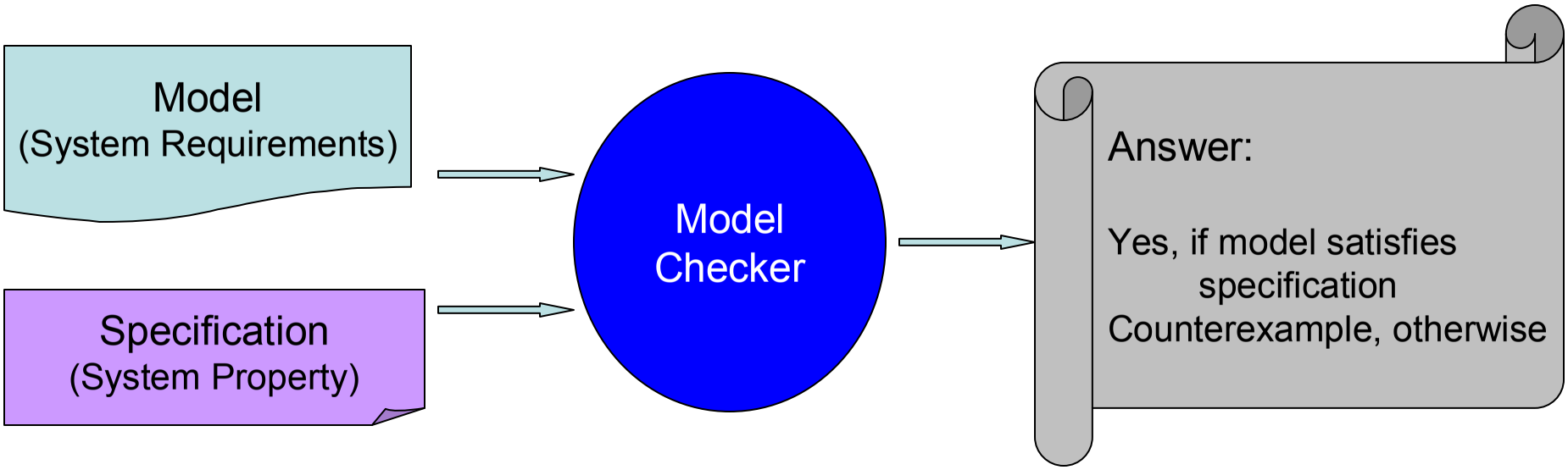
Model Checking

Model Checking Process



Increase our confidence in the correctness of the model:
-The model satisfied enough system properties
- Study counterexamples, pinpoint the source of the error, correct the model, and try again

Mutual Exclusion Example

The Model

(Willem Visser, http://ase.arc.nasa.gov/visser/ASE2002TutSoftwareMC-fonts.ppt)

- Two process mutual exclusion with shared semaphore
- Each process has three states
  - Non-critical (N)
  - Trying (T)
  - Critical (C)
- Semaphore can be available (S_0) or taken (S_1)
- Initially both processes are in the Non-critical state and the semaphore is available --- $N_1\, N_2\, S_0$

$$
\begin{array}{lll||lll}
N_1 & \rightarrow & T_1 & N_2 & \rightarrow & T_2 \\
T_1 \wedge S_0 & \rightarrow & C_1 \wedge S_1 & T_2 \wedge S_0 & \rightarrow & C_2 \wedge S_1 \\
C_1 & \rightarrow & N_1 \wedge S_0 & C_2 & \rightarrow & N_2 \wedge S_0
\end{array}
$$

Mutual Exclusion Example

Specification – Desirable Property

No matter where you are there is always a way to get to the initial state

$$K \models AG\ EF\ (N_1 \wedge N_2 \wedge S_0)$$

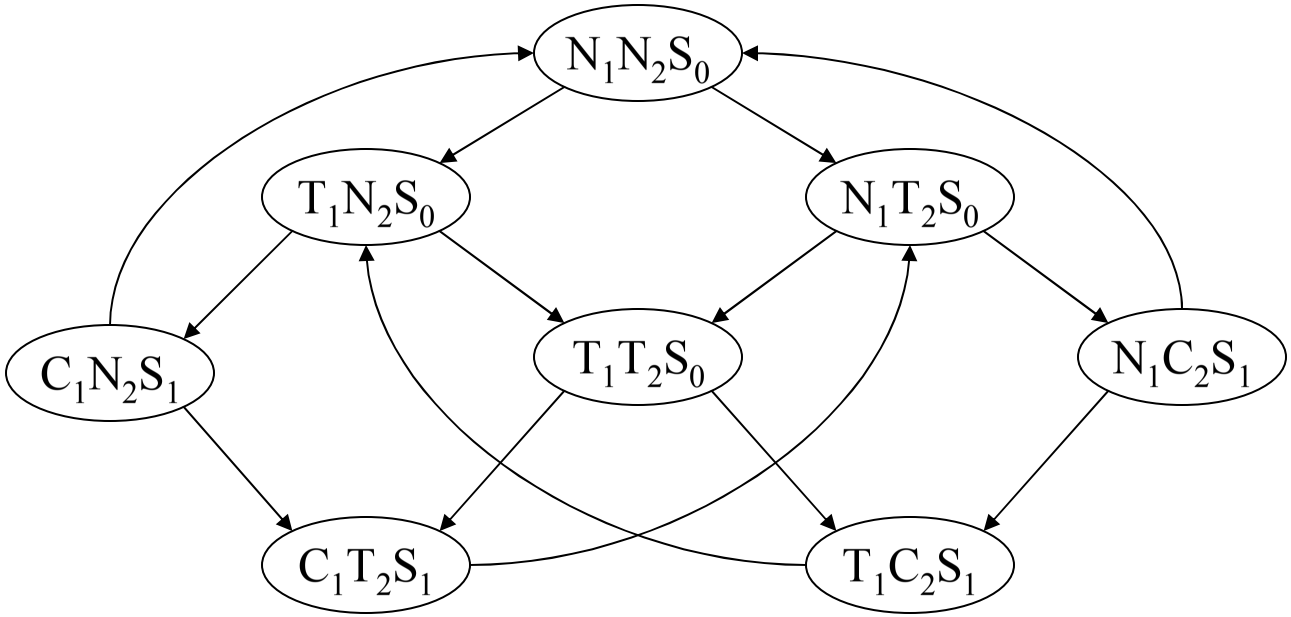
Mutual Exclusion Example

Model Checker

Answer: Yes

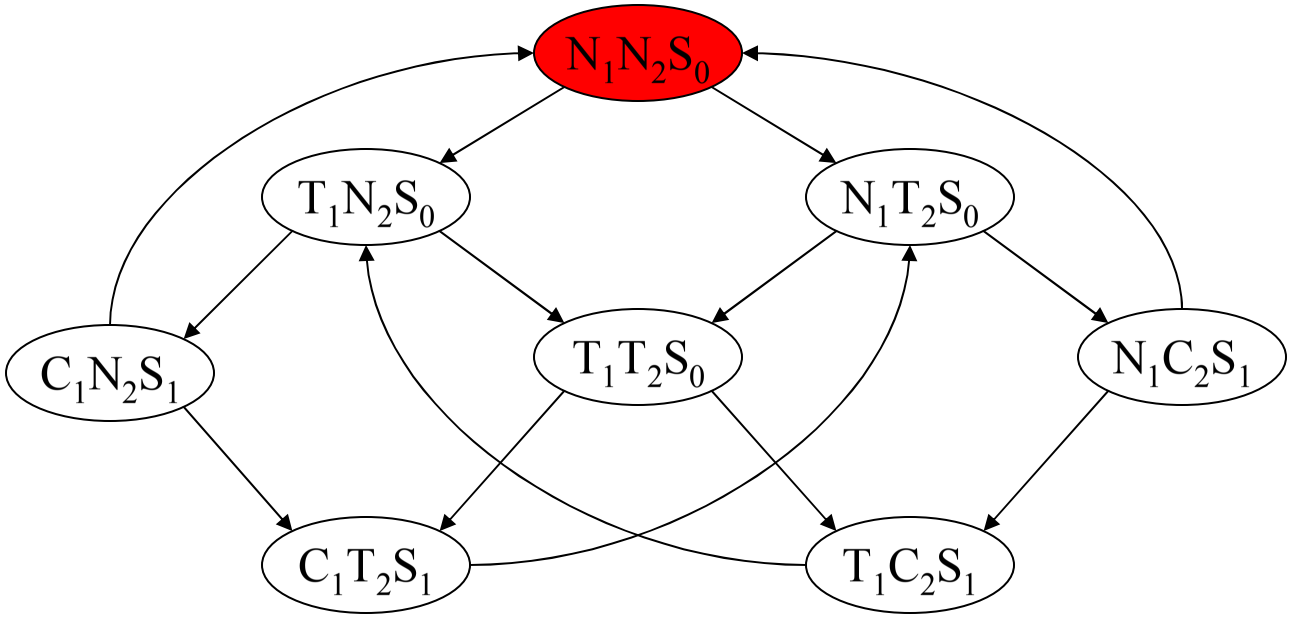
(A Proof:

All possible behaviors



Mutual Exclusion Example

Model Checker



Mutual Exclusion Example

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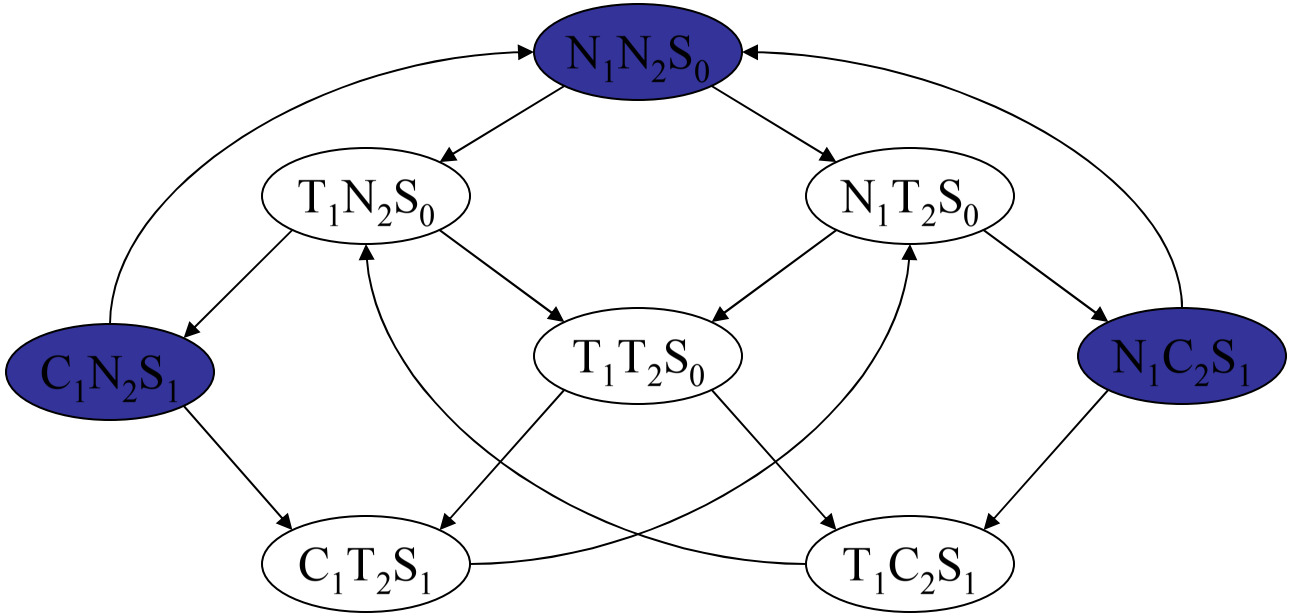

Mutual Exclusion Example

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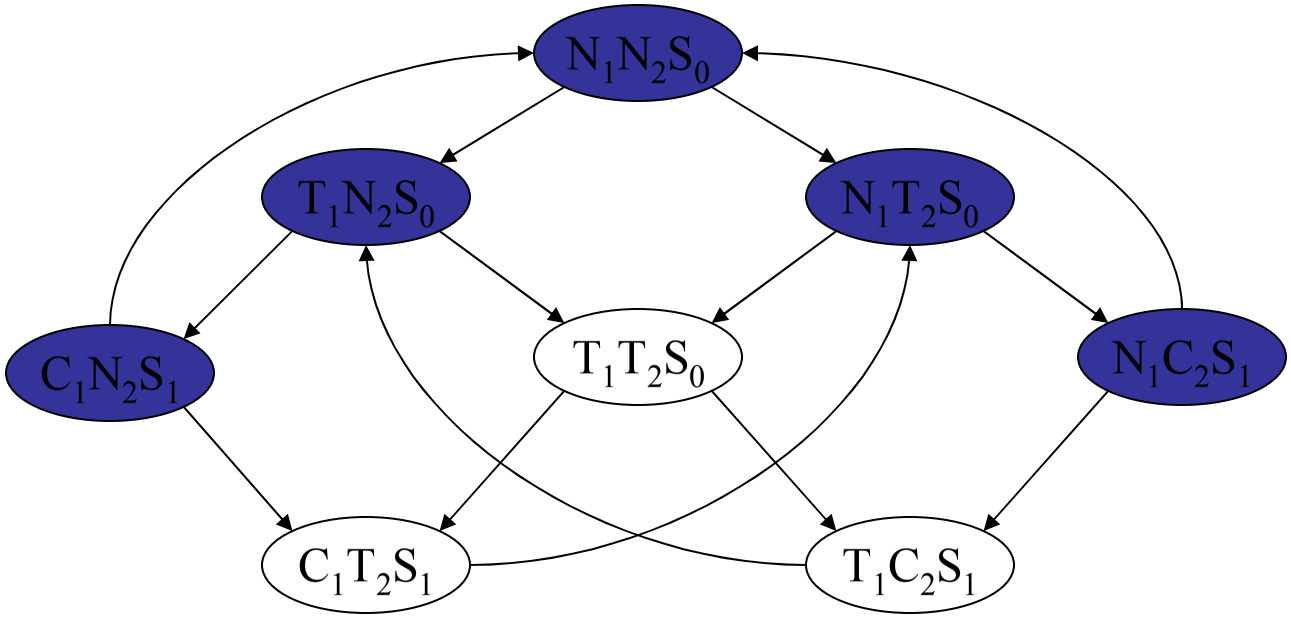

Mutual Exclusion Example

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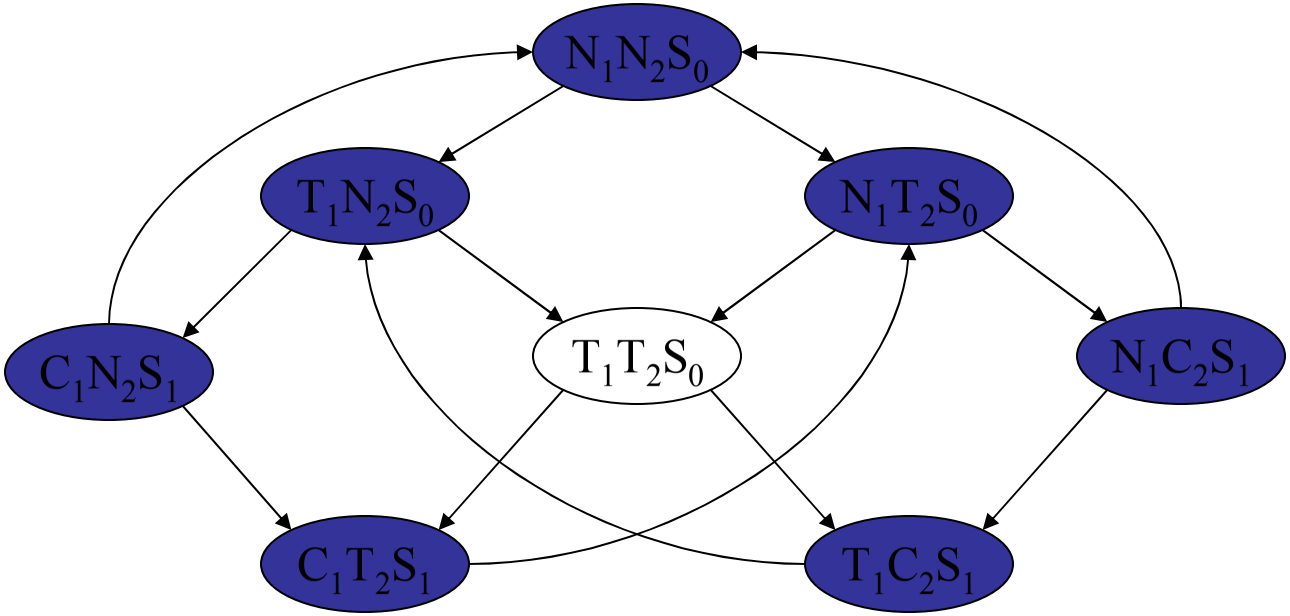
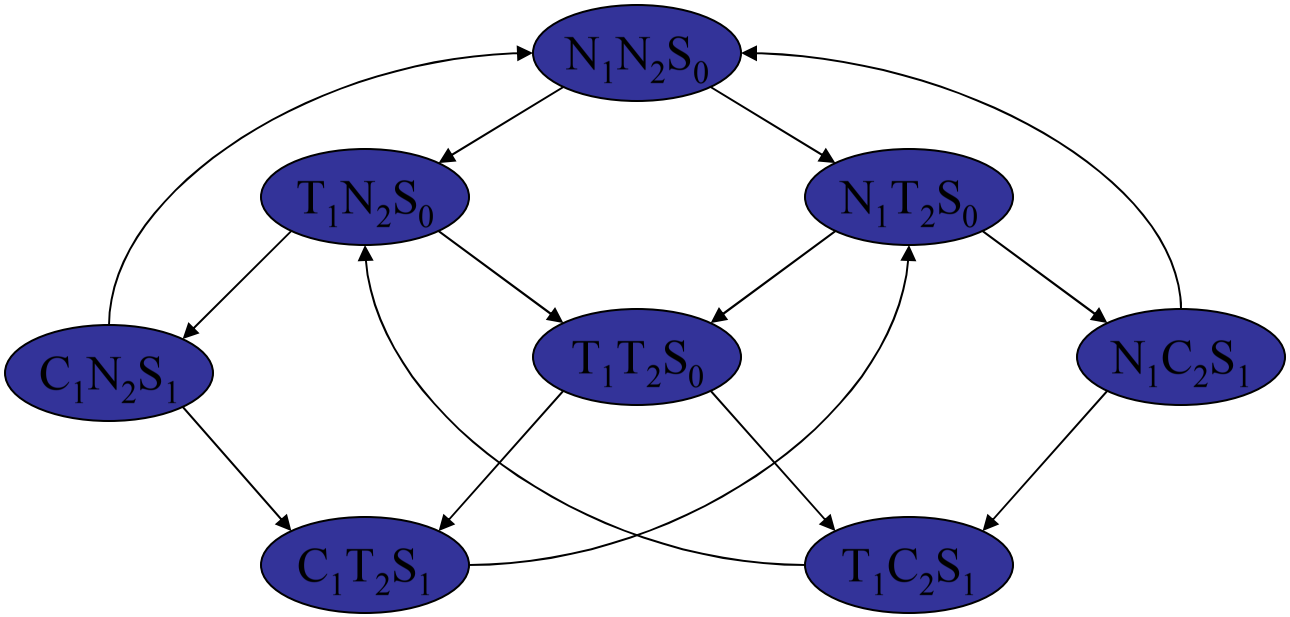


Mutual Exclusion Example

Model Checker



Mutual Exclusion Example

Specification – Desirable Property

No matter where you are there is no way to get to the initial state

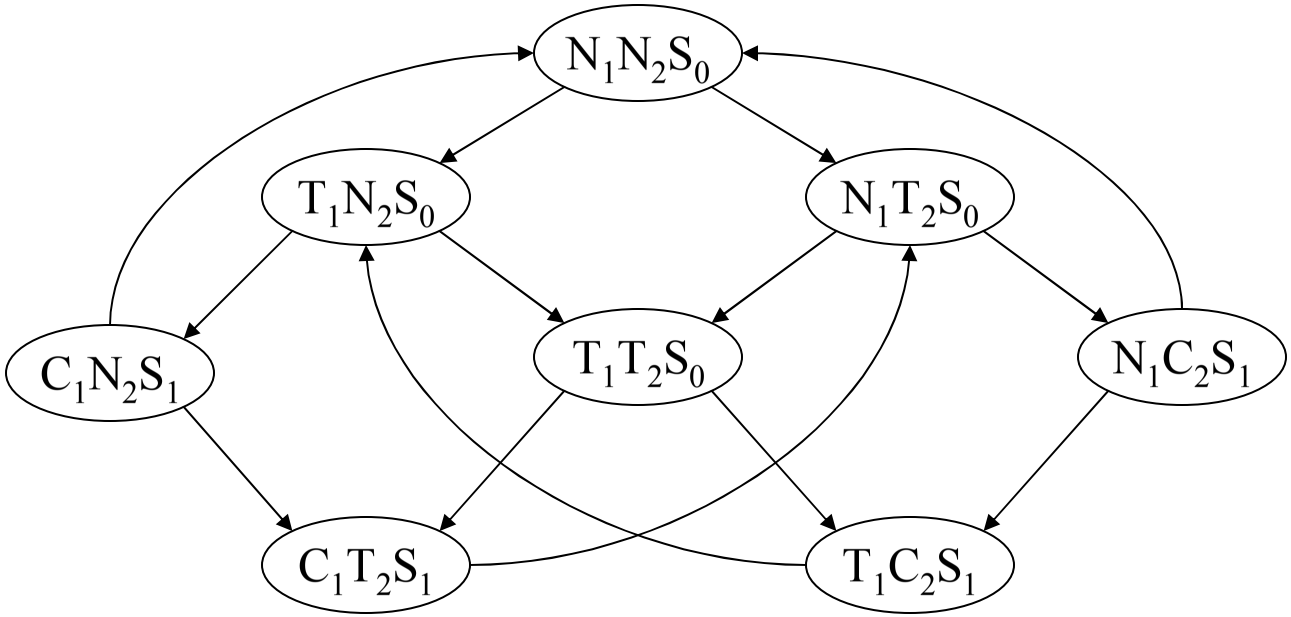
$$K \models AG\ EF\ (N_1 \wedge N_2 \wedge S_0)$$

Mutual Exclusion Example

Model Checker

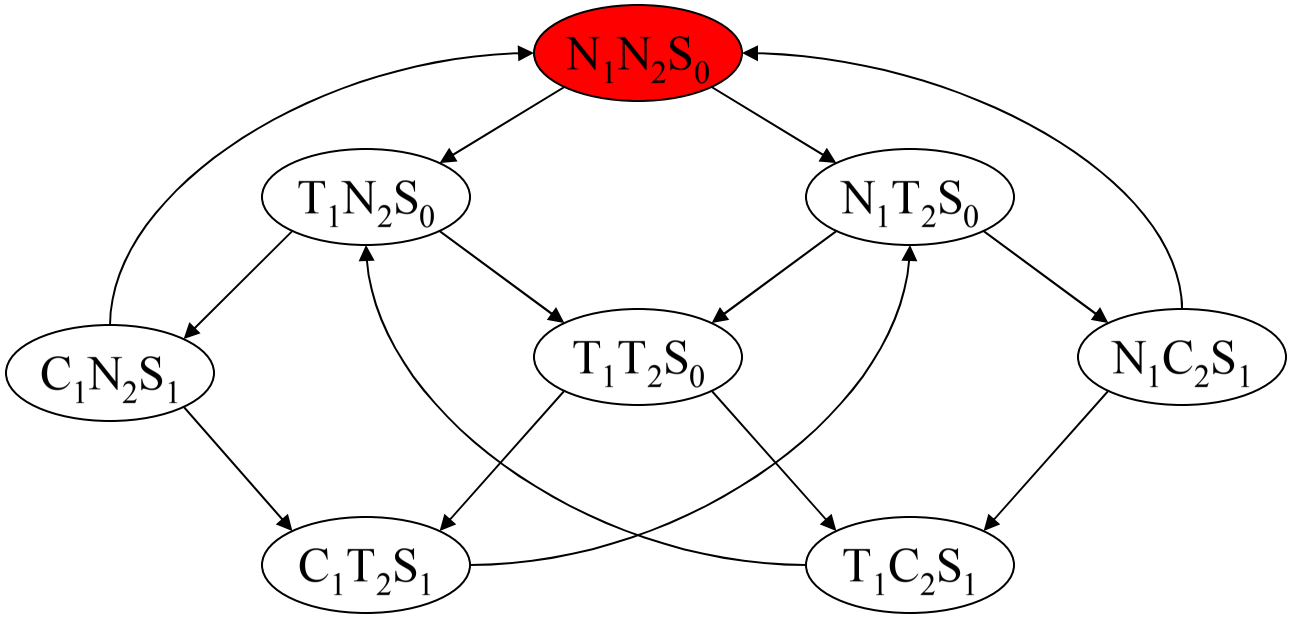
Answer: No

Counterexample: *All* possible behaviors



Mutual Exclusion Example

Model Checker



Mutual Exclusion Example

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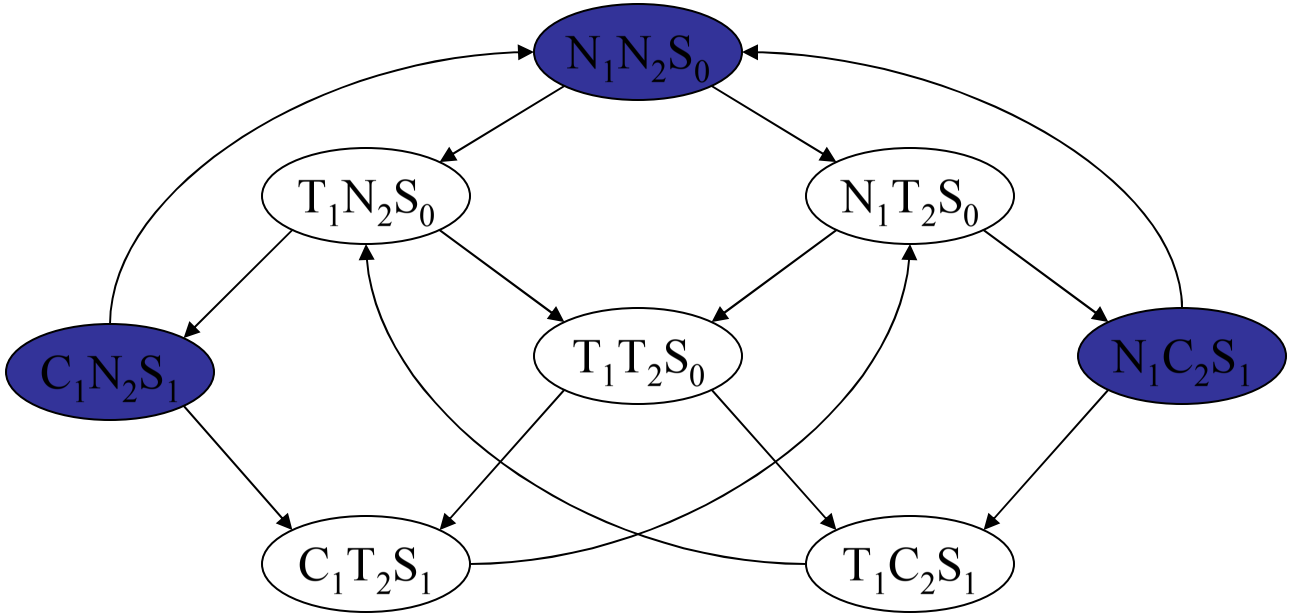


Defining Models

- Kripke Structure

K = < S ,p1, . . ., pk, R >

- S: the set of possible global states
- R(s,s'): the move from s to s' is a possible atomic transition
- Unary relations p1, . . ., pk express properties of the global states, e.g., being an initial state, being an accepting state, or that a particular variable has a special value.

- **Definition:** A *nondeterministic finite state machine* whose states are labeled with boolean variables, which are the evaluations of expressions in that state.

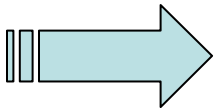
- **State explosion problem:** The size of S is often exponential in |requirements/design

- Model checking problem

K |= phi

Defining Models

- For a complex real-life control systems



Extended Finite State Machine (EFSM)

- FSM with a way to

-modularize the requirements to view them at different levels of detail

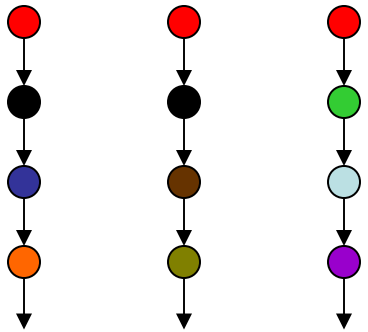
-combine requirements (or design) of components

- state variables and facilities in guards on transitions.

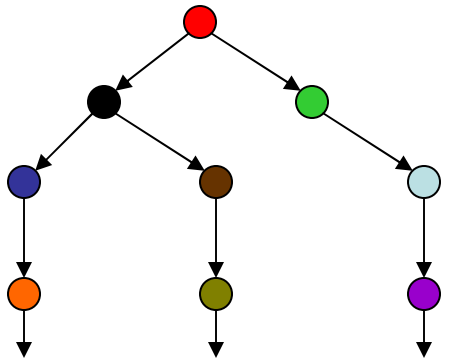
Defining Specifications

- Temporal Logic
  - Express properties of event orderings in time
  - e.g. “Always” when a packet is sent it will “Eventually” be received

- Linear Time
  - Every moment has a unique successor
  - Infinite sequences (words)
  - Linear Time Temporal Logic (LTL)



- Branching Time
  - Every moment has several successors
  - Infinite tree
  - Computation Tree Logic (CTL)



Safety and Liveness

- Safety properties
  - Invariants, deadlocks, reachability, etc.
  - Can be checked on finite traces
  - “something bad never happens”
- Liveness Properties
  - Fairness, response, etc.
  - Infinite traces
  - “something good will eventually happen”

Linear Temporal Logic (LTL)

- **Connectives of LTL (in addition to not, and, or, implication):**

[]	Always
<>	Eventually
o	Next cycle
(-)	previous cycle
U	Until

- **Examples of LTL**

```
[] p                    // p is always true
<>R -> (P U R)          //  Eventually it is the case that P exists
                        //  before R happens.
```

Linear Temporal Logic (LTL)

- **Safety Examples**
  - **[]({readySignal == 1} -> (){ackSignal == 0})**

- This assertion states "Always, readySignal equals one implies ackSignal equals zero on the next cycle".
  - It makes use of the Always operator (the box) and the Next Cycle operator (the empty parentheses pair).

  - **[]({readySignal == 1} -> (-){ackSignal == 0})**

- This assertion states “Always, readySignal equals one impliesackSignal equals zero on the previous cycle“
  - Makes use of the previous cycle operator (-)

- Liveness Example
  - <>({out1==1} && ()()[]{out2 < 2} && (-){out3==0})
  - This assertion states "Eventually, out1 will equal one, and then two cycles later and always after that, out2 is less than two and on the previous cycle out3 equals zero.
  - This example uses the Eventually operator (the diamond <>), the always operator (the box []), and the Next and Previous Cycle operators (the empty parentheses pair () and the parenthesized minus sign (-), respectively.

SPIN Model Checker

- Kripke structures are described as “programs” in the PROMELA language
  - Kripke structure is generated on-the-fly during model checking
- Automata based model checker
  - Translates LTL formula to Büchi automaton
- By far the most popular model checker
  - 10th SPIN Workshop held with ICSE – May 2003
- Relevant theoretical papers can be found here
  - http://netlib.bell-labs.com/netlib/spin/whatispin.html
- Ideal for software model checking due to expressiveness of the PROMELA language
  - Close to a real programming language
- Gerard Holzmann won the ACM software award for SPIN

Branching Temporal Logic (BTL)

- **Some temporal connectives in Computation Tree Logic (CTL)**

EX φ **true** in current state
if formula φ is **true** in at least one of the next states

EF φ **true** in current state
if there exists some state in some path beginning in current state
that satisfies the formula φ

EG φ **true** in current state
if every state in some path beginning in current state satisfies the formula φ

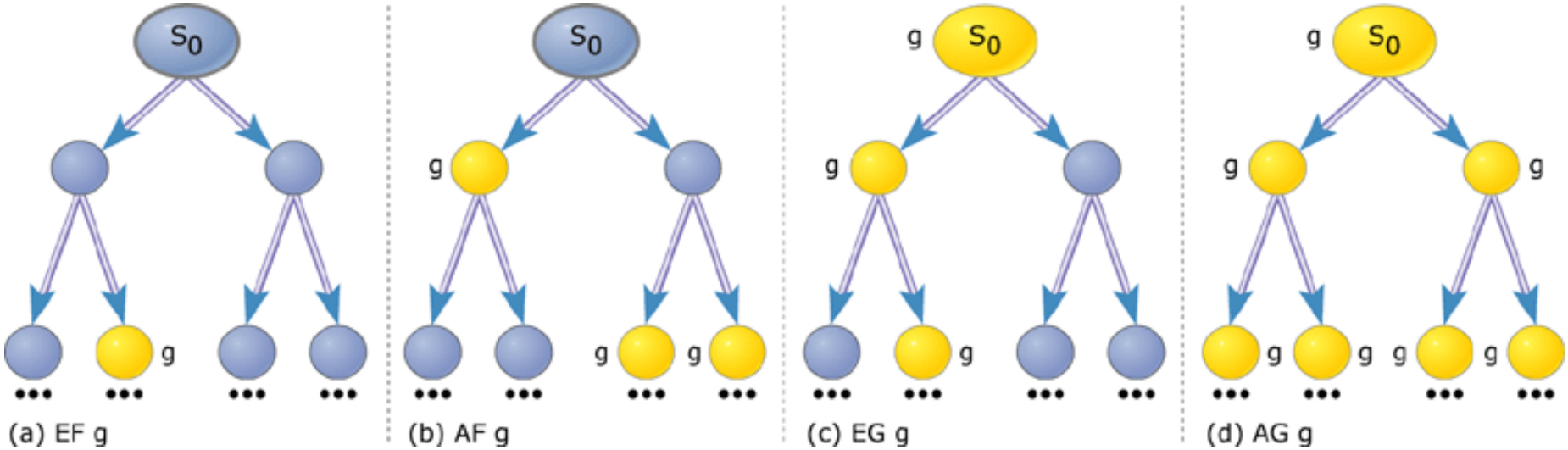
AX φ **true** in current state
if formula φ is **true** in every one of the next states

AF φ **true** in current state
if there exists some state in every path beginning in current state that
satisfies the formula φ

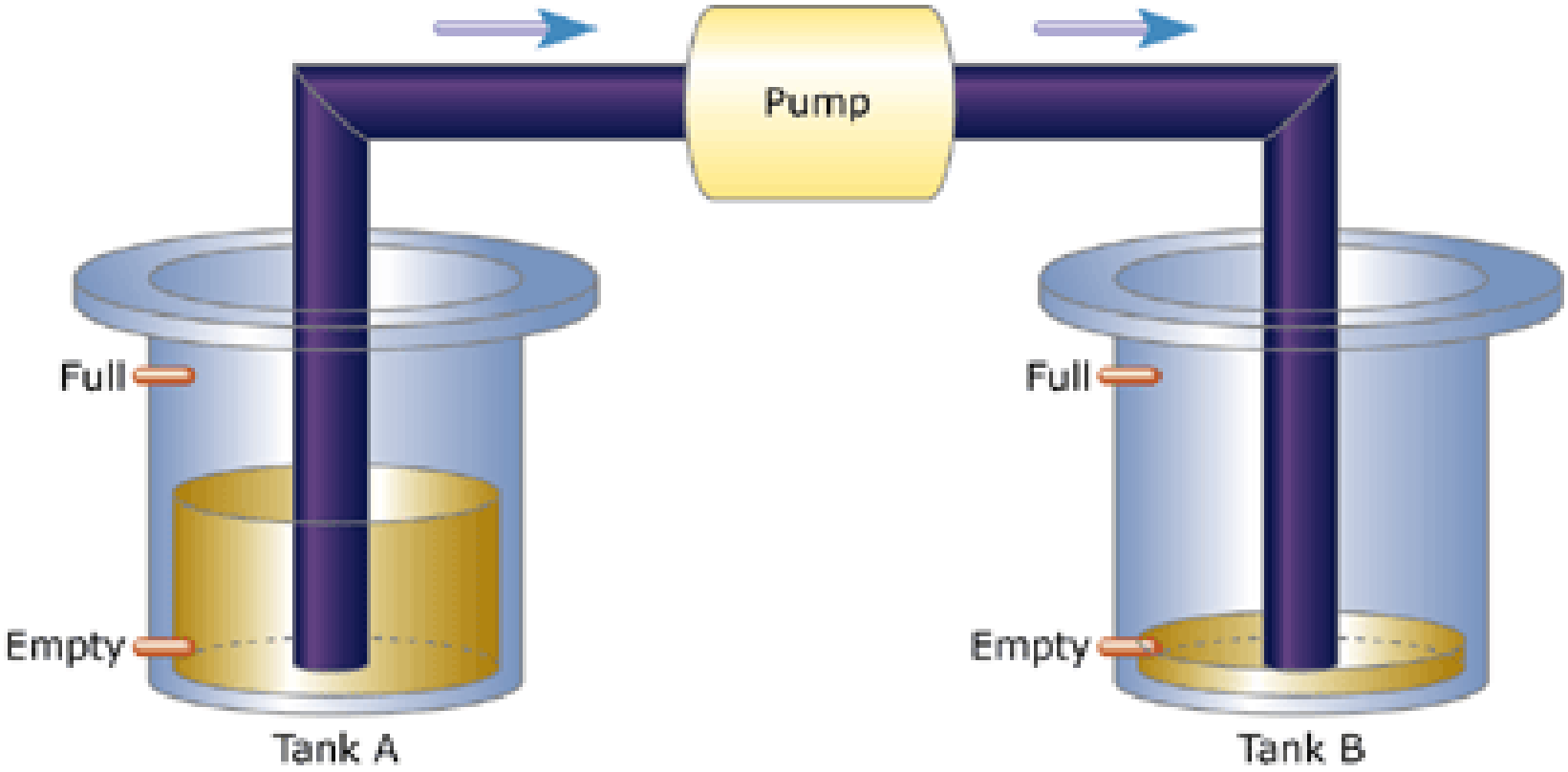
AG φ **true** in current state
if every state in every path beginning in current state satisfies the formula φ

Defining Specifications

- **Intuition for CTL formulae which are satisfied at state s0**



A Simple Two Tank System Example



By Girish Keshav Palshikar, Embedded Systems Programming
http://www.embedded.com/showArticle.jhtml?articleID=17603352

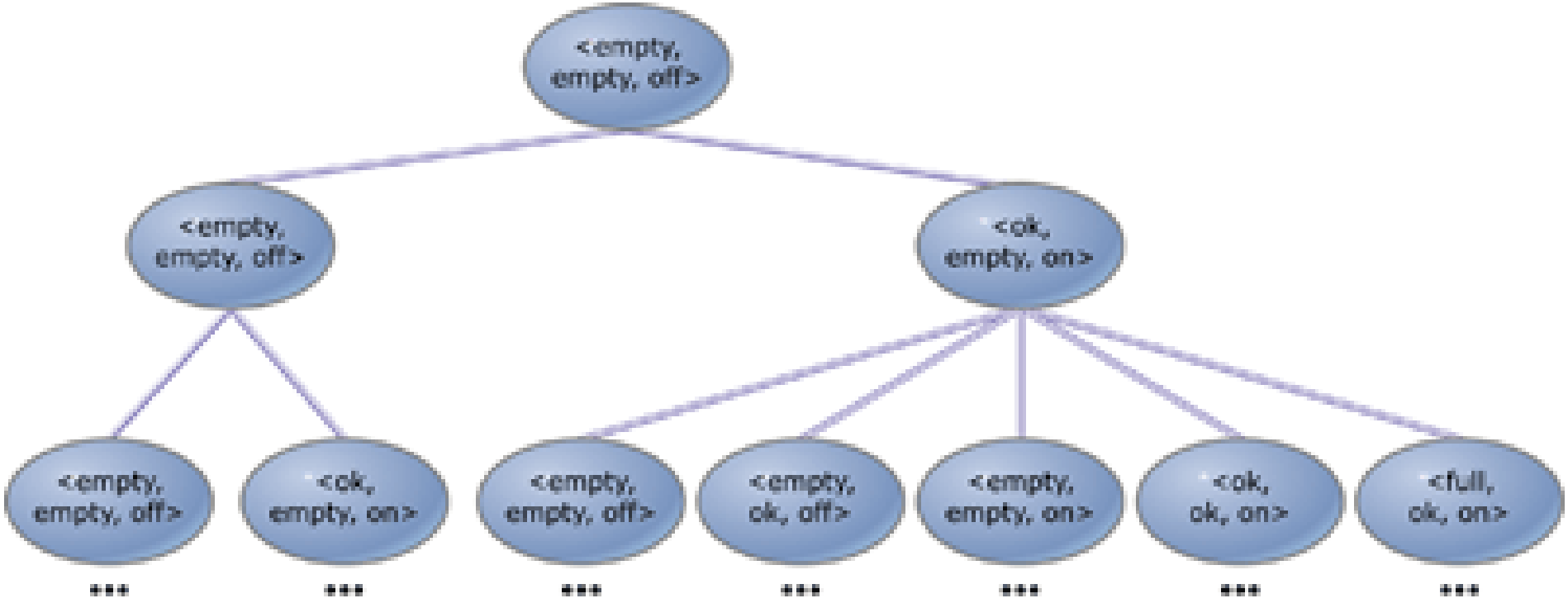
A Simple Two Tank System Example

In symbolic model verifier (SMV) model checking tool, CMU
http://www.cs.cmu.edu/~modelcheck/smv.html

```
MODULE main
VAR
  level_a : {empty, ok, full}; -- lower tank
  level_b : {empty, ok, full}; -- upper tank
  pump : {on, off};
ASSIGN
  next(level_a) := case
     level_a = empty : {empty, ok};
     level_a = ok & pump = off : {ok, full};
     level_a = ok & pump = on : {ok, empty, full};
     level_a = full & pump = off : full;
     level_a = full & pump = on : {ok, full};
     1 : {ok, empty, full};
  esac;
  next(level_b) := case
     level_b = empty & pump = off : empty;
     level_b = empty & pump = on : {empty, ok};
     level_b = ok & pump = off : {ok, empty};
     level_b = ok & pump = on : {ok, empty, full};
     level_b = full & pump = off : {ok, full};
     level_b = full & pump = on : {ok, full};
     1 : {ok, empty, full};
  esac;
  next(pump) := case
       pump = off & (level_a = ok | level_a = full) &
       (level_b = empty | level_b = ok) : on;
       pump = on & (level_a = empty | level_b = full) : off;
       1 : pump; -- keep pump status as it is
    esac;
INIT
  (pump = off)
SPEC
  -- pump if always off if ground tank is empty or up tank is full
  -- AG AF (pump = off -> (level_a = empty | level_b = full))
  -- it is always possible to reach a state when the up tank is ok or full
  AG (EF (level_b = ok | level_b = full))
```

A Simple Two Tank System Example

Initial part of the execution tree for the pump controller system



A Simple Two Tank System Example

Initial part of the execution tree for the pump controller system

-- specification AF pump = on is false

-- as demonstrated by the following execution sequence

-- loop starts here

state 1.1:

level_a = full
level_b = full
pump = off

state 1.2:

A Simple Two Tank System Example

Some other properties

- AF (pump = off)

--- for every path beginning at the initial state, there's a state in that path at which the pump is off.

trivially true at the initial state, since in the initial state itself (which is included in all paths) pump = off is true.

- AG ((pump = off) -> AF (pump = on))

--- it's always the case that if pump is off then it eventually becomes on.

clearly false in the initial state.

- AG AF (pump = off -> (level_a = empty | level_b = full))

---- pump is always off if ground tank is empty or the upper tank is full.

- AG (EF (level_b = ok | level_b = full))

--- it's always possible to reach a state when the upper tank is ok or full.

Issues

- Temporal logic: can be hard to work with
- Translations of requirements models to the input language of model checking engines: cannot be efficiently checked, due to state space explosion
- Counter-examples: do not mean anything to the stakeholders; need to be translated back into the original modeling language.
- Deals only with state-oriented behavioral requirements models