IA159 Formal Methods for Software Analysis

Verification Witnesses, SV-COMP, and Test-Comp

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Focus and sources

focus

- verification witnesses in GraphML and YAML
- competition on software verification (SV-COMP)
- competition on software testing (Test-Comp)

sources

- D. Beyer, M. Dangl, D. Dietsch, M. Heizmann, T. Lemberger, and M. Tautschnig: Verification Witnesses, ACM TOSEM 2022.
- P. Ayaziová, D. Beyer, M. Lingsch-Rosenfeld, M. Spiessl, and J. Strejček: Software Verification Witnesses 2.0, SPIN 2024.

Motivation

- verification tools contain bugs
  - 72 verifiers participated in the Overall category of SV-COMP 2018-2023
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- verification result should be accompanied by a witness
- witness can be checked by independent witness validators
- $\Longrightarrow$ witness format needed

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- witness can be checked by independent witness validators
- $\Longrightarrow$ witness format needed
- checking witness validity should be easier than deciding the verification task

Verification tasks and properties

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- property to be verified

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common properties

- reachability safety
  - error locations/functions are unreachable
  - many specific properties can be reduced to this: division by zero, assertion checking, ...
- memory safety
  - no invalid pointer dereference, no invalid deallocation, no memory leaks
- no signed integer overflow
- program termination
- no data race, ...

Violation witnesses

- a violation witness represents property violation, i.e., some program execution violating the property
- witnesses representing only the violating execution would be big and hard to validate as they have to represent
    - values of all inputs
    - interaction with environment
    - thread scheduling
    - program non-determinism
        - order of evaluation of subexpressions: `f(x) + g(y)`
        - addresses of allocations: `p = malloc(10)`
    - …

Example of program nondeterminism

```c
int g = 0;

int f1() {
  g = 2 * g;
  return 5;
}

int f2() {
  g++;
  return 7;
}

int h() {
  return f1() + f2();
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int main() {
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    - order of evaluation of subexpressions: `f(x) + g(y)`
    - addresses of allocations: `p = malloc(10)`
  - . . .
- $\Longrightarrow$ a violation witness can represent more executions
- it is considered valid if at least one of the represented executions violates the property

Correctness witnesses

- a correctness witness provides arguments that the program is correct
- it provides invariants for some locations
- it is considered valid if
  1. all the provided invariants are indeed invariants and
  2. the program satisfies the property
- witness validity does not depend on the relevance of the invariants in the witness to the property satisfaction

Witness format 1.0

aka GraphML witness format

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- based on automata represented in GraphML
- format for violation witnesses introduced in 2015
- correctness witnesses added in 2016
- semantics defined in terms of control flow automata (CFA)

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witness automaton

- a nondeterministic finite automaton accepting a set of program executions
- each edge is labelled with a pair (S, ψ) of
  - a source-code guard S representing a subset of CFA edges
  - a state-space guard ψ restricting the state space
- states are labelled with invariants
- sink states are non-accepting states without any successor

Source-code guards

- startline: *x* matches CFA edges that begin at line *x*
- endline: *x* matches CFA edges that end at line *x*
- startoffset: *x* matches CFA edges that start at column *x*
- endoffset: *x* matches CFA edges that end at column *x*
- control: *true*/*false* matches CFA edges entering *true*/*false* branch of a branching statement
- enterFunction: *name* matches calls of function *name*
- returnFromFunction: *name* matches returns from *name*
- enterLoopHead matches CFA edges entering a loop head (in CFA sense)
- support for concurrent programs: threadId and createThread
- an edge can contain more guards (all restrictions apply)

State-space guards

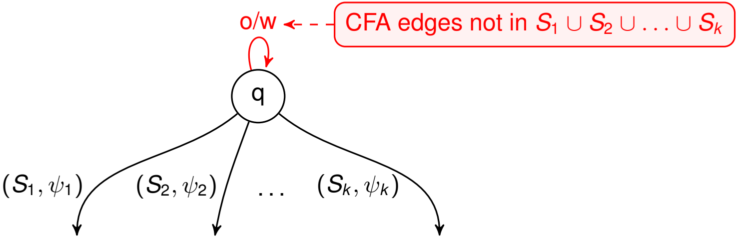
assumption: φ

- says that φ holds in the execution state immediately after the automaton edge is passed
- φ is an expression that
  - evaluates to a Boolean type or equivalent (`int` in C)
  - cannot contain function calls and cannot have any side-effects
  - can use only program variables and \result
- \result refers to the return value from the function given by assumption.resultfunction

Implicit loop edges

each non-sink state *q* has an implicit otherwise (o/w) loop with

- source-code guard that corresponds to all CFA edges not matched by explicit edges of *q* and



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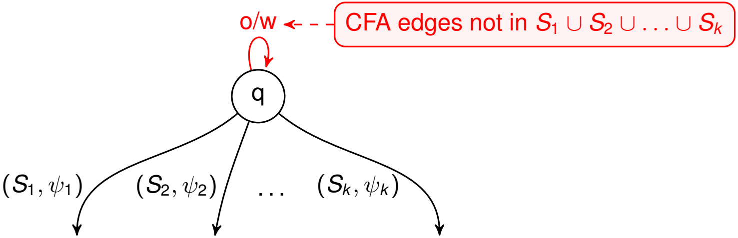

- state-space guard *true*

Violation witnesses

no invariants in automata states (*true* by default)

```c
void reach_error(){}
extern unsigned char __nondet_uchar(void);

int main() {
  unsigned char n = __nondet_uchar();
  if (n == 0) {
    return 0;
  }
  unsigned char v = 0;
  unsigned char s = 0;
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  while (i < n) {
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    s += v;
    ++i;
  }
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    return 1;
  }
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```

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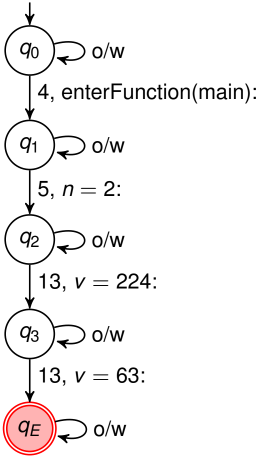

a label $S : \varphi$ is an abbreviation for (S, φ)
assumptions *true* are omitted

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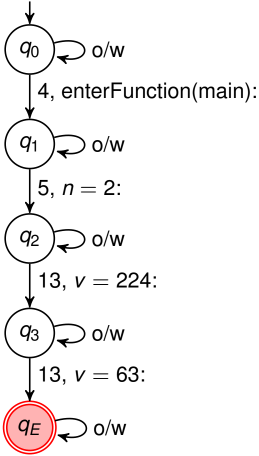

represents 1 violating execution

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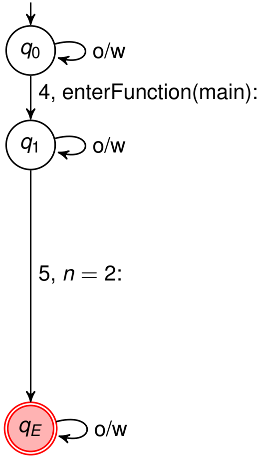

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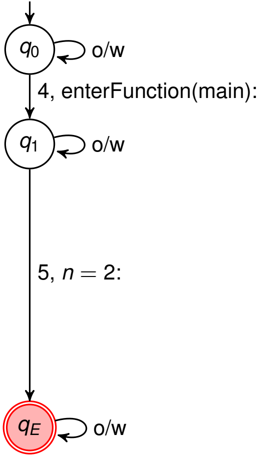

represents violating and non-violating executions

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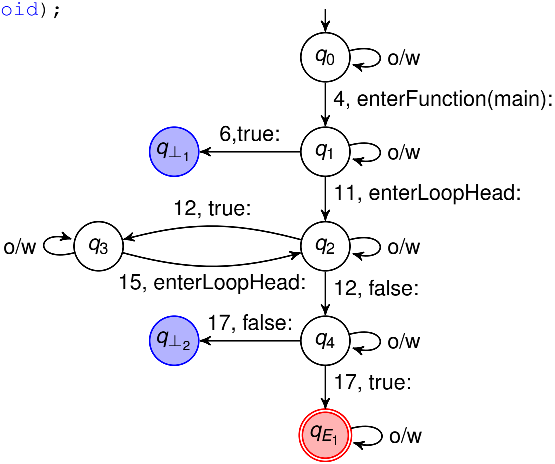

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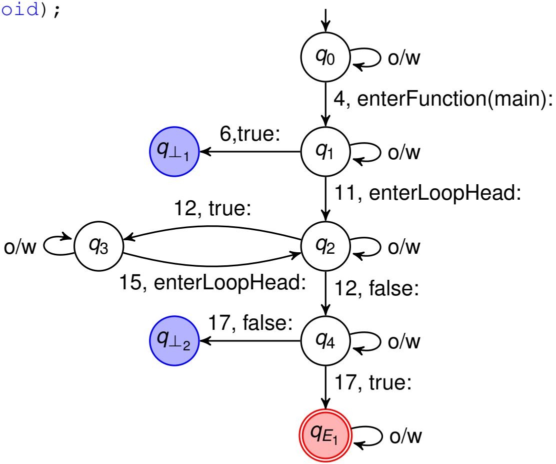

valid, but not very useful witness

Correctness witnesses

have to accept all executions, no sink nodes

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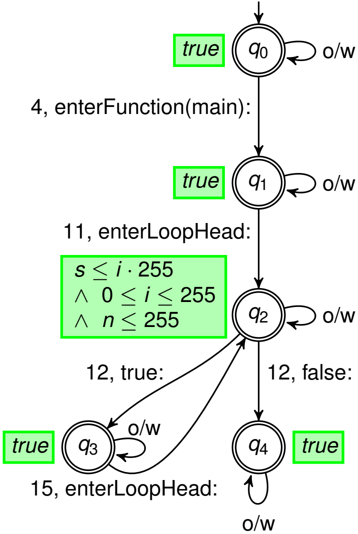

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witnesses contain also metadata about

- the corresponding verification task
- the witnessed verification result
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successes and fails of the GraphML format

+ widely accepted by the community
+ improved the quality of verification tools
+ other applications, e.g., cooperative verification
– witness validators do not support all features of the format
    - ignoring unsupported features may lead to incorrect verdict
– verifiers do not use the whole power of the format
– semantics given on CFA, but translation to CFA is ambiguous

Witness format 2.0

aka YAML witness format

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design goals

- clear semantics on source code
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design decisions

- start with the support of the most common properties and sequential programs and then extend it
- use YAML
- correctness witnesses specify invariants with the corresponding program locations
- violation witnesses describe executions with use of waypoints

Waypoints

waypoint = basic element of witnesses

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each waypoint has 4 aspects:

- action - the role within the witness
- location - code location the waypoint is associated to
  - file_name
  - file_hash (optional)
  - line
  - column (optional, the default is the first suitable column)
- type - the type of constraint it puts on runs
- constraint - the constraint itself

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5. target
   - location: the statement that violates the property
   - constraint: has to be omitted

Waypoint actions

- follow - the waypoint has to be passed as soon as the location is entered
- avoid - the run represented by the witness must not pass the waypoint (“sink node”)

Waypoint actions

➡ follow - the waypoint has to be passed as soon as the location is entered

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STOP - follow waypoint of type target

Segments

- sequence of 0+ avoid waypoints ended by 1 follow or target waypoint
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- segments ended by a target waypoint are final segments

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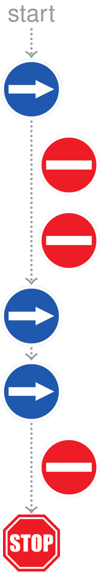
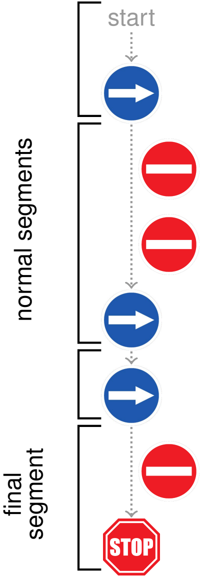
an execution matches a witness if

- it has a prefix that can be divided into parts that match the corresponding normal segments
- the rest does not pass any avoid waypoint of the final segment
- it violates the specified property by the target statement

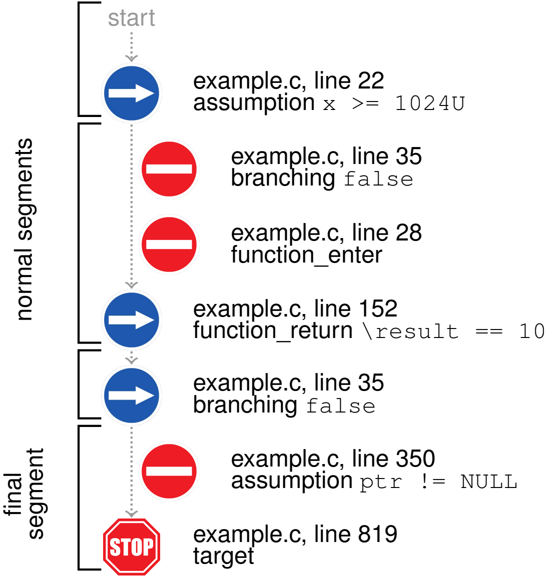
Witness example



Witness example



Witness example



start

normal segments

example.c, line 22
assumption `x >= 1024U`

example.c, line 35
branching `false`

example.c, line 28
function_enter

example.c, line 152
function_return `\result == 10`

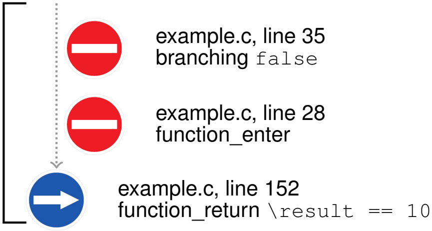
example.c, line 35
branching `false`

final segment

example.c, line 350
assumption `ptr != NULL`

example.c, line 819
target

Witness example - YAML notation



example.c, line 35
branching `false`

example.c, line 28
function_enter

example.c, line 152
function_return `\result == 10`

```yaml
- segment:
  - waypoint:
    action: avoid
    type: branching
    location:
      file_name: example.c
      line: 35
    constraint:
      value: false
  - waypoint:
    action: avoid
    type: function_enter
    location:
      file_name: example.c
      line: 28
  - waypoint:
    action: follow
    type: function_return
    location:
      file_name: example.c
      line: 152
    constraint:
      value: \result == 10
```

Correctness witnesses

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

```yaml
- entry_type: invariant_set
  metadata: <...>
  content:
  - invariant:
      type: loop_invariant
      location:
        file_name: "inv-a.c"
        line: 12
        column: 1
        function: main
      value: "s <= i*255 && 0 <= i && i <= 255 && n <= 255"
      format: c_expression
```

Notes

witness format 2.0

- published in 2024
- increasing number of verifiers and validators supporting the format
- better interoperability compared to the old format
- a bit less expressive than the old format
- should be the new standard of SV-COMP in several years
- needs to be extended to support
  - parallel programs
  - correctness witnesses for memory safety
  - violation and correctness witnesses of termination
  - . . .

Competition on Software Verification: SV-COMP

- running every year since 2012
- very popular and growing repository of C and Java verification tasks marked with expected results
- scoring schema

1	point for finding a program bug (if witness is validated)
2	points for proving correctness (if witness is validated)
-16	points for reporting bug in a correct program (false alarm)
-32	points for claiming correctness of an incorrect program (false negative)

  - points in the overall score are weighted by category sizes
- graphs indicate winners, speed, sequential portfolio of algorithms in tools, the number of incorrect answers, programming language of tools, . . .

`https://sv-comp.sosy-lab.org`

Competition on Software Testing: Test-Comp

- running every year since 2019
- uses the same benchmarks as SV-COMP
- the goal is to generate a test suit that
  - finds an error (category Cover-Error), benchmarks are programs with an error
  - has a high branch coverage (category Cover-Branches)

`https://test-comp.sosy-lab.org`