Cooperative Verification: Towards Reliable Safety-Critical Systems

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LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

SoSy-Lab Software Systems

Automatic Software Verification

C Program

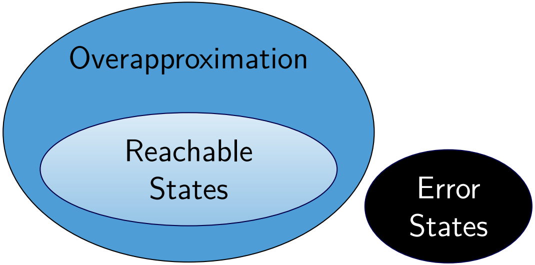
```c
int main() {
   int a = foo();
   int b = bar(a);

   assert(a == b);
}
```

Verification Tool

TRUE+witness
i.e., specification is satisfied

FALSE+witness
i.e., bug found

General method:
Create an overapproximation of the program states /
compute program invariants



Status on Verifiers

- From lack of verifiers to plentitude

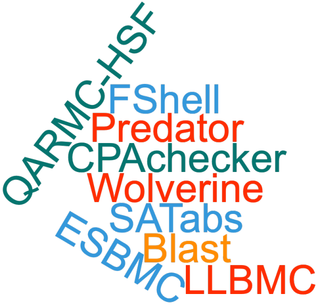
Competitions in Software Verification and Testing

Mature research area, and there are tool competitions:

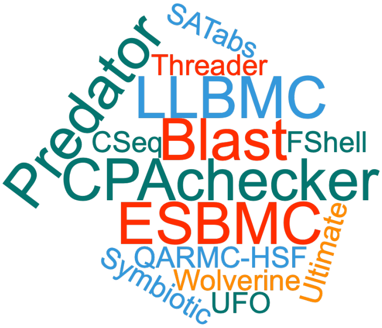
- RERS: off-site, tools, free-style [30]
- SV-COMP: off-site, automatic tools, controlled [1]
- Test-Comp: off-site, automatic tools, controlled [3]
- VerifyThis: on-site, interactive, teams [31]

(alphabetic order)

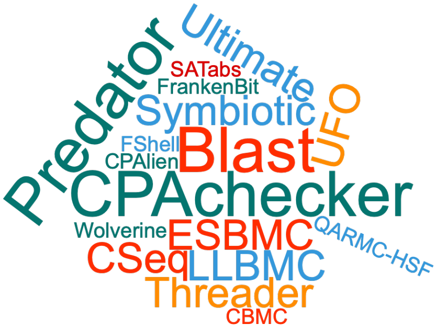
SV-COMP (Automatic Tools 2012)



SV-COMP (Automatic Tools 2013, cumulative)

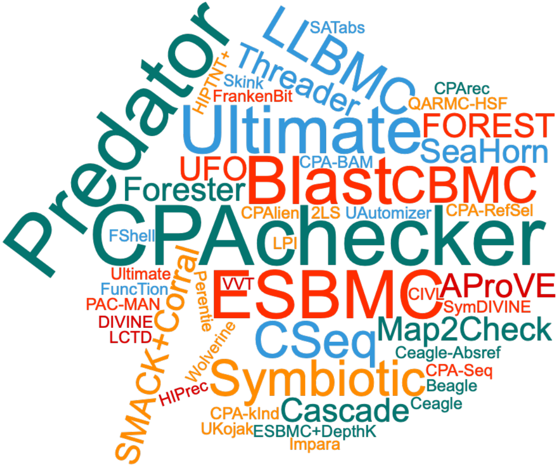


SV-COMP (Automatic Tools 2014, cumulative)

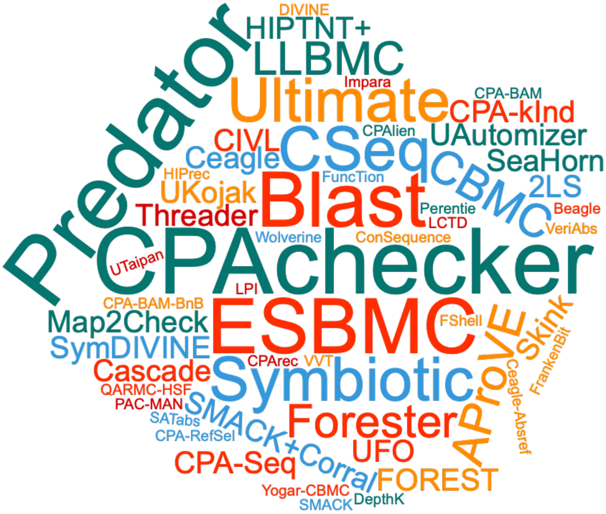


SV-COMP (Automatic Tools 2015, cumulative)

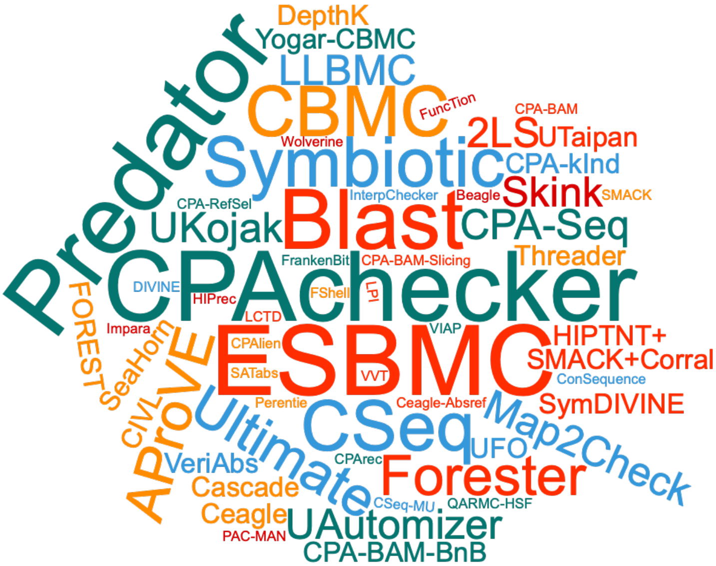
SV-COMP (Automatic Tools 2016, cumulative)



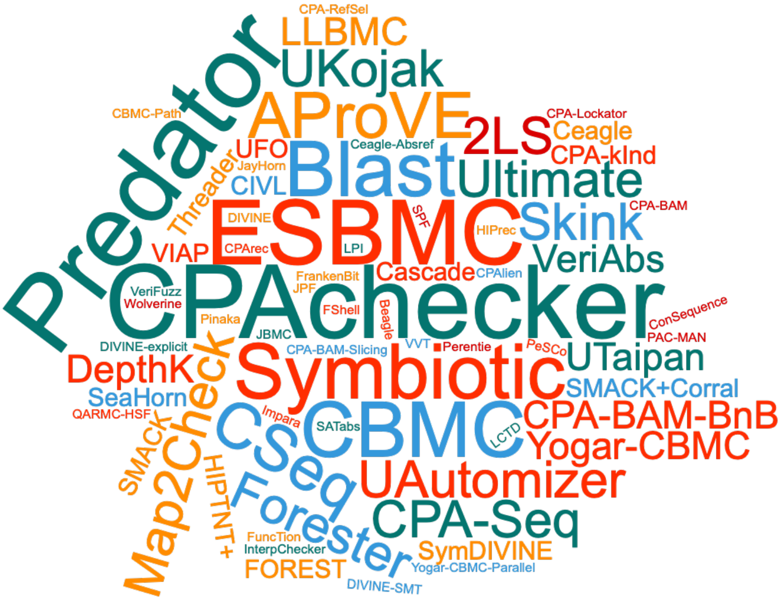
SV-COMP (Automatic Tools 2017, cumulative)



SV-COMP (Automatic Tools 2018, cumulative)

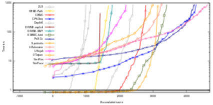


SV-COMP (Automatic Tools 2019, cumulative)

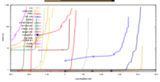


Different Strengths

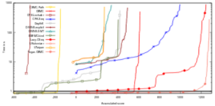
ReachSafety
1. VeriAbs
2. CPA-Seq
3. PeSCo



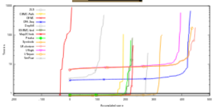
MemSafety
1. Symbiotic
2. PredatorHP
3. CPA-Seq



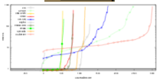
ConcurrencySafety
1. Yogar-CBMC
2. Lazy-CSeq
3. CPA-Seq



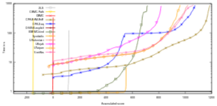
NoOverflows
1. UAutomizer
2. UTaipan
3. CPA-Seq



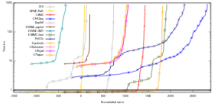
Termination
1. UAutomizer
2. AProVE
3. CPA-Seq



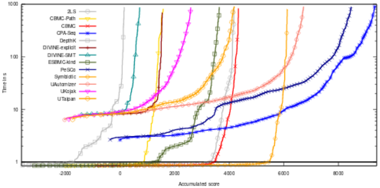
SoftwareSystems
1. CPA-BAM-BnB
2. CPA-Seq
3. VeriAbs



FalsificationOverall
1. CPA-Seq
2. PeSCo
3. ESBMC-kind



Overall
1. CPA-Seq
2. PeSCo
3. UAutomizer



https://sv-comp.sosy-lab.org/2019/results

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 [2]
https://doi.org/10.1007/978-3-030-17502-3_9

Example CPAchecker [18]: Many Concepts

- Included Concepts:
  - CEGAR [27]   Interpolation [21, 10]
  - Configurable Program Analysis [13, 14]
  - Adjustable-block encoding [19]
  - Conditional model checking [12]
  - Verification witnesses [8, 6]
  - Various abstract domains: predicates, intervals, BDDs, octagons, explicit values
- Available analyses approaches:
  - Predicate abstraction [4, 19, 14, 22]
  - Impact algorithm [32, 26, 10]
  - Bounded model checking [28, 10]
  - k-Induction [9, 10]
  - IC3/Property-directed reachability [5]
  - Explicit-state model checking [21]
  - Interpolation-based model checking [20]

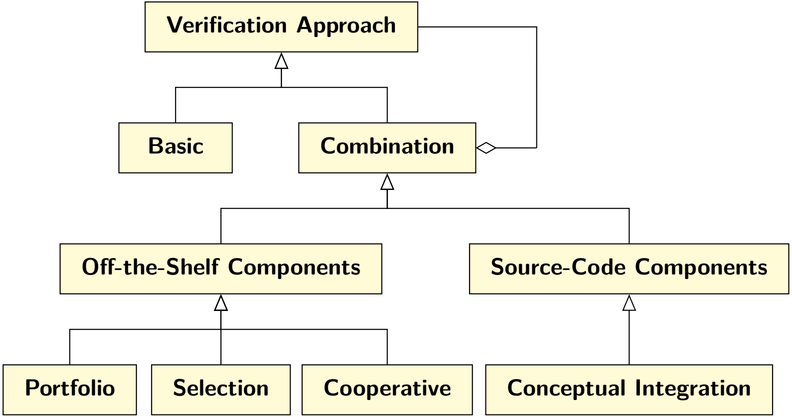
Insights from Software Model Checking

- Verifiers have different strengths
- There are plenty of tools
- $\Rightarrow$ Cooperative Verification Approaches

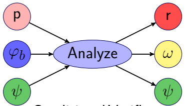
Cooperative Verification — Think big!

- Introduce a new level!
- Current tools are "low level" components (engines)
- Construct combinations
- Clear Interfaces
  via, e.g., Conditions, Witnesses, Test Suites
- Success: SAT, SMT
- See also: Little Engines [33], Evidential Tool Bus [29]

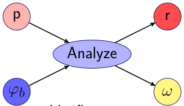
Approaches for Combinations



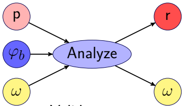
Graphical Visualization of the Coop Framework



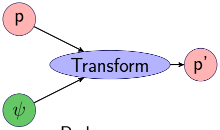
Conditional Verifier



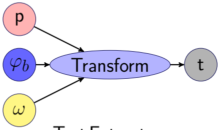
Verifier



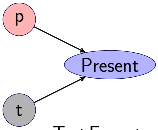
Validator



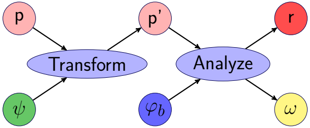
Reducer



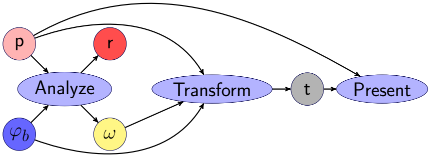
Test Extractor



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*.

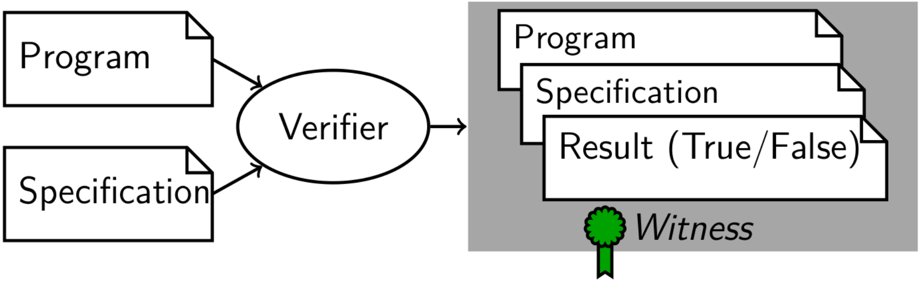
Definition of Cooperative Verification

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

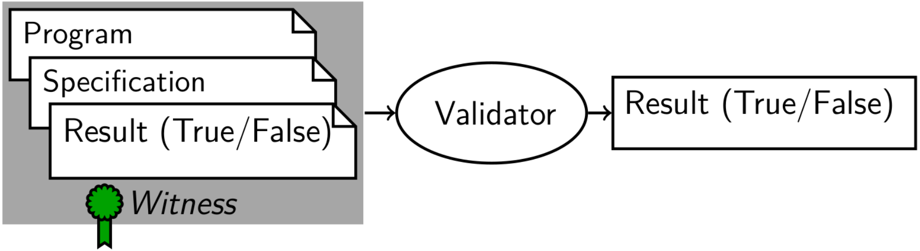
(A1) Software Verification with Witnesses

Witnesses are an important interface between tools.



[8, Proc. FSE 2015] [6, Proc. FSE 2016] [7, TOSEM 2022]

(A1) Witness Validation



- Validate untrusted results
- Easier than full verification

(A2) Example Combination (in DSL CoVeriTeam)

CoVeriTeam: Language and Tool [16, Proc. TACAS 2022]

Algorithm 1 Witness Validation [8, 6]

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)
```

(A3) Simple Combination without Cooperation

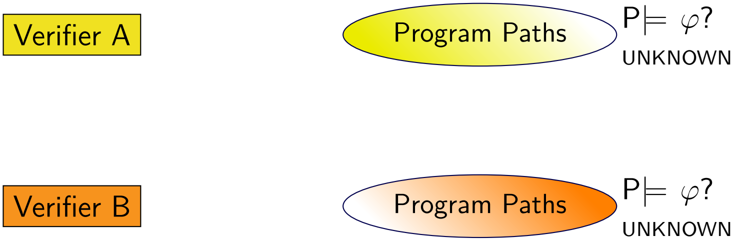
Often, even simple combinations help!

Portfolio construction using off-the-shelf
verification tools [17, 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)

(A4) Facing Hard Verification Tasks

Given: Program P$\models \varphi$?



(A4) Facing Hard Verification Tasks

Given: Program $P \models \varphi$?

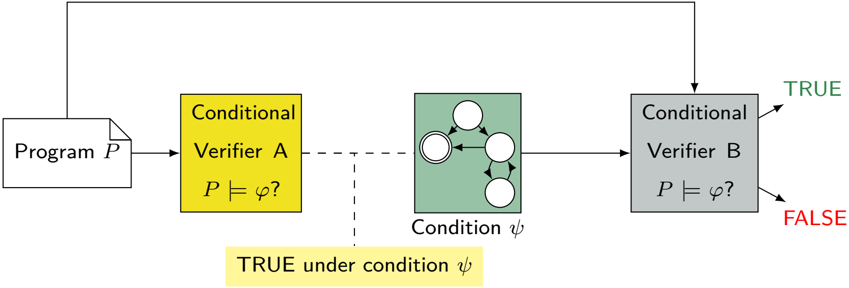
Verifier A — Program Paths — $P \models \varphi$? UNKNOWN

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

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

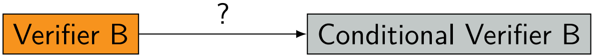
e.g., conditional model checking

(A4) Conditional Model Checking



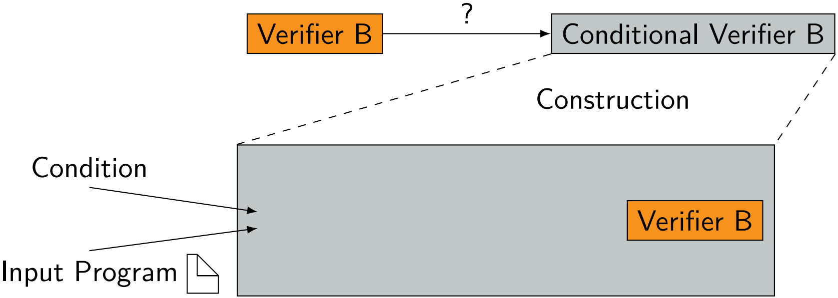
Proc. FSE 2012 [12]

(A4) Reducer-Based Construction



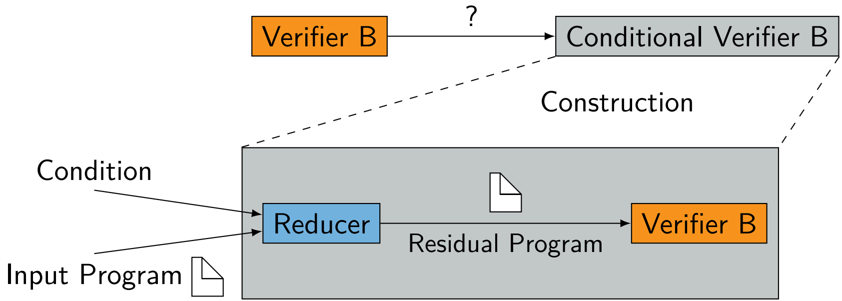
Proc. ICSE 2018 [15]

(A4) Reducer-Based Construction



Proc. ICSE 2018 [15]

(A4) Reducer-Based Construction

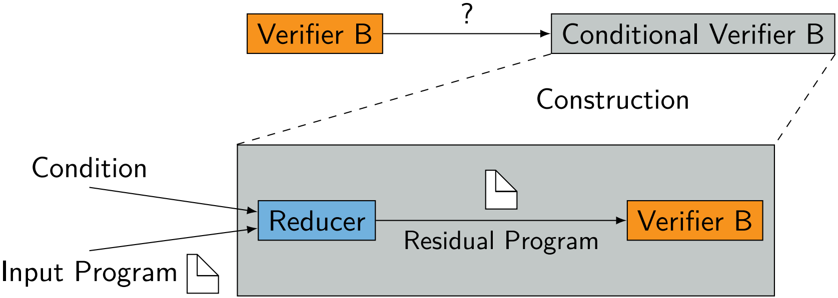


Reducer (preprocessor)

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

Proc. ICSE 2018 [15]

(A4) Reducer-Based Construction



Reducer (preprocessor)

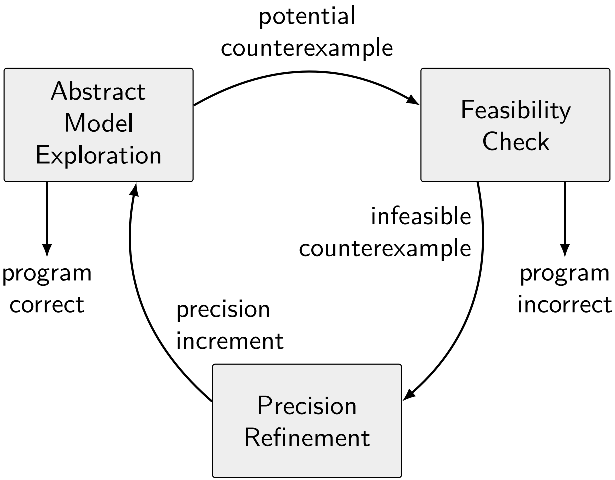
- Builds standard input (C program)
- Representing a subset of paths
- Contains at least all non-verified paths

\+ Verifier-unspecific approach

\+ Many conditional verifiers possible

Proc. ICSE 2018 [15]

(A5) CEGAR

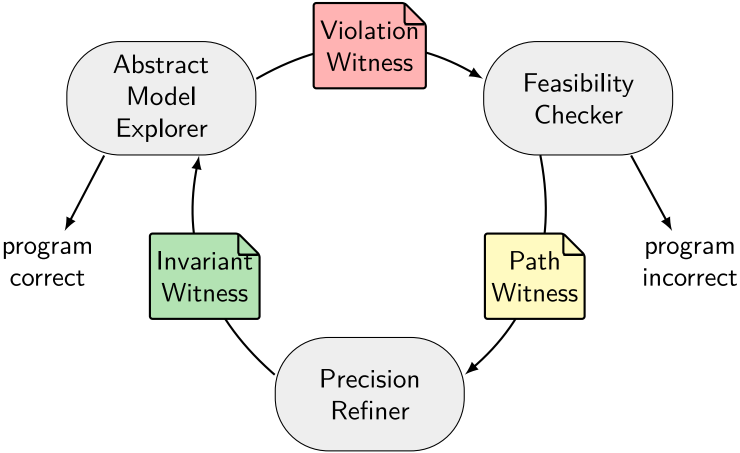

potential
counterexample
Abstract
Model
Exploration
Feasibility
Check
infeasible
counterexample
program
correct
program
incorrect
precision
increment
Precision
Refinement

(A5) Modularization of CEGAR

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

$\Rightarrow$ Modular reformulation

(A5) Workflow of modular CEGAR



Proc. ICSE 2022 [11]

(A6) Interactive and Automatic Methods

- How to achieve cooperation between automatic and interactive verifiers?
- Idea: Try to use existing interfaces for information exchange
- [25, Proc. SEFM '22]

```
//@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;
}
```

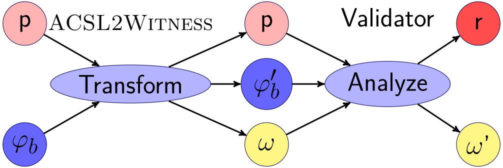
ACSL-annotated program, as used by Frama-C

```
...
<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>
...
```

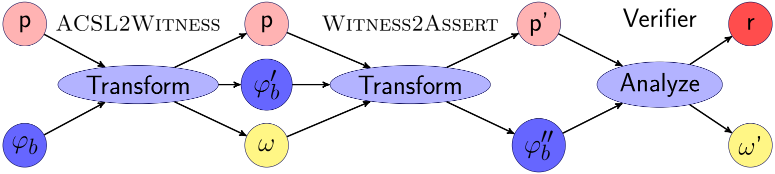
GraphML-based witness automaton generated by automatic verifiers

(A6) From Components: Construct Interactive Verifiers

- Turn a witness validator into an interactive verifier:



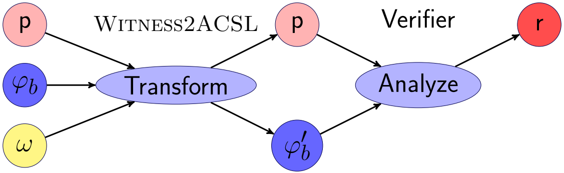
- Turn an automatic verifier into an interactive verifier:



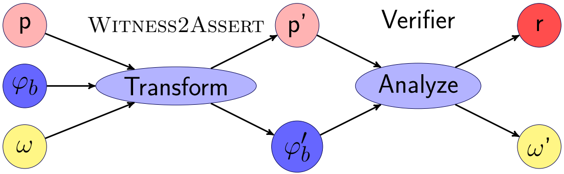
- Annotating in ACSL is more human-readable than witness automata
- Works for a wide range of automatic verifiers/validators

(A6) Component Framework: Constructing Validators

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

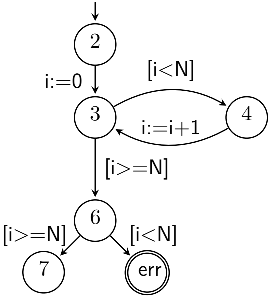


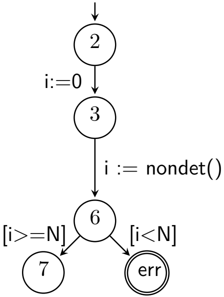
- Turn an automatic verifier into a validator [24, CAV '20]:



(A7) 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

(A7) Example: Havoc Abstraction

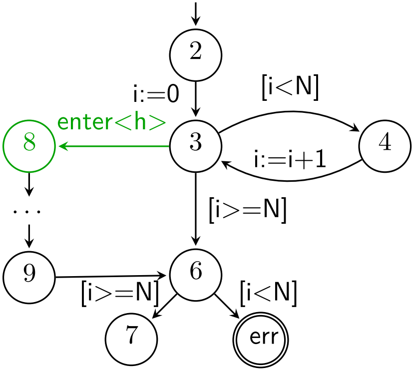
```
void main() {
  int i = 0;
  while (i<N) {
    i=i+1;
  }
  assert (i>=N);
}
```

```
void main() {
  int i = 0;
  if (i<N) {
    i = nondet();
    assume(!(i<N));
  }
  assert (i>=N);
}
```

- Havoc Abstraction: if loop is entered, havoc all input variables of the loop and perform one loop iteration, then assume the loop is left
- Only sound if the loop body does not contain assertions
- Overapproximation, but sometimes enough (as in this example)

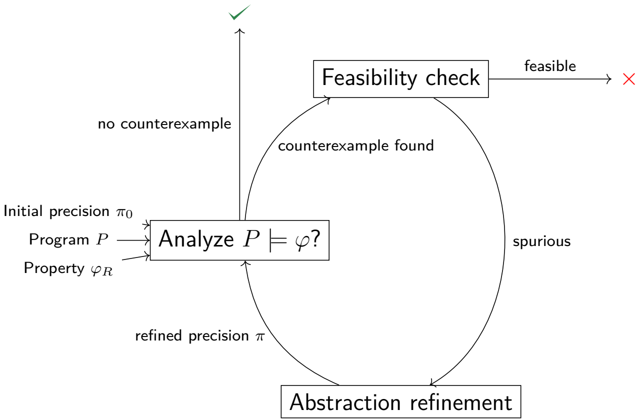
(A7) Configurable Solution a la CPAChecker

- 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: $\sigma : L \to S$
- In the example:
  $S = \{b, h\}$
  $\sigma(8) = h$
  $\sigma(l) = b$ for all l except 8
- Select allowed strategies during state-space exploration using σ
- [23, Proc. SEFM '22]



(A7) 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!



(A7) 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
- Leverage Cooperation between Tools

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