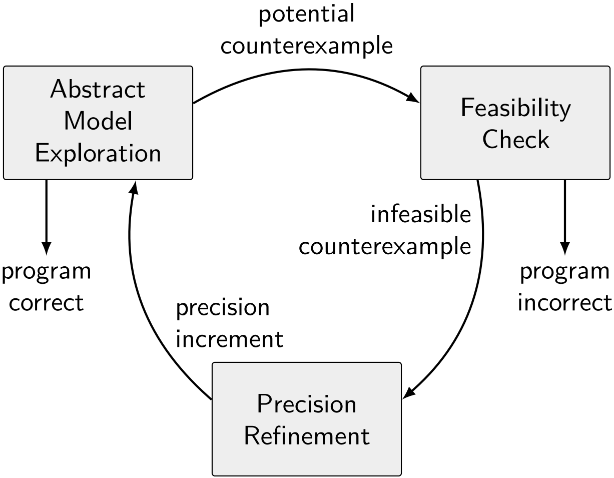

Reducer (preprocessor)

- Builds standard input (C program)
- Representing a subset of paths
- Contains at least all non-verified paths

+ Verifier-unspecific approach
+ Many conditional verifiers possible

Proc. ICSE 2018 [18]

# CEGAR

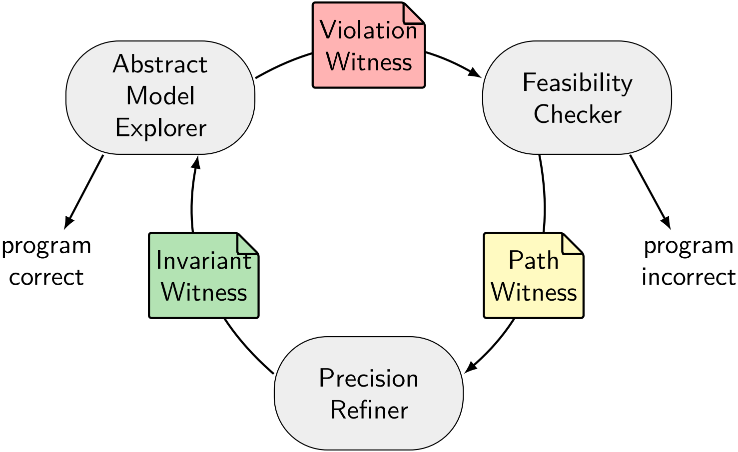

potential
counterexample
Abstract
Model
Exploration
Feasibility
Check
infeasible
counterexample
program
correct
program
incorrect
precision
increment
Precision
Refinement

# Modularization of CEGAR

- CEGARdefines I/O interfaces
- But instances not exchangeable
- Aim: generalize CEGAR, allow exchange of components

$\Rightarrow$ Modular reformulation

# Workflow of modular CEGAR




Proc. ICSE 2022 [13]

# Interactive and Automatic Methods

- How to achieve cooperation between automatic and interactive verifiers?
- Idea: Try to use existing interfaces for information exchange

```
//@ensures \return==0;
int main() {
  unsigned int x = 0;
  unsigned int y = 0;
  //@loop invariant x==y;
  while (nondet_int()) {
    x++;
    //@assert x==y+1;
    y++;
  }
  assert(x==y);
  return 0;
}
```

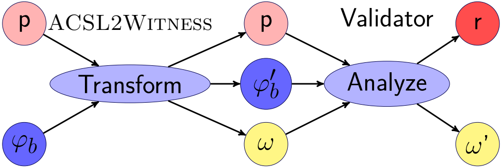
ACSL-annotated program, as used by FRAMA-C

```
...
<node id="q1">
<data key="invariant">( y == x )</data>
<data key="invariant.scope">main</data>
</node>
<edge source="q0" target="q1">
<data key="enterLoopHead">true</data>
<data key="startline">6</data>
<data key="endline">6</data>
<data key="startoffset">157</data>
<data key="endoffset">165</data>
</edge>
...
```

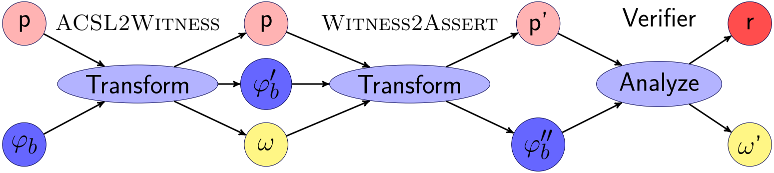
GraphML-based witness automaton generated by automatic verifiers

# From Components: Construct Interactive Verifiers

- Turn a witness validator into an interactive verifier:



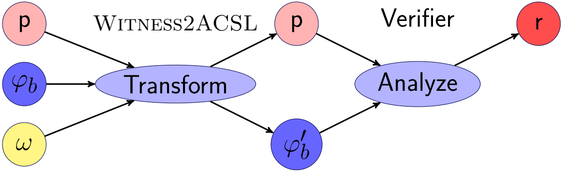

- Turn an automatic verifier into an interactive verifier::



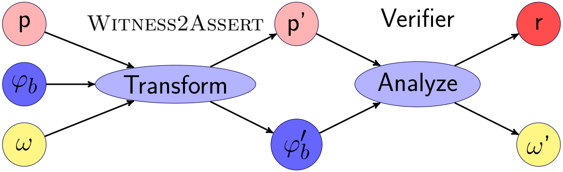

- Annotating in ACSL is more human-readable than witness automata
- Works for a wide range of automatic verifiers/validators

# Component Framework: Constructing Validators

- Turn an interactive verifier (Frama-C) into a validator:

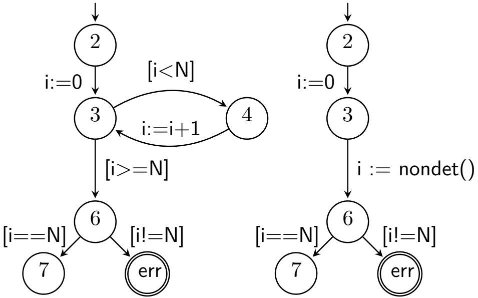



- Turn an automatic verifier into a validator:



# Loop Abstraction

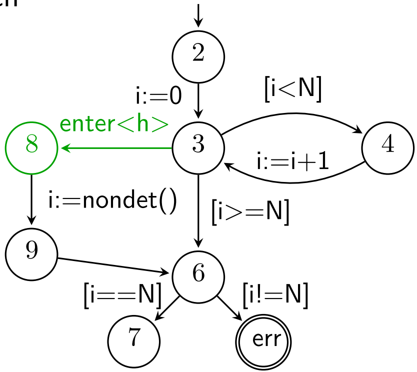
```
void main() {
  int i = 0;
  while (i<N) {
    i=i+1;
  }
  assert (i==N);
}
```




- Instead of a precise acceleration, we can also apply an overapproximating *abstraction*
- Here we just havoc all variables that are modified in the loop, but more elaborate abstraction strategies exist

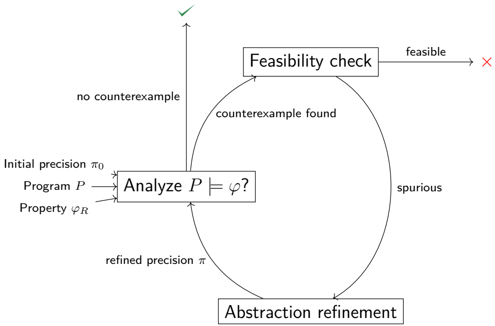
# Configurable Solution a la CPAchecker

- Use the CFA as interface
- Add our loop abstractions next to the original loop
- Mark the entry nodes of each added alternative with an identifier for the applied strategy: $\sigma : L \rightarrow S$
- In the example:
  $S = \{b, h\}$
  $\sigma(8) = h$
  $\sigma(l) = b$ for
  $l \in \{2, 3, 4, 6, 7, err, 9\}$
- Select allowed strategies during state-space exploration using $\sigma$



# CEGAR: Feasibility of Counterexamples

- In general, CEGAR works as shown on the right
- For our approach, we need to rethink what it means if a counterexample is feasible:
  Even if the path formula is satisfiable, the counterexample is only feasible if there are no over-approximating strategies used along the path!



# Accessibility of Loop Abstractions via Patches

- We provide loop abstractions as patches
- We also output a the abstracted version of the program in case we found a proof
- Can be used independently by other tools
- Does this work in practice?
  ⇒ Experiments

```
--- havoc.c
+++ havoc.c
-14,13 +14,16
    return ;
 }

 int main(void) {
   unsigned int x = 1000000;
- while (x > 0) {
- x -= 4;
+ // START HAVOCSTRATEGY
+ if (x > 0) {
+ x = __VERIFIER_nondet_uint();
   }
+ if (x > 0) abort();
+ // END HAVOCSTRATEGY
   __VERIFIER_assert(!(x % 4));
```

# Conclusion

- External combinations
- Interfaces
- Combinations and Cooperation

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