Open Source Formal Verification

engines

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Introduction

Model Checking

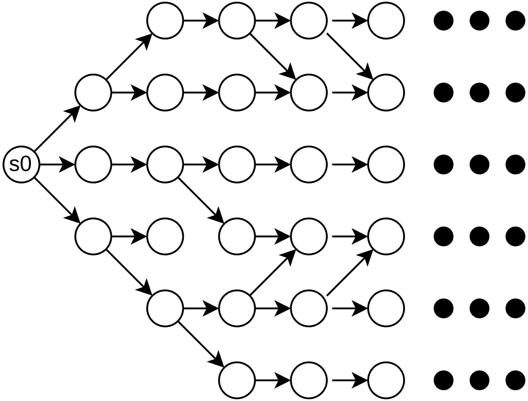
Model checking

Method for checking whether a finite-state model of a system meets a given specification

- Applied to state machines
  - A hardware model is by itself a state machine
    - State represented by the D flip-flops and memories
    - Inputs are simply the inputs of the module
  - The specification is given by properties and invariants

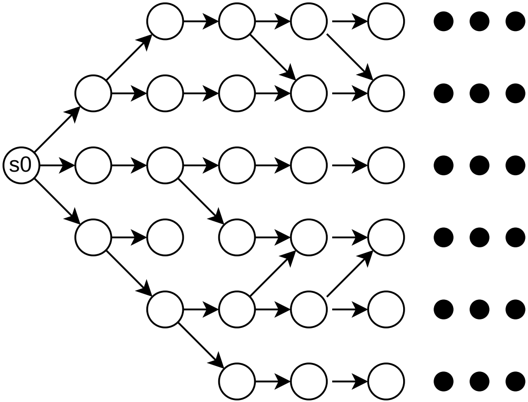
Model Checking

- Concept:
  - From a reset condition
  - Try to find a state where an assertion fails
- Process:
  1. Start from an initial state
  2. Check that assertions hold
  3. Generate the next states
  4. Back to 2
- *Success* if no failure is detected
- *Fail* if an assertion fails
- *Unconclusive* if the entire state space cannot be reached



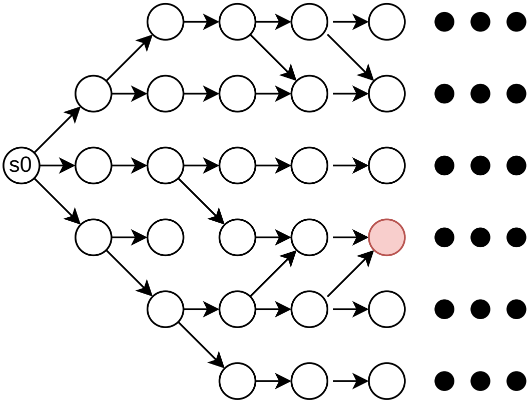
Bounded Model Checking

- Concept:
  - From a reset condition
  - Try to find a state where an assertion fails
  - For at most *N* steps (the depth)
- Process:
  1. Start from an initial state
  2. Check that assertions hold
  3. Generate the next states
  4. Back to 2
- *Success* if no failure is detected
- *Fail* if an assertion fails
- *Unconclusive* if the entire state space cannot be reached



Bounded Model Checking

- Red state corresponds to a failing assertion
- Found after 5 cycles
- If the depth is at least 5, then the failure will be detected
- If the depth is less that 5, then the checker will not detect it



What depth?

- Crucial question: What depth?
  - Too short $\Rightarrow$ Does not verify anything
  - Too big $\Rightarrow$ Too much processing time
- Depends on the system
- Examples:
  - For a FIFO, it seems fair not to check more writes than 4 times the FIFO size
  - For a counter, if it offers a load operation, 2-3 steps are sufficient
  - For a counter, without a load operation, should be at least the maximum value
    - A good argument for generic parameters

Proof

- BMC is not ideal because of the depth to be chosen
- Can we prove the correctness?
- Option: k-induction

k-induction

- Concept: Check correctness of K steps and then prove that if any K steps are correct, then the $(K+1)^{th}$ will be correct

Example: 1-induction

$$P(0) \wedge \forall n(P(n) \Rightarrow P(n+1)) \Rightarrow \forall n P(n)$$

Example: 2-induction

$$P(0) \wedge P(1) \wedge \forall n((P(n) \wedge P(n+1)) \Rightarrow P(n+2)) \Rightarrow \forall n P(n)$$

Interesting: `http://www.ccs.neu.edu/home/wahl/Publications/k-induction.pdf`

k-induction

- Mathematically, k-induction is identical to 1-induction
- Why k?
- Because it helps the proof, starting with more initial conditions

Verification

- The proof exploits a solver
- The solvers are usually based on SAT or SMT solvers
- SAT (Boolean satisfiability problem)
  - Is there a combination of variables that satisfy a boolean equation in its conjunctive form?
  - $(x1 \lor x3) \land (\overline{x2} \lor x3) \land (x1 \lor \overline{x3})$
  - NP-complete problem
- SMT (satisfiability modulo theories)
  - Generalizes SAT to more complex formulas involving:
    - Real numbers, integers
    - Lists, arrays, bit vectors
    - ...

Engines in SBY

Mode	**Engine**
bmc	smtbc [all solvers] btor btormc btor pono abc bmc3 abc sim3 aiger aigbmc
prove	smtbmc [all solvers] abc pdr aiger suprove
cover	smtbmc [all solvers] btor btormc

smtbmc solvers (1)

- The SMTBMC engine supports the following solvers:
  - yices (`https://yices.csl.sri.com/`)
    - Yices 2 is an SMT solver that decides the satisfiability of formulas containing uninterpreted function symbols with equality, real and integer arithmetic, bitvectors, scalar types, and tuples.
  - boolector (`https://boolector.github.io/`)
    - A Satisfiability Modulo Theories (SMT) solver for the theories of fixed-size bit-vectors, arrays and uninterpreted functions.
  - bitwuzla (`https://bitwuzla.github.io/`)
    - Bitwuzla is a Satisfiability Modulo Theories (SMT) solver for the theories of fixed-size bit-vectors, floating-point arithmetic, arrays and uninterpreted functions and their combinations.
  - z3 (`https://github.com/Z3Prover/z3`)
    - Z3 is a theorem prover from Microsoft Research.

smtbmc solvers (2)

- The SMTBMC engine supports the following solvers:
  - mathsat (https://mathsat.fbk.eu/)
    - MathSAT 5 is an efficient Satisfiability modulo theories (SMT) solver supporting a wide range of theories (including e.g. equality and uninterpreted functions, linear arithmetic, bit-vectors, and arrays) and functionalities.
  - cvc4 (https://cvc4.github.io/)
    - CVC4 is an efficient open-source automatic theorem prover for satisfiability modulo theories (SMT) problems. It can be used to prove the validity (or, dually, the satisfiability) of first-order formulas in a large number of built-in logical theories and their combination.
  - cvc5 (https://cvc5.github.io/)
    - cvc5 is an efficient open-source automatic theorem prover for Satisfiability Modulo Theories (SMT) problems. It can be used to prove the satisfiability (or, dually, the validity) of first-order formulas with respect to (combinations of) a variety of useful background theories.

btor

- The btor engine works with btor2 files. It supports the following solvers:
  - btormc: `https://github.com/Boolector/boolector`
  - pono: `https://github.com/stanford-centaur/pono`

aiger

- The aiger engine (`https://github.com/arminbiere/aiger`) offers two solvers:
  - aigbmc
  - suprove (quite good for proofs)

abc

- The abc engine (`https://github.com/berkeley-abc/abc`) offers three solvers:
  - pdr (most used)
  - bmc3
  - sim3

Prove vs BMC

- A proof can be faster than bounded model checking
- For BMC you need to setup the depth
  - Choice to be made
    - As small as possible, but not smaller
    - *"Aussi petite que possible, mais aussi grande que nécessaire"*

Conclusion

A proof is better than bounded model checking

$\Rightarrow$

Use a proof is possible, else go for model checking

- Do not hesitate to compare various engines to find the most efficient one
  - Can be done by hand
  - or with the `--autotune` option of `sby`
  - Reduces the computing time for regression tests