

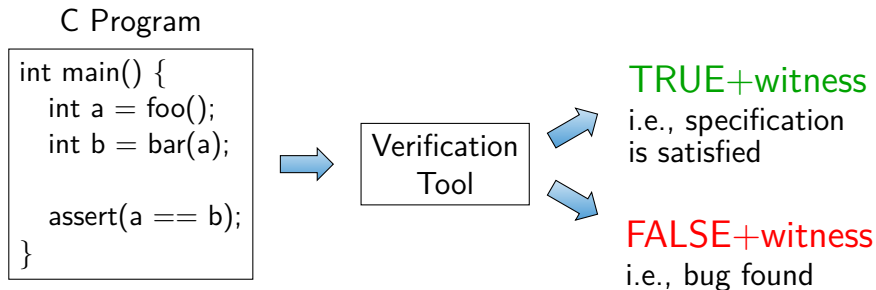
Cooperative Verification

Dirk Beyer
LMU Munich, Germany

Presentation at Dagstuhl, July 11, 2023



Scope of this presentation: Automatic Software Verification



Status on Verifiers

- ▶ From lack of verifiers to plentitude
- ▶ 76 verification tools available [28]

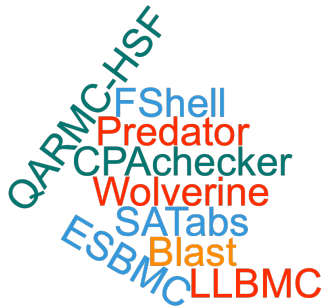
Competitions in Software Verification and Testing

Mature research area, and there are tool competitions:

- ▶ RERS: off-site, tools, free-style [32]
- ▶ SV-COMP: off-site, automatic tools, controlled [1]
- ▶ Test-Comp: off-site, automatic tools, controlled [3]
- ▶ VerifyThis: on-site, interactive, teams [33]

(alphabetic order)

SV-COMP (Automatic Tools 2012)



SV-COMP (Automatic Tools 2013, cumulative)



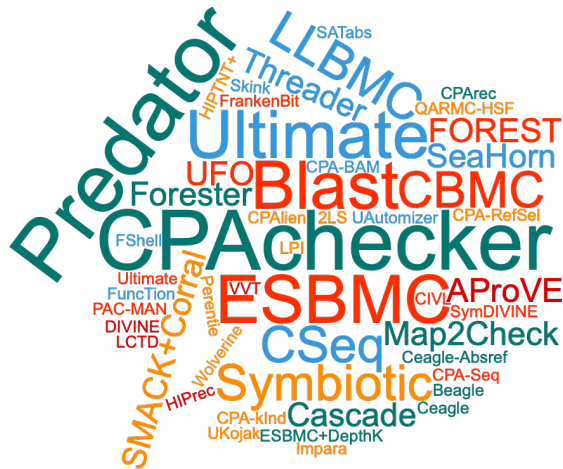
SV-COMP (Automatic Tools 2014, cumulative)



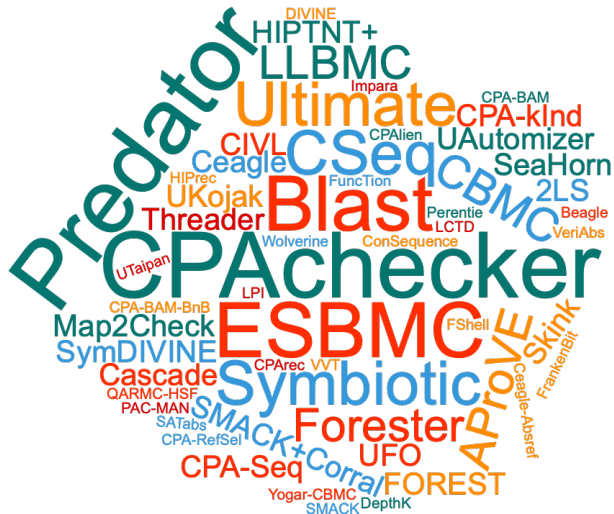
SV-COMP (Automatic Tools 2015, cumulative)



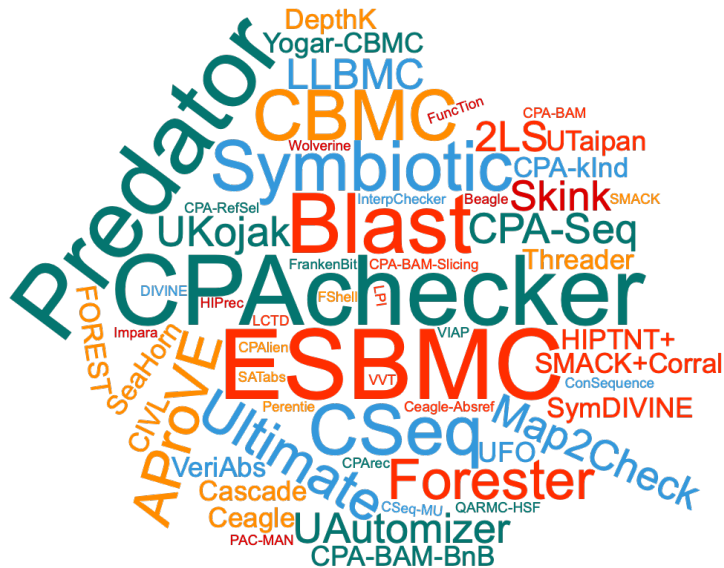
SV-COMP (Automatic Tools 2016, cumulative)



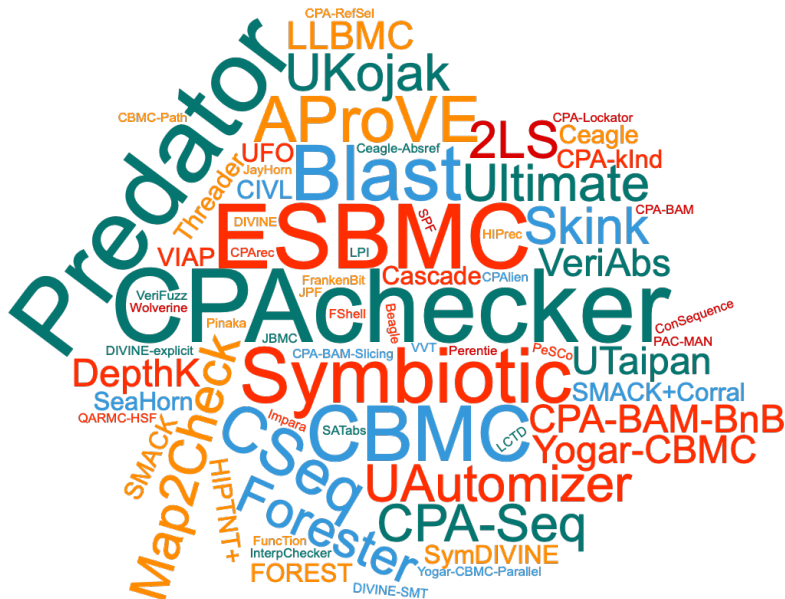
SV-COMP (Automatic Tools 2017, cumulative)



SV-COMP (Automatic Tools 2018, cumulative)



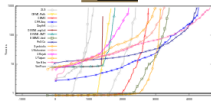
SV-COMP (Automatic Tools 2019, cumulative)



Different Strengths

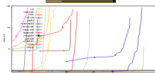
ReachSafety

1. VeriAbs
2. CPA-Seq
3. PeSCo



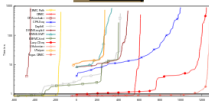
MemSafety

1. Symbiotic
2. PredatorHP
3. CPA-Seq



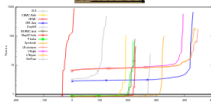
ConcurrencySafety

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



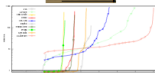
NoOverflows

1. UAutomizer
2. Utaipan
3. CPA-Seq



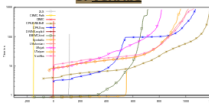
Termination

1. UAutomizer
2. AProVE
3. CPA-Seq



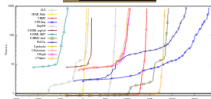
SoftwareSystems

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



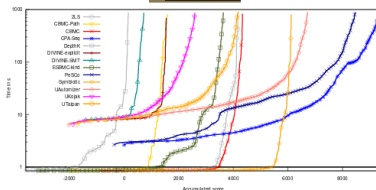
FalsificationOverall

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	✓	✓									✓	✓	✓	✓			✓	
UKOLAK	✓	✓									✓	✓	✓	✓				
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 [29] 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 [34, 27, 10]
 - ▶ Bounded model checking [30, 10]
 - ▶ k-Induction [9, 10]
 - ▶ IC3/Property-directed reachability [5]
 - ▶ Explicit-state model checking [21]
 - ▶ Interpolation-based model checking [20]

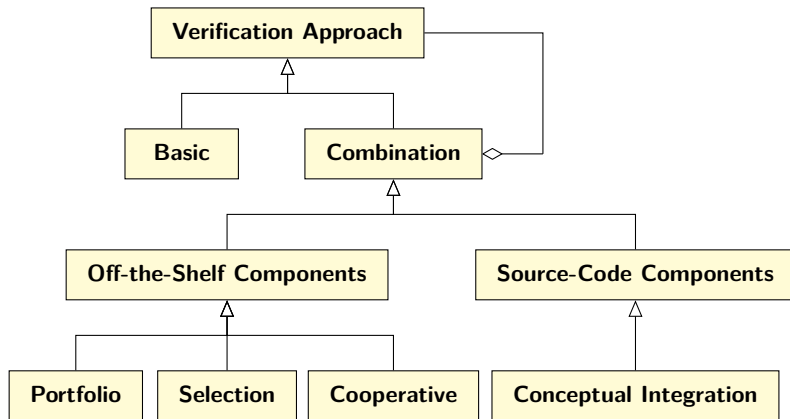
Insights from Software Model Checking

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

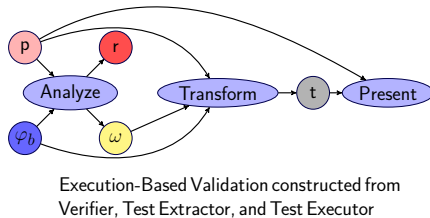
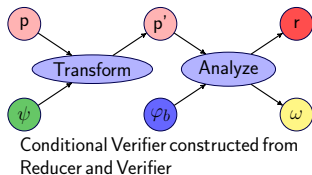
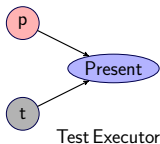
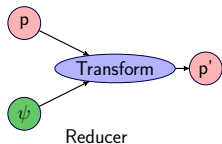
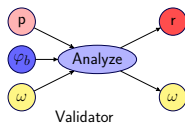
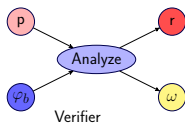
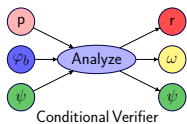
Cooperative Verification — Think big!

- ▶ Introduce a new level!
- ▶ Current tools should become "low level" components (engines)
- ▶ Construct combinations
- ▶ Clear Interfaces
via, e.g., Conditions, Witnesses, Test Suites
- ▶ Success: SAT, SMT (common interfaces, usable as libraries)
- ▶ See also: Little Engines [35], Evidential Tool Bus [31]

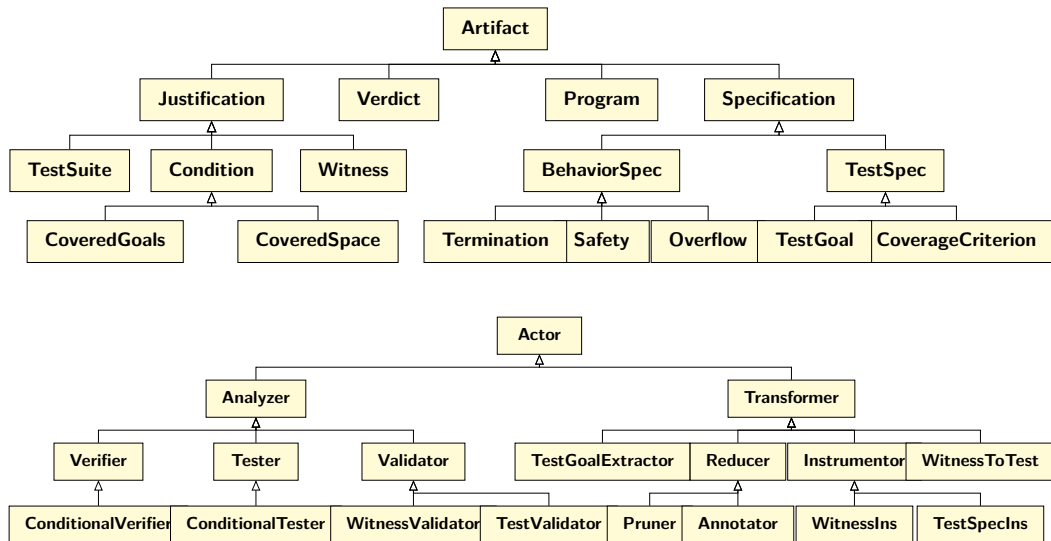
Approaches for Combinations [26]



Graphical Visualization of the Coop Framework [26]



Artifacts and Actors: Classification [16]



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*.

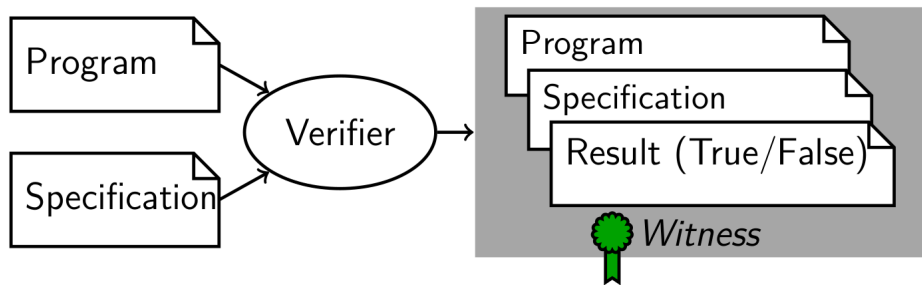
Definition of Cooperative Verification

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

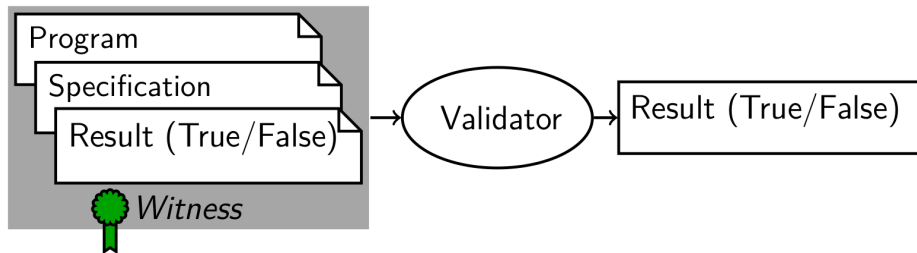
(A1) Software Verification with Witnesses

Witnesses are an important interface between tools.



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

(A1) Witness-Based Result Validation



- ▶ Validate untrusted results
- ▶ Reestablish proof of correctness or violation
- ▶ 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

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

(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 $P \models \varphi?$

Verifier A

Program Paths

$P \models \varphi?$
UNKNOWN

Verifier B

Program Paths

$P \models \varphi?$
UNKNOWN

(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

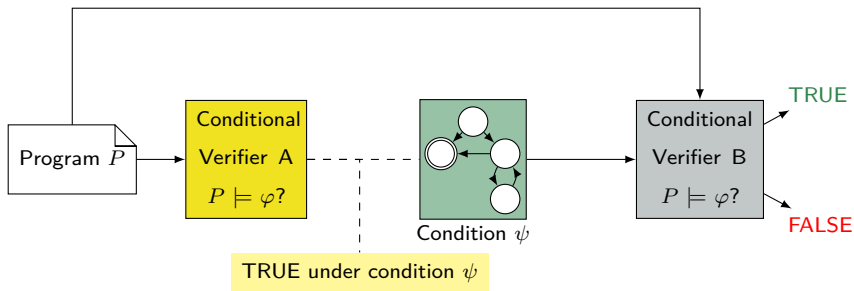
Verifier A + Verifier B

e.g., conditional model checking

Program Paths

$P \models \varphi \checkmark$

(A4) Conditional Model Checking



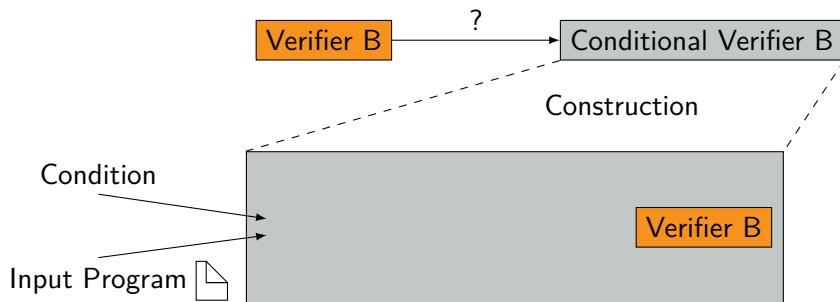
Proc. FSE 2012 [12]

(A4) Reducer-Based Construction



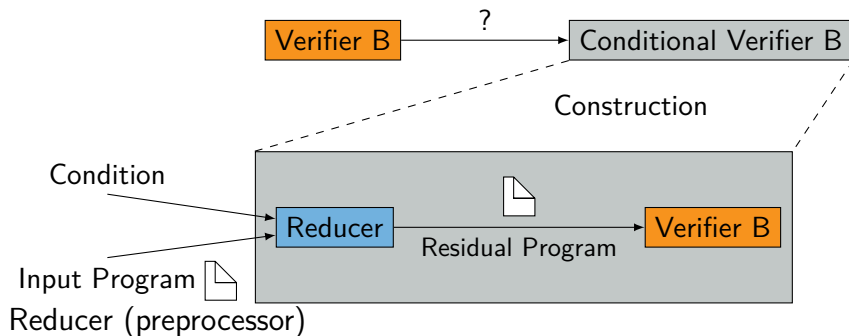
Proc. ICSE 2018 [15]

(A4) Reducer-Based Construction



Proc. ICSE 2018 [15]

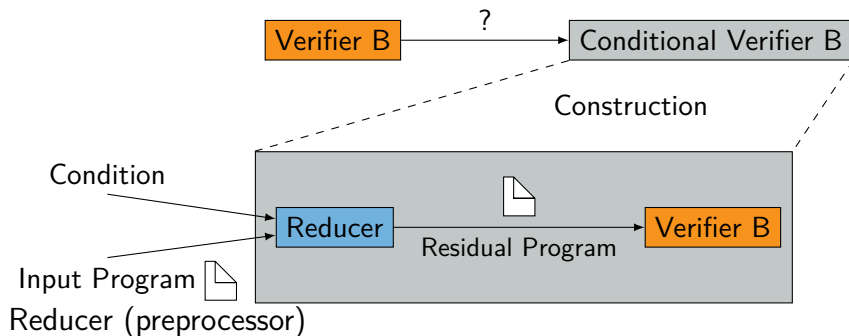
(A4) Reducer-Based Construction



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

Proc. ICSE 2018 [15]

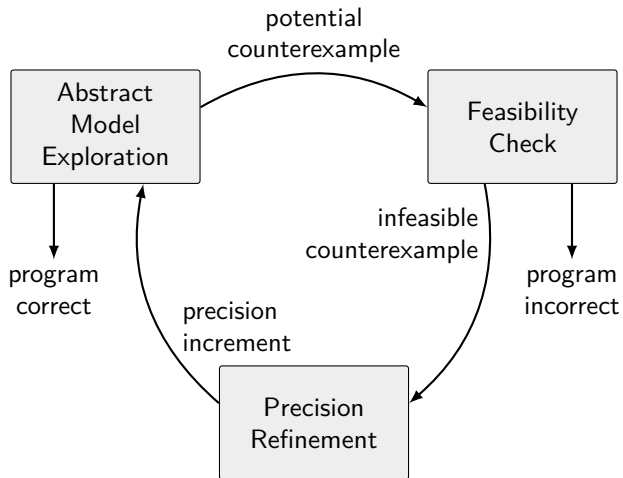
(A4) Reducer-Based Construction



- ▶ 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]

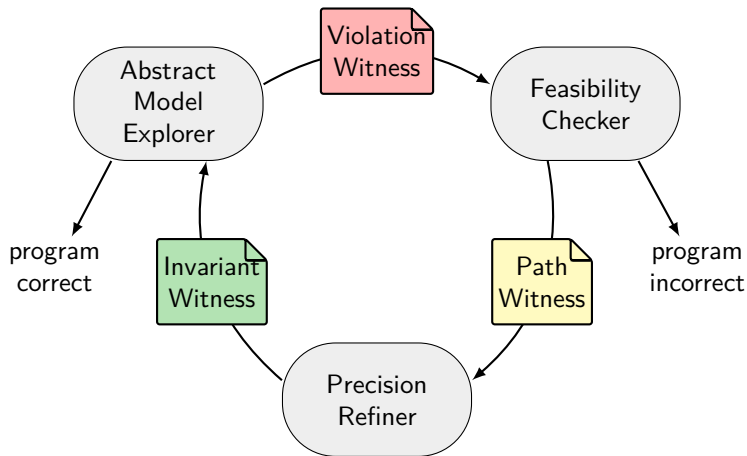
(A5) CEGAR



(A5) Modularization of CEGAR

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

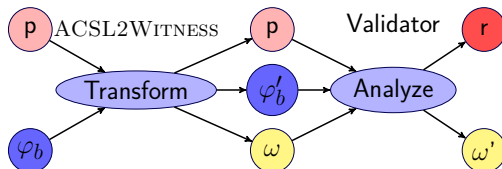
ACSL-annotated program, as used by
FRAMA-C

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

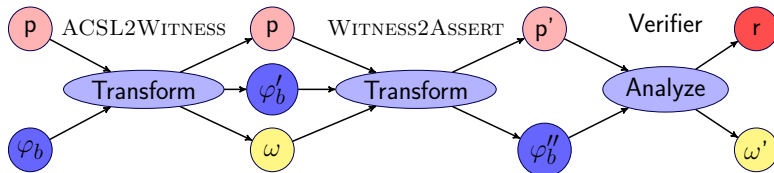
GraphML-based witness
automaton generated by
automatic verifiers

(A6) From Components: Construct Interactive Verifiers

- Turn a witness validator into an interactive verifier:



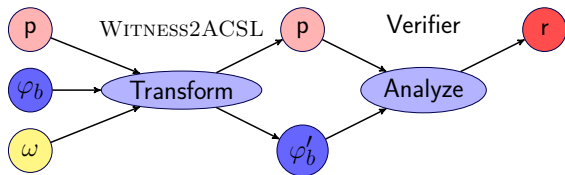
- Turn an automatic verifier into an interactive verifier:



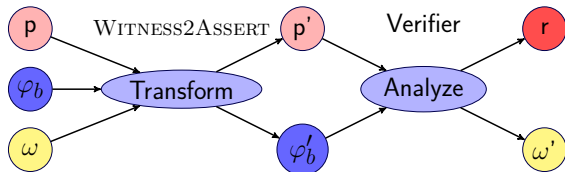
- Annotating in ACSL is more human-readable than witness automata
- Works for a wide range of automatic verifiers/validators

(A6) Component Framework: Constructing Validators

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

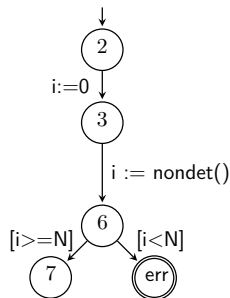
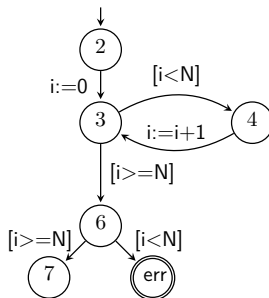


- Turn an automatic verifier into a validator [24, CAV '20]:



(A7) Loop Abstraction

```
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

(A7) Example: Havoc Abstraction

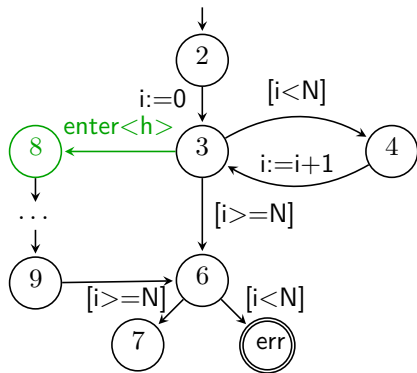
```
1 void main() {  
2   int i = 0;  
3   while (i<N) {  
4     i=i+1;  
5   }  
6   assert (i>=N);  
7 }
```

```
1 void main() {  
2   int i = 0;  
3   if (i<N) {  
4     i = nondet();  
5     assume(!(i<N));  
6   }  
7   assert (i>=N);  
8 }
```

- ▶ **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: $\sigma : L \rightarrow S$
- ▶ 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) 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

- ▶ Many verification tools and techniques
- ▶ External combinations are important
- ▶ Interfaces (artifacts, actors)
- ▶ Combinations and Cooperation
- ▶ Leverage Cooperation between Tools

References I

- [1] Beyer, D.: Competition on software verification (SV-COMP). In: Proc. TACAS. pp. 504–524. LNCS 7214, Springer (2012). https://doi.org/10.1007/978-3-642-28756-5_38
- [2] Beyer, D.: Automatic verification of C and Java programs: SV-COMP 2019. In: Proc. TACAS (3). pp. 133–155. LNCS 11429, Springer (2019). https://doi.org/10.1007/978-3-030-17502-3_9
- [3] Beyer, D.: Competition on software testing (Test-Comp). In: Proc. TACAS (3). pp. 167–175. LNCS 11429, Springer (2019). https://doi.org/10.1007/978-3-030-17502-3_11
- [4] Beyer, D., Cimatti, A., Griggio, A., Keremoglu, M.E., Sebastiani, R.: Software model checking via large-block encoding. In: Proc. FMCAD. pp. 25–32. IEEE (2009). <https://doi.org/10.1109/FMCAD.2009.5351147>
- [5] Beyer, D., Dangl, M.: Software verification with PDR: An implementation of the state of the art. In: Proc. TACAS (1). pp. 3–21. LNCS 12078, Springer (2020). https://doi.org/10.1007/978-3-030-45190-5_1
- [6] Beyer, D., Dangl, M., Dietsch, D., Heizmann, M.: Correctness witnesses: Exchanging verification results between verifiers. In: Proc. FSE. pp. 326–337. ACM (2016). <https://doi.org/10.1145/2950290.2950351>
- [7] Beyer, D., Dangl, M., Dietsch, D., Heizmann, M., Lemberger, T., Tautschnig, M.: Verification witnesses. ACM Trans. Softw. Eng. Methodol. **31**(4), 57:1–57:69 (2022). <https://doi.org/10.1145/3477579>
- [8] Beyer, D., Dangl, M., Dietsch, D., Heizmann, M., Stahlbauer, A.: Witness validation and stepwise testification across software verifiers. In: Proc. FSE. pp. 721–733. ACM (2015). <https://doi.org/10.1145/2786805.2786867>

References II

- [9] Beyer, D., Dangl, M., Wendler, P.: Boosting k-induction with continuously-refined invariants. In: Proc. CAV. pp. 622–640. LNCS 9206, Springer (2015). https://doi.org/10.1007/978-3-319-21690-4_42
- [10] Beyer, D., Dangl, M., Wendler, P.: A unifying view on SMT-based software verification. J. Autom. Reasoning **60**(3), 299–335 (2018). <https://doi.org/10.1007/s10817-017-9432-6>
- [11] Beyer, D., Haltermann, J., Lemberger, T., Wehrheim, H.: Decomposing Software Verification into Off-the-Shelf Components: An Application to CEGAR. In: Proc. ICSE. pp. 536–548. ACM (2022). <https://doi.org/10.1145/3510003.3510064>
- [12] Beyer, D., Henzinger, T.A., Keremoglu, M.E., Wendler, P.: Conditional model checking: A technique to pass information between verifiers. In: Proc. FSE. ACM (2012). <https://doi.org/10.1145/2393596.2393664>
- [13] Beyer, D., Henzinger, T.A., Théoduloz, G.: Configurable software verification: Concretizing the convergence of model checking and program analysis. In: Proc. CAV. pp. 504–518. LNCS 4590, Springer (2007). https://doi.org/10.1007/978-3-540-73368-3_51
- [14] Beyer, D., Henzinger, T.A., Théoduloz, G.: Program analysis with dynamic precision adjustment. In: Proc. ASE. pp. 29–38. IEEE (2008). <https://doi.org/10.1109/ASE.2008.13>
- [15] Beyer, D., Jakobs, M.C., Lemberger, T., Wehrheim, H.: Reducer-based construction of conditional verifiers. In: Proc. ICSE. pp. 1182–1193. ACM (2018). <https://doi.org/10.1145/3180155.3180259>
- [16] Beyer, D., Kanav, S.: CoVeriTTEAM: On-demand composition of cooperative verification systems. In: Proc. TACAS. pp. 561–579. LNCS 13243, Springer (2022). https://doi.org/10.1007/978-3-030-99524-9_31

References III

- [17] Beyer, D., Kanav, S., Richter, C.: Construction of Verifier Combinations Based on Off-the-Shelf Verifiers. In: Proc. FASE. pp. 49–70. Springer (2022). https://doi.org/10.1007/978-3-030-99429-7_3
- [18] Beyer, D., Keremoglu, M.E.: CPACHECKER: A tool for configurable software verification. In: Proc. CAV. pp. 184–190. LNCS 6806, Springer (2011). https://doi.org/10.1007/978-3-642-22110-1_16
- [19] Beyer, D., Keremoglu, M.E., Wendler, P.: Predicate abstraction with adjustable-block encoding. In: Proc. FMCAD. pp. 189–197. FMCAD (2010), https://www.sosy-lab.org/research/pub/2010-FMCAD.Predicate_Abstraction_with_Adjustable-Block-Encoding.pdf
- [20] Beyer, D., Lee, N.Z., Wendler, P.: Interpolation and SAT-based model checking revisited: Adoption to software verification. arXiv/CoRR 2208(05046) (July 2022). <https://doi.org/10.48550/arXiv.2208.05046>
- [21] Beyer, D., Löwe, S.: Explicit-state software model checking based on CEGAR and interpolation. In: Proc. FASE. pp. 146–162. LNCS 7793, Springer (2013). https://doi.org/10.1007/978-3-642-37057-1_11
- [22] Beyer, D., Löwe, S., Novikov, E., Stahlbauer, A., Wendler, P.: Precision reuse for efficient regression verification. In: Proc. FSE. pp. 389–399. ACM (2013). <https://doi.org/10.1145/2491411.2491429>
- [23] Beyer, D., Rosenfeld, M.L., Spiessl, M.: A unifying approach for control-flow-based loop abstraction. In: Proc. SEFM. pp. 3–19. LNCS 13550, Springer (2022). https://doi.org/10.1007/978-3-031-17108-6_1
- [24] Beyer, D., Spiessl, M.: METAVAL: Witness validation via verification. In: Proc. CAV. pp. 165–177. LNCS 12225, Springer (2020). https://doi.org/10.1007/978-3-030-53291-8_10

References IV

- [25] Beyer, D., Spiessl, M., Umbricht, S.: Cooperation between automatic and interactive software verifiers. In: Proc. SEFM. p. 111–128. LNCS 13550, Springer (2022). https://doi.org/10.1007/978-3-031-17108-6_7
- [26] Beyer, D., Wehrheim, H.: Verification artifacts in cooperative verification: Survey and unifying component framework. In: Proc. ISoLA (1). pp. 143–167. LNCS 12476, Springer (2020). https://doi.org/10.1007/978-3-030-61362-4_8
- [27] Beyer, D., Wendler, P.: Algorithms for software model checking: Predicate abstraction vs. IMPACT. In: Proc. FMCAD. pp. 106–113. FMCAD (2012), https://www.sosy-lab.org/research/pub/2012-FMCAD.Algorithms_for_Software_Model_Checking.pdf
- [28] Beyer, D., Podelski, A.: Software model checking: 20 years and beyond. In: Principles of Systems Design. pp. 554–582. LNCS 13660, Springer (2022). https://doi.org/10.1007/978-3-031-22337-2_27
- [29] Clarke, E.M., Grumberg, O., Jha, S., Lu, Y., Veith, H.: Counterexample-guided abstraction refinement for symbolic model checking. J. ACM **50**(5), 752–794 (2003). <https://doi.org/10.1145/876638.876643>
- [30] Clarke, E.M., Kröning, D., Lerda, F.: A tool for checking ANSI-C programs. In: Proc. TACAS. pp. 168–176. LNCS 2988, Springer (2004). https://doi.org/10.1007/978-3-540-24730-2_15
- [31] Cruanes, S., Hamon, G., Owre, S., Shankar, N.: Tool integration with the Evidential Tool Bus. In: Proc. VMCAI. pp. 275–294. LNCS 7737, Springer (2013). https://doi.org/10.1007/978-3-642-35873-9_18

References V

- [32] Howar, F., Isberner, M., Merten, M., Steffen, B., Beyer, D.: The RERS grey-box challenge 2012: Analysis of event-condition-action systems. In: Proc. ISoLA. pp. 608–614. LNCS 7609, Springer (2012). https://doi.org/10.1007/978-3-642-34026-0_45
- [33] Huisman, M., Klebanov, V., Monahan, R.: VerifyThis 2012: A program verification competition. STTT 17(6), 647–657 (2015). <https://doi.org/10.1007/s10009-015-0396-8>
- [34] McMillan, K.L.: Lazy abstraction with interpolants. In: Proc. CAV. pp. 123–136. LNCS 4144, Springer (2006). https://doi.org/10.1007/11817963_14
- [35] Shankar, N.: Little engines of proof. In: Proc. FME. pp. 1–20. LNCS 2391, Springer (2002). https://doi.org/10.1007/3-540-45614-7_1