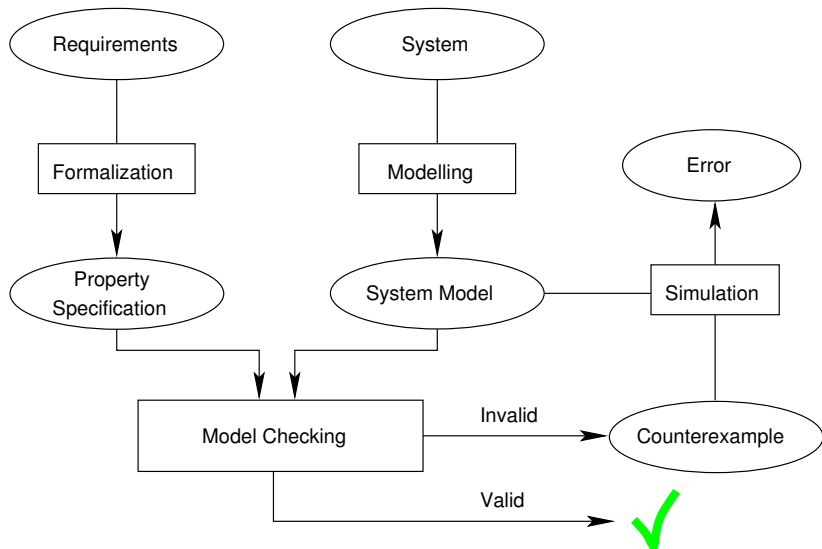


IA169 System Verification and Assurance

LTL Model Checking (continued)

Jiří Barnat

Model Checking – Schema



Property Specification

- English text.
- Formulae of Linear Temporal Logic.

System Description

- Source code in programming language.
- Source code in modelling language.
- Kripke structure representing the state space.

Problem

- Kripke structure M
- LTL formula φ
- $M \models \varphi$?

Automata-Based Approach to LTL Model Checking

Observation One

- System is a set of (infinite) runs.
- Also referred to as formal language of infinite words.

Observation Two

- Two different runs are equal with respect to an LTL formula if they agree in the interpretation of atomic propositions (need not agree in the states).
- Let $\pi = s_0, s_1, \dots$, then $I(\pi) \stackrel{def}{\iff} I(s_0), I(s_1), I(s_2), \dots$

Observation Three

- Every run either satisfies an LTL formula, or not.
- Every LTL formula defines a set of satisfying runs.

Reformulation as Language Problem

- Let $\Sigma = 2^{AP}$ be an alphabet.
- Language L_{sys} of all runs of system M is defined as follows.

$$L_{sys} = \{I(\pi) \mid \pi \text{ is a run in } M\}.$$

- Language L_φ of runs satisfying φ is defined as follows.

$$L_\varphi = \{I(\pi) \mid \pi \models \varphi\}.$$

Observation

$$M \models \varphi \iff L_{sys} \subseteq L_\varphi$$

Theorem

- For every LTL formula φ we can construct Büchi automaton A_φ such that $L_\varphi = L(A_\varphi)$.

[Vardi and Wolper, 1986]

Theorem

- For every Kripke structure $M = (S, T, I, s_0)$ we can construct Büchi automaton A_{sys} such that $L_{sys} = L(A_{sys})$.

Construction of A_{sys}

- Let AP be a set of atomic propositions.
- Then $A_{sys} = (S, 2^{AP}, s_0, \delta, S)$, where $q \in \delta(p, a)$ if and only if $(p, q) \in T \wedge I(p) = a$.

Property Specification

- English text.
- Formulae φ of Linear Temporal Logic.
- Buchi automaton accepting L_φ .

System Description

- Source code in programming language.
- Source code in modelling language.
- Kripke structure M representing the state space.
- Buchi automaton accepting L_{sys} .

Problem Reformulation

- $M \models \varphi \iff L_{sys} \subseteq L_\varphi$

Notation

- $co-L$ denotes complement of L with respect to Σ^{AP} .

Lemma

- $co-L(A_\varphi) = L(A_{\neg\varphi})$ for every LTL formula φ .

Reduction of $M \models \varphi$ to the emptiness of $L(A_{sys} \times A_{\neg\varphi})$

- $M \models \varphi \iff L_{sys} \subseteq L_\varphi$
- $M \models \varphi \iff L(A_{sys}) \subseteq L(A_\varphi)$
- $M \models \varphi \iff L(A_{sys}) \cap co-L(A_\varphi) = \emptyset$
- $M \models \varphi \iff L(A_{sys}) \cap L(A_{\neg\varphi}) = \emptyset$
- $M \models \varphi \iff L(A_{sys} \times A_{\neg\varphi}) = \emptyset$

Theorem

- Let $A = (S_A, \Sigma, s_A, \delta_A, F_A)$ and $B = (S_B, \Sigma, s_B, \delta_B, F_B)$ be Büchi automata over the same alphabet Σ . Then we can construct Büchi automaton $A \times B$ such that $L(A \times B) = L(A) \cap L(B)$.

Construction of $A \times B$

- $A \times B = (S_A \times S_B \times \{0, 1\}, \Sigma, (s_A, s_B, 0), \delta_{A \times B}, F_A \times S_B \times \{0\})$
- $(p', q', j) \in \delta_{A \times B}((p, q, i), a)$ for all
 - $p' \in \delta_A(p, a)$
 - $q' \in \delta_B(q, a)$
 - $j = (i + 1) \bmod 2$ if $(i = 0 \wedge p \in F_A) \vee (i = 1 \wedge q \in F_B)$
 - $j = i$ otherwise

Observation

- For the purpose of LTL model checking, we do not need general synchronous product of Büchi automata, since Büchi automaton A_{sys} is constructed in such a way that $F_A = S_A$, i.e. it has all states accepting.
- For such a special case the construction of product automata can be significantly simplified.

Construction of $A \times B$ when $F_A = S_A$

- $A \times B = (S_A \times S_B, \Sigma, (s_A, s_B), \delta_{A \times B}, S_A \times F_B)$
- $(p', q') \in \delta_{A \times B}((p, q), a)$ for all
 - $p' \in \delta_A(p, a)$
 - $q' \in \delta_B(q, a)$

Observation

- Any finite automaton may visit accepting state infinitely many times only if it contains a cycle through that accepting state.

Decision Procedure for $M \models \varphi$?

- Build a product automaton $(A_{sys} \times A_{\neg\varphi})$.
- Check the automaton for presence of an accepting cycle.
- If there is a reachable accepting cycle then $M \not\models \varphi$.
- Otherwise $M \models \varphi$.

Detection of Accepting Cycles

Reachability in Directed Graph

- Depth-first or breadth-first search algorithm.
- $\mathcal{O}(|V| + |E|)$.

Algorithmic Solution to Accepting Cycle Detection

- Compute the set of accepting states in time $\mathcal{O}(|V| + |E|)$.
- Detect self-reachability for every accepting state in $\mathcal{O}(|F|(|V| + |E|))$.
- Overall time $\mathcal{O}(|V| + |E| + |F|(|V| + |E|))$.

Can we do better?

- Yes, with **Nested DFS** algorithm in $\mathcal{O}(|V| + |E|)$.

Depth-First Search Procedure

```
proc Reachable( $V, E, v_0$ )
  Visited =  $\emptyset$ 
  DFS( $v_0$ )
  return (Visited)
end

proc DFS(vertex)
  if vertex  $\notin$  Visited
    then /* Visits vertex */
      Visited := Visited  $\cup$  {vertex}
      foreach {  $v \mid (vertex, v) \in E$  } do
        DFS( $v$ )
      od
      /* Backtracks from vertex */
    fi
  fi
```

Observation

- When running DFS on a graph all vertices can be classified into one of the three following categories (denoted with colours).

Colour Notation for Vertices

- White vertex – Has not been visited yet.
- Gray vertex - Visited, but yet not backtracked.
- Black vertex - Visited and backtracked.

Recursion Stack

- Gray vertices form a path from the initial vertex to the vertex that is currently processed by the outer procedure.

Observation

- If two distinct vertices v_1, v_2 satisfy that
 - $(v_0, v_1) \in E^*$,
 - $(v_1, v_1) \notin E^+$,
 - $(v_1, v_2) \in E^+$.
- Then procedure $DFS(v_0)$ backtracks from vertex v_2 before it backtracks from vertex v_1 .

DFS post-order

- If $(v, v) \notin E^+$ and $(v_0, v) \in E^*$, then upon the termination of sub-procedure $DFS(v)$, called within procedure $DFS(v_0)$, all vertices u such that $(v, u) \in E^+$ are visited and backtracked.

Observation

- If a sub-graph reachable from a given accepting vertex does not contain accepting cycle, then no accepting cycle starting in an accepting state outside the sub-graph can reach the sub-graph.

The Key Idea

- Execute the inner procedures in a bottom-up manner.
- The inner procedures are called in the same order in which the outer procedure backtracks from accepting states, i.e. the ordering of calls follows a DFS post-order.

Detection of Accepting Cycles in $\mathcal{O}(|V| + |E|)$

```
proc Detection_of_accepting_cycles
  Visited :=  $\emptyset$ 
  DFS( $v_0$ )
end
```

```
proc DFS(vertex)
  if (vertex)  $\notin$  Visited
  then Visited := Visited  $\cup$  {vertex}
  foreach {s | (vertex,s)  $\in$  E} do
    DFS(s)
  od
  if IsAccepting(vertex)
  then DetectCycle(vertex)
  fi
fi
end
```

Assumption On Early Termination

- The inner procedure reports the accepting cycle and terminates the whole algorithm if called for an accepting vertex that lies on an accepting cycle.

Consequences

- If the inner procedure called for an accepting vertex v reports no accepting cycle, then there is no accepting cycle in the graph reachable from vertex v .

Linear Complexity of Nested DFS Algorithm

- Employing DFS post-order it follows that vertices that have been visited by previous invocation of inner procedure may be safely skipped in any later invocation of the inner procedure.

$\mathcal{O}(|V| + |E|)$ Algorithm

- 1) Nested procedures are called in DFS post-order as given by the outer procedure, and are limited to vertices not yet visited by inner procedure.
- 2) All vertices are visited at most twice.

Theorem

- If the immediate successor to be processed by an inner procedure is grey (on the stack of the outer procedure), then the presence of an accepting cycle is guaranteed.

Application

- It is enough to reach a vertex on the stack of the outer procedure in the inner procedure in order to report the presence of an accepting cycle.

$O(|V| + |E|)$ Algorithm

```
proc Detection_of_accepting_cycles
  Visited := Nested := in_stack :=  $\emptyset$ 
  DFS( $v_0$ )
  Exit("Not Present")
end
```

```
proc DFS(vertex)
  if (vertex)  $\notin$  Visited
    then Visited := Visited  $\cup$  {vertex}
    in_stack := in_stack  $\cup$  {vertex}
    foreach {s | (vertex,s)  $\in$  E} do
      DFS(s)
    od
    if IsAccepting(vertex)
      then DetectCycle(vertex)
    fi
    in_stack := in_stack  $\setminus$  {vertex}
  fi
end
```

```
proc DetectCycle (vertex)
  if vertex  $\notin$  Nested
    then Nested := Nested  $\cup$  {vertex}
    foreach {s | (vertex,s)  $\in$  E} do
      if s  $\in$  in_stack
        then WriteOut(in_stack)
        Exit("Present")
      else DetectCycle(s)
    fi
  of
  fi
end
```

Outer Procedure

- Time: $\mathcal{O}(|V| + |E|)$
- Space: $\mathcal{O}(|V|)$

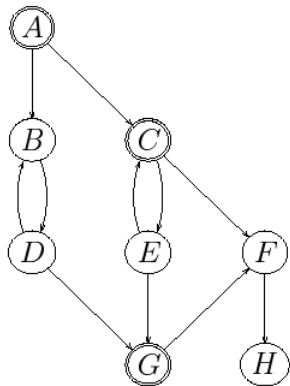
Inner Procedures

- Time (overall): $\mathcal{O}(|V| + |E|)$
- Space: $\mathcal{O}(|V|)$

Complexity

- Time: $\mathcal{O}(|V| + |E| + |V| + |E|) = \mathcal{O}(|V| + |E|)$
- Space: $\mathcal{O}(|V| + |V|) = \mathcal{O}(|V|)$

Nested DFS – Example



- 1st DFS: A,B,D,B,G,F,H,H,F,G
1st DFS stack: A,B,D,G
visited: A,B,D,F,G,H / –
- 2nd DFS: G,F,H,H,F,G
visited: A,B,D,F,G,H / F,G,H
- 1st DFS: G,D,B,C,E,C,G,E,F,C
1st DFS stack: A,C
visited: all / F,G,H
- 2nd DFS: C,E,C
counterexample: A,C,E,C

visited state backtrack non-accepting state backtrack accepting state

Classification of Büchi Automata

Terminal Büchi Automata

- All accepting cycles are self-loops on accepting states labelled with `true`.

Weak Büchi Automata

- Every strongly connected component of the automaton is composed either of accepting states, or of non-accepting states.

Automaton $A_{\neg\varphi}$

- For a number of LTL formulae φ is $A_{\neg\varphi}$ terminal or weak.
- $A_{\neg\varphi}$ is typically quite small.
- Type of $A_{\neg\varphi}$ can be pre-computed prior verification.
- Types of components of $A_{\neg\varphi}$
 - **Non-accepting** – Contains no accepting cycles.
 - **Strongly accepting** – Every cycle is accepting.
 - **Partially accepting** – Some cycles are accepting and some are not.

Product Automaton

- The graph to be analysed is a graph of product automaton $A_S \times A_{\neg\varphi}$.
- Types of components of $A_S \times A_{\neg\varphi}$ are given by the corresponding components of $A_{\neg\varphi}$.

$A_{\neg\varphi}$ is terminal Büchi automaton

- For the proof of existence of accepting cycle it is enough to proof reachability of any state that is accepting in $A_{\neg\varphi}$ part.
- Verification process is reduced to the reachability problem.

„Safety” Properties

- Those properties φ for which $A_{\neg\varphi}$ is a terminal BA.
- Typical phrasing: „Something bad never happens.”
- Reachability is enough to proof the property.

$A_{\neg\varphi}$ is weak Büchi automaton

- Contains no partially accepting components.
- For the proof of existence of accepting cycle it is enough to proof existence of reachable cycle in a strongly accepting component.
- Can be detected with a single DFS procedure.
- Time-optimal algorithm exists that does not rely on DFS.

„Weak” LTL Properties

- Those properties φ for which $A_{\neg\varphi}$ is a weak BA.
- Typically, responsiveness: $G(a \implies F(b))$.

Classification

- Every LTL formula belongs to one of the following classes:
Reactivity, Recurrence, Persistence, Obligation, Safety, Guarantee

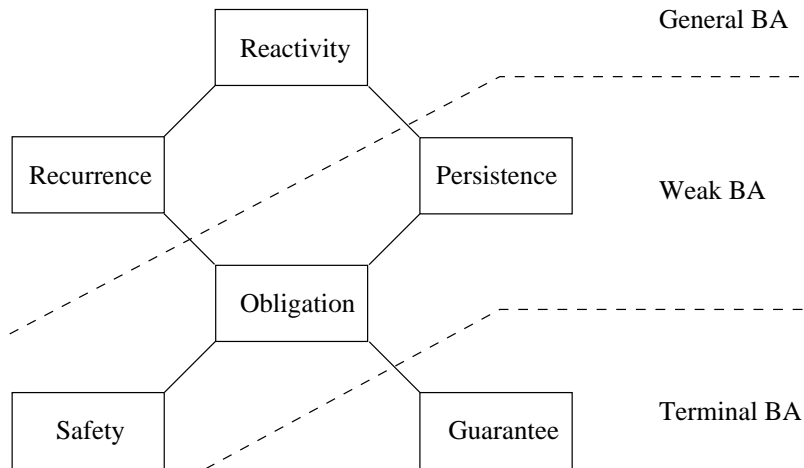
Interesting Relations

- **Guarantee** class properties can be described with a terminal Büchi automaton.
- **Persistence**, **Obligation**, and **Safety** class properties can be described with a weak Büchi automaton.

Negation in Verification Process ($\varphi \mapsto A_{\neg\varphi}$)

- $\varphi \in \text{Safety} \iff \neg\varphi \in \text{Guarantee}.$
- $\varphi \in \text{Recurrence} \iff \neg\varphi \in \text{Persistence}.$

Classification of LTL Properties



Fighting State Space Explosion

What is State Space Explosion

- System is usually given as a **composition of parallel processes**.
- Depending on the order of execution of actions of parallel processes various intermediate states emerge.
- The number of reachable states may be up to exponentially larger than the number of lines of code.

Consequence

- Main memory cannot store all states of the product automaton as they are too many.
- Algorithms for accepting cycle detection suffer for lack of memory.

State Compression

- Lossless compression.
- Lossy compression – Heuristics.

On-The-Fly Verification

Symbolic Representation of State Space

Reduced Number of States the Product Automaton

- Introduction of atomic blocks.
- Partial order on execution of process actions.
- Avoid exploration of symmetric parts.

Parallel and Distributed Verification

Observation

- Product automaton graph is defined implicitly with:
 - $|F|_{init}()$ — Returns initial state of automaton.
 - $|F|_{succs}(s)$ — Gives immediate successors of a given state.
 - $|Accepting|(s)$ — Gives whether a state is accepting or not.

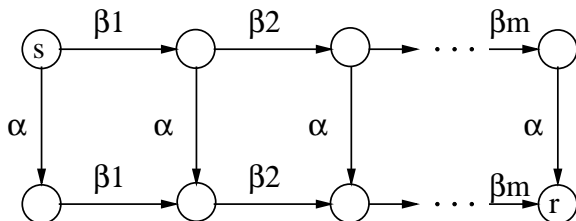
On-The-Fly Verification

- Some algorithms may detect the presence of accepting cycle without the need of complete exploration of the graph.
- Hence, $\mathcal{M} \models \varphi$ can be decided without the full construction of $A_{sys} \times A_{\neg\varphi}$.
- This is referred to as to **on-the-fly** verification.

Example

- Consider a system made of processes A and B .
- A can do a single action α , while B is a sequence of actions β , e.g. β_1, \dots, β_m .

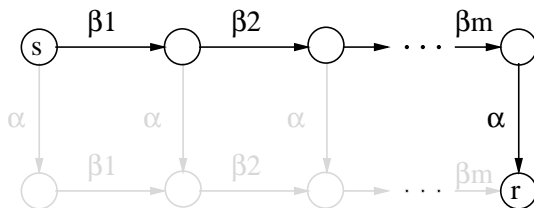
Unreduced State Space:



Property to be verified: Reachability of state r .

Observation

- Runs $(\alpha\beta_1\beta_2 \dots \beta_m)$, $(\beta_1\alpha\beta_2 \dots \beta_m)$, \dots , $(\beta_1\beta_2 \dots \beta_m\alpha)$ are equivalent with respect to the property.
- It is enough to consider only a representative from the equivalence class, say, e.g. $(\beta_1\beta_2 \dots \beta_m\alpha)$.



- The representative is obtained by postponing of action α .

Reduction Principle

- Do not consider all immediate successor during state space exploration, but pick carefully only some of them.
- Some states are never generated, which results in a smaller state space graph.

Technical Realisation

- To pick correct but optimal subset of successors is as difficult as to generate the whole state space. Hence, heuristics are used.
- The reduced state space must contain an accepting cycle if and only if the unreduced state space does so.
- LTL formula must not use X operator (subclass of *LTL*).

Principle

- Employ aggregate power of multiple CPUs.
- Increased memory and computing power.

Problem of Nested DFS

- Typical implementation relies on hashing mechanism, hence, the main memory is accessed extremely randomly. Should memory demands exceeds the amount of available memory, **thrashing** occurs.
- Mimicking serial Nested DFS algorithm in a distributed-memory setting is extremely slow. (Token-based approach).
- It unknown whether the DFS post-order can be computed by a time-optimal scale-able parallel algorithm (Still an open problem.)

Observation

- Instead of DFS other graph procedures are used.
- Tasks such as breadth-first search, or value propagation can be efficiently computed in parallel.
- Parallel algorithms do not exhibit optimal complexity.

	Complexity	Optimal	On-The-Fly
Nested DFS	$O(V+E)$	Yes	Yes
OWCTY			
general Büchi automata	$O(V.(V+E))$	No	No
weak Büchi automata	$O(V+E)$	Yes	No
MAP	$O(V.V.(V+E))$	No	Partially
OWCTY+MAP			
general Büchi automata	$O(V.(V+E))$	No	Partially
weak Büchi automata	$O(V+E)$	Yes	Partially

Model Checking – Summary

Properties Validity

- Property to be verified may be violated by a single particular (even extremely unlikely) run of the system under inspection.
- The decision procedure relies on exploration of state space graph of the system.

State Space Explosion

- Unless there are other reasons, all system runs have to be considered.
- The **number of states**, that system can reach is up to **exponentially larger** than the size of the system description.
- Reasons: Data explosion, asynchronous parallelism.

General Technique

- Applicable to Hardware, Software, Embedded Systems, Model-Based Development, ...

Mathematically Rigorous Precision

- The decision procedure results with $\mathcal{M} \models \varphi$, if and only if, it is the case.

Tool for Model Checking – Model Checkers

- The so called "Push-Button" Verification.
- No human participation in the decision process.
- Provides users with witnesses and counterexamples.

Not Suitable for Everything

- Not suitable to show that a program for computing factorial really computes $n!$ for a given n .
- Though it is perfectly fine to check that for a value of 5 it always returns the value of 120.

Often Relies on Modelling

- Need for model construction.
- Validity of a formula is guaranteed for the model, not the modelled system.

Size of the State Space

- Applicable mostly to system with finite state space.
- Due to state space explosion, practical applicability is limited.

Verifies Only What Has Been Specified

- Issues not covered with formulae need not be discovered.

Homework

- Analysis with DIVINE model checker on a more complex example (some homework from previous course on secure coding).