Lecture 4
Model Checking and Logic Synthesis

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EECI, 18 March 2013

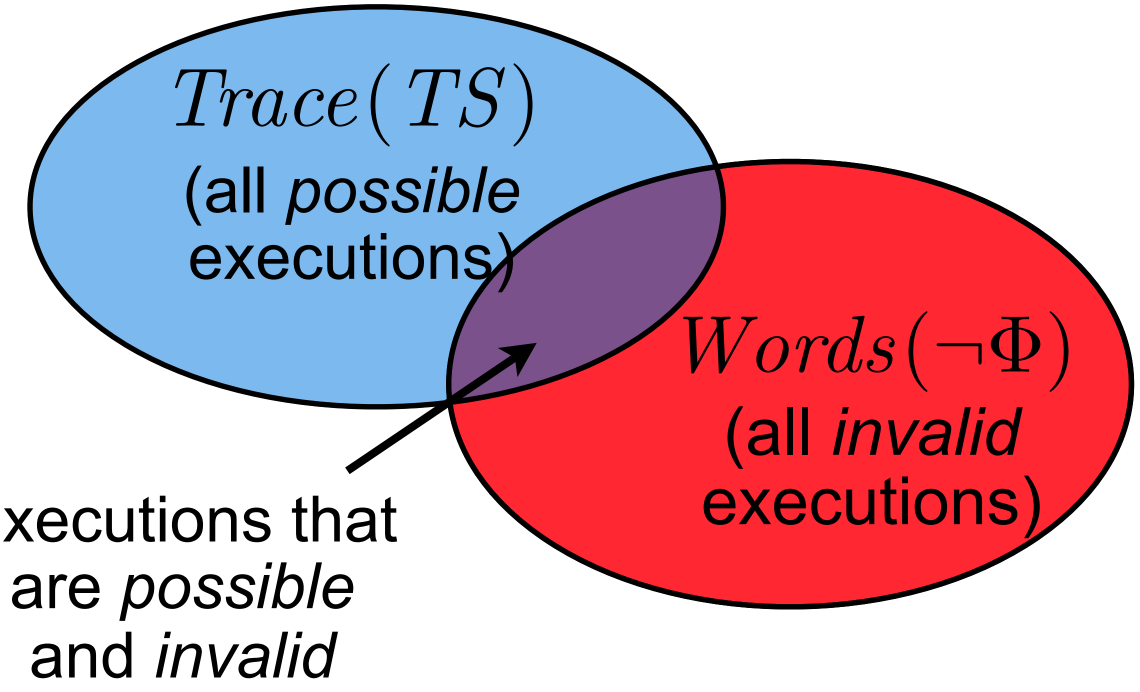
Outline

- Model checking: what it is, how it works, how it is used
- Computational complexity of model checking
- Closed system synthesis
- Examples using SPIN model checker

The basic idea behind model checking

Given:

- Transition system TS
- LTL formula Φ



$Trace(TS)$
(all *possible* executions)

$Words(\neg\Phi)$
(all *invalid* executions)

executions that are *possible* and *invalid*

Question: Does TS satisfy Φ, i.e.,

$$TS \models \Phi \text{ ?}$$

Answer (conceptual):

$TS \models \Phi$	[*TS* satisfies Φ]
$\Updownarrow$	
$Trace(TS) \subseteq Words(\Phi)$	[All executions of *TS* satisfy Φ]
$\Updownarrow$	
$Trace(TS) \cap Words(\neg\Phi) = \emptyset$	[No execution of *TS* violates Φ]

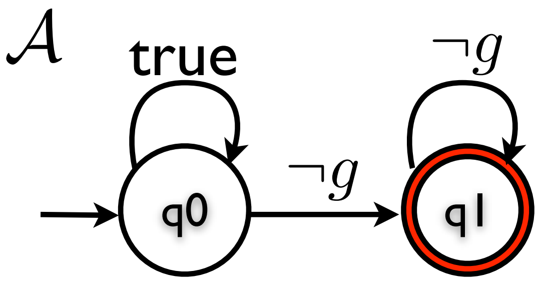
How to determine whether $Trace(TS) \cap Words(\neg\Phi) = \emptyset$ **?**

Preliminaries: LTL → Buchi automata

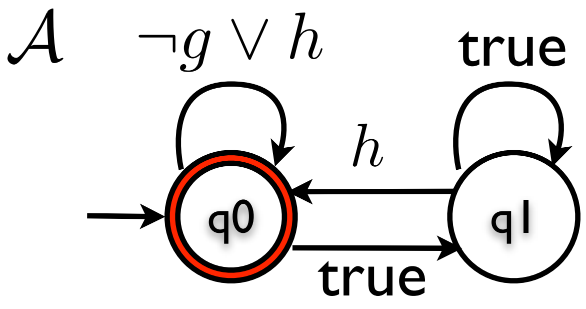
Theorem. *There exists an algorithm that takes an LTL formula Φ and returns a Büchi automaton $\mathcal{A}$ such that*

$$Words(\Phi) = \mathcal{L}_\omega(\mathcal{A})$$

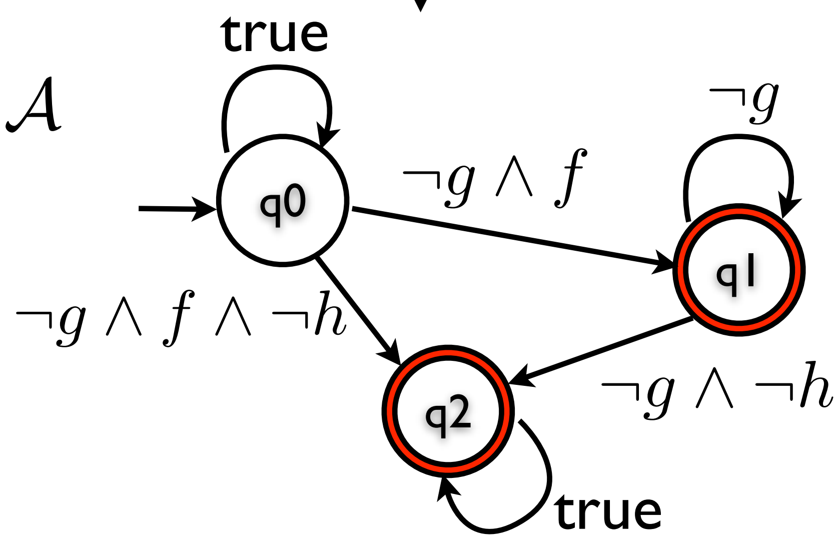
$\Phi = \neg\Box\Diamond g$



$\Phi = \Box(g \to \Diamond h)$



$\Phi = \Diamond(f \wedge \neg(g\mathcal{U}h))$



A tool for constructing Buchi automata from LTL formulas: LTL2BA
[http://www.lsv.ens-cachan.fr/~gastin/ltl2ba/index.php]

Preliminaries: transition system ⊗ Buchi automaton

Transition system:

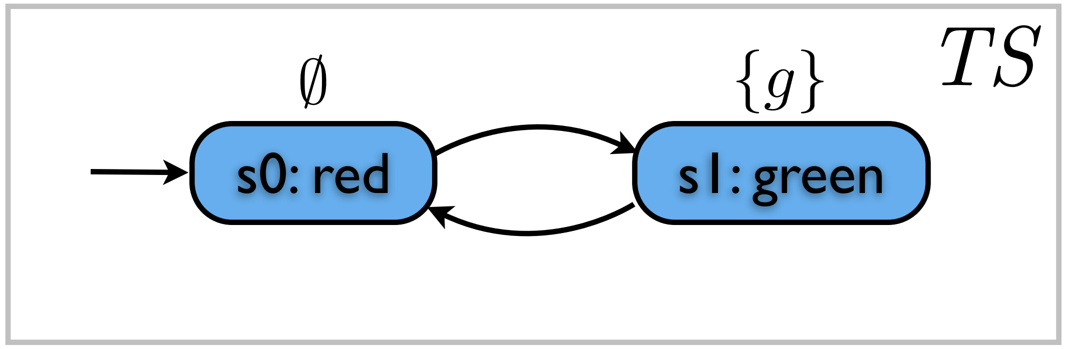
$$TS = (S, \mathrm{Act}, \rightarrow, I, \mathrm{AP}, L)$$

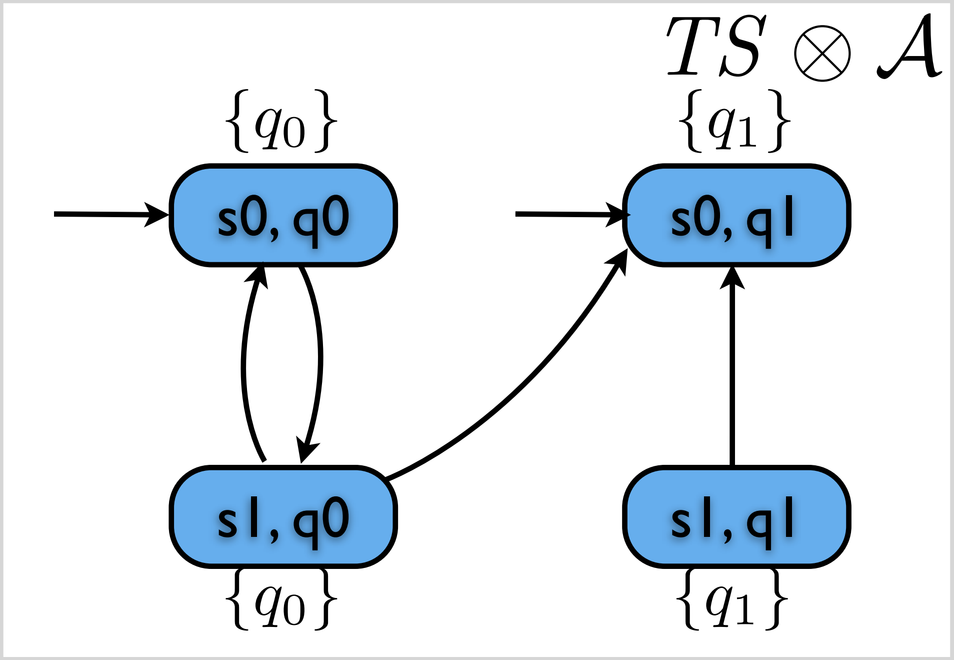
Nondeterministic Buchi automaton:

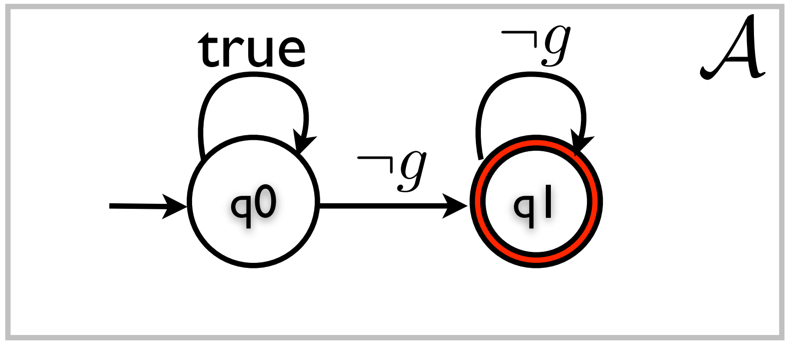
$$\mathcal{A} = (Q, 2^{\mathrm{AP}}, \delta, Q_0, F)$$

Define the product automaton: $TS \otimes \mathcal{A} = (S', \mathrm{Act}, \rightarrow', I', \mathrm{AP}', L')$, where

- $S' = S \times Q$
- $\forall s, t \in S, q, p \in Q$ with $s \xrightarrow{\alpha} t$ and $q \xrightarrow{L(t)} p$, there exists $\langle s, q \rangle \xrightarrow{\alpha}' \langle t, p \rangle$
- $I' = \{\langle s_0, q \rangle : s_0 \in I \text{ and } \exists q_0 \in Q_0 \text{ s.t. } q_0 \overset{L(s_0)}{\longrightarrow} q\}$
- $AP' = Q$
- $L' : S \times Q \rightarrow 2^Q$ and $L'(\langle s, q \rangle) = \{q\}$







Preliminaries

Transition system: $TS = (S, \mathrm{Act}, \rightarrow, I, \mathrm{AP}, L)$

Nondeterministic Buchi automaton: $\mathcal{A} = (Q, 2^{\mathrm{AP}}, \delta, Q_0, F)$

not in *F*

Theorem: $Trace(TS) \cap \mathcal{L}_\omega(\mathcal{A}) \neq \emptyset \quad \Leftrightarrow \quad TS \otimes \mathcal{A} \not\models \text{“eventually forever”} \neg F$

Proof idea (⇐): Pick a path π‘ in $TS \otimes \mathcal{A}$ s.t. $\pi' \not\models \text{“eventually forever”} \neg F$, and let π be its projection to *TS*. Then,

- *trace*(π) ∊ *Trace*(*TS*) -- by definition of product
- *trace*(π) ∊ $\mathcal{L}_\omega(\mathcal{A})$ -- by hypothesis and by definition of product (*L*’(‹*s*,*q*›) = {*q*})

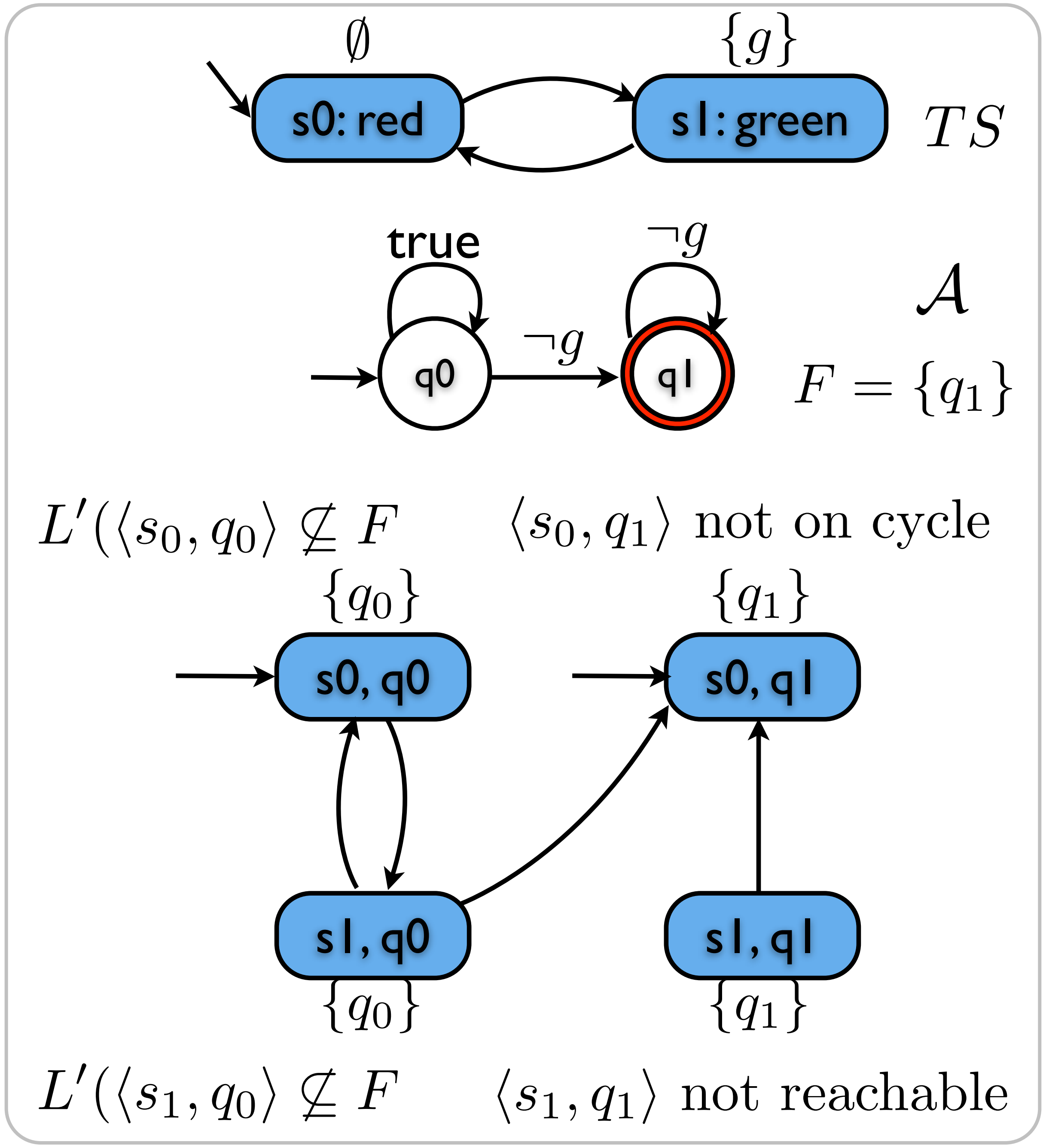
$TS \otimes \mathcal{A} \quad \not\models \text{“eventually forever”} \neg F$

$$\Updownarrow$$

There exists a state *x* in $TS \otimes \mathcal{A}$

- *x* is reachable
- *L’*(*x*) ⊆*F*
- *x* is on a directed cycle

} graph search, e.g., (nested) depth-first search


$\emptyset$
$\{g\}$
s0: red
s1: green
TS
true
$\neg g$
$\neg g$
q0
q1
$\mathcal{A}$
$F = \{q_1\}$
$L'(\langle s_0, q_0\rangle \not\subseteq F$
$\langle s_0, q_1\rangle$ not on cycle
$\{q_0\}$
$\{q_1\}$
s0, q0
s0, q1
s1, q0
s1, q1
$\{q_0\}$
$\{q_1\}$
$L'(\langle s_1, q_0\rangle \not\subseteq F$
$\langle s_1, q_1\rangle$ not reachable

Putting together

Given:

- Transition system TS
- LTL formula Φ
- NBA $\mathcal{A}_{\neg\Phi}$ accepting $\neg\Phi$ with the set *F* of accepting states

$$TS \not\models \Phi$$

$$\Updownarrow$$

$$Trace(TS) \not\subseteq Words(\Phi)$$

$$\Updownarrow$$

$$Trace(TS) \cap Words(\neg\Phi) \neq \emptyset$$

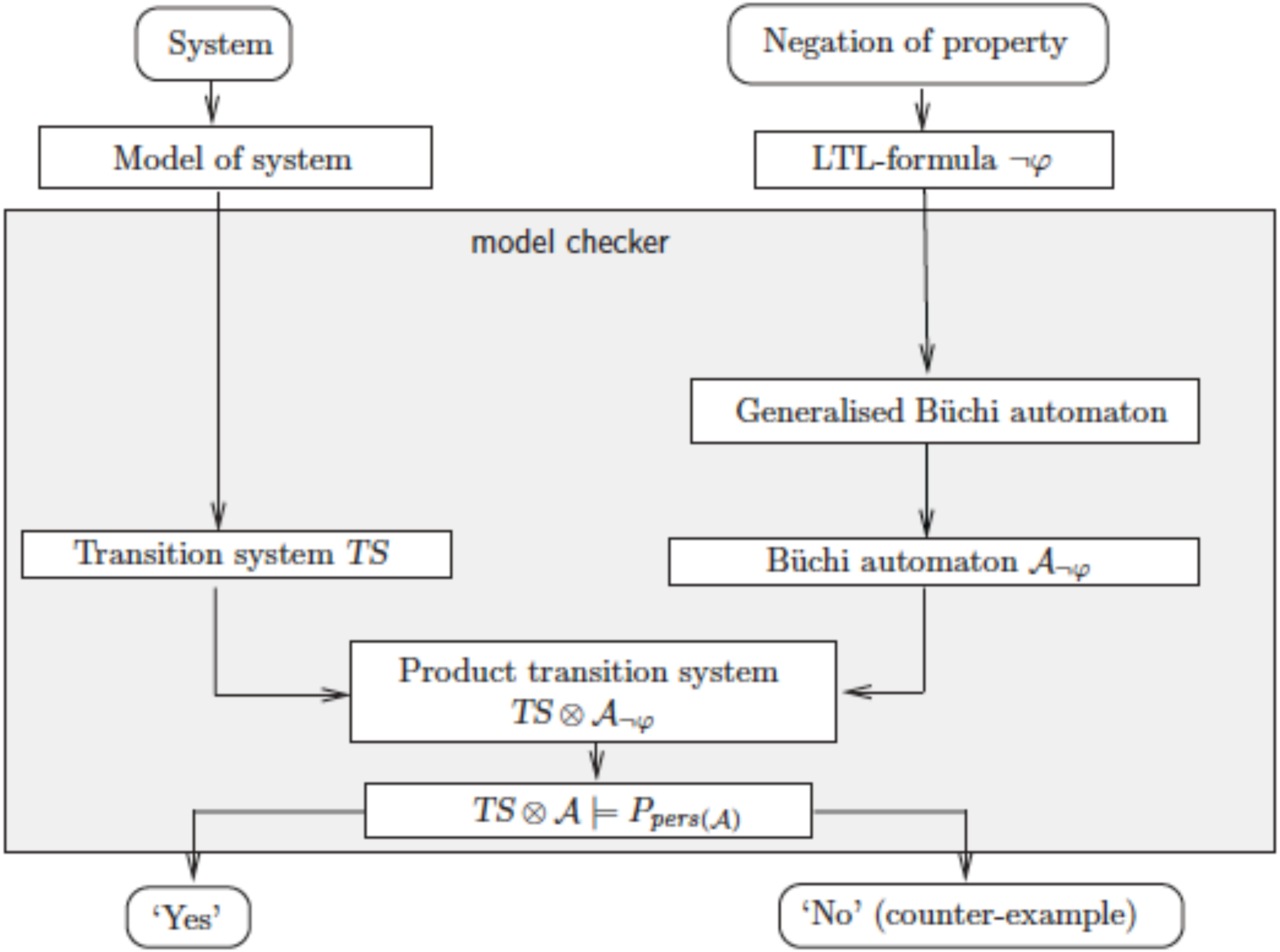
$$\Updownarrow$$

$$Trace(TS) \cap \mathcal{L}_\omega(\mathcal{A}_{\neg\Phi}) \neq \emptyset$$

$$\Updownarrow$$

$$TS \otimes \mathcal{A}_{\neg\Phi} \not\models \text{``eventually forever''} \neg F$$

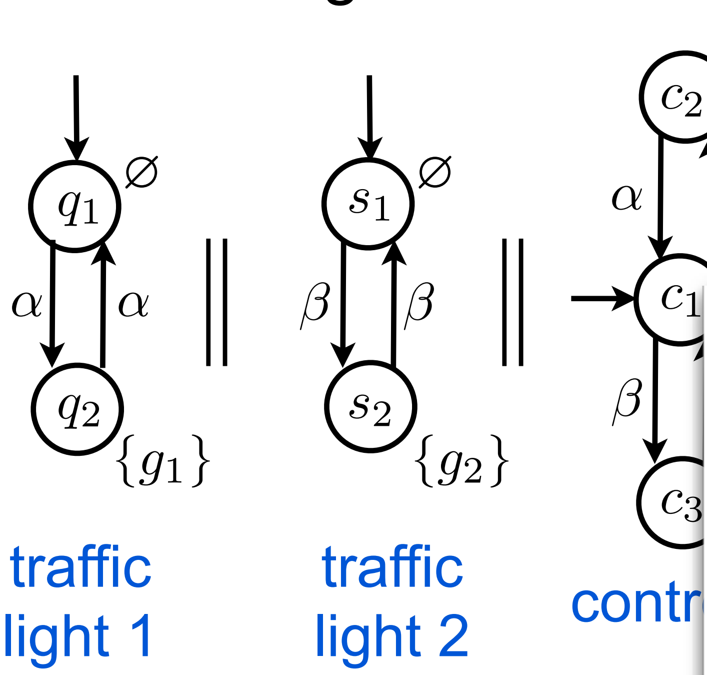
The process flow of model checking

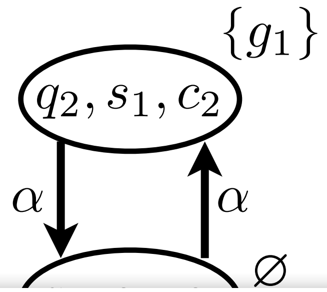

System
Model of system
Negation of property
LTL-formula $\neg\varphi$
model checker
Generalised Büchi automaton
Transition system TS
Büchi automaton $\mathcal{A}_{\neg\varphi}$
Product transition system
$TS \otimes \mathcal{A}_{\neg\varphi}$
$TS \otimes \mathcal{A} \models P_{pers(\mathcal{A})}$
'Yes'
'No' (counter-example)

Efficient model checking tools automate the process: SPIN, nuSMV, TLC,...

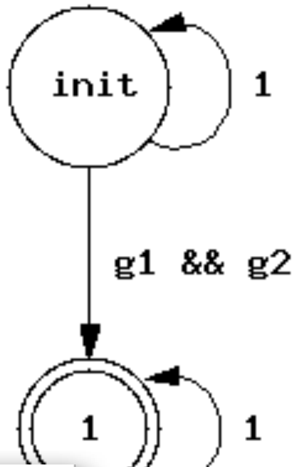
Example 1: traffic lights (property verified)

System *TS*: synchronous composition of two traffic lights and a controller





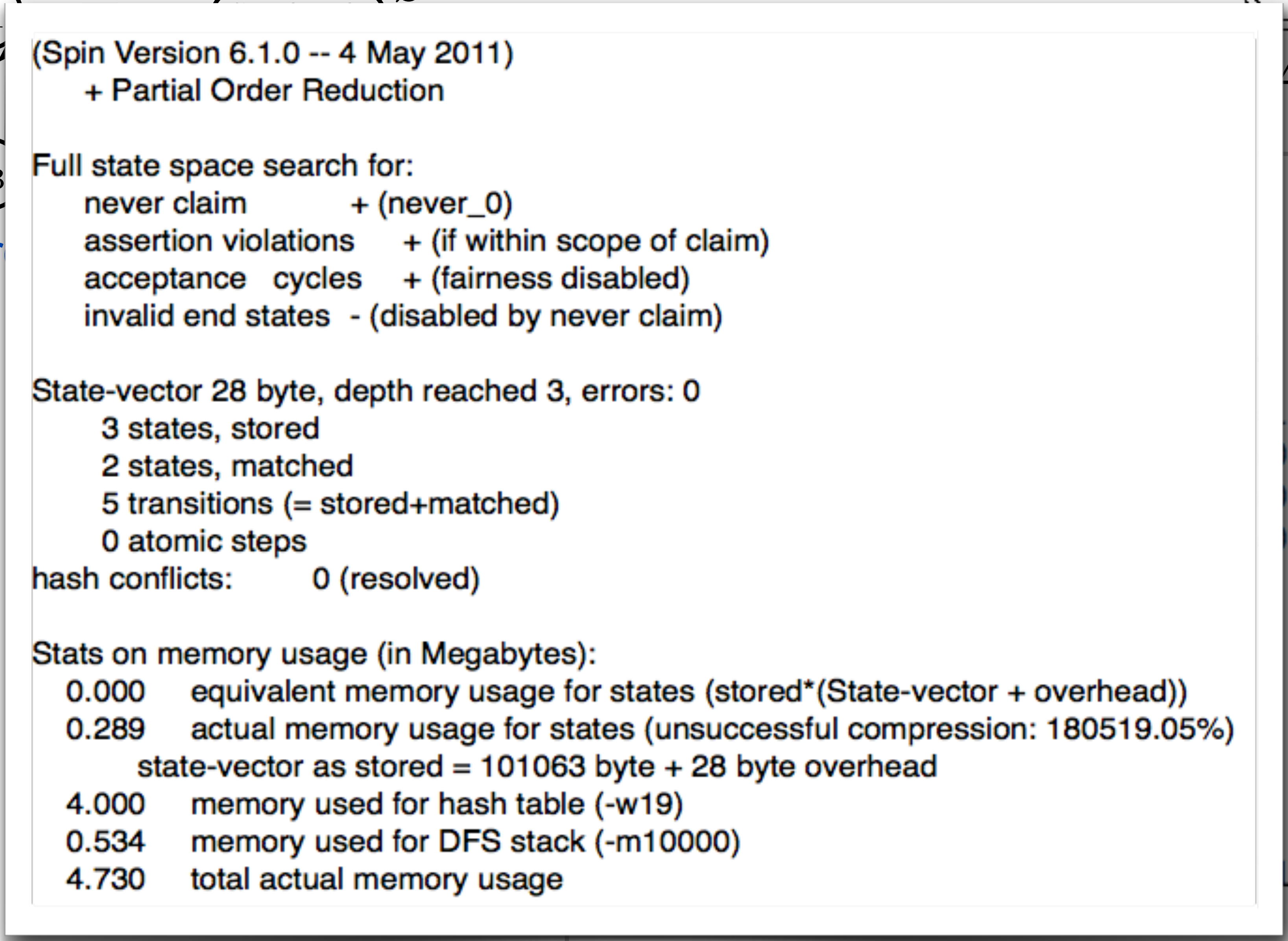
Specification P_1:
"The light are never green simultaneously."



$A_{\neg P_1}$

Property verified:

$$TS \vDash P_1$$

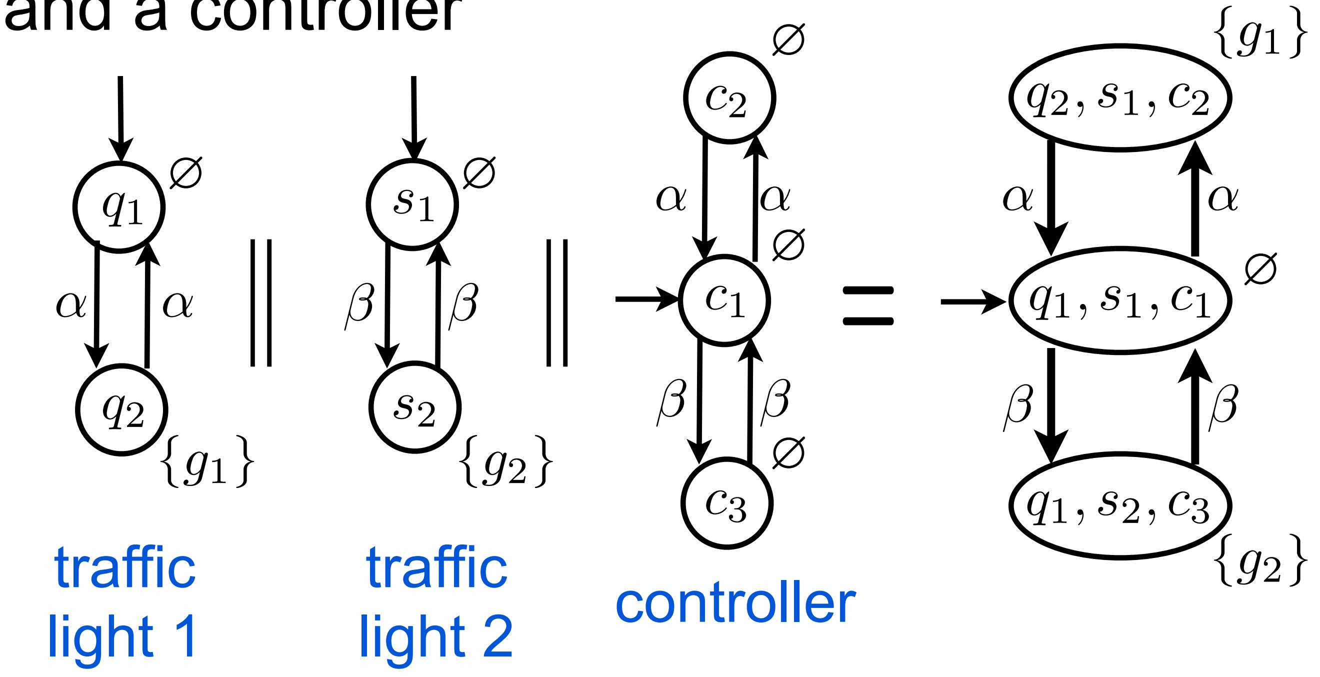


```
(Spin Version 6.1.0 -- 4 May 2011)
        + Partial Order Reduction

Full state space search for:
        never claim             + (never_0)
        assertion violations    + (if within scope of claim)
        acceptance   cycles     + (fairness disabled)
        invalid end states      - (disabled by never claim)

State-vector 28 byte, depth reached 3, errors: 0
          3 states, stored
          2 states, matched
          5 transitions (= stored+matched)
          0 atomic steps
hash conflicts:          0 (resolved)

Stats on memory usage (in Megabytes):
    0.000       equivalent memory usage for states (stored*(State-vector + overhead))
    0.289       actual memory usage for states (unsuccessful compression: 180519.05%)
            state-vector as stored = 101063 byte + 28 byte overhead
    4.000       memory used for hash table (-w19)
    0.534       memory used for DFS stack (-m10000)
    4.730       total actual memory usage
```

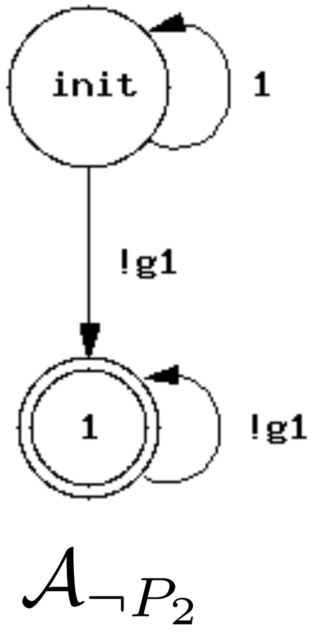
```
; g2=0 }
; g2=1 }
; g2=0 }
; g2=0 }
accept_all :     /* 1 */
```

Example 2: traffic lights (counterexample found → property not verified)

System *TS*: composition of two traffic lights and a controller



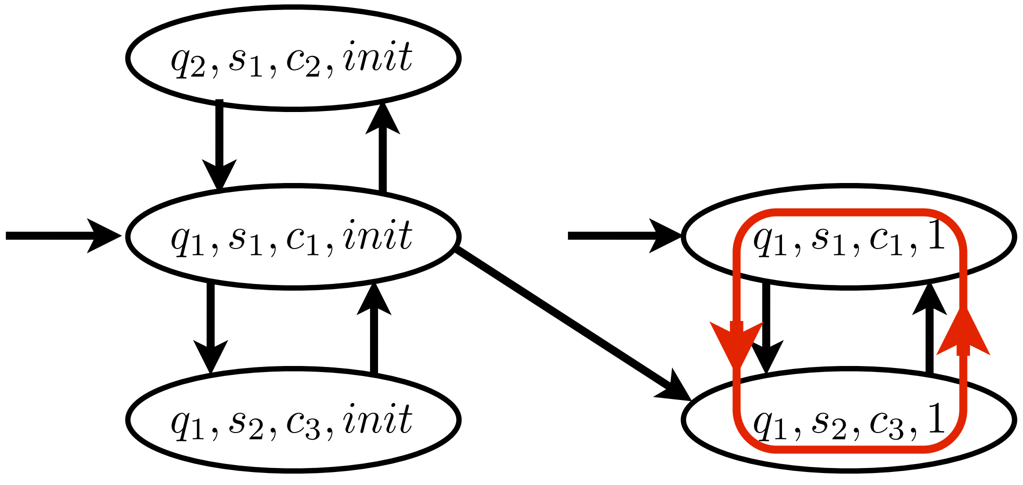
Specification P_2:
"The first light is infinitely often green."



Property not verified: $TS \not\models P_2$

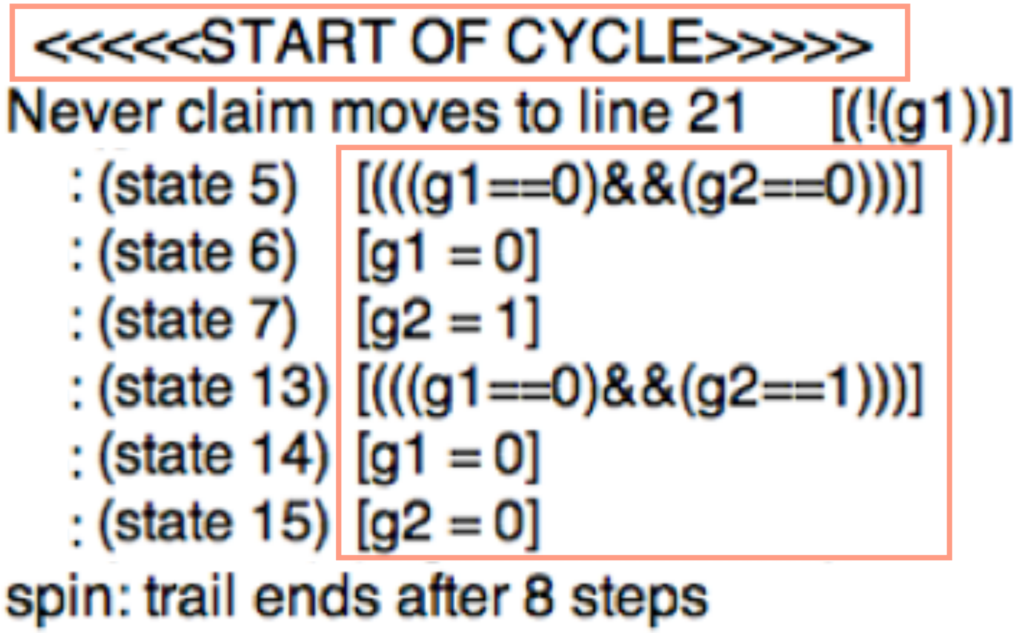
Counterexample:

$$(\langle q_1, s_1, c_1, 1\rangle \langle q_1, s_2, c_3, 1\rangle)^\omega$$



$TS \otimes \mathcal{A}_{\neg P_2}$

Counterexample from SPIN output:

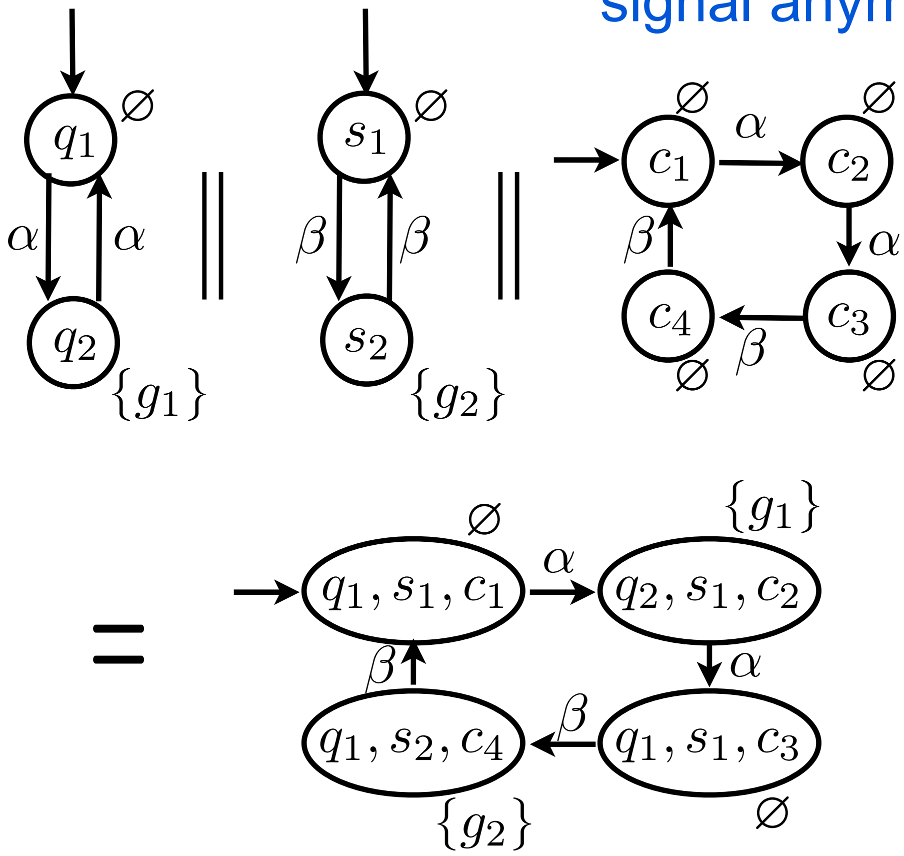


```
<<<<<START OF CYCLE>>>>>
Never claim moves to line 21     [((!(g1))]
   : (state 5)   [(((g1==0)&&(g2==0)))]
   : (state 6)   [g1 = 0]
   : (state 7)   [g2 = 1]
   : (state 13)  [(((g1==0)&&(g2==1)))]
   : (state 14)  [g1 = 0]
   : (state 15)  [g2 = 0]
spin: trail ends after 8 steps
```

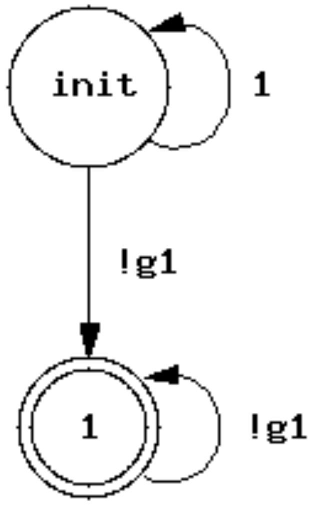
Example 3: traffic lights (counterexample used to modify the controller)

System *TS*: composition of two traffic lights and a modified controller

new controller: β^ω is not a valid control signal anymore



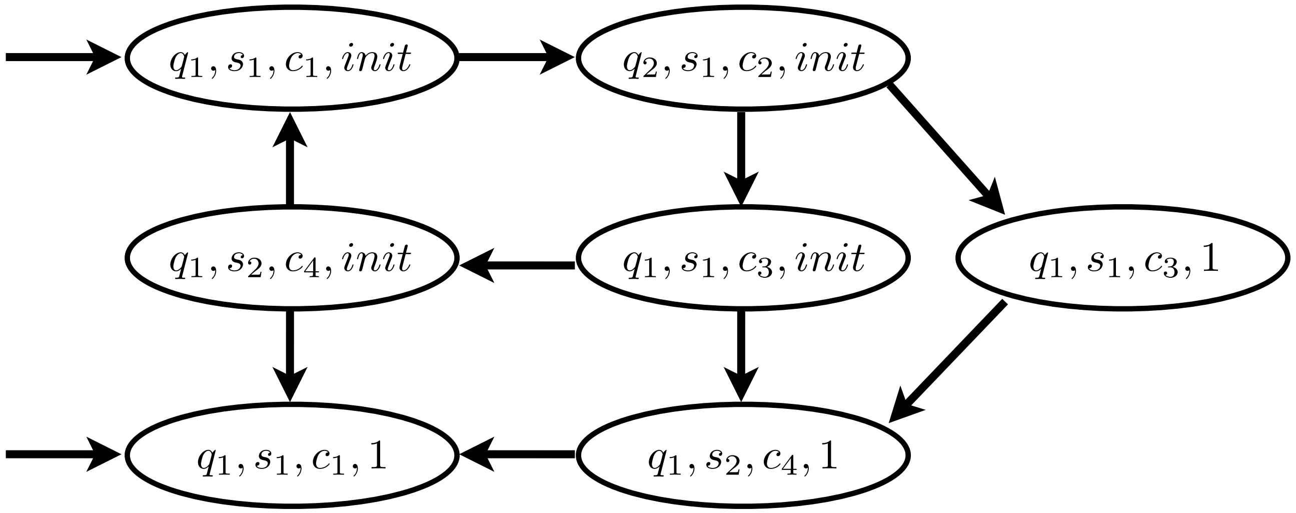
Specification P_2: "The first light is infinitely often green."



$\mathcal{A}_{\neg P_2}$

Property verified:

$$TS \models P_2$$



$TS \otimes \mathcal{A}_{\neg P_2}$

Computational complexity of model checking

Transition system: $TS = (S, \mathrm{Act}, \rightarrow, I, \mathrm{AP}, L)$. Specification: Φ

Problem size:

$$\underbrace{\begin{pmatrix} \#\text{ of reachable} \\ \text{states in } TS \end{pmatrix}}_{O(|S|)} \times \underbrace{\begin{pmatrix} \#\text{ of states} \\ \text{in } \mathcal{A}_{\neg\Phi} \end{pmatrix}}_{2^{O(|\neg\Phi|)}} \times \begin{pmatrix} \text{size of one} \\ \text{state in bytes} \end{pmatrix}$$

“length” of $\neg\Phi$, e.g., # of operators in $\neg\Phi$

Potential reductions:

- Restrict the ranges of variables
- Use abstraction, separation of concerns, generalization
- Use compressed representation of the state space (e.g. BDD)
  - Used in symbolic model checkers, e.g., SMV, NuSMV
- **Partial order reduction** (avoid computing equivalent paths)

- Use separable properties, instead of large, combined ones

- Lossy compression, e.g., hash-compact and bitstate hashing
  - May result in incompleteness
- Lossless compression and alternate state representation methods
  - May increase time while reduce memory

“**On-the-fly**” construction of TS, $\mathcal{A}_{\neg\Phi}$ and the product automaton (while searching the automaton) to avoid constructing the complete state space

Time complexity of DFS: $O(\#\text{ of states} + \#\text{ of transitions in } TS \otimes A_{\neg\Phi})$

Closed system synthesis

Closed system: behaviors are generated purely by the system itself without any external influence

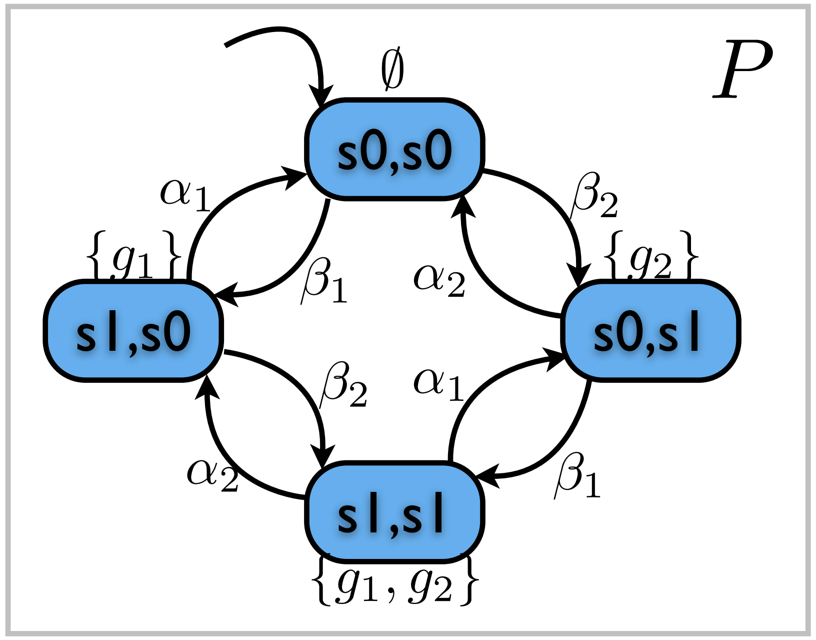
Given:

- A transition system *P*
- An LTL formula Φ

Compute: A path π of P such that

$$\pi \models \Phi$$

P: composition of two traffic lights



$$\Phi \quad = \quad \Box\neg(g_1 \wedge g_2) \wedge \Box\Diamond g_1 \wedge \Box\Diamond g_2$$

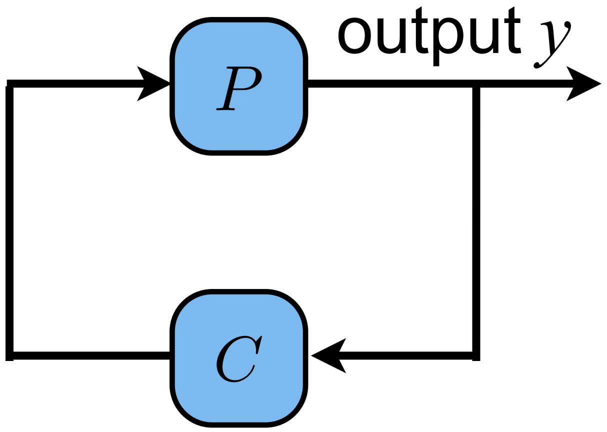
Sample paths of *P*:

$$\pi_1 \quad = \quad (\langle s_0 s_0\rangle\langle s_1 s_0\rangle\langle s_1 s_1\rangle\langle s_0 s_1\rangle)^\omega \text{ ✗}$$

$$\pi_2 \quad = \quad (\langle s_0 s_0\rangle\langle s_0 s_1\rangle)^\omega \text{ ✗}$$

$$\pi_3 \quad = \quad (\langle s_0 s_0\rangle\langle s_1 s_0\rangle\langle s_0 s_0\rangle\langle s_0 s_1\rangle)^\omega \text{ ✓}$$

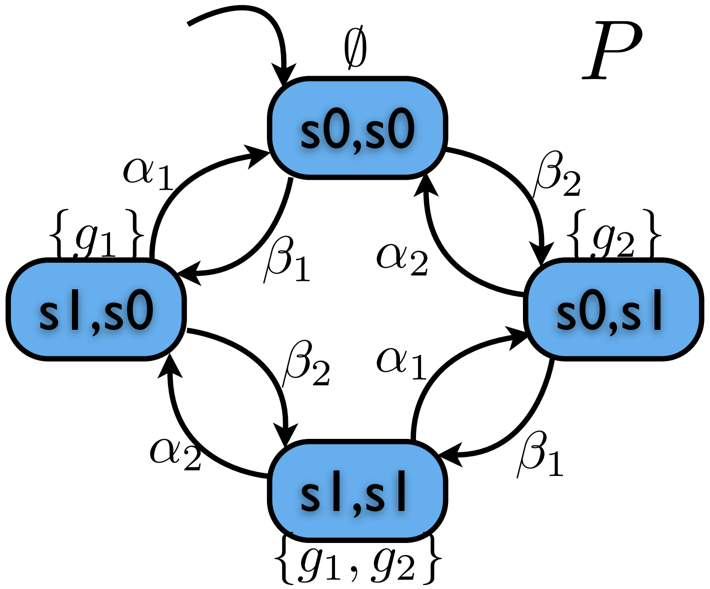
Closed system synthesis--a “controls” interpretation



memory domain

The controller *C* is a function $C : M \times S \to Act$

- The controller keeps some history of states
- It picks the next action for *P* such that the resulting path satisfies the specification Φ (i.e., *C* constrains the paths system can take.

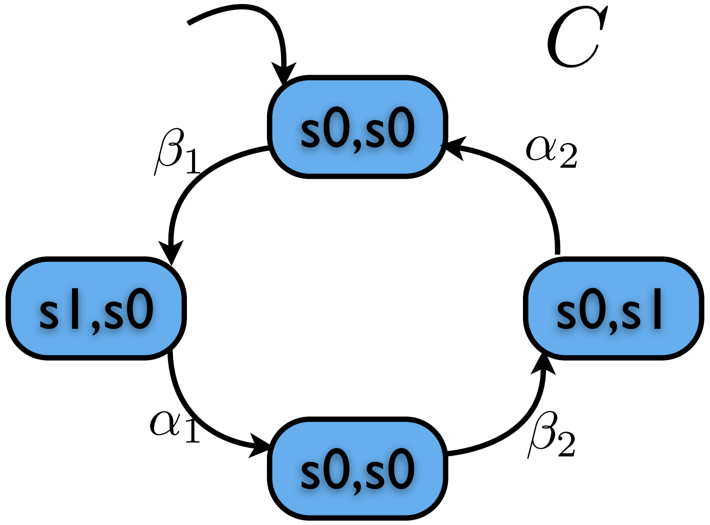


Let *M* be a sequence of length 1, i.e., the controller keeps only the previous state

$$\begin{aligned} C(\emptyset, \langle s_0 s_0 \rangle) &= \beta_1 \\ C(\langle s_0 s_1 \rangle, \langle s_0 s_0 \rangle) &= \beta_1 \\ C(\langle s_1 s_0 \rangle, \langle s_0 s_0 \rangle) &= \beta_2 \\ C(\langle s_0 s_0 \rangle, \langle s_1 s_0 \rangle) &= \alpha_1 \\ C(\langle s_0 s_0 \rangle, \langle s_0 s_1 \rangle) &= \alpha_2 \end{aligned}$$

$$\Rightarrow \pi = (\langle s_0 s_0 \rangle \langle s_1 s_0 \rangle \langle s_0 s_0 \rangle \langle s_0 s_1 \rangle)^\omega$$

and $\pi \models \Phi = \Box\neg(g_1 \wedge g_2) \wedge \Box\Diamond g_1 \wedge \Box\Diamond g_2$

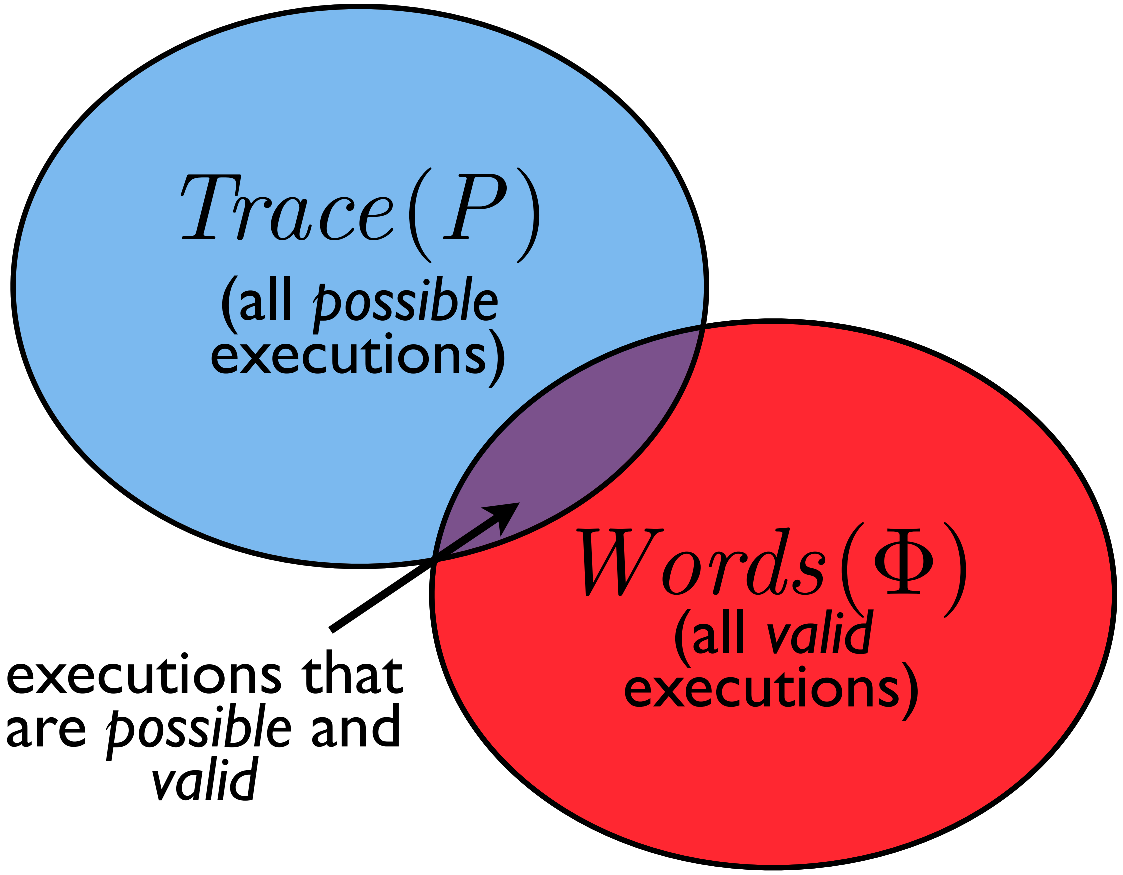


A solution approach

- Closed system synthesis can be formulated as a non-emptiness of the specification or satisfiability problem

$$\exists y \cdot \Phi(y)$$

- For synthesis problems, “interesting” behaviors are “good” behaviors (as opposed to verification problems where “interesting behaviors are “bad” behaviors)


$Trace(P)$
(all *possible* executions)
$Words(\Phi)$
(all *valid* executions)
executions that are *possible* and *valid*

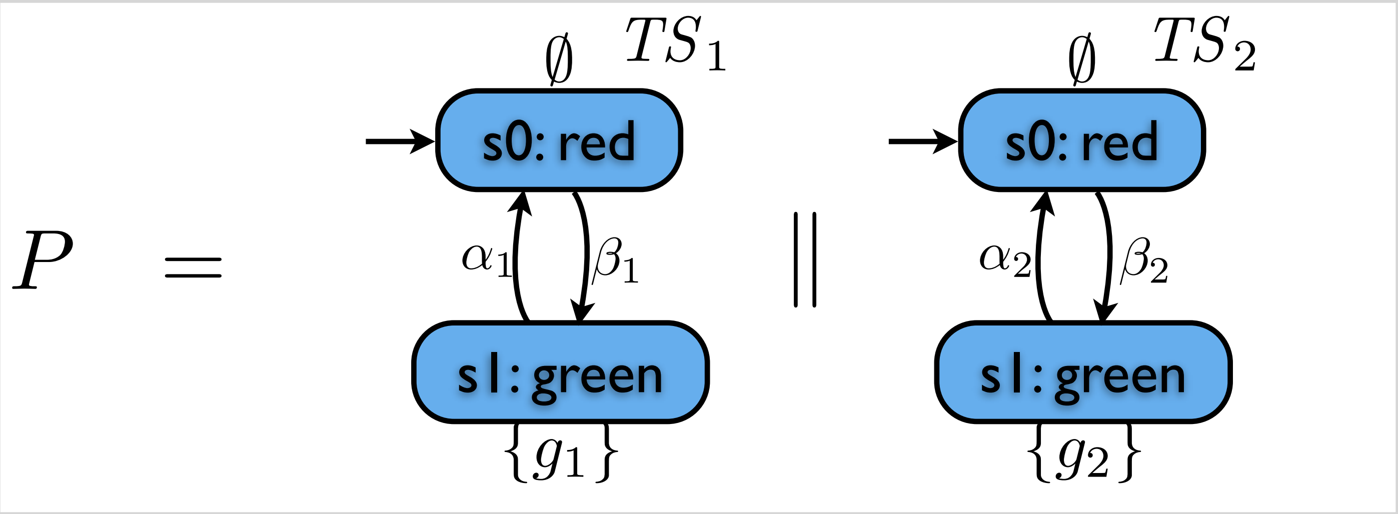
- Construct a verification model and claim that

$$Trace(P) \cap Words(\Phi) = \emptyset$$

  - A counterexample provided in case of negative result is a path π of *P* that satisfies Φ
  - Positive result means $Trace(P) \cap Words(\Phi) = \emptyset$, i.e., a path π of *P* that satisfies Φ does not exist

Example: traffic lights

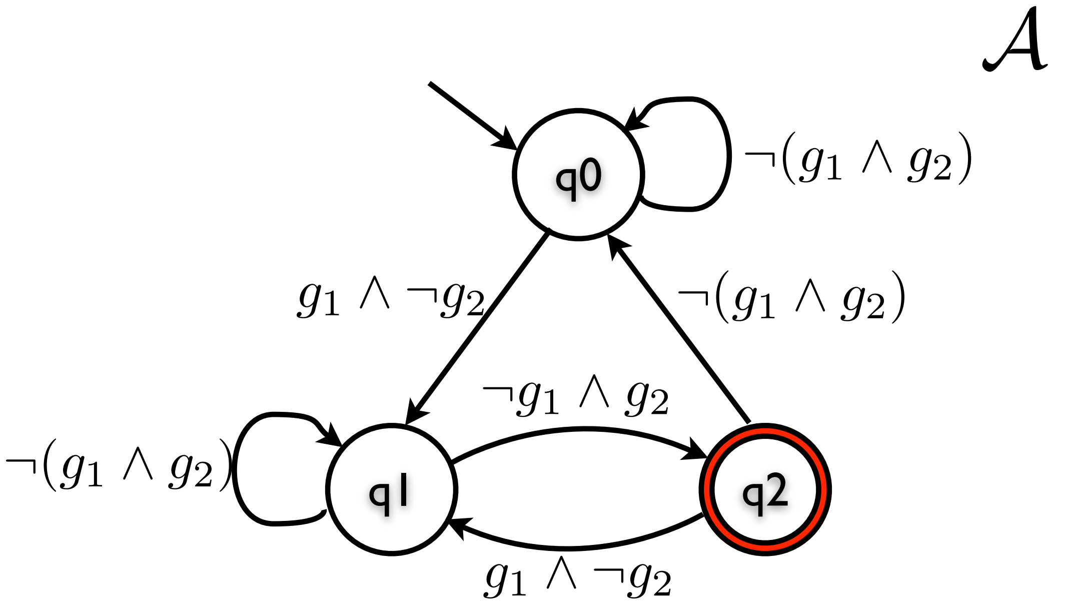
System model:



Specification:

$$\Phi \;=\; \Box\neg(g_1 \wedge g_2) \wedge \Box\Diamond g_1 \wedge \Box\Diamond g_2$$

$$\Big\Downarrow \; \mathcal{L}_\omega(\mathcal{A}) = Words(\Phi)$$



SPIN code:

System model (asynchronous composition):

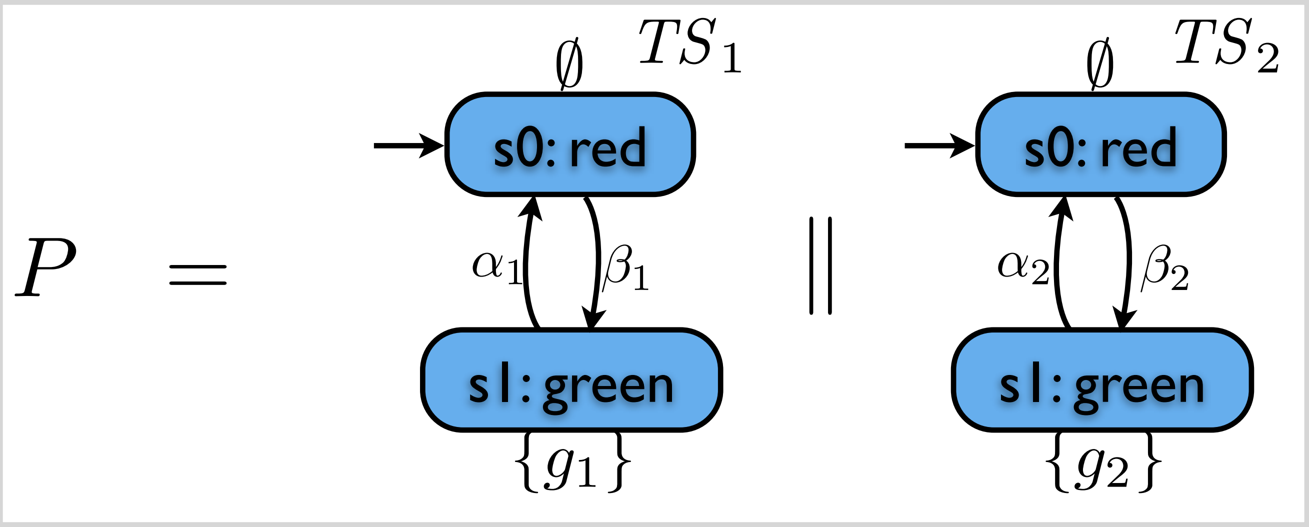
```
active proctype TL1() {
   do
   ::  atomic{ g1 == 0 -> g1 = 1}
   ::  atomic{ g1 == 1 -> g1 = 0 }
   od
}
active proctype TL2() {
   do
   ::  atomic{ g2 == 0 -> g2 = 1}
   ::  atomic{ g2 == 1 -> g2 = 0 }
   od
}
```

Automaton from LTL2BA:

```
T0_init:
   if
   ::  (!g1) || (!g2) -> goto T0_init
   ::  (g1 && !g2) -> goto T1_S1
   fi;
T1_S1:
   if
   ::  (!g1) || (!g2) -> goto T1_S1
   ::  (!g1 && g2) -> goto accept_S1
   fi;
accept_S1:
   if
   ::  (!g1) || (!g2) -> goto T0_init
   ::  (g1 && !g2) -> goto T1_S1
   fi;
}
```

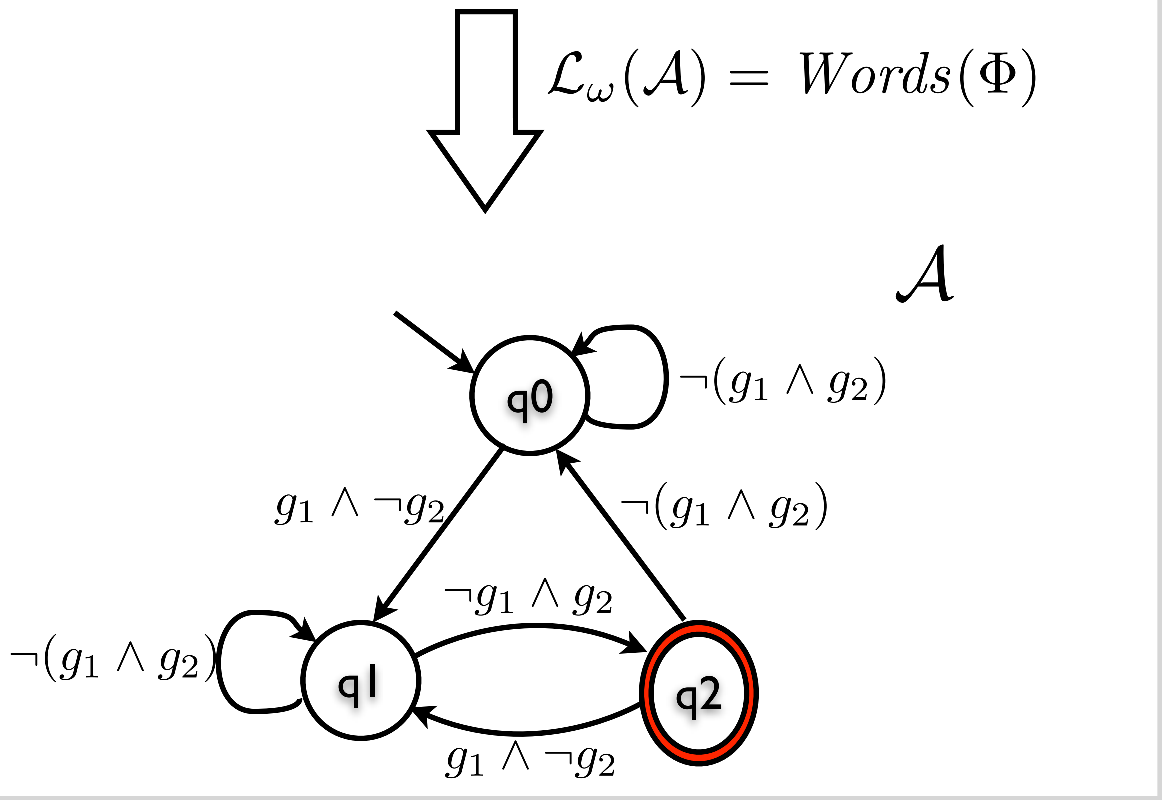
Solution to the traffic light problem

System model:

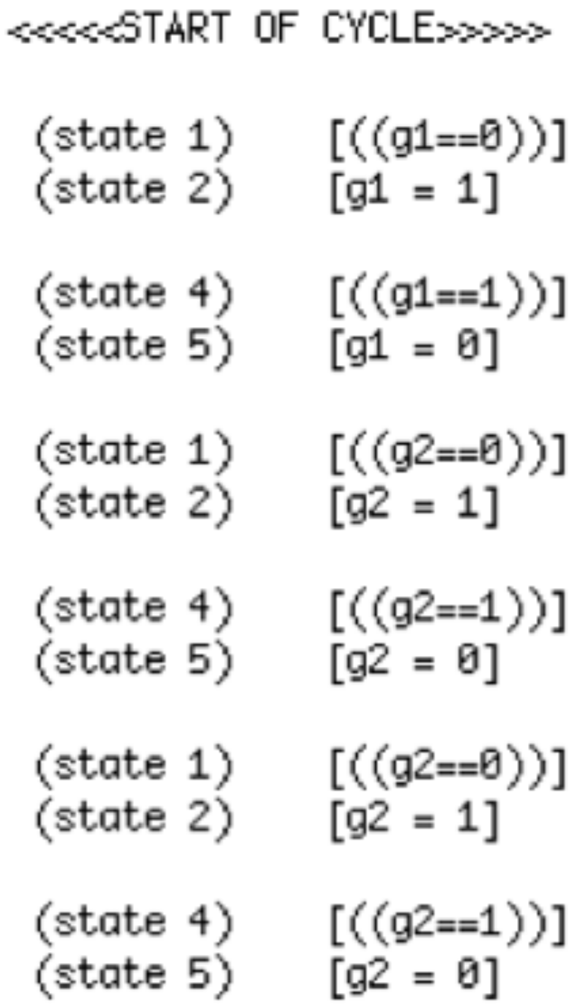


Specification:

$$\Phi = \Box\neg(g_1 \wedge g_2) \wedge \Box\Diamond g_1 \wedge \Box\Diamond g_2$$

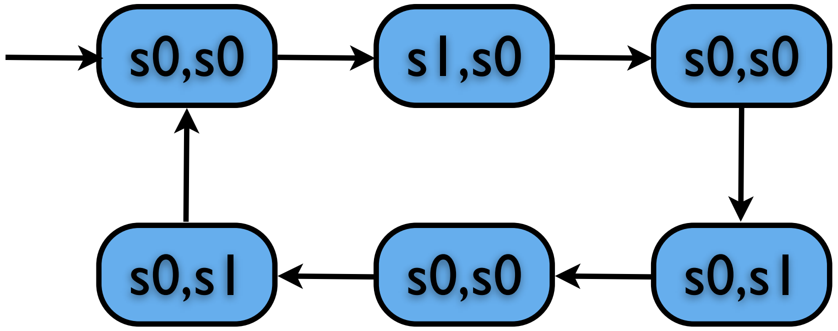


Solution from SPIN output:



```
<<<<<START OF CYCLE>>>>>

(state 1)    [((g1==0))]
(state 2)    [g1 = 1]

(state 4)    [((g1==1))]
(state 5)    [g1 = 0]

(state 1)    [((g2==0))]
(state 2)    [g2 = 1]

(state 4)    [((g2==1))]
(state 5)    [g2 = 0]

(state 1)    [((g2==0))]
(state 2)    [g2 = 1]

(state 4)    [((g2==1))]
(state 5)    [g2 = 0]
```

$$\pi = (\langle s_0 s_0\rangle\langle s_1 s_0\rangle\langle s_0 s_0\rangle\langle s_0 s_1\rangle\langle s_0 s_0\rangle\langle s_0 s_1\rangle)^\omega$$



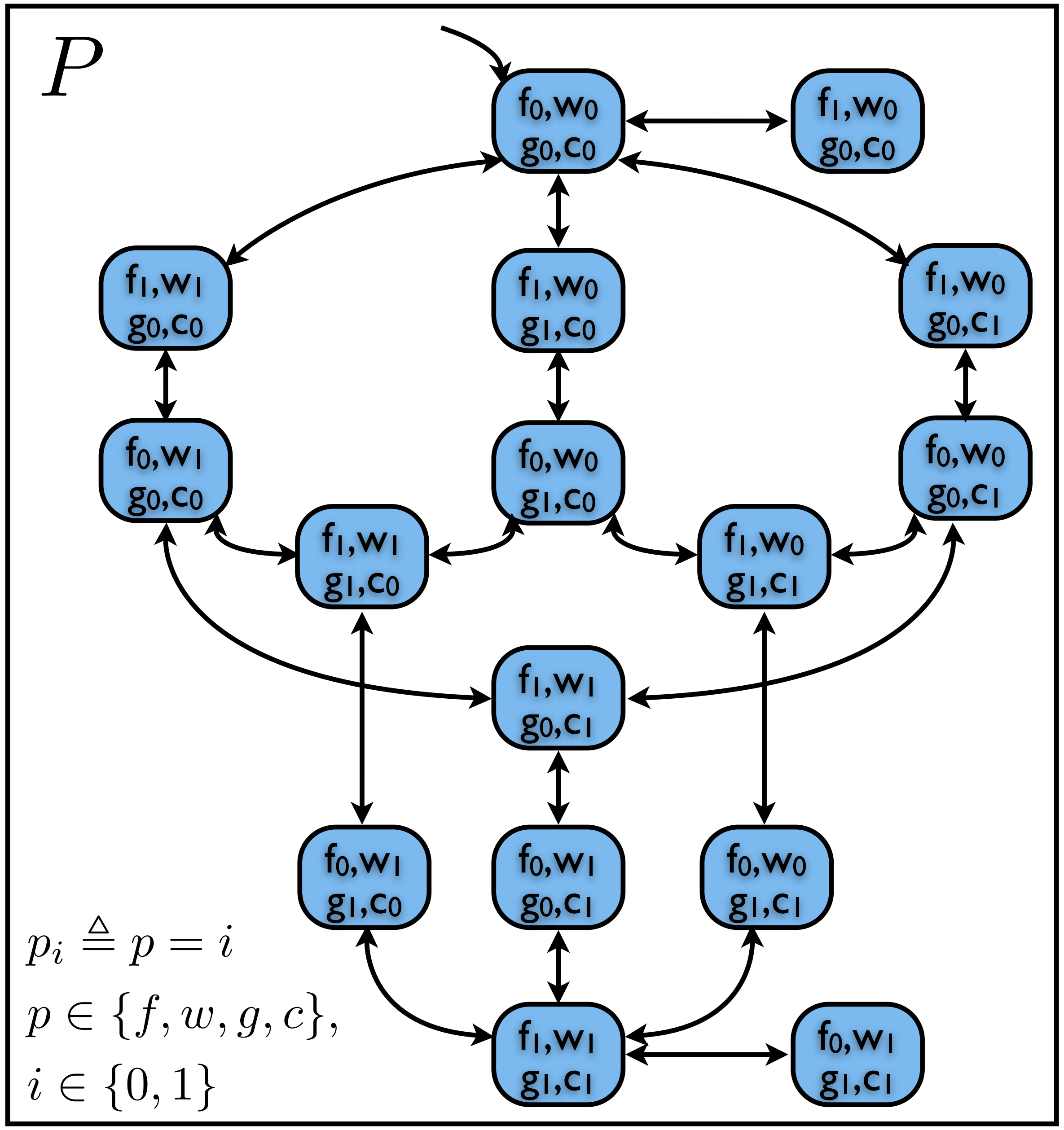
Example: the farmer puzzle

A farmer wants to cross a river in a little boat with a wolf, a goat and a cabbage.

Constraints:

- The boat is only big enough to carry the farmer plus one other animal or object.
- The wolf will eat the goat if the farmer is not present.
- The goat will eat the cabbage if the farmer is not present.

How can the farmer get both animals and the cabbage safely across the river?



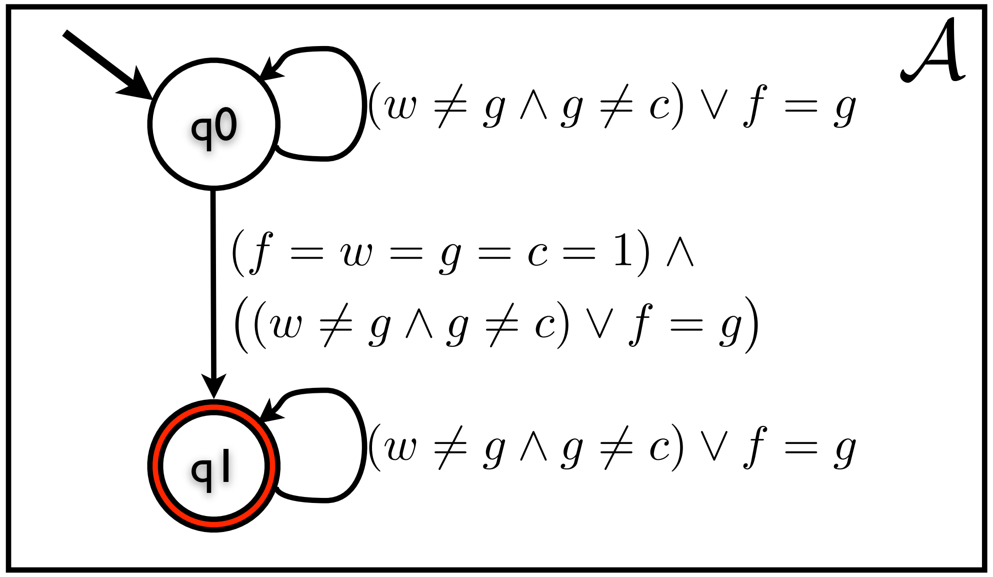
$p_i \triangleq p = i$

$p \in \{f, w, g, c\}$,

$i \in \{0, 1\}$

$$\begin{aligned}\Phi \quad = \quad & \Diamond(f = w = g = c = 1) \wedge \\ & \Box(w \neq g \vee f = g) \wedge \\ & \Box(g \neq c \vee f = g)\end{aligned}$$

$\mathcal{L}_\omega(\mathcal{A}) = Words(\Phi)$


$\mathcal{A}$
q0
$(w \neq g \wedge g \neq c) \vee f = g$
$(f = w = g = c = 1) \wedge$
$((w \neq g \wedge g \neq c) \vee f = g)$
q1
$(w \neq g \wedge g \neq c) \vee f = g$

Solving the farmer puzzle (using SPIN)

A farmer wants to cross a river in a little boat with a wolf, a goat and a cabbage.

Constraints:

- The boat is only big enough to carry the farmer plus one other animal or object.
- The wolf will eat the goat if the farmer is not present.
- The goat will eat the cabbage if the farmer is not present.

System model in SPIN:

```
active proctype P() {
   do
   ::  f=1-f
   ::  atomic{ f==g -> f=1-f; g=1-g }
   ::  atomic{ f==w -> f=1-f; w=1-w }
   ::  atomic{ f==c -> f=1-f; c=1-c }
   od
}
```

farmer crosses the river alone

farmer and goat cross the river

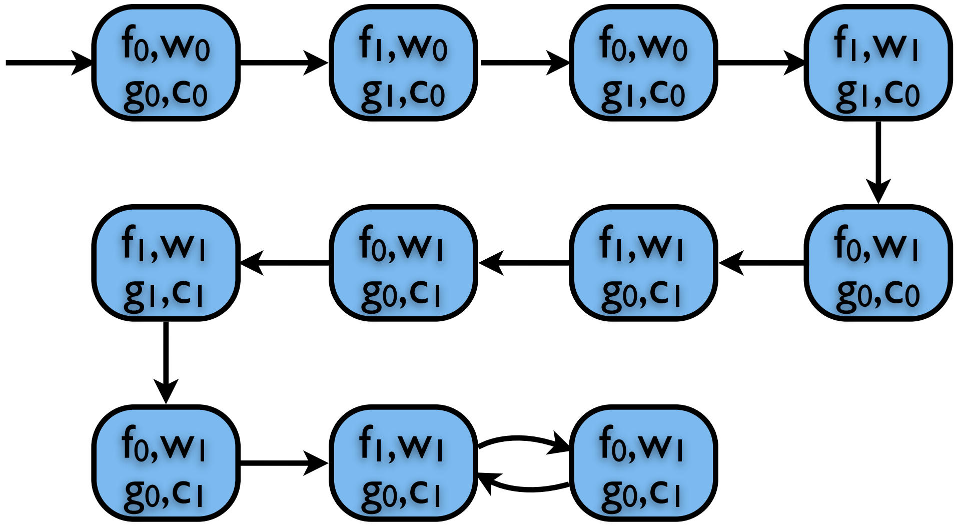
farmer and wolf cross the river

farmer and cabbage cross the river

Specification:

$$\begin{aligned}\Phi \quad = \quad & \Diamond(f = w = g = c = 1) \wedge \\ & \Box(w \neq g \vee f = g) \wedge \\ & \Box(g \neq c \vee f = g)\end{aligned}$$

A solution:



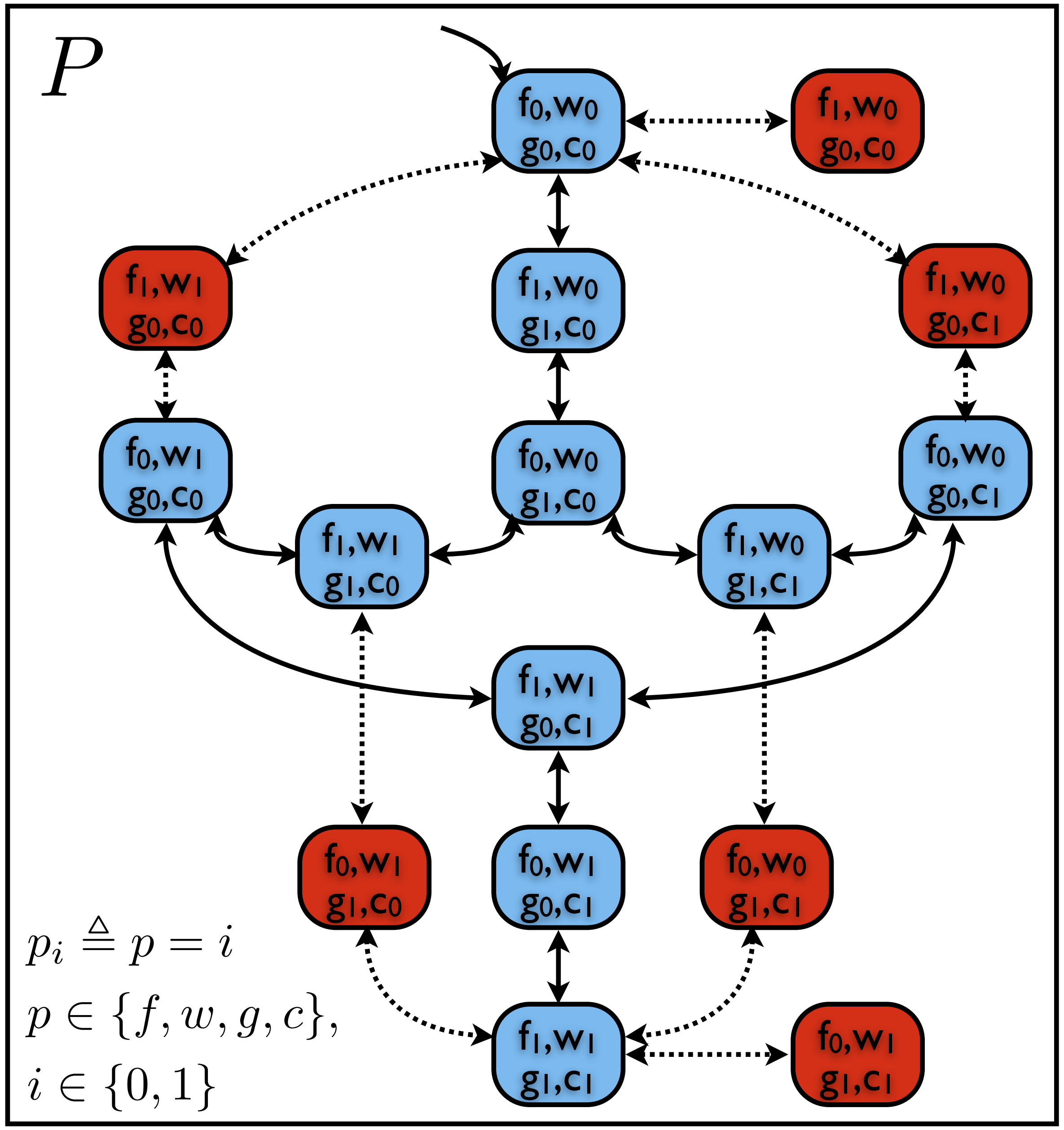
Alternative solution

A farmer wants to cross a river in a little boat with a wolf, a goat and a cabbage.

Constraints:

- The boat is only big enough to carry the farmer plus one other animal or object.
- The wolf will eat the goat if the farmer is not present.
- The goat will eat the cabbage if the farmer is not present.

How can the farmer get both animals and the cabbage safely across the river?



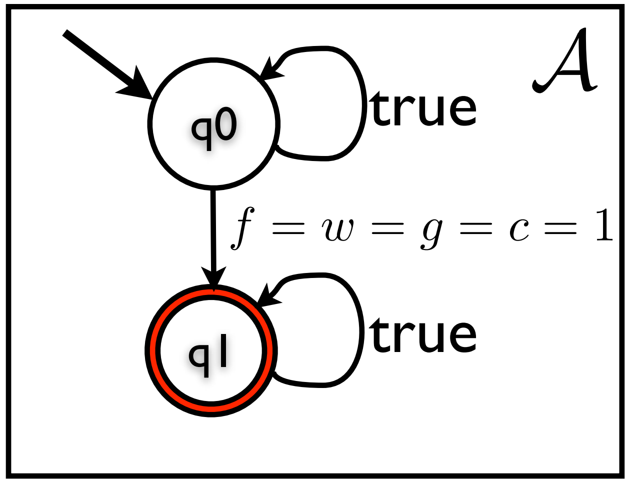
$p_i \triangleq p = i$

$p \in \{f, w, g, c\}$,

$i \in \{0, 1\}$

$$\Phi \quad = \quad \Diamond(f = w = g = c = 1)$$

$$\mathcal{L}_\omega(\mathcal{A}) \; = \; Words(\Phi)$$



Alternative solution

A farmer wants to cross a river in a little boat with a wolf, a goat and a cabbage.

Constraints:

- The boat is only big enough to carry the farmer plus one other animal or object.
- The wolf will eat the goat if the farmer is not present.
- The goat will eat the cabbage if the farmer is not present.

System model in SPIN:

```
active proctype P() {
   do
   ::  atomic{ (g!=c && g!=w) -> f=1-f }
   ::  atomic{ f==g -> f=1-f; g=1-g }
   ::  atomic{ (f==w && g!=c) -> f=1-f; w=1-w }
   ::  atomic{ (f==c && g!=w) -> f=1-f; c=1-c }
   od
}
```

farmer can cross only when goat and cabbage are not at the same place and goat and wolf are not

farmer and goat can cross only when they are at the same place

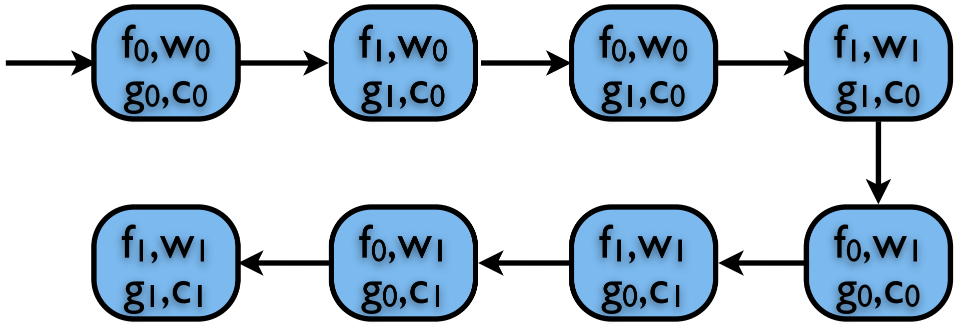
farmer and wolf can cross only when they are at the same place and goat and cabbage are not

farmer and cabbage can cross only when they are at the same place and goat and wolf are not

Specification:

$$\Phi \quad = \quad \Diamond(f = w = g = c = 1)$$

Another solution:

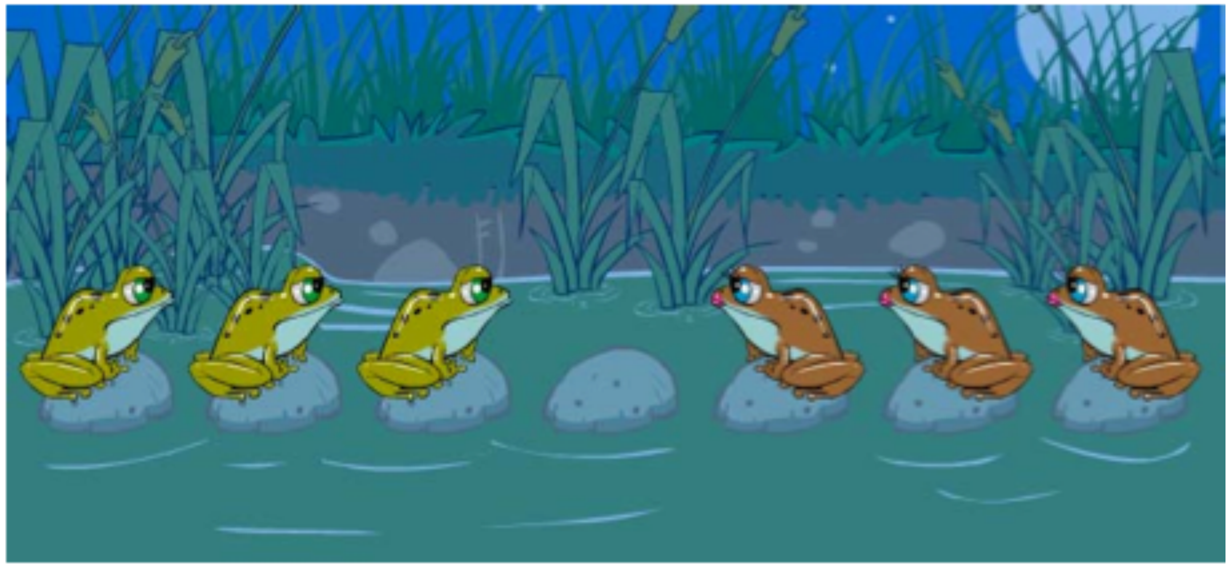


Example: frog puzzle

Find a way to send all the yellow frogs to the right hand side of the pond and send all the brown frogs to the left hand side.

Constraints:

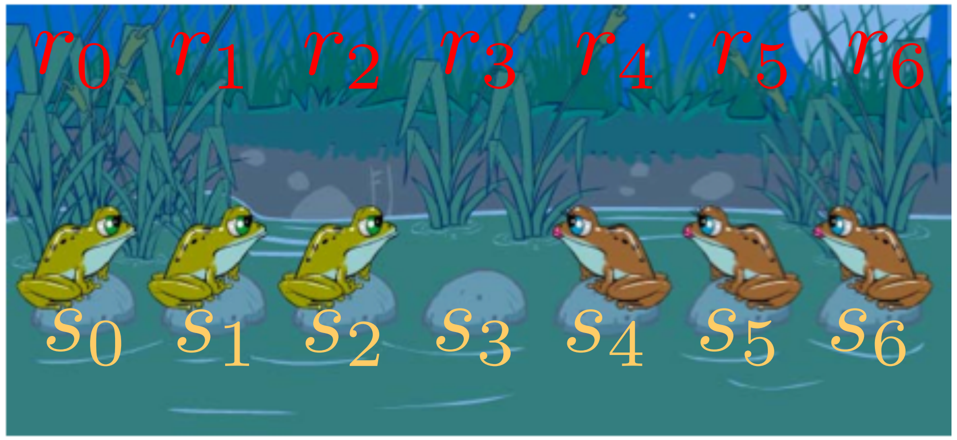
- Frogs can only jump in the direction they are facing.
- Frogs can either jump one rock forward if the next rock is empty or they can jump over a frog if the next rock has a frog on it and the rock after it is empty.

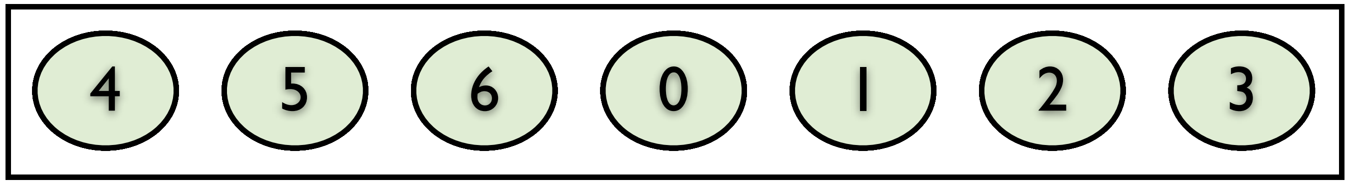


http://www.hellam.net/maths2000/frogs.html

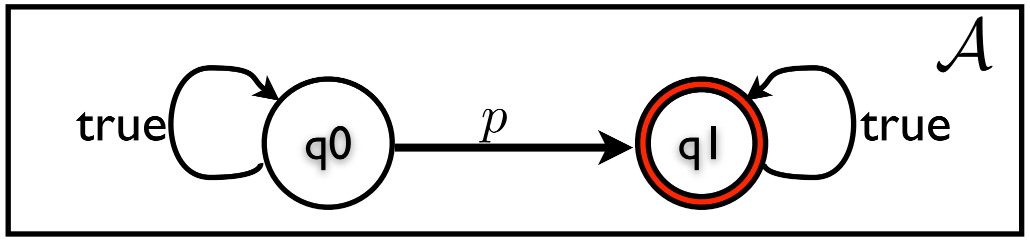
Solving the frog puzzle as logic synthesis

- Rock *i* is not occupied or occupied $r_i \in \{0,1\}$
- State of frog *i*: $s(F_i) \in \{s_0, s_1 \ldots, s_6\}$
- Transition system of frog *i*: F_i
- Overall system model: $P = F_1 \parallel F_2 \parallel \cdots \parallel F_6$


r_0 r_1 r_2 r_3 r_4 r_5 r_6
s_0 s_1 s_2 s_3 s_4 s_5 s_6



$$\Phi = \Diamond\big(s(F_1), s(F_2), s(F_3) \in \{s_4, s_5, s_6\} \wedge s(F_4), s(F_5), s(F_6) \in \{s_0, s_1, s_2\}\big)$$



$$p \triangleq \big(s(F_1), s(F_2), s(F_3) \in \{s_4, s_5, s_6\} \wedge s(F_4), s(F_5), s(F_6) \in \{s_0, s_1, s_2\}\big)$$