Extended Finite-State Machine Induction using SAT-Solver

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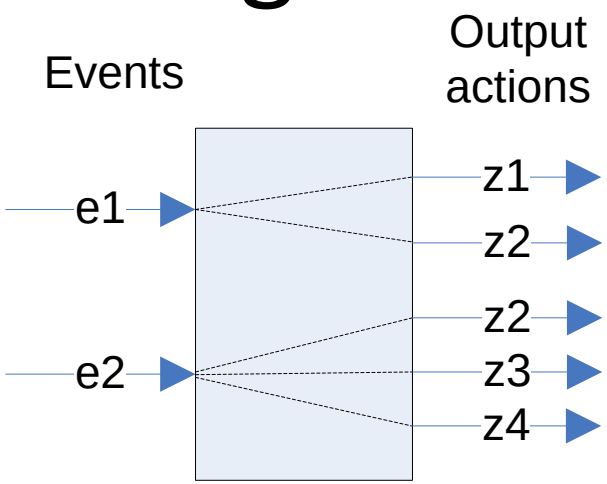
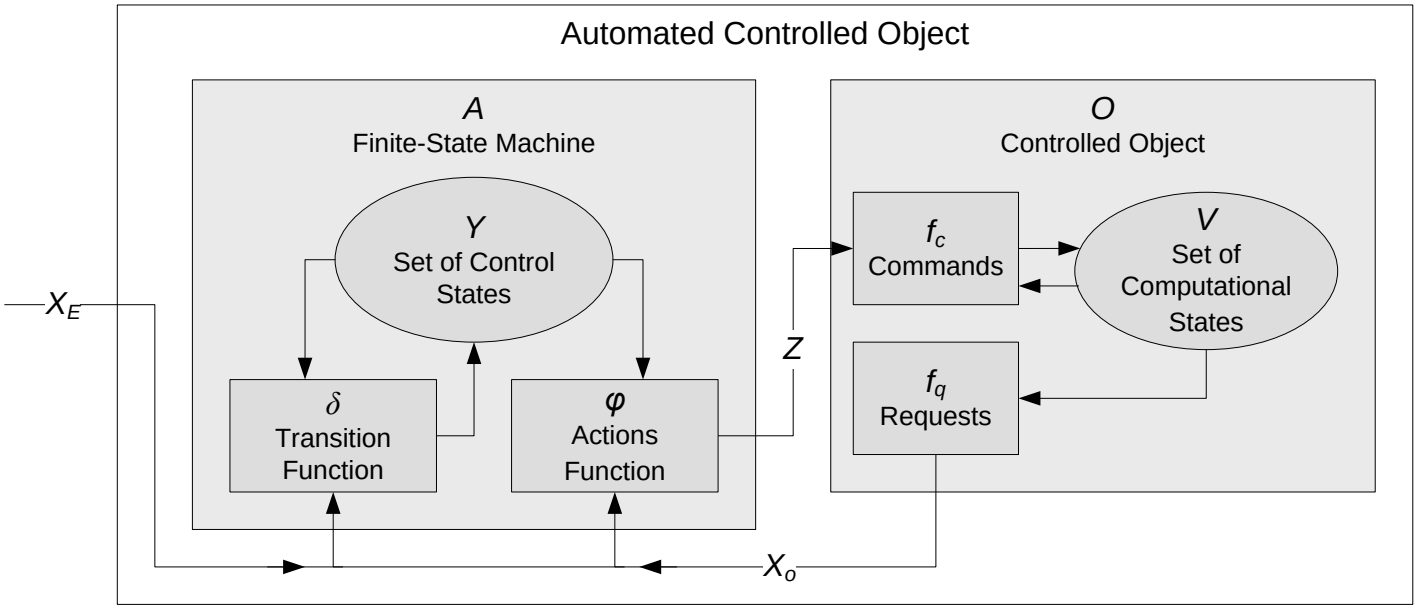
Automata-based Programming

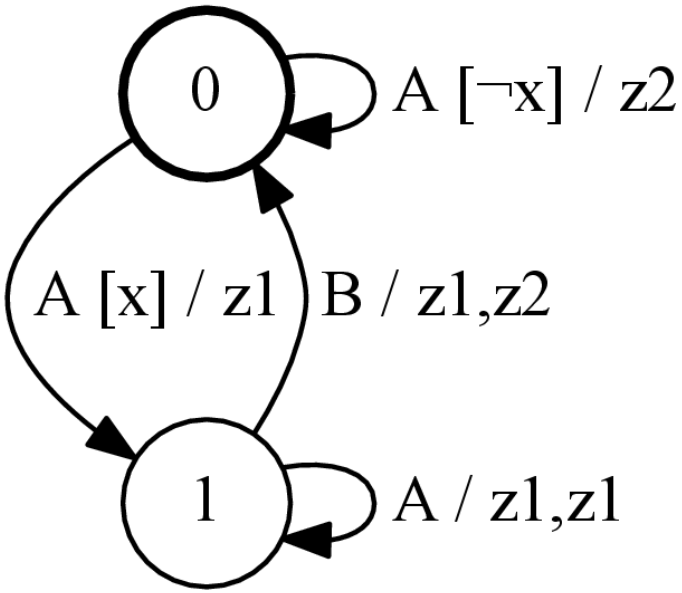
- Programs with complex behavior should be designed using automated controlled objects





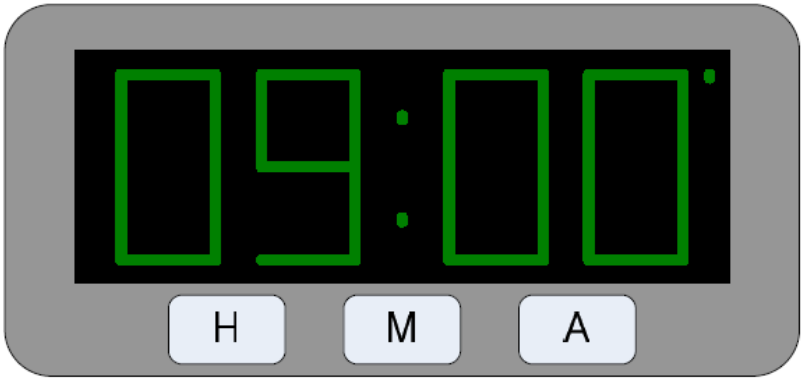
Extended Finite-State Machine and Test Scenarios

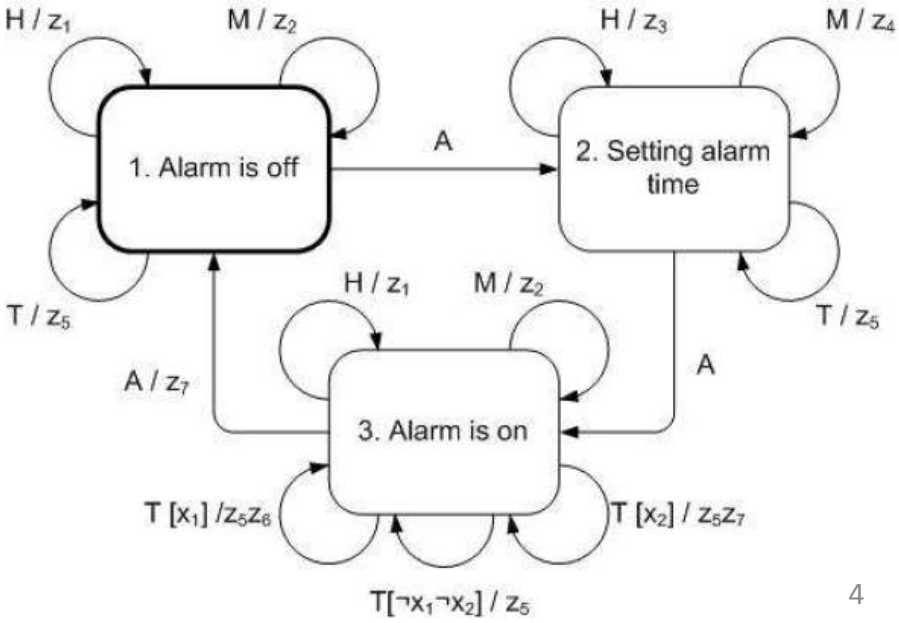
- EFSM:
  - input events
  - input Boolean variables
  - output actions
- Test scenario is a sequence of triples <*e*, *f*, *A*>
  - *e* – input event
  - *f* – guard condition – Boolean formula of input variables
  - *A* – sequence of output actions
- EFSM on the picture complies with <*A*, ¬*x*, (*z*2)> <*A*, *x*, (*z*1)>
- EFSM on the picture does not comply with <*A*, *x*, (*z*2)>



EFSM Example

- Alarm clock
- Four events
  - H – button “H” pressed
  - M – button “M” pressed
  - A – button “A” pressed
  - T – occurs on each time tick
- Two input variables
- Seven output actions





Goal of the Work

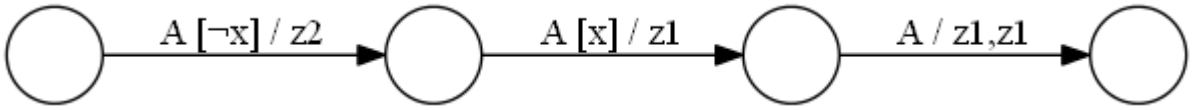
- Focus on automata-based programs with only one automated controlled object
- Given:
  - Set of test scenarios (Sc)
  - Number of EFSM states (*C*)
- Need to find a EFSM with *C* states complying with all scenarios

Works of Other Authors

- DFA and FST induction with genetic algorithms:
  - Lucas, S., Reynolds, J. *Learning DFA:* Evolution versus Evidence Driven State Merging. *The 2003 Congress on Evolutionary Computation* (CEC '03). Vol. 1, pp. 351–358.
  - Lucas, S., Reynolds, J. Learning Deterministic Finite Automata with a Smart State Labeling Algorithm. *IEEE Transactions on Pattern Analysis and Machine Intelligence*. Vol. 27, №7, 2005, pp. 1063–1074.
  - Lucas, S. Evolving Finite-State Transducers: Some Initial Explorations. *Lecture Notes in Computer Science*. Springer Berlin / Heidelberg. Volume 2610/2003, pp. 241–257.
  - Johnson, C. Genetic Programming with Fitness based on Model Checking. *Lecture Notes in Computer Science*. Springer Berlin / Heidelberg, 2007. Volume 4445/2007, pp. 114–124.
- DFA induction using SAT-solvers
  - Heule M., Verwer S. Exact DFA identification using sat solvers. *Grammatical Inference: Theoretical Results and Applications 10th International Colloquium, ICGI 2010*, ser. Lecture Notes in Computer Science, J. M. Sempere and P. Garca, Eds., vol. 6339. Springer, 2010, pp. 66–79.

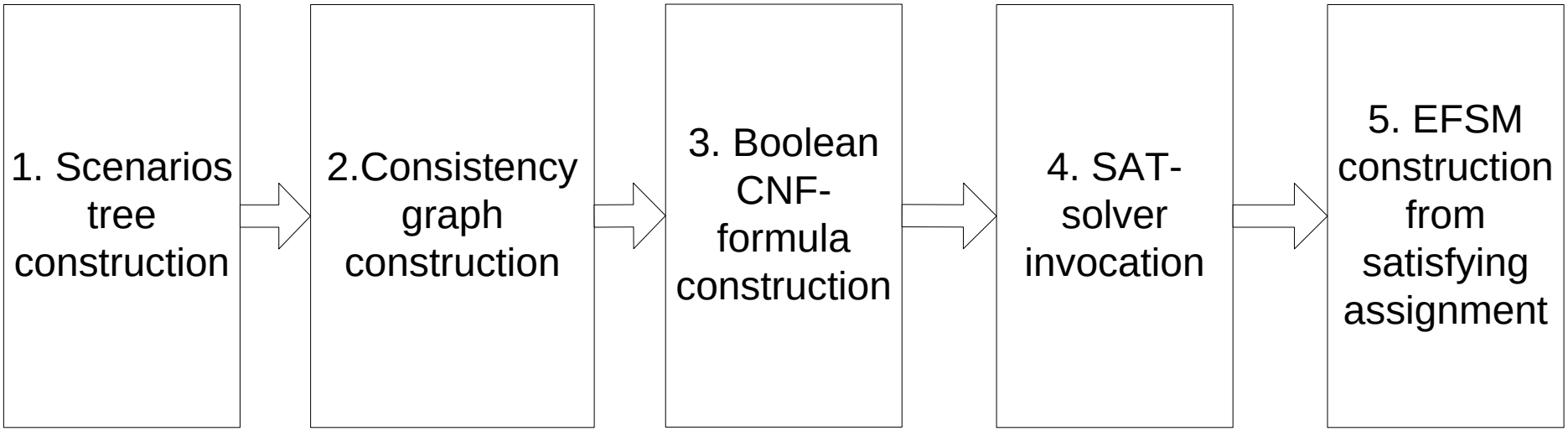
Main Idea

- Each scenario is similar to “linear” automaton



- Scenarios “coloring”
  - Each “state” of each scenario is to be mapped to some state of resulting EFSM
  - States of resulting EFSM <-> colors

Algorithm Outline

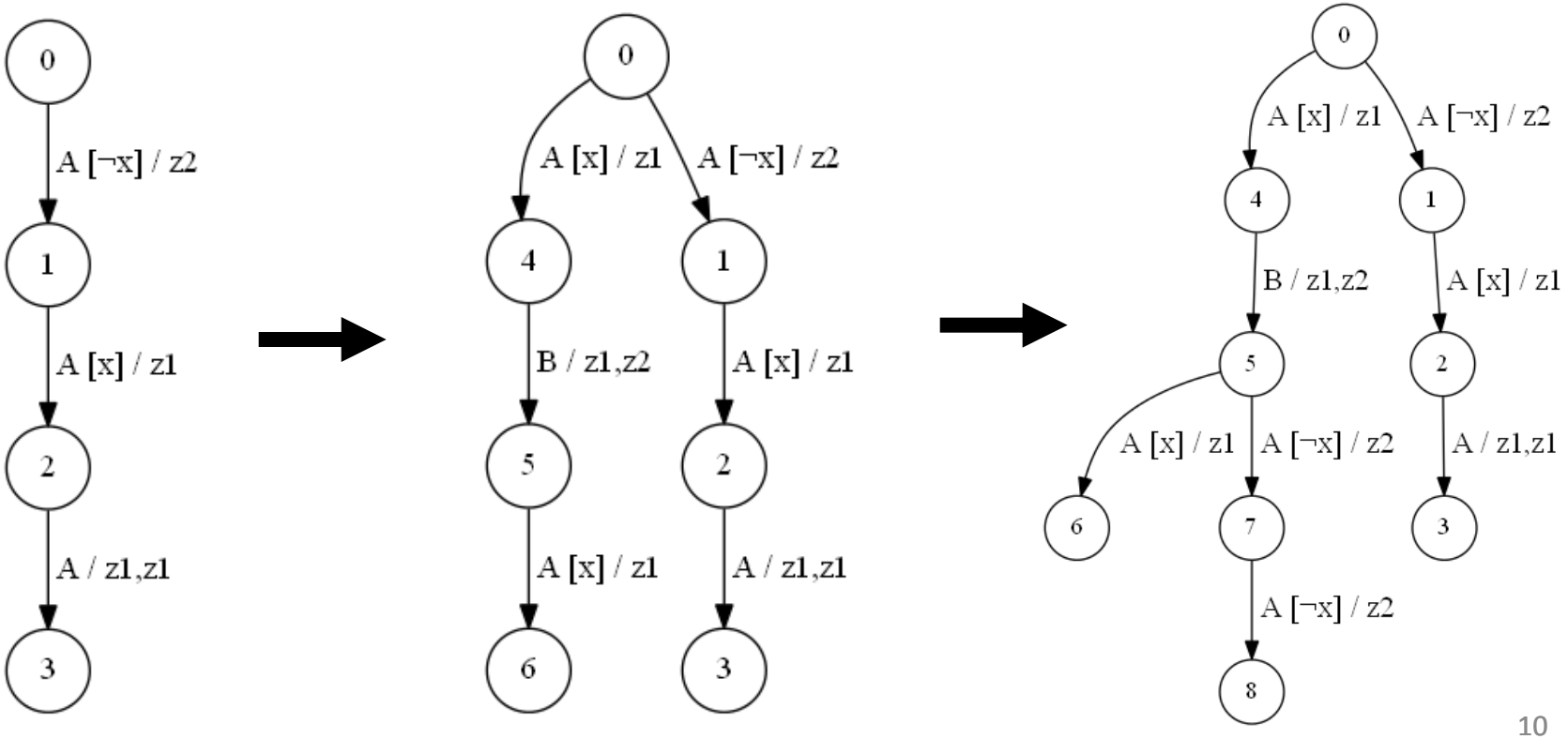


Precomputations

- For each pair of guard conditions from scenarios compute:
  - If they are same as Boolean functions
  - If they have common satisfying assignment
- Time complexity:
  - $O(n^2 2^{2m})$ where n is total size of scenarios, m is maximal number of input variables occurring in guard condition (in practice m is not greater than 5)

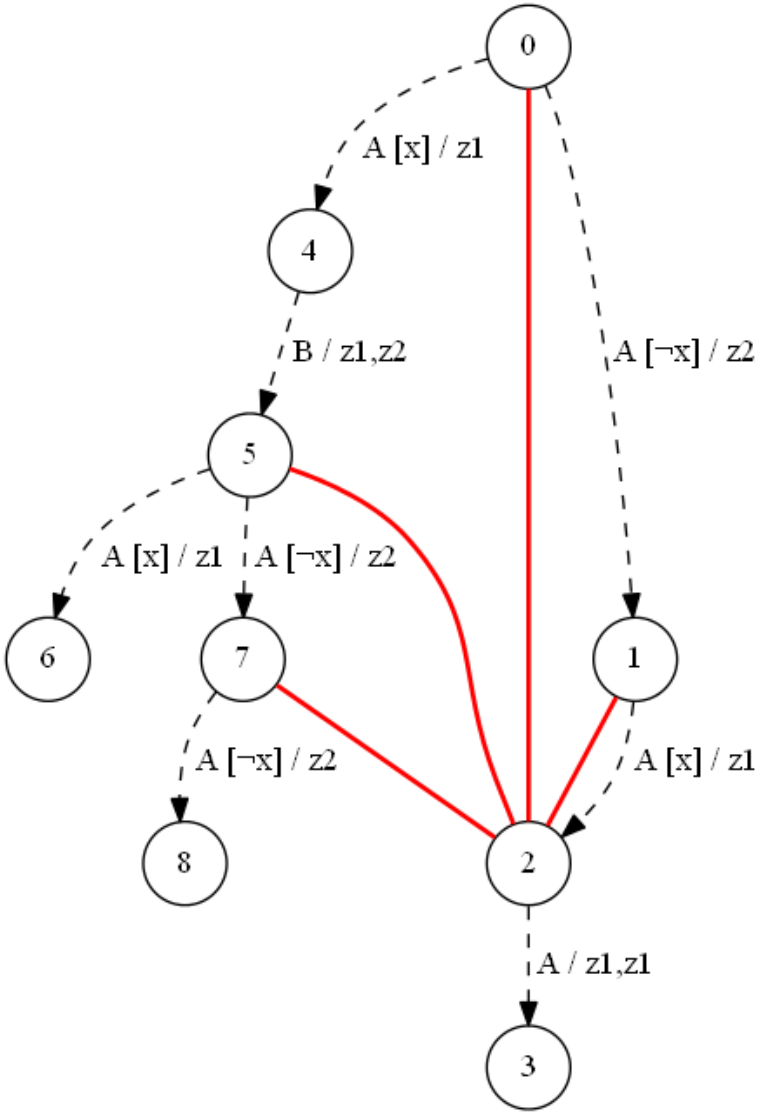
1. Scenarios Tree Construction

- Similar to syntax tree construction algorithm
- If contradiction is found, process is terminated



2. Consistency Graph Construction

- Vertices are same as in scenarios tree
- Two vertices are connected by an edge if there is a sequence telling them apart
- Sets of inconsistent vertices are constructed for each tree vertex starting from leaves using dynamic programming



3. Boolean CNF-formula construction (1)

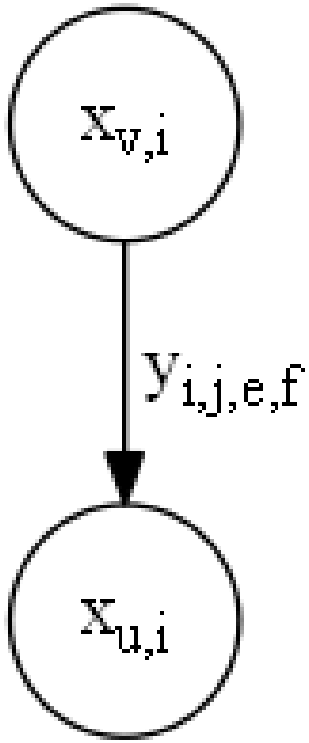
- Variables:
  - $x_{v,i}$ – is it true that vertex v has color i
  - $y_{a,b,e,f}$ – is it true that in resulting EFSM exists a transition from state a to state b labeled with event e and formula f

3. Boolean CNF-formula construction (2)

- Types of clauses:
  - $(x_{v,1} \vee \ldots \vee x_{v,C})$ – each vertex should be colored with some color
  - $(\neg x_{v,i} \vee \neg x_{v,j})$ – no vertex can be colored with two colors simultaneously
  - $(\neg x_{v,i} \vee \neg x_{u,i})$ – no pair of inconsistent vertices can be colored with same color
  - $(\neg y_{i,j,e,f} \vee \neg y_{i,k,e,f})$ – there is no more than one transition from each state of resulting EFSM marked with same event (e) and Boolean formula (f)

3. Boolean CNF-formula construction (3)

- Types of clauses:
  - $(y_{i,j,e,f} \vee \neg x_{v,i} \vee \neg x_{u,j})$ – each edge of scenarios tree must be present in resulting EFSM
  - $(\neg y_{i,j,e,f} \vee \neg x_{v,i} \vee x_{u,j})$ – vertex colors should not contradict with edges of scenarios tree

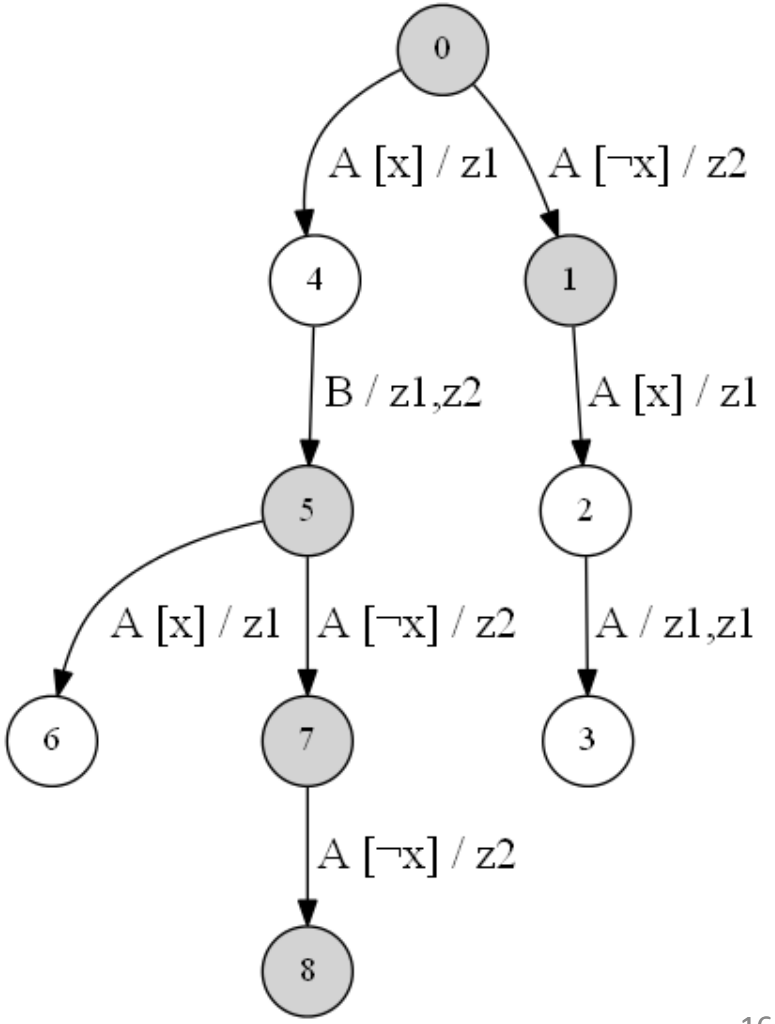


4. SAT-solver invocation

- CNF-formula is represented using DIMACS CNF format
- We use *cryptominisat* SAT-solver – winner of SAT RACE 2010

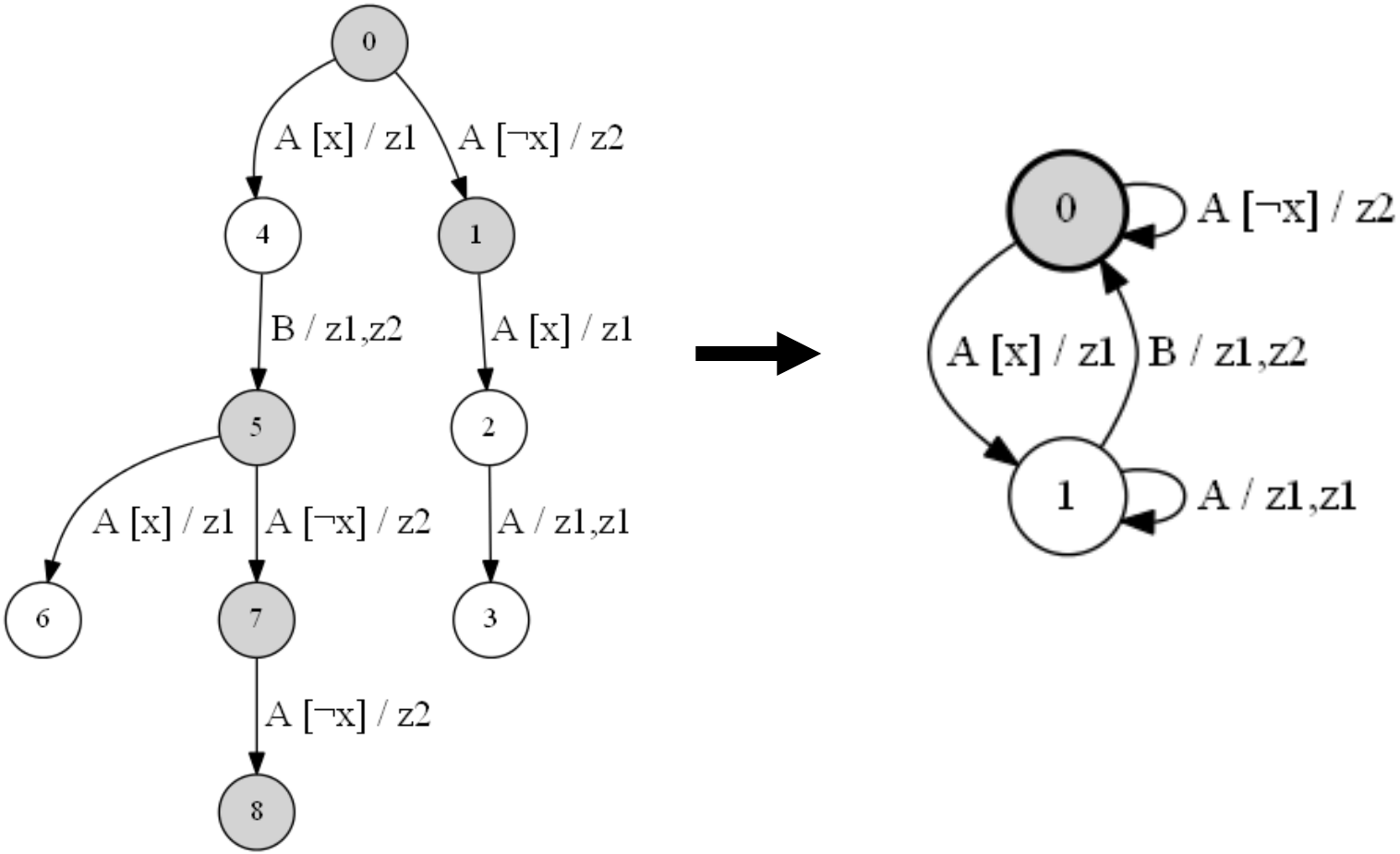
5. EFSM construction from satisfying assignment (1)

- Scenarios tree coloring
- Each vertex gets a color according to $x_{v,i}$ values



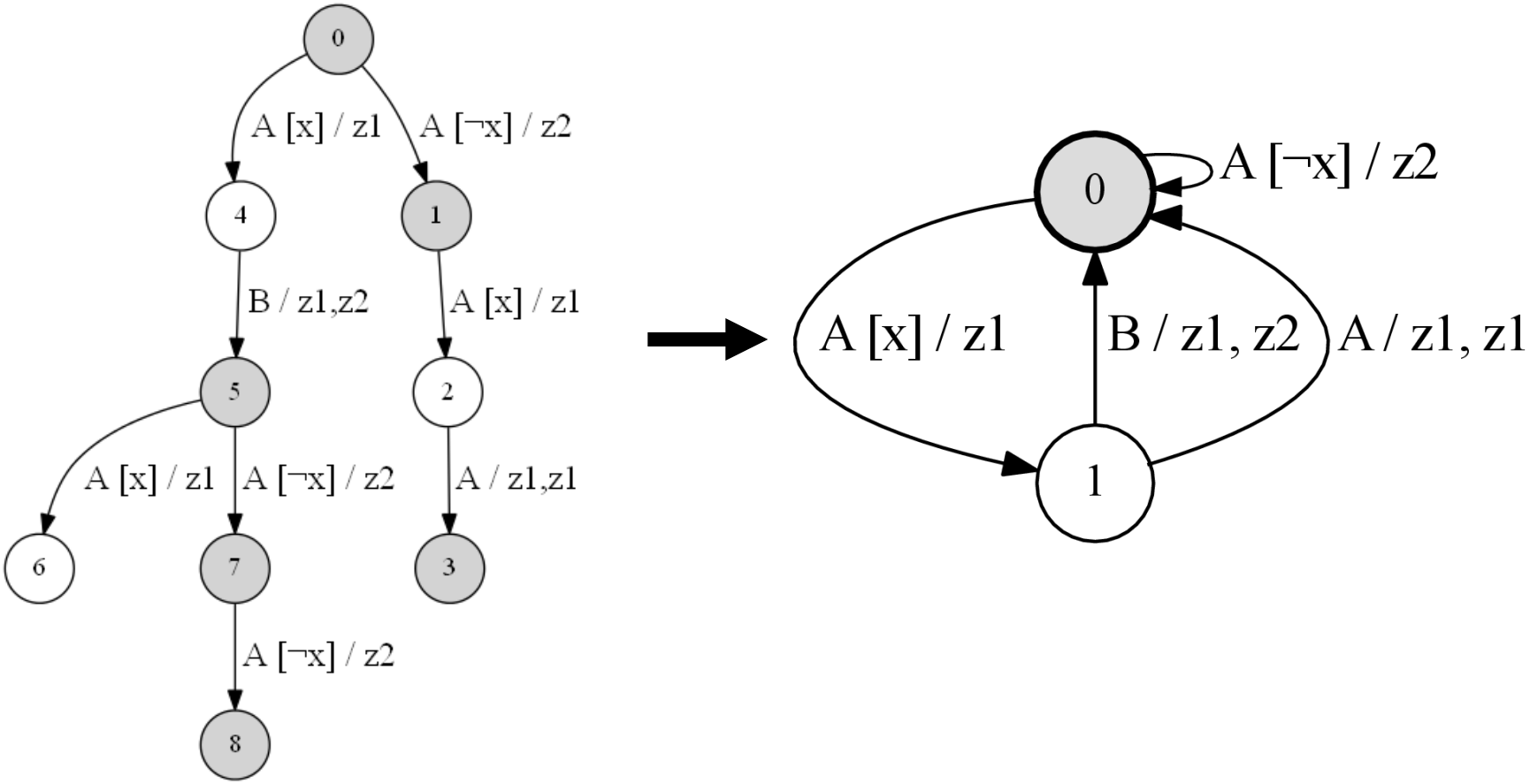
5. EFSM construction from satisfying assignment (2)

- All vertices with the same color are merged



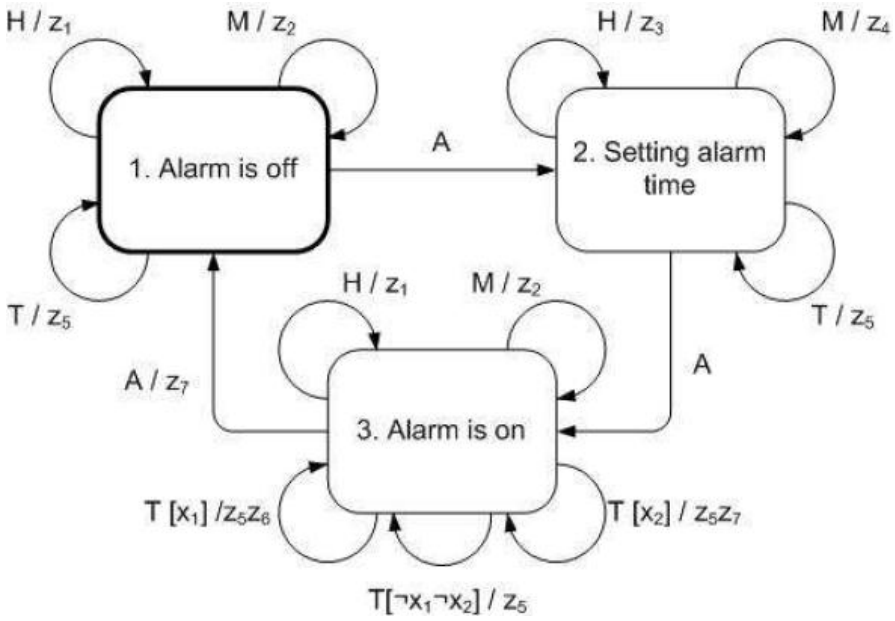
5. EFSM construction from satisfying assignment (3)

- Coloring is not necessarily unique



Experiments

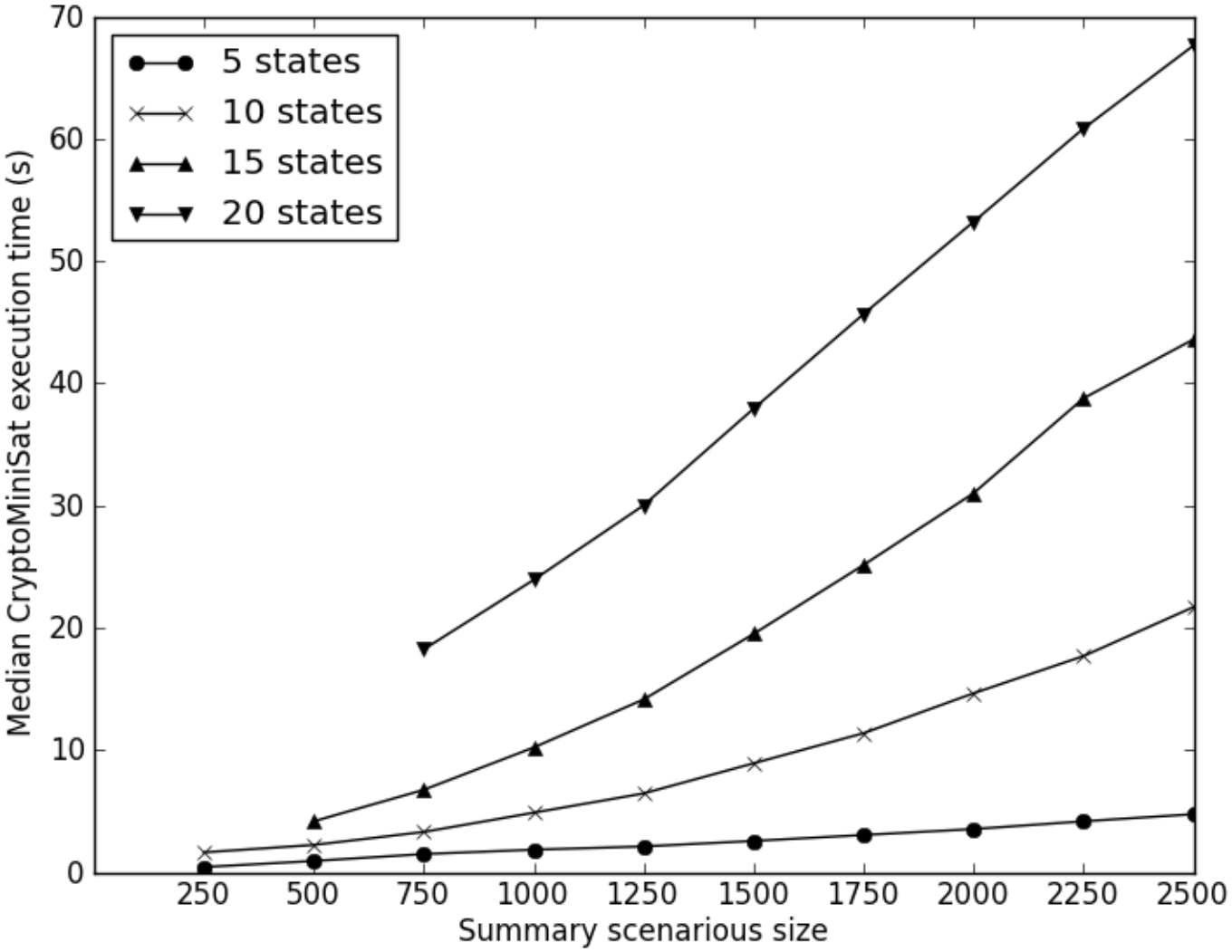
- First experiment – EFSM for alarm clock:
  - 38 scenarios of total length 242
  - Running time – 0.25 seconds
  - Genetic algorithm ~ 4 minutes



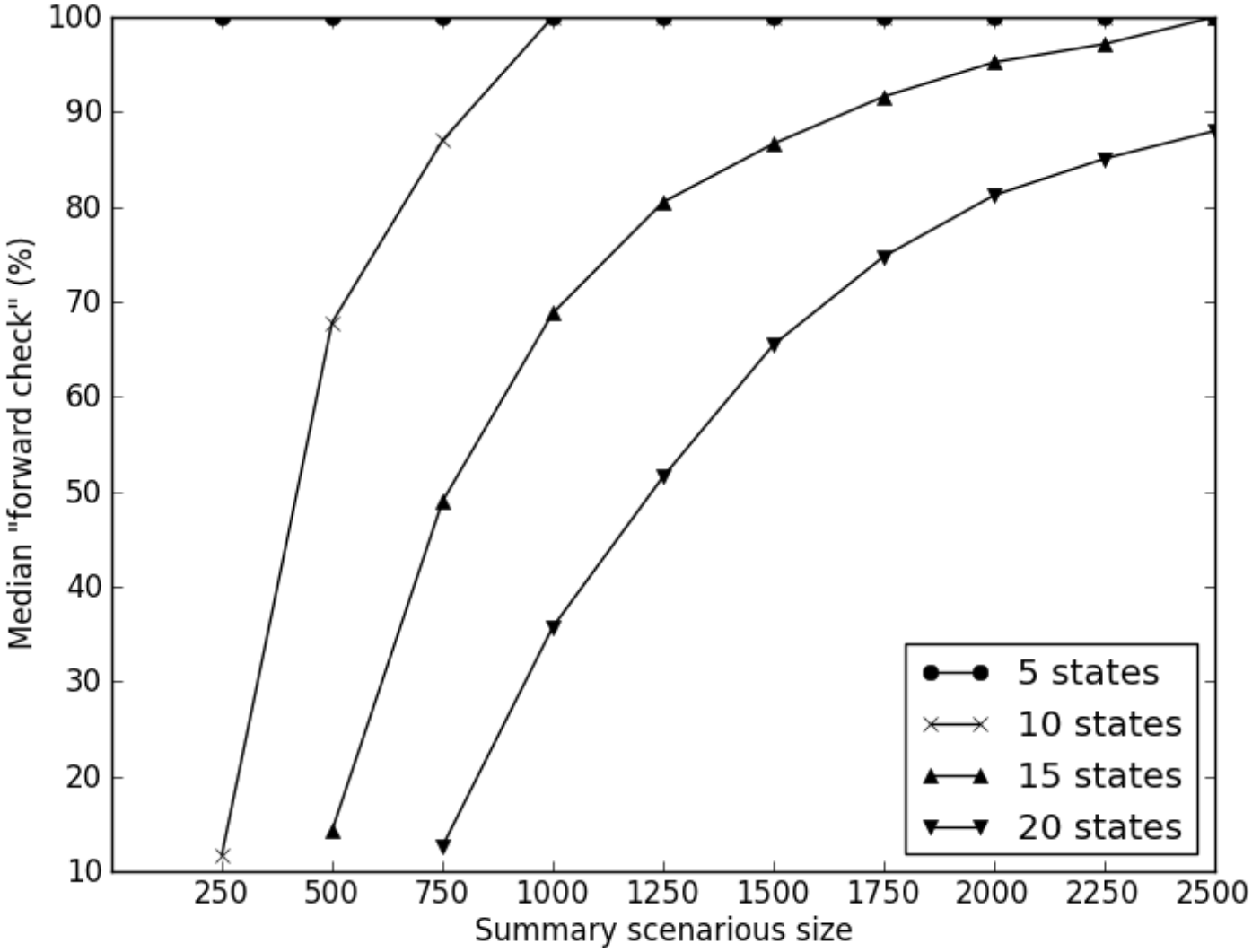
Second experiment

- Random EFSM *A*1 with *n* states generation
- Test scenarios generation (random paths in *A*1) with total size *l*
- EFSM *A*2 with *n* states induction
- “Forward check”
  - 1000*n* random scenarios of length 4*n* are generated from *A*1
  - *A*2 is checked against each of these scenarios
  - The part of scenarios *A*2 complies with is recorded
- 1000 runs for each *n* and *l*

Median execution time



Median “forward check” percent



Future work

- Use CSP-solver to fix errors in scenarios
- Use Ant Colony Optimization Algorithms for EFSM induction (ANTS'12)
- Negative scenarios
- Verification

Results

- A method for EFSM induction based on reduction to SAT problem was proposed
- It was tested and proved to be much faster than genetic algorithm for the same problem

Thank you!

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