

Cooperative Software Verification

Combination Approaches that Share Information

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Automatic Software Verification

C Program

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



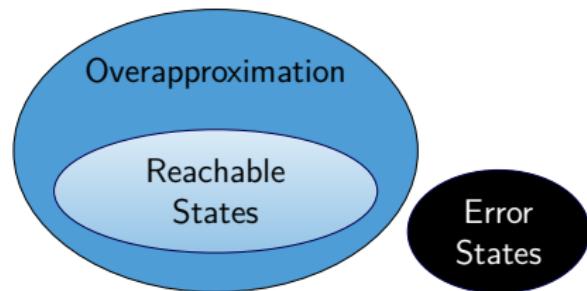
Verification
Tool



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



Two Points

- ▶ There is quite some history of software verification.
- ▶ We need more combinations and cooperation.

Some Historical Landmarks

- ▶ **70 years ago: Assertions and Proof Decomposition,**

Alan Turing, 1949 [42]

"In order that the man who checks may not have too difficult a task the programmer should make a number of definite assertions which can be checked individually, and from which the correctness of the whole program easily follows."

Landmarks, Alan Turing, 1949 [42]

Friday, 24th June.

Checking a large routine, by Dr. A. Turing.

How can one check a routine in the sense of making sure that it is right?

In order that the man who checks may not have too difficult a task the programmer should make a number of definite assertions which can be checked individually, and from which the correctness of the whole programme easily follows.

Consider the analogy of checking an addition. If it is given as:

$$\begin{array}{r} 1374 \\ 5906 \\ 6719 \\ 4337 \\ 7768 \\ \hline \end{array}$$

$$26104$$

one must check the whole at one sitting, because of the carries.

But if the totals for the various columns are given, as below:

$$\begin{array}{r} 1374 \\ 5906 \\ 6719 \\ 4337 \\ 7768 \\ \hline \end{array}$$

$$\begin{array}{r} 3974 \\ 2213 \\ \hline \end{array}$$

$$26104$$

the checker's work is much easier being split up into the checking of the various assertions $3 + 9 + 7 + 3 + 7 = 29$ etc, and the small addition

$$\begin{array}{r} 3794 \\ 2213 \\ \hline 26104 \end{array}$$

Some Historical Landmarks

- ▶ 70 years ago: Assertions and Proof Decomposition
- ▶ **60 years ago: Logic Interpolation,**
William Craig, J. Symb. Log. 1957 [32]
“Linear reasoning. A new form of the Herbrand-Gentzen theorem.”
Defines an interpolation for logic formulas
Made popular by Ken McMillan [39]

Some Historical Landmarks

- ▶ 70 years ago: Assertions and Proof Decomposition
- ▶ 60 years ago: Logic Interpolation
- ▶ **50 years ago: Data-Flow Analysis and Abstract States,**

Gary Kildall, POPL 1973 [38]

“A Unified Approach to Global Program Optimization”

Defines algorithm, meet operation, lattice, etc.

Extended and made popular for program analysis by

F. Nielson, H. R. Nielson, C. Hankin, P. Cousot, R. Cousot

Landmarks, Gary Kildall, POPL 1973 [38]

A UNIFIED APPROACH TO GLOBAL PROGRAM OPTIMIZATION

Gary A. Kildall

Computer Science Group
Naval Postgraduate School
Monterey, California

Abstract

A technique is presented for global analysis of program structure in order to perform compile time optimization of object code generated for expressions. The global expression optimization presented includes constant propagation, common subexpression elimination, elimination of redundant register load operations, and live expression analysis. A general purpose program flow analysis algorithm is developed which depends upon the existence of an "optimizing function." The algorithm is defined formally using a directed graph model of program flow structure, and is shown to be correct. Several optimizing functions are defined which, when used in conjunction with the flow analysis algorithm, provide the various forms of code optimization. The flow analysis algorithm is sufficiently general that additional functions can easily be defined for other forms of global code optimization.

Some Historical Landmarks

- ▶ 70 years ago: Assertions and Proof Decomposition
- ▶ 60 years ago: Logic Interpolation
- ▶ 50 years ago: Data-Flow Analysis and Abstract States
- ▶ **40 years ago: LTL and Model Checking,**
Pnueli, Clarke, Emerson, Sifakis, 1981
Specification languages, modeling languages, algorithms,
theory, tools
LTL, CTL, automata, Kripke structures, model checking,
→ software model checking

“Handbook of Model Checking”, Springer, 2018 [28]

Some Historical Landmarks

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- ▶ 50 years ago: Data-Flow Analysis and Abstract States
- ▶ 40 years ago: LTL and Model Checking
- ▶ **25 years ago: Predicate Abstraction,**
Graf, Saïdi, 1997 [34]
Enabling idea to project software to
a (smaller) finite state space

Some Historical Landmarks

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- ▶ 50 years ago: Data-Flow Analysis and Abstract States
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- ▶ 25 years ago: Predicate Abstraction
- ▶ **20 years ago: Tools for Software Model Checking**

“1st generation” of tools:

- ▶ Summer 2000: SLAM [2, 1]
- ▶ Fall 2000: BLAST [35, 14]
- ▶ 2004: SATABS [30]

SLAM paper received Test-of-Time Award from PLDI,
first to apply predicate abstraction + CEGAR to software.
BLAST received gold medals in competitions.

Some Historical Landmarks

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- ▶ 20 years ago: Tools for Software Model Checking
- ▶ **15 years ago: Satisfiability Modulo Theory**
 - Standard formula format SMTLIB [3]
 - Enormous breakthrough, many tools, ... [31]

Some Historical Landmarks

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- ▶ 20 years ago: Tools for Software Model Checking
- ▶ 15 years ago: Satisfiability Modulo Theory
- ▶ **10 years ago: Competition on Software Verification**
2012 [4]
Competitions create awareness of tools,
provide comparative evaluations, establish standards
(input, exchange, comparability, reproducibility)

Some Historical Landmarks

- ▶ 70 years ago: Assertions and Proof Decomposition
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- ▶ 25 years ago: Predicate Abstraction
- ▶ 20 years ago: Tools for Software Model Checking
- ▶ 15 years ago: Satisfiability Modulo Theory
- ▶ 10 years ago: Competition on Software Verification
- ▶ **today:** From **lack** of tools to **abundance** of tools
Problem: missing standard interfaces, missing cooperation

Status on Verifiers

- ▶ From lack of verifiers to plentitude

Example CPAchecker [21]: Many Concepts

- ▶ 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]

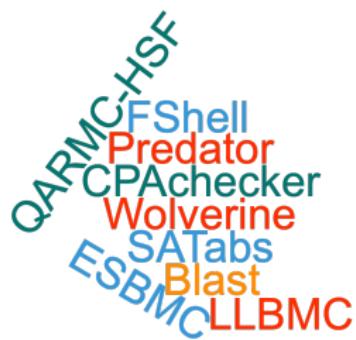
Competitions in Software Verification and Testing

Mature research area, and there are tool competitions:

- ▶ RERS: off-site, tools, free-style [36]
- ▶ SV-COMP: off-site, automatic tools, controlled [4]
- ▶ Test-Comp: off-site, automatic tools, controlled [6]
- ▶ VerifyThis: on-site, interactive, teams [37]

(alphabetic order)

SV-COMP (Automatic Tools 2012)



SV-COMP (Automatic Tools 2013, cumulative)



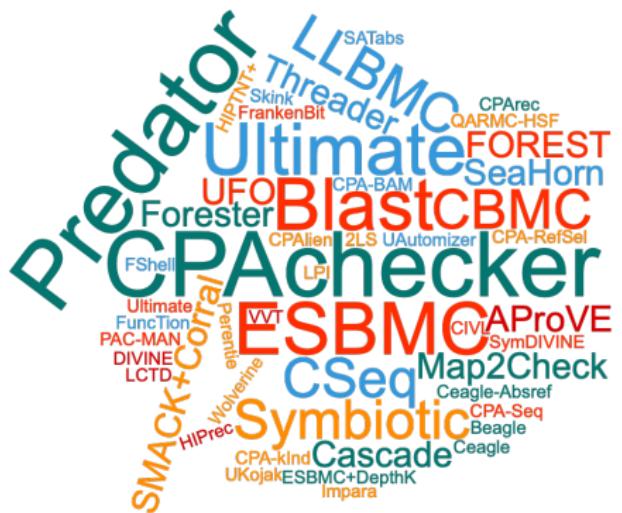
SV-COMP (Automatic Tools 2014, cumulative)



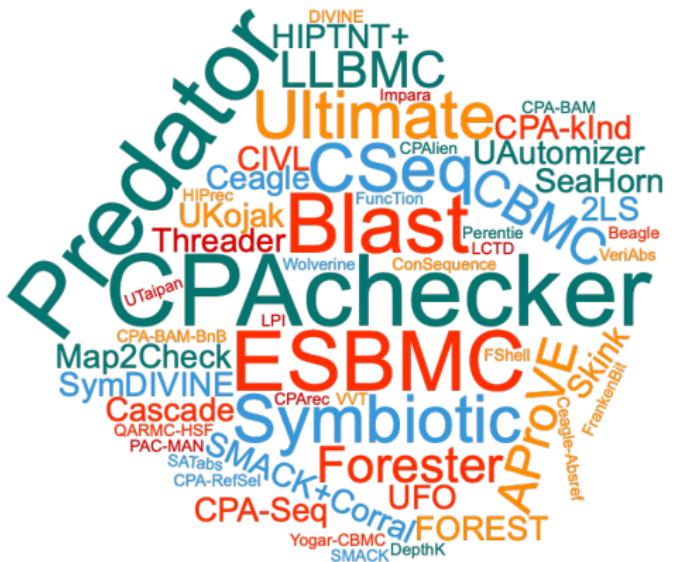
SV-COMP (Automatic Tools 2015, cumulative)



SV-COMP (Automatic Tools 2016, cumulative)



SV-COMP (Automatic Tools 2017, cumulative)



SV-COMP (Automatic Tools 2018, cumulative)



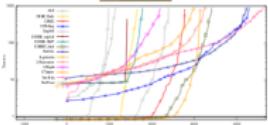
SV-COMP (Automatic Tools 2019, cumulative)



Different Strengths

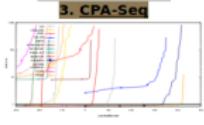
ReachSafety

1. VeriAbs
2. CPA-Seq
3. PeSCo



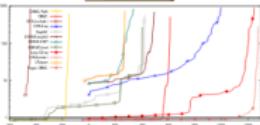
MemSafety

1. Symbiotic
2. PredatorHP
3. CPA-Seq



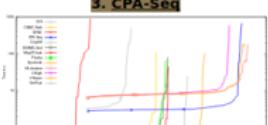
ConcurrencySafety

1. Yogar-CBMC
2. Lazy-CSeg
3. CPA-Seq



NoOverflows

1. UAutomizer
2. UTaipan
3. CPA-Seq



Termination

1. UAutomizer
2. AProVE
3. CPA-Seq



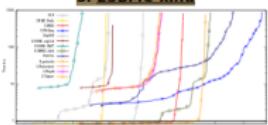
SoftwareSystems

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



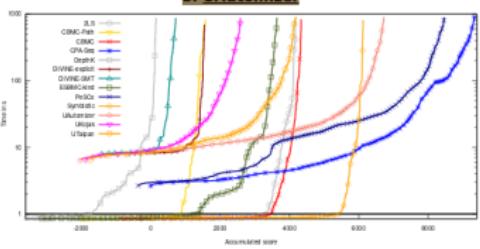
FalsificationOverall

1. CPA-Seq
2. PeSCo
3. FSBMC-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	✓	✓																
JPMC																		
JPF																		
LAZY-CSEQ																		
MAP2CHECK																		
PESCo	✓	✓																
PINAKA																		
PREDATORHP																		
SKINK	✓																	
SMACK	✓																	
SPF																		
SYMBIOTIC																		
UAUTOMIZER	✓	✓																
UKOJAK	✓	✓																
UTAI PAN	✓	✓																
VERIABs	✓																	
VERIFUZZ																		
VIAP																		
YOGAR-CBMC	✓																	
YOGAR-CBMC-PAR	✓																	

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

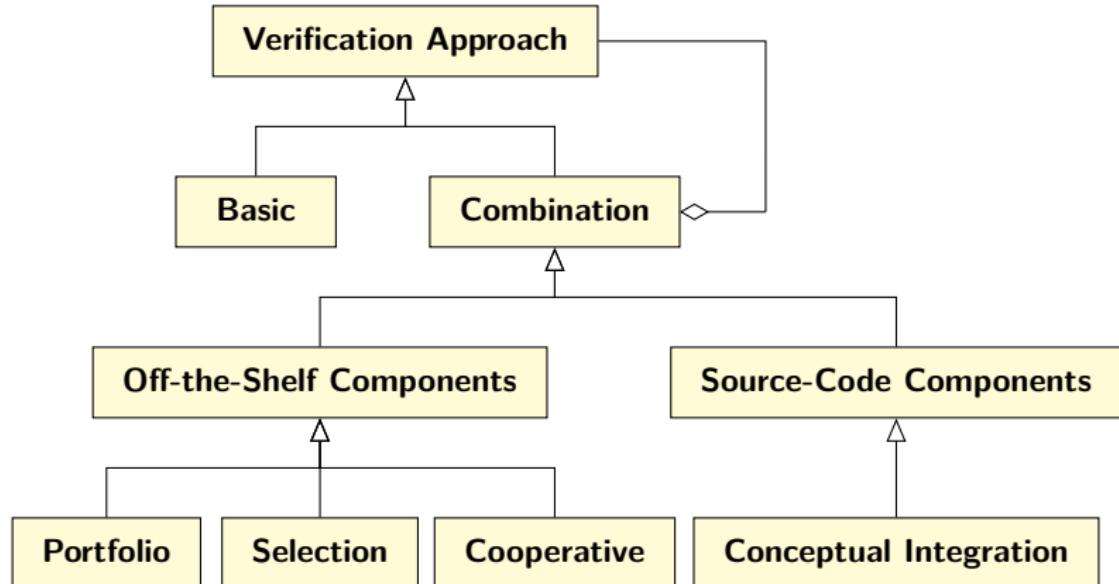
Insights from Software Model Checking

- ▶ Verifiers have different strengths
- ▶ There are plenty of tools
- ▶ ⇒ Cooperative Verification Approaches

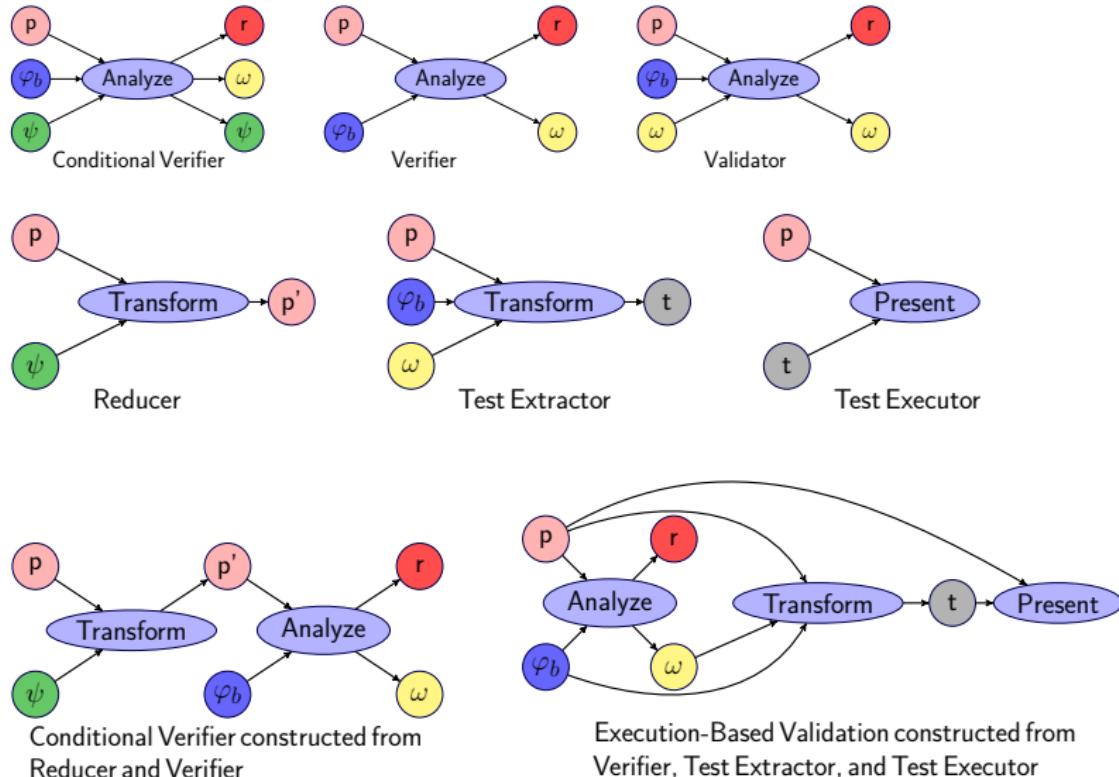
Cooperative Verification — Think big!

- ▶ 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 [41], Evidential Tool Bus [33]

Approaches for Combinations



Graphical Visualization of the Coop Framework



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*.

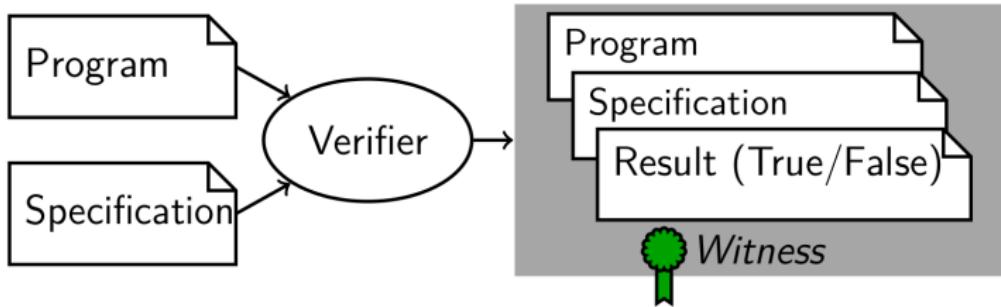
Definition of Cooperative Verification

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

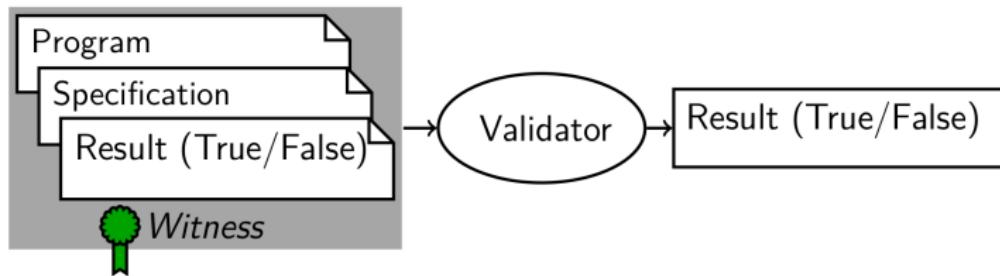
Software Verification with Witnesses

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

- 1: verifier := Verifier("Ultimate Automizer")
 - 2: validator := Validator("CPAchecker")
 - 3: result := verifier.verify(p, s)
 - 4: **if** result.verdict ∈ {TRUE, FALSE} **then**
 - 5: result = validator.validate (p, s, result.witness)
 - 6: **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)

Facing Hard Verification Tasks

Given: Program $P \models \varphi?$



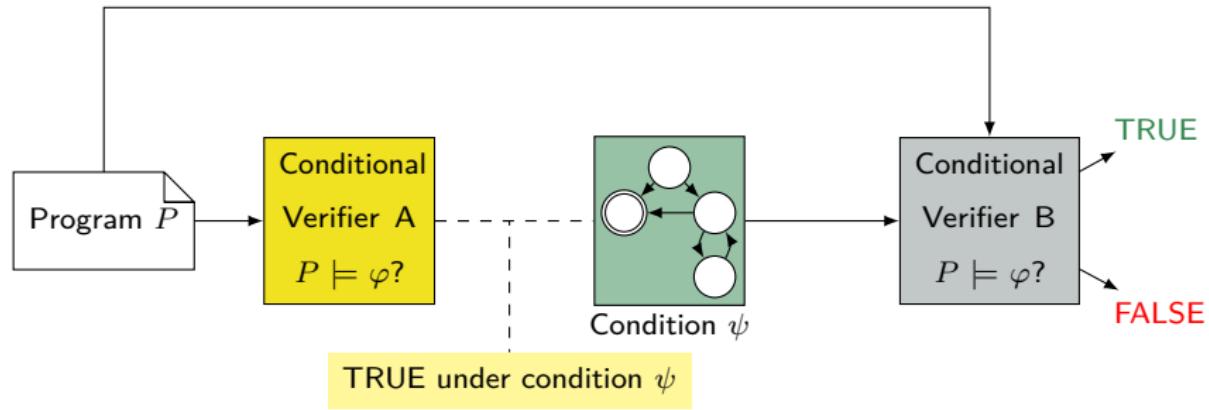
Facing Hard Verification Tasks

Given: Program $P \models \varphi ?$



e.g., conditional model checking

Conditional Model Checking

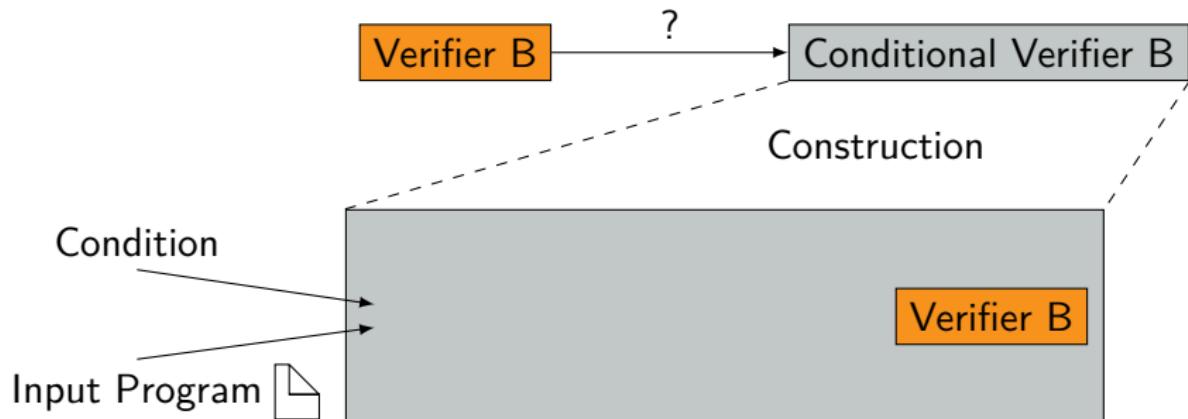


Proc. FSE 2012 [15]

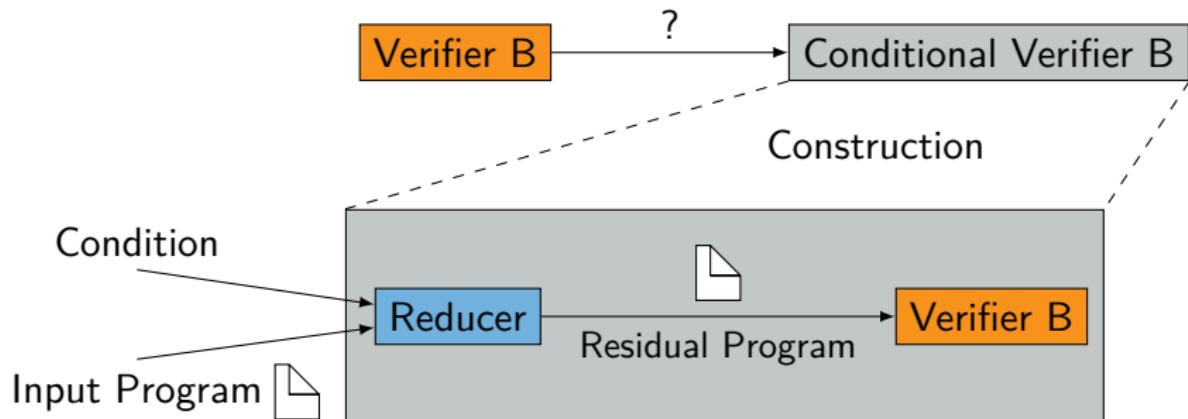
Reducer-Based Construction



Reducer-Based Construction



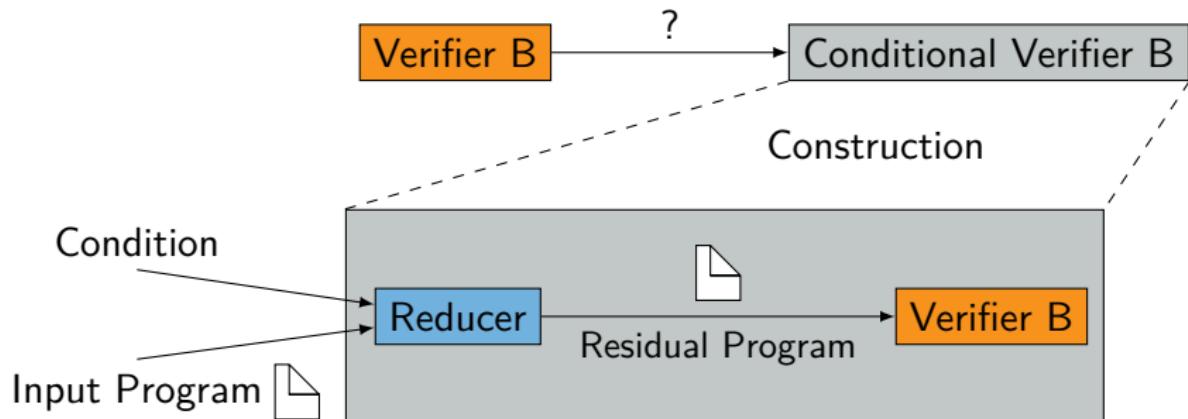
Reducer-Based Construction



Reducer (preprocessor)

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

Reducer-Based Construction

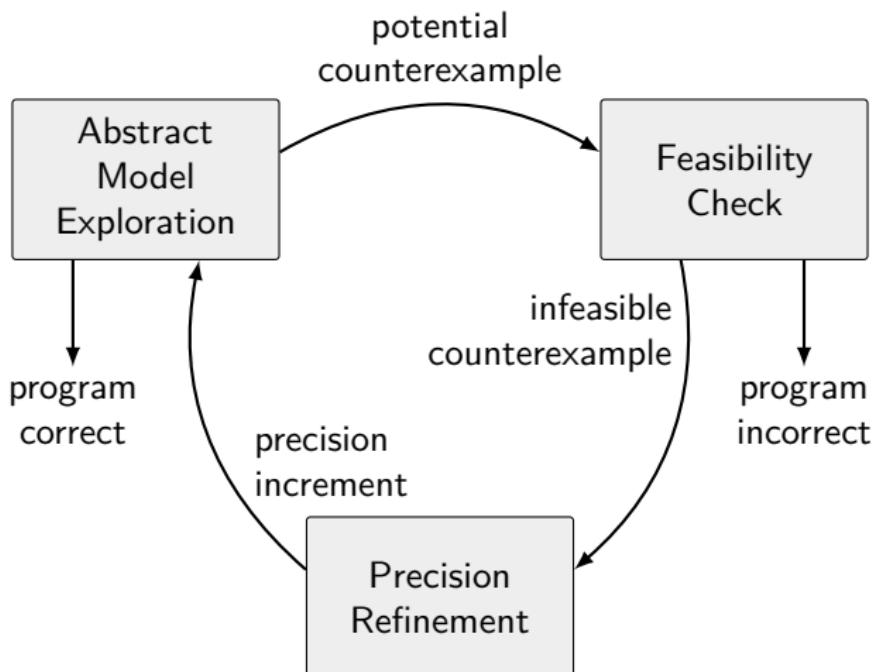


Reducer (preprocessor)

- ▶ 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]

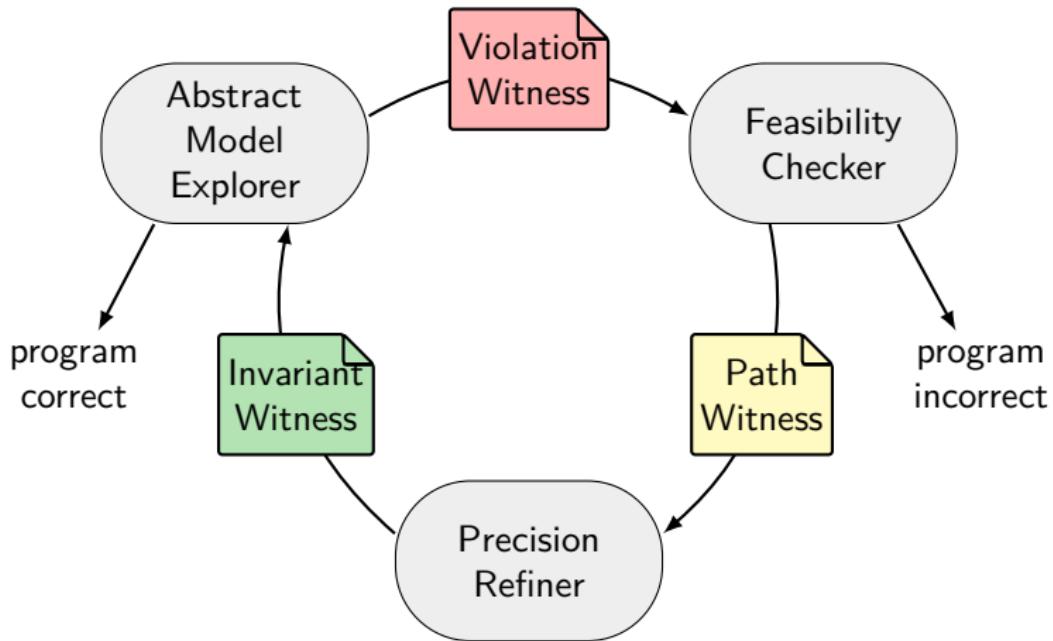
CEGAR



Modularization of CEGAR

- ▶ CEGAR defines I/O interfaces
- ▶ But instances not exchangeable
- ▶ Aim: generalize CEGAR, allow exchange of components
- ⇒ 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;
}
```

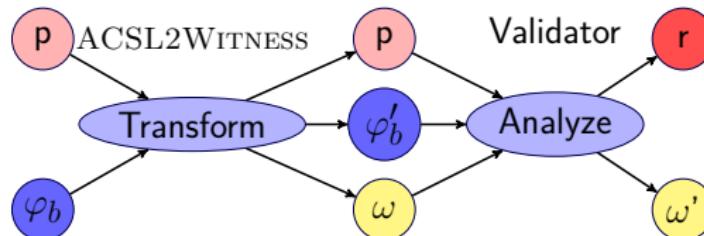
ACSL-annotated program, as used by FRAMA-C

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

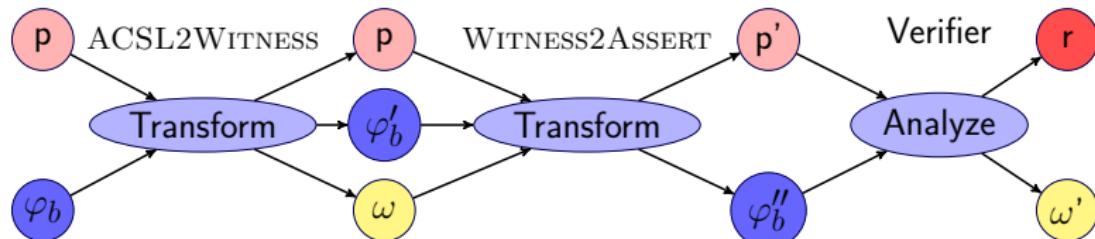
GraphML-based witness automaton generated by automatic verifiers

From Components: Construct Interactive Verifiers

- ▶ Turn a witness validator into an interactive verifier:



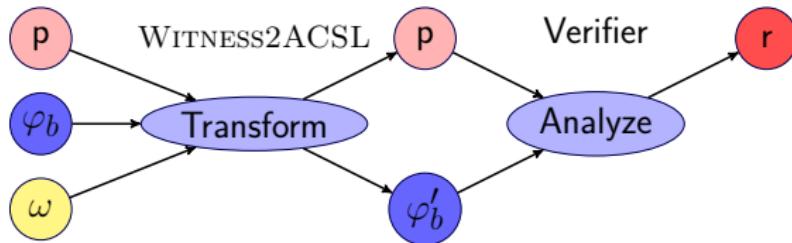
- ▶ Turn an automatic verifier into an interactive verifier::



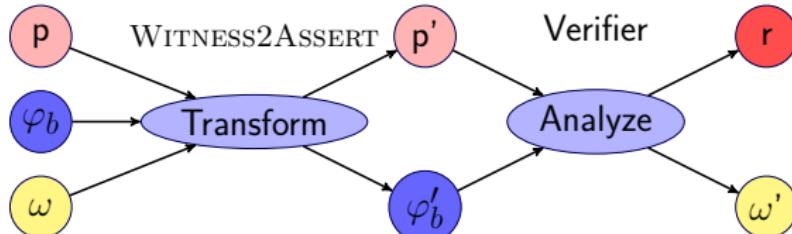
- ▶ Annotating in ACSL is more human-readable than witness automata
- ▶ Works for a wide range of automatic verifiers/validators

Component Framework: Constructing Validators

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

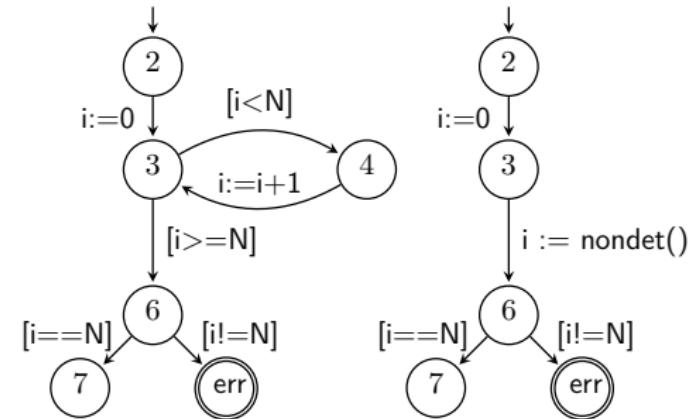


- ▶ Turn an automatic verifier into a validator:



Loop Abstraction

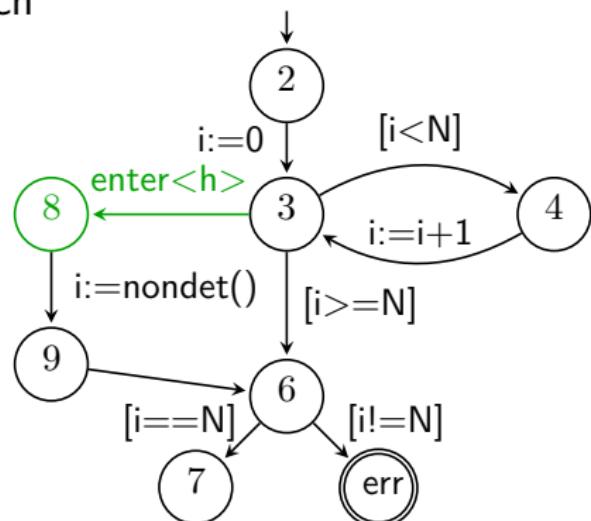
```
1 void main() {  
2     int i = 0;  
3     while (i<N) {  
4         i=i+1;  
5     }  
6     assert (i==N);  
7 }
```



- ▶ 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

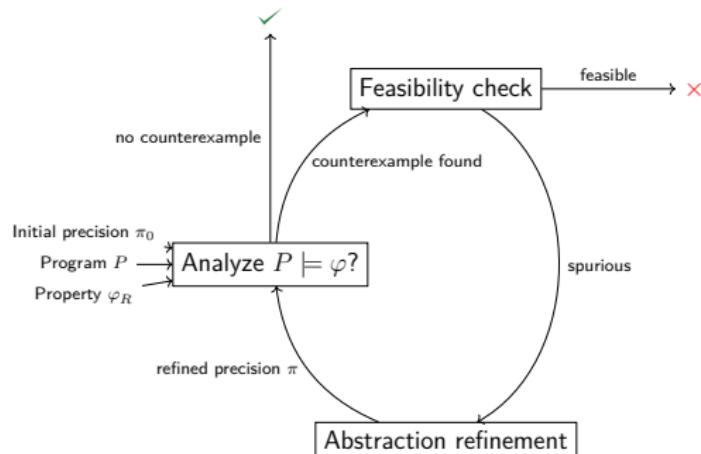
Configurable Solution a la CPAchecker

- ▶ 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
 $l \in \{2, 3, 4, 6, 7, \text{err}, 9\}$
- ▶ Select allowed strategies during state-space exploration using σ



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

References |

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