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A glimpse of nuXmv

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Introduction

- NUXMV: is a symbolic model checker for the analysis of synchronous finite-state and infinite-state systems
- state-of-the-art algorithms:
  - For the finite-state case:
    - BDD-based model-checking, like its predecessor nuSMV.
    - strong verification engine based on modern SAT-based algorithms, like BMC
  - For the infinite-state case: SMT-based verification techniques, implemented through a tight integration with MathSAT5.
- download it and try it!

`https://nuxmv.fbk.eu/`

Short tutorial

Today:

- modeling and specification languages
- simulation
- model checking

Manual:

`https://es-static.fbk.eu/tools/nuxmv/downloads/nuxmv-user-manual.pdf`

Modeling and Specification languages

Modeling language

- SMV language: Symbolic Model Verifier
  - introduced in 1993 in the seminal paper "Symbolic model checking: 10^{20} states and beyond"
- allows for the description of:
  - synchronous and asynchronous systems
  - networks/products of subsystems
  - non-deterministic behaviors
  - modular nature (very close to OO programming)
- SMV file = symbolic representation of a transition system (aka Kripke structure)

Variables

- State Variables (keyword `VAR`)
  - Boolean: `boolean`
  - enum : $\{item_1, item_2, \ldots, item_n\}$
  - integer : `int`
  - ... a lot of others ...
- Input Variables
  - they are variables "controlled" by the environment
  - we can observe their value but...
  - we can **not** constrain their value in anyway

SMV - Transition Relation

- Initial states
  - any Boolean formula over the set of state variables
  - it is specified by the keyword INIT
- Transition Relation
  - any Boolean formula over the following set:

$$\mathcal{V} := \{v \mid v \text{ is a state or input variable}\} \cup \{\texttt{next(v)} \mid v \text{ is a state variable}\}$$

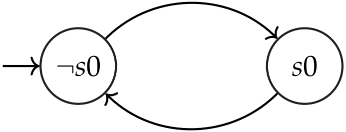
  - it is specified by the keyword TRANS

SMV - Transition Relation - cont'd

- SMV allows also:
  - all arithmetic operations (addition, multiplication, etc)
  - trigonometric functions
  - bitwise operations

An alternative way:

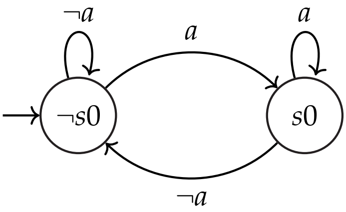
- `ASSIGN init(v) :=` ...
- `ASSIGN next(v) :=` ...




```
MODULE main
VAR
  s0 : boolean;
INIT
  !s0;
TRANS
  s0 <-> next(!s0);
```

Each of the 2^n assignments to the n state variables corresponds to a state of the explicit transition system.

Example with input variables




```
MODULE main
IVAR
   a    : boolean;
VAR
   s0   : boolean;
ASSIGN
   init(s0)  := FALSE;
   next(s0)  := case
      !s0 & a        : TRUE;
      !s0 & !a       : FALSE;
      s0  & a        : TRUE;
      s0  & !a       : FALSE;
   esac;
```

In this example, you can think of variables as letters of the alphabet of the automaton.

Specification Language

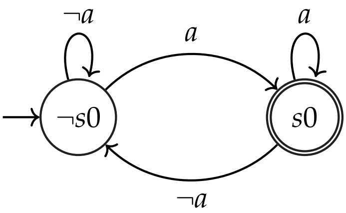
- Mainly LTL and CTL
- ... but also:
  - past operators
  - PSL
  - real-time CTL
  - ...

- LTL syntax:

$$\phi := p \mid \neg\phi \mid \phi_1 \vee \phi_2 \mid \mathsf{X}\phi \mid \phi_1 \,\mathcal{U}\, \phi_2$$
$$\mid \mathsf{F}\phi \mid \mathsf{G}\phi \mid \phi_1 \,\mathcal{R}\, \phi_2$$

- in SMV with the keyword LTLSPEC
  - LTLSPEC ltl_expr;
  - LTLSPEC NAME name_expr := ltl_expr;

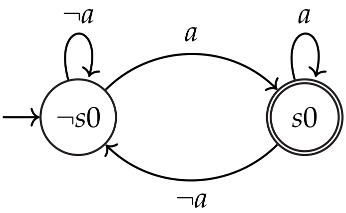
$\mathcal{A}$:



$\tau \models \mathsf{F}(s0)$ iff $\tau \in \mathcal{L}(\mathcal{A})$.

```
MODULE main
IVAR
  a   : boolean;
VAR
  s0  : boolean;
ASSIGN
  init(s0) := FALSE;
  next(s0) := case
    !s0 & a      : TRUE;
    !s0 & !a     : FALSE;
    s0  & a      : TRUE;
    s0  & !a     : FALSE;
  esac;
LTLSPEC
  NAME final_dfa := F(s0)
```

$\mathcal{A}$:



$\tau \models \mathsf{GF}(s0)$ iff $\tau \in \mathcal{L}(\mathcal{A})$.

```
MODULE main
IVAR
   a   : boolean;
VAR
   s0  : boolean;
ASSIGN
   init(s0) := FALSE;
   next(s0) := case
      !s0 & a      : TRUE;
      !s0 & !a     : FALSE;
      s0  & a      : TRUE;
      s0  & !a     : FALSE;
   esac;
LTLSPEC
   NAME final_buchi := GF(s0)
```

Simulation

Simulation

- Simulation generates a trace (or a set of traces) of the SMV model.
- It can be used, for example,
  - for exploring different behaviors of the model
  - for checking if the model is an accurate representation of reality
- Simulation is different from model checking: it is not exhaustive.

Generic commands

These commands are prerequisites for all the other commands:

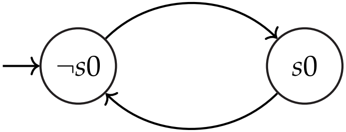
- `set_input_file file_name`: sets the file containing the model
- `go`: it parses the model file, it populates all the necessary data structures like BDD, etc.
- `go_bmc`: similar to the previous command
- `reset`: undo the effects of all the commands

Simulation - Commands

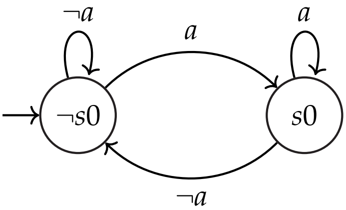
Commands:

- `pick_state -v -i`: it picks an initial state for the trace
  - `-v`: verbose
  - `-i`: interactive mode, the user can choose the state from a set of possibilities
- `simulate -v -i -k 5`
  - `-k`: length of the trace

Without input variables:



With input variables:



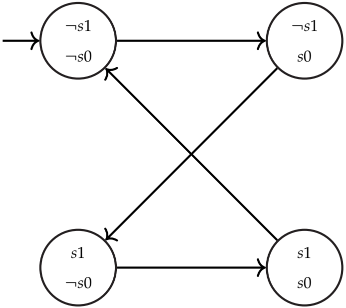
LTL Model Checking

LTL Model Checking

Plethora of commands for model checking:

- BDD-based model checking:
  - `check_ltlspec`
  - Burch, Jerry R., et al. "Symbolic model checking: 10^{20} states and beyond." (1992)
- SAT-based model checking:
  - BMC
    - `check_ltlspec_bmc`
    - Biere, Armin, et al. "Bounded model checking." (2003).
  - K-Liveness
    - `check_ltlspec_ic3`
    - Claessen, Koen, and Niklas Sörensson. "A liveness checking algorithm that counts." (2012)
  - IC3
    - `check_invar_ic3`
    - Bradley, Aaron R. "SAT-based model checking without unrolling." (2011)
    - it is tailored for *invariant* properties, that is, of type $\mathsf{G}(\alpha)$

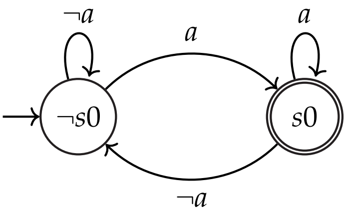
Example - Modulo 4 counter



- $\phi_1 := \mathsf{GF}(s0 \land s1)$ ✓
- $\phi_2 := \mathsf{FG}(\neg s0 \land \neg s1)$ ✗
- $\phi_2 := \mathsf{G}(s1 \rightarrow s0)$ ✗ : invariant spec, we can use IC3

Example - Simple Büchi automata

$\mathcal{A}$:

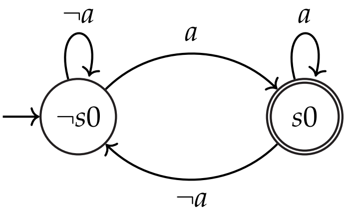


- we want to check the emptiness of the Büchi automaton $\mathcal{A}$:

$$\mathcal{L}(\mathcal{A}) \stackrel{?}{=} \varnothing$$

Example - Simple Büchi automata

$\mathcal{A}$:

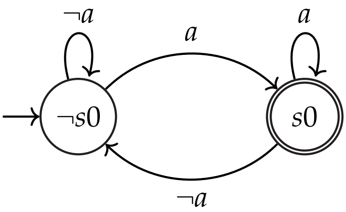


- we want to check the emptiness of the Büchi automaton $\mathcal{A}$:

$$\mathcal{L}(\mathcal{A}) \stackrel{?}{=} \varnothing$$

- how can we check it?
- ... with model checking?

$\mathcal{A}$:



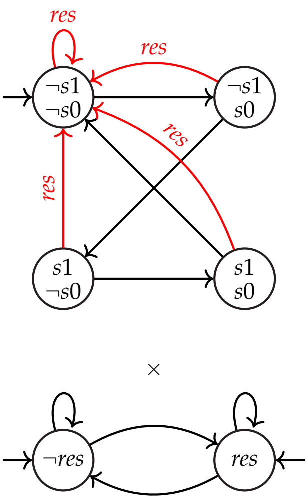
- it holds that:

$$\mathcal{L}(\mathcal{A}) \neq \varnothing$$
$$\Leftrightarrow$$
there exists an accepting run
$$\Leftrightarrow$$
$$\mathcal{A} \models E(\mathsf{GF}s0)$$
$$\Leftrightarrow$$
$$\mathcal{A} \not\models \mathsf{A}(\mathsf{FG}\neg s0)$$

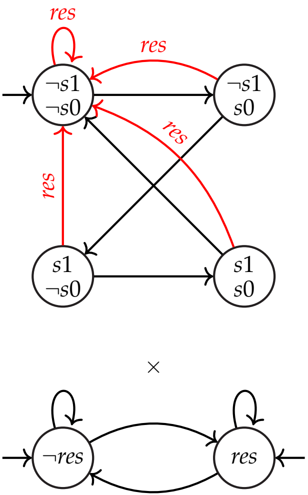
CTL Model Checking

CTL Model Checking

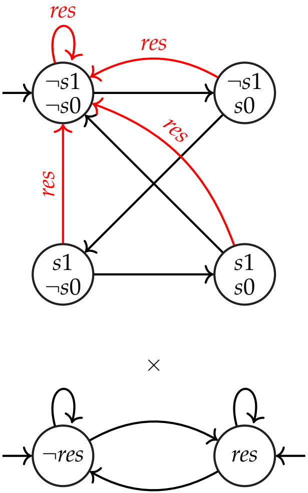
- BDD-based model checking:
  - `check_ctlspec`
  - Burch, Jerry R., et al. "Symbolic model checking: 1020 states and beyond." Information and computation 98.2 (1992): 142-170.



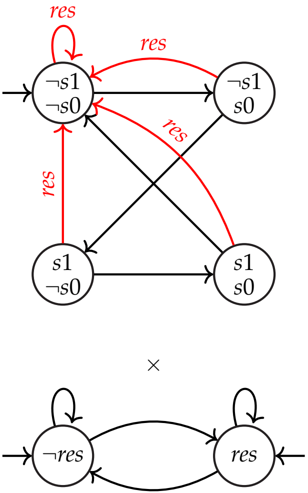

```
MODULE main
VAR
   reset       : boolean;
   counter     : Counter4(reset);
DEFINE
   out := toint(counter.s0) + 2*toint(counter.s1);

MODULE Counter4(reset)
VAR
   s0      : boolean;
   s1      : boolean;
ASSIGN
   init(s0) := FALSE;
   next(s0) := case
     reset     :    FALSE;
     !reset    :    !s0;
   esac;

   init(s1) := FALSE;
   next(s1) := case
     reset     :    FALSE;
    TRUE : ((!s0 & s1) | (s0 & !s1));
   esac;
```



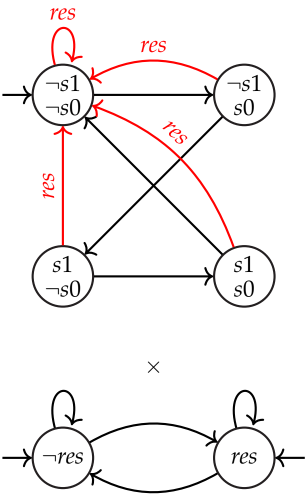
- It is possible to reach a state in which out = 3:



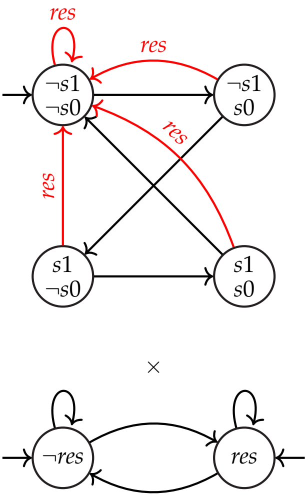
- It is possible to reach a state in which out = 3:
  `CTLSPEC EF out = 3`



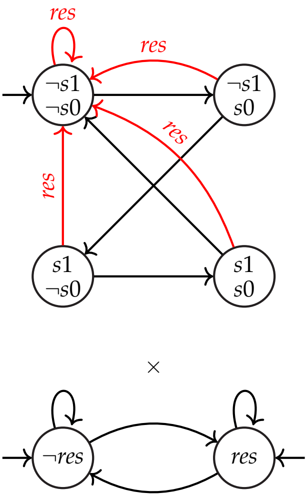
- It is possible to reach a state in which out = 3:
  `CTLSPEC EF out = 3` ✓



- It is possible to reach a state in which out = 3:
  `CTLSPEC EF out = 3` ✓
- It is inevitable that out = 3 is eventually reached



- It is possible to reach a state in which out = 3:
  `CTLSPEC EF out = 3` ✓
- It is inevitable that out = 3 is eventually reached
  `CTLSPEC AF out = 3`



- It is possible to reach a state in which out = 3:
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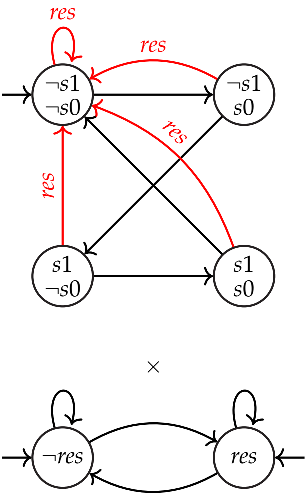
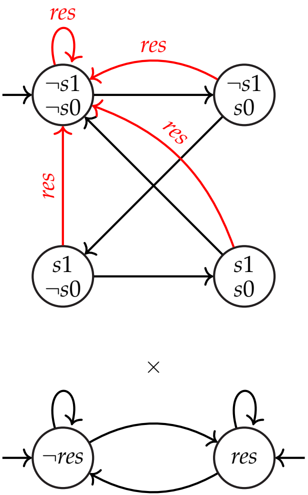


- It is possible to reach a state in which out = 3:
  `CTLSPEC EF out = 3` ✓
- It is inevitable that out = 3 is eventually reached
  `CTLSPEC AF out = 3` ✗
- It is always possible to reach a state in which out = 3



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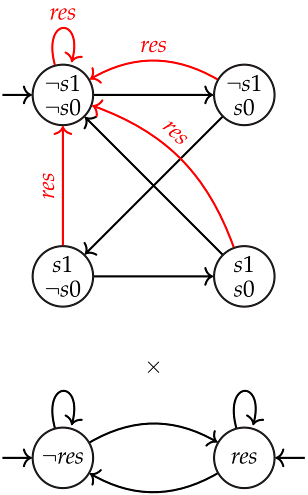

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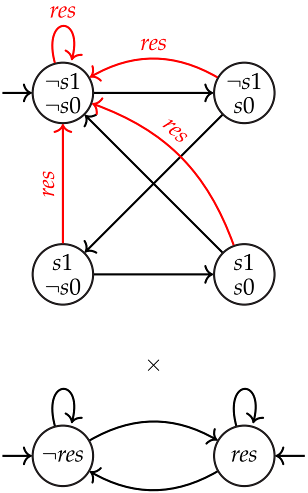

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  `CTLSPEC EF out = 3` ✓
- It is inevitable that out = 3 is eventually reached
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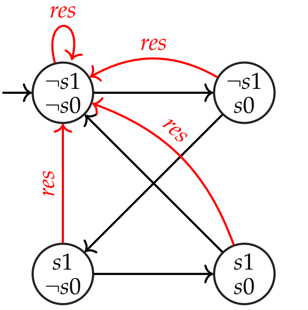
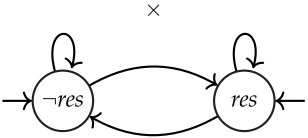
- It is always possible to reach a state in which out = 3 `CTLSPEC AG EF out = 3` ✓
- Every time a state with out = 2 is reached, a state with out = 3 is reached afterward





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- It is inevitable that out = 3 is eventually reached `CTLSPEC AF out = 3` ✗
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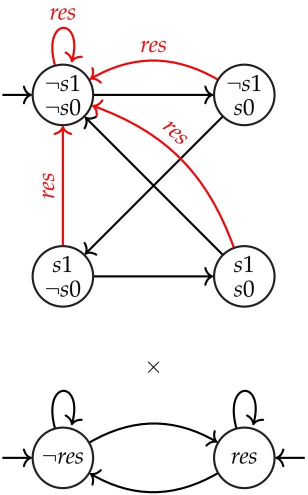
- Every time a state with out = 2 is reached, a state with out = 3 is reached afterward `CTLSPEC AG (out = 2 -> AF out = 3)`



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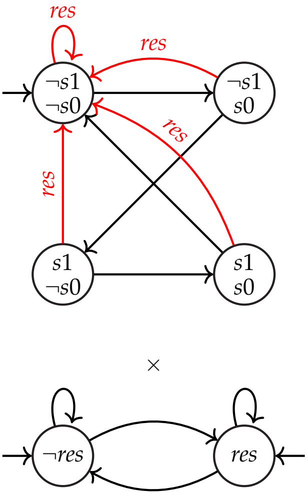

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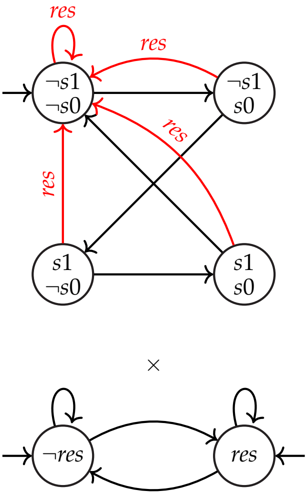
- Every time a state with out = 2 is reached, a state with out = 3 is reached afterward `CTLSPEC AG (out = 2 -> AF out = 3)` ✗
- The reset operation is correct



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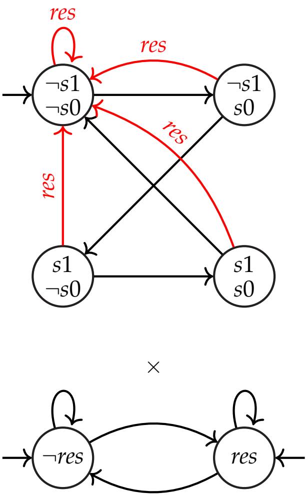
- Every time a state with out = 2 is reached, a state with out = 3 is reached afterward `CTLSPEC AG (out = 2 -> AF out = 3)` ✗
- The reset operation is correct `CTLSPEC AG (reset -> AX out = 0)`



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- It is always possible to reach a state in which out = 3 `CTLSPEC AG EF out = 3` ✓
- Every time a state with out = 2 is reached, a state with out = 3 is reached afterward `CTLSPEC AG (out = 2 -> AF out = 3)` ✗
- The reset operation is correct `CTLSPEC AG (reset -> AX out = 0)` ✓

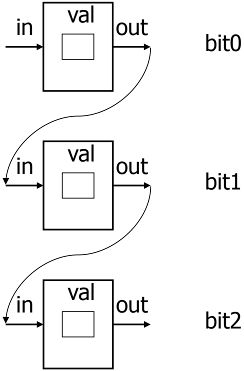
Appendix

A Three-Bit Counter

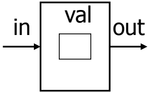
```
MODULE main
VAR
  bit0 : counter_cell(TRUE);
  bit1 : counter_cell(bit0.carry_out);
  bit2 : counter_cell(bit1.carry_out);

SPEC  AG AF bit2.carry_out

MODULE counter_cell(carry_in)
VAR
  value : boolean;
ASSIGN
  init(value) := FALSE;
  next(value) := value xor carry_in;
DEFINE
  carry_out := value & carry_in;
```

value + carry_in mod 2

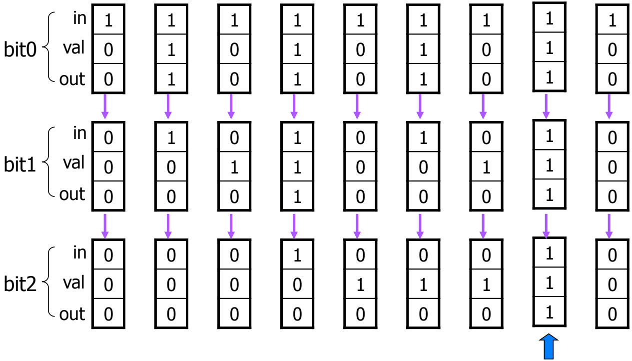
module instantiations



module declaration



`AG AF bit2.carry_out` is true



bit2.carry_out is ture

REFERENCES

Bibliography I