Behavior models and verification

Lecture 4

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Explicit LTL model checking

Model

AG(start → AF heat)

Property specification

Model checker

Property satisfied

Property violated

Error report

AG(start → AF heat)

CTL

LTL

PCTL

Markov chains

Timed automata

Labelled transition system

Kripke structure

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Example
Büchi Automaton $A_M$
LTL model checking – basic idea

- Given: $M$ (and a state in $M$) and $f$
  1. create $A_M$
  2. negate the property $f$
  3. create a Büchi automaton $A_{\neg f}$.
     • This automaton accepts all violations of the property $f$
  4. it holds that $M \models f$ iff $L(A_M \times A_{\neg f}) = \emptyset$
Example: LTL Model Checking

- Check whether $M \models f$
  - $f = G(req \rightarrow (F\ ack))$
- By checking product automaton $P$, whether $L(P) = \emptyset$
  - $P = A_M \times A_{\neg f}$
  - If so, then $M \models f$, otherwise $M \models \neg f$.

![Diagram showing a product automaton](image-url)
• Büchi Automaton $A_{\neg f}$
  
  $\neg f = F(req \land (G\neg ack))$

  • Recall $f = G(req \rightarrow (F ack))$
Büchi product automaton $P$
Specific for $F_1 = S_1$ !!!

Let $A_1 = (\Sigma, S_1, S_0, \Delta_1, F_1)$ and $A_2 = (\Sigma, S_2, S_0, \Delta_2, F_2)$ be Büchi automata. We have defined the product Büchi automaton $A = A_1 \times A_2$, accepting the intersection of $L(A_1)$ and $L(A_2)$.

In the special case $F_1 = S_1$, we can use a simpler product automaton denoted by $A' = A_1 \otimes A_2$:

- $A = (\Sigma, S, S_0, \Delta, F)$
- $S = S_1 \times S_2$
- $S_0 = S_{01} \times S_{02}$
- for all $s, s' \in S_1, t, t' \in S_2, a \in \Sigma$:
  - $((s, t), a, (s', t')) \in \Delta$ iff $(s, a, s') \in \Delta_1$ and $(t, a, t') \in \Delta_2$
- $F = S_1 \times F_2 = F_1 \times F_2$

Recall that the special case $F_1 = S_1$ occurs whenever $A_1$ is a Kripke structure automaton $A_M$. 

Translating LTL into Büchi automaton

- There are several algorithms for translating LTL formulae into Büchi automata.
- We show a variant due to Gerth, Peled, Vardi, and Wolper.
  - Given an LTL formula $f$, it will generate a Büchi automaton $A_f$ with at most $O(2^{|f|})$ states.
  - The automaton $A_f$ will accept the language $\{w \in \Sigma^\omega : w \models f \}$, where $\Sigma = 2^{AP}$.  

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Translation procedure overview

• Build automaton by starting with an initial node then expanding according to LTL formula.

  ▪ Each node labeled with 3 sets of formulae:
    • New: formulae not yet processed, that may force further expansions.
    • Old: formulae already processed and holding in this state
    • Next: formulae which should hold in any of the next states

• Idea: along any computation path, the New plus Old formulae at any point should hold of the remainder of the path.
  ▪ Construction similar to “tableaux” theorem proving.
We put a formula $\varphi$ into negation normal form

- Also called positive normal form
- All negations appear only in front of atomic propositions

To avoid the blow-up of the LTL formula, we will use a new operator $R$ (release)

$$\varphi_1 R \varphi_2 = (G \varphi_2) \lor (\varphi_2 U (\varphi_1 \land \varphi_2))$$

Informally: $\varphi_1$ “releases” $\varphi_2$
A simplification

• Before constructing the automata, put the LTL formula in *negation normal form*:
  - mentions only AP elements, \( \neg, \land, \lor, X, R, U \);
  - and all \( \neg \)'s only in front of AP elements

• Repeatedly rewrite using the LTL equivalences:
  - \( F \ g = \text{true } U \ g \)
  - \( G \ g = \text{false } R \ g \)
  - \( \neg(f \ U \ g) = \neg f \ R \neg g \)
  - \( \neg(f \ R \ g) = \neg f \ U \neg g \)
  - and Boolean equivalences (De Morgan)
Translating LTL into Büchi automaton

- Translation into negation normal form
  - $\neg X \varphi_1 = X \neg \varphi_1$
  - $\neg (\varphi_1 U \varphi_2) = \neg \varphi_1 R \neg \varphi_2$
  - $\neg (\varphi_1 R \varphi_2) = \neg \varphi_1 U \neg \varphi_2$
Translating LTL into Büchi automaton

- The algorithm for the LTL formula $\rightarrow$ Büchi automata translation
  - The algorithm will manipulate a date structure called `node` during its run
    - ID: A unique identifier of a node (a number)
    - Incoming: A list of node IDs
    - Old $\subseteq$ sub(f)
    - New $\subseteq$ sub(f)
    - Next $\subseteq$ sub(f)
  - The nodes will form a graph, where the arcs of the graph are stored in the `Incoming` list of the end node of the arc for easier manipulation
  - The initial node is marked by having a special node ID called `init` in its `Incoming` list
  - All nodes are stored in a set (use e.g., a hash table for implementation) called `nodes`
Technical: To implement the algorithm, the following functions are defined

- Neg(true) = false
- Neg(false) = true
- Neg(p) = \lnot p, p \in AP
- Neg(\lnot p) = p, p \in AP
Translating LTL into Büchi automaton

- The functions $\text{New1}(f)$, $\text{Next1}(f)$, and $\text{New2}(f)$ are tabulated below. They match the recursive definitions for disjunction, until, release, and next-time:

<table>
<thead>
<tr>
<th>$f$</th>
<th>$\text{New1}(f)$</th>
<th>$\text{Next1}(f)$</th>
<th>$\text{New2}(f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1 \lor f_2$</td>
<td>${f_2}$</td>
<td>$\emptyset$</td>
<td>${f_1}$</td>
</tr>
<tr>
<td>$f_1 U f_2$</td>
<td>${f_1}$</td>
<td>${f_1 U f_2}$</td>
<td>${f_2}$</td>
</tr>
<tr>
<td>$f_1 R f_2$</td>
<td>${f_2}$</td>
<td>${f_1 R f_2}$</td>
<td>${f_1, f_2}$</td>
</tr>
<tr>
<td>$X f_1$</td>
<td>$\emptyset$</td>
<td>${f_1}$</td>
<td>$\emptyset$</td>
</tr>
</tbody>
</table>
Translating LTL into Büchi automaton

- Basic idea of the LTL formula $\rightarrow$ Büchi automata translation
  - To prove that $w \models \varphi_1 \lor \varphi_2$ it suffices to either prove that
    - $w \models \varphi_1$, or
    - $w \models \varphi_2$
  - To prove that $w \models \varphi_1 \mathbf{U} \varphi_2$ it suffices to either prove that
    - $w \models \varphi_2$, or
    - $w \models \varphi_1$ and $w \models X(\varphi_1 \mathbf{U} \varphi_2)$
    - The only restriction is that the second case can only be used infinitely often iff the first case is also used infinitely often (we will use Büchi acceptance sets to handle that)
  - To prove that $w \models \varphi_1 \mathbf{R} \varphi_2$ it suffices to either prove that
    - $w \models \varphi_1$ and $w \models \varphi_2$, or
    - $w \models \varphi_2$ and $w \models X(\varphi_1 \mathbf{R} \varphi_2)$
Algorithm 1 The top-level LTL to Büchi translation algorithm

global nodes: Set of Node; // Use e.g., a hash table

procedure translate(f: Formula)
    
local node: Node;

nodes := ∅; // Initialize the result to empty set

node := NewNode(); // Allocate memory for a new node

node.ID := GetID(); // Allocate a new node ID

node.Incoming := \{init\}; // Incoming can be implemented as a list

node.New = \{f\}; // Use e.g., bit-arrays of size sub(f) for these sets

node.Old = ∅;

node.Next = ∅;

expand(node); // Call the recursive expand procedure

return nodes;

end procedure
Algorithm 2  \textit{LTL to Büchi translation main loop}

\begin{verbatim}
procedure expand(node: Node)
    local node, node1, node2: Node;
    local f: Formula;
    if node.New = 0 then
        if \exists node1 \in nodes with node1.Old = node.Old \land node1.Next = node.Next then
            node1.Incoming := node1.Incoming \cup node.Incoming; // redirect arcs to "node1"
            return; // Discard "node" by not storing it to "nodes"
        else
            nodes := nodes \cup \{ node \}; // "node" is ready, add it to the automaton
            node2 := NewNode(); // Create "node2" to prove formulas in "node.Next"
            node2.ID := GetID();
            node2.Incoming := \{ node.ID \};
            node2.New = \{ node.Next \};
            node2.Old = \emptyset;
            node2.Next = \emptyset;
            expand(node2);
            return:
        end if
    end if
end procedure
\end{verbatim}
else // node.New ≠ ∅ holds
    pick f from node.New; // Any formula “f” in “node.New” will do
    node.New := node.New \ { f }; // Remove “f” from proof objectives
switch begin(FormulaType(f))
    case atomic proposition, negated atomic proposition, true, false:
        expand_simple(node,f);
        return;
    case conjunction:
        expand_conjunction(node,f);
        return;
    case disjunction, until, release:
        expand_disjunction(node,f);
        return;
    case next:
        expand_next(node,f);
        return;
switch end
    // Not reached
    return;
end procedure
Algorithm 3  *Expanding simple formulas*

procedure expand_simple(node: Node, f: Formula)
    if f = false or Neg(f) ∈ node.Old then
        return;  // “node” contains a contradiction (false / both p and ¬p), discard it
    else
        node.Old := node.Old ∪ { f };  // Recall that this node proves “f”
        expand(node);  // Handle the rest of the formulas in “node.New”
    return;
end procedure
Algorithm 4  *Expanding conjunction*

procedure expand_conjunction(node: Node, f: Formula)

    local f1, f2: Formula;
    f1 := left(f); // Obtain subformula “f1” from left side of $f_1 \land f_2$
    f2 := right(f); // Obtain subformula “f2” from right side of $f_1 \land f_2$
    node.New := node.New \cup \{ f1, f2 \} \setminus node.Old; // Prove both “f1” and “f2”
    node.Old := node.Old \cup \{ f \}; // Recall that this node proves “f”
    expand(node); // Handle the rest of the formulas in “node.New”

return;

end procedure
Algorithm 5  Expanding disjunction

procedure expand_disjunction(node: Node, f: Formula)
   local f1, f2: Formula;
   local node1, node2: node;

   // This one handles all the cases: $f_1 \lor f_2$, $f_1 \cup f_2$, $f_1 \Rightarrow f_2$

   // Replace “node” with two nodes “node1” and “node2” (The blow-up happens here!)
   // Do the proof using strategy (b)

   node1 := NewNode(); // Create “node1” to prove formulas using strategy (b)
   node1.ID := GetID();
   node1.Incoming := node.Incoming;
   node1.New = node.New \cup (NewI(f) \setminus node.Old); // Prove things in NewI(f)
   node1.Old := node.Old \cup \{ f \}; // Recall that “node1” node proves “f”
   node1.Next = node.Next \cup NextI(f); // On the next time, prove things in NextI(f)
// Do the proof using strategy (a)

node2 := NewNode(); // Create "node2" to prove formulas using strategy (a)
node2.ID := GetID();
node2.Incoming := node.Incoming;
node2.New = node.New \ (New2(f) \ node.Old); // Prove things in New2(f)
node2.Old := node.Old \ \{ f \}; // Recall that "node2" node proves "f"
node2.Next = node.Next; // In case (a) Next2(f) is always empty

expand(node1); // "node1" does the proof using strategy (b)
expand(node2); // "node2" does the proof using strategy (a)
return; // discard "node" by not storing it to "nodes"

end procedure
Algorithm 6  \textit{Expanding next} \\

\textbf{procedure} expand\_next(node: Node, f: Formula) \\
    \textbf{local} f1: Formula; \\
    f1 := left(f); // Obtain subformula “f1” from $Xf_1$ \\

    // This one handles the case $Xf_1$ \\
    node.Old := node.Old $\cup \{ f \}$; // Recall that “node” node proves “f” 
    node.Next = node.Next $\cup Next1(f)$; // On the next time, prove things in $Next1(f)$ 
    expand(node); // Handle the rest of the formulas in “node.New” 
    \textbf{return}; \\
\textbf{end procedure}
When expansion is completed, to get a Büchi automaton we need to add two things:

- Transition labels: for each edge \((u,v)\), add a label \(X\) for each set \(X\) of variables making all the literals in \(Old(v)\) true.

- Accepting states: Consider an arbitrary path, and suppose
  \(p \bigcup q\) is true at the start. By construction,
  
  - either \(q\) is labeled true at some point,
  - or \(p\) and \(p \bigcup q\) both labeled true forever.
    - Need to rule out the second case
  
  Note: for formulas not containing \(\bigcup\), all infinite paths are accepting
Accepting states

- For each subformula (of the original formula) of the form $pUq$, add a set $F_{pUq}$ of accepting states: put $s$ in $F_{pUq}$ iff either
  - $q \in \text{Old}(s)$,
  - or $pUq \notin \text{Old}(s)$

- **Recall:** A path (run) is accepted iff for each accepting set $F_i$, infinitely many states (nodes) in the path are in $F_i$

- **Observe:** A path is NOT accepted iff there is some subformula $pUq$ such that at some point in the path, $pUq$ becomes continuously true, but $q$ never becomes true
Let’s trace through the algorithm with the following input:

\[ a \cup (p \land q) \]
Solution

\[ a \cup (p \land q) \]
\( N_1.\text{NEW} = \{ \ a \cup ( p \land q ) \ \} \)
\( N_1.\text{OLD} = 0; \)
\( N_1.\text{NEXT} = 0; \)
• Select a formula from the NEW set and process it in suitable way.
• The only formula here is
  \[ a \cup ( p \land q ) \]
  \[ \rightarrow \text{create 2 nodes} \]
\[ N_2.\text{NEW} = \{ a \} \]
\[ N_2.\text{OLD} = \{ a \cup ( p \land q ) \} \]
\[ N_2.\text{NEXT} = \{ a \cup ( p \land q ) \} \]
\[ N_3.\text{NEW} = \{ p \land q \} \]
\[ N_3.\text{OLD} = \{ a \cup ( p \land q ) \} \]
\[ N_3.\text{NEXT} = 0 \]
$N_2$.NEW = 0
$N_2$.OLD = \{ a \cup ( p \land q ) ; a \} 
$N_2$.NEXT = \{ a \cup ( p \land q ) \}
\[ N_4.\text{NEW} = \{ a \cup ( p \land q ) \} \]
\[ N_4.\text{OLD} = 0 \]
\[ N_4.\text{NEXT} = 0 \]
..skip some steps...

\[ N_5.\text{NEW} = 0 \]

\[ N_5.\text{OLD} = \{ \text{a U (} p \land q \text{)} ; \text{a} \} \]

\[ N_5.\text{NEXT} = \{ \text{a U (} p \land q \text{)} \} \]

\[ N_6.\text{NEW} = \{ p \land q \} \]

\[ N_6.\text{OLD} = \{ \text{a U (} p \land q \text{)} \} \]

\[ N_6.\text{NEXT} = 0 \]
Since $N_5$ is “equivalent” to $N_2$, discard the $N_5$ node and redirect edges to $N_2$. 
\[ N_6.\text{NEW} = \{ \ p ; q \ \} \]
\[ N_6.\text{OLD} = \{ \ a \cup ( p \land q ) ; p \land q \ \} \]
\[ N_6.\text{NEXT} = 0 \]

\[ N_6.\text{NEW} = 0 \]
\[ N_6.\text{OLD} = \{ \ a \cup ( p \land q ) ; p \land q ; p ; q \ \} \]
\[ N_6.\text{NEXT} = 0 \]
\[ N_7.\text{NEW} = 0 \]
\[ N_7.\text{OLD} = 0 \]
\[ N_7.\text{NEXT} = 0 \]
N₈.NEW = 0
N₈.OLD = 0
N₈.NEXT = 0
Since $N_8$ is “equivalent” to $N_7$, discard the $N_8$ node and redirect edges to $N_7$
Backtrack and process node $N_3$...

$N_3.\text{NEW} = 0$

$N_3.\text{OLD} = \{a \cup (p \land q); p \land q; p; q\}$

$N_3.\text{NEXT} = 0$
Since $N_3$ is “equivalent” to $N_6$, discard the $N_3$ node and redirect edges to $N_6$

$N_2.\text{OLD} = \{ a \cup (p \land q); a \}$
$N_6.\text{OLD} = \{ a \cup (p \land q); p \land q; p; q \}$
$N_7.\text{OLD} = 0$
Accepting states and transitions

\[ a \cup (p \land q) \]